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Estimating Body Mass through Bone Mineral Density Studies Using Dexa (Dual-Energy X-Ray Absorptiometry)

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ESTIMATING BODY MASS THROUGH BONE MINERAL DENSITY STUDIES USING DEXA (DUAL-ENERGY X-RAY ABSORPTIOMETRY)

by

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ABSTRACT

Identification of a decedent is one of the primary goals of forensic anthropologists. In order to do this, one must build a biological profile based on the remains that are provided. Sex, age, ancestry, and stature are four of the most common, however a fifth addition piece of information that could be beneficial is body mass. The goal of this research is to explore the relationship between bone mineral density (BMD) and body mass, using data collected from dual x-ray absorptiometry (DEXA) scans of 107 collegiate football athletes. Athletes are a good fit for this study because they have achieved or almost achieved their peak bone mass by this age, and the weight fluctuations that occur throughout an individual's lifetime have yet to occur. The bone mineral density values were analyzed by individual body sections (arms, legs, and pelvis) as well as the total body. The analysis calculated correlations between the different BMD sections and variables such as height, weight, and ancestral background. The results show that there is not a strong relationship between BMD and body mass of young, male, collegiate football players. In European Americans, the sample had a higher correlation of arm BMD to body weight than leg BMD. In contrast in the African American sample they had a higher correlation of leg BMD to body weight. The findings of this study are similar to others using DEXA and other body mass measures in that the estimations are not sufficiently reliable for forensic purposes.

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I have a few people who I'd like to dedicate this to because without them and their support I would have not gotten this far.

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LIST OF ABBREVIATIONS

BMD	Bone Mineral Density
BMI	Body Mass Index
DEXA	Dual-Energy X-ray Absorptiometry
GRF	Ground Reaction Force

CHAPTER I - INTRODUCTION

Identification of a decedent is one of the primary goals of forensic anthropologists. When given skeletal remains, the analysis that is possible with them depends upon the condition of the remains and what elements are present. Sex and age determinations of an individual have well accepted methods with high degrees of accuracy, while ancestry determination is less definitive, especially with the increasing migration and admixture associated with globalization of the world (Thomas, Parks, and Richard 2017; 2016). In comparison, stature is a piece of the biological profile that has a more concrete foundation of methods (Brandt 2009). However, body mass is another aspect of an individual that would be highly beneficial for identification in forensic investigations in terms of narrowing down the possibilities, especially with the increasing variability in body mass in modern populations; however, there currently is no well accepted method to make such an estimation from skeletal remains.

Studies have established a correlation between bone density and body mass on living and non-living individuals (Lacoste Jeanson et al. 2017; Moore 2008; Moore and Schaefer 2011; Navega et al. 2018; Wheatley 2005) and offer one strategy that might be used by forensic anthropologists in their estimation efforts. Bone mineral density provides information about the health and strength of the bones. The bones have to be dense enough to support an individual with the daily physical necessities of life; therefore, a heavier individual will need to have denser bones. If the bones are not strong enough, they will fail and result in fractures (Moore 2008). Considering the lower half of an individual is load bearing, the main focus for body mass estimation has been on the

lower limbs (Lacoste Jeanson et al. 2017; Moore 2008; Navega et al. 2018; Wheatley 2005).

Bones react to the mechanical loading that is placed upon them. Loading can best be described as the force exerted on bone. There are four different ways by which bone can be loaded, depending on the angle and amount of force: tension, compression, shear, and bending forces (Frankel and Nordin 1980). In order to withstand compression and tension that occurs to some regions of bones, they increase in surface area and/or in a cross-sectional area. In addition to strength, bones have a little flexibility similar to a fresh tree branch or if you try to bend a plastic ruler (Larsen 1997). They will have just enough give to withstand the pressures of activities that involve the flexing of the knee such as walking upstairs or hiking (Larsen 1997; Lovejoy, Burstein, and Heiple 1976; Ruff 1987).

Overall, research suggests that bone mineral density should be higher in obese or larger individuals while individuals with low body mass index (BMI) should have a lower bone mineral density. Individuals who are obese do have a higher risk of developing osteoarthritis which is rarely associated with osteoporosis (Moore 2008). To study bone mineral density of individuals, whether researching living individuals or skeletal remains, a number of methodologies have been used, ranging from Computed Tomography (CT) to photodensitometry.

For the last 32 years, Dual-Energy X-ray Absorptiometry (DEXA) has been used to estimate bone density of a living individual ("DXA-Evolution_Feb2011.Pdf," n.d.) and can potentially be a method to estimate body mass used by forensic anthropologists. DEXA takes a more mechanical approach to determine body mass index by scanning the

full body of an individual and sending two beams of energy; one measures the soft tissue, while the other focuses on the bone. It is also rather sensitive to even the smallest of changes in bone density and body composition. In comparison, the more traditional and physical measurements focus on the different regions of the body, which these measurements are then calculated with height and weight to output a body mass percentage (Rothney et al. 2009). Compared to this ‘by hand’ method, DEXA is more accurate while being less subjective and quicker, minimizing inter/intra-observer error (López-Taylor et al. 2018; Raymond et al. 2017).

Due to the precision of the DEXA machine, I employed it as a method of testing whether body mass can be predicted from bone density for forensic purposes. The sample used in this study were collegiate athletes, football players specifically; although they all play the same sport, they represent a variety of different body compositions from individuals who are more likely to be tall and slender, such as a wide receiver or quarterback versus more robust players such as linemen. The regularity of DEXA scans on athletes as well as their variability in body composition makes them an ideal sample on which to test the relationship of bone density with body mass. Athletes are routinely measured, and their health is monitored, which is another reason why they were especially appropriate to study. Furthermore, athletes are all young adults, which is the same primary population as most individuals involved in forensic cases (“Homicide Fact Sheet 2017”; Perkins 1997).

I analyzed scans from 107 collegiate athletes of a range of body types to determine the strength of the correlation with BMI as determined by DEXA. I looked at the measurements of different portions of the skeleton on the scans, such as the arms,

legs, and pelvis, as well as the total bone mineral density (BMD). It was my hypothesis that bone mineral density would have a strong, positive relationship with body mass. I believed that the lower limbs would be a better predictor of body mass than the remainder of the skeleton. I also predicted that larger, heavier individuals who have a higher body mass estimation would have a thicker or higher bone mineral density amount.

This study contributed to the research and literature in the field because the current data and methods on estimating an individual's body mass relies largely on skeletal collections, rather than scans of living individuals. If this methodology is proven to be accurate on an individual level, it could bring a new and beneficial technique to use in forensic cases. The few previous investigations that utilized DEXA and bone density for body mass estimation techniques used skeletal remains instead of living individuals, employing rice or sand to compensate for the lack of soft tissue surrounding the bones. My study was unique in that it used living individuals, and it had young adults as its primary component rather than one skewed more towards older aged individuals typically seen in samples derived from donations. Young adults also have not had any "lifetime fluctuations" in their body weight, which need to be accounted for in a sample of older individuals. In all, body mass potentially provides a valuable new dimension to the biological profile.

CHAPTER II – LITERATURE REVIEW

There are multiple variables involved in the analysis of bone density, and therefore a review of each factor is important for proper understanding of the study. First, bone morphology and how stress impacts the bones will be discussed. Next, a review of how DEXA operates is given along with the different potential bone mineral density estimation methods. Following this is an examination of specific applications of DEXA on bone mineral density of individuals with a focus on body mass estimation research. Then the chapter closes with a review of previous studies using athletes as a sample population and DEXA.

Bone Morphology

Bone morphology reflects the stresses experienced. The more stress that is placed on the bone, the more the bone will try to adapt to that outside pressure. Tension, shear, bending and compression are the four ways that pressure can be placed on bones (Frankel and Nordin 1980). The biggest influence among these is compression.

To understand the how the loading forces affect the bone, one must first understand that the structure of bone is made of both organic and nonorganic components. They each play a role in the strength and flexibility of bone. These components come from our diets that we eat; therefore, as we choose our diet (such as athletes do), it is important to have a well-balanced diet with all the proper nutrients to keep our bodies healthy and running properly. Calcium is a main contributor for the bone strength support. In contrast, the flexibility of the skeleton results from the fact that collagen comprises about one-third of the bone tissue (Burstein et al. 1975). This is how we can do daily activities and exercise regularly without our bones snapping from simply

walking up a flight of stairs or hiking up a mountain. However, collagen can only allow our bones to be flexible up to a certain point. If too much stress is put on the bones too quickly, the stress will cause the bone to fracture. If an individual falls, the sudden movement of trying to catch or brace for the impact that hitting the ground creates will sometimes break the bone if the force or pressure is placed on just the right spot or exceeds the threshold of the bone.

Intertwined Variables

Sex

There are a number of variables that must be taken into account when looking at body mass and bone mineral density (BMD) relationships, one of the most important being sex. Whether an individual is male or female determines the rate at which bone mineral density declines. A consensus among researchers is that bone density in females will be relatively stable until they hit about 40 years old, and then a slow decline begins, which rapidly accelerates after age 55 (Gibson et al. 2004; Miyabara et al. 2007). That is why elderly women who fall are more likely to suffer fractures as compared to their male counterparts. Males, on the other hand, will remain somewhat consistent in their BMD during their lifetime until about 60 years old when they also begin to decline to levels that are almost equivalent with those of females (Rogucka et al. 2000).

It also has been commonly observed that smaller women have a higher chance to have osteoporosis than do larger women. The reasoning behind this is because of the effect of estrogen on a female's body. Estrogen affects the bone in multiple ways, but the biggest impact, is it works as a bone resorption inhibitor (Kameda et al. 1997). This means that every time estrogen levels rise, osteoclasts work harder to tear down bone,

and at the same time the estrogen blocks osteoblasts from synthesizing. Thus, when estrogen levels rise every month, it tilts the equilibrium of osteoclasts and osteoblasts, tearing down more bone than it can build (Eviō et al. 2004). Moore explored the possible explanations and concluded that it could be from "increased estrogen stores in adipose tissue of heavier women or beta cell hormones, recognized for maintenance of bone metabolism, or due to decreased bone strength from decreased compression, or a combination of the two" (Moore 2008, 18). It also explains why the number of menstrual cycles following menarche is strongly correlated with BMD (Gibson et al. 2004; Miyabara et al. 2007).

Ancestry

Another variable affecting BMD is ancestry (Leslie 2012; Liel et al. 1988; Manifold 2014; Nelson and Villa 2003; Shen et al. 2012; Wheatley 2005), which plays a role in total body mineral content as well as that of certain bones (Manifold 2014). On average, individuals of African descent have a higher BMD than individuals of other backgrounds (Nelson and Villa 2003), as seen in Figure 1 which shows the risk for osteoporosis and the risk of fracture among different ethnic groups (Leslie 2012).

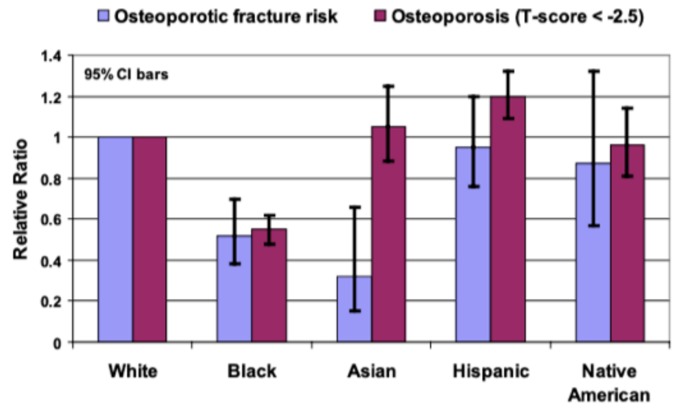

Figure 1. *Osteoporosis and Fracture Risk by Ethnicity.*

(Leslie 2012, 4332)

Black women have a lower risk for a t-score in the osteoporotic range and also have a relatively low range for a potential fracture. Hispanic and Native American women, on the other hand, have values similar to those seen in White women. The ethnic group that was most different from the others is Asian women. They have a higher risk of osteoporosis of the group, but their fracture risk is noticeably lower. When circling back to Black women, the BMD fracture relationship is very different from than that seen in Asian women. Therefore, when studying skeletal remains, if the ancestry of the individual is not known, it could make the results less accurate.

In general, it has been found that African Americans have a higher BMD than European Americans. Baker and Newman (1957) researched the bone weight differences between European Americans and African Americans. They assessed the bones of 20 African Americans and 95 European Americans in their study. Baker and Newman (1957) compared the reported living weights to the dry skeletal weight, in addition to specific bones such as the dry weight of the femur. Their research showed that on average

African American skeletons were approximately 7% heavier than European American skeletons (Baker and Newman 1957, 605).

Nutrition

Nutrition has a significant impact on an individual's BMD. This is why it is crucial to get the necessary amount of nutrients of the correct vitamins and minerals as a child. As a child is growing, undernutrition can cause growth problems that will affect the mineral density of the bones, which leads to problems as an adult. Undernutrition can cause a thinning of the cortical bone that is directly linked to nutritional stress (Hummert 1983). The development of bone mass is mostly related to calcium and protein. Calcium is the most important nutrient to take in throughout life for the best bone health. A sufficient intake will help maintain the demands for bone maintenance. An adequate or average amount of protein is the best for the skeleton because a low or high protein diet can result in lower bone mineral density. This result has been seen in studies of Inuit due to their high protein diets (Lynnerup and von Wowern 1997).

Phosphorous is another major player in bone health. However, it is not as likely to receive as much attention as calcium because of its abundance in the daily diet (Manifold 2014). The third most important nutrient is vitamin D. If calcium is not readily available, vitamin D is the best substitute, though it cannot replace calcium. A lack of Vitamin D can lead to rickets which displays the bowing of the long weight-bearing bones because they are not strong enough to support an individual. As a result, their BMD would be assumed to be low. Childhood health experience is the primary factor when it comes to the quality of life/health as an adult. A child with inadequate protein and low caloric intake can suffer from a number of health problems, including slow growth and the

decreased formation of cortical bone growth (Garn 1970). Even as an adult, it is important to maintain the intake of these vitamins and minerals for the upkeep of bone health.

Exercise

Exercise is another variable that should be taken into account. Our ancestors had a greater emphasis on heavy lifting and labor-intensive lives. Given the much less physical demand of modern times, bones are generally not being pushed to their limits in a healthy way to strengthen and maintain them. The use of weights and exercise helps to maintain bone strength rather than losing it slowly over time (Andreoli et al. 2001). Exercise such as weightlifting assists the bones to adapt to this weight being lifted and therefore the density grows stronger to support it. This is the same concept as why body mass and bone density should be correlated.

Genetics

In addition to these factors, a variable which cannot be controlled is genetics. Genetics can be a factor in low bone mineral density and increase the likelihood of developing osteoporosis. Genetics is estimated to be responsible for 60-80% of the variability in peak bone mass between individuals as determined through multiple adult and twin studies (Albagha and Ralston 2003). If an osteoporotic woman has a daughter, her daughter is more likely to have lower bone mass than compared with a non-osteoporotic woman (with all the same other variables equal) (Smith and Wordsworth 2016). This suggests that rather than a difference in the loss of BMD, it would be more closely related to the peak bone mass achieved during childhood. Researchers know that

the variability is due to genetics; however, they are not sure what genes are responsible, only those that have been implicated (Nelson and Villa 2003).

Medical Conditions

Finally, there are less widely acknowledged factors that can also play a role on an individual's bone density. Certain medical conditions and medications can have an effect on an individual's bone density. This is referred to as secondary osteoporosis. Secondary osteoporosis can be caused by dietary, lifestyle, endocrine, metabolic, systemic diseases, surgery/transplantation, and certain medications (Miazgowski et al. 2012). Common dietary causes can be from excessive vitamin A or protein intake, or an inadequate amount of vitamin D intake. Excessive alcohol intake as well as smoking are also dietary causes. Having low physical activity or being immobilized for a longer period of time are lifestyle risk factors. Other factors that may affect BMD are endocrine factors such as diabetes, hyperthyroidism or pregnancy. Metabolic diseases involved could be malabsorption syndrome or chronic metabolic acidosis (Miazgowski et al. 2012). Certain systemic diseases, such as inflammatory bowel disease, cystic fibrosis and rheumatoid arthritis, can cause secondary osteoporosis. Particular surgeries can play a role such as bariatric surgery or organ transplantation. Lastly, one of the most common influences are long-term use of medications such as corticosteroids, antiepileptics, and heparin (Miazgowski et al. 2012).

Body Weight

Even though all of these controllable and non-controllable variables affect our bone morphology and bone mineral density, one of the final and most important forces in shaping bones is an individual's body weight. Body weight would fall into the

compression category of the forces affecting bone loading. Bones adapt to mechanical pressure that is placed upon them. When a heavier load is placed on bone, the internal structure of the bone changes to become stronger to resist the pressure, which is known as Wolff's Law (Ruff, Holt, and Trinkaus 2006). Trabecular (porous, spongy bone) will go through remodeling first, while the cortical bone remodels after, thereby making the bone denser. Wolff's law explains the opposite action as well. If an individual loses weight, lightening the load on bones, the bones will become less dense and weaker in a sense because they no longer need to support as much of a load (Ruff, Holt, and Trinkaus 2006). Since the trabecular bone is the first to strengthen itself when a load is placed on the bone, it is the first to lose it, making it more vulnerable than cortical bone (Foster, Buckley, and Tayles 2012). Trabecular bone is concentrated towards the ends of long bones and the bodies of vertebrae. Due to this, these sites on the skeleton are the first to become manipulated, leaving them to be the focal points when studying anything relating to bone density.

The effects of compression on bone occur in other ways as well. Obese individuals have a greater axial-loading with hinge joints of the lower limbs, such as the flexion of the knee, which causes their bone diaphysis to have a thick but circular cross-section (Moore 2008). Due to the load applied to the knee joint, there is a correlation with osteoarthritis, a degenerative reaction, in obese individuals. This thickness of the lower limbs (the femur and tibia) means that obese individuals have a higher bone mineral density in addition to the higher likelihood of osteoarthritis (Ford et al. 2005; Mannienen, Heliövaara, and Mäkelä 1996). Individuals who are on the other end of the weight

spectrum are more at risk for osteoporosis because their bones are more at risk of fracture from the high correlation of low BMI and osteopenia, or low BMD.

Athletes and Bone Mass Density

Athletes are one particular population for whom muscle and bone health are rather consistently monitored (Steffen, Soligard, and Engebretsen 2012). This is largely done in part to prevent injury while participating in the conditioning or training as well as playing in games or matches. It is easier to nurture a weak spot in bone ahead of time rather than wait until a more serious break happens with a longer period of remission afterwards. Typically, those who partake in high impact, weight bearing sports and activities such as soccer and football are going to have stronger, more dense bones than those who are involved in sports involving non-weight bearing activities such as swimming or cycling because of the stress this type of movement places on the bones (Andreoli et al. 2001). The bones are put to the test over and over and are strengthened by these types of activities. This process will be discussed further in a later section.

Earlier Methods for Assessing Bone Mineral Density

To study bone mineral density (BMD), whether in living individuals or skeletal remains, a couple of different methods can be used. Bone density became of interest when doctors and physicians wanted to observe the changes in bone from conditions such as arthritis or cranial dysplasia (Mainland 1956; Mortimer, Levene, and Rowe 1937). The first attempts at actually assessing bone density occurred in the 1950s using very loose methods based on estimates from x-rays via the opaqueness of the bone. There was skepticism of accuracy because of the lack of standardization and the variables involved with X-ray that make the contrast/outcome of the X-ray vary (Mainland 1956). A few

techniques from earlier times that are still being employed are quantitative computed tomography (QCT), photodensitometry, single-photon absorptiometry, and quantitative ultrasound, each varying in their accuracy and applicability.

The QCT scanner “generates slice images as an array of pixels, with each pixel having a value depending on the attenuation of the X-rays as they pass through the object being scanned” (Carlton and Adler 2001, 35). These pixels are then scaled and calibrated, and changed into many different shades of gray, which then is remapped to about 20 shades, producing the best possible resolution for viewing the structure of the bone (Lynnerup 2007). This particular method has an advantage to studying trabecular bone because of its ability to display detail. Peripheral quantitative tomography is a particular type of QCT, focusing on the arms or legs, instead of the spine or hips.

Photodensitometry is the simplest method of all since it uses radiographs to look at the internal structure of a bone. This method was one of the first used for estimating bone density. It involves passing electromagnetic waves through the remains through an electronic field, and then a negative image is captured which results in an X-ray (Mays 2008). A standard step-wedge is used during the taking of the X-rays along with an optical densitometer which is the standard. There are also online software packages that can be used that calculate the optical density for the researcher (Mays 2008).

During a single-photon scan, the scan does not differentiate between cortical or trabecular bone of the bone cross section (Huddleston 1988). Due to this, an individual cannot determine whether bone loss is occurring from the cortex or marrow portion of the bone. A second photon was eventually added to improve this method, allowing for increased recognition of soft tissue vs bone. When dual-photon absorptiometry was

introduced, it was actually seen as less accurate than single-photon (Watt 1975). However, with minor improvements in the statistical portion of the analysis, this method became highly accurate, with scans of the spine with an error rate ranging from 1%-5% (Huddleston 1988).

Quantitative ultrasound (QUS) estimates bone density "by determining how rapidly sound travels through the tissue and how different sonic wavelengths are absorbed" ("Quantitative Ultrasound | Definition of Quantitative Ultrasound by Medical Dictionary" 2009). In essence, it measures the speed of sound. One advantage to this technique is it does not expose the patient to any radiation. It also is a quickly done procedure, which is convenient when working with infants and children. As well, QUS is less expensive, portable, and a trained technician is not required to operate the device (Allen and Krohn 2014). The disadvantage of QUS is the influence that soft tissue has upon the scan. The soft tissue blocks the QUS from getting a clear view of the bone. Due to this effect, it is confined to assessing only the appendicular skeleton (Allen and Krohn 2014).

These methods all have the strengths of being non-invasive and providing a high degree of detail about the internal structure of the bone. On the other hand, their shared weakness is that they only focus on a specific place on an individual bone or else the type of bone (cortical or trabecular) involved.

DEXA Technology

The most common method for estimating bone density currently is dual-energy x-ray absorptiometry, otherwise known as DEXA. DEXA is unlike any of the previous methods for estimations because of the stable X-ray source for the measurement of

mineral content. Dual-energy x-ray absorptiometry was nonexistent in the literature until the late 1980s, when its popularity increased dramatically into the 1990s. As with any technology, updates to software and hardware has drastically improved the overall quality of DEXA machines, which now include multiple manufacturers such as GE Healthcare, DMS Imaging, and Osteosys. The manufacturer may vary, but all DEXA machines work in the same manner by sending a thin, invisible beam of low-dose x-rays with two distinct energy peaks through the bones being examined. One of those peaks will be absorbed by mainly the soft tissue, while the other will focus on the bone.

When someone is scanned using a DEXA machine, the technician will input the individual's height and weight into the machine. The individual will lay on the table in minimal tight fitted clothing and the technician can set the machine to focus on the full body or focus more specifically on certain regions such as the hip or lumbar spine. The machine can also be tailored to focus specifically on the cortical bone or the trabecular bone of an individual. If doing a full body scan, the different parts of the body are split up into the head, arms, legs, trunk, ribs, pelvis, and spine. See Figure 2 below for a visual of an individual being scanned. The process typically takes five to ten minutes, depending on the size of the individual on the table. The bigger an individual, the longer it takes because the beams have more soft tissue to get through to get to the bone.

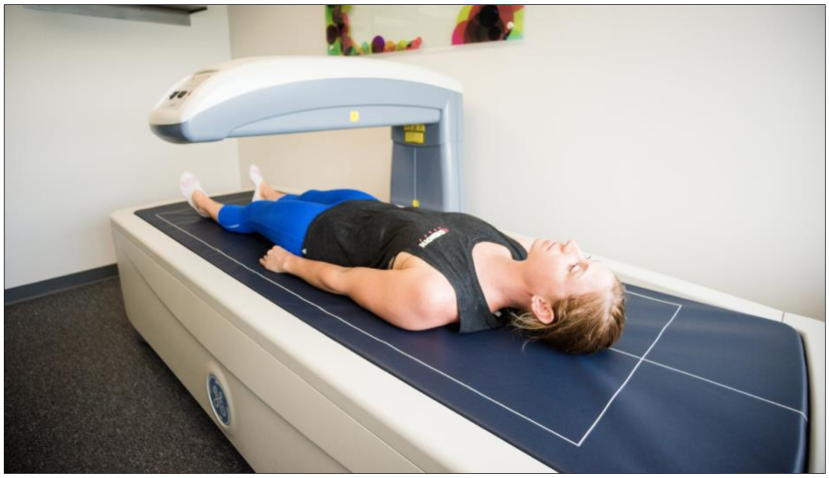

Figure 2. *Individual Being Scanned by DEXA.*

(“Image of Individual DEXA Scan” n.d.)

When finished scanning, the DEXA machine produces a report that displays several different variables. When looking at densitometry, the report will display two different images of the scan, one highlighting the skeleton with the other displaying a shadow of the whole body (soft tissue). The densitometry report displays the T and Z scores which are displayed on the reference tab are an efficient, quick way to diagnose osteoporosis. Moore (2008) explains that “the T-score compares the subject to the optimal bone density of a young healthy individual” and the Z score “compares the subject’s density to sex and age-matched individuals” (Moore 2008, 71). To diagnose an individual with osteoporosis, the individuals T-score has to fall 2.5 standard deviations. In addition, a DEXA report can display a chart with T-scores to show how the individual compares to the database from NHANES (National Health and Nutrition Examination Survey) to inform if he or she is above, below, or at average.

Figure 3 below shows an example of what a DEXA scan report typically looks like. The scan on the left side is displayed regardless of which page is presented on the

screen. The page displayed below is that of the reference page. The alternative pages are densitometry, trend, composition and information. The densitometry page displays the anatomically separated bone mineral densities. The trend page displays any trends that occur with individuals being scanned multiple times, over a period of time. The composition page displays the individual's body composition, broken down into segmental groups, such as right arm, right leg, left arm, left leg, trunk, and total providing the composition for each section (tissue, fat, lean). Due to this, it is beneficial to use DEXA on athletes concerning the recovery process from injuries (observing injury side to non-injury side) (Buehring et al. 2014). The information page shows measurement and analysis parameters (data measured, date analyzed, version, and mode).

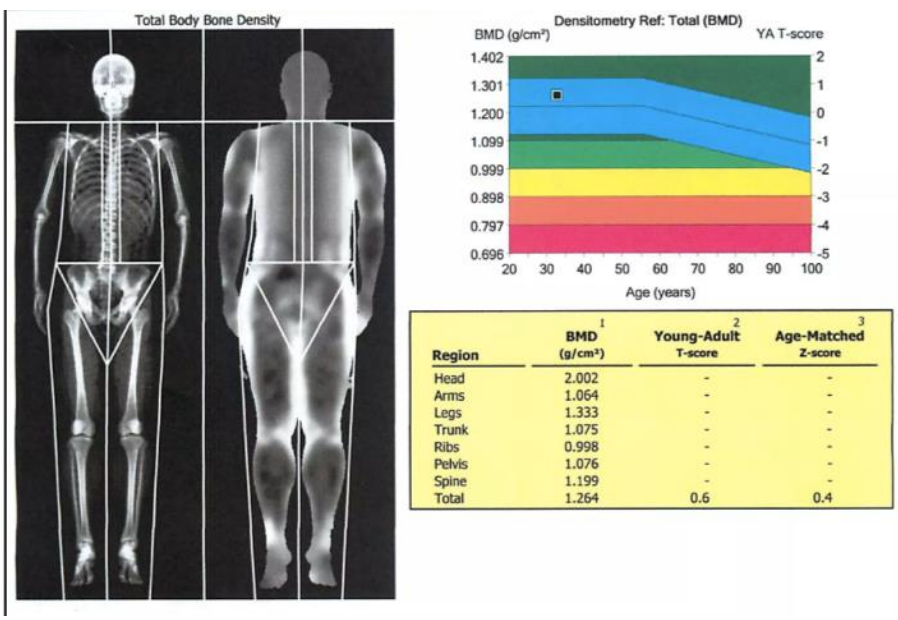

Figure 3. *DEXA Scan Example.*

("My DEXA Scan for Body Composition - The BJJ Caveman" 2013)

One of the many advantages of DEXA is the ability to look at the internal aspects of the bones and to measure the complete skeletal density. It uses less radiation compared to other radiographic methods, and therefore is healthier or less harmful to the patient.

(Moore 2008) Another benefit is how sensitive the machine is to even the smallest changes in bone density and body composition. A few disadvantages of DEXA are that it only provides a summary measure of density across the path that it scans; it does not determine volumetric density (Moore 2008, 71). In DEXA, cross-sectional geometry is assumed to be circular instead of assessing the individual's specific shape or morphology of the bone while scanning. This could be troublesome in determining the accuracy of density since the cross-sectional geometry method can provide information on the individual's body mass and lifestyle based upon a bone or two. Another variable that might be viewed as a disadvantage when studying skeletal remains is that one must account for the absence of tissue, which has been accommodated by using rice or even water as substitutes (Manifold 2014; Moore 2008).

Case Studies in Estimation of Body Mass

Applications in Forensic Anthropology

One of the earlier studies for estimating body mass from the skeleton was done by Baker and Newman in 1957 who observed the correlation between bone weight and body weight. Their study consisted of 125 individuals of both European and African American ancestry. They used skeletal remains of the war dead that were being repatriated during "Operation Glory" from Japan. Baker and Newman included only those individuals whose remains had been naturally skeletonized. They removed the moisture from the bones by drying at a warm temperature and then measured this as their dry weight. They also took note of the weights after they absorbed water, which they did so by placing the dry bones into specific containers filled with water. They used these weights of the full body, as well as specific bones, and compared them to the records after identification.

Baker and Newman (1957) discovered that the relationship was not very strong but could provide a broad weight range when comparing stature with dry bone weight. One limitation to their study was they had control over how long to let the bones dry, while with forensic purposes, taphonomy is variable and the moisture level could not be monitored. Another limitation is the necessity for the completed skeleton, which is not common in forensic cases.

In another study, Ruff, Scott, and Liu (1991) used radiographs to observe how body mass changes in adults takes a toll on articular size and diaphyseal morphology of the proximal femurs of 80 living individuals. These individuals had a wide age range of 24 to 81 years old and included males and females of both European and African American descents. Ruff et al. (1991) found that mechanical loading from an individual's weight did not change the articular size but did change the diaphyseal cross-section shape. They did create body mass estimation equations, which had an average of between 10% and 16% error rate. For forensic applications, Ruff et al. (1991) mentioned how it is difficult to create a formula that accommodates an accurate, representative sample.

The effectiveness of other methods in body mass estimation for forensic purposes has been mixed. Lacoste Jeanson et al. (2017) did a study testing 11 methods used in body mass estimation. They used five of the most commonly employed methods via CT scans to measure bone density: Grine et al. (1995), McHenry (1992), Ruff et al. (1991), Ruff (1994), and Ruff et al. (2005). In addition, they utilized the five newest equations from Elliott et al. (2016) for estimating body mass through CT scans; the formulas were all very similar with the varying factor being the different levels of the femoral diaphysis. All of the methods share certain variables in common, including the femoral head

breadth, stature, maximum breadth of body from the bi-iliac breadth, and the estimated cortical area that is measured at different locations along the femoral diaphysis (Elliott et al. 2016; Lacoste Jeanson et al. 2017). The research used a Danish population that had a range of body mass indexes (measured with all of the tissue intact). Each individual was scanned through a CT machine, and the body mass index was then estimated from the bones in the CT, most commonly using the femoral head breadth, stature and bi-iliac breadth, and estimated cortical area. The actual body mass versus the predicted body mass from the individuals was then compared, with the differences ranging from -14kg to 25kg. The accuracy was deemed adequate and reliable when doing body mass estimations of a population, but it was concluded that the accuracy was not sufficient for forensic purposes (Lacoste Jeanson et al. 2017).

Wheatley (2005) undertook an investigation on body mass and bone mineral density and found that there was a strong correlation between the two. R^2 values were as high as 0.49, but again it was not strong enough for forensic use because the standard error rates ranged from 22 to 25% (Wheatley 2005, 143). Wheatley conducted two different studies on sex and body weight determination. Both of Wheatley's data sets consisted of living individuals of European and African American descents, both male and females, of various ages. In the first study, the data set consisted of 41 Europe descended patients (17 males and 24 females) ranging in age from 61 to 79 years and weighing from 99 to 242 lbs. He used DEXA as his choice of body density applications, focusing on bone mineral density in the femoral neck, greater trochanter and Ward's triangle in his first study. Ward's triangle is "a radiolucent area between principal compressive, secondary compressive and primary tensile trabeculae in the neck of the

femur" ("Ward Triangle | Radiology Reference Article | Radiopaedia.Org" n.d.). The results of the first study showed that there were "statistically significant sex determination relationships ($p < 0.02$, t-tests for equality of means) at the supero-inferior femoral neck and lesser trochanter diameters, and from BMD at the femoral neck, trochanter, and Ward's triangle," (Wheatley 2005, 141). It did correctly predict the sex of over 92% of the individuals. Body mass of the various points were statistically significant; however, Wheatley states that "their standard errors of the estimates are too wide to be of much forensic use" (Wheatley 2005, 141).

In Wheatley's second study, the bone mineral content of the femoral neck was added, while deleting the minimum shaft diameter below the lesser trochanter. This investigation focused on ethnicity differences between African Americans and European Americans. His data set consisted of 128 female patients (71 African American, 57 European), ranging from 23 to 47 years old and weighing between 69 and 217 lbs. There were statistically significant differences found at Ward's triangle between the two ethnicities. When it came to body mass estimation, "some body weight relationships were again statistically significant such as between the BMC of the femoral neck and the BMD of the greater trochanter and the BMC of the neck and the minimum neck diameter", though the standard error rates were still too high to be very useful (Wheatley 2005, 141).

Moore (2008) added to the study by Wheatley (2005) by expanding the different body mass estimation methods used to figure out which techniques were most accurate. She used cross-sectional geometry and shape analysis, bone density, and osteological analysis of degenerative conditions to create the best predictive model for estimation. The sample that Moore used was from the William M. Bass Donated Skeletal Collection at

the University of Tennessee, consisting only of European American males and females who had height and weight information documented. They identified four different categories of weight classes: emaciated, normal, obese, and morbidly obese. Moore (2008) pointed out that since obesity has become a global problem, especially in juveniles, representation of the obese in forensic cases will also increase.

Moore found that in emaciated individuals, there was an absence of hypertrophic pathologies along with low bone mineral density whereas obese individuals were nearly eight times more likely to have diffuse idiopathic skeletal hyperostosis in the spine (Moore 2008). Obese individuals were also seven or eight times more likely to have osteoarthritis in their tibia. Biomechanical methods were found to not be as helpful as hoped when predicting body mass. Cross-sectional area and bone mineral density had the highest correlation with body mass and body weight (Moore 2008). She concluded that bone density analysis could be useful for body mass estimation to help identify individual human skeletal remains. More studies on the relationship between bone mineral density and body mass could, in turn, provide a regression formula for body mass estimation (Moore and Schaefer 2011). This regression formula could be used in bioarchaeological and forensic cases to determine body mass from skeletal remains.

Body mass determination techniques have varied through time, but bone density has remained the primary method of estimating body mass. The bone density has to adapt to the weight which it has to support, therefore leaving bone density as one of the better methods to determine body mass. Sample size is one weakness in the literature available on testing bone density and body mass estimation methods. Many are convenience samples and are either not very large, or are unbalanced between ages, sex, or ethnicities.

The use of DEXA for this process has computerized and standardized body composition and bone density estimations. By using DEXA as the method for bone density estimation, it can add and contribute to the studies that have been done on skeletal remains (Moore and Schaefer 2011; Moore 2008). It eliminates interobserver error that is common in many of the biological profile methods, creating a more level set of standardization that populations can be comparatively paralleled to.

Applications in Athletic Studies

Athletes, especially collegiate and professional, are more closely monitored than the average individual because of the impact that the intense exercise can have on their risk of injury. The goal is to push them to their maximum athletic ability, without negatively affecting their bodies. The pressure that is placed on individuals, in turn, puts stress on their bodies, whether it be to eat less, eat more, lift heavier, run longer, etc. Due to this, athletes' bodies are monitored, with a focus on their supporting bony structure. Research carried out on athletes of different sports shows the trend that those who have the highest bone mineral density are those who partake in these high-impact sports such as soccer, karate, basketball, football, and even tennis (Andreoli et al. 2001; Bennell et al. 1997; Fredericson et al. 2007; McClanahan et al. 2002; Nazarian, Khayambashi, and Rahnama 2010).

Athletic Comparison Studies

There have been quite a few studies comparing different sports with a control group to determine the influence of the sport on the bone mineral density and occasionally muscle mass. Andreoli et al. (2001) focused on the differences among males involved in water polo, karate, and judo. In these particular sports, the athlete stays

relatively in the same area with minimal running. They found that those who took part in karate or judo had a higher bone mineral density than the control group as well as the water polo athletes. It is possible that since water polo has less ground reaction force, the bones do not have to bulk up to withstand these pressures. Andreoli et al. (2001) did notice that the appendicular muscle mass was higher in all of the sports compared to the control group, so at least those non-weight bearing activities still build or maintain muscle mass better than those who were in the control group. The researchers found through this study that those who partake in high impact, weight bearing sports and activities are going to have stronger, more dense bones than those who do non-weight bearing activities. This conclusion will also be seen with later studies.

Fredericson et al. (2007) used male athletes for the study and observed the bone density of specific sites on the skeleton. They focused on soccer players and runners with particular attention paid to the bone mineral density of the lumbar spine, right hip, right leg, and total body, which were obtained through DEXA, as well as the density of the calcaneus which was measured through standard X-ray (Fredericson et al. 2007). Through this study, Frederickson and colleagues witnessed soccer players having the highest bone mineral density compared to runners and control because of their "intermittent and high intensity activities that include sprinting, jumping, accelerating, and decelerating as well as transverse and torsional loads brought about by fast changes in body displacement and direction" (Fredericson et al. 2007, 666). The high level of ground reaction forces involved in these types of activities help strengthen and thicken the bones, while running involves a more moderate level of ground reaction force. This

ground reaction force and high impact that soccer players partake in has been shown to have a positive bone adaptation response.

Both Andreoli et al. (2001) and Fredericson et al. (2007) came to a similar conclusion from their studies. Fredericson et al. (2007, 664) stated, “Weight bearing physical activity is essential for healthy bone development and maintenance. Mechanical loading with weight-bearing activity produces strains on the bone that provide the stimulus for bone remodeling and structural adaptation.” This quick maneuver type of activity is healthier for the athlete’s bones than the less spontaneous and more steady movements such as running or karate.

Mirror Studies

Other investigations focused less on variability among sports, and instead looked at the bone density differences between dominant and non-dominant limbs. McClanahan et al. (2002) did a study on this using both men and women, looking at both the upper and lower limbs. McClanahan et al. (2002) evaluated 184 collegiate athletes of various sports (baseball, basketball, football, golf, soccer, tennis, cross-country, indoor and outdoor track, and volleyball). The study found that in upper limbs, the most pronounced differences were in men and women’s tennis and men’s baseball (McClanahan et al. 2002). According to McClanahan et al. (2002), tennis players’ dominant forearms, among other sites, tend to have a higher bone density than non-athletes. The lower limbs did not show a significant difference in women, men showed significant differences in the football and tennis. The non-dominant legs were denser than the dominant legs. One intriguing result was that volleyball and basketball athletes have a higher bone mineral density in their calcanei and lumbar spines compared to the non-athletes. This could

possibly be from all the jumping that these sports require. These particular studies are beneficial to exercise science professionals because they assist in "the development of exercise prescriptions that will enhance bone status at sites that are more susceptible to stress and fractures, thus possibly preventing injuries," (McClanahan et al. 2002, 5) There is also a recommendation for a consideration of more unilateral training in order to optimize the bone mass development (McClanahan et al. 2002, 5).

Nazarian et al. (2010) did a similar study but specifically compared the bone density of the legs of professional soccer players and non-athlete subjects. The results were consistent with the results of McClanahan et al. (2002) where the non-dominant legs had a higher bone density than the dominant legs. This was due to spontaneous actions and movements that are involved. The non-dominant leg, although not the priority, actually does a lot to help support the dominant leg. This action can be a boost in a take-off, slowing down, the stabilization and grounding step for the dominant leg to go through to shoot for a goal. One limitation of this particular study is the smaller sample size of 15 athletes, for a total of 29 participants in the study (Nazarian, Khayambashi, and Rahnama 2010).

Longitudinal Studies

Alternatively, some bone density studies on athletes are longitudinal (Bennell et al. 1997; Uzunca 2005; Zanker et al. 2004). Bennell et al. (1997) researched the differences in power athletes, endurance athletes, and non-athletic controls in a 12-month longitudinal study. The trends visible during the beginning of the study were that endurance athletes had a higher bone mineral density than the controls, specifically lower limb sites. Power athletes had a higher bone mineral density in the lower limbs, lumbar

spine, and upper limbs than the controls. However, the power athletes did have a greater bone density in the lower spine than the endurance athletes (Bennell et al. 1997). Over the 12-month span, the results showed “modest but significant increases in total bone mineral content and femur bone mineral density,” (Bennell et al. 1997, 483).

Most of these studies of bone density in athletes were done over a decade ago, with machines that were even older than the publication dates. Since then, a variety of new technologies has emerged, such as DEXA. Their work can also be improved by using updated technology allowing for more accurate estimations, in addition to using living individuals rather than dry bone. Using young adults as a sample can also avoid any instances or outliers of children still growing towards their peak bone mass, but also eliminates aging individuals with declining bone density. These studies could also focus on one sex rather than both, allowing a more in-depth focus to make better comparisons.

CHAPTER III - METHODS AND MATERIALS

This chapter will describe the athletes whose bone density measurements were used for this investigation along with the way in which the scans were taken as well as analyzed.

The Sample

Former collegiate football athletes were used for this study. These athletes played a sport that required different body compositions for a well-rounded team. Unlike most clinical settings in which those who are usually scanned have it done for pathological diagnosis such as osteoporosis or a variety of other health issues, the athlete's bones are going to be relatively healthy. Their scans were done by a faculty member at the University of Southern Mississippi during the late 2000's. The athletes' names remained anonymous as to protect their identities, but their sex, age, ancestry, weight, stature and sport played were all provided.

This study used football players to allow for a heavier focus on the bone density to body mass ratio, as well as provide variability of body compositions and various positions. It is unknown whether these individuals played multiple sports or solely football, though it is likely as most athletes play seasonal sports, year-round. Although the sample is not ideal, because of high activity levels, it represents a younger sample which is the largest segment involved in forensic contexts ("Homicide Fact Sheet 2017"; Perkins 1997). The sample size was dependent upon availability, and ultimately included 107 scans. The demographics of the athletes used is presented below in Table 1.

Table 1 *Demography of USM Football Player Sample*

	European American	African American	Total	S.E.
N	27	80	107	
Mean height (in)	74.7	72.7	73.2	0.272
Mean weight (lbs.)	242	218	224	3.946
Mean BMI	30.4	28.9	29.3	0.438

The DEXA Scanning Method and Analysis

The DEXA machine used in this study was the GE Lunar Prodigy with Oncore 2003 7.51.008 software. The use of the DEXA machine was provided by the School of Kinesiology and Nutrition at the University of Southern Mississippi. The DEXA scans show a number of the variables mentioned above, in addition to the specific proportions of bone mineral density and body mass throughout different segments of the body (arms, legs, torso, head). In addition, body mass index (BMI) was studied in comparison to the other variables. The BMI was calculated for each individual with the equation of (703*weight)/(height)^2)=BMI and this information was input into an Excel spreadsheet. In addition, the individual's body composition (tissue, fat, lean mass) and biological profile (height, weight, ancestry, sex) along with the total BMD for arms, pelvis, legs, and total was also inputted into the same excel spreadsheet, so that all of the variables were in the same place for the convenience of seeing the relationships.

Statistical analysis using Excel's CORREL formula was used to explore the relationship between the two variables. In doing this, I looked at bone density at a variety of points on the skeleton, comparing each variable to one another. I focused on weight versus total bone density and height versus bone density, but also looked at correlations between arm density to total density and BMI to total density. I calculated mean scores

and correlations of variables for the sample as a whole. I next sorted them to their ancestral backgrounds and ran the tests within those ancestries, since as mentioned in the previous chapter, ancestry can play a role in BMD. I also broke the sample into above and below the average means of height and weight for both separate ancestries and analyzed the scan values. Finally, I sorted the data based on the individual's BMI values. BMI was broken down into three different categories: 18.5-24.9 is normal, 25-30 is overweight, and 30+ is obese. Following this, I used the CORREL function to again find the relationship between weight and total density, using the different BMI categories for the total as well as separated ancestral backgrounds for a more in-depth look. The last calculation that was done was the standard error of the mean of the height, weight, and BMI. The standard error was calculated by using the standard deviation formula in Excel, divided by the square root of the total number of samples.

The results of these procedures may be found in the next chapter.

CHAPTER IV – RESULTS

This study examined the relationship between body mass and bone mineral density to examine whether this methodology might successfully be applied in forensic applications in the future. The main hypothesis of the study was that there would be a strong, positive relationship between the two variables.

The initial analysis conducted looked at the relationship between weight and BMD, both overall and by body section (Table 2). The highest correlation was seen between weight and total BMD with European Americans having a slightly higher value compared to African Americans. When the body section BMDs were compared to body weight individually, the correlations dropped. Curiously, the correlations for arm BMD were higher than leg BMD. Comparing the ancestries, the only apparent difference was that those of African American descent had a noticeably higher correlation for weight and BMD in the legs. None of the correlations observed were statistically significant.

Table 2 *Weight and Bone Density Correlations*

	European Americans	African Americans	Total
Weight | Total BMD	0.802	0.568	0.572
Weight | Total BMD Arms	0.536	0.417	0.454
Weight | Total BMD Legs	0.073	0.257	0.203
Weight | Total BMD Pelvis	0.239	0.253	0.152

The second relationship that was studied involved the correlations between height and bone mineral density, by both overall and by body section (Table 3). The highest correlation was observed between height and the total bone density of the pelvis.

However, the remaining correlations were all rather weak and around the same values, with minimal differences between ancestral backgrounds.

Table 3 *Height and Bone Density Correlations*

	European Americans	African Americans	Total
Height | Total BMD	0.484	0.324	0.313
Height | Total BMD Arms	0.246	0.314	0.326
Height | Total BMD Legs	0.304	0.32	0.292
Height | Total BMD Pelvis	0.695	0.324	0.258

Next, the correlation between body mass index and total bone mineral density was considered (Table 4). The entire athlete sample did not show signs of a strong correlation between the two variables. Interestingly, the European ancestry appeared to have a stronger correlation than to those of African American ancestry by a difference of 0.22. When looking at the relationship between the total BMD compared to the fat percent of the tissue of the individuals (Table 4), none of the correlations were particularly high. The European ancestry had a higher correlation than African American ancestry, while the total sample combined had the lowest correlation value.

Table 4 *Bone Mineral Density Correlations with BMI and Body Composition (% Fat)*

	European Americans	African Americans	Total
BMI | BMD	0.73	0.51	0.54
Total BMD | Tissue (% Fat)	0.552	0.411	0.359

The individuals were then sorted based on their BMI and correlations between body weight and total BMD were tested again to observe the results (Table 5). The highest correlation value is seen when looking at the sample as a whole with a value of 0.572. The individuals who are of normal weight or overweight have a lower correlation value of no more than 0.4. There is an increase in correlation present when looking at individuals who have a BMI of 30 or higher.

Table 5 *Correlations of BMI Categories of Body Weight to Total BMD*

BMI	Category	N	Total BMD
18.5-25	Normal	16	0.373
25-30	Overweight	58	0.346
30+	Obese	33	0.535
Total		107	0.572

The data was then broken down by ancestral background with weight and total BMD correlations run based on the different BMI categories (Table 6 and 7). When looking at the European Americans correlation values those who are within a normal BMI range have a correlation of -1, indicating that the only two individuals who qualified had a perfect negative correlation, which is presumed to be entirely a statistical artefact. Although these values are not strong, there is an increase in the strength of the correlation of weight to BMD, displaying that Wolff's Law is in operation among the individuals in the same for this study. The same pattern is seen when viewing the African American ancestry but has weaker correlation values than European Americans, but as BMI increases so do the correlation values.

Table 6 *Correlations of BMI Categories of Body Weight to Total BMD in European Americans*

Combined Sample BMI	Category	N	Weight | Total BMD
18.5-25	Normal	2	-1
25-30	Overweight	13	0.491
30+	Obese	12	0.673

Table 7 *Correlations of BMI Categories of Body Weight to Total BMD in African Americans*

Combined Sample BMI	Category	N	Weight | Total BMD
18.5-25	Normal	14	0.39
25-30	Overweight	45	0.443
30+	Obese	19	0.517

Observing the height to total BMD, the correlations increase from those of a normal BMI to those who have an overweight BMI (Table 8). The correlation values then decrease for those who fit into the obese category, resulting in a 0.062 correlation.

Table 8 *Correlations of BMI Categories of Height to Total BMD*

Combined Sample BMI	Category	N	Height | Total BMD
18.5-25	Normal	16	0.294
25-30	Overweight	56	0.405
30+	Obese	33	0.062

The sample was also broken down by ancestral category to see if it would result in any stronger correlations (Table 9 and 10). The same pattern was seen with each ancestral background, with an increase in the correlation values from normal to

overweight, but then a decrease with the obese. The obese African American category has the lowest correlation of 0.018.

Table 9 *Correlations of BMI Categories of Height to Total BMD in European Americans*

EA	Category	N	Height | Total BMD
18.5-25	Normal	2	-1
25-30	Overweight	13	0.589
30+	Obese	12	0.336

Table 10 *Correlations of BMI Categories of Height to Total BMD in African Americans*

AA	Category	N	Height | Total BMD
18.5-25	Normal	14	0.312
25-30	Overweight	45	0.498
30+	Obese	21	0.018

The BMI of the individuals compared to the total BMD, when categorized into different BMI classifications a different pattern appears compared to weight and height (Table 11). The normal and overweight categories have low correlation values, but the obese category has the strongest correlation. It is nearly triple compared to the other categories at 0.593.

Table 11 *Correlations of BMI Categories of BMI to Total BMD*

Combined Sample BMI	Category	N	BMI | Total BMD
18.5-25	Normal	16	0.172
25-30	Overweight	58	0.114
30+	Obese	33	0.593

Once again, the categories were divided into their ancestral groups, resulting in an increase in correlation with the increase in BMI (Table 12 and 13). The correlation

between European Americans who have a normal BMI show a result of a strong negative correlation, but the sample size for that category was only two.

Table 12 *Correlations of BMI Categories of BMI to Total BMD in European Americans*

EA	Category	N	BMI | Total BMD
18.5-25	Normal	2	-1
25-30	Overweight	13	0.061
30+	Obese	12	0.568

Table 13 *Correlations of BMI Categories of BMI to Total BMD in African Americans*

AA	Category	N	BMI | Total BMD
18.5-25	Normal	14	0.093
25-30	Overweight	45	0.185
30+	Obese	21	0.599

Further breaking down the sample, the above and below averages of both height and weight by ancestry were tested separately for a more intimate observation (Table 14 and 15). Among the athletes of European descent who were above the average weight (242 lbs.), only the total BMD could be correlated with the weight because of the positioning of the bodies to accommodate for the individual's body mass; therefore, the body sections could not be accurately assessed. In assessing the correlation of BMD with height (mean value=74.7 in.) the above average height grouping had a striking correlation of 1; however, there were only two individuals who fit the criterion. The individuals below the average weight had the highest correlation compared to total BMD, and also the lowest correlation that went negative when compared to the total BMD of legs. The below average height individuals had the highest correlation of 0.636 when compared to the total BMD of the pelvis.

Table 14 *Correlations of Above and Below Mean Weight and Height Compared to BMD in European American*

European Americans	N	Total BMD	BMD Arms	BMD Legs	BMD Pelvis
Above Mean					
Weight	22	0.426	N/A	N/A	N/A
Height	23	0.333	1	1	1
Below Mean					
Weight	5	0.566	0.457	-0.002	0.102
Height	4	0.256	0.142	0.290	0.636

When observing the BMD correlations for those above and below height and weight for those of African American ancestry, we see the most negative correlations (Table 15). Those above the average weight (218 lbs.) had negative correlations when compared to the individual body portions. Those above average height (mean value= 72.7) had almost no correlation across the board when compared to BMD. The individuals who are below the mean weight had low correlations, with the highest correlation seen being with total BMD. The individuals who are below average height have no apparent correlation when compared to total BMD and the BMD of the legs, while the relationship to the BMD of arms was negative and the relationship to the BMD of the pelvis was low.

Table 15 *Correlations of Above and Below Mean Weight and Height Compared to BMD in African American*

African Americans	N	Total BMD	BMD Arms	BMD Legs	BMD Pelvis
Above Mean					
Weight	19	0.242	-0.258	-0.462	-0.563
Height	19	0.014	0.005	0.265	0.134
Below Mean					
Weight	61	0.320	0.237	0.184	0.297
Height	61	0.026	-0.254	0.053	0.219

Following the previous analyses, the relationships between the BMD of arms and legs was further separated out (Table 16). The highest correlation was the BMD of the arms of Europeans compared to the total BMD at 0.829. The lower correlations observed was when arm BMD was compared to height. There appears to be minimal or no correlation to arm BMD and height. The analysis of the leg BMD showed the highest correlation between the African American ancestry BMD and the total BMD. The second strongest correlation was the total leg BMD compared to the total BMD. The lowest correlation observed was surprisingly the relationship between European leg BMD and weight. All the remaining values showed no notable relationships.

Table 16 *Correlations of Arm and Leg BMD to Height, Weight and Total BMD*

	Height	Weight	Total BMD
European American Arm BMD	0.246	0.536	0.829
African American Arm BMD	0.314	0.417	0.767
Total Population Arm BMD	0.326	0.454	0.723
European American Leg BMD	0.304	0.073	0.380
African American Leg BMD	0.32	0.257	0.807
Total Sample Leg BMD	0.292	0.203	0.762

In summary, the results show that there is not a particularly consistent pattern between BMD and any of the variables considered, either when considered as a whole or broken down by ancestry. In a few instances, weight had higher correlations with BMD than did height, yet depending on the variable that was being compared, height also had higher correlations than weight. Overall, no relationships between the variables of height, weight, BMD, and BMI was sufficiently strong to suggest their use in forensic settings.

CHAPTER V – DISCUSSION & CONCLUSION

The goal of this project was to explore the relationship between bone mineral density (BMD) and body mass to test whether results suggested the method might be used by those in law enforcement to help identify individuals in a forensic realm when only skeletal remains are available. It was argued that DEXA could be used to create a more standardized method of estimating bone density without concerns of interobserver variability. The sample used for this project was comprised of university football players. The data from the athletes' DEXA scans were documented and analyzed to bring to light any relationships that might exist between BMD and weight, height, and BMI.

Weight

According to Wolff's Law, the heavier the individual, the stronger the bones will be, and therefore the BMD should have correlated with body weight. In the present study, the correlation of weight with total BMD of the entire sample was 0.572, which is much lower than anticipated. There were some ancestry differences present with European-Americans having a much stronger correlation than that seen in African Americans. All of the subsequent comparisons made, including the correlations of above or below mean weight with total BMD and body portion (arm, leg, pelvis) with total BMD yielded very low values, some even negative. Furthermore, no consistent pattern appeared among these correlations.

Wheatley (2005) also used DEXA to gather the BMD of living individuals with a variety of ages and weights, focusing on location points of the proximal femur. In this study, the men and women's weights ranged from 99 to 242lbs (Wheatley 2005, 142). Statistical testing showed that there was a strong relationship between the proximal femur

BMD and body weight, but large standard errors were seen. In my study, using an entirely male sample, I had a mean weight of about 50 lbs. more than in Wheatley's investigation, and found much different results. In fact, the results for the leg to total BMD had some of the lowest correlations in my study, and there were stronger results for the arms. Some of the large outliers in Wheatley's investigation could have been caused by the sample including both men and women. This was not the case for the present analysis, which had only males in the sample, but the correlation was still low. Wheatley conducted a second study in which only females were included, but largely the same results were seen: there were statistically significant correlations, yet the standard errors were still very high. Similarly, statistically significant relationships were seen between the BMC of the femoral neck and the BMD of the greater trochanter; as well as with the BMC of the neck and the minimum neck diameter (Wheatley 2005, 144). This would suggest that sex was not making a difference in the leg producing the best results with DEXA, and as a result it remains surprising that a similar pattern was not seen in the present study.

Ruff, Scott, and Liu (1991) used older, living individuals for their study examining the change of diaphyseal cross-section shape of the proximal femur with body weight. They compared the femoral head and diaphyseal shape with the individual's current body weight as well as with their body weight at 18 years old. This was to test the theory that with a change in mechanical loading of the lower limb, the femoral diaphyseal cross-sectional size should match the current weight. The average age of their individuals was 52.3 years old, which is about 30 years older than my sample. The average weight of the male individuals was about 50lbs. lighter than in my sample. The correlations were

higher for the current weight than for the weight at 18 years old except for the head breadths and in African Americans the neck breadth (Ruff, Scott, and Liu 1991, 401). These results reinforce the idea that the femur should give good results in estimating weight. The correlations of the proximal femur dimension with weight were consistently a little higher for European Americans compared to African Americans. In the present study, the same pattern appeared with European Americans having higher correlations of weight to the total BMD, although, using the leg BMD to correlate to body weight, there was a stronger correlation in African Americans than with European Americans.

Height and BMI

The relationship between the different variables and height did not yield very high correlation rates in the present study. All of the correlation rates involving height to the BMD values were very low, indicating that the relationships between height and these variables were rather weak. In addition, no consistent pattern is seen when looking at the correlations by either body portion or above-below the mean stature. When focusing on the relationship between BMI and BMD, the European American sample had a higher correlation than the African American sample.

The percentage of fat compared to bone density was also higher for European descendants than African Americans. Even by breaking down the data into different BMI classifications, the correlations remained rather weak. The correlation values did rise as the BMI rose, showing that Wolff's Law is in play in this study when looking at the weight to total BMD correlations. Then by looking at the height to total BMD with these classifications, there was a trend of an increase in values from normal to overweight but dropped for the obese category. A similar pattern followed with BMI as well, but the

correlation values were low for normal and overweight categories, with a jump in the value of the obese individuals.

One issue that must be mentioned is that many of the taller individuals had to have their body portion correlations excluded because their scans would be cut off at the ankles since the athletes were longer than the DEXA machine. This could be one downside to studying athletes on a DEXA machine. Even though the results for above average height European Americans show there is a perfect correlation of 1 between these two variables, they should be excluded because of the sample size (N=2). If trying to determine the height of an individual from remains using DEXA, it may not be the best method considering those who are tall and thin would not be likely to have the same BMD as those of similar weight but shorter height. Those individuals who are slenderer have a higher risk for osteopenia leading to osteoporosis (Edelstein and Barrett-Connor 1993; Nuti and Martini 1992; Wardlaw 1996).

Ancestry

By comparing this study to previous ones, the ancestry differences did seem to play a role depending on which body section or variables that were being compared. The average bone density for African Americans was slightly higher than for European Americans, but not a big enough difference to truly support Nelson and Villa’s (2003) information about the ancestral differences. Nelson and Villa discuss how those of African ancestry have significantly greater BMD than those of European ancestries in both children and adults. It is believed that the difference in bone density in African Americans is due to genetics (Nelson and Villa 2003). To provide evidence, they cite studies that compare Blacks in South Africa (Solomon 1979; Patel et al. 1992; Daniels et

al. 1997) and Gambia (Prentice et al. 1990; Aspray et al. 2009) to Europeans living in the same region and found that the Blacks had about the same and sometimes lower BMDs than the Europeans. Nelson and Villa (2003) propose the idea that there are gradations within those individuals of African descent, and it is possible that the differences we see in many of our studies in the US can be attributed to admixture and acculturation.

Another study supporting greater BMD in African Americans is Liel et al. (1988). They scanned 182 women of European and African American ethnicity, some of whom were obese and the rest nonobese. The mean BMD of the radius, hip, and lumbar spine were higher in the non-obese African American women than the non-obese European American women (Liel et al. 1988). In this present study, the specific bones were not singled out; however, the mean BMD for the arms was higher for men of European descent rather than African descent. Coinciding with Liel and colleague's study, the mean BMD of the legs and pelvis were higher in African American's than European Americans.

In a more direct analysis of BMD by ancestry, Baker and Newman looked at the weight differences of dry bones between 20 African Americans and 95 European Americans. They discovered that the African American skeletons were approximately 7% heavier than the European skeletons (Baker and Newman 1957, 605). All of the extremities and the skulls were heavier on average for African Americans when compared to European Americans except for the innominate bone. When they compared the living weight to the dry skeletal weight and the dry femur weight, their results looked similar to my results, having no significant correlations, although in Baker and Newman's study, the Europeans had a higher correlation value between the dry bone

weight to living body weight than did the African Americans. Comparing their sample's characteristics to mine, the average age is the same as my oldest individuals (~22-23 years old). The average height for my sample was 5.4 inches taller than Baker and Newman's individuals. The biggest differences of demographics between my study and Baker and Newman's was that the average weight of my sample is 90.7 lbs. heavier than the average weight of Baker and Newman's sample. This difference in height and weight may have played a role in why my results varied compared to Baker and Newman's.

Additional Factors Potential Affecting BMD

Of all the correlations tested, the most surprising result was the lack of a correlation between weight and BMD. According to Wolff's law, the bone should have built up to support the weight and muscles that these football players acquire by training and playing the sport. I expected the correlation to be larger for these two variables in particular. There may be a few possible reasons why the results did not turn out the way that was expected.

Nutrition

One factor that may have affected the data/results is the individual's nutrition. As previously mentioned in Chapter II, if protein intake is inadequate or in a surplus, this can affect BMD and even lower it as Lynnerup and von Wowern (1997) demonstrated while studying the mandibles of an Inuit population. They used radiographs to study the bone density and did stable isotope analysis to reconstruct their diets. They compared the findings to those seen at a later site, noticing how the change in diet in the later site, also affected their bone densities (Lynnerup and von Wowern 1997). The athletes in the present study should not have this influence as a factor affecting their BMD since they

are not provided with any special diets to follow besides a protein drink after practice and the remand to stay hydrated.

Another aspect of nutrition that could affect the results of the study, is the childhood diet of these individuals. If an adolescent does not have access to a proper diet, their peak bone mass may not be achieved (Stang and Story 2005). This can have an effect on their bone mineral density as an adult as well. For the study, it is unknown whether these athletes had access to an adequate, well-balanced diet throughout their childhood.

Year-round Exercise

Another variable to consider is many, but not all, collegiate athletes are year-round athletes. This fluctuation in exercise and training could affect the bone strength, as exercise helps maintain this. Andreoli et al. (2001) used a smaller sample size of 62 athletes, with a more narrowed age range that was similar to mine. The type of sport played by an individual can affect the capacity of achieving a higher BMD, lowering the risk for osteoporosis. Andreoli et al. (2001) found that those who participated in high-impact sports had the strongest results. Therefore, those playing the high-impact sport of football should display significant BMD, which may take part in the strength of the correlations. The athletes in the present study practice nearly year-round. During football season they are practicing five times a week, with a game on Saturdays. Their only rest day is on Sunday. Then when the sport is not in season, the athletes continue to spend their time weight training and conditioning with many having the intention of trying to bulk up. This might lead to a higher BMD in all body parts regardless of the players size or weight. Once summer practices start, then this weight training turns into more

endurance-based training. Thus, if the athletes partake in year-round exercise-related activities, they are constantly maintaining and strengthening their bones.

Effects of Data Collection Methods

There could also have been flaws in the data collection process itself. If the individual was reaching the upper limits for height and weight for the DEXA machine, the results become less accurate. The larger or thicker the individual is in girth, the more time it takes for the machine to scan, and the results are a bit more pixelated than other individuals who are on the lower end of the size range. In addition to this, the maximum weight the machine will handle is 300 lbs.; if the weight is input by the DEXA operator as more than 300 lbs., the machine will not run the test. Therefore, the operator may under-register the weight as 300 lbs. in order to get a scan. This misinformation could affect the weight to BMD ratio as well. Height can also affect the results because while reviewing the scans since again there were a few individuals whose feet had been cut off mid-foot or even cut off at the ankles, although including the feet in the scans for these individuals may not have been the largest priority of the scans/investigator. Another factor is many of the studies mentioned above focused on a specific region of the skeleton when estimating bone density and correlating to body mass (Bennell et al. 1997; Lacoste Jeanson et al. 2017; Moore 2008; Ruff, Scott, and Liu 1991; Wheatley 2005). The hip region, especially the proximal femur, was one of the most common areas used for estimating body mass with both morphological features and BMD. This is because of its vulnerability to changes in the bone density as well as the location being a key spot on our skeleton where we hold and support ourselves.

Sample Size Issues

Although not as much of a concern for the present investigation, studies previously examining bone density and body mass estimation, whether using QCT, X-ray, DEXA, or physical methods, had relatively small sample sizes, including all of the athletic studies that were looked consulted (Andreoli et al. 2001; Fredericson et al. 2007; Nazarian, Khayambashi, and Rahnama 2010; Zanker et al. 2004). Larger sample size would have benefitted all of these studies and also might have strengthened the present study as well. Many were convenience samples, as was this one, and they tend to be smaller sizes or unbalanced between sex, age, or ethnicity (Moore 2008). The larger the sample, the more variation becomes involved which is more accurate reflection of the human population today due to the increasing amount of admixture.

Forensic Potential of Using DEXA to Estimate Body Mass

The several studies that attempted body mass estimation from bone density all resulted in rather similar results to those in the present analysis. Some areas of the body and weight tend to have statistically significantly correlations with BMD, but not all, and furthermore their results had large estimates of standard error. For that reason, the results were determined to be not specific enough for forensics (Ruff, Scott, and Liu 1991; Lacoste Jeanson et al. 2017; Moore 2008; Wheatley 2005).

In their study, Ruff, Scott, and Liu (1991) used their body mass estimation equations from the diaphyseal cross-section shape of the proximal femur. Their results showed that they had a 10-16% error rate. This is promising for population demographics, but not specific enough for forensics. In comparison, Lacoste Jeanson et al. (2017) used CT scans to measure the bone density of the cadavers of a Danish

population. They focused their estimations from the density of the femoral head breadth, stature and bi-iliac breadth along with the estimated cortical area. They found that their estimated body mass versus the predicted body mass had rather inconsistent differences (ranging from -14kg to 25kg) (Lacoste Jeanson et al. 2017). Wheatley (2005) used living individuals with a variety of ages and weights. Wheatley’s study focused on certain areas of the proximal femur and found that there were statistically significant relationships between BMD and body weight relationships, except the standard error rates were still too high for forensic purposes (Wheatley 2005). Lastly, Moore (2008) used European American skeletal remains and found the highest correlations of cross-sectional area and BMD with body mass. Moore explains that it is possible with more research to create a regression formula for estimating body mass from bone density because of the strength of the correlations found in the study. It is just not feasible to create a widely used formula currently because of the specificity and size of the sample used in the study.

Viewing all of these studies, it is possible that the use of living individuals versus skeletal individuals, combined with the methodology that is used, could potentially affect the results. Whether using living or skeletal samples, all of the results are not conclusive enough for forensic use. To be an acceptable method, the techniques being used have to follow the Frye and Daubert standards. This means that there are certain qualifications the method has to pass in order to be admissible in court. These include whether the method can be retested and assessed for reliability and whether the potential rate of error is known. There also has to be maintenance of standards and controls and finally, the method or technique has to be generally accepted in the scientific community (Cappellino

2018). Currently, this methodology of estimating body mass from BMD through the use of DEXA does not yet meet most of these standards.

Conclusions

Of the multiple variables that were studied, there were few correlations that were found. The highest correlation of this study was between the overall BMD and body mass, although, it was still too low to be used in the forensic realm. Additional correlations with weight and height as well as considerations by ancestry also failed to yield acceptable results.

If this research were to be further studied, I would recommend a few improvements. First, I would have a larger, more diverse sample in order to observe the differences between sports being played. Many of the studies that were investigated for athletes and bone density are focused on the differences between sports or types of athletes, as well as the differences between dominant and non-dominant upper and lower bodies (Christopher B. Ruff, Scott, and Liu 1991; Lacoste Jeanson et al. 2017; Moore 2008; Wheatley 2005). Due to my sample being a convenience sample, I used specifically football players because of availability of a large number of scans. DEXA scans from other male athletics were not available. In the future, I would have also preferred to have the athletes scanned on a newer machine and analyzed with the most up to date software and also possibly include female athletes as well.

Despite the fact that this study did not produce the expected correlations, it still contributes to forensic anthropology in that it suggests that body mass estimation from bone density using DEXA is not yet accurate enough for forensic purposes, despite its use of a single sex and a younger, narrower age range. Previous studies used a variety of

ages, which can weaken the relationships of bone density to body mass because of how the human body ages and loses density over time. Therefore, the lack of strong correlations in this sample of athletes suggests that the ability of BMD values to predict body weight need much more research at best and at worst may prove too inconsistent to be of use in forensic anthropology. Future studies having a larger sample and a more specific focus on different regions of the body and perhaps and especially using more sophisticated technology might produce more encouraging results, but current studies are not promising for BMD to prove a valuable indicator of body size.

APPENDIX A – IRB Exemption Letter

Office *of* Research Integrity

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NOTICE OF INSTITUTIONAL REVIEW BOARD ACTION

The project below has been reviewed by The University of Southern Mississippi Institutional Review Board in accordance with Federal Drug Administration regulations (21 CFR 26, 111), Department of Health and Human Services regulations (45 CFR Part 46), and University Policy to ensure:

- The risks to subjects are minimized and reasonable in relation to the anticipated benefits.
- The selection of subjects is equitable.
- Informed consent is adequate and appropriately documented.
- Where appropriate, the research plan makes adequate provisions for monitoring the data collected to ensure the safety of the subjects.
- Where appropriate, there are adequate provisions to protect the privacy of subjects and to maintain the confidentiality of all data.
- Appropriate additional safeguards have been included to protect vulnerable subjects.
- Any unanticipated, serious, or continuing problems encountered involving risks to subjects must be reported immediately. Problems should be reported to ORI via the Incident template on Cayuse IRB.
- The period of approval is twelve months. An application for renewal must be submitted for projects exceeding twelve months.

PROTOCOL NUMBER: IRB-19-5
PROJECT TITLE: Body Mass Estimation using DEXA: Applications in Forensic Anthropology
SCHOOL/PROGRAM: School of SSGS
RESEARCHER(S): Kaitlin Harstine

IRB COMMITTEE ACTION: Exempt
CATEGORY: Exempt

Category 4. Research involving the collection or study of existing data, documents, records, pathological specimens, or diagnostic specimens, if these sources are publicly available or if the information is recorded by the investigator in such a manner that subjects cannot be identified, directly or through identifiers linked to the subjects.

APPROVED STARTING: May 3, 2019

Donald Sacco Jr.

Donald Sacco, Ph.D.

Institutional Review Board Chairperson

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