The influence of body size on adult skeletal age estimation methods.

by

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Abstract

When human skeletal remains are found in prehistoric, historic, or forensic contexts, establishing age at death is an important step in reconstructing life histories, building demographic profiles, and identifying victims. Reliability for adult skeletal age estimations is generally lower than ideal, especially for individuals over the age of 40 years. A factor rarely considered in age estimation is that of body size; namely, how individuals of varying body sizes experience skeletal aging. This thesis explores the variables of BMI, stature, and body mass to quantify the influence of error from body size on adult skeletal age estimates.

Eight age estimation methods were tested on 764 adult skeletons from the Hamann-Todd and William Bass Collections. These individuals were documented to have ranged in stature from 1.30m to 1.93m and body mass from 24.0kg to 99.8kg. Each age estimation method was evaluated separately.

Analyses show that underweight individuals have the most error associated with their age estimations for all methods. All methods under-age underweight individuals by 5 to 15 years compared to average and obese individuals. The Kunos et al. method is the most reliable rib method, and the Lovejoy et al. and Suchey-Brooks methods are the most reliable pelvic methods.

The İşcan et al. fourth rib method under-ages individuals by the highest degree compared to all other methods. The DiGangi et al. method is the most unreliable method with low accuracy (over twenty years) and high bias scores (under-aging individuals by almost 20 years).

Body mass has a stronger influence on age estimation than stature. Studies have shown that body mass has a strong impact on bone resorption and remodelling rates, regardless of nutrition, and that tissue type (i.e. fat vs. muscle), physical activity, and mechanical loading influence bone remodelling. Skeletal remains of underweight individuals have fewer age markers while obese individuals show an increase in surface texture degeneration and osteophytic lipping. This is the first study to show that body size influences skeletal age estimation, and that age estimations are significantly different between weight-bearing and non-weight-bearing joints.

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Chapter 1: Introduction and Literature Review

1.1 Introduction

When human skeletal remains are found in prehistoric, historic, or forensic contexts, establishing age at death is an important step to reconstruct life histories, build demographic profiles, and identify victims of mass disasters, genocides, and homicides. The most common methods used to estimate age at death are based on changes to dental and skeletal features; these indicators provide relatively accurate and precise age estimations for juveniles who died during the period of growth and development (Crowder and Austin, 2005; Cameriere and Ferrante, 2008; Cardoso, 2008 a; b; Lee et al., 2008; Meinl et al., 2008), but are less accurate and precise for adult age estimations (Saunders et al., 1992; Bednarek and Sliwka, 2004; Martrille et al., 2007; Storey, 2007; Dorandeu et al., 2008; Konigsberg et al., 2008; Meinl et al., 2008).

The age phases of adult age estimation methods follow a typical pattern: the younger phases tend to have smaller age ranges because they are based on clear, time-limited indicators of the maturation processes, while the older phases tend to have larger age ranges because they are based on degenerative and remodelling processes. The changes associated with maturation occur in a fairly predictable pattern until individuals reach the age of 40 years; once over the age of 40 years, degenerative changes are not always associated with specific stages of aging and ages are more difficult to assess (Falys and Lewis, 2011). The reliance on degenerative processes to assess adult age at death results in two main problems: first, the age categories of current protocols are very inclusive for older individuals (e.g. “24–92 years”), and are often vague (e.g. “60+”); second, while methods tend to work well on the collections on which they were developed, they fail to work as well on other cadaver or archaeological collections (Bedford et al., 1993; Bocquet-Appel and Masset, 1996).

The most commonly used age estimation standards were developed using skeletons of varying body sizes from North American skeletal collections without controlling for body size. Often, when our age standards are applied to early populations of *Homo sapiens*, as well as our hominin ancestors, the trend shows a higher than expected young adult mortality, i.e., their adult ages at death are between 20 and 35 years of age (Storey, 2007; Roksandic and Armstrong, 2011). If

body size does play a role in adult age estimation, and, for example, individuals with smaller body sizes have different patterns of aging compared with average or heavier individuals, then we may need to reconsider the mortality curves of small bodied hominin and *Homo sapiens* ancestors. The interaction between body size and skeletal aging has been largely neglected, yet it could be highly relevant to our reconstruction of the population history of our species.

In all biological studies of whole organisms it is important to control for body size (i.e. stature, body mass, body mass index [BMI]) when analyzing and interpreting data (Stillwell et al., 2011); however, in biological anthropology, age estimation studies have not systematically considered body size as a variable that could influence our standards. Understanding how the predicted modifications of joints that occur during the skeletal aging process differ among individuals with varying statures and body masses may help explain some of the unattributed variance in skeletal age estimations. For example, do individuals of the same stature but different body masses show the same patterns of skeletal aging? Similarly, do individuals of the same body mass but different statures show the same patterns of skeletal aging?

This thesis will quantify the influence of body size on individual adult skeletal age estimation methods, using current standard assessment methods, with the goal of determining the ways in which body size affects skeletal aging. The central research questions are:

- (1) Does the body mass index influence skeletal age estimations?
- (2) Does stature influence skeletal age estimations?
- (3) Does body mass influence skeletal age estimations?
- (4) Are there differences between non-weight-bearing and weight-bearing joint age estimations?

The study sample includes 764 adult skeletons with a broad range of sizes. The skeletons are from the Hamann-Todd Collection and the William Bass Collection, two North American skeletal collections of known individuals with documented age, sex, stature, body mass, and cause of death. Eight age estimation methods were used for this project: the Kunos et al. (1999) first rib method, the DiGangi et al. (2009) first rib method, the İşcan et al. (1984, 1985) fourth rib method, the Passalacqua sacrum method (2009), the Lovejoy et al. (1985) auricular surface

method, the Buckberry and Chamberlain (2002) auricular surface method, the Rougé-Maillart et al. (2009) auricular surface and acetabulum method, and the Suchey-Brooks (1990) pubic symphysis method. These age estimation methods were selected based on element preservation, and how often researchers reported using certain age estimation methods (to be explained further in Section 1.5).

1.2 Skeletal Biology and Aging

The process of skeletal aging is universal and cumulative, but age-related processes show great variation among individuals and populations in the level and degree of change. Individual biological aging is determined by a complex set of ongoing interactions among genes, culture, health, and environment that contribute to their specific life history, and this variation has significant effects on an individual's chronological age at death assessment (Harper and Crews 2000). The relationship between chronological age and biological age is neither constant nor linear, which is the reason adult age at death cannot be estimated with great accuracy from skeletal data (Cox, 2000). This is not to discount the fact that, indeed, changes to the skeleton are related to chronological age; however, researchers must take into account that this relationship is influenced by factors that are difficult to assess in a linear equation, Bayesian statistic, or morphological feature. Most adult age estimation methods are based on maturation and degenerative forces acting on the particular skeletal feature being examined; for example, methods assessing the pubic symphysis, auricular surface, acetabulum, sacrum, first rib, or fourth rib are based primarily on the ossification or breakdown of features that occur as an individual ages. These maturational changes occur in a fairly predictable, yet variable, pattern until individuals reach the age of 40 years; however, over the age of 40 years, degenerative changes tend to be difficult to assess and are not always associated with specific stages of aging (Franklin, 2010).

The skeleton is a dynamic organ that provides the foundation for a number of mechanical and homeostatic functions, including the protection of internal organs, locomotion and load-bearing, haematopoiesis, and it is the reservoir for calcium homeostasis (Boskey and Coleman, 2010). As a person ages, these functions can become impaired, bone becomes more fragile and less able to perform its mechanical functions, and the calcium stores can become depleted (Chan and Duque,

2002); however, the factors that control these aging processes are variable and are not completely understood.

Bone has a hierarchical structure: at the level of the skeleton, there are different types of bones—long, short, flat, irregular, and sesamoid; at the tissue level, bone is arranged into cortical (compact), trabecular (cancellous), and subchondral structures; at the microscopic level, bone consists of organic and inorganic matrices; and at the nanometer level, the individual mineral crystals and collagen fibrils are woven together to form a triple helix (Boskey and Coleman, 2010). The composition of bone varies with species, tissue site, health and disease, body size, and age, but it is the variation with age at both the micro- and macro-level in humans that is the focus of this thesis.

There are four major types of bone cells: chondrocytes, osteoblasts, osteocytes, and osteoclasts. Of these four, three are of mesenchymal cell origin: chondrocytes, osteoblasts, and osteocytes. Chondrocytes are the cells that deposit the growth plate and are responsible for its subsequent remodelling; osteoblasts are the cells that synthesize the bone matrix and facilitate the mineralization process; and osteocytes are the cells that respond to load and regulate bone resorption and formation (Adachi et al., 2009). Osteoclasts, on the other hand, are of hematopoietic origin. They are large, multinucleated cells responsible for removing bone (resorption) following signals from osteoblasts and osteocytes (Bar-Shavit, 2007). In studies using animal models, older animals have impaired osteoclast differentiation compared to younger animals, and the relative rates of bone removal in older animals far exceeds the rates of new bone formation (Cao et al., 2005, 2007; Pietschmann et al., 2007). Similarly, a study using bovine bone *in vitro* has shown that osteoclast resorption occurs at a much higher rate on older bone than on young bone, indicating that older bone may be preferentially selected for resorption (Henriksen et al., 2007). Compounded with the increased osteoclast resorption of older bone cells, as an individual ages, the amount of bone deposited by osteoblasts decreases with each cycle of remodelling (Lee et al., 2005; Szulc and Seeman, 2009); therefore, the rate of bone removal occurs faster than bone deposition throughout the aging process. All older humans experience this shift in tissue balance, but the shift presents most clearly in post-menopausal women (Kaptoge et al., 2003).

All normal cells in the human body, including the bone cells, have a limited lifespan. The Hayflick limit of cell division has shown that cells can only undergo a certain number of divisions and replications (i.e. mitosis) before mistakes occur (Hayflick, 1965). As an individual ages, cell divisions and replications begin to accumulate errors at the ends of chromosomes (telomeres); each time a cell undergoes mitosis, the telomeres decrease in length because of the cell's inability to fully replicate in this region, and after an unknown number of divisions and replications (determined by genetic, health, and environmental factors), the telomere length reaches a point where the errors begin to jeopardize the stability of the cell (Calado, 2009). Age estimation methods using telomere length have been developed but they are still in the testing phase (Meissner and Ritz-Timme, 2010).

Not only do cells have a limited number of divisions and replications, studies have shown that cell differentiation and proliferation is age dependent. Jiang et al. (2008) used a sample of 80 patients between the ages of 15 and 79 years to examine the potential of bone marrow stem cells to differentiate into chondrocytes, osteoblasts, or osteoclasts by measuring changes in the gene expression of major lineage-defining factors. Their data suggest that aging affects gene expressions differently, and that as a person ages, the lineage of bone marrow cells is modified. These modifications include a decrease in bone marrow osteoblastogenesis and an increase in osteoclastogenesis, corroborating evidence that bone resorption occurs at a faster rate than bone deposition in older individuals. Similarly, Zhou et al. (2008) report age-related decreases in osteoblast proliferation and differentiation in human cells both *in vivo* and *in vitro*, as well as an increase in cell apoptosis in older individuals.

Apoptosis, programmed cell death, is a regulatory mechanism in most tissues and it plays a role in normal tissue maintenance. When apoptosis becomes dysregulated, this can cause an imbalance between bone resorption and formation, as well as cause changes in tissue mechanical properties in the affected areas (Carrington, 2005). Studies have found that osteocyte apoptosis increases with tissue age, causing a weakening of the bone independent of bone mineral density (BMD). Jilka et al. (2007) and Manolagas and Parfitt (2010) have postulated that this occurs through two mechanisms. First is the process of micropetrosis, a bone condition associated with aging where the canaliculae and empty lacunae are filled with mineralized tissue instead of bone matrix after osteocyte apoptosis has occurred; although this increases the fragility of bone, it

does not decrease BMD. An early study by Frost (1960) found that almost no micropetrosis exists at birth, whereas an average of 15% of the volume of bone from patients over the age of 70 years was micropetrotic; in three cases, 40% of the volume was micropetrotic. The second process is the disruption of the canalicular system by apoptosis, thereby decreasing the repair of microcracks. The canaliculi are responsible for communication between the bone cells, and once this system becomes disrupted, responses to events such as microcracks are impaired.

1.2.1 Organic and Inorganic Bone Matrix Aging

The organic matrix of bone accounts for 35% of the dry mass of bone. Ninety percent of this dry body mass consists of protein collagen, mainly type I, and approximately 5% consists of non-collagenous proteins (Chan and Duque, 2002). Type 1 collagen is the most abundant protein collagen in the body, comprising about 36% of the volume of compact bone, and of all the collagen types it has the lowest rate of turnover during remodelling (Collins et al., 2002).

Collagen gives the bone structure its flexibility, and it is this flexibility that provides resistance to impact loading, and serves as a template for the oriented deposition of mineral crystals. Collagen is secreted from the osteoblasts as triple-helix fibrils which self-associate to form larger fibrils and then fibers. The three helices are held together by hydrogen bonds, giving collagen much of its stability and elasticity (Collins et al., 1995).

Collagen helices are bonded together through cross-links, and they vary with age. There are two different types of cross-links: enzyme and non-enzyme cross-links. The enzyme cross-links are originally formed by two enzymes, lysyl hydroxylase and lysyloxidase, and they connect the N- or C-terminus of one collagen molecule to the helical region of another. Once catalyzed, they become pyridinoline (PYD) and pyrrole (PYL) cross-links, and this increases the stiffness of the collagen molecule (Vashishth et al., 2001). The increased presence of PYD and PYL in blood or urine typically signifies the degradation of bone, and this begins to occur in older individuals (Samma et al., 1997). The non-enzyme cross-links are formed by glycation or oxidation induced non-enzymatic processes, and the presence of advanced glycation endproducts (AGEs) increase as the collagen molecules age. The formation and accumulation of AGEs have been implicated in the progression of age-related diseases (Tan et al., 2006)

Studies investigating the relationship between aging and collagen cross-links using human samples (Viguet-Carrin et al., 2010) and bovine samples (Tang et al., 2007) report that the rate of enzymatic cross-linking decreases with age while the non-enzymatic cross-linking increases with age. With the collagen fibers at the terminus ends of the molecule becoming weaker, combined with the increasing number of AGEs, the accumulated effect is a decrease in bone strength and toughness and, ultimately, decreased resistance to crack propagation. Viguet-Carrin et al.'s (2010) study also found evidence to suggest that the accumulated AGEs within bone tissue can only be removed by bone resorption, and their presence increases osteoclast activity while decreasing formation by osteoblasts, thereby contributing to the fragility of bone with increasing age.

The organic matrix of bone also contains non-collagenous proteins that are synthesized and secreted by osteoblasts, and they produce, nurture, and remodel the extracellular matrix by responding to mechanical and homeostatic signals. Decreased non-collagenous protein production is associated with aging (Grynpas et al., 1994; Kloss and Gassner, 2006). Grynpas and colleagues (1994) compared the composition of proteins in the trabecular bone of the femoral neck from individuals of varying ages, and their results showed that individuals under the age of 40 years had more extracellular bone matrix proteins than individuals over the age of 50 years, and that there was an increase in bone matrix protein fragments in the older group. As an individual ages, non-collagenous proteins decrease in number, thereby impairing their ability to respond to mechanical and homeostatic signals.

The inorganic matrix of bone accounts for approximately 65% of its dry body mass and consists primarily of calcium hydroxyapatite and osteocalcium phosphate, or brushite (White and Folkens, 2000). In bone, the collagen triple helix is interspersed with the inorganic matrix of hydroxyapatite and brushite and gives bone its strength (in other cells of the body, the triple helix is interspersed with water). During the process of growth and development, the mineral content of bone increases until the age of 30 to 35 years, and studies have shown that as an individual ages, the breaking stress of bone increases exponentially with mineral content while the toughness of bone declines, thus making the bone more brittle and less resistant to fractures (Currey, 1969; Zioupos and Currey, 1998; Manjubala et al., 2009). These results are confirmed with BMD; BMD measurements have been compared using a variety of techniques for a variety

of species, demonstrating the increase in mineral content during growth and development, and the decline with later aging (Cerroni et al., 2000; Somerville et al., 2004).

1.2.2 Trabecular Bone Aging

A decrease in trabecular bone volume and the number of connectivity networks along with the increase in trabecular bone microcracks have been well documented in older individuals (Parfitt et al., 1983; Bergot et al., 1988; Mosekilde, 1998). These changes are due to a variety of factors, including hormones, nutrition, health, and physical activity. Furthermore, in post-menopausal women, there is a reduction in estrogen levels, which leads to slower bone remodelling (Kaptoge et al., 2003). Ascádi and Nemeskéri (1970) and Szilvassy and Kritscher (1990) proposed methods of age estimation using trabecular bone involution; however, these methods have been proven unreliable (Walker and Lovejoy, 1985; Gehring et al., 2002; Jones, 2003) and they are not widely used by biological anthropologists (Falys and Lewis, 2011; Garvin and Passalacqua, 2012).

1.2.3 Cortical Bone Aging

In addition to a decrease in overall trabecular bone in older individuals, there is also a decrease in overall cortical bone (McCalden et al., 1993). As an individual ages, the decrease in cortical bone is primarily attributed to resorption on the endosteal surface, which occurs at a faster rate than periosteal growth (Tsuboyama et al., 1989). This loss of cortical bone manifests itself both by texture and body mass. With age, a bone becomes more brittle, the texture becomes roughened, there is an increase in porosity, and the bone is lighter in body mass. These age-related changes to cortical bone occur on a spectrum, and because there is so much variation in the timing of these events, predicting age at death from skeletal markers is a difficult task. Most adult age estimation methods are based on changes to the periosteal surface of the bone, and the degenerative forces acting on the skeletal features are assessed.

1.2.4 Subchondral Bone Aging

Subchondral bone is found immediately deep to the articular cartilage of a synovial joint surface. It is a complex structure comprising of two mineralized layers; one of calcified cartilage and the other of osseous material. Collagen fibrils from the non-calcified cartilage extend into the

calcified cartilage to create a strong bond between the two layers. The calcified cartilage extends towards the marrow cavity where it is remodelled and replaced by woven/lamellar bone. These layers of lamellar bone are stacked like sheets rather than latticed like the structure of the supporting trabecular bone below. Subchondral bone is highly vascularized with many nerves and blood vessels nourishing the joint tissues (Madry et al., 2010). With age, and the effects of loading, synovial joints are subject to osteoarthritis, a degenerative process resulting in the loss of cartilage and sclerosis of the underlying subchondral bone (Cox et al., 2013). The subchondral bone volume and trabecular thickness significantly increase as cartilage degenerates, while the number of trabecular strata and degree of trabecular bone separation decrease (Bobinac et al., 2003).

1.2.5 Bone Mineral Content (BMC) and Bone Mineral Density (BMD)

Bone mineral content (BMC) is the amount of mineral in one gram of bone. BMD is the amount of BMC measured in one square centimetre of bone (Anon, 2012). The most common method of measuring BMD is dual energy x-ray absorptiometry (DXA or DEXA), a scan where x-ray beams are projected onto the area in question (typically the spine or hip), and BMD and BMC can be calculated (Anon, 2012). BMD is one of the most common variables studied in relation to body size, especially in older individuals where loss of BMD results in osteoporosis and increased rates of fractures. BMD is used to assess the strength of bones. As an individual ages, bone becomes thinner with the increase in osteoclast resorption and decrease in osteoblast deposition (described in Section 1.2.1). As a result, the mineral concentration decreases, causing the bone to become light in body mass, less dense, and more fragile, and these factors can be assessed with skeletal age estimation methods. However, it is well documented that there is a positive relationship between body mass and BMD; as body mass increases, there is increased mechanical stress on bone, resulting in decreased bone resorption and higher BMD in heavier individuals (Felson et al., 1993; Looker et al., 2001; Lim et al., 2004).

Studies have shown that the correlations between BMD and age, and BMD and body mass are similar (Felson et al., 1993; Britz et al., 2009), suggesting that body mass is just as important as age when predicting BMD. For individuals categorized as having a normal BMI, BMD decreases with age, and they will exhibit the age related changes of increased fragility, loss of bone mass, and decreased bone density. However, for individuals with an obese BMI, BMD is maintained or

even increased (Felson et al., 1993; Albala et al., 1996); therefore, heavier individuals may not exhibit the age related changes of decreased fragility, body mass, and bone density, suggesting that body mass is an important variable to consider in age estimation. Conversely, recent studies have shown that men and women with high BMIs have low BMD scores (Zhao et al., 2008; Greco et al., 2010).

A study by Britz et al. (2009) investigated the relationship of osteon size to stature and body mass. Using a sample of 87 femora sections and controlling for sex and age, the authors found that body mass has a positive significant effect on osteon size, but stature does not. When the effect of BMI on osteon size was calculated, the trend was less significant. The authors suggest that inhibitory activity of osteoclasts reduces the diameter of bone multicellular unit (BMU) resorptive areas, thus maintaining the integrity of the bone. Research by van Oers et al. (2008) found an inverse relationship between osteon size and bone strain, which might provide a partial explanation for Britz et al.'s findings. One of the limitations of using skeletal materials is the inability to account for lean body mass (LBM) vs. fat mass (FM). As the authors point out, although both LBM and FM contribute to the mechanical loading of the skeleton, FM has an additional effect on bone (Britz et al., 2009). As body mass in the form of FM increases, bone mass increases through a series of endocrine changes, a plausible explanation for increased osteon size in heavier individuals who have more FM, and supports previous studies on the relationship between body size and BMD.

1.2.6 Summary of Skeletal Aging Processes

Age changes in bone at the micro-level are a complex interaction between bone cells and the organic and inorganic matrix. As an individual ages, osteocyte apoptosis in bone tissue becomes more probable. Bone cell differentiation is modified with age, and there is an increase in the number of osteoclasts and decrease in the number of osteoblasts produced. This impaired cell differentiation increases the relative rates by which bone is removed and decreases the rates by which new bone is formed. Compounded with this, evidence suggests that older bone may be targeted for resorption and the amount of bone deposited by osteoblasts decreases with each cycle of remodelling. Part of this targeting of older bone for osteoclast resorption may have to do with the increase in AGEs in the collagen protein, which can only be removed by osteoclasts. Increased osteoclast activity vacates a number of lacunae, and often these spaces become filled

with mineral content, thus increasing the breaking stress and decreasing the toughness of the bone, causing the bone to become more brittle and less resistant to fractures. These changes at the micro-level occur in trabecular, cortical, and subchondral bone. The age changes expressed at the cellular level are also expressed at the surface level, and these are the changes that are being evaluated when assessing skeletal age.

For skeletal age estimation studies, it is important to remember that bone aging does not occur in a vacuum—cartilage, connective tissue, and bone are one functioning unit with inter-related cell types, and these changes are influenced by external and internal factors, including body mass and BMI.

1.3 Body Mass Index

Body size plays an important role in many physiological functions, and should also be considered as a potential factor influencing our age estimation methods. Body size in this study will be measured by stature, body mass, and body mass index (BMI). Stature and body mass were recorded post-mortem, while BMI was calculated using these two measurements. BMI was calculated for each individual using the formula:

$$\frac{\text{body mass (kg)}}{\text{stature (m)}^2}$$

where an individual's body mass is divided by stature squared in order to estimate body fat (Keys, 1972). Calculations for BMI classify individuals into one of four main categories, with the cut-off points in this study based on the World Health Organization (WHO) standards (World Health Organization, 2013): underweight (<18.49), normal (18.50 to 24.99), overweight (25.00 to 29.99), or obese (>30.00).

A potentially problematic area with BMI is ancestry. BMI was developed on individuals of European ancestry from North America, and its applicability to other populations has been questioned. It has been acknowledged that BMI calculators do not work as well for individuals of African, Asian, and Pacific Island ancestries (Jackson et al., 2002; Rush et al., 2009); however, there are no recognized standards available to account for these variations. The WHO conducted an international expert consultation in 2002 to review the applicability of the BMI calculator to other populations, specifically Asia and the Pacific Islands; they concluded that, based on the

incidence of type 2 diabetes and cardiovascular disease in each BMI group, the current standards in use are applicable to all populations (WHO Expert Consultation, 2004).

BMI is not always the best measure of body fat composition. Since the BMI formula depends only upon stature and body mass, the assumptions made about the distribution between lean mass and fat tissue are only an approximation. BMI generally overestimates body fat on those with more lean body mass and underestimates excess body fat on those with less lean body mass (Romero-Corral et al., 2008). A study by Romero-Corral and colleagues (2008) examined 13,601 individuals from the United States' third National Health and Nutrition Examination Survey and report that BMI obesity ($\text{BMI} > 30$) was present in 21% of men and 31% of women. Using body fat percentages (BF%), BF% obesity was found to be significantly higher in men and women (50% for men and 62% for women). Despite this underrepresentation of BMI obesity, BMI values in the intermediate BMI range of 20 to 30 were found to be associated with a wide range of body fat percentages. For men with a BMI of 25, about 20% have a body fat percentage below 20% and about 10% have body fat percentage above 30%.

BMI is particularly inaccurate for athletes and individuals who regularly exercise, as higher muscle mass tends to classify these individuals in the overweight BMI category, even though their body fat percentages frequently fall between 10–15%, which is below that of a sedentary person who has a normal BMI (Ode et al., 2007). Body composition for athletes is often better calculated using measures of body fat, as determined by skin-fold measurements. Alternative methods to measure obesity, such as the body volume index and body frame size (Frisancho, 1984; Heuberger et al., 2007), have been proposed. Unfortunately these alternative measures to estimate body size are not available for use on skeletal remains; therefore, BMI is used in this study.

1.4 Weight-Bearing and Non-Weight-Bearing Joints

In the assessment of adult age at death, morphological age estimation methods do not take into account the influence of body size, nor do they differentiate between factors influencing weight-bearing and non-weight-bearing joint surfaces, and how they are affected differently by skeletal aging. The most common sites used by biological and forensic anthropologists to assess age are the pubic symphysis and auricular surface, both weight-bearing joints, as well as the fourth rib, a non-weight-bearing joint (Falys and Lewis, 2011; Garvin and Passalacqua, 2012). When

comparing weight-bearing and non-weight-bearing surfaces in relation to BMD, there are significant differences between the two sites. Mikkola et al. (2008) compared the tibia and radius BMD from 217 older female twins and were able to show that the weight-bearing tibia is affected by the environment significantly more than the non-weight-bearing radius. These findings indicate that researchers should be aware that there are bone remodelling differences between the two sites, and this may affect skeletal age estimations.

Activity level also has different responses on weight-bearing and non-weight-bearing bones. Tommerup et al. (1993) studied the effect of weight-bearing activities on weight-bearing versus non-weight-bearing bone; their results show that weight-bearing exercise is sufficient to stimulate periosteal bone formation in the femur, but not in the ribs, indicating that bone response to weight-bearing exercises is specific to the loaded, weight-bearing bones. Similarly, Nikander et al.'s 2006 study comparing the BMD of weight-bearing and non-weight-bearing bones of elite female athletes found that bone mass was substantially higher at the loaded bone sites compared to nonathletic individuals. For the non-weight-bearing surfaces (radius and humerus), athletes had a higher BMD than nonathletes, indicating that with increased activity, loaded non-weight-bearing bone that can also have increased BMD. The only morphological, non-weight-bearing sites used in age estimation are the ribs, which are typically not subject to external loading factors.

Age also appears to influence weight-bearing and non-weight-bearing bone differently. A study by McNeil and colleagues (2009) compared the cross-section geometry of the tibia (weight-bearing) and fibula (non-weight-bearing) in 39 men who were categorized as young (aged 23–31 years), old (aged 61–69 years), and very old (aged 80–91 years). With increasing age, they found that there were greater differences in bone geometry in the tibia compared to the fibula, suggesting that the weight-bearing role of the tibia makes it more susceptible than the fibula to the reduced activity typically associated with aging.

Obese individuals have an increased risk of osteoarthritis at weight-bearing joints (Felson, 1996). Osteoarthritis is characterized by the decrease of cartilage in a joint. As the cartilage breaks down, the space in the joint capsule between the two bones decreases until eventually the cartilage is completely destroyed and the bones are in contact with each other. This typically

results in an increase in osteophytic activity around the joint capsule to compensate for the loss of cartilage. The hip joint is an area where osteoarthritis commonly develops, and three methods of age estimation using the acetabulum have been developed over the past decade (Rissech et al., 2006; Rougé-Maillart et al., 2007; Calce, 2012). For all three methods, osteophytic activity along the apex and lunate surface are used as markers of aging; however, these factors may be accelerated in obese individuals who are more prone to osteoarthritis, potentially resulting in over-age assessments of obese individuals. Therefore, it is important to understand the ways in which body size, especially mass, may influence the ways in which bone responds to external forces that are not directly related to the aging process, but could be interpreted as such.

1.5 Adult Skeletal Age Estimation

Adult skeletal age estimation methods quantify changes from the tissue level to the morphological level. To be considered a reliable age estimation method, the osseous feature being evaluated must display the following three features: first, there should be visible, progressive, unilateral degenerative changes; second, these progressive, unilateral changes should occur at approximately the same time in all individuals; and third, the traits scored should be easily identified and show low intra- and inter-observer error (Milner and Boldsen, 2012). Of these three features, the most difficult to quantify is the second: that degenerative changes should occur at the same time in all individuals. Often, there are differences between sexes (Işcan et al., 1984 a, 1985; Brooks and Suchey, 1990), populations (Işcan et al., 1987; Oettlé and Steyn, 2000; Bednarek et al., 2002; Djurić et al., 2007), and even socio-economic classes of the same population (Harper and Crews, 2000), making the creation of one universal system of age estimation difficult to establish.

There have been many historical developments and paradigm shifts over the past century in the ways biological anthropologists approach skeletal age estimation. As Rogers (2009) notes, the historical developments in skeletal age estimation studies follow a similar trajectory to the theoretical shifts in the field of biological anthropology. Prior to the 1940's, much of the field of anthropology was concerned with typology, and the first pubic symphysis and cranial suture closure age estimation methods described by Todd and Lyon in the 1920's followed this trend (Todd, 1920; Todd and Lyon, 1925). Although the two authors did note differences between

sexes and populations, individuals who did not follow what they determined as “normal” aging were eliminated from their sample (Todd, 1920).

As the field of biological anthropology continued to focus on typological differences between sexes and ancestral groups throughout the 1930’s and 1940’s, there was a theoretical shift in the 1950’s. Instead of focusing on descriptive typologies, Sherwood Washburn stated that anthropologists needed to move towards an understanding the evolutionary processes and functional morphology of traits, rather than description (Van Gerven and Armelagos, 2003). For biological anthropologists, this shift in theoretical approaches brought to the forefront two major problems researchers had been trying to resolve for 30 years; first, paleodemographic analyses of archaeological populations almost always yielded mean ages at death around 30 years of age, and second, rarely were individuals over the age of 40 years recorded in these populations. Brooks (1955) opened this conversation through the first critical analysis of the Todd methods on samples from Aboriginal populations from California and samples from the Hamann-Todd Collection. Her results were significant because they showed that cranial suture closure and pubic symphyseal changes were not as strongly correlated with age at death as originally thought, especially cranial suture closure, and that applying these methods to individuals of differing populations yielded poor results.

In response to this new theoretical shift focusing on functional morphology, the 1950’s to 1970’s saw a change in the study of skeletal age estimation. The methods that were developed during this time period focused on the *process* of development and degeneration (for example, the McKern, Stewart, and Gilbert pubic symphysis methods [McKern and Stewart, 1957; Gilbert and McKern, 1973]), and population studies became commonplace. Though the methods were still descriptive, researchers attempted to explain the evolutionary adaptations of the observed changes. Combined with the new theoretical approaches in archaeology proposed by Binford and Binford in the 1960’s (Binford and Bindford, 1968), biological anthropologists began to apply a biocultural approach to their analyses, and in 1977 Buikstra coined the term “bioarchaeology” to encompass this holistic approach. The bioarchaeological approach of incorporating culture and biology to explain evolutionary adaptation and functional morphology began to emerge as a theme in age estimation studies, and remains an important aspect of age estimation studies today (Rogers, 2009).

The 1980's saw another paradigm shift in age estimation. In 1982, Bocquet-Appel and Masset's article "Farewell to Paleodemography" (Bocquet-Appel and Masset, 1982) brought to the forefront two major issues in archaeological skeletal age estimation studies: first, the age structures of archaeological skeletal samples often reflected the age structures of the reference populations used to create the age estimation standards; and second, the estimated ages at death of archaeological skeletons were not reliable enough to allow researchers to conduct paleodemographic analyses. Though van Gerven and Armelagos vehemently opposed these findings (van Gerven and Armelagos, 1983), skeletal age estimation studies began to move in a new direction. First, researchers started to investigate other areas of the skeleton that could be used for age estimation, i.e. fourth rib, auricular surface, trabecular bone involution (Işcan et al., 1984 b; Meindl et al., 1985; Walker and Lovejoy, 1985). Second, researchers began to see the potential advantage of combining several methods in principal component analysis (PCA) multifactorial analyses instead of single element analyses (Lovejoy et al., 1985 a). Third, Lovejoy, Meindl, and colleagues advocated for blind testing of age methods, and they were the first to introduce a new way expressing the relationship between chronological age and skeletal age—by the degree and direction of bias. Fourth, sex and population variation differences in age estimation studies became a common theme addressed by researchers. And fifth, researchers began to attribute health, diet, disease, genetics, and activity as factors that influence the correlations between chronological age and biological age.

The 1990's ushered in a self-reflective era in skeletal age estimation. In spite of the improvements brought about by the 1970's and 1980's, biological anthropologists began to acknowledge the limitations of the age estimation methods. First, the statistical methods used to develop the methods came under question. As noted by Aykroyd et al. (1997), the common age estimation methods used by biological anthropologists were created using linear regression models, and these methods tend to over-age younger individuals and under-age older individuals, and typically the majority of individuals cluster between the ages of 35 to 50 years. These are inherent problems in using linear regression formulae to create models, and because they were used as the foundation for the majority of the age estimation methods, and they do not reflect true population parameters. Several solutions have been proposed to overcome the limitations of regression models, including classical calibration (Aykroyd et al., 1997), likelihood estimations (Paine, 1989), Bayesian statistics (Hoppa and Vaupel, 2002 a), transition analysis (Boldsen et al.,

2002) , and the Sugeno fuzzy integral (Anderson et al., 2010); however, few researchers report using these new statistical methods, and few researchers use multivariate statistics when reporting their findings (Falys and Lewis, 2011; Garvin and Passalacqua, 2012). Second, most age estimation methods were developed on two North American skeletal collections of individuals who died in the early- to mid-20th century, and researchers began to question the applicability of the methods created on these populations to past and contemporary populations. Early 20th century populations differ from both past and modern populations in terms of health, diet, lifestyle, and occupations—all factors that affect skeletal aging. Even the applicability of skeletal age estimation methods developed on one collection to other skeletal collections from similar time periods has been problematic (Saunders et al., 1992; Bedford et al., 1993).

To address these issues, researchers have proposed new or revised age estimation methods since the turn of the century in an attempt to improve age estimation accuracy and precision (Kunos et al., 1999; Buckberry and Chamberlain, 2002; DiGangi et al., 2009; Passalacqua, 2009; Rougé-Maillart et al., 2009). One area that new age estimation methods address more than the older methods is the issue of under-aging older individuals, and a common trend among newer methods is to include more individuals over the age of 60 years in the sample (see Table 1). All of the original age estimation methods were developed on samples with fewer than 25% of the studied individuals having ages at death older than 60 years; the method with the highest proportion of individuals over the age of 60 years is the Todd method. Despite having 24% of the sample over the age of 60 years, the final age phase of the Todd method is simply “50+” with no description of the degenerative changes that occur once an individual has reached full maturity. Most of the newer methods (i.e. methods created or revised in the last fifteen years) were developed using samples where more than 25% of their sample consisted of individuals over the age of 60 years; three consisted of samples with more than 40% of individuals older than 60 years. Increasing the number of individuals over the age of 60 years has decreased the range of statistical biases for older individuals (Schmitt and Murail, 2004; Kurki, 2005; Mulhern and Jones, 2005; Falys et al., 2006; Nagaoka and Hirata, 2008; Rougé-Maillart et al., 2009; Hens and Belcastro, 2012), but the overall contribution of genetics, environment, disease, and lifestyle to skeletal aging are still poorly understood.

		N	% of sample over age 60 years
New and Revised Methods	DiGangi et al.	N/A ^a	N/A
	Passalacqua	216/635	34%
	Buckberry & Chamberlain	86/180	48%
	Rougé-Maillart et al.	12/52	23%
Original Methods	Kunos et al.	16/74	22%
	İşcan et al.	23/118	19%
	Lovejoy et al.	N/A	13% ^b
	Suchey-Brooks	151/1012	15%

^a N/A = not available

^b Personal communication, Owen Lovejoy.

Table 1: Number of individuals and percentage of samples with ages at death of 60 years or more used to develop age estimation methods.

To work around these problems of unreliable statistical models, population and sex differences, and under-aging of older individuals, some researchers have suggested shifting to life history models as methods of age estimation, as they do not require point ages, nor do they reflect the biases of the methods and reference samples. Life history theory considers the interaction of the trade-offs between growth, reproduction, and maintenance (McDade, 2003), and how these factors affect the evolution of a life history pattern. Roksandic and Armstrong (2011) suggest using life history models based on skeletal start- and end-points that reflect biologically meaningful stages to classify individuals at first, and then assign chronological ages. Although they argue their model carries sufficient age information to build mortality profiles, this has not been systematically tested with a large sample, and it still does not address the issues of estimating the ages of older individuals.

Overall, attempting to quantify morphological skeletal age changes to chronological age is a difficult task, especially since chronological age is not always related to biological age, and there are intra- and inter-population differences that need to be considered. The timing of specific stages of aging are difficult to predict, and not everyone will go through all the stages of aging at the same time, or even go through all the stages. For example, most age estimation methods characterize osseous material in their oldest age phases as “irregular” with “pitting and porosity” and “lipping”; however, not all older individuals will exhibit these age changes, and these age markers may be observed in younger individuals. Conversely, they may not necessarily reflect the aging process, but rather responses to loading or disease, making it difficult to always equate these changes to chronological age (Franklin, 2010).

For this project, only macroscopic age estimation methods were used, and only the methods used will be reviewed. Cranial suture closure and methods based on changes to teeth were not applied. Cranial suture closure has been shown to be an unreliable method of age estimation (Singer, 1953; Brooks, 1955; Powers, 1962; Gruspier and Mullen, 1991; HersHKovitz et al., 1997; Galera et al., 1998; Ginter, 2005; Beauthier et al., 2010) and is rarely used (Garvin and Passalacqua, 2012); and dental wear age methods are population specific and are not reliable when used on modern populations (Scott, 1979; Kieser et al., 1983; Lovejoy, 1985; Solheim, 1993). While it has been argued that the Lamedin method or methods assessing cementum annulations are reliable ways to estimate dental age (Baccino et al., 1999; Jankauskas et al., 2001; Martrille et al., 2007; Meinl et al., 2008; Robbins Schug et al., 2012), they are destructive methods and require the presence of specific teeth.

The eight age estimation methods used in this study were purposely selected to encompass a wide range of non-weight-bearing and weight-bearing sites; specifically, the ribs and pelvis. There are very few age estimation methods developed on non-weight-bearing joints that are reliable, and those selected for this study are all based on the ribs. The three non-weight-bearing rib methods selected were the Kunos et al. (1999) and DiGangi et al. (2009) first rib methods and the İşcan et al. (1984, 1985) fourth rib methods. Cranial suture closure and dental age estimation methods were avoided for the reasons reviewed in the above paragraphs (poor performance and population specific). For the weight-bearing joints, all aspects of the pelvis with new or reliable age estimations methods were considered: the Passalacqua (2009) sacrum method; the Lovejoy et al. (1985) and Buckberry and Chamberlain (2002) auricular surface methods; the Rougé-Maillart et al. acetabulum and auricular surface method (2007); and the Suchey-Brooks pubic symphysis method (1990). Age estimation methods that were developed on Asian or Balkan populations were not used in this study. The Rissech et al. acetabulum method was not selected as Calce and Rogers (2011) report poor replicability of the method on North American collections, specifically the J.C.B. Grant Collection curated at the University of Toronto. The Todd (1920) and McKern and Stewart (1957) and Gilbert and McKern (1973) pubic symphysis methods were also not included in the study because they perform poorly on older individuals. The Hartnett rib and pubic symphysis methods had not been published when the study data collection began in early 2010, so they were not included.

Multifactorial methods and statistical analyses were not used for this project, as the purpose was to evaluate each method individually. Multifactorial methods combine the scores of many age estimation methods to produce a final age, which is inconsistent with the goal of this research. See Table 2 for a list of methods used for this project.

Methods	Sample	Tests	Overall
Kunos et al., 1999	N = 74 European/African(M/F)	Kurki 2005, Getz 2011; Merritt 2013	Kunos et al. method more precise for older individuals; DiGangi et al. method performs poorly on older individuals.
DiGangi et al., 2009	N = 470 European (M)		
İşcan et al., 1984; 1985	N = 204 European (M/F)	Dudar et al. 1993, Russell et al. 1993, Loth 1995, Yavuz et al. 1998, Oettle and Steyn 2000, Fanton et al. 2010; Merritt 2013	Potential population differences; some inter/intra-observer discrepancies; generally accurate.
Passalacqua, 2009	N = 633 European/African(M/F)	Merritt 2013	More precise for older individuals; large age ranges; generally works well.
Lovejoy et al., 1985	N= 764 European/African(M/F)	Murray and Murray 1991, Schmitt 2004, Osborne et al. 2004, Mulhern and Jones 2005, Falys et al. 2006, Nagaoka and Hirata 2008, Merritt 2013	Potential population differences; large range of error with Lovejoy method but better with younger individuals; Buckberry and Chamberlain more accurate with older individuals.
Buckberry and Chamberlain, 2002	N = 180 European (M/F)		
Rougé-Maillart et al., 2007	N = 52 European (M/F)	Rougé-Maillart et al. 2009, Merritt 2013	Rougé-Maillart over 80% accurate with European sample.
Suchey Brooks, 1990	N = 1012 European/African/ Asian/Hispanic (M/F)	Meindl et al. 1985, Katz and Suchey 1989, Klepinger et al. 1992, Hoppa 2000, Djuric et al. 2007, Kimmerle et al. 2008, Schmitt 2004, Berg 2008, Merritt 2013	Potential population differences; females have most variability; generally accurate and precise.

Table 2: List of each age estimation method, composition of the sample used for development, tests of each method, and comments from the literature on each method's overall performance.

1.5.1 Adult Age Estimation Using Rib Morphology

The ribs have one primary centre of ossification on the body and three areas of epiphyseal ossification—one for the rib head and two for the articular and non-articular parts of the tubercle facet—except for the 11th and 12th ribs, which only have two epiphyseal centres. The epiphyses appear between the ages of 12 and 18 years, and fusion is complete by the age of 25 years (Scheuer and Black, 2000). As an individual ages, mineralization of the costal cartilage occurs. McCormick (1980) was the first to create a grading system to assess the mineralization of costal

cartilage from thoracic x-rays. He observed that mineralization of the costal cartilage did not occur before the age of 15 years, it was rarely visible before the age of 50 years, and dense mineralization was typically only seen in individuals over the age of 55 years. In 1984 and 1985, basing their research on the original observations of McCormick, İşcan, et al. created a system to estimate adult skeletal age at death using the sternal rib ends (İşcan et al., 1984, 1985). They observed morphological changes at the sternal end of the fourth ribs that were consistent with the aging process, and developed an eight-phase system using the fourth ribs from 93 males between the ages of 17 and 90 years, and 86 females between the ages of 14 and 90 years, all of European ancestry. Their method has been widely tested and accepted as a reliable, replicable, single indicator for estimating age (Dudar et al., 1993; Russell et al., 1993; Yavuz et al., 1998; Yoder et al., 2001). In 2010, Hartnett revised the İşcan et al. methods by combining the male and female methods and reducing the number of phases from eight to seven, truncating the younger phases; however, this method was not used in this project as it was not published at the time of data collection.

Researchers have cited the frequent occurrence of damage to the sternal rib ends in archaeological or forensic contexts, and the dangers inherent in relying solely on the morphological changes of the costal face of the rib, while ignoring other aspects of the rib that change throughout life as concerns in relying upon the fourth ribs as age estimation methods (Kunos et al., 1999). Kunos and colleagues (1999) created a new method of age estimation based on three aspects of first rib development—the costal face, rib head, and tubercle facet. They developed their method on the Hamann-Todd skeletal collection, with a reference sample size of 74 individuals and a test sample size of 182 individuals. Using the first rib has several advantages over the fourth rib method: it is easily identifiable and recognizable; it is not influenced by mechanical stress (respiration) in the same manner as the lower ribs; it is more likely to be preserved intact in forensic and archaeological contexts; and it exhibits a prolonged span of remodelling into the eighth decade of life (Kunos et al., 1999; Kurki, 2005). Tests of the Kunos et al. method have brought about two concerns; first, the length of time required to assess each age marker, and second, the amount of subjectivity required in scoring several traits for each feature (Schmitt and Murail, 2004; Kurki, 2005). However, the scoring is very thorough and allows researchers the flexibility of assessing each feature individually rather than forcing them into phases.

DiGangi and colleagues (2009) introduced a revised first rib method using the traits as described by Kunos et al. (1999), but the authors applied a Bayesian statistical approach to determine the two most accurate features to establish age at death (DiGangi et al., 2009). They determined that the geometric shape of the costal face in conjunction with the tubercle facet surface texture produced the most reliable age estimations. Recently, the DiGangi et al. method was tested by Getz (2011) and found to perform at the same level as the commonly used age estimation methods, yet few researchers report using this method (Garvin and Passalacqua, 2012).

1.5.2 Adult Age Estimation Using Sacrum Morphology

The sacrum has 21 primary ossification centres and three areas of articulation to other surfaces used for age estimation: the auricular surfaces, the lumbar vertebral plate. Both McKern and Stewart (1957) and Lovejoy et al. (1985) identified the patterns of fusion on the sacral body but concluded that, while definable morphological changes occur on the lateral auricular joints, it was not possible to use them for adult age at death estimations. Scheuer and Black (2000) describe the growth and development of the sacrum up to the age of 25 years. The sacrum exhibits age related changes in childhood, adolescence, and early adulthood. Before the age of 6 years, the 21 segments fuse into five central bodies; at the age of 14 years, the lateral elements forming the sacro-iliac joint at S3 and S5 fuse; during puberty, the vertebral plates between the epiphyses of the vertebral bodies begin to fuse; and after the age of 25 years the vertebral bodies between S1 and S2 fuse, completing the sacrum.

In 2009, Passalacqua developed a method of adult age estimation using the sacrum. Using 249 males from the Hamann-Todd Collection and William Bass Collection, he identified changes to the sacrum based on vertebral body fusion, porosity, vertebral ring fusion, and osteophytic activity. This method was tested by Merritt (2014); the author was able to correctly classify over 90% of individuals into the correct phase; however, a major drawback of this method is the large age ranges and confidence intervals associated with the age phases.

1.5.3 Adult Age Estimation Using Auricular Surface Morphology

The auricular surface forms part of the primary centre of ossification of the ilium, and articulates with the sacrum through the sacro-iliac joint. It is a large joint surface on the posterior/inferior region of the ilium (Scheuer and Black, 2000). The assessment of the auricular surface as a

method of age estimation was established by Lovejoy and colleagues, who used approximately 250 male and female skeletons from the Libben archaeological population, and 512 skeletons from the Hamann-Todd collection to create the method (Lovejoy et al., 1985 b). By observing age changes in the surface texture, organization, and degeneration of the auricular surface, they created an eight-phase system for age intervals between 20 and 59 years, with an age category for those over 60 years. This method was tested by Murray and Murray (1991) with 189 individuals from the Terry Collection and they concluded that when used on its own, the auricular surface is not a reliable indicator of age and should be used in conjunction with other methods; however, the method has the beneficial feature that sex and ancestry do not significantly affect age estimations (Bedford et al., 1993; Osborne et al., 2004). Bedford and colleagues tested the method on the University of Toronto's J.C.B. Grant Collection and found that adults between the ages of 49 and 60 years were typically over-aged by 5 to 7 years, and individuals over the age of 60 years were under-aged by 10 years (Bedford et al., 1993). Osborne et al. (2004) tested the Lovejoy et al. method on 266 male and female skeletons from the Bass Collection and Terry Collection and report that only 33% of the sample is correctly aged when using the 5 year age ranges. When tested on an Asian population from Thailand, the accuracy of the method decreases (Schmitt, 2004). In spite of the critiques of this method, it is still widely used (Falys and Lewis, 2011; Garvin and Passalacqua, 2012).

Buckberry and Chamberlain (2002) created a new system of auricular surface age scoring using 180 individuals from the Spitalfields Collection. Instead of using a defined 5-year phase system, they developed a scoring system for individual morphological features of the auricular surface, resolving previous issues with forcing traits into one category. The sum of scores are calculated to give a total score and subsequently they are assigned to a phase. Falys et al. (2006) tested the Buckberry and Chamberlain method on a sample from 167 males and females from St. Bride's, London, a documented skeletal assemblage from the late 17th to early 19th century. They looked at the correlation of the traits used by Buckberry and Chamberlain to age at death and found that only three of the traits have a high correlations with aging. When comparing the Lovejoy et al. and Buckberry and Chamberlain methods, Mulhern and Jones (2005), Nagaoka and Hirata (2008), and Hens and Belcastro (2012) found that Lovejoy et al.'s method was more accurate for individuals between 20 and 49 years of age, and Buckberry and Chamberlain's method was more accurate for older individuals (50+ years).

1.5.4 Adult Age Estimation Using Acetabular Morphology

Similar to the auricular surface, the acetabulum begins as part of the primary ossification centre of the ilium, and after the age of 10 years it starts to fuse with the ischium and pubis. Typically, the ilium, ischium, and pubis are fully fused by the age of 19 years (Scheuer and Black, 2000). Because the acetabulum is commonly preserved in archaeological and forensic contexts and it shows age-related changes, it is an ideal area to assess age. In a preliminary study of 30 male os coxae conducted by Rougé-Maillart et al. in 2004, they reported observable age-related changes such as osteophytes and osteoarthritis on the rim of the acetabulum, the breakdown of the acetabular fossa, porosity of the lunate surface, and arthritic lipping on the apex of the posterior cornu. Rougé-Maillart et al. observed that these acetabular aging traits complemented Lovejoy et al.'s (1985) auricular surface method to estimate age, but they use Buckberry and Chamberlain's scoring method to record the auricular surface changes. Stull and James (2010) evaluated Rougé-Maillart et al.'s original 2004 method and found that, although acetabular features demonstrate the capability to estimate age, an improved coding system and percent correct classification approach is necessary to determine accuracy and precision. Two of the authors on the original 2004 paper, Rougé-Maillart and Rissech, developed differing methods using the acetabulum. Rougé-Maillart continued to use the acetabulum in conjunction with the auricular surface, while Rissech focused solely on the acetabulum. In 2011, Rissech et al.'s method was tested by Calce and Rogers on the J.C.B. Grant Collection curated at the University of Toronto, and the authors reported low intra- and inter-observer reliability, and poor accuracy and precision on this North American collection. The authors conclude that the Rissech et al. method, which was developed on Iberian and Portuguese collections, is inappropriate to use on North American populations due to differences in physical activity, diet, health, and disease; therefore, this method was not used for this study. Rougé-Maillart and colleagues revised their original 2004 method and tested it on a sample 514 males of known age from Portugal and France (Rougé-Maillart et al., 2007, 2009), reporting high intra-observer agreement as well as high precision and accuracy. This revised method was evaluated by Merritt (2014) on the J.C.B. Grant Collection and the author found that, similar to Passalacqua's sacrum method, the majority of individuals were scored into the correct age phase and there was high intra- and inter-observer reliability. Therefore, the revised Rougé-Maillart et al. method was used for this study.

1.5.5 Adult Age Estimation Using Pubic Symphysis Morphology

The pubic symphysis is part of the primary centre of ossification of the pubis, and forms the midline cartilaginous joint that unites the superior rami of the left and right pubic bones (Scheuer and Black, 2000). The pubic symphysis has been considered one of the most reliable sites for adult age estimation. First described by Todd (1920, 1921), he observed age-related changes on the pubic symphyses of 306 male skeletons and 47 females housed at the Western Reserve University, now known as the Hamann-Todd Collection. He established a ten-phase system of age estimation, focusing on the early- and mid-adult changes to the pubic symphysis. He divided this observations into three major phases: the post-adolescent phase (18 to 24 years), where the symphyseal face is rugged with horizontal ridges, deep grooves, and no margins or ossific nodules, and progresses to one where ossific nodules fill in the deep grooves and the face becomes bevelled, and there is a formation of a dorsal plateau and dorsal margin; the buildup phase (25 to 35 years), where the symphyseal face is granular and there is a completion of the oval outline of the face, along with the near completion of the ventral rampart and dorsal margin; and the degenerative phase (35 years and over), where the symphyseal face becomes fine-grained to dense, the ventral rampart and dorsal margin progress from completion to lipping on the edges, and eventually the symphyseal face itself is marked by irregular ossification. The Todd method remains one of the most widely used age estimation methods in spite of the critiques of narrow age ranges (e.g. 18–19 years), a tendency to over-age individuals in their 30's and 40's, and inability to account for variability in individuals over the age of 50 years. Brooks (1955) found that the Todd ten-phase system was accurate only 30% of the time when applied to the same skeletal collection. She revised the Todd phase system (Brooks, 1955) and later collaborated with Suchey (Brooks and Suchey, 1990) on refinements to the method using a large sample of 739 males and 273 females of different ancestral backgrounds with age ranges from 14 to 92 years. This resulted in a new series of pubic symphyseal age standards, which incorporated an approach focusing on the total pattern of the symphyseal face. Using this system requires comparison of the morphology of the symphysis of interest to six sex-specific reference phases (both early and late), each of which has accompanying descriptions, photographs, and casts available for purchase. A reference table corresponding to the phase to which the unknown specimen appears to most clearly fit provides the necessary statistics, including a mean age estimate, standard deviation, and 95% confidence interval range (albeit broad). This method has

been widely tested (Saunders et al., 1992; Sinha and Gupta, 1995; Bednarek et al., 2002; Sitchon and Hoppa, 2005; Djurić et al., 2007; Hens et al., 2008; Kimmerle et al., 2008) and is the method used most frequently by researchers and forensic anthropologists (Falys and Lewis, 2011; Garvin and Passalacqua, 2012)

Several other methods of pubic symphysis age estimation have been developed. For example, McKern, Stewart, and Gilbert formulated a three-component method using the dorsal plateau, ventral rampart, and symphyseal rim (McKern and Stewart, 1957; Gilbert and McKern, 1973); however, subsequent testing by a large cohort of experienced anthropologists yielded unfavorable results (Suchey, 1979; Suchey et al., 1986), and few researchers use this method (Falys and Lewis, 2011; Garvin and Passalacqua, 2012). In 2010, Hartnett published revisions of the Suchey-Brooks pubic symphysis method. Hartnett expanded the Suchey-Brooks method by including a seventh phase to account for individuals over the age of 70 years, similar to Berg (2008). The Hartnett method was not used for this study as it was not published at the time of data collection. The Suchey-Brooks method was selected over the Berg method for evaluation as it is the more commonly used method (Falys and Lewis, 2011; Garvin and Passalacqua, 2012).

1.6 Application of Body Size to Age Estimation in Paleodemography, Paleoanthropology, and Forensic Anthropology

Understanding the role of body size in skeletal age estimation will be useful for biological anthropologists, particularly those who study paleodemography, paleoanthropology, and forensic anthropology. Accurate age-at-death estimations are the foundation of all work that interprets health, disease, and adaptation in past populations and communities. With accurate age at death estimations, researchers can explore life expectancy and population structure; for example, the presence or absence of older adults in the skeletal record affects the interpretation of roles and dynamics within a group, as adult longevity is a measure of a population's success. In both prehistorical and historical skeletal collections, the under-representation of infants or older adults seriously affects paleodemographic interpretations of fertility rates, death rates, mortality curves, and general health of past populations (see Cipriano-Betchtle et al., 1996; Guy et al., 1997; Paine and Harpending, 1998). Paine and Harpending (1998) observed that the lack of older individuals (i.e. individuals over the age of 45 years) in paleodemographic studies inflates birth rates by 10%

to 20%. In historical collections, it is common for researchers to compare the representativeness of their sample to documented historical accounts; however, this does not alleviate the problem of under-representation of individuals in skeletal assemblages. New biostatistical approaches to estimating age at death have helped researchers focus more on mortality distribution of samples on the basis of individual age indicators (Hoppa and Vaupel, 2002 b); however, if these age indicators are inaccurate, the problem is cyclical (i.e. inaccurate age estimations lead to inaccurate biostatistical data which lead to inaccurate interpretations of the assemblage). My research assesses the effects of body size on skeletal age estimation methods, and this will help researchers determine which age methods should be relied upon more heavily during analyses.

The reconstruction of mortality patterns is important to understanding the living conditions and environment of past human populations. Body size is an important factor when considering health and environmental adaptation in human history because it correlates well with the ways in which habitat, life history, and life span affect skeletal biology. Demands for improved methods to obtain mortality data at both the individual and population levels have increased in recent years, especially as current studies illustrate the impact of individual age estimation methods on population analyses (Nagar and HersHKovitz, 2004; Bonneuil, 2005; Nagaoka and Hirata, 2007, 2008). For example, debates about the life conditions of past populations often cite the absence of older individuals from the archaeological record. However, this presumed absence may not exist, since our current age standards may not be adequate to account for the lighter, leaner body composition of our ancestors. Body size plays an important role in changes to skeletal morphology, but it has never been systematically assessed as a factor in skeletal age estimation. We know that body size composition has changed over time (McHenry, 1992; Ruff et al., 1997; Katzmarzyk and Leonard, 1998; Ruff, 2002; Rosenberg et al., 2006; Leonard and Katzmarzyk, 2010), and recently it has been shown that body mass does affect the skeletal morphology (Agostini and Ross, 2011). If body mass influences the morphology of long bones, it is important to consider the ways body mass may influence the skeletal elements used for age estimation.

Understanding the influence of body size on age estimation could re-position theories on human small-bodied ancestors and could give anthropologists and evolutionary biologists a new perspective on their interpretations of human history. Important information regarding human biology, adaptation, and migratory history has be derived from studying our smaller, leaner

ancestors (Holliday, 1997, 2002; Holliday and Ruff, 1997; Ruff et al., 1997). With new information about the ways in which body size impacts our age standards, researchers will have an opportunity to re-examine these skeletal materials and more accurately determine age at death, with the possibility of refining our knowledge base about the lifespan of past human and ancestral populations.

As previous research has shown, modern human populations are generally taller and heavier than most past populations of *Homo sapiens*, as well as the majority of our hominin ancestors. Hominin ancestors and early *Homo sapiens* populations were generally short and light (see Table 3). Our current age standards were developed on North American skeletal collections of individuals that are generally tall and heavy, and they are often applied to these smaller, lighter individuals with the understanding that there are differences in the life histories, lifestyles, and environments, as well as body size. Often, when our age standards are applied to hominin ancestors and early populations of *Homo sapiens*, the trend is thought to demonstrate that populations experienced substantial young adult mortality, i.e., samples show most of their adult ages at death between 30 and 45 years of age. However, if body size does play a role in adult age estimation, and individuals with smaller body sizes are, for example, under-aged, then we may need to reconsider the mortality curves of small bodied hominin and *Homo sapiens* ancestors.

Forensic anthropologists rely on accurate age estimations to create biological profiles and to narrow searches for missing persons as accurate age-at-death estimations assist law enforcement agencies in the identification of skeletal remains. This is important for not only identifying victims of crime, but also casualties of war. For example, the US Army's Central Identification Laboratory and the Physicians for Human Rights are dedicated to recovering and identifying the war dead from conflicts all over the world; reliable osteological age at death estimation methods are critical to this important work. With obesity rates in Canada and the USA steadily increasing, understanding the ways in which modern populations age, and the ways in which skeletal aging is affected by body size, is an important topic that has not been considered systematically in forensic anthropology.

Species	Stature (cm)	Body mass (kg)
<i>A. afarensis</i>		
$\bar{x}$	128.0	37.0
<i>s.d.</i>	-	-
<i>n</i>	9	9
<i>A. africanus</i>		
$\bar{x}$	126.5	35.5
<i>s.d.</i>	-	-
<i>n</i>	12	12
<i>P. robustus</i>		
$\bar{x}$	121.0	36.0
<i>s.d.</i>	-	-
<i>n</i>	4	4
<i>P. bosei</i>		
$\bar{x}$	130.5	41.5
<i>s.d.</i>	-	-
<i>n</i>	2	2
<i>A. sediba</i>		
$\bar{x}$	130.0	44.2
<i>s.d.</i>	-	-
<i>n</i>	2	2
<i>H. habilis</i>		
$\bar{x}$	141.0	47.0
<i>s.d.</i>	-	-
<i>n</i>	5	5
<i>H. erectus</i>		
$\bar{x}$	170.0	68.0
<i>s.d.</i>	-	-
<i>n</i>	2	2
<i>H. neanderthalensis</i>		
$\bar{x}$	162.4	71.0
<i>s.d.</i>	3.6	10.5
<i>n</i>	17	12
<i>H. floresiensis</i>		
$\bar{x}$	106.0	30.0
<i>s.d.</i>	-	-
<i>n</i>	2	2
<i>H. sapiens</i> (Paleolithic European)		
$\bar{x}$	163.6	63.4
<i>s.d.</i>	6.0	6.6
<i>n</i>	41	17
<i>H. sapiens</i> (modern European)		
$\bar{x}$	164.4	63.8
<i>s.d.</i>	5.6	6.2
<i>n</i>	482	213
<i>H. sapiens</i> (modern Sub-Saharan Africa)		
$\bar{x}$	158.5	51.5
<i>s.d.</i>	7.8	7.5
<i>n</i>	109	78

Table 3: Stature and body mass estimations of hominin species. Stature is estimated from long bones, body mass is predicted by femoral head diameter or bi-iliac breadth (adapted from (McHenry, 1992, 2005; Kappelman, 1996; Helmuth, 1998; Holliday, 2002; Ruff, 2010).

Chapter 2: Materials and Methods

2.1 Materials

There are several human skeletal collections with known age and stature at death; however, there are very few established skeletal collections with known body mass at death. In North America, there are only two: the Hamann-Todd Collection curated at the Cleveland Museum of Natural History in Cleveland, Ohio and the William Bass Collection curated at the University of Tennessee in Knoxville, Tennessee. Both were used for this project.

2.1.1 Sample Selection

Prior to visiting each collection, skeletons were age and size selected to ensure representation from a broad spectrum of stature and body mass categories. Age, sex, ancestry, stature, body mass, and cause of death were known for most individuals in both collections. Individuals with unknown statures, body masses, and causes of death were eliminated from the collection samples, leaving available approximately 2700 individuals from the Hamann-Todd Collection and 550 individuals from the William Bass Collection.

Skeletons from both collections were classified into arbitrary groups based on their stature, body mass, and combination of stature and body mass to evaluate the range of body sizes potentially available for study (see Appendix 1 for the Hamann-Todd Collection; see Appendix 2 for the William Bass Collection). There were 49 stature and mass categories created. Individuals were then eliminated from the sample based on the following criteria:

1. Skeletons of persons who had a stature greater than 1.64m (5.4ft) and body mass less than 45.35kg (100lbs), as the cause of death for the majority of these individuals was a wasting disease (i.e. cancer, tuberculosis, etc.);
2. Skeletons of persons who had a stature greater than 1.95m (6.4ft) and body mass more than 102.1kg (225lbs) based on low sample sizes;
3. Skeletons of persons who had a stature of less than 1.60m (5.4ft) and body mass more than 79.35kg (175lbs) based on low sample sizes;
4. Skeletons of persons who died of cancer, tuberculosis, or any other wasting disease.

Once these skeletons were removed from the sample, 29 stature and mass groups were represented (see Table 4). Several groups had high representation; therefore, subsets were selected. Skeletons were not excluded based on sex or ancestry; however, the collections are mostly comprised of older North American males of European descent, and the sample used for this project reflects these characteristics.

	< 1.54m (< 5.0ft)	1.55–1.62m (5.1–5.3ft)	1.63–1.70m (5.4–5.6ft)	1.72–1.78m (5.7–5.9ft)	1.79–1.84m (5.10–6.0ft)	1.85–1.92m (6.1–6.3ft)	Total
<45.0kg (< 100lbs)	54	106	0	0	0	0	160
45.4–56.5kg (100–124lbs)	44	132	243	254	104	0	777
56.7–67.6kg (125–149lbs)	29	102	373	408	164	35	1111
68.0–79.0kg (150–174lbs)	8	34	147	174	118	39	520
79.4–89.8kg (175–199lbs)	0	5	20	42	44	26	137
90.2–101.6kg (200–224lbs)	0	0	20	34	38	16	108
Total	135	379	803	912	468	140	2813

Table 4: Number of skeletons in 29 stature and mass categories from the Hamann-Todd and William Bass Collections as categorized prior to arriving at the collections. Skeletons were subsequently excluded based on questionable age estimates and inadequate preservation of skeletal elements.

Skeletal inventories were not available before visits to each collection; therefore, inventories were conducted on site at the Hamann-Todd and William Bass Collections prior to data collection. To be considered in the study, each sample skeleton had to contain at least one rib to assess age (i.e. a first rib or fourth rib), and at least one pelvic element to assess age (i.e. sacrum, pubic symphysis, auricular surface, acetabulum). Skeletons who did not meet these inventory requirements were removed from the planned sample; when possible, they were replaced with skeletons of similar statures and body masses.

2.1.2 Hamann-Todd Collection

The Hamann-Todd Collection was established in 1839 and skeletons were collected until 1938 by Carl August Hamann and T. Wingate Todd. The collection consists of approximately 3100 human skeletons with both males and females represented. Ages at death range from fetal to 105 years, and most are of European or African-American descent. Most of these skeletons were

derived from positively identified individuals of known age, but some of the skeletons are derived from individuals where age was determined through soft tissue markers (Meindl et al., 1990). For this project, cases where ages at death were estimated by soft tissue markers were not used. Table 5 shows the sample distribution of skeletons from the Hamann-Todd Collection that were used for this project. The mean age at death is 49.6 years, with a range of 19 to 87 years. The average recorded stature at time of death is 1.69m (5.6ft) with a range of 1.30m to 1.92m (4.3ft to 6.3ft), and the average recorded body mass at time of death is 62.6kg (138lbs), with a range of 24.0kg to 99.8kg (53lbs to 220lbs).

	n	Mean Age (yrs)	Average Stature (m/ft)	Stature Range (m/ft)	Average Body Mass (kg/lbs)	Body Mass Range (kg/lbs)
Males	373	50.4	1.73/5.7	1.30–1.92/ 4.3–6.3	65.9/145	32.2–99.8/ 71–220
Females	163	47.8	1.60/5.3	1.30–1.83/ 4.3–6.0	54.9/121	24.0–90.7/ 53–200
European Ancestry	334	52.6	1.68/5.5	1.30–1.92/ 4.3–6.3	62.7/138	26.3–99.8/ 58–220
African Ancestry	199	44.6	1.71/5.6	1.50–1.92/ 4.9–6.3	62.5/138	24.0–99.8/ 53–220
Other Ancestry	3	43.0	1.65/5.4	1.59–1.80/ 5.2–5.9	56.3/124	42.6–64.4/ 94–142
19–29 years	47	24.7	1.70/5.6	1.37–1.90/ 4.5–6.2	61.2/135	37.2–89.8/ 82–198
30–39 years	120	34.9	1.70/5.6	1.30–1.92/ 4.3–6.3	65.1/143	24.0–90.7/ 53–200
40–49 years	106	43.8	1.69/5.6	1.44–1.90/ 4.7–6.2	64.1/141	27.7–99.8/ 61–220
50–59 years	89	53.5	1.70/5.6	1.30–1.92/ 4.3–6.1	64.4/144	27.7–93.0/ 61–205
60–69 years	103	63.8	1.70/5.6	1.50–1.90/ 4.9–6.3	60.5/133	30.4–99.8/ 67–220
70–79 years	67	73.8	1.65/5.4	1.38–1.86/ 4.5–6.1	57.6/127	26.3–93.9/ 58–207
80–89 years	4	82.0	1.63/5.3	1.55–1.74/ 5.1–5.7	56.1/124	31.3–97.5/ 69–215
Total	536	49.6	1.69/5.6	1.30–1.92/ 4.3–6.3	62.6/138	24.0–99.8/ 53–220

Table 5: Sample distribution of skeletons selected from the Hamann-Todd Collection, including age at death, ancestry, reported stature and body mass at time of death.

2.1.3 William Bass Collection

The William Bass Collection was established in 1981 by William Bass as a donor program in Knoxville, Tennessee, and the Anthropology Research Facility at the University of Tennessee continues to accept donors. Currently, the collection houses approximately 1000 skeletons, both males and females, with birth years ranging from 1892 to 2011. Most individuals were born after 1940 and most are of European or African-American ancestry. Table 6 shows the sample distribution of skeletons from the William Bass Collection used for this project. The mean age at death is 57.4 years, with a range of 19 to 89 years. The average recorded stature at time of death is 1.70m (5.6ft) with a range of 1.47m to 1.93m (4.8ft to 6.3ft); the average recorded body mass at time of death is 71.7kg (158lbs) with a range of 32.0kg to 99.8kg (71lbs to 220lbs).

	n	Mean Age (yrs)	Average Stature (m/ft)	Stature Range (m/ft)	Average Body Mass (kg/lbs)	Body Mass Range (kg/lbs)
Males	74	55.5	1.75/5.7	1.55–1.93/ 5.1–6.3	74.9/165	45.4–99.8/ 100–220
Females	186	63.8	1.62/5.3	1.47–1.87/ 4.8–6.1	63.8/141	32.0–99.8/ 71–220
European Ancestry	235	58.5	1.70/5.6	1.47–1.93/ 4.8–6.3	72.1/159	32.0–99.8/ 71–220
African Ancestry	18	53.6	1.75/5.7	1.65–1.90/ 5.4–6.24	69.6/154	48.5–93/ 107–205
Other Ancestry	7	58.0	1.59/5.2	1.52–1.74/ 5.0–5.7	59.3/132	44.5–93/ 98–205
19–29 years	7	24.6	1.74/5.7	1.57–1.90/ 5.2–6.2	71.8/158	54.4–79.4/ 120–175
30–39 years	18	35.7	1.78/5.8	1.63–1.87/ 5.3–6.14	78.1/172	48.5–99.8/ 107–220
40–49 years	54	45.4	1.73/5.7	1.54–1.93/ 5.1–6.3	71.5/157	40.8–99.8/ 90–220
50–59 years	63	54.3	1.72/5.6	1.50–1.88/ 4.9–6.2	76.1/168	43.5–99.8/ 96–220
60–69 years	58	64.2	1.70/5.6	1.50–1.93/ 5.0–6.3	71.0/157	32.0–99.8/ 71–220
70–79 years	41	74.2	1.68/5.5	1.47–1.86/ 4.8–6.1	67.0/148	33.1–99.8/ 73–220
80–89 years	19	83.4	1.65/5.4	1.47–1.85/ 4.8–6.1	63.8/141	35.8–99.8/ 79–220
Total	260	57.9	1.70/5.6	1.47–1.93/ 4.8–6.3	71.7/158	32.0–99.8/ 71–220

Table 6: Sample distribution of skeletons selected from the William Bass Collection, including age, ancestry, reported stature and body mass at time of death.

2.2 Methods

2.2.1 Age Estimation Methods

The rib age estimation methods used for this project were developed by Kunos et al. (1999), DiGangi et al. (2009), and İşcan et al. (1984, 1985). The pelvic age estimation methods were developed by Passalacqua (2009), Lovejoy, et al. (1985), Buckberry and Chamberlain (2002), Rougé-Maillart et al. (2009), and Suchey and Brooks (1990). Age assessments were performed on each skeleton without knowledge of the age, ancestry, stature, body mass, or cause of death for the specimen under consideration; the author had a research assistant for data collection at the Hamann-Todd Collection to help with this process. Sex was known for all individuals as the İşcan et al. and Suchey-Brooks methods have sex-specific criteria. All methods were applied as described by the authors. Casts for the Suchey-Brooks method were used, and colour image slides of the auricular surface for the Lovejoy et al. method were available. In all cases, the authors' specifications with regard to the side to be used were followed. When scoring the pubic symphysis, auricular surface, sacrum, and acetabulum, the methods were applied to the left side; with the right side used if the left was unavailable. When scoring the first ribs, the Kunos et al. (1999) and DiGangi et al. (2009) methods were applied to the right first ribs; if unavailable, the left ones were assessed. When scoring the fourth ribs, the ribs were seriated by the author, and the İşcan et al. (1984; 1985) method was applied to the right fourth ribs; if the right fourth rib was unavailable or damaged, the right third or fifth ribs were used. Each individual was assigned to an age phase, as specified by each method. The mean age at death within each phase for each method was then compared to the actual age at death recorded in the Hamann-Todd and William Bass collection documentation.

Prior to data collection, the author performed an intra- and inter-observer error study using the J.C.B Grant Collection curated at the University of Toronto. The purpose of this study was to become familiar with the age methods and ensure that the age estimations generated using each method were reliable. Results from the study show a high level of both intra- and inter-observer agreement (Merritt, 2013).

2.3 Terms and Statistical Methods

2.3.1 Terms

Reliability is the degree to which a method produces the same results when used at different times, either by multiple observers or the same observer (Nance, 1987). A highly reliable age estimation method produces consistent age estimates for the same sample when applied by the same observer and different observers. Reliability for a method is tested by conducting inter-observer or intra-observer variation studies to determine error rates. Low inter- or intra- observer variation (or error) indicates high reliability. Reliability can also be referred to as repeatability, indicating that the technique or method applied produces similar measurements of the same quantity or entity being measured (Adams and Byrd, 2002).

Accuracy is the degree of error in a measurement as calculated from the true value or the closeness of agreement between a quantity value obtained by measurement and the true value of the measure (Youden, 1998). For skeletal age estimation, this is the ability of a method to continually and consistently provide age intervals that encompass the true age at death of individuals. Calculations of inaccuracy, the absolute difference between actual and estimated ages at death, and bias, the directionality of these differences, are used to measure error and determine the validity of a method.

Precision is linked to accuracy and can be defined as the degree to which repeated measurements in the same conditions yield similar results (White and Folkens, 2005). Precision is determined by the number of deviations of an individual measurement from the average of the total measurements expressed as a standard deviation or variance (Youden, 1998). An age estimation method is considered precise if the estimated age at death has a small standard deviation from the average value measured for a sample.

2.3.2 Statistical Methods

The age distribution of the sample was tested for normalcy using the Shapiro-Wilk test. Mann-Whitney U nonparametric tests were used to compare the Hamann-Todd and William Bass Collection data to determine the likelihood that the individuals from the two collections come from the same population. More specifically, Mann-Whitney U tests were used to assess the differences between the descriptive statistics between the two collections. Univariate models,

including descriptive statistics, and the analysis of variance (ANOVA) were used to evaluate differences between the two skeletal collections.

Reliability was calculated for each method by evaluating the inaccuracy and bias. Inaccuracy is the average absolute error of the age estimation, without reference to over- or under-prediction:

$$\sum |\text{estimated age} - \text{actual age}| / n;$$

whereas bias is the mean over- or under- prediction of the individual:

$$\sum (\text{estimated age} - \text{actual age}) / n$$

(Lovejoy et al., 1985 a). Accuracy and bias were calculated for each method on the entire sample, as well as by sex and ancestry.

Multivariate analysis of variance (MANOVA) and discriminant function analysis (DFA) were used to assess influence of the dependent variables (BMI, stature, body mass, and weight-bearing joints) on the independent variables (inaccuracy and bias of each method). MANOVA and DFA use the same statistical principles, which are similar to multiple linear regression, to predict an outcome. However, multiple linear regression is limited to cases where the DV is a continuous or interval variable so that the combination of predictors will, through the regression equation, produce estimated mean population numerical Y values (DV) for given values of weighted combinations of X (IV) values. MANOVA and DFA perform similar analyses, but for categorical DV. MANOVAs differ from DFAs as they examine the effect of an IV on a number of DVs, whereas DFA examines which combination of IV is best able to predict a DV.

Prior to conducting the MANOVA, a series of Pearson correlations were performed between all of the DVs in order to test the MANOVA assumption that the DVs would be correlated with each other in the moderate range of 0.20 to 0.60 (Meyers et al., 2006). Box's M *p*-values were considered non-significant at $p < 0.005$ based on Huberty and Petoskey's (2000) guidelines. Pillai's Trace was used to report the ANOVA results as it is the most robust to violations of the covariation assumption (Johnson and Field, 1993). As the IVs in this study have three or more levels, eigenvalues and canonical correlations could be extracted by the MANOVA and used to calculate how much of the variance in the discriminant function derived scores can be accounted

for by BMI, stature, and body mass. To interpret the MANOVA effects, the standardized discriminant function coefficients were used to calculate the correlations between the subscale scores and the canonically derived scores. To estimate the group centroids (i.e. canonically derived group means) for the IV categories (for example, underweight, normal, overweight, and obese for the BMI IV), the sample subscale scores were multiplied by the corresponding subscale unstandardized discriminant function coefficients and then averaged across the entire sample. In accordance with Enders (2003), an ANOVA was performed on the canonically derived data. However, because the sampling distribution associated with multivariate derived data is known to be different from univariate derived data (Neufeld and Gardner, 1990), a conservative approach to statistical significance testing was applied. Specifically, an alpha level of 0.001 was specified for the ANOVA. Cohen's *d*-values were evaluated to determine effect size. Effect size was evaluated as small = 0.2, medium = 0.5, and large = 0.8 (Cohen, 1992).

Tukey Honestly Significant Difference (HSD), or Tukey *b* in cases of uneven sample sizes, post-hoc tests were used to determine significant differences between IV categories for each DV. Fisher's Least Significant Differences (LSD) tests are associated with increased type I errors (Hayter, 1986) and Bonferonni Corrections have been criticized for being too conservative (Nakagawa, 2004).

A random sample of 200 individuals was assessed to control for intra-observer error; a reliability analysis using the Kappa statistic was performed to determine consistency, with the exception of the Kunos et al. method. The Kappa statistic measures inter- and intra-observer agreement for categorical data. The Kappa evaluation criteria are based on the following: 0.41–0.60 = moderate agreement, 0.61–0.80 = substantial agreement, 0.81–1.00 = near perfect agreement (Landis and Koch, 1977). For the Kunos et al. method, three traits are scored and assigned an age range; each trait assessment takes into account multiple features and results in a new age range rather than a set, previously defined phase. Because the Kunos et al. method does not have categorical age phases, interclass correlation coefficients (ICC) were used to evaluate the repeatability of this method. ICC measures how similar two or more repeated observations on continuous data are to each other rather than comparing categorically structured observations. ICC evaluation criteria are based on the following: 0.5–0.6 = moderate agreement, 0.7–0.8 = strong agreement, and >

0.8 = near perfect agreement (Bartko, 1976). All statistical tests were performed with SPSS 20.0 (IBM Corp, 2012)

Chapter 3: Results

The results chapter is divided into seven sections. Section 3.1 presents the comparisons between the individuals from the Hamann-Todd and William Bass collections to evaluate whether they can be used as one pooled sample. Section 3.2 presents the test results from the eight age estimation methods, and the descriptive statistics of the final, combined sample. Section 3.3 presents the results from the first research question: does BMI influences skeletal age estimations? Section 3.4 presents the results from the second research question: does stature influences skeletal age estimations? Section 3.5 presents the results from the third research question: does body mass influences skeletal age estimations? Section 3.6 presents the results from the fourth research question: are there differences between weight-bearing and non-weight-bearing joint age estimations? Section 3.7 presents additional analyses of the skeletal materials.

3.1 Comparison of the Individuals from the Hamann-Todd and William Bass Collections

3.1.1 Descriptive Differences Between the Collections

Mann-Whitney U tests show there are significant differences between the individuals selected from each of the collections with regard to age at death and ancestry, but not sex (Table 7). The samples used from the William Bass Collection largely consists of older individuals of European descent, while the samples used from the Hamann-Todd Collection are younger with more African-Americans represented (Figure 1 and Table 8). This is to be expected as the William Bass Collection is a donor collection from Tennessee with an average age at death over 50 years of age, with most donors self-identified as “white” males. The Hamann-Todd Collection consists of migrant workers who lived during the late 19th and early 20th centuries and died in the Cuyahoga County of Ohio and whose bodies were not claimed at time of death.

Collection		N	Mean Rank	Sum of Ranks	Mann-Whitney U	Wilcoxon W	Z	Sig. (2-tail)
Sex	Hamann-Todd Collection	536	401.03	214954.00	68322.000	102252.000	-0.564	0.573
	William Bass Collection	260	393.28	102252.00				
	Total	796						
Ancestry	Hamann-Todd Collection	536	433.75	232490.50	50785.500	84715.500	-7.923	<0.001
	William Bass Collection	260	325.83	84715.50				
	Total	796						
Age	Hamann-Todd Collection	536	359.61	192748.50	48832.500	192748.500	-6.854	<0.001
	William Bass Collection	260	478.68	124457.50				
	Total	796						

Table 7: Mann-Whitney U tests for significance for age at death, sex, and ancestry between samples from the Hamann-Todd and William Bass Collections.

Figure 1: Age at death distribution for the samples from the Hamann-Todd and William Bass Collections.

Ancestry	Hamann-Todd Collection	William Bass Collection	Total
European	334	235	569
African	199	18	217
Hispanic	0	4	4
Asian	1	1	2
Aboriginal	0	1	1
Other	2	1	3

Table 8: Number of individuals in each ancestry category for samples from the Hamann-Todd and William Bass Collections.

Mann-Whitney U tests show there are no significant differences in stature between the samples from the two collections (Table 9); however, there are significant differences in body mass, with individuals from the William Bass Collection heavier on average compared to individuals from the Hamann-Todd Collection. The distribution of stature and mass from the sample is illustrated in Figure 2.

Collection		n	Mean Rank	Sum of Ranks	Mann-Whitney U	Wilcoxon W	Z	Sig. (2-tail)
Stature (m)	Hamann-Todd Collection	536	388.03	207982.00	64066.000	207982.000	-1.845	0.065
	William Bass Collection	260	420.09	109224.00				
	Total	796						
Mass (kg)	Hamann-Todd Collection	536	355.68	190647.00	46731.000	190647.000	-7.545	<0.001
	William Bass Collection	260	486.77	126559.00				
	Total	796						

Table 9: Mann-Whitney U tests for significance between stature and body mass for the samples from the Hamann-Todd and William Bass Collections.

Figure 2: Distribution of stature and body mass for the samples from the Hamann-Todd and William Bass Collections.

As described in Chapter 2, each individual was classified into a BMI group based on stature and body mass. Mann-Whitney U tests show there are significant differences between the two skeletal collections for BMI. There are more overweight and obese individuals from the William Bass Collection sample while the Hamann-Todd Collection sample has a higher proportion of individuals in the underweight and normal-sized BMI categories (Table 10 and Figure 3).

Collection		n	Mean Rank	Sum of Ranks	Mann-Whitney U	Wilcoxon W	Z	Sig. (2-tail)
BMI	Hamann-Todd Collection	536	358.68	192253.50				
	William Bass Collection	260	480.59	124952.50				
	Total	796			48337.500	192253.500	-7.676	<0.001

Table 10: Mann-Whitney U Tests showing significant differences among BMI categories between the samples from the Hamann-Todd and William Bass Collections.

Figure 3: Distribution of BMI categories between the samples from the Hamann-Todd and William Bass Collections.

Individuals were chosen based on strict inclusion criteria for this project; therefore, any discrepancies between the samples from the two collections reflects decisions made to meet the parameters of this project.

3.1.2 The Combined Sample from the Hamann-Todd and William Bass Collections

Table 11 shows the combined sample composition of the 796 individuals from the Hamann-Todd and William Bass Collections. The mean age at death is 52.1 years, with a range of 19 to 89 years; the average stature is 1.70m (5.6ft), with a range of 1.30m to 1.93m (4.3ft to 6.3ft); and the average body mass is 65.5kg (145lbs), with a range of 25.0kg to 99.8kg (53lbs to 220lbs). Most individuals are North American of European ancestry, and more males than females are represented.

	n	Mean Age (yrs)	Average Stature (m/ft)	Stature Range (m/ft)	Average Body Mass (kg/lbs)	Body Mass Range (kg/lbs)
Males	559	52.1	1.74/5.7	1.30–1.93/ 4.3–6.3	68.9/152	32.2–99.8/ 71–220
Females	237	52.8	1.60/5.3	1.30–1.87/ 4.3–6.1	57.7/127	24.0–99.8/ 53–220
European Ancestry	569	55.1	1.69/5.6	1.30–1.93/ 4.3–6.3	66.6/147	26.3–99.8/ 58–220
African Ancestry	217	45.4	1.72/5.6	1.50–1.92/ 4.9–6.3	63.1/139	24.0–99.8/ 53–220
Other Ancestry	10	50.7	1.60/5.3	1.50–1.92/ 5.0–6.3	57.5/127	42.6–99.8/ 94–220
18–29 years	54	24.7	1.71/5.6	1.37–1.90/ 4.5–6.2	62.5/138	37.2–89.8/ 82–198
30–39 years	138	35.0	1.71/5.6	1.30–1.92/ 4.3–6.3	66.8/147	24.0–99.8/ 53–220
40–49 years	160	44.3	1.70/5.6	1.44–1.93/ 4.7–6.3	66.6/147	27.7–99.8/ 61–220
50–59 years	152	53.8	1.70/5.6	1.30–1.92/ 4.3–6.3	69.3/153	27.7–99.8/ 61–220
60–69 years	161	64.0	1.70/5.6	1.49–1.93/ 4.9–6.3	64.3/142	30.4–99.8/ 67–220
70–79 years	108	74.0	1.66/5.5	1.38–1.86/ 4.5–6.1	61.1/135	26.3–99.8/ 58–220
80–89 years	23	83.0	1.65/5.4	1.47–1.85/ 4.8–6.1	62.5/138	31.3–99.8/ 69–220
Total	796	52.1	1.70/5.6	1.30–1.93/ 4.3–6.3	65.5/145	24.0–99.8/ 53–220

Table 11: Sample distribution by sex, ancestry, and age categories.

Table 12 shows the total number of individuals from each stature and body mass category included in the combined sample to be evaluated (see Appendix 3 for the composition of individuals from the Hamann-Todd Collection; see Appendix 4 for the composition of individuals from the William Bass Collection). The distribution of individuals by stature and body mass shows a wide range of body sizes in the sample, with most individuals falling within a normal distribution (Figure 4 and Figure 5).

	< 1.54m (< 5.0ft)	1.55–1.62m (5.1–5.3ft)	1.63–1.70m (5.4–5.6ft)	1.72–1.78m (5.7–5.9ft)	1.79–1.84m (5.10–6.0ft)	1.85–1.92m (6.1–6.3ft)	Total
<45.0kg (< 100lbs)	24	47	0	0	0	0	71
45.4–56.5kg (100–124lbs)	26	37	41	36	29	0	169
56.7–67.6kg (125–149lbs)	20	37	43	46	38	13	197
68.0–79.0kg (150–174lbs)	5	23	44	42	44	19	177
79.4–89.8kg (175–199lbs)	0	6	19	40	38	21	124
90.2–101.6kg (200–224lbs)	0	0	15	15	15	13	58
Total	75	150	162	179	164	66	796

Table 12: Distribution of the combined sample by stature and body mass categories.

Figure 4: Distribution of the combined sample by stature.

Figure 5: Distribution of the combined sample by body mass.

When separated by BMI, 420 individuals are classified as normal-sized, 144 individuals as underweight, 181 individuals as overweight, and 51 individuals as obese, as defined by the WHO (Table 13).

BMI	n	Mean Age (yrs)	Average Stature (m/ft)	Stature Range (m/ft)	Average Body Mass (kg/lbs)	Body Mass Range (kg/lbs)
Underweight	144	54.0	1.68/5.5	1.46-1.92/ 4.8-6.3	46.5/103	24.0-83.9/ 53-185
Normal	420	51.9	1.70/5.6	1.35-1.93/ 4.2-6.3	63.6/140	42.2-97.5/ 93-215
Overweight	181	50.7	1.70/5.6	1.40-1.90/ 4.5-6.2	78.1/172	51.3-99.8/ 113-220
Obese	51	56.6	1.67/5.5	1.30-1.87/ 4.3-6.1	90.7/200	63.5-99.8/ 140-220

Table 13: Distribution of the combined sample by BMI, including number of individuals in each category, average recorded stature and body mass, and stature and body mass ranges.

3.1.3 Tests for Normality

The Shapiro-Wilk test shows the age at death is not normally distributed ($0.983, p < 0.001$); however, the histogram (Figure 6), Q-Q Plots (Figure 7), and Detrended normal Q-Q Plots of Age (Figure 8) show that the data is normally distributed. The Central Limit Theorem states that the larger the number of individuals in a sample, the more likely the sample mean will represent a normal distribution, even when the sample itself is not an independent sample. Also, with large datasets, normality tests are often over-powered and give significant results. Therefore, both parametric and non-parametric tests will be used for the analysis, with more focus on the parametric results as they are more robust to deviations with large datasets.

In order to use the inaccuracy and bias scores in MANOVA and DFA analyses, the results were tested for multivariate normality. Mardia's tests show that both the inaccuracy ($p = 0.065$) and bias values ($p = 0.078$) are normally distributed for multivariate analyses.

Figure 6: Histogram showing total sample size by age with a normal distribution curve.

Figure 7: Q-Q Plot for Age showing a normal distribution.

Figure 8: Detrended normal Q-Q Plot for age showing a normal distribution.

3.2 Tests of the Age Estimation Methods

3.2.1 Kunos et al. First Rib Method

Appendix 5 provides the descriptive statistics for the Kunos et al. (1999) method. Intra-observer reliability shows a high level of agreement for the randomly selected test sample [ICC = 0.799 ($F = 8.950$, $df = 212$, $p < 0.001$)]; therefore, the age estimations are considered reliable.

Table 14 and Table 15 present the accuracy and bias scores for the Kunos et al. method.

Parametric, independent samples t-tests show there are no significant differences between males and females for accuracy ($t = -1.398$, $df = 778$, $p = 0.163$); however, there are significant differences between males and females for bias ($t = 3.897$, $df = 390.864$, $p < 0.001$). Similar results are generated from non-parametric Mann-Whitney U tests (inaccuracy: $U = 66,437$, $p = 0.346$; bias: $U = 53,951.50$, $p = 0.001$). Females are typically under-aged ($\bar{x} = -0.39$ years, $s.d. = 13.84$ years), while males are over-aged by approximately 3.5 years ($\bar{x} = 3.68$ years, $s.d. = 12.13$ years).

When accuracy and bias are compared by ancestry, independent sample t-tests indicate there are no significant differences between individuals of European and African ancestry for accuracy ($t = -1.070$, $df = 768$, $p = 0.285$), but there are for bias ($t = -4.089$, $df = 768$, $p < 0.001$). These results are similar when using non-parametric Mann-Whitney U tests (inaccuracy: $U = 63,446$, $p = 0.152$; bias: $U = 70,849$, $p < 0.001$). Individuals of European ancestry are typically over-aged by approximately one year ($\bar{x} = 1.24$ years, $s.d. = 12.860$ years) while individuals of African ancestry are typically over-aged by approximately 5.5 years ($\bar{x} = 5.41$ years, $s.d. = 12.089$ years).

		Male			Female			Total		
		n	Kunos et al. Inaccuracy	Kunos et al. Bias	n	Kunos et al. Inaccuracy	Kunos et al. Bias	n	Kunos et al. Inaccuracy	Kunos et al. Bias
Age (yrs)	19-29	34	18.97	18.85	18	11.89	11.56	52	16.52	16.33
	30-39	94	14.40	14.40	43	12.42	12.14	137	13.78	13.69
	40-49	114	10.91	10.51	43	9.12	7.21	157	10.42	9.61
	50-59	113	6.23	3.33	37	6.51	2.84	150	6.30	3.21
	60-69	117	7.03	-4.80	40	8.88	-8.28	157	7.50	-5.69
	70-79	64	12.34	-12.34	40	15.35	-15.35	104	13.50	-13.50
	80-89	11	18.55	-18.55	12	24.25	-24.25	23	21.52	-21.52
	Total	547	10.54	3.68	233	11.33	-0.39	780	10.77	2.46

Table 14: Inaccuracy and bias scores from the Kunos et al. first rib age estimates for males and females. All values are in years.

		European			African				Other Ancestry	
		n	Kunos et al. Inaccuracy	Kunos et al. Bias	n	Kunos et al. Inaccuracy	Kunos et al. Bias		Kunos et al. Inaccuracy	Kunos et al. Bias
Age (yrs)	19-29	21	18.48	18.48	29	14.76	14.41	2	21.50	21.50
	30-39	73	14.92	14.92	62	12.39	12.19	2	15.50	15.50
	40-49	106	10.57	10.00	49	10.00	8.61	2	13.00	13.00
	50-59	123	6.01	3.60	25	8.00	1.68	2	3.00	-2.00
	60-69	132	7.55	-5.62	24	7.33	-6.08	1	5.00	-5.00
	70-79	82	13.89	-13.89	22	12.05	-12.05	0	N/A	N/A
	80-89	19	21.42	-21.42	3	23.33	-23.33	1	18.00	-18.00
	Total	556	10.57	1.24	214	11.20	5.41	10	12.90	7.30

Table 15: Inaccuracy and bias scores from the Kunos et al. first rib age estimates separated by ancestry. All values are in years.

When known age at death is plotted against bias, the whisker-box plots show that younger individuals are over-aged and older individuals are under-aged (Figure 9). Individuals between the ages of 30 and 39 years, and 60 and 79 years have the most outliers at four each, and most are under-aged. Overall, the Kunos et al. method follows the expected bias patterns in age estimation with younger individuals over-aged and older individuals under-aged.

Figure 9: Mean bias scores for the Kunos et al. method categorized by age at death.

3.2.2 DiGangi et al. First Rib Method

Appendix 6 provides the descriptive statistics for the DiGangi et al. method. Intra-observer reliability shows a high level of agreement for the randomly selected test sample [$Kappa = 0.659$, 95% CI (0.591 – 0.728)]; therefore, the age estimations are considered reliable.

Table 16 and Table 17 present the accuracy and bias scores for the DiGangi et al. method. Parametric, independent samples t-tests show there are significant differences between males and females for accuracy ($t = -3.692$, $df = 362.381$, $p < 0.001$) and bias ($t = 4.146$, $df = 764$, $p < 0.001$). Similar results are generated from non-parametric Mann-Whitney U tests (inaccuracy: $U = 52,303.00$, $p = 0.001$; bias: $U = 51,309.00$, $p < 0.001$). Inaccuracy is 14.90 years for males ($s.d. = 10.75$ years) and 18.55 years for females ($s.d. = 13.23$ years), with males under-aged by approximately 12 years ($\bar{x} = -12.34$ years, $s.d. = 13.63$ years) and females under-aged by almost 17 years ($\bar{x} = -16.96$ years, $s.d. = 15.23$ years).

When accuracy and bias are compared by ancestry, independent sample t-tests indicate there are significant differences between individuals of European and African ancestry for accuracy ($t = 4.931$, $df = 464.68$, $p < 0.001$), and bias ($t = -4.890$, $df = 425.33$, $p < 0.001$). These results are similar when using non-parametric Mann-Whitney U tests (inaccuracy: $U = 45,912.50$, $p < 0.001$; bias: $U = 45,263.50$, $p < 0.001$). Inaccuracy is 17.20 years for individuals of European descent ($s.d. = 12.06$ years) and 12.99 years for individuals of African ancestry descent ($s.d. = 9.90$ years). Individuals of European ancestry are typically under-aged by approximately 15 years ($\bar{x} = -15.21$ years, $s.d. = 14.50$ years) while individuals of African ancestry are typically under-aged by approximately 10 years ($\bar{x} = -9.89$ years, $s.d. = 13.02$ years).

		Male			Female			Total		
		n	DiGangi et al. Inaccuracy	DiGangi et al. Bias	n	DiGangi et al. Inaccuracy	DiGangi et al. Bias	n	DiGangi et al. Inaccuracy	DiGangi et al. Bias
Age (yrs)	19-29	33	8.45	3.12	18	6.11	-4.33	51	7.63	0.49
	30-39	92	7.42	-2.16	43	9.12	-4.74	135	7.96	-2.99
	40-49	111	9.30	-5.69	43	13.21	-10.88	154	10.39	-7.14
	50-59	112	13.00	-12.20	36	14.81	-13.53	148	13.44	-12.52
	60-69	116	20.84	-20.65	39	26.95	-26.95	155	22.37	-22.23
	70-79	62	28.35	-28.35	39	29.54	-29.54	101	28.81	-28.81
	80-89	11	34.27	-34.27	11	40.27	-40.27	22	37.27	-37.27
	Total	537	14.90	-12.34	229	18.55	-16.96	766	15.99	-13.72

Table 16: Inaccuracy and bias scores from the DiGangi et al. first rib age estimates for males and females. All values are in years.

		European			African			Other Ancestry		
		n	DiGangi et al. Inaccuracy	DiGangi et al. Bias	n	DiGangi et al. Inaccuracy	DiGangi et al. Bias	n	DiGangi et al. Inaccuracy	DiGangi et al. Bias
Age (yrs)	19-29	21	8.19	2.95	29	7.41	-1.21	1	2.00	-2.00
	30-39	71	7.65	-2.35	62	8.40	-3.63	2	5.50	-5.50
	40-49	104	10.93	-7.49	48	9.56	-6.60	2	2.00	-2.00
	50-59	121	13.05	-12.26	25	14.76	-13.16	2	20.50	-20.50
	60-69	130	22.22	-22.05	24	23.00	-23.00	1	28.00	-28.00
	70-79	79	29.56	-29.56	22	26.14	-26.14	0	N/A	N/A
	80-89	19	37.95	-37.35	2	31.50	-31.50	1	36.00	-36.00
	Total	545	17.20	-15.21	212	12.99	-9.89	9	13.56	-13.56

Table 17: Inaccuracy and bias scores from the DiGangi et al. first rib age estimates separated by ancestry. All values are in years.

When known age at death is plotted against bias, the pattern shows that individuals are almost always under-aged for all age categories (Figure 10). Individuals in the younger age categories (19 to 39 years) have a large number of outliers, and most are over-aged. Older individuals between the ages of 70 and 89 years have negatively-skewed bias scores. Overall, the bias values follow the expected trend of under-aging individuals in older age categories.

Figure 10: Mean bias scores for the DiGangi et al. method categorized by age at death.

3.2.3 İşcan et al. Fourth Rib Method

Appendix 7 provides the descriptive statistics for the İşcan et al. method. Intra-observer reliability shows a high level of agreement for the randomly selected test sample [Kappa = 0.898, 95% CI (0.853 – 0.943)]; therefore, the age estimations are considered reliable.

Table 18 and Table 19 present the accuracy and bias scores for the İşcan et al. method.

Parametric, independent samples t-tests show there are significant differences between males and females for accuracy ($t = -2.986$, $df = 310.034$, $p = 0.003$) and bias ($t = 5.495$, $df = 338.510$, $p < 0.001$). Similar results are generated from non-parametric Mann-Whitney U tests (inaccuracy: $U = 52,403.50$, $p = 0.038$; bias: $U = 43,629.50$, $p < 0.001$). Inaccuracy is 10.75 years for males ($s.d. = 8.31$ years) and 13.31 years for females ($s.d. = 11.46$ years), with males over-aged by one year ($\bar{x} = 0.77$ years, $s.d. = 13.58$ years) and females under-aged by almost 6 years ($\bar{x} = -6.18$ years, $s.d. = 16.47$ years).

When accuracy and bias are compared by ancestry, independent sample t-tests indicate there are no significant differences between individuals of European and African ancestry for accuracy (t

= 0.900, $df = 741$, $p = 0.368$), and bias ($t = -0.355$, $df = 741$, $p = 0.723$). These results are similar when using non-parametric Mann-Whitney U tests (inaccuracy: $U = 53,541.50$, $p = 0.357$; bias: $U = 53,940.50$, $p = 0.442$). Inaccuracy is 11.77 years for individuals of European descent ($s.d. = 9.43$ years) and 11.06 years for individuals of African ancestry descent ($s.d. = 9.35$ years). Individuals of European and African ancestry are typically under-aged by 1 to 1.5 years (European ancestry: $\bar{x} = -1.57$ years, $s.d. = 14.96$ years; African ancestry: $\bar{x} = -1.03$ years, $s.d. = 14.42$ years).

		Male			Female			Total		
		n	İşcan et al. Inaccuracy	İşcan et al. Bias	n	İşcan et al. Inaccuracy	İşcan et al. Bias	n	İşcan et al. Inaccuracy	İşcan et al. Bias
Age (yrs)	19-29	34	8.03	3.62	19	9.74	6.89	53	8.64	4.79
	30-39	92	9.45	5.40	43	10.23	0.88	135	9.70	3.96
	40-49	111	10.19	4.19	42	9.10	-4.71	153	9.89	1.75
	50-59	110	10.17	0.81	34	9.85	-3.26	144	10.10	-0.15
	60-69	116	12.06	-2.23	35	16.66	-11.00	151	13.13	-4.26
	70-79	63	12.76	-5.30	32	17.88	-13.44	95	14.48	-8.04
	80-89	11	16.27	-15.18	11	34.45	-34.45	22	25.36	-24.82
	Total	537	10.75	0.77	216	13.31	-6.18	753	11.49	-1.22

Table 18: Inaccuracy and bias scores from the İşcan et al. fourth rib age estimates for males and females. All values are in years.

		European			African			Other Ancestry		
		n	İşcan et al. Inaccuracy	İşcan et al. Bias	n	İşcan et al. Inaccuracy	İşcan et al. Bias	n	İşcan et al. Inaccuracy	İşcan et al. Bias
Age (yrs)	19-29	21	9.00	4.71	30	8.80	5.00	2	2.50	2.50
	30-39	73	10.67	5.77	61	8.74	1.59	2	3.50	3.50
	40-49	103	9.81	2.58	50	10.34	-1.30	2	13.00	12.00
	50-59	119	9.48	-0.27	25	12.32	0.00	2	17.00	-3.00
	60-69	129	12.69	-3.50	21	15.48	-8.24	1	20.00	-20.00
	70-79	77	14.99	-8.96	21	14.71	-7.67	0	N/A	N/A
	80-89	18	25.50	-25.50	3	26.00	-22.00	1	21.00	-21.00
	Total	540	11.77	-1.57	211	11.06	-1.03	10	11.30	-0.90

Table 19: Inaccuracy and bias scores from the İşcan et al. fourth rib age estimates separated by ancestry. All values are in years.

When known age at death is plotted against bias, the whisker box plot pattern shows very little variation in the age at death estimations for younger individuals and older individuals up to the age of 79 years (Figure 11). Individuals between the ages of 30 and 39 years have the greatest number of outliers, and most are under-aged. Individuals in the oldest age categories have a

larger amount of error associated with their bias scores compared to younger individuals, and generally the mean bias scores decrease as age increases.

Figure 11: Bias scores for the İscan et al. method categorized by age at death.

3.2.4 Passalacqua Sacrum Method

Appendix 8 provides the descriptive statistics for the Passalacqua method. Intra-observer reliability shows a high level of agreement for the randomly selected test sample [Kappa = 0.923, 95% CI (0.878 – 0.968)]; therefore, the age estimations are considered reliable.

Table 20 and Table 21 present the accuracy and bias scores for the Passalacqua method.

Parametric, independent samples t-tests show there are no significant differences between males and females for accuracy ($t = -1.559$, $df = 784$, $p = 0.119$) and bias ($t = 1.265$, $df = 784$, $p = 0.206$). Similar results are generated from non-parametric Mann-Whitney U tests (inaccuracy: $U = 59,657.50$, $p = 0.101$; bias: $U = 59,353.50$, $p = 0.081$). Inaccuracy is 11.50 years for males ($s.d. = 8.48$ years) and 12.55 years for females ($s.d. = 8.70$ years), with males under-aged by approximately one year ($\bar{x} = -1.23$ years, $s.d. = 14.25$ years) and females under-aged by almost 3 years ($\bar{x} = -2.67$ years, $s.d. = 15.05$ years).

When accuracy and bias are compared by ancestry, independent sample t-tests indicate there are no significant differences between individuals of European and African ancestry for accuracy ($t = 0.129$, $df = 774$, $p = 0.897$), but there are for bias ($t = -3.980$, $df = 774$, $p < 0.001$). These results are similar when using non-parametric Mann-Whitney U tests (inaccuracy: $U = 59,616.50$, $p = 0.805$; bias: $U = 49,403.00$, $p < 0.001$). Inaccuracy is 11.81 years for individuals of European descent ($s.d. = 8.50$ years) and 11.72 years for individuals of African ancestry descent ($s.d. = 8.64$ years). Individuals of European ancestry are typically under-aged by approximately 3 years ($\bar{x} = -3.01$ years, $s.d. = 14.25$ years), while individuals of African ancestry are typically over-aged by approximately 1.5 years ($\bar{x} = 1.56$ years, $s.d. = 14.50$ years).

		Male			Female			Total		
		n	Passalacqua Inaccuracy	Passalacqua Bias	n	Passalacqua Inaccuracy	Passalacqua Bias	n	Passalacqua Inaccuracy	Passalacqua Bias
Age (yrs)	19-29	35	12.54	10.94	18	16.11	15.00	53	13.75	12.32
	30-39	95	11.86	9.38	43	14.26	10.81	138	12.61	9.83
	40-49	112	10.85	4.60	45	7.87	0.09	157	9.99	3.31
	50-59	114	9.50	-0.83	37	9.05	-1.97	151	9.39	-1.11
	60-69	119	9.32	-8.29	40	10.58	-9.48	159	9.64	-8.59
	70-79	67	16.58	-16.58	39	17.23	-17.23	106	16.82	-16.82
	80-89	11	25.27	-25.27	11	21.45	-21.45	22	23.36	-23.36
	Total	553	11.50	-1.23	233	12.55	-2.67	786	11.81	-1.66

Table 20: Inaccuracy and bias scores from the Passalacqua sacrum age estimates for males and females. All values are in years.

		European			African			Other Ancestry		
		n	Passalacqua Inaccuracy	Passalacqua Bias	n	Passalacqua Inaccuracy	Passalacqua Bias	n	Passalacqua Inaccuracy	Passalacqua Bias
Age (yrs)	19-29	22	12.82	11.82	29	13.45	11.59	2	28.50	28.50
	30-39	74	12.88	10.01	62	12.24	9.47	2	14.00	14.00
	40-49	105	9.69	4.92	50	10.72	0.32	2	8.00	-7.00
	50-59	124	9.73	-1.36	25	7.68	0.40	2	9.50	-4.50
	60-69	132	9.46	-8.49	24	10.88	-9.63	1	3.00	3.00
	70-79	84	17.85	-17.85	22	12.91	-12.91	0	N/A	N/A
	80-89	18	22.17	-22.17	3	32.67	-32.67	1	17.00	-17.00
	Total	561	11.81	-3.01	215	11.72	1.56	10	14.00	4.80

Table 21: Inaccuracy and bias scores from the Passalacqua sacrum age estimates separated by ancestry. All values are in years.

When known age at death is plotted against bias, the pattern generally follows the expected over-aging of younger individuals and under-aging of older individuals (Figure 12); however, there are several deviations in the pattern. There are a large number of outliers in the 30 to 39 year old

age category in both directions (i.e. under- and over-aging); individuals over the age of 40 years show a negatively-skewed bias; the mean bias score for individuals between the ages of 50 and 59 years and 60 and 69 years are almost equal; and the age estimations of individuals in the 80 to 89 year age category show very little variation with a large number of outliers.

Figure 12: Mean bias scores for the Passalacqua method categorized by age at death.

3.2.5 Lovejoy et al. Auricular Surface Method

Appendix 9 provides the descriptive statistics for the Lovejoy et al. method. Intra-observer reliability shows a high level of agreement for the randomly selected test sample [Kappa = 0.916, 95% CI (0.875 – 0.957)]; therefore, the age estimations are considered reliable.

Table 22 and Table 23 present the accuracy and bias scores for the Lovejoy et al. method. Parametric, independent samples t-tests show there are no significant differences between males and females for accuracy ($t = -0.823$, $df = 792$, $p = 0.411$), but there are significant differences for bias ($t = 2.456$, $df = 792$, $p = 0.014$). The results generated from non-parametric Mann-Whitney U tests are different from those of the parametric tests. There are no significant differences between males and females for accuracy ($U = 65,713.00$, $p = 0.921$) or bias ($U =$

60,257.00, $p = 0.052$). Inaccuracy is 8.97 years for males ($s.d. = 7.04$ years) and 9.44 years for females ($s.d. = 8.14$ years), with males under-aged by approximately 5 years ($\bar{x} = -5.35$ years, $s.d. = 10.07$ years) and females under-aged by approximately 7 years ($\bar{x} = -7.27$ years, $s.d. = 10.13$ years).

When accuracy and bias are compared by ancestry, independent sample t-tests indicate there are significant differences between individuals of European and African ancestry for accuracy ($t = 4.620$, $df = 484.395$, $p < 0.001$), and bias ($t = -6.145$, $df = 425.617$, $p < 0.001$). These results are similar when using non-parametric Mann-Whitney U tests (inaccuracy: $U = 50,455.00$, $p < 0.001$; bias: $U = 44,642.00$, $p < 0.001$). Inaccuracy is 9.74 years for individuals of European descent ($s.d. = 7.67$ years) and 7.31 years for individuals of African descent ($s.d. = 6.15$ years). Individuals of European ancestry are typically under-aged by approximately 7 years ($\bar{x} = -7.21$ years, $s.d. = 10.09$ years), while individuals of African ancestry are typically under-aged by approximately 2.5 years ($\bar{x} = -2.57$ years, $s.d. = 9.21$ years).

		Male			Female			Total		
		n	Lovejoy et al. Inaccuracy	Lovejoy et al. Bias	n	Lovejoy et al. Inaccuracy	Lovejoy et al. Bias	n	Lovejoy et al. Inaccuracy	Lovejoy et al. Bias
Age (yrs)	19-29	33	6.97	6.91	19	4.89	4.58	52	6.21	6.06
	30-39	95	5.14	3.54	43	3.84	0.44	138	4.73	2.57
	40-49	115	4.67	-1.19	45	4.93	-3.91	160	4.74	-1.96
	50-59	115	7.48	-5.13	37	7.41	-5.51	152	7.46	-5.22
	60-69	120	11.80	-11.27	41	11.56	-10.73	161	11.74	-11.13
	70-79	68	17.84	-17.84	40	17.73	-17.73	108	17.80	-17.80
	80-89	11	22.82	-22.82	12	25.0	-25.00	23	23.96	-23.96
	Total	557	8.97	-5.35	237	9.44	-7.27	794	9.11	-5.92

Table 22: Inaccuracy and bias scores from the Lovejoy et al. auricular surface age estimates for males and females. All values are in years.

		European			African			Other Ancestry		
		n	Lovejoy et al. Inaccuracy	Lovejoy et al. Bias	n	Lovejoy et al. Inaccuracy	Lovejoy et al. Bias	n	Lovejoy et al. Inaccuracy	Lovejoy et al. Bias
Age (yrs)	19-29	21	6.57	6.38	30	5.90	5.77	1	8.00	8.00
	30-39	74	4.49	2.51	62	4.84	2.39	2	10.50	10.50
	40-49	108	4.74	-2.04	50	4.76	-1.80	2	4.50	-1.50
	50-59	125	7.62	-5.34	25	6.36	-4.12	2	11.50	-11.50
	60-69	135	11.61	-11.08	25	12.16	-11.12	1	18.00	-18.00
	70-79	86	18.26	-18.26	22	16.00	-16.00	0	N/A	N/A
	80-89	19	24.32	-24.32	3	18.67	-18.67	1	33.00	-33.00
	Total	568	9.74	-7.21	217	7.31	-2.57	9	12.44	-5.33

Table 23: Inaccuracy and bias scores from the Lovejoy et al. auricular surface age estimates separated by ancestry. All values are in years.

When known age at death is plotted against bias, the whisker box-plots show that age at death estimations for younger individuals are over-estimated and age at death estimations of older individuals are under-estimated (Figure 13). The majority of outliers are for individuals between the ages of 40 and 49 years, and all are over-aged. The youngest age category has the least amount of variation, and the range of bias scores increase as age increases.

Figure 13: Mean bias scores for the Lovejoy et al. method categorized by age at death.

3.2.6 Buckberry and Chamberlain Auricular Surface Method

Appendix 10 provides the descriptive statistics for the Buckberry and Chamberlain method.

Intra-observer reliability shows a high level of agreement for the randomly selected test sample [Kappa = 0.864, 95% CI (0.813 – 0.915)]; therefore, the age estimations are considered reliable.

Table 24 and Table 25 present the accuracy and bias scores for the Buckberry and Chamberlain method. Parametric, independent samples t-tests show there are significant differences between males and females for accuracy ($t = 2.757$, $df = 493.120$, $p = 0.006$) and bias ($t = 3.250$, $df = 791$, $p = 0.001$). The results generated from non-parametric Mann-Whitney U tests are similar to those of the parametric tests (inaccuracy: $U = 58,645.50$, $p = 0.016$; bias: $U = 55,660.00$, $p = 0.001$). Inaccuracy is 12.03 years for males ($s.d. = 7.04$ years) and 10.30 years for females ($s.d. = 8.14$ years), with males over-aged by approximately 7 years ($\bar{x} = 6.75$ years, $s.d. = 13.24$ years) and females over-aged by approximately 3.5 years ($\bar{x} = 3.46$ years, $s.d. = 12.44$ years).

When accuracy and bias are compared by ancestry, independent sample t-tests indicate there are significant differences between individuals of European and African ancestry for accuracy ($t = -2.652$, $df = 336.383$, $p = 0.008$), and bias ($t = -3.614$, $df = 782$, $p < 0.001$). These results are similar when using non-parametric Mann-Whitney U tests (inaccuracy: $U = 55,274.50$, $p = 0.032$; bias: $U = 51,612.00$, $p = 0.001$). Inaccuracy is 10.95 years for individuals of European descent ($s.d. = 7.97$ years) and 12.88 years for individuals of African descent ($s.d. = 9.50$ years). Individuals of European ancestry are typically over-aged by approximately 4.5 years ($\bar{x} = 4.66$ years, $s.d. = 12.73$ years), while individuals of African ancestry are typically over-aged by approximately 8.5 years ($\bar{x} = 8.41$ years, $s.d. = 13.64$ years).

		Male			Female			Total		
		n	Buckberry-Chamberlain Inaccuracy	Buckberry-Chamberlain Bias	n	Buckberry-Chamberlain Inaccuracy	Buckberry-Chamberlain Bias	n	Buckberry-Chamberlain Inaccuracy	Buckberry-Chamberlain Bias
Age (yrs)	19-29	32	16.94	16.44	18	7.67	7.11	51	13.41	12.90
	30-39	95	18.23	17.37	43	14.16	9.88	138	16.96	15.04
	40-49	115	14.61	12.78	45	12.58	8.71	160	14.04	11.64
	50-59	115	10.24	8.47	37	11.73	8.59	152	10.61	8.50
	60-69	120	6.69	0.99	41	5.32	0.29	161	6.34	-0.66
	70-79	68	8.94	-8.76	40	7.85	-7.65	108	8.54	-8.35
	80-89	11	13.82	-13.82	12	12.67	-12.67	23	13.22	-13.22
	Total	557	12.03	6.75	236	10.30	3.46	793	11.51	5.77

Table 24: Inaccuracy and bias scores from the Buckberry and Chamberlain auricular surface age estimates for males and females. All values are in years.

		European			African			Other Ancestry		
		n	Buckberry-Chamberlain Inaccuracy	Buckberry-Chamberlain Bias	n	Buckberry-Chamberlain Inaccuracy	Buckberry-Chamberlain Bias	n	Buckberry-Chamberlain Inaccuracy	Buckberry-Chamberlain Bias
Age (yrs)	19-29	21	15.10	14.14	29	12.17	11.97	1	14.00	14.00
	30-39	74	15.92	14.19	62	17.95	15.73	2	25.00	25.00
	40-49	108	13.81	12.08	50	14.30	10.34	2	20.00	20.00
	50-59	125	10.85	8.82	25	9.84	7.20	2	5.00	5.00
	60-69	135	6.38	-0.78	25	6.12	-0.36	1	7.00	7.00
	70-79	86	8.90	-8.76	22	7.14	-6.77	0	N/A	N/A
	80-89	19	13.21	-13.21	3	15.00	-15.00	1	8.00	-8.00
	Total	568	10.95	4.66	216	12.88	8.41	9	14.33	12.56

Table 25: Inaccuracy and bias scores from the Buckberry and Chamberlain auricular surface age estimates separated by ancestry. All values are in years.

When known age at death is plotted against bias, the pattern generally shows that age at death estimations for younger individuals are over-estimated and age at death estimations of older individuals are under-estimated (Figure 14). However, individuals in the youngest age category have a lower bias score than expected, and individuals under the age of 49 years have a larger amount of variation associated with their bias scores. Individuals between the ages of 50 and 69 years have the greatest number of outliers, and there is very little variation in the bias scores for individuals between the oldest age category. The bias scores are negatively skewed for individuals between the ages of 40 and 79 years.

Figure 14: Mean bias scores for the Buckberry and Chamberlain method categorized by age at death.

3.2.7 Rougé-Maillart et al. Acetabulum and Auricular Surface Method

Appendix 11 provides the descriptive statistics for the Rougé-Maillart et al. method. Intra-observer reliability shows a high level of agreement for the randomly selected test sample [Kappa = 0.919, 95% CI (0.876 – 0.962)]; therefore, the age estimations are considered reliable.

Table 26 and Table 27 present the accuracy and bias scores for the Rougé-Maillart et al. method. Parametric, independent samples t-tests show there are no significant differences between males and females for accuracy ($t = -0.205$, $df = 791$, $p = 0.838$), but there are for bias ($t = 2.029$, $df = 791$, $p = 0.043$). The results generated from non-parametric Mann-Whitney U tests are different from those of the parametric tests. There are no significant differences between males and females for accuracy ($U = 64,820.50$, $p = 0.759$) or bias ($U = 60,418.00$, $p = 0.072$). Inaccuracy is 10.66 years for males ($s.d. = 8.15$ years) and 10.79 years for females ($s.d. = 8.91$ years), with males under-aged by approximately 5 years ($\bar{x} = -4.83$ years, $s.d. = 12.53$ years) and females under-aged by approximately 7 years ($\bar{x} = -6.79$ years, $s.d. = 12.25$ years).

When accuracy and bias are compared by ancestry, independent sample t-tests indicate there are significant differences between individuals of European and African ancestry for inaccuracy ($t = 2.800$ $df = 781$, $p = 0.005$), and bias scores ($t = -5.587$, $df = 781$, $p < 0.001$). These results are similar when using non-parametric Mann-Whitney U tests (inaccuracy: $U = 52,344.00$, $p = 0.002$; bias: $U = 44,673.50$, $p < 0.001$). Inaccuracy is 11.20 years for individuals of European descent ($s.d. = 8.44$ years) and 9.33 years for individuals of African descent ($s.d. = 8.06$ years). Individuals of European ancestry are typically under-aged by 7 years ($\bar{x} = -7.00$ years, $s.d. = 12.16$ years), while individuals of African ancestry are typically under-aged by approximately 1.5 years ($\bar{x} = -1.55$ years, $s.d. = 12.24$ years).

		Male			Female			Total		
		n	Rougé-Maillart et al. Inaccuracy	Rougé-Maillart et al. Bias	n	Rougé-Maillart et al. Inaccuracy	Rougé-Maillart et al. Bias	n	Rougé-Maillart et al. Inaccuracy	Rougé-Maillart et al. Bias
Age (yrs)	19-29	34	10.38	10.21	18	5.94	4.94	52	8.85	8.38
	30-39	94	7.56	5.33	43	6.09	2.47	137	7.10	4.43
	40-49	115	6.23	1.00	45	6.49	-2.80	160	6.31	-0.07
	50-59	115	8.25	-4.58	37	7.81	-4.19	152	8.14	-4.49
	60-69	120	13.09	-12.44	41	12.41	-10.56	161	12.92	-11.96
	70-79	68	20.41	-20.38	40	20.15	-20.05	108	20.31	-20.26
	80-89	11	22.55	-22.55	12	23.50	-23.50	23	23.04	-23.04
	Total	557	10.66	-4.83	236	10.79	-6.79	793	10.70	-5.41

Table 26: Inaccuracy and bias scores from the Rougé-Maillart et al. acetabulum and auricular surface age estimates for males and females. All values are in years.

		European			African			Other Ancestry		
		n	Rougé-Maillart et al. Inaccuracy	Rougé-Maillart et al. Bias	n	Rougé-Maillart et al. Inaccuracy	Rougé-Maillart et al. Bias	n	Rougé-Maillart et al. Inaccuracy	Rougé-Maillart et al. Bias
Age (yrs)	19-29	21	8.76	8.48	29	8.59	7.97	2	13.50	13.50
	30-39	74	7.00	3.76	61	7.16	5.10	2	9.00	9.00
	40-49	108	6.29	-0.05	50	6.42	-0.30	2	4.50	4.50
	50-59	125	8.32	-4.58	25	7.08	-3.56	2	10.50	-10.50
	60-69	135	12.99	-12.38	25	12.56	-10.72	1	13.00	13.00
	70-79	86	20.60	-20.68	22	19.18	-19.00	0	N/A	N/A
	80-89	19	21.74	-21.74	3	28.33	-28.33	1	32.00	-32.00
	Total	568	11.20	-7.00	215	9.33	-1.55	10	12.00	1.40

Table 27: Inaccuracy and bias scores from the Rougé-Maillart et al. acetabulum and auricular surface age estimates separated by ancestry. All values are in years.

When known age at death is plotted against bias, the whisker box-plots show the typical pattern of over-aging younger individuals and under-aging older individuals (Figure 15). There is a large amount of variation in the bias scores for individuals between the ages of 50 and 79 years, and individuals in the oldest age category have a the greatest number of outliers.

Figure 15: Mean bias scores for the Rougé-Maillart et al. method categorized by age at death.

3.2.8 Suchey-Brooks Pubic Symphysis Method

Appendix 12 provides the descriptive statistics for the Suchey-Brooks method. Intra-observer reliability shows a high level of agreement for the randomly selected test sample [Kappa = 0.962, 95% CI (0.935 – 0.989)]; therefore, the age estimations are considered reliable.

Table 28 and Table 29 present the accuracy and bias scores for the Suchey-Brooks method. Parametric, independent samples t-tests show there are no significant differences between males and females for accuracy ($t = -0.510$, $df = 791$, $p = 0.542$) and bias ($t = 0.483$, $df = 791$, $p = 0.392$). The results generated from non-parametric Mann-Whitney U tests are similar to the parametric tests (inaccuracy: $U = 63,793.50$, $p = 0.584$; bias: $U = 64,470.00$, $p = 0.751$). Inaccuracy is 9.59 years for males ($s.d. = 7.74$ years) and 9.96 years for females ($s.d. = 7.99$ years).

years), with males and females under-aged by approximately 7 years (males $\bar{x} = -6.71$ years, *s.d.* = 10.40 years; females $\bar{x} = -7.10$ years, *s.d.* = 10.62 years).

When accuracy and bias are compared by ancestry, independent sample t-tests indicate there are significant differences between individuals of European and African ancestry for accuracy ($t = 3.418$ $df = 444.711$, $p < 0.001$), and bias ($t = -4.246$, $df = 781$, $p < 0.001$). These results are similar when using non-parametric Mann-Whitney U tests (inaccuracy: $U = 51,663.00$, $p = 0.001$; bias: $U = 49,408.50$, $p < 0.001$). Inaccuracy is 10.29 years for individuals of European descent (*s.d.* = 8.03 years) and 8.17 years for individuals of African descent (*s.d.* = 6.91 years). Individuals of European ancestry are typically under-aged by 8 years ($\bar{x} = -7.79$ years, *s.d.* = 10.47 years), while individuals of African ancestry are typically under-aged by approximately 4 years ($\bar{x} = -4.29$ years, *s.d.* = 9.81 years).

	Male			Female			Total		
	n	Suchey-Brooks Inaccuracy	Suchey-Brooks Bias	n	Suchey-Brooks Inaccuracy	Suchey-Brooks Bias	n	Suchey-Brooks Inaccuracy	Suchey-Brooks Bias
Age (yrs) 19-29	35	5.17	3.17	19	4.95	4.00	54	5.09	3.46
30-39	95	4.16	1.13	43	4.58	1.05	138	4.29	1.10
40-49	115	5.66	-1.21	45	7.00	-4.16	160	6.04	-2.04
50-59	115	8.79	-6.18	37	7.76	-4.24	152	8.54	-5.71
60-69	120	13.26	-13.21	40	10.83	-10.83	160	12.65	-12.61
70-79	68	18.25	-18.25	38	18.24	-18.24	106	18.25	-18.25
80-89	11	26.45	-26.45	12	26.00	-26.00	23	26.22	-26.22
Total	559	9.59	-6.71	234	9.96	-7.10	793	9.70	-6.82

Table 28: Inaccuracy and bias scores from the Suchey-Brooks pubic symphysis age estimates for males and females. All values are in years.

	European			African			Other Ancestry		
	n	Suchey-Brooks Inaccuracy	Suchey-Brooks Bias	n	Suchey-Brooks Inaccuracy	Suchey-Brooks Bias	n	Suchey-Brooks Inaccuracy	Suchey-Brooks Bias
Age (yrs) 19-29	22	4.77	3.68	30	5.37	3.30	2	4.50	3.50
30-39	74	4.32	1.05	62	4.35	1.16	2	1.00	1.00
40-49	108	5.87	-1.76	50	6.54	-2.82	2	2.50	2.50
50-59	125	8.20	-5.13	25	9.48	-7.64	2	18.00	-18.00
60-69	135	12.21	-12.17	24	14.71	-14.71	1	22.00	-22.00
70-79	85	18.76	-18.76	21	16.14	-16.14	0	N/A	N/A
80-89	19	27.05	-27.05	3	23.00	-23.00	1	20.00	-20.00
Total	568	10.29	-7.79	215	8.17	-4.29	10	9.40	-6.40

Table 29: Inaccuracy and bias scores from the Suchey-Brooks pubic symphysis age estimates separated by ancestry. All values are in years.

When known age at death is plotted against bias, the whisker box-plots show the expected pattern of over-aging younger individuals and under-aging older individuals (Figure 16). The least amount of variation is seen in the youngest age category, and the most number of outliers are between the ages of 40 and 59 years, and the largest variation in bias scores are for individuals between the ages of 40 and 69 years. The bias scores are negatively skewed between the ages of 60 and 89 years.

Figure 16: Mean bias scores for the Suchey-Brooks method categorized by known age at death.

3.2.9 Descriptive Statistics for the Final Sample and Each Age Estimation Method

Based on the evaluation of the age estimation methods, analyses will be divided by sex and ancestry as there were significant interactions between the age estimations generated for each method and sex and ancestry. Only individuals of European and African ancestry will be evaluated in the following sections as there are too few individuals of Asian, Hispanic, Aboriginal, and mixed ancestry to assess their influence on age standards. Individuals over the

age of 80 years will also be eliminated from further analysis as their accuracy and bias scores are unreliable for all age estimation methods.

The descriptive statistics of the final sample, including the final number of individuals in the BMI, stature, and body mass categories, can be seen in Table 30, Table 31, Table 32, and Table 33. Thirty-two individuals were removed from the study; 23 individuals between the ages of 80 and 89 years and nine individuals of Asian, Hispanic, Aboriginal, and mixed ancestry (note: one Asian male over the age of 80 years was eliminated in the 80 to 89 year old category), leaving a total of 764 individuals to be included in further analyses. Of the 540 males, 407 are of European ancestry (75.4%) and 133 are of African ancestry (24.6%). Of the 224 females, 143 are of European ancestry (63.8%) and 81 are of African ancestry (36.2%). Of the 550 individuals of European ancestry, 407 are male (74%) and 143 are female (26%). Of the 214 individuals of African ancestry, 133 are male (62.2%) and 81 are female (37.8%).

	n	Mean Age	Average Stature (m/ft)	Stature Range (m/ft)	Average Body Mass (kg/lbs)	Body Mass Range (kg/lbs)
Males	540	52.6	1.74/5.7	1.30–1.93/ 4.3–6.3	68.9/152	32.2–99.8/ 71–220
Females	224	51.2	1.60/5.3	1.30–1.87/ 4.3–6.1	57.7/127	24.0–99.8/ 53–220
European Ancestry	550	54.1	1.69/5.6	1.30–1.93/ 4.3–6.3	66.7/147	26.3–99.8/ 58–220
African Ancestry	214	45.0	1.72/5.6	1.50–1.92/ 4.9–6.3	63.1/139	24.0–99.8/ 53–220
18–29 years	52	24.7	1.71/5.6	1.37–1.90/ 4.5–6.24	62.5/138	37.2–89.8/ 82–198
30–39 years	136	35.0	1.71/5.6	1.30–1.92/ 4.3–6.3	66.8/147	24.0–99.8/ 53–220
40–49 years	158	44.3	1.70/5.6	1.44–1.93/ 4.7–6.3	66.6/147	27.7–99.8/ 61–220
50–59 years	150	53.8	1.70/5.6	1.30–1.92/ 4.3–6.3	69.3/153	27.7–99.8/ 61–220
60–69 years	160	64.0	1.70/5.6	1.49–1.93/ 4.9–6.3	64.3/142	30.4–99.8/ 67–220
70–79 years	108	74.0	1.66/5.5	1.38–1.86/ 4.5–6.1	61.1/135	26.3–99.8/ 58–220
Total	764	51.5	1.70/5.6	1.30–1.93/ 4.3–6.3	65.5/145	24.0–99.8/ 53–220

Table 30: Final sample distribution by sex, ancestry, and age categories.

	Males	Females	Total
European Ancestry	407	143	550
African Ancestry	133	81	214
Total	540	224	764

Table 31: Total number of males, females, and individuals of European and African ancestry.

	< 1.54m (< 5.0ft)	1.55–1.62m (5.1–5.3ft)	1.63–1.70m (5.4–5.6ft)	1.72–1.78m (5.7–5.9ft)	1.79–1.84m (5.10–6.0ft)	1.85–1.92m (6.1–6.3ft)	Total
<45.0kg (< 100lbs)	22	42	0	0	0	0	64
45.4–56.5kg (100–124lbs)	25	34	40	35	29	0	163
56.7–67.6kg (125–149lbs)	18	33	43	45	37	13	189
68.0–79.0kg (150–174lbs)	5	22	42	41	43	19	172
79.4–89.8kg (175–199lbs)	0	6	19	39	37	20	121
90.2–101.6kg (200–224lbs)	0	0	14	14	14	13	55
Total	70	137	158	174	160	65	764

Table 32: Final number of individuals from 29 stature and body mass categories.

BMI	n	Mean Age	Average Stature m/ft	Stature Range (m/ft)	Average Body Mass (kg/lbs)	Body Mass Range (kg/lbs)
Underweight	137	52.9	1.69/5.5	1.46-1.92/ 4.3-6.3	46.7/103	24.0-68.0/ 53-150
Normal	406	51.1	1.71/5.6	1.35-1.93/ 4.3-6.3	63.5/141	42.2-86.4/ 93-191
Overweight	172	50.2	1.70/5.6	1.40-1.90/ 4.5-6.2	78.9/173	54.4-99.8/ 120-220
Obese	49	55.4	1.67/5.5	1.30-1.88/ 4.3-6.1	90.1/199	63.5-99.8/ 140-220

Table 33: Sample distribution by BMI for the total number of individuals in the sample.

Table 34 displays the descriptive statistics for the eight age estimation methods. Paired t-tests between the mean age at death, inaccuracy, and bias scores for all methods are not significantly different from the results for the age estimation analyses in Section 3.2 (see Table 35). The nine individuals of Hispanic, Asian, Aboriginal, and mixed ancestry did not influence the overall sample statistics; they were simply removed to eliminate any possible confounding factors and create a parsimonious sample.

Kunos et al.					DiGangi et al.				
Age Method	n	Mean age at death	Inaccuracy	Bias	Age Method	n	Mean age at death	Inaccuracy	Bias
Kunos et al.	748	54.50	10.43	3.11	DiGangi et al.	736	38.31	15.41	-13.04
Males	528	55.48	10.33	4.02	Males	519	39.53	14.58	-11.92
Females	220	52.18	10.66	0.93	Females	217	35.40	17.41	-15.72
European	537	56.01	10.19	2.05	European	526	39.57	16.45	-14.39
African	211	50.70	11.03	5.82	African	210	35.15	12.81	-9.68
19-29 years	50	40.78	16.32	16.12	19-29 years	50	25.28	7.74	0.54
30-39 years	135	48.62	13.76	13.67	30-39 years	133	32.12	8.00	-2.95
40-49 years	155	53.94	10.39	9.56	40-49 years	152	37.09	10.50	-7.21
50-59 years	148	56.98	6.34	3.28	50-59 years	146	41.33	13.34	-12.41
60-69 years	156	58.28	7.51	-5.69	60-69 years	154	41.70	22.34	-22.19
70-79 years	104	60.44	13.50	-13.50	70-79 years	101	45.22	28.81	-28.81
İşcan et al.					Passalacqua				
Age Method	n	Mean age at death	Inaccuracy	Bias	Age Method	n	Mean age at death	Inaccuracy	Bias
İşcan et al.	722	43.90	11.08	-0.53	Passalacqua	755	50.35	11.45	-1.13
Males	518	45.92	10.66	1.06	Males	534	50.73	11.17	-0.87
Females	204	38.89	12.14	-4.58	Females	221	49.42	12.14	-1.76
European	515	46.52	11.20	-0.50	European	543	51.69	11.47	-2.37
African	207	37.43	10.78	-0.61	African	212	46.92	11.42	2.05
19-29 years	51	28.86	8.88	4.88	19-29 years	51	36.43	13.18	11.69
30-39 years	133	36.78	9.79	3.97	30-39 years	136	44.81	12.59	9.76
40-49 years	151	42.41	9.85	1.60	40-49 years	155	47.83	10.02	3.44
50-59 years	142	46.90	10.00	-0.11	50-59 years	149	52.69	9.39	-1.07
60-69 years	150	49.69	13.08	-4.16	60-69 years	158	55.31	9.68	-8.66
70-79 years	95	50.77	14.48	-8.04	70-79 years	106	57.13	16.82	-16.82
Lovejoy et al.					Buckberry and Chamberlain				
Age Method	n	Mean age at death	Inaccuracy	Bias	Age Method	n	Mean age at death	Inaccuracy	Bias
Lovejoy et al.	763	46	8.65	-5.42	Buckberry and Chamberlain	762	57.8	11.42	6.24
Males	539	46.50	8.69	-5.07	Males	539	58.73	11.94	7.04
Females	224	44.81	8.57	-6.27	Females	223	55.62	10.19	4.34
European	549	47.42	9.24	-6.62	European	549	59.43	10.87	5.28
African	214	42.40	7.15	-2.35	African	213	53.68	12.85	8.74
19-29 years	51	30.82	6.18	6.02	19-29 years	50	37.74	13.40	12.88
30-39 years	136	37.49	4.65	2.46	30-39 years	136	49.93	16.85	14.89
40-49 years	158	42.35	4.75	-1.96	40-49 years	158	55.89	13.96	11.53
50-59 years	150	48.46	7.41	-5.14	50-59 years	150	62.29	10.68	8.55
60-69 years	160	52.66	11.70	-11.09	60-69 years	160	63.26	6.34	-0.71
70-79 years	108	55.99	17.80	-17.80	70-79 years	108	65.60	8.54	-8.35

Age Method	n	Mean age at death			Age Method	n	Mean age at death		
		Inaccuracy	Bias				Inaccuracy	Bias	
Rougé-Maillart et al.	761	46.60	10.34	-5.01	Suchey-Brooks	761	45.20	9.22	-6.26
Males	538	47.12	10.43	-4.60	Males	540	45.26	9.29	-6.39
Females	223	45.33	10.10	-5.98	Females	221	44.93	9.04	-6.00
European	549	47.66	10.83	-6.49	European	549	46.93	9.70	-7.12
African	212	43.81	9.06	-1.17	African	212	40.58	7.96	-4.02
19-29 years	50	33.04	8.66	8.18	19-29 years	52	28.08	5.12	3.46
30-39 years	135	39.40	7.07	4.36	30-39 years	136	36.15	4.34	1.10
40-49 years	158	44.23	6.33	-0.13	40-49 years	158	42.26	6.08	-2.09
50-59 years	150	49.34	8.11	-4.41	50-59 years	150	48.20	8.41	-5.55
60-69 years	160	51.86	12.92	-12.12	60-69 years	159	51.42	12.59	-12.55
70-79 years	108	53.69	20.31	-20.26	70-79 years	106	55.75	18.25	-18.25

Table 34: Age estimation methods mean age at death, inaccuracy, and bias scores for the final sample of 764 individuals. All age, inaccuracy, and bias values are in years.

Method		Mean age at death	Inaccuracy	Bias
Kunos et al.	Collective Sample	54.70	10.77	2.46
	New Collective Sample	54.51	10.43	3.11
	Paired t-test	$t=0.412, p=0.681$	$t=0.923, p=0.356$	$t=1.015, p=0.310$
DiGangi et al.	Collective Sample	38.48	15.99	-13.72
	New Collective Sample	38.31	15.41	-13.04
	Paired t-test	$t=0.291, p=0.771$	$t=0.989, p=0.323$	$t=0.511, p=0.610$
İşcan et al.	Collective Sample	44.22	11.57	-1.41
	New Collective Sample	43.93	11.17	-0.74
	Paired t-test	$t=0.401, p=0.688$	$t=0.841, p=0.400$	$t=0.887, p=0.375$
Passalacqua	Collective Sample	50.60	11.81	-1.66
	New Collective Sample	50.35	11.45	-1.13
	Paired t-test	$t=0.404, p=0.687$	$t=0.836, p=0.403$	$t=0.727, p=0.468$
Lovejoy et al.	Collective Sample	46.35	9.11	-5.92
	New Collective Sample	46.01	8.65	-5.42
	Paired t-test	$t=0.679, p=0.498$	$t=1.266, p=0.206$	$t=0.996, p=0.320$
Buckberry & Chamberlain	Collective Sample	58.19	11.51	5.77
	New Collective Sample	57.82	11.42	6.24
	Paired t-test	$t=0.581, p=0.562$	$t=0.208, p=0.835$	$t=0.715, p=0.475$
Rougé-Maillart et al.	Collective Sample	47.00	10.70	-5.41
	New Collective Sample	46.57	10.34	-5.01
	Paired t-test	$t=0.768, p=0.443$	$t=0.860, p=0.390$	$t=0.640, p=0.522$
Suchey-Brooks	Collective Sample	45.42	9.70	-6.82
	New Collective Sample	45.16	9.22	-6.26
	Paired t-test	$t=0.479, p=0.632$	$t=1.252, p=0.211$	$t=1.044, p=0.297$

Table 35: Differences between original collective sample and new collective sample. All age, inaccuracy, and bias values are in years.

3.3 Research Question I: Does BMI influence skeletal age estimation?

BMI was calculated by dividing body mass by stature squared to estimate body fat, as described in Section 3.1. Figure 17 and Figure 18 illustrate the age distribution and stature and mass distribution for individuals in each BMI category. The age distribution for individuals in each BMI category follows a normal distribution, except for the underweight category where there are fewer individuals in the 40 to 59 year age range. The stature and body mass ranges for all individuals in Figure 18 illustrate the demarcations for each BMI group, and the number of individuals in each group. The normal-sized BMI category has more than double the number of individuals than the other BMI categories (see Table 33), as would be expected in a normally distributed population.

Figure 17: Age distribution of individuals by BMI category. Age categories are in years.

Figure 18: Distribution of individuals by BMI category for stature and mass.

This section will test the influence of BMI on age at death estimations. The sample will be separated by sex and ancestry, and differences between accuracy and bias scores between BMI groups will be evaluated for each method using MANOVA and DFA.

3.3.1 Sex

3.3.1.1 Accuracy

Males

A series of Pearson correlations were performed between the accuracy scores for each age method. Table 36 shows that the pattern of correlations observed among the accuracy scores are generally lower than ideal for a MANOVA, and the Box's M value of 195.455 is associated with a p -value of < 0.001 , which is significant. A covariance matrix (Appendix 13) was run to ensure

that no covariance values were more than four times greater than each other (Howell, 2007). Although there are instances where the covariance values are greater than four times their value, typically associated with the DiGangi et al., Passalacqua, and Buckberry and Chamberlain methods, overall the covariance matrices between the BMI groups were assumed to be equal for the purposes of the MANOVA.

	1.	2.	3.	4.	5.	6.	7.	8.	Mean (yrs)	S.D. (yrs)
1. Kunos et al.	1.00								10.33	6.975
2. DiGangi et al.	0.01 (0.948)	1.00							14.58	10.430
3. İscan et al.	0.12 (0.008)	0.29 (<0.001)	1.00						10.76	8.374
4. Passalacqua	0.18 (<0.001)	0.16 (<0.001)	0.10 (0.024)	1.00					11.17	8.235
5. Lovejoy et al.	0.04 (0.380)	0.50 (<0.001)	0.11 (0.009)	0.22 (<0.001)	1.00				8.69	6.802
6. Buckberry & Chamberlain	0.42 (<0.001)	-0.30 (<0.001)	0.01 (0.769)	0.10 (0.028)	-0.05 (0.212)	1.00			11.94	8.757
7. Rougé-Maillart et al.	0.12 (0.005)	0.50 (<0.001)	0.21 (<0.001)	0.23 (<0.001)	0.62 (<0.001)	0.12 (0.006)	1.00		10.43	7.983
8. Suchey-Brooks	-0.02 (0.594)	0.54 (<0.001)	0.16 (<0.001)	0.15 (0.001)	0.49 (<0.001)	-0.23 (<0.001)	0.46 (<0.001)	1.00	9.29	7.356

Table 36: Pearson Correlations, Means, and Standard Deviations of the accuracy scores for males for each age estimation method for males. P-values are in brackets.

A MANOVA was conducted to test the hypothesis that there would be differences between BMI categories (underweight, normal, overweight, obese) and accuracy scores for each method. The MANOVA was statistically significant with Pillai's Trace = 0.359, $F(27, 1476) = 7.433$, $p < 0.001$, indicating there are differences among BMI group accuracy scores. The multivariate effect size is estimated at 0.12, which implies that 12% of the variance in the canonically derived DV is accounted for by BMI.

As the IV was associated with four levels, three eigenvalues and canonical correlations were extracted by the MANOVA. The first eigenvalue is 0.050 and accounts for 49.0% of the model variance. The canonical correlation associated with the first eigenvalue is 0.218, where 4.8% of the variance in the discriminant function derived scores is accounted for by BMI. The second eigenvalue is 0.043 and accounts for 42.2% of the model variance with a corresponding canonical correlation of 0.203. The third eigenvalue is 0.009 and accounts for 8.8% of the model

variance and a corresponding canonical correlation of 0.095, which is not statistically significant [Wilks $\Lambda = 0.991$, $F(6, 495) = 0.618$, $p = 0.687$].

The standardized discriminant function coefficients from the first and second eigenvalues were used to determine the statistical significance of the MANOVA. As seen in Table 37, the Function 1 standardized discriminant function coefficients suggest that the four BMI groups were maximally differentiated by a canonical variate with significant weightings from the DiGangi et al. (0.633), Passalacqua (0.408), Rougé-Maillart et al. (0.377), and Kunos et al. (0.331) methods accuracy scores. The standardized coefficients suggest relatively minimal individual contributions to the MANOVA effect from all other accuracy scores, except for the Buckberry and Chamberlain method, which has almost no contribution (0.007). The correlations between the accuracy scores and the canonically derived scores for all methods are positive and with moderate scores (range = 0.273 to 0.693), except for the Buckberry and Chamberlain method, which has a weak correlation (0.090). The Function 2 standardized discriminant function coefficients suggest that the four BMI groups were maximally differentiated by a canonical variate with significant weightings from the Işcan et al. (0.756), Suchey-Brooks (0.640), and DiGangi et al. (-0.562) methods accuracy scores. The standardized coefficients suggest minimal individual contributions to the MANOVA effect from all other methods. The correlations between accuracy scores and the canonically derived scores are weak to moderate for all methods. The scores from Function 1 were used in further analyses as the results from Function 2 are not as strong as those from Function 1.

	Function 1			Function 2		
	Raw	Stand.	Struc.	Raw	Stand.	Struc.
Kunos et al.	0.048	0.331	0.468	-0.052	-0.361	-0.225
DiGangi et al.	0.061	0.633	0.693	-0.055	-0.562	0.061
Işcan et al.	0.020	0.160	0.440	0.093	0.756	0.637
Passalacqua	0.050	0.408	0.575	0.015	0.123	0.165
Lovejoy et al.	-0.046	-0.307	0.273	0.064	0.430	0.363
Buckberry & Chamberlain	0.001	0.007	0.090	0.013	0.116	-0.057
Rougé-Maillart et al.	0.049	0.377	0.596	-0.033	-0.255	0.143
Suchey-Brooks	-0.020	-0.142	0.280	0.088	0.640	0.528

Table 37: Discriminant function coefficients associated with the MANOVA for males. Note: Raw = unstandardized coefficients, Stand. = standardized coefficients, Struc. = structure coefficients.

To estimate the group centroids for Function 1 (i.e. the canonically derived group means) for the four BMI groups, the sample inaccuracy scores were multiplied by the corresponding inaccuracy

unstandardized discriminant function coefficients and then averaged across the samples. The means and standard deviations are listed in Table 38. An ANOVA with four levels in the IV (underweight, normal, overweight, obese) was performed on the canonically derived accuracy score DV, and is significant [$F(3, 8.273) = 8.303, p < 0.001$].

	n	Mean	S.D.
Underweight	80	2.39	1.29
Normal	286	2.17	0.99
Overweight	110	1.77	0.78
Obese	26	1.66	0.87

Table 38: Means and Standard Deviations for the male canonically derived variables.

The Cohen's d absolute values were as follows, from highest to lowest: underweight vs. obese = 0.519; underweight vs. overweight = 0.450; normal-sized vs. obese = 0.337; normal-sized vs. overweight = 0.244; underweight vs. normal-sized = 0.213; and overweight vs. obese = 0.098. The differences between underweight and obese, and underweight and overweight males are suggestive of a medium effect size, while the differences between normal-sized and obese, normal-sized and overweight, and underweight and normal-sized males are suggestive of a small effect size. There is no discernible difference between overweight and obese males.

Table 39 shows the results from Tukey's b post-hoc tests for unequal sample sizes. There are no significant differences among the BMI group inaccuracy scores for males using the Kunos et al., Lovejoy et al., and Buckberry and Chamberlain methods. The DiGangi et al. method inaccuracy scores for obese male are significantly lower compared to normal-sized and underweight males; underweight male inaccuracy scores are significantly higher compared to obese and overweight males. The Işcan et al. inaccuracy scores for underweight males are significantly higher than obese, normal-sized, and overweight males. The Passalacqua inaccuracy scores for underweight males are significantly higher compared to overweight males. The Rougé-Maillart et al. inaccuracy scores for obese males are significantly lower compared to normal-sized and underweight males. The Suchey-Brooks inaccuracy scores for underweight males are significantly higher than normal-sized and overweight males.

Method	BMI Categories	n	Subset (yrs)		
			1	2	3
Kunos et al.	Obese	26	8.58		
	Overweight	110	9.02		
	Underweight	80	10.58		
	Normal	286	10.74		
DiGangi et al.	Obese	26	11.54		
	Overweight	110	12.45	12.45	
	Normal	286		15.10	15.10
	Underweight	80			16.99
İşcan et al.	Obese	26	9.46		
	Normal	286	10.07		
	Overweight	110	10.18		
	Underweight	80		13.74	
Passalacqua	Overweight	110	9.36		
	Obese	26	10.88	10.88	
	Normal	286	11.41	11.41	
	Underweight	80		13.03	
Lovejoy et al.	Obese	26	7.85		
	Normal	286	8.38		
	Overweight	110	8.44		
	Underweight	80	10.15		
Buckberry and Chamberlain	Obese	26	10.69		
	Overweight	110	11.75		
	Underweight	80	11.89		
	Normal	286	11.94		
Rougé-Maillart et al.	Obese	26	7.27		
	Overweight	110	9.39	9.39	
	Normal	286		10.49	
	Underweight	80		12.19	
Suchey-Brooks	Overweight	110	8.73		
	Normal	286	8.83		
	Obese	26	9.85	9.85	
	Underweight	80		11.31	

Table 39: Tukey's *b* post-hoc test results for male accuracy scores separated by BMI. Note: alpha level = 0.05

A discriminant function analysis (DFA) was applied to assess how well BMI could be predicted from the accuracy scores of the eight age estimation methods. The DV is BMI (i.e. underweight, normal, overweight, obese), and the IVs are the accuracy scores generated from the age methods. Since the MANOVA and DFA use the same statistical models and produce the same results, only the cross-validated classification are reported. The cross-validated classification shows that only 34.3% of males are correctly classified into their BMI group based on accuracy scores. Underweight males are classified correctly at a rate of 36.3%, normal-sized males at a rate of 34.3%, overweight males at a rate of 30.9%, and obese males at a rate of 42.3%.

The discriminant scores from Function 1 and Function 2 were used to plot the sample on the discriminant dimensions. The underweight group is associated with the largest group centroid (0.294), the normal-sized group is associated with the next largest group centroid (0.080), the overweight group is associated with the second smallest centroid (-0.320) and, finally, the obese group is associated with the smallest group centroid (-0.434) (see Figure 19).

Figure 19: Canonically derived centroids for the BMI groups for males.

Females

A series of Pearson correlations were performed between the accuracy scores for each age method. Table 40 shows that the pattern of correlations observed among the accuracy scores are generally lower than ideal for a MANOVA, but the Box's M value of 208.675 is associated with a p -value of 0.013, which is not significant. Therefore, the covariance matrices between the BMI groups were assumed to be equal for the purposes of the MANOVA.

	1.	2.	3.	4.	5.	6.	7.	8.	Mean (yrs)	S.D. (yrs)
1. Kunos et al.	1.00								10.57	7.210
2. DiGangi et al.	0.27 (<0.001)	1.00							16.64	11.920
3. İşcan et al.	0.11 (0.113)	0.35 (<0.001)	1.00						12.03	10.047
4. Passalacqua	0.26 (<0.001)	0.06 (0.381)	0.15 (0.033)	1.00					11.98	8.536
5. Lovejoy et al.	0.20 (0.003)	0.49 (<0.001)	0.26 (<0.001)	0.21 (0.002)	1.00				7.99	6.898
6. Buckberry & Chamberlain	0.12 (0.073)	-0.19 (0.005)	-0.06 (0.361)	0.05 (0.483)	-0.05 (0.423)	1.00			10.45	7.989
7. Rougé-Maillart et al.	0.25 (<0.001)	0.48 (<0.001)	0.27 (<0.001)	0.30 (<0.001)	0.66 (<0.001)	0.08 (0.243)	1.00		9.55	8.065
8. Suchey-Brooks	0.19 (0.004)	0.49 (<0.001)	0.30 (<0.001)	0.23 (0.001)	0.51 (<0.001)	-0.07 (0.322)	0.57 (<0.001)	1.00	8.68	6.959

Table 40: Pearson Correlations, Means, and Standard Deviations of the accuracy scores for females for each age estimation method for females. P-values are in brackets.

A MANOVA was conducted to test the hypothesis that there would be differences between BMI group accuracy scores for each method. The MANOVA was statistically significant with Pillai's Trace = 0.687, $F(27, 564) = 6.207$, $p < 0.001$, indicating that there are differences among the BMI group accuracy scores. The multivariate effect size is estimated at 0.229, which implies that 22.9% of the variance in the canonically derived DV is accounted for by BMI groups.

As the IV was associated with four levels, three eigenvalues and canonical correlations were extracted by the MANOVA. The first eigenvalue is 0.100 and accounts for 56.2% of the model variance. The canonical correlation associated with the first eigenvalue is 0.301, where 9.1% of the variance in the discriminant function derived scores is accounted for by BMI group. The second eigenvalue is 0.058 and accounts for 33.0% of the model variance with a corresponding canonical correlation of 0.235. The third eigenvalue is 0.019 and accounts for 10.8% of the model variance and a corresponding canonical correlation of 0.137, which is not statistically significant [Wilks $\Lambda = 0.981$, $F(6, 189) = 0.604$, $p = 0.727$].

The standardized discriminant function coefficients from the first eigenvalue were used to determine the statistical significance of the MANOVA. As seen in Table 41, the standardized discriminant function coefficients suggest that the four BMI groups were maximally differentiated by a canonical variate with significant weightings from the Lovejoy et al. (-0.996), Rougé-Maillart et al. (0.472), İşcan et al. (0.470), and Kunos et al. (0.462) methods accuracy

scores. The standardized coefficients suggest relatively minimal individual contributions to the MANOVA effect from all other accuracy scores. The correlations between the accuracy scores and the canonically derived scores for all methods are weak to moderate (range = -0.366 to 0.484).

	Function 1		
	Raw	Stand.	Struc.
Kunos et al.	0.064	0.462	-0.366
DiGangi et al.	0.022	0.264	-0.200
İşcan et al.	0.048	0.470	-0.383
Passalacqua	-0.027	-0.229	0.129
Lovejoy et al.	-0.146	-0.996	0.484
Buckberry & Chamberlain	-0.038	-0.308	0.211
Rougé-Maillart et al.	0.058	0.472	0.349
Suchey-Brooks	-0.034	-0.235	0.162

Table 41: Discriminant function coefficients associated with the MANOVA for females.
Note: Raw = unstandardized coefficients, Stand. = standardized coefficients, Struc. = structure coefficients.

To estimate the group centroids for the four BMI groups, the sample inaccuracy scores were multiplied by the corresponding inaccuracy unstandardized discriminant function coefficients and then averaged across the samples. The means and standard deviations for each BMI group are in Table 42. An ANOVA with four levels in the IV (underweight, normal, overweight, obese) was performed on the canonically derived accuracy score DV, and is statistically significant [$F(3, 6.46) = 6.433, p < 0.001$].

	n	Mean	S.D.
Underweight	38	2.41	1.053
Normal	102	2.35	1.230
Overweight	45	2.26	0.100
Obese	13	1.75	0.767

Table 42: Means and Standard Deviations for the female canonically derived variables.

The Cohen's d absolute values were as follows, from highest to lowest: overweight vs. obese = 1.056; underweight vs. obese = 0.666; normal-sized vs. obese = 0.552; underweight vs. overweight = 0.205; normal-sized vs. overweight = 0.096; and underweight vs. normal-sized = 0.055. The differences between overweight and obese females are suggestive of a large effect size; the differences between underweight and obese, and normal-sized and obese females are suggestive of a medium effect size; the differences between underweight and overweight females

are suggestive of a small effect size. There is no discernible difference between normal-sized and overweight, and underweight and normal-sized females.

Table 43 shows the results from Tukey's *b* post-hoc tests for unequal sample sizes. There are no significant differences among the BMI group accuracy scores for females using the Kunos et al., DiGangi et al., Passalacqua, Buckberry and Chamberlain, Rougé-Maillart et al., and Suchey-Brooks methods. The İşcan et al. method accuracy scores for underweight females are significantly lower than obese and overweight females. The Lovejoy et al. method obese female accuracy scores are significantly higher compared to overweight, underweight, and normal-sized females.

Method	BMI Categories	n	Subset (yrs)		
			1	2	3
Kunos et al.	Obese	13	6.69		
	Underweight	38	10.42		
	Overweight	45	10.93		
	Normal	102	10.95		
DiGangi et al.	Obese	13	13.31		
	Overweight	45	15.58		
	Underweight	38	17.08		
	Normal	102	17.36		
İşcan et al.	Overweight	45	9.42		
	Obese	13	9.85		
	Normal	102	12.05	12.05	
	Underweight	38		15.82	
Passalacqua	Underweight	38	11.26		
	Normal	102	11.85		
	Overweight	45	12.60		
	Obese	13	13.00		
Lovejoy et al.	Overweight	45	6.38		
	Underweight	38	7.37		
	Normal	102	8.48		
	Obese	13		11.62	
Buckberry and Chamberlain	Underweight	38	9.68		
	Overweight	45	9.98		
	Normal	102	10.76		
	Obese	13	11.92		
Rougé-Maillart et al.	Overweight	45	8.20		
	Obese	13	9.54		
	Underweight	38	9.55		
	Normal	102	10.14		
Suchey-Brooks	Underweight	38	7.66		
	Overweight	45	7.80		
	Obese	13	8.92		
	Normal	102	9.42		

Table 43: Tukey's *b* post-hoc test results for female accuracy scores separated by BMI.

Note: alpha level = 0.05

A DFA was applied to assess how well BMI could be predicted from the accuracy scores of the eight age estimation methods. The cross-validated classification shows that only 37.4% of females are correctly classified into their BMI group based on accuracy scores. Underweight females are classified correctly at a rate of 57.9%, normal-sized females at a rate of 19.6%, overweight females at a rate of 51.1%, and obese females at a rate of 69.2%.

The discriminant scores from Function 1 and Function 2 were used to plot the sample on the discriminant dimensions. The obese group is associated with the largest group centroid (1.046), the normal group is associated with the next largest group centroid (0.028), the overweight group is associated with the second smallest centroid (-0.065) and, finally, the underweight group is associated with the smallest group centroid (-0.365) (see Figure 20).

Figure 20: Canonically derived centroids for the BMI groups for females.

3.3.1.2 Bias

Males

A series of Pearson correlations were performed between the bias scores for each age method. Table 44 shows that the pattern of correlations observed among the bias scores are generally strong for a MANOVA, and the Box's M value of 250.604 is associated with a p -value of < 0.001 , which is significant. A covariance matrix (Appendix 14) was run to ensure that no covariance values were more than four times greater than each other. Although there are instances where the covariance values are greater than four times their value, typically associated with the DiGangi et al. method, overall the covariance matrices between the BMI groups were assumed to be equal for the purposes of the MANOVA.

	1.	2.	3.	4.	5.	6.	7.	8.	Mean (yrs)	S.D. (yrs)
1. Kunos et al.	1.00								4.02	11.804
2. DiGangi et al.	0.86 (<0.001)	1.00							-11.92	13.390
3. İscan et al.	0.20 (<0.001)	0.05 (0.292)	1.00						0.83	13.614
4. Passalacqua	0.61 (<0.001)	0.52 (<0.001)	0.20 (<0.001)	1.00					-0.87	13.857
5. Lovejoy et al.	0.70 (<0.001)	0.60 (<0.001)	0.30 (<0.001)	0.58 (<0.001)	1.00				-5.07	9.807
6. Buckberry & Chamberlain	0.70 (<0.001)	0.59 (<0.001)	0.25 (<0.001)	0.56 (<0.001)	0.76 (<0.001)	1.00			7.04	13.028
7. Rougé-Maillart et al.	0.72 (<0.001)	0.63 (<0.001)	0.26 (<0.001)	0.58 (<0.001)	0.80 (<0.001)	0.86 (<0.001)	1.00		-4.60	12.312
8. Suchey-Brooks	0.68 (<0.001)	0.61 (<0.001)	0.25 (<0.001)	0.50 (<0.001)	0.62 (<0.001)	0.61 (<0.001)	0.66 (<0.001)	1.00	-6.36	10.003

Table 44: Pearson Correlations, Means, and Standard Deviations of the bias scores for males for each age estimation method for males. P-values are in brackets.

A MANOVA was conducted to test the hypothesis that there would be differences between BMI group bias scores for each method. The MANOVA was statistically significant with Pillai's Trace = 0.191, $F(24, 1479) = 4.196$, $p < 0.001$, indicating there are differences among the BMI group bias scores. The multivariate effect size is estimated at 0.064, which implies that 6.4% of the variance in the canonically derived DV is accounted for by the BMI groups.

Three eigenvalues and canonical correlations were extracted by the MANOVA. The first eigenvalue is 0.173 and accounts for 79.2% of the model variance. The canonical correlation associated with the first eigenvalue is 0.384, where 14.8% of the variance in the discriminant

function derived scores is accounted for by BMI group. The second eigenvalue is 0.035 and accounts for 16.4% of the model variance with a corresponding canonical correlation of 0.184. The third eigenvalue is 0.010 and accounts for 4.7% of the model variance and a corresponding canonical correlation of 0.100, which is not statistically significant [Wilks $\Lambda = 0.990$, $F(6, 493) = 0.835$, $p = 0.544$].

The standardized discriminant function coefficients from the first eigenvalue were used to determine the statistical significance of the MANOVA, as it is the strongest. As seen in Table 45, the standardized discriminant function coefficients suggest that the four BMI groups are maximally differentiated by a canonical variate with significant weightings from the İşcan et al. (0.946), Rougé-Maillart et al. (-0.442), and Kunos et al. (0.413) methods bias scores. The standardized coefficients suggest relatively minimal individual contributions to the MANOVA effect from all other bias scores. The correlations between the bias scores and the canonically derived scores for all methods are positive with weak to strong correlations (range = 0.168 to 0.900).

	Function 1		
	Raw	Stand.	Struc.
Kunos et al.	0.035	0.413	0.331
DiGangi et al.	0.001	0.016	0.182
İşcan et al.	0.075	0.946	0.900
Passalacqua	0.022	0.297	0.365
Lovejoy et al.	-0.031	-0.298	0.195
Buckberry & Chamberlain	0.017	0.218	0.226
Rougé-Maillart et al.	-0.036	-0.442	0.168
Suchey-Brooks	-0.007	-0.065	0.247

Table 45: Discriminant function coefficients associated with the MANOVA for males. Note: Raw = unstandardized coefficients, Stand. = standardized coefficients, Struc. = structure coefficients.

To estimate the group centroids (i.e. the canonically derived group means) for the four BMI groups, the sample bias scores were multiplied by the corresponding bias unstandardized discriminant function coefficients and then averaged across the samples. The means and standard deviations are listed in Table 46. An ANOVA with four levels in the IV (underweight, normal, overweight, obese) was performed on the canonically derived bias score DV, and is statistically significant [$F(3, 28.512) = 28.650$, $p < 0.001$].

	n	Mean	S.D.
Underweight	80	-0.29	1.274
Normal	286	0.87	0.913
Overweight	110	0.77	1.002
Obese	26	0.71	0.902

Table 46: Means and Standard Deviations for the male canonically derived variables.

The Cohen's d absolute values were as follows, from highest to lowest: underweight vs. normal-sized = 1.165; underweight vs. overweight = 1.003; underweight vs. obese = 0.919; normal-sized vs. obese = 0.168; normal-sized vs. overweight = 0.103; and overweight vs. obese = 0.061. The differences between underweight and normal-size, underweight and overweight, and underweight and obese males are suggestive of a large effect size, while the differences between normal-sized and obese, and normal-sized and overweight males are suggestive of a small effect size. There is no discernible difference between overweight and obese males.

Table 47 shows the results from Tukey's b post-hoc tests for unequal sample sizes. There are no significant differences among the BMI group bias scores for males using the Lovejoy et al., Buckberry and Chamberlain, and Rougé-Maillart et al. methods. The Kunos et al. and DiGangi et al. methods under-age underweight males significantly compared to obese males. The Işcan et al. method under-ages underweight males significantly compared to obese, normal-sized, and overweight males. The Passalacqua and Suchey-Brooks methods under-age underweight males significantly compared to overweight males.

A DFA was applied to assess how well BMI group could be predicted from the bias scores of the eight age estimation methods. The cross-validated classification shows that only 40.0% of males are correctly classified into their BMI group based on bias scores. Underweight males are classified correctly at a rate of 57.5%, normal-sized males at a rate of 37.8%, overweight males at a rate of 35.5%, and obese males at a rate of 30.8%.

The discriminant scores from Function 1 and Function 2 were used to plot the sample on the discriminant dimensions. The normal-sized group is associated with the largest group centroid (0.214), the overweight group is associated with the next largest group centroid (0.116), the obese group is associated with the second smallest centroid (0.062) and, finally, the underweight group is associated with the smallest group centroid (-0.944) (see Figure 21).

Method	BMI Categories	n	Subset (yrs)		
			1	2	3
Kunos et al.	Underweight	80	0.03		
	Normal	286	4.28	4.28	
	Overweight	110	4.96	4.96	
	Obese	26		5.96	
DiGangi et al.	Underweight	80	-14.49		
	Normal	286	-11.99	-11.99	
	Overweight	110	-10.84	-10.84	
	Obese	26		-8.23	
İşcan et al.	Underweight	80	-9.61		
	Obese	26		0.08	
	Overweight	110		1.84	
	Normal	286		3.68	
Passalacqua	Underweight	80	-5.85		
	Normal	286	-0.49	-0.49	
	Obese	26	-0.27	-0.27	
	Overweight	110		1.36	
Lovejoy et al.	Underweight	80	-6.83		
	Obese	26	-5.46		
	Normal	286	-4.71		
	Overweight	110	-4.31		
Buckberry and Chamberlain	Underweight	80	4.04		
	Normal	286	6.89		
	Obese	26	8.23		
	Overweight	110	9.36		
Rougé-Maillart et al.	Underweight	80	-6.41		
	Obese	26	-4.42		
	Normal	286	-4.25		
	Overweight	110	-3.23		
Suchey-Brooks	Underweight	80	-8.86		
	Normal	286	-6.55	-6.55	
	Obese	26	-6.23	-6.23	
	Overweight	110		-3.87	

Table 47: Tukey's *b* post-hoc test results for male bias scores separated by BMI. Note: alpha level = 0.05

Figure 21: Canonically derived centroids for the BMI groups for males.

Females

A series of Pearson correlations were performed between the bias scores for each age method. Table 48 shows that the pattern of correlations observed among the bias scores are generally strong for a MANOVA, and the Box's M value of 194.558 is associated with a p -value of < 0.001 , which is significant. A covariance matrix (Appendix 15) was run to ensure that no covariance values were more than four times greater than each other (Howell, 2007). Although there are instances where the covariance values are greater than four times their value, typically associated with the DiGangi et al. method, overall the covariance matrices between the BMI groups were assumed to be equal for the purposes of the MANOVA.

	1.	2.	3.	4.	5.	6.	7.	8.	Mean (yrs)	S.D. (yrs)
1. Kunos et al.	1.00								0.93	12.917
2. DiGangi et al.	0.86 (<0.001)	1.00							-15.72	14.331
3. İşcan et al.	0.24 (0.001)	0.20 (0.005)	1.00						-4.73	15.114
4. Passalacqua	0.65 (<0.001)	0.57 (<0.001)	0.30 (<0.001)	1.00					-1.76	14.764
5. Lovejoy et al.	0.63 (<0.001)	0.53 (<0.001)	0.38 (<0.001)	0.58 (<0.001)	1.00				-6.27	9.320
6. Buckberry & Chamberlain	0.56 (<0.001)	0.46 (<0.001)	0.29 (<0.001)	0.50 (<0.001)	0.61 (<0.001)	1.00			4.31	12.178
7. Rougé-Maillart et al.	0.65 (<0.001)	0.55 (<0.001)	0.41 (<0.001)	0.61 (<0.001)	0.77 (<0.001)	0.77 (<0.001)	1.00		-5.98	11.748
8. Suchey-Brooks	0.67 (<0.001)	0.55 (<0.001)	0.36 (<0.001)	0.65 (<0.001)	0.58 (<0.001)	0.51 (<0.001)	0.64 (<0.001)	1.00	-6.00	9.837

Table 48: Pearson Correlations, Means, and Standard Deviations of the bias scores for females for each age estimation method for females.

A MANOVA was conducted to test the hypothesis that there would be differences between BMI group bias scores for each method. The MANOVA is statistically significant with Pillai's Trace = 0.291, $F(24, 567) = 2.536$, $p < 0.001$, indicating there are differences among the BMI group bias scores. The multivariate effect size is estimated at 0.097, which implies that 9.7% of the variance in the canonically derived DV is accounted for by the BMI groups.

Three eigenvalues and canonical correlations were extracted by the MANOVA. The first eigenvalue is 0.295 and accounts for 81.7% of the model variance. The canonical correlation associated with the first eigenvalue is 0.477, where 22.8% of the variance in the discriminant function derived scores is accounted for by BMI group. The second eigenvalue is 0.051 and accounts for 14.2% of the model variance with a corresponding canonical correlation of 0.221. The third eigenvalue is 0.015 and accounts for 4.1% of the model variance and a corresponding canonical correlation of 0.121, which is not statistically significant [Wilks $\Lambda = 0.986$, $F(6, 189) = 0.466$, $p = 0.833$].

The standardized discriminant function coefficients from the first eigenvalue were used to determine the statistical significance of the MANOVA as it was the strongest. As seen in Table 49, the standardized discriminant function coefficients suggest that the four BMI groups were maximally differentiated by a canonical variate with significant weightings from the İşcan et al. (-1.028), DiGangi et al. (-0.856), and Kunos et al. (0.713) methods bias scores. The standardized

coefficients suggest moderate individual contributions to the MANOVA effect from several bias scores (i.e. Passalacqua, Lovejoy et al., and Buckberry and Chamberlain methods), with minimal contribution from the Suchey-Brooks method. The correlations between the bias scores and the canonically derived scores are weak for all methods (range = -0.086 to 0.186) except the İşcan et al. method, which has a moderate negative correlation (-0.690).

	Function 1		
	Raw	Stand.	Struc.
Kunos et al.	0.056	0.713	0.130
DiGangi et al.	-0.061	-0.856	-0.056
İşcan et al.	-0.072	-1.028	-0.690
Passalacqua	0.031	0.453	0.186
Lovejoy et al.	0.014	0.130	0.056
Buckberry & Chamberlain	-0.037	-0.458	-0.086
Rougé-Maillart et al.	0.039	0.445	0.031
Suchey-Brooks	0.006	0.053	0.102

Table 49: Discriminant function coefficients associated with the MANOVA for females.
Note: Raw = unstandardized coefficients, Stand. = standardized coefficients, Struc. = structure coefficients.

To estimate the group centroids for the four BMI groups, the sample bias scores were multiplied by the corresponding bias unstandardized discriminant function coefficients and then averaged across the samples. The means and standard deviations for each BMI group are in Table 50. An ANOVA with four levels in the IV (underweight, normal, overweight, obese) was performed on the canonically derived bias score DV, and is significant [$F(3, 19.041) = 19.041, p < 0.001$].

	n	Mean	S.D.
Underweight	38	1.87	0.746
Normal	102	0.45	1.064
Overweight	45	0.90	1.014
Obese	13	0.53	1.027

Table 50: Means and Standard Deviations for the female canonically derived variables.

The Cohen's d absolute values were as follows, from highest to lowest: underweight vs. obese = 1.484; underweight vs. normal-sized = 1.435; underweight vs. overweight = 1.027; normal-sized vs. overweight = 0.439; overweight vs. obese = 0.437; and normal-sized vs. obese = 0.078. The differences between underweight and obese, underweight and normal-sized, and underweight and overweight females are suggestive of a large effect size; the differences between overweight and obese females are suggestive of a medium effect size. There is no discernible difference between normal-sized and obese females.

Table 51 shows the results from Tukey's *b* post-hoc tests for unequal sample sizes. There are no significant differences among the BMI group bias scores for females using any method except the İşcan et al. method. The İşcan et al. method under-ages underweight females significantly compared to overweight, obese, and normal-sized females.

Method	BMI Categories	n	Subset (yrs)		
			1	2	3
Kunos et al.	Normal	102	0.42		
	Underweight	38	2.89		
	Obese	13	4.23		
	Overweight	45	4.31		
DiGangi et al.	Underweight	38	-16.71		
	Normal	102	-15.75		
	Overweight	45	-12.02		
	Obese	13	-11.15		
İşcan et al.	Underweight	38	-14.87		
	Overweight	45		-4.27	
	Obese	13		-3.54	
	Normal	102		-0.72	
Passalacqua	Normal	102	-2.15		
	Obese	13	-1.77		
	Overweight	45	0.96		
	Underweight	38	1.63		
Lovejoy et al.	Obese	13	-9.15		
	Normal	102	-5.60		
	Underweight	38	-5.32		
	Overweight	45	-4.20		
Buckberry and Chamberlain	Underweight	38	3.47		
	Normal	102	4.94		
	Overweight	45	5.49		
	Obese	13	5.92		
Rougé-Maillart et al.	Obese	13	-5.54		
	Normal	102	-5.51		
	Underweight	38	-5.13		
	Overweight	45	-3.49		
Suchey-Brooks	Normal	102	-6.74		
	Underweight	38	-5.29		
	Obese	13	-4.46		
	Overweight	45	-4.02		

Table 51: Tukey's *b* post-hoc test results for female bias scores separated by BMI. Note: alpha level = 0.05

A DFA was applied to assess how well BMI group could be predicted from the bias scores of the eight age estimation methods. The cross-validated classification shows that only 40.9% of females are correctly classified into their BMI group based on bias scores. Underweight females are classified correctly at a rate of 65.8%, normal-sized females at a rate of 40.2%, overweight females at a rate of 20%, and obese females at a rate of 46.2%.

The discriminant scores from Function 1 and Function 2 were used to plot the sample on the discriminant dimensions. The normal-sized group is associated with the largest group centroid (0.377), the obese group is associated with the next largest group centroid (0.301), the overweight group is associated with the second smallest centroid (-0.062) and, finally, the underweight group is associated with the smallest group centroid (-1.042) (see Figure 22).

Figure 22: Canonically derived centroids for the BMI groups for females.

3.3.2 Ancestry

3.3.2.1 Accuracy

European Ancestry

A series of Pearson correlations were performed between the accuracy scores for each age method. Table 52 shows that the pattern of correlations observed among the accuracy scores are generally lower than ideal for a MANOVA, and the Box's M value of 177.830 is associated with a p -value of < 0.001 , which is significant. A covariance matrix (Appendix 16) was run to ensure

that no covariance values were more than four times greater than each other. Although there are instances where the covariance values are greater than four times their value, typically associated with the İşcan et al. and Buckberry and Chamberlain methods, overall the covariance matrices between the BMI groups were assumed to be equal for the purposes of the MANOVA.

	1.	2.	3.	4.	5.	6.	7.	8.	Mean (yrs)	S.D. (yrs)
1. Kunos et al.	1.00								10.19	7.139
2. DiGangi et al.	0.15 (0.001)	1.00							16.45	11.370
3. İşcan et al.	0.09 (0.039)	0.30 (<0.001)	1.00						11.30	8.983
4. Passalacqua	0.20 (<0.001)	0.15 (<0.001)	0.12 (0.005)	1.00					11.47	8.365
5. Lovejoy et al.	0.08 (0.054)	0.48 (<0.001)	0.14 (0.002)	0.23 (<0.001)	1.00				9.24	7.177
6. Buckberry & Chamberlain	0.30 (<0.001)	-0.24 (<0.001)	-0.01 (0.954)	0.06 (0.162)	-0.06 (0.137)	1.00			10.87	8.072
7. Rouge-Maillart et al.	0.15 (0.001)	0.49 (<0.001)	0.24 (<0.001)	0.29 (<0.001)	0.63 (<0.001)	0.08 (0.050)	1.00		10.83	8.218
8. Suchey-Brooks	0.05 (0.281)	0.49 (<0.001)	0.17 (<0.001)	0.21 (<0.001)	0.49 (<0.001)	-0.19 (<0.001)	0.50 (<0.001)	1.00	9.70	7.448

Table 52: Pearson Correlations, Means, and Standard Deviations of the accuracy scores for males for each age estimation method for individuals of European ancestry. P-values are in brackets.

A MANOVA was conducted to test the hypothesis that there would be differences between BMI accuracy scores for each method. The MANOVA was statistically significant with Pillai's Trace = 0.076, $F(24, 1464) = 1.596$, $p = 0.034$, indicating there are differences among the BMI group accuracy scores. The multivariate effect size is estimated at 0.025, which implies that 2.5% of the variance in the canonically derived DV is accounted for by the BMI groups.

Three eigenvalues and canonical correlations were extracted by the MANOVA. The first eigenvalue is 0.045 and accounts for 57.4% of the model variance. The canonical correlation associated with the first eigenvalue is 0.208, where 4.3% of the variance in the discriminant function derived scores is accounted for by BMI group. The second eigenvalue is 0.024 and accounts for 30.9% of the model variance with a corresponding canonical correlation of 0.155. The third eigenvalue is 0.009 and accounts for 11.7% of the model variance and a corresponding canonical correlation of 0.096, which is not statistically significant [Wilks $\Lambda = 0.991$, $F(6, 488) = 0.755$, $p = 0.606$].

The standardized discriminant function coefficients from the first eigenvalue were used to determine the statistical significance of the MANOVA. As seen in Table 53, the standardized discriminant function coefficients suggest that the four BMI groups were maximally differentiated by a canonical variate with significant weightings from the DiGangi et al. (0.622), Rougé-Maillart et al. (0.608), and Lovejoy et al. (-0.475) methods accuracy scores. The standardized coefficients suggest moderate individual contributions to the MANOVA effect from the Kunos et al., Passalacqua methods, with minimal contributions from the Işcan et al. and Suchey-Brooks methods (0.044 and -0.072). The correlations between the accuracy scores and the canonically derived scores for all methods are positive and moderate to strong (range = 0.223 to 0.756), except for the Buckberry and Chamberlain method, which has negative, weak correlations (-0.054).

	Function 1		
	Raw	Stand.	Struc.
Kunos et al.	0.056	0.398	0.510
DiGangi et al.	0.056	0.622	0.756
Işcan et al.	0.005	0.044	0.349
Passalacqua	0.012	0.101	0.302
Lovejoy et al.	-0.067	-0.475	0.223
Buckberry & Chamberlain	-0.016	-0.126	-0.054
Rougé-Maillart et al.	0.077	0.608	0.664
Suchey-Brooks	-0.010	-0.072	0.341

Table 53: Discriminant function coefficients associated with the MANOVA for individuals of European ancestry. Note: Raw = unstandardized coefficients, Stand. = standardized coefficients, Struc. = structure coefficients.

To estimate the group centroids for the four BMI groups, the sample inaccuracy scores were multiplied by the corresponding inaccuracy unstandardized discriminant function coefficients and then averaged across the samples. The means and standard deviations are listed in Table 54. An ANOVA with four levels in the IV (underweight, normal, overweight, obese) was performed on the canonically derived accuracy score DV, and is statistically significant [$F(3, 14.196) = 5.688, p = 0.001$].

	n	Mean	S.D.
Underweight	69	-1.363	1.544
Normal	272	-0.791	1.704
Overweight	122	-0.493	1.377
Obese	34	-0.262	1.260

Table 54: Means and Standard Deviations for the European canonically derived variables.

The Cohen's d absolute values were as follows, from highest to lowest: underweight vs. obese = 0.955; underweight vs. overweight = 0.743; normal-sized vs. obese = 0.577; underweight vs. normal-sized = 0.447; and overweight vs. obese = 0.285; and normal-sized vs. overweight = 0.258. The differences between underweight and obese, and underweight and overweight individuals of European ancestry are suggestive of a large effect size; the differences between normal-sized and obese, underweight and normal-sized individuals of European ancestry are suggestive of a medium effect size; and the differences between normal-sized and overweight individuals of European ancestry are suggestive of a small effect size.

Table 55 shows the results from Tukey's b post-hoc tests for unequal sample sizes. There are no significant differences among the BMI group accuracy scores for individuals of European ancestry using the Kunos et al., İşcan et al., Passalacqua, Lovejoy et al., Buckberry and Chamberlain, and Suchey-Brooks methods. The DiGangi et al. method accuracy scores for underweight individuals of European ancestry are significantly higher than obese and overweight individuals of European ancestry. The Rougé-Maillart et al. method accuracy scores for underweight individuals of European ancestry are significantly higher compared to obese and overweight individuals of European ancestry.

A DFA was applied to assess how well BMI could be predicted from the accuracy scores of the eight age estimation methods. The cross-validated classification shows that only 29.0% of individuals of European ancestry are correctly classified into their BMI group based on accuracy scores. Underweight individuals of European ancestry are classified correctly at a rate of 39.1%, normal-sized individuals of European ancestry at a rate of 21.7%, overweight individuals of European ancestry at a rate of 33.6%, and obese individuals of European ancestry at a rate of 50.0%.

The discriminant scores from Function 1 and Function 2 were used to plot the sample on the discriminant dimensions. The underweight group is associated with the largest group centroid (0.201), the normal-sized group is associated with the next largest group centroid (0.118), the overweight group is associated with the second smallest centroid (-0.229) and, finally, the obese group is associated with the smallest group centroid (-0.527) (see Figure 23).

Method	BMI Categories	n	Subset (yrs)		
			1	2	3
Kunos et al.	Obese	34	7.88		
	Overweight	122	9.25		
	Underweight	69	9.55		
	Normal	272	10.90		
DiGangi et al.	Obese	34	13.09		
	Overweight	122	13.89		
	Normal	272	17.23	17.23	
	Underweight	69		18.75	
İşcan et al.	Obese	34	9.56		
	Overweight	122	10.60		
	Normal	272	11.07		
	Underweight	69	13.14		
Passalacqua	Overweight	122	10.06		
	Normal	272	11.62		
	Obese	34	11.76		
	Underweight	69	12.67		
Lovejoy et al.	Overweight	122	8.12		
	Normal	272	9.15		
	Obese	34	9.74		
	Underweight	69	10.38		
Buckberry and Chamberlain	Underweight	69	10.39		
	Normal	272	10.93		
	Obese	34	10.97		
	Overweight	122	10.99		
Rougé-Maillart et al.	Obese	34	8.38		
	Overweight	122	9.35		
	Normal	272	10.96	10.96	
	Underweight	69		12.84	
Suchey-Brooks	Overweight	122	8.66		
	Obese	34	9.56		
	Normal	272	9.56		
	Underweight	69	11.74		

Table 55: Tukey's *b* post-hoc test results for European accuracy scores separated by BMI.
Note: alpha level = 0.05

Figure 23: Canonically derived centroids for the BMI groups for individuals of European ancestry.

African Ancestry

A series of Pearson correlations were performed between the accuracy scores for each age method. Table 56 shows that the pattern of correlations observed among the accuracy scores are generally lower than ideal for a MANOVA, and the Box's M value of 96.973 is associated with a p -value of 0.083, which is not significant. Therefore, the covariance matrices between the BMI groups were assumed to be equal for the purposes of the MANOVA.

	1.	2.	3.	4.	5.	6.	7.	8.	Mean (yrs)	S.D. (yrs)
1. Kunos et al.	1.00								11.03	6.889
2. DiGangi et al.	-0.02 (0.807)	1.00							12.81	9.772
3. İşcan et al.	0.19 (0.008)	0.37 (<0.001)	1.00						10.85	8.683
4. Passalacqua	0.24 (<0.001)	0.07 (0.318)	0.11 (0.129)	1.00					11.42	8.265
5. Lovejoy et al.	0.15 (0.031)	0.47 (<0.001)	-0.21 (0.002)	0.16 (0.017)	1.00				7.15	6.028
6. Buckberry & Chamberlain	0.39 (<0.001)	-0.30 (<0.001)	-0.04 (0.569)	0.11 (0.098)	0.02 (0.754)	1.00			12.85	9.555
7. Rougé-Maillart et al.	0.23 (0.001)	0.44 (<0.001)	0.17 (0.013)	0.14 (0.047)	0.63 (<0.001)	0.20 (0.003)	1.00		9.06	7.734
8. Suchey-Brooks	0.05 (<0.001)	0.55 (<0.001)	0.29 (<0.001)	0.07 (0.284)	0.49 (<0.001)	-0.16 (0.021)	0.45 (<0.001)	1.00	7.96	6.717

Table 56: Pearson Correlations, Means, and Standard Deviations of the accuracy scores for each age estimation method for individuals of African ancestry. P-values are in brackets.

A MANOVA was conducted to test the hypothesis that there would be differences between BMI accuracy scores for each method. The MANOVA was statistically significant with Pillai's Trace = 0.192, $F(24, 582) = 1.659$, $p = 0.026$, indicating there are differences among the BMI group accuracy scores. The multivariate effect size is estimated at 0.064, which implies that 6.4% of the variance in the canonically derived DV is accounted for by the BMI groups.

Three eigenvalues and canonical correlations were extracted by the MANOVA. The first eigenvalue is 0.173 and accounts for 79.1% of the model variance. The canonical correlation associated with the first eigenvalue is 0.384, where 9.1% of the variance in the discriminant function derived scores is accounted for by BMI. The second eigenvalue is 0.034 and accounts for 15.7% of the model variance with a corresponding canonical correlation of 0.182. The third eigenvalue is 0.011 and accounts for 5.2% of the model variance and a corresponding canonical correlation of 0.106, which is not statistically significant [Wilks $\Lambda = 0.989$, $F(6, 194) = 0.365$, $p = 0.900$].

The standardized discriminant function coefficients from the first eigenvalue were used to determine the statistical significance of the MANOVA. As seen in Table 57, the standardized discriminant function coefficients suggest that the four BMI groups were maximally differentiated by a canonical variate with significant weighting from the İşcan et al. (0.965) method accuracy scores. The standardized coefficients suggest relatively minimal individual

contributions to the MANOVA effect from all other method accuracy scores, except the Suchey-Brooks method (-0.497). The correlations between the accuracy scores and the canonically derived scores for all methods are weak to moderate (range = 0.-0.050 to 0.322), except the İşcan et al. method, which has a strong, positive correlation (0.919).

	Function 1		
	Raw	Stand.	Struc.
Kunos et al.	0.012	0.080	0.210
DiGangi et al.	0.021	0.199	0.322
İşcan et al.	0.118	0.965	0.919
Passalacqua	0.001	0.001	0.115
Lovejoy et al.	0.028	0.160	0.195
Buckberry & Chamberlain	-0.010	-0.098	-0.050
Rougé-Maillart et al.	-0.002	-0.013	0.108
Suchey-Brooks	-0.074	-0.497	0.015

Table 57: Discriminant function coefficients associated with the MANOVA for individuals of African ancestry. Note: Raw = unstandardized coefficients, Stand. = standardized coefficients, Struc. = structure coefficients.

To estimate the group centroids for the four BMI groups, the sample inaccuracy scores were multiplied by the corresponding inaccuracy unstandardized discriminant function coefficients and then averaged across the samples. The means and standard deviations for each BMI group are in Table 58. An ANOVA with four levels in the IV (underweight, normal, overweight, obese) was performed on the canonically derived accuracy score DV, and is statistically significant [$F(3, 32.297) = 14.558, p < 0.001$].

	n	Mean	S.D.
Underweight	49	-1.245	1.997
Normal	116	0.402	1.293
Overweight	33	0.252	1.137
Obese	5	-0.172	2.038

Table 58: Means and Standard Deviations for the individuals of African ancestry canonically derived variables.

The Cohen's d absolute values were as follows, from highest to lowest: underweight vs. overweight = 2.500; underweight vs. normal-sized = 2.230; underweight vs. obese = 1.092; normal-sized vs. obese = 0.849; overweight vs. obese = 0.632; and normal-sized vs. overweight = 0.145. The differences between underweight and overweight, underweight and normal-sized, underweight and obese, and normal-sized and obese individuals of African ancestry are suggestive of a large effect size; the difference between underweight and overweight individuals

of African ancestry is suggestive of a medium effect size; the difference between normal-sized and overweight individuals of African ancestry is suggestive of a small effect size.

Table 59 shows the results from Tukey's *b* post-hoc tests for unequal sample sizes. There are no significant differences among the BMI group accuracy scores for individuals of African ancestry using the Kunos et al., Passalacqua, Lovejoy et al., Buckberry and Chamberlain, Rougé-Maillart et al., and Suchey-Brooks methods. The DiGangi et al. method accuracy scores for underweight individuals of African ancestry are significantly lower than obese individuals of African ancestry. The İşcan et al. method accuracy scores for underweight individuals of African ancestry are significantly lower than overweight individuals of African ancestry.

Method	BMI Categories	n	Subset (yrs)		
			1	2	3
Kunos et al.	Obese	5	8.40		
	Normal	116	10.57		
	Overweight	33	10.76		
	Underweight	49	11.90		
DiGangi et al.	Obese	5	5.60		
	Overweight	33	11.39	11.39	
	Normal	116	12.11	12.11	
	Underweight	49		14.57	
İşcan et al.	Overweight	33	7.61		
	Normal	116	9.47	9.47	
	Obese	5	9.80	9.80	
	Underweight	49		16.18	
Passalacqua	Obese	5	10.40		
	Overweight	33	11.21		
	Normal	116	11.31		
	Underweight	49	12.16		
Lovejoy et al.	Obese	5	4.80		
	Normal	116	6.66		
	Overweight	33	6.79		
	Underweight	49	7.67		
Buckberry and Chamberlain	Obese	5	12.00		
	Overweight	33	12.12		
	Underweight	49	12.29		
	Normal	116	13.26		
Rougé-Maillart et al.	Obese	5	5.60		
	Overweight	33	7.91		
	Normal	116	9.09		
	Underweight	49	9.22		
Suchey-Brooks	Normal	116	7.62		
	Overweight	33	7.33		
	Underweight	49	7.88		
	Obese	5	9.40		

Table 59: Tukey's *b* post-hoc test results for individuals of African ancestry accuracy scores separated by BMI. Note: alpha level = 0.05

A DFA was applied to assess how well BMI could be predicted from the accuracy scores of the eight age estimation methods. The cross-validated classification shows that only 34.5% of individuals of African ancestry are correctly classified into their BMI group based on accuracy scores. Underweight individuals of African ancestry are classified correctly at a rate of 46.9%, normal-sized individuals of African ancestry at a rate of 25.9%, overweight individuals of African ancestry at a rate of 42.4%, and obese individuals of African ancestry at a rate of 60.0%.

The discriminant scores from Function 1 and Function 2 were used to plot the sample on the discriminant dimensions. The underweight group is associated with the largest group centroid (0.714), the normal-sized group is associated with the next largest group centroid (-0.170), the overweight group is associated with the second smallest centroid (-0.394) and, finally, the obese group is associated with the smallest group centroid (-0.460) (see Figure 24).

Figure 24: Canonically derived centroids for the BMI groups for individuals of African ancestry.

3.3.2.2 Bias

European Ancestry

A series of Pearson correlations were performed between the bias scores for each age method. Table 60 shows that the pattern of correlations observed among the bias scores are generally strong for a MANOVA, and the Box's M value of 196.319 is associated with a p -value of < 0.001 , which is significant. A covariance matrix (Appendix 17) was run to ensure that no covariance values were more than four times greater than each other. Although there are instances where the covariance values are greater than four times their value, typically associated with the İşcan et al. method, overall the covariance matrices between the BMI groups were assumed to be equal for the purposes of the MANOVA.

	1.	2.	3.	4.	5.	6.	7.	8.	Mean (yrs)	S.D. (yrs)
1. Kunos et al.	1.00								2.05	12.278
2. DiGangi et al.	0.85 (<0.001)	1.00							-14.39	13.895
3. İşcan et al.	0.23 (<0.001)	0.11 (0.012)	1.00						-0.74	14.423
4. Passalacqua	0.63 (<0.001)	0.52 (<0.001)	0.25 (<0.001)	1.00					-2.37	14.002
5. Lovejoy et al.	0.67 (<0.001)	0.56 (<0.001)	0.34 (<0.001)	0.57 (<0.001)	1.00				-6.62	9.650
6. Buckberry & Chamberlain	0.66 (<0.001)	0.55 (<0.001)	0.30 (<0.001)	0.56 (<0.001)	0.73 (<0.001)	1.00			5.28	12.477
7. Rougé-Maillart et al.	0.68 (<0.001)	0.57 (<0.001)	0.33 (<0.001)	0.59 (<0.001)	0.78 (<0.001)	0.84 (<0.001)	1.00		-6.49	11.953
8. Suchey-Brooks	0.65 (<0.001)	0.60 (<0.001)	0.29 (<0.001)	0.54 (<0.001)	0.57 (<0.001)	0.58 (<0.001)	0.62 (<0.001)	1.00	-7.12	9.951

Table 60: Pearson Correlations, Means, and Standard Deviations of the bias scores for each age estimation method for individuals of European ancestry.

A MANOVA was conducted to test the hypothesis that there would be differences among the BMI group bias scores for each method. The MANOVA was statistically significant with Pillai's Trace = 0.180, $F(24, 1464) = 3.884$, $p < 0.001$, indicating there are differences among the BMI group bias scores. The multivariate effect size is estimated at 0.060, which implies that 6.0% of the variance in the canonically derived DV is accounted for by the BMI groups.

Three eigenvalues and canonical correlations were extracted by the MANOVA. The first eigenvalue is 0.148 and accounts for 73.8% of the model variance. The canonical correlation associated with the first eigenvalue is 0.359, where 12.9% of the variance in the discriminant

function derived scores is accounted for by BMI group. The second eigenvalue is 0.039 and accounts for 19.6% of the model variance with a corresponding canonical correlation of 0.194. The third eigenvalue is 0.013 and accounts for 6.6% of the model variance and a corresponding canonical correlation of 0.114, which is not statistically significant [Wilks $\Lambda = 0.987$, $F(6, 488) = 1.076$, $p = 0.376$].

The standardized discriminant function coefficients from the first eigenvalue was used to determine the statistical significance of the MANOVA, as it is the strongest. As seen in Table 61, the standardized discriminant function coefficients suggest that the four BMI groups are maximally differentiated by a canonical variate with significant weighting from the Işcan et al. (1.013) method bias scores. The standardized coefficients suggest relatively minimal individual contributions to the MANOVA effect from all other bias scores, and the correlations between the bias scores and the canonically derived scores for all methods are positive and with weak scores (range = 0.136 to 0.300), except for the Işcan et al. method, which has a strong correlation (0.917).

	Function 1		
	Raw	Stand.	Struc.
Kunos et al.	0.017	0.204	0.300
DiGangi et al.	0.019	0.253	0.245
Işcan et al.	0.075	1.013	0.917
Passalacqua	-0.001	-0.015	0.210
Lovejoy et al.	-0.047	-0.446	0.136
Buckberry & Chamberlain	0.024	0.290	0.271
Rougé-Maillart et al.	-0.017	-0.194	0.214
Suchey-Brooks	-0.012	-0.117	0.203

Table 61: Discriminant function coefficients associated with the MANOVA for individuals of European ancestry. Note: Raw = unstandardized coefficients, Stand. = standardized coefficients, Struc. = structure coefficients.

To estimate the group centroids for the four BMI groups, the sample bias scores were multiplied by the corresponding bias unstandardized discriminant function coefficients and then averaged across the samples. The means and standard deviations are listed in Table 62. An ANOVA with four levels in the IV (underweight, normal, overweight, obese) was performed on the canonically derived bias score DV, and is statistically significant [$F(3, 24.163) = 24.292$, $p < 0.001$].

	n	Mean	S.D.
Underweight	69	-0.570	0.999
Normal	272	0.572	1.019
Overweight	122	0.325	1.000
Obese	32	0.475	0.777

Table 62: Means and Standard Deviations for the European canonically derived variables.

The Cohen's d absolute values were as follows, from highest to lowest: underweight vs. normal-sized = 1.134; underweight vs. obese = 1.084; underweight vs. overweight = 0.985; normal-sized vs. overweight = 0.245; overweight vs. obese = 0.154; and normal-sized vs. obese = 0.097. The differences between underweight and normal-size, underweight and obese, and underweight and overweight individuals of European ancestry are suggestive of a large effect size, while the differences between normal-sized and overweight, and overweight and obese individuals of European ancestry are suggestive of a small effect size. There is no discernible difference between normal-sized and obese individuals of European ancestry.

Table 63 shows the results from Tukey's b post-hoc tests for unequal sample sizes. There are no significant differences among the BMI group bias scores for individuals of European ancestry using the Lovejoy et al. method. The Kunos et al. and DiGangi et al. methods significantly under-age underweight individuals of European ancestry compared to overweight and obese individuals of European ancestry. The Işcan et al. method under-ages underweight individuals of European ancestry compared to obese, overweight, and normal-sized individuals of European ancestry. The Passalacqua, Rougé-Maillart et al., and Suchey-Brooks methods significantly under-age underweight individuals of European ancestry compared to overweight individuals of European ancestry. The Buckberry and Chamberlain method significantly under-ages underweight individuals of European ancestry compared to overweight and obese individuals.

Method	BMI Categories	n	Subset (yrs)		
			1	2	3
Kunos et al.	Underweight	69	-1.99		
	Normal	272	2.04	2.04	
	Overweight	122		4.09	
	Obese	34		4.94	
DiGangi et al.	Underweight	69	-18.43		
	Normal	272	-14.79	-14.79	
	Overweight	122		-11.73	
	Obese	34		-9.74	
İşcan et al.	Underweight	69	-11.78		
	Obese	34		-1.38	
	Overweight	122		-0.78	
	Normal	272		2.50	
Passalacqua	Underweight	69	-5.88		
	Normal	272	-2.56	-2.56	
	Obese	34	-0.59	-0.59	
	Overweight	122		0.48	
Lovejoy et al.	Underweight	69	-8.12		
	Obese	34	-6.97		
	Normal	272	-6.51		
	Overweight	122	-4.91		
Buckberry and Chamberlain	Underweight	69	1.46		
	Normal	272	5.21	5.21	
	Overweight	122		7.60	
	Obese	34		7.79	
Rougé-Maillart et al.	Underweight	69	-9.22		
	Normal	272	-6.32	-6.32	
	Obese	34	-5.03	-5.03	
	Overweight	122		-1.14	
Suchey-Brooks	Underweight	69	-9.86		
	Normal	272	-7.51	-7.51	
	Obese	34	-6.56	-6.56	
	Overweight	122		-4.48	

Table 63: Tukey's *b* post-hoc test results for European bias scores separated by BMI. Note: alpha level = 0.05

A DFA was applied to assess how well BMI group could be predicted from the bias scores of the eight age estimation methods. The cross-validated classification shows that only 39.6% of individuals of European ancestry are correctly classified into their BMI group based on bias scores. Underweight individuals of European ancestry are classified correctly at a rate of 56.5%, normal-sized individuals of European ancestry at a rate of 39.3%, overweight individuals of European ancestry at a rate of 31.1%, and obese individuals of European ancestry at a rate of 38.2%.

The discriminant scores from Function 1 and Function 2 were used to plot the sample on the discriminant dimensions. The normal-sized group is associated with the largest group centroid

(0.227), the obese group is associated with the next largest group centroid (0.125), the overweight group is associated with the second smallest centroid (-0.022) and, finally, the underweight group is associated with the smallest group centroid (-0.919) (see Figure 25).

Figure 25: Canonically derived centroids for the BMI groups for individuals of European ancestry.

African Ancestry

A series of Pearson correlations were performed between the bias scores for each age method. Table 64 shows that the pattern of correlations observed among the bias scores are generally strong for a MANOVA, and the Box's M value of 121.864 is associated with a p -value of 0.002, which is significant. A covariance matrix (Appendix 18) was run to ensure that no covariance values were more than four times greater than each other (Howell, 2007). Although there are instances where the covariance values are greater than four times their value, typically associated

with the İşcan et al. method, overall the covariance matrices between the BMI groups were assumed to be equal for the purposes of the MANOVA.

	1.	2.	3.	4.	5.	6.	7.	8.	Mean (yrs)	S.D. (yrs)
1. Kunos et al.	1.00								5.82	11.648
2. DiGangi et al.	0.87 (<0.001)	1.00							-9.68	12.897
3. İşcan et al.	0.20 (0.004)	0.12 (0.099)	1.00						-0.73	13.895
4. Passalacqua	0.59 (<0.001)	0.54 (<0.001)	0.18 (0.009)	1.00					2.05	13.972
5. Lovejoy et al.	0.68 (<0.001)	0.60 (<0.001)	0.30 (<0.001)	0.55 (<0.001)	1.00				-2.35	9.064
6. Buckberry & Chamberlain	0.63 (<0.001)	0.55 (<0.001)	0.19 (0.006)	0.47 (<0.001)	0.69 (<0.001)	1.00			8.74	13.435
7. Rougé-Maillart et al.	0.72 (<0.001)	0.66 (<0.001)	0.27 (<0.001)	0.54 (<0.001)	0.79 (<0.001)	0.82 (<0.001)	1.00		-1.17	11.868
8. Suchey-Brooks	0.71 (<0.001)	0.63 (<0.001)	0.24 (<0.001)	0.52 (<0.001)	0.66 (<0.001)	0.55 (<0.001)	0.69 (<0.001)	1.00	-4.02	9.616

Table 64: Pearson Correlations, Means, and Standard Deviations of the bias scores for each age estimation method for individuals of African ancestry.

A MANOVA was conducted to test the hypothesis that there would be differences between BMI group bias scores for each method. The MANOVA effect was statistically significant with Pillai's Trace = 0.274, $F(24, 582) = 2.438$, $p < 0.001$, indicating there are differences among the BMI group bias scores. The multivariate effect size is estimated at 0.091, which implies that 9.1% of the variance in the canonically derived DV is accounted for by the BMI groups.

Three eigenvalues and canonical correlations were extracted by the MANOVA. The first eigenvalue is 0.257 and accounts for 77.8% of the model variance. The canonical correlation associated with the first eigenvalue is 0.452, where 20.4% of the variance in the discriminant function derived scores is accounted for by BMI group. The second eigenvalue is 0.055 and accounts for 16.8% of the model variance with a corresponding canonical correlation of 0.229. The third eigenvalue is 0.018 and accounts for 5.4% of the model variance and a corresponding canonical correlation of 0.121, which is not statistically significant [Wilks $\Lambda = 0.982$, $F(6, 194) = 0.578$, $p = 0.748$].

The standardized discriminant function coefficients from the first eigenvalue was used to determine the statistical significance of the MANOVA as it was the strongest. As seen in Table

65, the standardized discriminant function coefficients suggest that the four BMI groups were maximally differentiated by a canonical variate with significant weightings from the İşcan et al. (0.996), DiGangi et al. (0.525), and Rougé-Maillart et al. (-0.679) methods bias scores. The standardized coefficients suggest moderate individual contributions to the MANOVA effect from all other bias scores. The correlations between the bias scores and the canonically derived scores for all methods are positive and weak (range = 0.060 to 0.241), except the İşcan et al. method (0.888), which has a strong correlation.

	Raw	Function 1	
		Stand.	Struc.
Kunos et al.	-0.035	-0.401	0.093
DiGangi et al.	0.042	0.525	0.122
İşcan et al.	0.078	0.996	0.888
Passalacqua	0.011	0.154	0.190
Lovejoy et al.	0.038	0.327	0.241
Buckberry & Chamberlain	0.025	0.340	0.138
Rougé-Maillart et al.	-0.058	-0.679	0.074
Suchey-Brooks	-0.028	-0.263	0.060

Table 65: Discriminant function coefficients associated with the MANOVA for individuals of African ancestry. Note: Raw = unstandardized coefficients, Stand. = standardized coefficients, Struc. = structure coefficients.

To estimate the group centroids for the four BMI groups, the sample bias scores were multiplied by the corresponding bias unstandardized discriminant function coefficients and then averaged across the samples. The means and standard deviations for each BMI group are in Table 66. An ANOVA with four levels in the IV (underweight, normal, overweight, obese) was performed on the canonically derived bias score DV, and is statistically significant [$F(3, 16.933) = 17.015, p < 0.001$].

	n	Mean	S.D.
Underweight	49	-1.203	1.340
Normal	116	-0.014	0.861
Overweight	33	-0.092	0.855
Obese	5	-0.388	0.894

Table 66: Means and Standard Deviations for the canonically derived variables for individuals of African ancestry.

The Cohen's d absolute values were as follows, from highest to lowest: underweight vs. normal-sized = 1.232; underweight vs. overweight = 1.089; underweight vs. obese = 0.724; normal-sized vs. obese = 0.403; overweight vs. obese = 0.319; and normal-sized vs. overweight = 0.084. The differences between underweight and normal-sized and underweight and overweight individuals

of African ancestry are suggestive of a large effect size; the difference between underweight and obese and normal-size and obese individuals of African ancestry are suggestive of a medium effect size; the difference between overweight and obese individuals of African ancestry is suggestive of a small effect size. There is no discernible difference between normal-sized and overweight individuals of African ancestry.

Table 67 shows the results from Tukey's *b* post-hoc tests for unequal sample sizes. There are no significant differences among the BMI group bias scores for individuals of African ancestry using any method except the İşcan et al. method. The İşcan et al. method under-ages underweight individuals of African ancestry significantly compared to obese, normal-sized, and overweight individuals of African ancestry.

A DFA was applied to assess how well BMI could be predicted from the bias scores of the eight age estimation methods. The cross-validated classification shows that only 50.2% of individuals of African ancestry are correctly classified into their BMI group based on bias scores.

Underweight individuals of African ancestry are classified correctly at a rate of 69.4%, normal-sized individuals of African ancestry at a rate of 45.7%, overweight individuals of African ancestry at a rate of 36.4%, and obese individuals of African ancestry at a rate of 60.0%.

The discriminant scores from Function 1 and Function 2 were used to plot the sample on the discriminant dimensions. The normal-sized group is associated with the largest group centroid (0.309), the overweight group is associated with the next largest group centroid (0.233), the obese group is associated with the second smallest centroid (-0.067) and, finally, the underweight group is associated with the smallest group centroid (-0.882) (see Figure 26).

Method	BMI Categories	n	Subset (yrs)		
			1	2	3
Kunos et al.	Underweight	49	5.08		
	Normal	116	6.14		
	Overweight	33	7.30		
	Obese	5	8.40		
DiGangi et al.	Underweight	49	-10.65		
	Overweight	33	-9.15		
	Normal	116	-8.73		
	Obese	5	-5.60		
İşcan et al.	Underweight	49	-10.63		
	Obese	5		-0.60	
	Normal	116		2.59	
	Overweight	33		3.18	
Passalacqua	Obese	5	-2.00		
	Underweight	49	0.00		
	Normal	116	2.90		
	Overweight	33	4.06		
Lovejoy et al.	Obese	5	-4.80		
	Underweight	49	-3.84		
	Overweight	33	-1.94		
	Normal	116	-1.28		
Buckberry and Chamberlain	Obese	5	5.20		
	Underweight	49	7.22		
	Normal	116	9.10		
	Overweight	33	10.61		
Rougé-Maillart et al.	Obese	5	-3.20		
	Underweight	49	-1.47		
	Normal	116	-0.52		
	Overweight	33	-0.21		
Suchey-Brooks	Underweight	49	-4.69		
	Normal	116	-4.45		
	Overweight	33	-1.85		
	Obese	5	0.60		

Table 67: Tukey's *b* post-hoc test results for individuals of African ancestry bias scores separated by BMI. Note: alpha level = 0.05

Figure 26: Canonically derived centroids for the BMI groups for individuals of African ancestry.

3.3.3 Results Summary

3.3.3.1 Accuracy

For males, females, individuals of European ancestry, and individuals of African ancestry, there are statistically significant differences among the BMI group accuracy scores. The MANOVA effect size is estimated at 12% for males and 22.9% for females, suggesting that the BMI accuracy scores for females show more variance than males using this model, though both have low effect sizes. Similarly, the MANOVA effect size is estimated at 2.5% for individuals of European ancestry and 6.4% for individuals of African ancestry, suggesting that the BMI accuracy scores for individuals of African ancestry show more variance than individuals of European ancestry using this model, though both have low effect sizes. Although females and individuals of African ancestry have stronger differences among the mean accuracy scores of

each BMI group according to the MANOVA, they are not as statistically significant as those of males and individuals of European ancestry because of small sample sizes in the obese group.

Using the standardized coefficients from the MANOVA:

- Males have the highest contribution to the model from the Kunos et al., DiGangi et al., Passalacqua, and Rougé-Maillart et al. methods, which have the most variance in their BMI accuracy scores. The Buckberry and Chamberlain method has the lowest contributions to the MANOVA model, and the least amount of variance in its BMI group accuracy scores. The İşcan et al., Lovejoy et al., and Suchey-Brooks methods have moderate contributions to the model, indicating that there are differences among the BMI group accuracy scores, but they are not as substantial as those from the Kunos et al., DiGangi et al., Passalacqua, and Rougé-Maillart et al. methods (see Table 37).
- Females have the highest contribution to the model from the Kunos et al., İşcan et al., Lovejoy et al., and Rougé-Maillart et al. methods, which have the greatest variance in the BMI group accuracy scores. The DiGangi et al., Passalacqua, Buckberry and Chamberlain, and Suchey-Brooks methods have moderate contributions to the model, indicating that there are differences among the BMI group accuracy scores, but they are not as substantial as those from the other four methods (see Table 41).
- Individuals of European ancestry have the highest contribution to the model from the Kunos et al., DiGangi et al., and Rougé-Maillart et al. methods, which have the greatest variance in their BMI group accuracy scores. The Buckberry and Chamberlain method has the lowest contributions to the MANOVA model, and the least amount of variance in its BMI group accuracy scores. The İşcan et al., Passalacqua, Lovejoy et al., and Suchey-Brooks methods have moderate contributions to the model, indicating that there are differences among the BMI group accuracy scores, but they are not as substantial as those from the Kunos et al., DiGangi et al., and Rougé-Maillart et al. methods (see Table 53).
- Individuals of African ancestry have the have the highest contribution to the model from the İşcan et al. method, which has the greatest variance in the BMI group accuracy scores. The Buckberry and Chamberlain and Suchey-Brooks methods have little contribution to the model, indicating that they have the least amount of variance in their BMI group accuracy scores. The Kunos et al., DiGangi et al., Passalacqua, Lovejoy et al.,

and Rougé-Maillart et al. methods have moderate contributions to the model, indicating that there are differences among the BMI group accuracy scores, but they are not as substantial as those from the İşcan et al. method (see Table 57).

There are significant differences in group centroid values generated from the MANOVA for the male, female, European ancestry, and African ancestry accuracy scores. Underweight males have significantly lower accuracy scores compared to overweight and obese males, and the Cohen's *d* values indicate this is a medium effect size. Normal-sized males have significantly lower accuracy scores compared to obese males, but the effect size is small. Obese females have significantly higher accuracy scores compared to underweight, normal-sized, and overweight females. There is a large effect size between the accuracy scores of obese females and underweight and overweight females, and a medium effect size between the accuracy scores of obese females and normal-sized females. Underweight individuals of European ancestry have significantly lower accuracy scores compared to overweight and obese individuals of European ancestry, and the Cohen's *d* values indicate these are both large effect sizes. Underweight individuals of African ancestry have significantly lower accuracy scores compared to normal-sized and overweight individuals of African ancestry, with large effect sizes.

The results from the group centroid and Cohen's *d* analyses are corroborated by the discriminant function canonical results: underweight males have lower accuracy scores than obese and overweight males, with normal-sized males between the two (see Figure 19); obese females have higher accuracy scores, while the underweight, normal-sized, and overweight females cluster together with lower accuracy scores (see Figure 20); underweight individuals of European ancestry have lower accuracy scores than obese and normal-sized individuals of European ancestry (see Figure 23); and underweight individuals of African ancestry have lower accuracy scores, while the underweight normal-sized and overweight individuals of African ancestry cluster together with higher accuracy scores, and obese individuals of African ancestry have the farthest distance from the underweight group (see Figure 24).

Table 68 shows the inaccuracy scores for males, females, individuals of European ancestry, and individuals of African ancestry separated by BMI for each age method. The Kunos et al. method has higher accuracy scores for obese individuals of European ancestry compared to underweight

and normal-sized individuals of European ancestry. The DiGangi et al. method has lower accuracy scores for underweight males and individuals of European ancestry compared to overweight and obese males individuals of European ancestry. The İşcan et al. method has lower accuracy scores for underweight males, females, and individuals of African ancestry compared to individuals in the other BMI groups. The Passalacqua method has lower accuracy scores for underweight males compared to overweight and obese males. The Lovejoy et al. method has lower bias scores for obese females compared to females in the other BMI groups. The Buckberry and Chamberlain method has no significant differences among BMI group accuracy scores for all individuals. The Rougé-Maillart et al. method has higher accuracy scores for obese males and individuals of European ancestry compared to normal-sized and underweight males and individuals of European ancestry. The Suchey-Brooks method has lower accuracy scores for males compared to overweight males. For all methods, the İşcan et al. method performs poorly on underweight individuals, and the DiGangi et al. method performs poorly overall (see Figure 27, Figure 28, Figure 29, and Figure 30).

BMI		Kunos et al.	DiGangi et al.	İşcan et al.	Passal- acqua	Lovejoy et al.	Buckberry & Chamberlain	Rougé-Maillart et al.	Suchey- Brooks
Males	Underweight	10.58	16.99	13.74	13.03	10.15	11.89	12.19	11.31
	Normal	10.74	15.10	10.07	11.41	8.38	11.94	10.46	8.83
	Overweight	9.02	12.45	10.18	9.36	8.44	11.75	9.39	8.73
	Obese	8.58	11.54	9.46	10.88	7.85	10.69	7.27	9.85
Females	Underweight	10.42	17.08	15.82	11.26	7.37	9.68	9.55	7.66
	Normal	10.95	17.36	12.05	11.85	8.48	10.76	10.14	9.42
	Overweight	10.93	15.58	9.42	12.60	6.38	9.98	7.80	7.80
	Obese	6.69	13.31	9.85	13.00	11.62	11.92	8.92	8.92
European	Underweight	9.55	18.75	13.14	12.67	10.38	10.39	12.84	11.74
	Normal	10.90	17.23	11.07	11.62	9.15	10.93	10.96	9.56
	Overweight	9.25	13.89	10.60	10.06	8.12	10.99	9.35	8.66
	Obese	7.88	13.09	9.56	11.76	9.74	10.97	8.38	9.56
African	Underweight	11.90	14.57	16.18	12.16	7.67	12.29	9.22	7.88
	Normal	10.57	12.11	9.47	11.31	6.66	13.26	9.09	7.62
	Overweight	11.76	11.39	7.61	11.21	6.79	12.12	7.91	7.33
	Obese	8.40	5.60	9.80	10.40	4.80	12.00	5.60	9.40

Table 68: Inaccuracy scores (in years) for each age-at-death estimation method separated by BMI for males, females, individuals of European ancestry, and individuals of African ancestry. Significant differences are noted by boxes.

Discriminant function analyses show that accuracy scores are poor predictors of BMI for all individuals. Overweight males (30.9%), normal-sized females (19.6%), normal-sized individuals of European ancestry (21.7%), and individuals of African ancestry (25.9%) have the lowest classification scores. Obese males (42.3%), females (69.2%), individuals of European ancestry

(50.0%), and individuals of African ancestry (60.0%) have the highest classification scores. These results indicate that accuracy scores cannot be used reliably to predict BMI groups.

Figure 27: Mean inaccuracy scores for the age estimation methods categorized by BMI for males.

Figure 28: Mean inaccuracy scores for the age estimation methods categorized by BMI for females.

Figure 29: Mean inaccuracy scores for the age estimation methods categorized by BMI for individuals of European ancestry.

Figure 30: Mean inaccuracy scores for the age estimation methods categorized by BMI for individuals of African ancestry.

3.3.3.2 Bias

For males, females, individuals of European ancestry, and individuals of African ancestry, there are statistically significant differences among the BMI groups for bias scores. The MANOVA effect size is estimated at 6.4% for males and 9.7% for females, suggesting that BMI has a larger effect for females than males using this model, though both are low effect sizes. Similarly, the MANOVA effect size is estimated at 6% for individuals of European ancestry and 9.1% for individuals of African ancestry, suggesting that BMI has a larger effect for individuals of African ancestry than individuals of European ancestry using this model, though both are low effect sizes. Although females and individuals of African ancestry have stronger differences among the mean bias scores of each BMI group according to the MANOVA, they are not as statistically significant as those of males and individuals of European ancestry because of small sample sizes in the obese group.

Using the standardized coefficients from the MANOVA:

- Males have the highest contribution to the model from the İşcan et al., Rougé-Maillart et al., and Kunos et al. methods, which have the greatest variance among the BMI groups. The DiGangi et al., Passalacqua, Lovejoy et al., Buckberry and Chamberlain, and Suchey-Brooks methods have moderate contributions to the model, indicating that there are differences among the BMI group bias scores, but they are not as substantial as those from the other three methods (see Table 45).
- Females have the highest contribution to the model from the İşcan et al., DiGangi et al., and Kunos et al. methods, which have the greatest variance in the BMI group bias scores. The Rougé-Maillart et al. and Lovejoy et al. methods have the lowest bias scores, and the least amount of variance in their BMI group bias scores. The Passalacqua, Buckberry and Chamberlain, and Suchey-Brooks methods have moderate contributions to the model, indicating that there are differences among the BMI group bias scores, but they are not as substantial as those from the İşcan et al., DiGangi et al., and Kunos et al. methods (see Table 49).
- Individuals of European ancestry have the highest contribution to the model from the İşcan et al. method, which has the greatest amount of variance in the BMI group bias scores. All other methods make moderate contributions to the model, indicating that there are differences among their BMI group bias scores, but they are not as substantial as those from the İşcan et al. method (see Table 54).
- Individuals of African ancestry have the highest contribution to the model from the İşcan et al., DiGangi et al., and Rougé-Maillart et al. methods, which have the most variance among their BMI bias scores. The Passalacqua, Lovejoy et al., and Buckberry and Chamberlain methods have moderate contributions to the model, indicating that there are differences among their BMI group bias scores, but they are not as substantial as those from the İşcan et al. method. The Kunos et al. and Suchey-Brooks methods do not make significant contributions, and have the least amount of variance in their BMI group bias scores (see Table 58).

- The İşcan et al. method has the highest bias scores for all individuals.

The differences in group centroid values generated from the MANOVA for male, female, individuals of European, and individuals of African ancestry bias scores are significant. Underweight males and females have significantly higher negative bias scores compared to normal-sized, overweight, and obese males, and the Cohen's d values indicate these are large effect sizes. Underweight individuals of European ancestry have significantly higher negative bias scores compared to normal-sized, overweight, and obese individuals of European ancestry, and the Cohen's d values indicate these all have large effect sizes. Underweight individuals of African ancestry have significantly higher negative bias scores compared to normal-sized and overweight individuals of African ancestry, with large effect sizes. These results are corroborated by the discriminant function canonical analyses results: underweight individuals are under-aged more than normal-sized, overweight, and obese individuals (see Figure 21, Figure 22, Figure 25 and Figure 26).

Table 69 shows the bias scores for males and females separated by BMI. There are no significant differences among the BMI bias scores using the Lovejoy et al. method. The İşcan et al. method under-ages all underweight individuals significantly compared to individuals in all BMI groups. The Kunos et al., DiGangi et al., Passalacqua, and Suchey-Brooks methods under-age underweight males and individuals of European ancestry compared to obese males and individuals of European ancestry. The Buckberry and Chamberlain and Rougé-Maillart et al. methods under-age underweight Europeans compared to individuals in all other BMI groups. The İşcan et al. method under-ages all underweight individuals by the largest degree, and the DiGangi et al. method performs poorly overall (see Figure 31, Figure 32, Figure 33, Figure 34).

Discriminant function analyses show that bias scores are poor predictors of BMI. Obese males (30.8%), overweight females (20%), overweight individuals of European ancestry (31.1%), and overweight individuals of African ancestry (36.4%) have the lowest classification scores. Underweight males (57.5%), females (65.8%), individuals of European ancestry (56.5%), and individuals of African ancestry (69.4%) have the highest classification scores. These results indicate that bias scores cannot be used reliably to predict BMI groups.

BMI		Kunos et al.	DiGangi et al.	İşcan et al.	Passalacqua	Lovejoy et al.	Buckberry & Chamberlain	Rougé-Maillart et al.	Suchey-Brooks
Males	Underweight	0.03	-14.49	-9.61	-5.85	-6.83	4.04	-6.41	-8.86
	Normal	4.28	-11.99	3.68	-0.49	-4.71	6.89	-4.42	-6.55
	Overweight	4.96	-10.84	1.84	1.36	-4.31	9.36	-3.23	-3.87
	Obese	5.96	-8.23	0.08	-0.27	-5.46	8.23	-4.42	-6.23
Females	Underweight	2.89	-16.71	-14.87	1.63	-5.32	3.47	-5.29	-5.29
	Normal	0.42	-15.75	-0.72	-2.15	-5.60	4.94	-5.51	-6.74
	Overweight	4.31	-12.02	-4.27	0.96	-4.20	5.49	-3.49	-4.02
	Obese	4.23	-11.15	-3.54	-1.77	-9.15	5.92	-5.54	-4.46
European	Underweight	-1.99	-18.43	-11.78	-5.88	-8.12	1.46	-9.22	-9.86
	Normal	2.04	-14.79	2.50	-2.56	-6.51	5.21	-6.32	-7.51
	Overweight	4.09	-11.73	-0.78	0.48	-4.91	7.60	-1.14	-4.48
	Obese	4.94	-9.74	-1.38	-0.59	-6.97	7.79	-5.03	-6.56
African	Underweight	5.08	-10.65	-10.63	0.00	-3.84	7.22	-1.47	-4.69
	Normal	6.14	-8.73	-0.60	2.90	-1.28	9.10	-0.52	-4.45
	Overweight	7.30	-9.15	2.59	4.06	-1.94	10.61	-0.21	-1.85
	Obese	8.40	-5.60	3.18	-2.00	-4.80	5.20	-3.20	0.60

Table 69: Bias scores (in years) for each age-at-death estimation method separated by BMI for males and females. Significant differences are noted by boxes.

Figure 31: Mean bias scores for the age estimation methods categorized by BMI for males.

Figure 32: Mean bias scores for the age estimation methods categorized by BMI for females.

Figure 33: Mean bias scores for the age estimation methods categorized by BMI for individuals of European ancestry.

Figure 34: Mean bias scores for the age estimation methods categorized by BMI for individuals of African ancestry.

3.4 Research Question II: Does stature influence skeletal age estimation?

Figure 35 shows the sample distribution for stature. The average stature for this sample of 764 individuals is 1.70m (range 1.30m to 1.93m), 1.74m for males (range 1.30m to 1.83m), 1.61m for females (range 1.30m to 1.87m), 1.70m for individuals of European ancestry (range 1.30m to 1.93m), and 1.72m for individuals of African ancestry (range 1.50m to 1.92m). A cluster analysis was used to assign individuals into approximately equal, unbiased stature groups, and the results are shown in Figure 35 and Table 70.

Figure 35: Stature distribution of the sample by age at death. Lines demarcate cluster analysis cut-off points.

Group	n	Stature (m)	S.D.
1	198	1.20-1.60	0.0533
2	229	1.61-1.72	0.0328
3	230	1.73-1.80	0.0259
4	139	1.81-1.94	0.0277

Table 70: Stature group descriptive statistics.

This section will test the influence of stature on age at death estimations. The sample will be separated by sex and ancestry, and differences between accuracy and bias scores between stature groups will be evaluated for each method using MANOVA and DFA.

3.4.1 Sex

3.4.1.1 Accuracy

Males

As shown in Table 36 of Section 3.3.1.1, the pattern of correlations observed among the accuracy scores are generally lower than ideal for a MANOVA. The Box's M value of 163.031 is associated with a p -value of 0.001, which is significant. A covariance matrix (Appendix 19) was run to ensure that no covariance values were more than four times greater than each other. Although there are instances where the covariance values are greater than four times their value, typically associated with the Kunos et al. and Buckberry and Chamberlain methods, overall the covariance matrices between the stature groups were assumed to be equal for the purposes of the MANOVA.

A MANOVA was conducted to test the hypothesis that there would differences between stature group accuracy scores for each method. The MANOVA was significant with Pillai's Trace = 0.073, $F(24, 1479) = 1.531$, $p = 0.048$, indicating there are differences among the stature group accuracy scores. The multivariate effect size is estimated at 0.024, which implies that 2.4% of the variance in the canonically derived DV is accounted for by the stature groups.

Three eigenvalues and canonical correlations were extracted by the MANOVA. The first eigenvalue is 0.054 and accounts for 71.0% of the model variance. The canonical correlation associated with the first eigenvalue is 0.226, where 5.1% of the variance in the discriminant function derived scores is accounted for by stature group. The second eigenvalue is 0.017 and accounts for 22.3% of the model variance with a corresponding canonical correlation of 0.129. The third eigenvalue is 0.005 and accounts for 6.7% of the model variance and a corresponding canonical correlation of 0.071, which is not statistically significant [Wilks $\Lambda = 0.994$, $F(6, 493) = 0.417$, $p = 0.868$].

The standardized discriminant function coefficients from the first eigenvalue were used to determine the statistical significance of the MANOVA, as it is the strongest. As seen in Table 71, the standardized discriminant function coefficients suggest that the four stature groups were maximally differentiated by a canonical variate with significant weightings from the Rougé-Maillart et al. (0.862), Buckberry and Chamberlain (-0.848), and DiGangi et al. (-0.630) methods accuracy scores. The standardized coefficients suggest relatively minimal individual contributions to the MANOVA effect from all other accuracy scores. The correlations between the accuracy scores and the canonically derived scores for all methods are weak to moderate (range = -0.449 to 0.628).

	Function 1		
	Raw	Stand.	Struc.
Kunos et al.	0.035	0.242	-0.008
DiGangi et al.	-0.061	-0.630	0.214
İşcan et al.	0.004	0.031	0.062
Passalacqua	-0.014	-0.117	0.006
Lovejoy et al.	0.027	0.184	0.494
Buckberry & Chamberlain	-0.098	-0.848	-0.499
Rougé-Maillart et al.	0.111	0.862	0.628
Suchey-Brooks	0.023	0.165	0.484

Table 71: Discriminant function coefficients associated with the MANOVA for males. Note: Raw = unstandardized coefficients, Stand. = standardized coefficients, Struc. = structure coefficients.

To estimate the group centroids for the four stature groups, the sample inaccuracy scores were multiplied by the corresponding inaccuracy unstandardized discriminant function coefficients and then averaged across the samples. The means and standard deviations are listed in Table 72. An ANOVA with four levels in the IV was performed on the canonically derived accuracy score DV, and is significant [$F(3, 8.879) = 8.925, p < 0.001$].

	n	Mean	S.D.
1.20-1.60m	55	0.249	1.038
1.61-1.72m	132	-0.304	1.047
1.73-1.80m	191	-0.089	1.000
1.81-1.93m	124	-0.509	0.919

Table 72: Means and Standard Deviations for the male canonically derived variables.

The Cohen's d absolute values were as follows, from highest to lowest: Group 1 vs. Group 4 = 0.776; Group 1 vs. Group 2 = 0.551; Group 1 vs. Group 3 = 0.337; Group 2 vs. Group 3 = 0.213; Group 2 vs. Group 4 = 0.207; and Group 3 vs. Group 4 = 0.207. The differences between Groups

1 and 4 are suggestive of a large effect size; the differences between Groups 1 and 2 are suggestive of a medium effect size, and the differences between Groups 2 and 3, Groups 2 and 4, and Groups 3 and 4 are suggestive of a small effect size.

Table 73 shows the results from Tukey's *b* post-hoc tests for unequal sample sizes. There are no significant differences among the stature group inaccuracy scores for males using the Kunos et al., DiGangi et al., İşcan et al., and Passalacqua methods. The inaccuracy scores for the Lovejoy et al., Rougé-Maillart et al., and Suchey-Brooks methods are higher for males in Group 1 compared to males in Group 4, while the inaccuracy scores for the Buckberry and Chamberlain method are higher for males in Group 4 compared to males in Group 1.

Method	Stature Group	n	Subset (yrs)		
			1	2	3
Kunos et al.	Group 4	124	10.10		
	Group 3	191	10.13		
	Group 1	55	10.20		
	Group 2	132	10.50		
DiGangi et al.	Group 4	124	13.70		
	Group 3	191	14.73		
	Group 2	132	14.95		
	Group 1	55	15.69		
İşcan et al.	Group 4	124	10.34		
	Group 3	191	10.56		
	Group 2	132	10.83		
	Group 1	55	11.44		
Passalacqua	Group 4	124	10.47		
	Group 1	55	10.65		
	Group 3	191	11.17		
	Group 2	132	12.12		
Lovejoy et al.	Group 4	124	7.36		
	Group 3	191	8.77	8.77	
	Group 2	132	8.98	8.98	
	Group 1	55		10.31	
Buckberry and Chamberlain	Group 1	55	9.44		
	Group 3	191	11.46	11.46	
	Group 2	132	12.30	12.30	
	Group 4	124		12.94	
Rougé-Maillart et al.	Group 4	124	8.71		
	Group 2	132	9.93	9.93	
	Group 3	191	11.21	11.21	
	Group 1	55		12.09	
Suchey-Brooks	Group 4	124	7.82		
	Group 3	191	9.22	9.22	
	Group 2	132	9.84	9.84	
	Group 1	55		11.18	

Table 73: Tukey's *b* post-hoc test results for male accuracy scores separated by stature.
Note: alpha level = 0.05

A DFA was applied to assess how well stature could be predicted from the accuracy scores of the eight age estimation methods. The cross-validated classification shows that only 37.8% of males are correctly classified into their stature group based on accuracy scores. Males in Group 1 are classified correctly at a rate of 0%, Group 2 at a rate of 16.7%, Group 3 at a rate of 79.6%, and Group 4 at a rate of 12.9%.

The discriminant scores from Function 1 and Function 2 were used to plot the sample on the discriminant dimensions. The Group 4 is associated with the largest group centroid (0.297), Group 2 is associated with the next largest group centroid (0.092), Group 3 is associated with the second smallest centroid (-0.124) and, finally, Group 1 is associated with the smallest group centroid (-0.463) (see Figure 36).

Figure 36: Canonically derived centroids for the stature groups for males.

Females

As shown in Table 40 of Section 3.3.1.1, the pattern of correlations observed among the accuracy scores are generally lower than ideal for a MANOVA. Box's M value of 97.848 is associated with a p -value of 0.131, which is not significant; therefore, the covariance between the stature groups were assumed to be equal for the purposes of the MANOVA.

A MANOVA was conducted to test the hypothesis that there would be differences between stature group accuracy scores for each method. The MANOVA effect was not statistically significant with Pillai's Trace = 0.142, $F(24, 567) = 1.171$, $p = 0.262$. The multivariate effect size is estimated at 0.047, which implies that 4.7% of the variance in the canonically derived DV is accounted for by the stature groups. As none of the functions are significant, there is no relationship between the stature groups and accuracy scores for females.

A DFA was applied to assess how well stature could be predicted from the accuracy scores of the eight age estimation methods. The cross-validated classification shows that only 56.6% of females are correctly classified into their stature group based on accuracy scores. Females in Group 1 are classified correctly at a rate of 78.3%, Group 2 at a rate of 39.7%, and females in Group 3 and Group 4 are never classified in the correct stature group.

3.4.1.2 Bias

Males

As shown in Table 44 of Section 3.3.1.2, the pattern of correlations observed among the bias scores are generally strong for a MANOVA. The Box's M value of 110.863 is associated with a p -value of 0.512, which is not significant; therefore, the covariance between the stature groups are equal for the purposes of the MANOVA.

A MANOVA was conducted to test the hypothesis that there would be differences between stature group bias scores for each method. The MANOVA was statistically significant with Pillai's Trace = 0.116, $F(24, 1479) = 2.473$, $p < 0.001$, indicating there are differences among the stature group bias scores. The multivariate effect size is estimated at 0.039, which implies that 3.9% of the variance in the canonically derived DV is accounted for by the stature groups.

Three eigenvalues and canonical correlations were extracted by the MANOVA. The first eigenvalue is 0.076 and accounts for 62.2% of the model variance. The canonical correlation associated with the first eigenvalue is 0.266, where 7.1% of the variance in the discriminant function derived scores is accounted for by stature group. The second eigenvalue is 0.030 and accounts for 24.2% of the model variance with a corresponding canonical correlation of 0.170. The third eigenvalue is 0.017 and accounts for 13.6% of the model variance and a corresponding canonical correlation of 0.128, which is not statistically significant [Wilks $\Lambda = 0.984$, $F(6, 493) = 1.363$, $p = 0.228$].

The standardized discriminant function coefficients from the first eigenvalue were used to determine the statistical significance of the MANOVA, as it is the strongest. As seen in Table 74, the standardized discriminant function coefficients suggest that the stature groups are maximally differentiated by a canonical variate with significant weightings from the Rougé-Maillart et al. (1.073) and DiGangi et al. (-0.744), methods bias scores. The standardized coefficients suggest moderate individual contributions to the MANOVA effect from all other bias scores. The correlations between the bias scores and the canonically derived scores for all methods are positive and with weak to strong scores (range = 0.176 to 0.702).

	Function 1		
	Raw	Stand.	Struc.
Kunos et al.	0.030	0.352	0.423
DiGangi et al.	-0.055	-0.744	0.176
İşcan et al.	0.014	0.190	0.413
Passalacqua	-0.012	-0.170	0.297
Lovejoy et al.	-0.050	-0.487	0.452
Buckberry & Chamberlain	0.020	0.250	0.702
Rougé-Maillart et al.	0.090	1.073	0.198
Suchey-Brooks	0.027	0.262	0.546

Table 74: Discriminant function coefficients associated with the MANOVA for males. Note: Raw = unstandardized coefficients, Stand. = standardized coefficients, Struc. = structure coefficients.

To estimate the group centroids for the stature groups, the sample bias scores were multiplied by the corresponding bias unstandardized discriminant function coefficients and then averaged across the samples. The means and standard deviations are listed in Table 75. An ANOVA with four levels in the IV was performed on the canonically derived bias score DV, and is statistically significant [$F(3, 27.214) = 9.510$, $p < 0.001$].

	n	Mean	S.D.
1.20-1.60m	55	-0.700	1.674
1.61-1.72m	132	0.168	1.674
1.73-1.80m	191	-0.054	1.783
1.81-1.93m	124	0.697	1.569

Table 75: Means and Standard Deviations for the male canonically derived variables.

The Cohen's d absolute values were as follows, from highest to lowest: Group 1 vs. Group 4 = 1.104; Group 1 vs. Group 2 = 0.671; Group 3 vs. Group 4 = 0.576; Group 1 vs. Group 3 = 0.487; Group 2 vs. Group 3 = 0.415; and Group 2 vs. Group 4 = 0.415. The differences between Groups 1 and 4, and Groups 1 and 2 are suggestive of a large effect size; the differences between Groups 3 and 4, Groups 1 and 3, Groups 2 and 3 and Groups 2 and 4 are suggestive of a medium effect size.

Table 76 shows the results from Tukey's b post-hoc tests for unequal sample sizes. There are no significant differences among the stature group bias scores for males using the DiGangi et al. and Passalacqua methods. The Kunos et al., Lovejoy et al., Buckberry and Chamberlain, and Suchey-Brooks methods under-age males in Group 1 compared to males in Group 3. The İşcan et al. method under-age males in Group 1 compared to males in Groups 2, 3, and 4. The Rougé-Maillart et al. method under-age males in Group 1 compared to males in Groups 3 and 4. Males in Group 2 are under-aged compared to males in Group 4.

Method	Stature	n	Subset (yrs)		
			1	2	3
Kunos et al.	Group 1	55	0.49		
	Group 2	132	3.59	3.59	
	Group 3	191	3.68	3.68	
	Group 4	124		5.82	
DiGangi et al.	Group 3	191	-12.54		
	Group 2	132	-12.36		
	Group 1	55	-12.24		
	Group 4	124	-10.43		
İşcan et al.	Group 1	55	-3.65		
	Group 3	191		0.70	
	Group 4	124		2.03	
	Group 2	132		2.30	
Passalacqua	Group 1	55	-2.95		
	Group 2	132	-1.98		
	Group 3	191	-1.13		
	Group 4	124	1.40		
Lovejoy et al.	Group 1	55	-7.62		
	Group 2	132	-5.58	-5.58	
	Group 3	191	-5.18	-5.18	
	Group 4	124		-2.94	
Buckberry and Chamberlain	Group 1	55	3.40		
	Group 3	191	5.27	5.27	
	Group 2	132	7.57	7.57	
	Group 4	124		10.84	
Rougé-Maillart et al.	Group 1	55	-8.67		
	Group 2	132	-6.04	-6.04	
	Group 3	191		-3.96	-3.96
	Group 4	124			-0.37
Suchey-Brooks	Group 1	55	-9.18		
	Group 2	132	-7.07	-7.07	
	Group 3	191	-6.69	-6.69	
	Group 4	124		-3.66	

Table 76: Tukey's *b* post-hoc test results for male bias scores separated by stature. Note: alpha level = 0.05

A DFA was applied to assess how well stature could be predicted from the bias scores of the eight age estimation methods. The cross-validated classification shows that only 40.0% of males are correctly classified into their stature group based on bias scores. Males in Group 1 are classified correctly at a rate of 3.6%, Group 2 at a rate of 20.5%, Group 3 at a rate of 76.4%, and Group 4 at a rate of 30.6%.

The discriminant scores from Function 1 and Function 2 were used to plot the sample on the discriminant dimensions. Group 4 is associated with the largest group centroid (0.364), Group 2 is associated with the next largest group centroid (0.105), Group 3 is associated with the second

smallest centroid (-0.157) and, finally, Group 1 is associated with the smallest group centroid (-0.527) (see Figure 37).

Figure 37: Canonically derived centroids for the stature groups for males.

Females

As shown in Table 48 of Section 3.3.1.2, the pattern of correlations observed among the bias scores are generally strong for a MANOVA. The Box's M value of 102.048 is associated with a p -value of 0.082, which is not significant; therefore, the covariance observed between the stature groups are equal for the MANOVA.

A MANOVA was conducted to test the hypothesis that there would be differences between stature group bias scores for each method. The MANOVA was not statistically significant with Pillai's Trace = 0.118, $F(24, 567) = 0.968$, $p = 0.507$. The multivariate effect size is estimated at

0.039, which implies that 3.9% of the variance in the canonically derived DV is accounted for by the stature groups. As none of the functions are significant, there is no relationship between the stature groups and bias scores for females.

A DFA was applied to assess how well stature could be predicted from the bias scores of the eight age estimation methods. The cross-validated classification shows that only 51.7% of females are correctly classified into their stature group based on bias scores. Females in Group 1 are classified correctly at a rate of 84.0%, Group 2 at a rate of 32.9%, and females in Groups 3 and 4 are never classified correctly.

3.4.2 Ancestry

3.4.2.1 Accuracy

European Ancestry

As shown in Table 52 of Section 3.3.2.1, the pattern of correlations observed among the accuracy scores are generally lower than ideal for a MANOVA. The Box's M value of 163.518 is associated with a p -value of 0.001, which is significant. A covariance matrix (Appendix 20) was run to ensure that no covariance values were more than four times greater than each other. Although there are instances where the covariance values are greater than four times their value, typically associated with the DiGangi et al. and Buckberry and Chamberlain methods, overall the covariance matrices between the stature groups were assumed to be equal for the purposes of the MANOVA.

A MANOVA was conducted to test the hypothesis that there would be differences between stature group accuracy scores for each method. The MANOVA was statistically significant with Pillai's Trace = 0.107, $F(24, 1464) = 2.249$, $p = 0.001$, indicating there are differences among the stature group accuracy scores. The multivariate effect size is estimated at 0.036, which implies that 3.6% of the variance in the canonically derived DV is accounted for by the stature groups.

Three eigenvalues and canonical correlations were extracted by the MANOVA. The first eigenvalue is 0.073 and accounts for 65.1% of the model variance. The canonical correlation associated with the first eigenvalue is 0.262, where 6.9% of the variance in the discriminant function derived scores is accounted for by stature group. The second eigenvalue is 0.033 and

accounts for 29.0% of the model variance with a corresponding canonical correlation of 0.178. The third eigenvalue is 0.007 and accounts for 5.9% of the model variance and a corresponding canonical correlation of 0.081, which is not statistically significant [Wilks $\Lambda = 0.993$, $F(6, 488) = 0.540$, $p = 0.778$].

The standardized discriminant function coefficients from the first eigenvalue were used to determine the statistical significance of the MANOVA, as it was the strongest. As seen in Table 77, the standardized discriminant function coefficients suggest that the four stature groups were maximally differentiated by a canonical variate with significant weightings from the Buckberry and Chamberlain (0.784) and the Rougé-Maillart et al. (-0.875) methods accuracy scores. The standardized coefficients suggest minimal to moderate individual contributions to the MANOVA effect from all other accuracy scores. The correlations between the accuracy scores and the canonically derived scores for all methods are weak to moderate (range = -0.633 to 0.607).

	Function 1		
	Raw	Stand.	Struc.
Kunos et al.	0.010	0.068	-0.161
DiGangi et al.	0.009	0.104	0.416
İşcan et al.	-0.032	-0.278	0.384
Passalacqua	-0.002	-0.015	0.140
Lovejoy et al.	0.024	0.170	0.306
Buckberry & Chamberlain	0.099	0.784	-0.633
Rougé-Maillart et al.	-0.111	-0.875	0.607
Suchey-Brooks	0.023	0.167	0.306

Table 77: Discriminant function coefficients associated with the MANOVA for individuals of European ancestry. Note: Raw = unstandardized coefficients, Stand. = standardized coefficients, Struc. = structure coefficients.

To estimate the group centroids for the stature groups, the sample inaccuracy scores were multiplied by the corresponding inaccuracy unstandardized discriminant function coefficients and then averaged across the samples. The means and standard deviations are listed in Table 78. An ANOVA with four levels in the IV was performed on the canonically derived accuracy score DV, and is statistically significant [$F(3, 12.139) = 12.057$, $p < 0.001$].

	n	Mean	S.D.
1.20-1.60m	120	-0.184	1.020
1.61-1.72m	152	0.396	1.021
1.73-1.80m	147	0.117	0.977
1.81-1.93m	78	0.590	0.991

Table 78: Means and Standard Deviations for individuals of European ancestry canonically derived variables.

The Cohen's d absolute values were as follows, from highest to lowest: Group 1 vs. Group 4 = 0.771; Group 1 vs. Group 2 = 0.574; Group 3 vs. Group 4 = 0.477; Group 1 vs. Group 3 = 0.302; Group 2 vs. Group 3 = 0.279; and Group 2 vs. Group 4 = 0.193. The differences between Groups 1 and 4 are suggestive of a large effect size; the differences between Groups 1 and 2, and Groups 3 and 4 are suggestive of a medium effect size; and the differences between Groups 1 and 3, Groups 2 and 3, and Groups 1 and 4 are suggestive of a small effect size.

Table 79 shows the results from Tukey's b post-hoc tests for unequal sample sizes. There are no significant differences among the stature group accuracy scores for individuals of European ancestry using the Kunos et al., Passalacqua, Lovejoy et al., and Suchey-Brooks methods. The DiGangi et al. and Buckberry and Chamberlain methods accuracy scores for Group 1 are significantly lower than Group 4. The İşcan et al. method accuracy scores for Group 1 are significantly lower than Group 3 and Group 4. The Rougé-Maillart et al. method accuracy scores for Group 1 and Group 3 are significantly lower compared to Group 4.

A DFA was applied to assess how well stature could be predicted from the accuracy scores of the eight age estimation methods. The cross-validated classification shows that only 40.4% of individuals of European ancestry are correctly classified into their stature group based on accuracy scores. individuals of European ancestry in Group 1 are classified correctly at a rate of 28.3%, Group 2 at a rate of 59.2%, Group 3 at a rate of 51.0%, and Group 4 at a rate of 2.6%.

The discriminant scores from Function 1 and Function 2 were used to plot the sample on the discriminant dimensions. Group 4 is associated with the largest group centroid (0.385), Group 2 is associated with the next largest group centroid (0.192), Group 3 is associated with the second smallest centroid (-0.087) and, finally, Group 1 is associated with the smallest group centroid (-0.386) (see Figure 38).

Method	Stature	n	Subset (yrs)		
			1	2	3
Kunos et al.	Group 3	147	9.29		
	Group 1	120	10.02		
	Group 4	78	10.28		
	Group 2	152	10.86		
DiGangi et al.	Group 4	78	13.76		
	Group 3	147	15.27	15.27	
	Group 2	152	16.73	16.73	
	Group 1	120		18.83	
İşcan et al.	Group 3	147	10.17		
	Group 4	78	10.40		
	Group 2	152	10.74	10.74	
	Group 1	120		13.31	
Passalacqua	Group 4	78	10.63		
	Group 3	147	11.22		
	Group 2	152	11.52		
	Group 1	120	11.93		
Lovejoy et al.	Group 4	78	7.88		
	Group 3	147	8.88		
	Group 2	152	9.17		
	Group 1	120	10.11		
Buckberry and Chamberlain	Group 1	120	8.85		
	Group 3	147	10.78	10.78	
	Group 2	152	11.30	11.30	
	Group 4	78		13.35	
Rougé-Maillart et al.	Group 4	78	8.81		
	Group 2	152	9.57	9.57	
	Group 3	147		11.40	11.40
	Group 1	120			12.29
Suchey-Brooks	Group 4	78	8.04		
	Group 3	147	9.56		
	Group 2	152	9.86		
	Group 1	120	10.51		

Table 79: Tukey's *b* post-hoc test results for European accuracy scores separated by stature. Note: alpha level = 0.05

Figure 38: Canonically derived centroids for the stature groups for individuals of European ancestry.

African Ancestry

As shown in Table 56 of Section 3.3.2.1, the pattern of correlations observed among the accuracy scores are generally lower than ideal for a MANOVA. The Box's M value of 153.890 is associated with a p -value of 0.015, which is not significant; therefore, the covariance between the stature groups were assumed to be equal for the purposes of the MANOVA.

A MANOVA was conducted to test the hypothesis that there would be differences between stature group accuracy scores for each method. The MANOVA was not statistically significant with Pillai's Trace = 0.131, $F(24, 582) = 1.104$, $p = 0.333$. The multivariate effect size is estimated at 0.044, which implies that 4.4% of the variance in the canonically derived DV is accounted for by the stature groups. As none of the functions were significant, there is no relationship between the stature groups and accuracy scores for individuals of African ancestry.

A DFA was applied to assess how well stature could be predicted from the accuracy scores of the eight age estimation methods. The cross-validated classification shows that only 36.9% of individuals of African ancestry are correctly classified into their stature group based on accuracy scores. individuals of African ancestry in Group 1 are classified correctly at a rate of 4.9%, Group 2 at a rate of 49.1%, Group 3 at a rate of 57.4%, and Group 4 at a rate of 25.0%.

3.4.2.2 Bias

European Ancestry

As shown in Table 60 of Section 3.3.2.2, the pattern of correlations observed among the bias scores are generally strong for a MANOVA. The Box's M value of 137.668 is associated with a p -value of 0.049, which is not significant; therefore, the covariance between the stature groups were assumed to be equal for the purposes of the MANOVA.

A MANOVA was conducted to test the hypothesis that there would be differences between stature group bias scores for each method. The MANOVA was statistically significant with Pillai's Trace = 0.161, $F(24, 1464) = 3.572$, $p < 0.001$, indicating there are differences among the stature group bias scores. The multivariate effect size is estimated at 0.055, which implies that 5.5% of the variance in the canonically derived DV is accounted for by stature groups.

Three eigenvalues and canonical correlations were extracted by the MANOVA. The first eigenvalue is equal to 0.127 and accounts for 69.7% of the model variance. The canonical correlation associated with the first eigenvalue is equal to 0.336, where 11.3% of the variance in the discriminant function derived scores is accounted for by stature group. The second eigenvalue is equal to 0.039 and accounts for 21.2% of the model variance with a corresponding canonical correlation of 0.193. The third eigenvalue is equal to 0.016 and accounts for 9.0% of the model variance and a corresponding canonical correlation of 0.127, which is not statistically significant [Wilks $\Lambda = 0.984$, $F(6, 488) = 1.331$, $p = 0.241$].

The standardized discriminant function coefficients from the first eigenvalue were used to determine the statistical significance of the MANOVA, as it is the strongest. As seen in Table 80, the standardized discriminant function coefficients suggest that the stature groups are maximally differentiated by a canonical variate with significant weighting from the Buckberry and

Chamberlain (0.650), İşcan et al. (0.496), and Kunos et al. (0.753) method bias scores. The standardized coefficients also suggest relatively moderate individual contributions to the MANOVA effect from all bias scores. The correlations between the bias scores and the canonically derived scores for all methods are positive and with weak to moderate correlations (range = 0.244 to 0.744).

	Function 1		
	Raw	Stand.	Struc.
Kunos et al.	0.063	0.753	0.585
DiGangi et al.	-0.020	-0.277	0.386
İşcan et al.	0.036	0.496	0.587
Passalacqua	-0.027	-0.375	0.244
Lovejoy et al.	-0.057	-0.543	0.403
Buckberry & Chamberlain	0.054	0.650	0.744
Rougé-Maillart et al.	0.035	0.397	0.680
Suchey-Brooks	-0.019	-0.182	0.375

Table 80: Discriminant function coefficients associated with the MANOVA for individuals of European ancestry. Note: Raw = unstandardized coefficients, Stand. = standardized coefficients, Struc. = structure coefficients.

To estimate the group centroids for the four stature groups, the sample bias scores were multiplied by the corresponding bias unstandardized discriminant function coefficients and then averaged across the samples. The means and standard deviations are listed in Table 81. An ANOVA with four levels in the IV was performed on the canonically derived bias score DV, and is not statistically significant [$F(3, 1.904) = 2.012, p = 0.111$].

	n	Mean	S.D.
1.20-1.60m	120	0.545	0.819
1.61-1.72m	152	0.659	1.011
1.73-1.80m	147	0.637	0.954
1.81-1.93m	78	0.887	1.138

Table 81: Means and Standard Deviations for individuals of European ancestry canonically derived variables.

The Cohen's d absolute values were as follows, from highest to lowest: Group 1 vs. Group 4 = 0.352; Group 3 vs. Group 4 = 0.248; Group 2 vs. Group 4 = 0.222; Group 1 vs. Group 2 = 0.118; Group 1 vs. Group 3 = 0.097; and Group 2 vs. Group 3 = 0.023. The differences between Groups 1 and 4, Groups 3 and 4, Groups 2 and 4, and Groups 1 and 2 are suggestive of a small effect size. There is no discernible difference between Groups 1 and 3 and Groups 2 and 3.

Table 82 shows the results from Tukey's *b* post-hoc tests for unequal sample sizes. There are no significant differences among the stature group bias scores for individuals of European ancestry using the Passalacqua method. The Kunos et al. and İscan et al. methods significantly under-age individuals of European ancestry in Group 1 compared to those in Groups 2, 3, and 4. The DiGangi et al. method under-ages individuals of European ancestry in Group 1 compared to those in Group 4. The Lovejoy et al. method under-ages individuals of European ancestry in Groups 1 and 2 compared to those in Groups 3 and 4. The Buckberry and Chamberlain and Rougé-Maillart et al. methods significantly under-age individuals of European ancestry in Groups 1 compared to those in Groups 2 and 4, and individuals of European ancestry in Group 4 are over-aged compared to all other groups. The Suchey-Brooks method significantly over-ages individuals of European ancestry in Group 1 compared to those in Groups 1, 2, and 3.

Method	Stature	n	Subset (yrs)		
			1	2	3
Kunos et al.	Group 1	120	-1.93		
	Group 2	152		2.67	
	Group 3	147		3.05	
	Group 4	78		5.92	
DiGangi et al.	Group 1	120	-17.20		
	Group 2	152	-14.30	-14.30	
	Group 3	147	-13.41	-13.41	
	Group 4	78		-10.86	
İşcan et al.	Group 1	120	-5.63		
	Group 2	152		-0.09	
	Group 3	147		0.97	
	Group 4	78		3.47	
Passalacqua	Group 1	120	-3.44		
	Group 3	147	-2.57		
	Group 2	152	-2.32		
	Group 4	78	1.04		
Lovejoy et al.	Group 1	120	-8.24		
	Group 2	152	-6.93		
	Group 3	147	-5.97	-5.97	
	Group 4	78		-3.17	
Buckberry and Chamberlain	Group 1	120	1.38		
	Group 3	147	4.47	4.47	
	Group 2	152		6.32	
	Group 4	78			11.88
Rougé-Maillart et al.	Group 1	120	-9.61		
	Group 3	147	-7.18	-7.18	
	Group 2	152		-5.16	
	Group 4	78			-0.47
Suchey-Brooks	Group 1	120	-8.54		
	Group 2	152	-7.35		
	Group 3	147	-7.23		
	Group 4	78		-3.68	

Table 82: Tukey's *b* post-hoc test results for European bias scores separated by stature.
Note: alpha level = 0.05

A DFA was applied to assess how well stature group could be predicted from the bias scores of the eight age estimation methods. The cross-validated classification shows that only 39.6% of individuals of European ancestry are correctly classified into their stature group based on bias scores. individuals of European ancestry in Group 1 are classified correctly at a rate of 41.7%, Group 2 at a rate of 48.7%, Group 3 at a rate of 45.6%, and Group 4 a rate of 11.5%.

The discriminant scores from Function 1 and Function 2 were used to plot the sample on the discriminant dimensions. Group 4 is associated with the largest group centroid (0.525), Group 2 is associated with the next largest group centroid (0.172), Group 3 is associated with the second

smallest centroid (-0.006) and, finally, Group 1 is associated with the smallest group centroid (-0.552) (see Figure 39).

Figure 39: Canonically derived centroids for the stature groups for individuals of European ancestry.

African Ancestry

As shown in Table 64 of Section 3.3.2.2, the pattern of correlations observed among the bias scores are generally strong for a MANOVA. The Box's M value of 117.455 is associated with a p -value of 0.459, which is not significant; therefore, the covariance between the stature groups were assumed to be equal for the purposes of the MANOVA.

A MANOVA was conducted to test the hypothesis that there would be differences between the stature group bias scores for each method. The MANOVA was not statistically significant, Pillai's Trace = 0.071, $F(24, 582) = 0.587$, $p = 0.942$. The multivariate effect size is estimated at 0.024, which implies that 2.4% of the variance in the canonically derived DV is accounted for by

the stature groups. As none of the functions were significant, there is no relationship between the stature groups and bias scores for individuals of African ancestry.

A DFA was applied to assess how well stature could be predicted from the bias scores of the eight age estimation methods. The cross-validated classification shows that only 31.5% of individuals of African ancestry are correctly classified into their stature group based on bias scores. individuals of African ancestry in Group 1 are classified correctly at a rate of 26.8%, Group 2 at a rate of 22.6%, Group 3 at a rate of 55.7%, and Group 4 at a rate of 14.6%.

3.4.3 Results Summary

3.4.3.1 Accuracy

For males and individuals of European ancestry, there are weak, statistically significant differences among the stature groups for accuracy scores. The MANOVA effect size is low at 2.4% and 3.6%, respectively. For females and individuals of African ancestry, there are no statistically significant differences among the stature group accuracy scores. There are too few females in the tallest stature group to evaluate ($n = 2$).

Using the standardized coefficients from the MANOVA:

- Males have the highest contribution to the model from the DiGangi et al., Buckberry and Chamberlain, and Rougé-Maillart et al. methods, which have the most variance in their stature group accuracy scores. The Kunos et al. and Passalacqua methods have moderate contributions to the model, indicating that there are differences among the stature group accuracy scores, but they are not as substantial as those from the DiGangi et al., Buckberry and Chamberlain, and Rougé-Maillart et al. methods. The İşcan et al., Lovejoy et al., and Suchey-Brooks have little contribution to the model, and have the least amount of variance in their stature group accuracy scores (see Table 71).
- Individuals of European ancestry have the highest contribution to the model from the Buckberry and Chamberlain and Rougé-Maillart et al. methods, which have the greatest variance in the stature group accuracy scores. All other methods have moderate contributions to the model, indicating that there are differences among the stature group

accuracy scores, but they are not as substantial as those from the Buckberry and Chamberlain and Rougé-Maillart et al. methods (see Table 53).

The differences in group centroid values generated from the MANOVA for the male and European accuracy scores are significant. Males and individuals of European ancestry in the short stature groups have significantly lower accuracy scores compared to males and individuals of European ancestry all other stature groups. Males in the second tallest group have significantly lower accuracy scores compared to males in the tallest stature group. Individuals of European ancestry in the second tallest stature group have significantly lower accuracy scores compared to males in the tallest stature group. The Cohen's d values indicate the a large effect size between the shortest and tallest males and shortest and tallest Europeans , and a medium effect size between males in the shortest and second shortest groups. All other relationships have medium effect sizes. These results are corroborated by the discriminant function canonical analyses results: short males and short individuals of European ancestry have lower accuracy scores than tall males and tall individuals of European ancestry, while males and individuals of European ancestry in Groups 2 and 3 cluster between the two (see Figure 36 and Figure 38).

Table 83 shows the inaccuracy scores for males, females, individuals of European ancestry, and individuals of African ancestry separated by stature. There are no significant differences among the stature group accuracy scores for the Kunos et al. and Passalacqua methods. The DiGangi et al. and İscan et al. methods accuracy scores for short individuals of European ancestry are significantly lower than tall individuals of European ancestry. The Lovejoy et al. and Suchey-Brooks methods accuracy scores are lower for males in the shortest stature group compared to males in the tallest stature group. The Buckberry and Chamberlain and Rougé-Maillart et al. methods accuracy scores are lower for males and individuals of European ancestry in the tallest stature group compared to males and individuals of European ancestry in the shortest stature group. For females and individuals of African ancestry, there are no significant differences among the stature group accuracy scores. For all individuals, the DiGangi et al. method performs poorly (see Figure 40, Figure 41, Figure 42, and Figure 43).

Stature (m)		Kunos et al.	DiGangi et al.	İşcan et al.	Passal- acqua	Lovejoy et al.	Buckberry & Chamberlain	Rougé-Maillart et al.	Suchey- Brooks
Males	1.20-1.60	10.20	15.69	11.44	10.65	10.31	9.44	12.09	11.18
	1.61-1.72	10.50	14.95	10.83	12.12	8.98	12.30	9.93	9.84
	1.73-1.80	10.13	14.73	10.56	11.17	8.77	11.46	11.21	9.22
	1.81-1.94	10.10	13.70	10.34	10.47	7.36	12.94	8.71	7.82
Females	1.20-1.60	10.41	19.26	13.39	12.95	9.42	9.51	10.56	9.75
	1.61-1.72	11.28	16.01	11.08	11.89	8.00	11.89	9.12	8.77
	1.73-1.80	9.47	12.35	10.12	8.65	5.65	9.94	5.76	5.00
European	1.20-1.60	10.02	18.83	13.31	11.93	10.11	8.85	12.29	10.51
	1.61-1.72	10.86	16.73	10.74	11.52	9.17	11.30	9.57	9.86
	1.73-1.80	9.29	15.27	10.17	11.22	8.88	10.78	11.40	9.56
	1.81-1.94	10.28	13.76	10.40	10.63	7.88	13.35	8.81	8.04
African	1.20-1.60	9.44	12.80	11.10	11.59	6.56	11.34	7.54	8.12
	1.61-1.72	11.62	10.87	10.72	14.13	6.70	14.60	9.87	8.23
	1.73-1.80	11.97	12.79	10.69	10.34	7.64	12.67	9.23	7.23
	1.81-1.94	9.85	13.38	10.75	9.90	6.38	12.25	8.33	7.54

Table 83: Inaccuracy scores (in years) for each age-at-death estimation method separated by stature for males, females, individuals of European ancestry, and individuals of African ancestry. Significant differences are noted by boxes.

Discriminant function analyses show that accuracy scores are poor predictors of stature. Males in the shortest stature group and females in the tallest stature groups are never classified correctly. Tall individuals of European ancestry (2.6%) and short individuals of African ancestry (4.9%) have the lowest classification scores. Males in the second tallest stature group (79.6%), females in the shortest stature group (78.3%), individuals of European ancestry in the second shortest stature group (59.2%), and individuals of African ancestry in the second tallest stature group (49.1%) have the highest classification scores. These results indicate that accuracy scores cannot be used reliably to predict stature groups, except for males in the second tallest stature group and females in the shortest stature group.

Figure 40: Mean inaccuracy scores for the age estimation methods categorized by stature for males.

Figure 41: Mean inaccuracy scores for the age estimation methods categorized by stature for females.

Figure 42: Mean inaccuracy scores for the age estimation methods categorized by stature for individuals of European ancestry.

Figure 43: Mean inaccuracy scores for the age estimation methods categorized by stature for individuals of African ancestry.

3.4.3.2 Bias

For males and individuals of European ancestry, there are statistically significant differences among the stature groups for bias scores. The MANOVA effect sizes are weak at 3.9% and 5.5%, respectively. For females and individuals of European ancestry there are no statistically significant differences among the stature groups for bias scores.

Using the standardized coefficients from the MANOVA:

- Males have the highest contribution to the model from the DiGangi et al. and Rougé-Maillart et al. methods, which have the greatest amount of variance in their stature group bias scores. All other methods have moderate contributions to the model, indicating that there are differences among the stature group bias scores, but they are not as substantial as those from the DiGangi et al. and Rougé-Maillart et al. methods (see Table 74).
- Individuals of European ancestry have the highest contribution to the model from the İşcan et al., Buckberry and Chamberlain, and Kunos et al. methods, which have the greatest amount of variance in their stature group bias scores. All other methods have moderate contributions to the model, indicating that there are differences among the stature group bias scores, but they are not as substantial as those from the İşcan et al., Buckberry and Chamberlain, and Kunos et al. methods (see Table 54).

The differences in group centroid values generated from the MANOVA for the male bias scores are significant, but not for individuals of European ancestry. Short males are under-aged significantly compared to males in all other stature groups. The Cohen's *d* values indicate these are large effect sizes between the shortest and tallest groups for males, and medium effect sizes for all other relationships. These results are corroborated by the discriminant function canonical analyses results: males and individuals of European ancestry in the short stature group are under-aged more than males and individuals of European ancestry in the other stature categories, with the greatest difference between short and tall individuals (see Figure 37 and Figure 39).

Table 84 shows the bias scores for males, females, individuals of European ancestry, and individuals of African ancestry separated by stature. For the Kunos et al., İşcan et al., Lovejoy et al., Buckberry and Chamberlain, Rougé-Maillart et al. and Suchey-Brooks methods, males and

individuals of European ancestry in the shortest stature group are under-aged significantly compared to males and individuals of European ancestry in the tallest stature group. For the DiGangi et al. and Passalacqua methods, individuals of European ancestry in the shortest stature group are under-aged significantly compared to individuals of European ancestry in the tallest stature group. For all individuals, the DiGangi et al. method performs poorly (see Figure 44, Figure 45, Figure 46, and Figure 47).

Stature (m)		Kunos et al.	DiGangi et al.	İşcan et al.	Passalacqua	Lovejoy et al.	Buckberry & Chamberlain	Rougé-Maillart et al.	Suchey-Brooks
Males	1.20-1.60	0.49	-12.24	-3.65	-2.95	-7.62	3.40	-8.67	-9.18
	1.61-1.72	3.59	-12.36	2.30	-1.98	-5.58	7.57	-6.04	-7.07
	1.73-1.80	3.68	-12.54	0.70	-1.13	-5.18	5.27	-3.96	-6.69
	1.81-1.94	5.82	-10.43	2.03	1.40	-2.94	10.84	-0.37	-3.66
Females	1.20-1.60	-0.42	-16.60	-4.61	-2.04	-6.52	2.98	-6.59	-7.27
	1.61-1.72	4.47	-12.93	-4.27	1.01	-4.82	6.65	-3.56	-4.38
	1.73-1.80	4.41	-12.35	-3.41	0.18	-2.12	7.82	-2.00	-1.12
European	1.20-1.60	-1.93	-17.20	-5.63	-3.44	-8.24	1.38	-9.61	-8.54
	1.61-1.72	2.67	-14.30	-0.09	-2.32	-6.93	6.32	-7.18	-7.35
	1.73-1.80	3.05	-13.41	0.97	-2.57	-5.97	4.47	-5.16	-7.23
	1.81-1.94	5.92	-10.86	3.47	1.04	-3.17	11.88	-0.47	-3.68
African	1.20-1.60	5.24	-9.00	-0.37	0.85	-2.95	8.22	-0.56	-6.12
	1.61-1.72	7.85	-7.58	0.11	3.11	-0.66	9.89	0.02	-2.57
	1.73-1.80	5.41	-10.39	-1.11	2.70	-2.43	7.92	-2.15	-3.82
	1.81-1.94	5.90	-9.58	-0.75	1.98	-2.50	9.21	-0.04	-3.83

Table 84: Bias scores (in years) for each age-at-death estimation method separated by stature for males, females, individuals of European ancestry, and individuals of African ancestry. Significant differences are noted by boxes.

Discriminant function analyses show that bias scores are poor predictors of stature. Short males (3.6%), tall females (0%), tall individuals of European ancestry (11.5%), and tall individuals of African ancestry (14.6%) have the lowest classification scores. Males in the second tallest group (76.4%), females in the shortest stature group (84.0%), individuals of European ancestry in the second shortest stature group (48.7%), and individuals of African ancestry in the second tallest stature group (55.7%) have the highest classification scores. These results indicate that bias cannot be used reliably to predict stature groups, except for short females.

Figure 44: Mean bias scores for the age estimation methods categorized by stature for males.

Figure 45: Mean bias scores for the age estimation methods categorized by stature for females.

Figure 46: Mean bias scores for the age estimation methods categorized by stature for individuals of European ancestry.

Figure 47: Mean bias scores for the age estimation methods categorized by stature for individuals of African ancestry.

3.5 Research Question III: Does body mass influence skeletal age estimation?

Figure 48 shows the sample distribution for body mass. The average body mass for this sample of 764 individuals is 65.66kg (range 24.04kg to 99.79kg), 68.89kg for males (range 32.21kg to 99.97kg), 57.88kg for females (range 24.04kg to 99.79kg), 66.66kg for individuals of European ancestry (range 26.31kg to 99.79kg), and 63.10kg for individuals of African ancestry (range 24.04kg to 99.79kg). A cluster analysis was used to assign individuals into equal, unbiased body mass groups, and the results are shown in Figure 48 and Table 85.

Figure 48: Body mass distribution of the sample by age at death. Lines demarcate cluster analysis cut-off points.

Group	n	Mass (kg)	S.D.
1	166	24.04-54.37	6.484
2	240	54.38-66.10	3.560
3	202	66.11-80.20	3.840
4	156	80.21-99.79	5.802

Table 85: Body mass descriptive statistics.

This section will test the influence of body mass on age at death estimations. The sample will be separated by sex and ancestry, and differences between accuracy and bias scores between body mass groups will be evaluated for each method using MANOVA and DFA.

3.5.1 Sex

3.5.1.1 Accuracy

Males

As shown in Table 36 of Section 3.3.1.1, the pattern of correlations observed among the accuracy scores are generally lower than ideal for a MANOVA. The Box's M value of 215.234 is associated with a p -value of < 0.001 , which is significant. A covariance matrix (Appendix 21) was run to ensure that no covariance values were more than four times greater than each other. Although there are instances where the covariance values are greater than four times their value, typically associated with the DiGangi et al. and Buckberry and Chamberlain methods, overall the covariance matrices between the body mass groups were assumed to be equal for the purposes of the MANOVA.

A MANOVA was conducted to test the hypothesis that there would be differences between body mass group accuracy scores for each method. The MANOVA was statistically significant with Pillai's Trace = 0.123, $F(27, 1479) = 2.641$, $p < 0.001$, indicating there are differences among the body mass group accuracy scores. The multivariate effect size is estimated at 0.041, which implies that 4.1% of the variance in the canonically derived DV is accounted for by the body mass groups.

As the IV was associated with four levels, three eigenvalues and canonical correlations were extracted by the MANOVA. The first eigenvalue is 0.092 and accounts for 70.0% of the model variance. The canonical correlation associated with the first eigenvalue is 0.291, where 8.5% of the variance in the discriminant function derived scores is accounted for by body mass. The second eigenvalue is 0.030 and accounts for 22.3% of the model variance with a corresponding canonical correlation of 0.169. The third eigenvalue is 0.010 and accounts for 7.7% of the model variance and a corresponding canonical correlation of 0.100, which is not statistically significant [Wilks $\Lambda = 0.990$, $F(6, 493) = 0.832$, $p = 0.546$].

The standardized discriminant function coefficients from the first eigenvalue were used to determine the statistical significance of the MANOVA, as it is the strongest. As seen in Table 86, the standardized discriminant function coefficients suggest that the four body mass groups were maximally differentiated by a canonical variate with significant weightings from the Rougé-Maillart et al. (0.486) and Suchey-Brooks (0.360) methods accuracy scores. The standardized coefficients suggest relatively moderate individual contributions to the MANOVA effect from all other accuracy scores. The correlations between the accuracy scores and the canonically derived scores for all methods are positive and moderate (range = 0.310 to 0.692), except for the Buckberry and Chamberlain method, which has a weak negative correlation (-0.158).

	Function 1		
	Raw	Stand.	Struc.
Kunos et al.	0.046	0.323	0.321
DiGangi et al.	0.021	0.217	0.692
İşcan et al.	0.040	0.324	0.535
Passalacqua	0.014	0.116	0.310
Lovejoy et al.	-0.039	-0.260	0.389
Buckberry & Chamberlain	-0.027	-0.234	-0.158
Rougé-Maillart et al.	0.064	0.486	0.688
Suchey-Brooks	0.055	0.390	0.686

Table 86: Discriminant function coefficients associated with the MANOVA for males. Note: Raw = unstandardized coefficients, Stand. = standardized coefficients, Struc. = structure coefficients.

To estimate the group centroids for the body mass groups, the sample inaccuracy scores were multiplied by the corresponding inaccuracy unstandardized discriminant function coefficients and then averaged across the samples. The means and standard deviations are listed in Table 87. An ANOVA with four levels in the IV was performed on the canonically derived accuracy score DV, and is significant [$F(3, 15.383) = 15.342, p < 0.001$].

	n	Mean	S.D.
24.04-54.37kg	75	2.222	1.356
54.38-66.10kg	151	2.205	1.100
66.11-80.20kg	156	1.601	0.771
80.21-99.79kg	120	1.601	0.868

Table 87: Means and Standard Deviations for the male canonically derived variables.

The Cohen's d absolute values were as follows, from highest to lowest: Group 1 vs. Group 3 = 0.634; Group 2 vs. Group 3 = 0.625; Group 1 vs. Group 4 = 0.605; Group 2 vs. Group 4 = 0.605; Group 1 vs. Group 2 = 0.016; and Group 3 vs. Group 4 = 0.000. The differences between males

in Groups 1 and 3, Groups 2 and 3, Groups 1 and 4, and Groups 2 and 4 are suggestive of a medium effect size. There is no discernible difference between males in Groups 1 and 2, and Groups 3 and 4.

Table 88 shows the results from Tukey's *b* post-hoc tests for unequal sample sizes. There are no significant differences among the body mass group accuracy scores for males using the Kunos et al., Lovejoy et al., and Buckberry and Chamberlain methods. The DiGangi et al. method inaccuracy scores for males in Group 2 are lower compared to males in Groups 3 and 4, while the inaccuracy scores for males in Group 1 are lower compared to males in Group 4. The Rougé-Maillart et al. method inaccuracy scores for males in Groups 1 and 2 are significantly higher compared to males in Groups 3 and 4. The İşcan et al. inaccuracy scores for males in Group 1 are significantly higher than those in Groups 3 and 4. The Passalacqua inaccuracy scores for males in Group 1 are significantly higher compared to those in Group 4. The Suchey-Brooks inaccuracy scores for males in Group 1 are significantly higher than those in Groups 3 and 4, and the inaccuracy scores for males in Group 2 are significantly higher than males in Group 3.

A DFA was applied to assess how well body mass could be predicted from the accuracy scores of the eight age estimation methods. The cross-validated classification shows that only 40.2% of males are correctly classified into their body mass group based on accuracy scores. Males in Group 1 are classified correctly at a rate of 5.3%, Group 2 at a rate of 50.3%, Group 3 at a rate of 60.9%, and Group 4 at a rate of 22.5%.

The discriminant scores from Function 1 and Function 2 were used to plot the sample on the discriminant dimensions. Group 1 is associated with the largest group centroid (0.347), Group 2 is associated with the next largest group centroid (0.329), Group 3 is associated with the second smallest centroid (-0.273) and, finally, Group 4 is associated with the smallest group centroid (-0.275) (see Figure 49).

Method	Body Mass	n	Subset (yrs)		
			1	2	3
Kunos et al.	Group 4	120	9.03		
	Group 3	156	10.07		
	Group 2	151	10.85		
	Group 1	75	11.23		
DiGangi et al.	Group 4	120	11.71		
	Group 3	156	13.47		
	Group 1	75		16.72	
	Group 2	151		17.14	
İşcan et al.	Group 3	156	9.04		
	Group 4	120	10.02		
	Group 2	151	11.57	11.57	
	Group 1	75		13.13	
Passalacqua	Group 4	120	10.04		
	Group 3	156	10.87	10.87	
	Group 2	151	11.64	11.64	
	Group 1	75		12.80	
Lovejoy et al.	Group 4	120	7.75		
	Group 3	156	8.07		
	Group 2	151	9.48		
	Group 1	75	9.59		
Buckberry and Chamberlain	Group 1	75	11.31		
	Group 2	151	11.39		
	Group 4	120	11.54		
	Group 3	156	12.71		
Rougé-Maillart et al.	Group 4	120	8.39		
	Group 3	156	9.31		
	Group 1	75		11.95	
	Group 2	151		12.20	
Suchey-Brooks	Group 3	156	7.33		
	Group 4	120	8.65	8.65	
	Group 2	151		10.27	10.27
	Group 1	75			11.21

Table 88: Tukey's *b* post-hoc test results for male accuracy scores separated by body mass.
Note: alpha level = 0.05

Figure 49: Canonically derived centroids for the body mass groups for males.

Females

As shown in Table 40 of Section 3.3.1.1, the pattern of correlations observed among the accuracy scores are generally lower than ideal for a MANOVA. The Box's M value of 197.613 is associated with a p -value < 0.001 , which is significant. A covariance matrix (Appendix 22) was run to ensure that no covariance values were more than four times greater than each other. Although there are instances where the covariance values are greater than four times their value, typically associated with the DiGangi et al. and Buckberry and Chamberlain methods, overall the covariance matrices between the body mass groups were assumed to be equal for the purposes of the MANOVA.

A MANOVA was conducted to test the hypothesis that there would be differences between body mass group accuracy scores for each method. The MANOVA effect was not statistically

significant with Pillai's Trace = 0.138, $F(24, 567) = 1.136$, $p = 0.298$. The multivariate effect size is estimated at 0.046, which implies that 4.6% of the variance in the canonically derived DV is accounted for by the body mass groups. As none of the functions were significant, there is no relationship between the body mass groups and accuracy scores for females.

A DFA was applied to assess how well body mass could be predicted from the accuracy scores of the eight age estimation methods. The cross-validated classification shows that only 46.5% of females are correctly classified into their body mass group based on accuracy scores. Females in Group 1 are classified correctly at a rate of 34.9%, Group 2 at a rate of 81.0%, and females in Groups 3 and 4 were never classified in the correct body mass group.

3.5.1.2 Bias

Males

As shown in Table 44 of Section 3.3.1.2, the pattern of correlations observed among the bias scores are generally strong for a MANOVA, and the Box's M value of 191.561 is associated with a p -value of < 0.001 , which is significant. A covariance matrix (Appendix 23) was run to ensure that no covariance values were more than four times greater than each other. Although there are instances where the covariance values are greater than four times their value, typically associated with the DiGangi et al. method, overall the covariance matrices between the body mass groups were assumed to be equal for the purposes of the MANOVA.

A MANOVA was conducted to test the hypothesis that there would be differences between body mass group bias scores for each method. The MANOVA was statistically significant with Pillai's Trace = 0.141, $F(24, 1479) = 3.038$, $p < 0.001$, indicating there are differences among the body mass group accuracy scores. The multivariate effect size is estimated at 0.047, which implies that 4.7% of the variance in the canonically derived DV is accounted for by the body mass groups.

As the IV was associated with four levels, three eigenvalues and canonical correlations were extracted by the MANOVA. The first eigenvalue is 0.089 and accounts for 58.9% of the model variance. The canonical correlation associated with the first eigenvalue is 0.286, where 8.2% of the variance in the discriminant function derived scores is accounted for by body mass. The second eigenvalue is 0.058 and accounts for 38.0% of the model variance with a corresponding

canonical correlation of 0.233. The third eigenvalue is 0.005 and accounts for 3.1% of the model variance and a corresponding canonical correlation of 0.068, which is not statistically significant [Wilks $\Lambda = 0.995$, $F(6, 493) = 0.385$, $p = 0.889$].

The standardized discriminant function coefficients from the first eigenvalue were used to determine the statistical significance of the MANOVA, as it is the strongest. As seen in Table 89, the standardized discriminant function coefficients suggest that the body mass groups are maximally differentiated by a canonical variate with significant weightings from the İşcan et al. (0.850) and Kunos et al. (0.702) methods bias scores. The standardized coefficients suggest moderate individual contributions to the MANOVA effect from all bias scores, except the Rougé-Maillart et al. method, which has little contribution to the model (-0.007). The correlations between the bias scores and the canonically derived scores for all methods are positive and with weak to strong scores (range = 0.220 to 0.888).

	Function 1		
	Raw	Stand.	Struc.
Kunos et al.	0.060	0.702	0.456
DiGangi et al.	-0.022	-0.294	0.220
İşcan et al.	0.065	0.850	0.888
Passalacqua	0.016	0.212	0.432
Lovejoy et al.	-0.021	-0.204	0.357
Buckberry & Chamberlain	0.010	0.127	0.391
Rougé-Maillart et al.	-0.001	-0.007	0.381
Suchey-Brooks	-0.030	-0.294	0.257

Table 89: Discriminant function coefficients associated with the MANOVA for males. Note: Raw = unstandardized coefficients, Stand. = standardized coefficients, Struc. = structure coefficients.

To estimate the group centroids for the body mass groups, the sample bias scores were multiplied by the corresponding bias unstandardized discriminant function coefficients and then averaged across the samples. The means and standard deviations are listed in Table 90. An ANOVA with four levels in the IV was performed on the canonically derived bias score DV, and is statistically significant [$F(3, 14.706) = 14.813$, $p < 0.001$].

	n	Mean	S.D.
24.04-54.37kg	75	0.237	1.299
54.38-66.10kg	151	0.943	1.032
66.11-80.20kg	156	1.157	0.811
80.21-99.79kg	120	0.970	0.952

Table 90: Means and Standard Deviations for the male canonically derived variables.

The Cohen's d absolute values were as follows, from highest to lowest: Group 1 vs. Group 3 = 0.935; Group 1 vs. Group 4 = 0.704; Group 1 vs. Group 2 = 0.667; Group 3 vs. Group 4 = 0.200; and Group 2 vs. Group 3 = 0.223; and Group 2 vs. Group 4 = 0.027. The differences between males in Groups 1 and 3, and Groups 1 and 4 are suggestive of a large effect size; differences between males in Groups 1 and 2 are suggestive of a medium effect size; the differences between males in Groups 3 and 4, and Groups 2 and 3 are suggestive of a small effect size. There is no discernible difference between males in Groups 2 and 4.

Table 91 shows the results from Tukey's b post-hoc tests for unequal sample sizes. There are no differences among the body mass group bias scores using the DiGangi et al. method. Using the Kunos et al. method, males in Groups 1 and 2 are significantly under-aged compared to males in Groups 3 and 4. The İşcan et al. method under-ages males in Group 1 compared to males in Groups 2, 3, and 4. The Passalacqua, Rougé-Maillart et al. and Buckberry and Chamberlain methods show that males in Group 1 are under-aged significantly compared to males in Group 3 and 4. The Lovejoy et al. method under-ages males in Group 1 compared to Group 3. The Suchey-Brooks method under-ages males in Group 2 compared to males in Groups 3 and 4 and males in Group 1 are under-aged significantly under-aged compared to Group 4.

A DFA was applied to assess how well body mass could be predicted from the bias scores of the eight age estimation methods. The cross-validated classification shows that only 38.8% of males are correctly classified into their body mass group based on bias scores. Males in Group 1 are classified correctly at a rate of 26.7%, Group 2 at a rate of 51.7%, Group 3 at a rate of 49.4%, and Group 4 at a rate of 16.7%.

The discriminant scores from Function 1 and Function 2 were used to plot the sample on the discriminant dimensions. Group 3 is associated with the largest group centroid (0.248), Group 4 is associated with the next largest group centroid (0.059), Group 2 is associated with the second smallest centroid (0.033) and, finally, Group 1 is associated with the smallest group centroid (-0.676) (see Figure 50).

Method	Body Mass	n	Subset (yrs)		
			1	2	3
Kunos et al.	Group 1	75	0.93		
	Group 2	151	1.74		
	Group 4	120		5.34	
	Group 3	156		6.11	
DiGangi et al.	Group 2	151	-14.54		
	Group 1	75	-13.12		
	Group 4	120	-10.34		
	Group 3	156	-10.08		
İşcan et al.	Group 1	75	-6.97		
	Group 2	151		1.57	
	Group 4	120		1.75	
	Group 3	156		3.62	
Passalacqua	Group 1	75	-4.35		
	Group 2	151	-3.02	-3.02	
	Group 4	120		0.94	
	Group 3	156		1.30	
Lovejoy et al.	Group 1	75	-7.03		
	Group 2	151	-6.08	-6.08	
	Group 4	120	-4.03	-4.03	
	Group 3	156		-3.72	
Buckberry and Chamberlain	Group 1	75	3.95		
	Group 2	151	5.28	5.28	
	Group 3	156		8.53	
	Group 4	120		9.28	
Rougé-Maillart et al.	Group 1	75	-7.15		
	Group 2	151	-5.96	-5.96	
	Group 3	156		-2.81	
	Group 4	120		-2.71	
Suchey-Brooks	Group 2	151	-9.28		
	Group 1	75	-7.36	-7.36	
	Group 3	156		-4.90	-4.90
	Group 4	120			-3.77

Table 91: Tukey's *b* post-hoc test results for male bias scores separated by body mass.
Note: alpha level = 0.05

Figure 50: Canonically derived centroids for the body mass groups for males.

Females

As shown in Table 48 of Section 3.3.1.2, the pattern of correlations observed among the bias scores are generally strong for a MANOVA, and the Box's M value of 156.828 is associated with a p -value of 0.031, which is not significant. The covariance between the body mass groups were assumed to be equal for the purposes of the MANOVA.

A MANOVA was conducted to test the hypothesis that there would be differences between body mass group bias scores for each method. The MANOVA effect was statistically significant with Pillai's Trace = 0.235, $F(24, 567) = 2.004$, $p = 0.003$, indicating there are differences among the body mass group bias scores. The multivariate effect size is estimated at 0.078, which implies that 7.8% of the variance in the canonically derived DV is accounted for by the body mass groups.

As the IV was associated with four levels, three eigenvalues and canonical correlations were extracted by the MANOVA. The first eigenvalue is 0.157 and accounts for 59.7% of the model variance. The canonical correlation associated with the first eigenvalue is 0.368, where 13.5% of the variance in the discriminant function derived scores is accounted for by body mass. The second eigenvalue is 0.079 and accounts for 30.0% of the model variance with a corresponding canonical correlation of 0.270. The third eigenvalue is 0.027 and accounts for 10.2% of the model variance and a corresponding canonical correlation of 0.162, which is not statistically significant [Wilks $\Lambda = 0.974$, $F(6, 189) = 0.846$, $p = 0.536$].

The standardized discriminant function coefficients from the first eigenvalues were used to determine the statistical significance of the MANOVA as it was the strongest. As seen in Table 92, the standardized discriminant function coefficients suggest that the body mass groups were maximally differentiated by a canonical variate with significant weightings from the DiGangi et al. (0.858), Kunos et al. (-0.770), and İşcan et al. (0.706) methods bias scores. The standardized coefficients suggest moderate to minimal individual contributions to the MANOVA effect from all other bias scores. The correlations between the bias scores and the canonically derived scores for all methods are positive with weak to strong correlations (range = 0.135 to 0.773).

	Function 1		
	Raw	Stand.	Struc.
Kunos et al.	-0.061	-0.770	0.248
DiGangi et al.	0.061	0.858	0.400
İşcan et al.	0.049	0.706	0.773
Passalacqua	-0.036	-0.538	0.135
Lovejoy et al.	0.032	0.286	0.510
Buckberry & Chamberlain	-0.006	-0.076	0.343
Rougé-Maillart et al.	0.031	0.347	0.536
Suchey-Brooks	0.021	0.198	0.349

Table 92: Discriminant function coefficients associated with the MANOVA for females.

Note: Raw = unstandardized coefficients, Stand. = standardized coefficients, Struc. = structure coefficients.

To estimate the group centroids for the body mass groups, the sample bias scores were multiplied by the corresponding bias unstandardized discriminant function coefficients and then averaged across the samples. The means and standard deviations for each body mass group are in Table 93. An ANOVA with four levels in the IV was performed on the canonically derived bias score DV, and is significant [$F(3, 10.270) = 10.127$, $p < 0.001$].

	n	Mean	S.D.
24.04-54.37kg	69	-2.195	1.097
54.38-66.10kg	84	-1.302	0.899
66.11-80.20kg	29	-1.583	0.893
80.21-99.79kg	16	-1.812	1.307

Table 93: Means and Standard Deviations for the female canonically derived variables.

The Cohen's *d* absolute values were as follows, from highest to lowest: Group 1 vs. Group 3 = 0.450; Group 1 vs. Group 4 = 0.337; Group 2 vs. Group 4 = 0.244; Group 3 vs. Group 4 = 0.213; and Group 2 vs. Group 3 = 0.098. The differences between individuals in Groups 1 and 3 and Groups 1 and 4 are suggestive of a medium effect size. The differences between individuals in Groups 2 and 4, and Groups 3 and 4 are suggestive of a small effect size. There is no discernible difference between individuals in Groups 2 and 3.

Table 94 shows the results from Tukey's *b* post-hoc tests for unequal sample sizes. There are no significant differences among the body mass group bias scores for females using any method except the İşcan et al. method. The İşcan et al. method under-ages females in Group 1 significantly compared to females in Group 2.

A DFA was applied to assess how well body mass could be predicted from the bias scores of the eight age estimation methods. The cross-validated classification shows that only 53.0% of females are correctly classified into their body mass group based on bias scores. Females in Group 1 are classified correctly at a rate of 60.9%, Group 2 at a rate of 72.6%, Group 3 at a rate of 6.9%, and no females in Group 4 are classified correctly.

The discriminant scores from Function 1 and Function 2 were used to plot the sample on the discriminant dimensions. Group 2 is associated with the largest group centroid (0.391), Group 3 is associated with the next largest group centroid (0.110), Group 4 is associated with the second smallest centroid (-0.116) and, finally, Group 1 is associated with the smallest group centroid (-0.496) (see Figure 51).

Method	Body Mass	n	Subset (yrs)		
			1	2	3
Kunos et al.	Group 1	69	-0.35		
	Group 2	84	2.21		
	Group 4	16	4.50		
	Group 3	29	5.79		
DiGangi et al.	Group 1	69	-18.33		
	Group 2	84	-13.37		
	Group 4	16	-12.17		
	Group 3	29	-11.69		
İşcan et al.	Group 1	69	-9.67		
	Group 4	16	-7.69	-7.69	
	Group 3	29	-3.59	-3.59	
	Group 2	84		0.21	
Passalacqua	Group 4	16	-2.38		
	Group 1	69	-1.43		
	Group 3	29	-0.86		
	Group 2	84	0.30		
Lovejoy et al.	Group 4	16	-8.44		
	Group 1	69	-7.55		
	Group 2	84	-3.77		
	Group 3	29	-3.72		
Buckberry and Chamberlain	Group 1	69	2.16		
	Group 2	84	5.68		
	Group 4	16	6.31		
	Group 3	29	8.03		
Rougé-Maillart et al.	Group 1	69	-8.28		
	Group 4	16	-4.44		
	Group 3	29	-3.34		
	Group 2	84	-2.94		
Suchey-Brooks	Group 1	69	-7.84		
	Group 2	84	-5.00		
	Group 4	16	-4.19		
	Group 3	29	-3.41		

Table 94: Tukey's *b* post-hoc test results for female bias scores separated by body mass.
Note: alpha level = 0.05

Figure 51: Canonically derived centroids for the body mass groups for females.

3.5.2 Ancestry

3.5.2.1 Accuracy

European Ancestry

As shown in Table 52 of Section 3.3.2.1, the pattern of correlations observed among the accuracy scores are generally lower than ideal for a MANOVA, and the Box's M value of 215.304 is associated with a p -value of < 0.001 , which is significant. A covariance matrix (Appendix 24) was run to ensure that no covariance values were more than four times greater than each other. Although there are instances where the covariance values are greater than four times their value, typically associated with the DiGangi et al., İşcan et al. and Buckberry and Chamberlain methods, overall the covariance matrices between the mass groups were assumed to be equal for the purposes of the MANOVA.

A MANOVA was conducted to test the hypothesis that there would be differences between body mass group accuracy scores for each method. The MANOVA was statistically significant with Pillai's Trace = 0.126, $F(24, 1464) = 2.675$, $p < 0.001$, indicating there are differences among the body mass group accuracy scores. The multivariate effect size is estimated at 0.042, which implies that 4.2% of the variance in the canonically derived DV is accounted for by the body mass groups.

As the IV was associated with four levels, three eigenvalues and canonical correlations were extracted by the MANOVA. The first eigenvalue is 0.097 and accounts for 71.2% of the model variance. The canonical correlation associated with the first eigenvalue is 0.297, where 8.8% of the variance in the discriminant function derived scores is accounted for by body mass. The second eigenvalue is 0.034 and accounts for 24.7% of the model variance with a corresponding canonical correlation of 0.180. The third eigenvalue is 0.006 and accounts for 4.1% of the model variance and a corresponding canonical correlation of 0.075 which is not statistically significant [Wilks $\Lambda = 0.994$, $F(6, 488) = 0.456$, $p = 0.841$].

The standardized discriminant function coefficients from the first eigenvalue were used to determine the statistical significance of the MANOVA. As seen in Table 95, the standardized discriminant function coefficients suggest that the body mass groups were maximally differentiated by a canonical variate with significant weightings from the Rougé-Maillart et al. (0.529) and DiGangi et al. (0.454) methods accuracy scores. The standardized coefficients suggest relatively minimal individual contributions to the MANOVA effect from all accuracy scores. The correlations between the accuracy scores and the canonically derived scores for all methods are positive with weak to strong correlations (range = 0.165 to 0.796), except for the Buckberry and Chamberlain method, which has a negative moderate correlation (-0.233).

	Function 1		
	Raw	Stand.	Struc.
Kunos et al.	0.049	0.348	0.371
DiGangi et al.	0.042	0.454	0.796
İşcan et al.	0.020	0.172	0.427
Passalacqua	-0.010	-0.080	0.165
Lovejoy et al.	-0.043	-0.303	0.374
Buckberry & Chamberlain	-0.032	-0.258	-0.233
Rougé-Maillart et al.	0.068	0.529	0.695
Suchey-Brooks	0.031	0.226	0.596

Table 95: Discriminant function coefficients associated with the MANOVA for individuals of European ancestry. Note: Raw = unstandardized coefficients, Stand. = standardized coefficients, Struc. = structure coefficients.

To estimate the group centroids for the body mass groups, the sample inaccuracy scores were multiplied by the corresponding inaccuracy unstandardized discriminant function coefficients and then averaged across the samples. The means and standard deviations are listed in Table 96. An ANOVA with four levels in the IV was performed on the canonically derived accuracy score DV, and is statistically significant [$F(3, 16.004) = 15.867, p < 0.001$].

	n	Mean	S.D.
24.04-54.37kg	100	1.982	1.299
54.38-66.10kg	150	1.798	1.075
66.11-80.20kg	139	1.335	0.814
80.21-99.79kg	108	1.190	0.791

Table 96: Means and Standard Deviations for individuals of European ancestry canonically derived variables.

The Cohen's d absolute values were as follows, from highest to lowest: Group 1 vs. Group 4 = 0.778; Group 1 vs. Group 3 = 0.642; Group 2 vs. Group 4 = 0.622; Group 2 vs. Group 3 = 0.474; Group 1 vs. Group 2 = 0.171; and Group 3 vs. Group 4 = 0.162. The differences between Group 1 and 4 are suggestive of a large effect size; the differences between Groups 1 and 3, Groups 2 and 4, and Groups 2 and 3 are suggestive of a medium effect size; and the differences between Groups 1 and 2, and Groups 3 and 4 are suggestive of a small effect size.

Table 97 shows the results from Tukey's b post-hoc tests for unequal sample sizes. There are no significant differences among the body mass group accuracy scores for individuals of European ancestry using the Passalacqua, Lovejoy et al., and Buckberry and Chamberlain methods. The Kunos et al. method Group 1 inaccuracy scores are significantly higher than the Group 4 scores. The DiGangi et al. method inaccuracy scores for Group 1 are significantly higher than Groups 3 and 4, and Group 1 have higher inaccuracy scores compared to Group 3. The İşcan et al. Group 1

inaccuracy scores are significantly higher than Group 3. The Rougé-Maillart et al. method Groups 1 and 2 inaccuracy scores are significantly higher compared to Groups 3 and 4. The Suchey-Brooks method Group 2 inaccuracy scores are significantly higher than Groups 3 and 4, and the inaccuracy scores from Group 1 are significantly higher than Group 3.

Method	Body Mass	n	Subset (yrs)		
			1	2	3
Kunos et al.	Group 4	108	8.82		
	Group 3	139	9.75	9.75	
	Group 2	150	10.61	10.61	
	Group 1	100		11.20	
DiGangi et al.	Group 4	108	12.23		
	Group 3	139	15.04	15.04	
	Group 2	150		18.21	18.21
	Group 1	100			19.78
İşcan et al.	Group 3	139	9.63		
	Group 4	108	10.37	10.37	
	Group 2	150	11.92	11.92	
	Group 1	100		12.88	
Passalacqua	Group 4	108	10.41		
	Group 3	139	11.46		
	Group 1	100	11.67		
	Group 2	150	11.85		
Lovejoy et al.	Group 3	139	8.25		
	Group 4	108	8.31		
	Group 2	150	9.79		
	Group 1	100	10.14		
Buckberry and Chamberlain	Group 1	100	9.66		
	Group 2	150	10.81		
	Group 4	108	11.26		
	Group 3	139	11.53		
Rougé-Maillart et al.	Group 4	108	8.55		
	Group 3	139	9.37		
	Group 2	150		11.93	
	Group 1	100		12.77	
Suchey-Brooks	Group 3	139	7.53		
	Group 4	108	8.95	8.95	
	Group 1	100		10.91	10.91
	Group 2	150			11.25

Table 97: Tukey's *b* post-hoc test results for European accuracy scores separated by body mass. Note: alpha level = 0.05

A DFA was applied to assess how well body mass could be predicted from the accuracy scores of the eight age estimation methods. The cross-validated classification shows that only 34.6% of individuals of European ancestry are correctly classified into their body mass group based on accuracy scores. individuals of European ancestry in Group 1 are classified correctly at a rate of 10.0%, Group 2 at a rate of 44.7%, Group 3 at a rate of 51.1%, and Group 4 at a rate of 22.2%.

The discriminant scores from Function 1 and Function 2 were used to plot the sample on the discriminant dimensions. Group 1 is associated with the largest group centroid (0.407), Group 2 is associated with the next largest group centroid (0.224), the Group 3 is associated with the second smallest centroid (-0.238) and, finally, Group 4 is associated with the smallest group centroid (-0.381) (see Figure 52).

Figure 52: Canonically derived centroids for the body mass groups for individuals of European ancestry.

African Ancestry

As shown in Table 56 of Section 3.3.2.1, the pattern of correlations observed among the accuracy scores are generally lower than ideal for a MANOVA, and the Box's M value of 190.046 is associated with a p -value of < 0.001 , which is significant. A covariance matrix (Appendix 25) was run to ensure that no covariance values were more than four times greater than each other. Although there are instances where the covariance values are greater than four

times their value, typically associated with the Kunos et al. and Buckberry and Chamberlain methods, overall the covariance matrices between the mass groups were assumed to be equal for the purposes of the MANOVA.

A MANOVA was conducted to test the hypothesis that there would be differences between body mass group accuracy scores for each method. The MANOVA was not statistically significant with Pillai's Trace = 0.172, $F(24, 582) = 1.475$, $p = 0.068$. The multivariate effect size is estimated at 0.057, which implies that 5.7% of the variance in the canonically derived dependent variable is accounted for by the body mass groups. As none of the functions are significant, there is no relationship between the body mass groups and accuracy scores for individuals of African ancestry.

A DFA was applied to assess how well body mass could be predicted from the accuracy scores of the eight age estimation methods. The cross-validated classification shows that only 47.3% of individuals of African ancestry are correctly classified into their body mass group based on accuracy scores. individuals of African ancestry in Group 1 are classified correctly at a rate of 27.3%, Group 2 at a rate of 87.1%, Group 3 at a rate of 21.7%. No individuals of African ancestry in Group 4 were classified correctly into their body mass group.

3.5.2.2 Bias

European Ancestry

As shown in Table 60 of Section 3.3.2.2, the pattern of correlations observed among the bias scores are generally strong for a MANOVA. The Box's M value of 168.123 is associated with a p -value of < 0.001 , which is significant. A covariance matrix (Appendix 26) was run to ensure that no covariance values were more than four times greater than each other. Although there are instances where the covariance values are greater than four times their value, typically associated with the İşcan et al. method, overall the covariance matrices between the body mass groups were assumed to be equal for the purposes of the MANOVA.

A MANOVA was conducted to test the hypothesis that there would be differences between body mass group bias scores for each method. The MANOVA was statistically significant with Pillai's Trace = 0.170, $F(24, 1464) = 3.662$, $p < 0.001$, indicating there are differences among the body

mass bias scores. The multivariate effect size is estimated at 0.057, which implies that 5.7% of the variance in the canonically derived DV is accounted for by the body mass groups.

As the IV was associated with four levels, three eigenvalues and canonical correlations were extracted by the MANOVA. The first eigenvalue is 0.116 and accounts for 62.5% of the model variance. The canonical correlation associated with the first eigenvalue is 0.322, where 10.4% of the variance in the discriminant function derived scores is accounted for by body mass. The second eigenvalue is 0.061 and accounts for 32.8% of the model variance with a corresponding canonical correlation of 0.240. The third eigenvalue is 0.009 and accounts for 4.7% of the model variance and a corresponding canonical correlation of 0.093, which is not statistically significant [Wilks $\Lambda = 0.991$, $F(6, 488) = 0.707$, $p = 0.644$].

The standardized discriminant function coefficients from the first eigenvalue were used to determine the statistical significance of the MANOVA, as it is the strongest. As seen in Table 98, the standardized discriminant function coefficients suggest that the body mass groups are maximally differentiated by a canonical variate with significant weighting from the İşcan et al. (0.715) and the Kunos et al. (0.545) methods bias scores. The standardized coefficients suggest relatively minimal to moderate individual contributions to the MANOVA effect from all other bias scores. The correlations between the bias scores and the canonically derived scores for all methods are positive and with moderate to strong correlations (range = 0.372 to 0.744).

	Function 1		
	Raw	Stand.	Struc.
Kunos et al.	0.046	0.545	0.692
DiGangi et al.	0.019	0.251	0.601
İşcan et al.	0.052	0.715	0.744
Passalacqua	-0.012	-0.170	0.372
Lovejoy et al.	-0.034	0.325	0.449
Buckberry & Chamberlain	0.027	0.324	0.603
Rougé-Maillart et al.	0.006	0.070	0.571
Suchey-Brooks	-0.021	-0.208	0.410

Table 98: Discriminant function coefficients associated with the MANOVA for individuals of European ancestry. Note: Raw = unstandardized coefficients, Stand. = standardized coefficients, Struc. = structure coefficients.

To estimate the group centroids for the body mass groups, the sample bias scores were multiplied by the corresponding bias unstandardized discriminant function coefficients and then averaged across the samples. The means and standard deviations are listed in Table 99. An ANOVA with

four levels in the IV was performed on the canonically derived bias score DV, and is statistically significant [$F(3, 19.456) = 19.047, p < 0.001$].

	n	Mean	S.D.
24.04-54.37kg	100	-0.352	1.248
54.38-66.10kg	150	0.336	1.007
66.11-80.20kg	139	0.588	0.904
80.21-99.79kg	108	0.494	0.895

Table 99: Means and Standard Deviations for individuals of European ancestry canonically derived variables.

The Cohen's d absolute values were as follows, from highest to lowest: Group 1 vs. Group 3 = 0.918; Group 1 vs. Group 4 = 0.820; Group 1 vs. Group 2 = 0.684; Group 2 vs. Group 3 = 0.258; Group 2 vs. Group 4 = 0.161; and Group 3 vs. Group 4 = 0.099. The differences between individuals of European ancestry in Groups 1 and 3, and Groups 1 and 4 are suggestive of a large effect size, the differences between individuals of European ancestry in Groups 1 and 2 are suggestive of a medium effect size, and the differences between individuals of European ancestry in Groups 2 and 3, Groups 2 and 4, and Groups 3 and 4 are suggestive of a small effect size.

Table 100 shows the results from Tukey's b post-hoc tests for unequal sample sizes. The Kunos et al., DiGangi et al., and Suchey-Brooks methods significantly under-age individuals of European ancestry in Groups 1 and 2 compared to individuals of European ancestry in Groups 3 and 4. The İşcan et al. method under-ages individuals of European ancestry in Group 1 compared to individuals of European ancestry in Groups 2, 3, and 4. The Passalacqua and Lovejoy et al. methods significantly under-age individuals of European ancestry in Group 1 compared to individuals of European ancestry in Groups 3 and 4. The Buckberry and Chamberlain and Rougé-Maillart et al. methods significantly under-age individuals of European ancestry in Group 1 compared to individuals of European ancestry in Groups 3 and 4, and individuals of European ancestry in Group 2 are significantly under-aged compared to individuals of European ancestry in Group 4.

Method	Body Mass	n	Subset (yrs)		
			1	2	3
Kunos et al.	Group 1	100	-2.50		
	Group 2	150	0.52		
	Group 4	108		4.99	
	Group 3	139		5.16	
DiGangi et al.	Group 1	100	-19.70		
	Group 2	150	-16.47		
	Group 3	139		-11.45	
	Group 4	108		-10.40	
İşcan et al.	Group 1	100	-7.62		
	Group 4	108		-0.37	
	Group 2	150		1.36	
	Group 3	139		2.32	
Passalacqua	Group 1	100	-4.99		
	Group 2	150	-3.53	-3.53	
	Group 3	139		-0.37	
	Group 4	108		0.15	
Lovejoy et al.	Group 1	100	-8.86		
	Group 2	150	-7.07	-7.07	
	Group 4	108		-5.15	
	Group 3	139		-4.78	
Buckberry and Chamberlain	Group 1	100	1.08		
	Group 2	150	4.26	4.26	
	Group 3	139		7.31	7.31
	Group 4	108			8.78
Rougé-Maillart et al.	Group 1	100	-10.11		
	Group 2	150	-7.01	-7.01	
	Group 3	139		-4.40	-4.40
	Group 4	108			-3.31
Suchey-Brooks	Group 2	150	-9.46		
	Group 1	100	-8.79		
	Group 3	139		-5.23	
	Group 4	108		-4.32	

Table 100: Tukey's *b* post-hoc test results for European bias scores separated by body mass. Note: alpha level = 0.05

A DFA was applied to assess how well body mass could be predicted from the bias scores of the eight age estimation methods. The cross-validated classification shows that only 38.8% of individuals of European ancestry are correctly classified into their body mass group based on bias scores. individuals of European ancestry in Group 1 are classified correctly at a rate of 41.0%, Group 2 at a rate of 48.0%, Group 3 at a rate of 38.8%, and Group 4 at a rate of 24.1%.

The discriminant scores from Function 1 and Function 2 were used to plot the sample on the discriminant dimensions. Group 3 is associated with the largest group centroid (0.282), Group 4 is associated with the next largest group centroid (0.187), Group 2 is associated with the second

smallest centroid (0.036) and, finally, Group 1 is associated with the smallest group centroid (-0.649) (see Figure 53).

Figure 53: Canonically derived centroids for the body mass groups for individuals of European ancestry.

African Ancestry

As shown in Table 64 of Section 3.3.2.2, the pattern of correlations observed among the bias scores are generally strong for a MANOVA, and the Box's M value of 169.498 is associated with a p -value of 0.002, which is significant. A covariance matrix (Appendix 27) was run to ensure that no covariance values were more than four times greater than each other. Although there are instances where the covariance values are greater than four times their value, typically associated with the İscan et al. method, overall the covariance matrices between the body mass groups were assumed to be equal for the purposes of the MANOVA.

A MANOVA was conducted to test the hypothesis that there would be differences between body mass group bias scores for each method. The MANOVA effect was statistically significant with Pillai's Trace = 0.228, $F(24, 582) = 1.991$, $p = 0.004$, indicating there are differences among the body mass group bias scores. The multivariate effect size is estimated at 0.076, which implies that 7.6% of the variance in the canonically derived DV is accounted for by the body mass groups.

As the IV was associated with four levels, three eigenvalues and canonical correlations were extracted by the MANOVA. The first eigenvalue is 0.168 and accounts for 65.5% of the model variance. The canonical correlation associated with the first eigenvalue is 0.379, where 14.4% of the variance in the discriminant function derived scores is accounted for by body mass. The second eigenvalue is 0.060 and accounts for 23.6% of the model variance with a corresponding canonical correlation of 0.239. The third eigenvalue is 0.028 and accounts for 10.9% of the model variance and a corresponding canonical correlation of 0.165, which is not statistically significant [Wilks $\Lambda = 0.973$, $F(6, 194) = 0.904$, $p = 0.493$].

The standardized discriminant function coefficients from the first eigenvalue were used to determine the statistical significance of the MANOVA as it was the strongest. As seen in Table 101, the standardized discriminant function coefficients suggest that body mass groups were maximally differentiated by a canonical variate with significant weighting from the İşcan et al. (0.970) method bias scores. The standardized coefficients suggest minimal individual contributions to the MANOVA effect from all other bias scores. The correlations between the bias scores and the canonically derived scores for all methods are weak (range = -0.071 to 0.228), except for the İşcan et al. method, which has strong, positive correlations (0.946).

	Function 1		
	Raw	Stand.	Struc.
Kunos et al.	-0.046	-0.514	-0.038
DiGangi et al.	0.005	0.059	-0.071
İşcan et al.	0.075	0.970	0.946
Passalacqua	-0.001	-0.019	0.064
Lovejoy et al.	0.017	0.145	0.228
Buckberry & Chamberlain	0.015	0.192	0.135
Rougé-Maillart et al.	-0.013	-0.152	0.149
Suchey-Brooks	0.019	0.183	0.176

Table 101: Discriminant function coefficients associated with the MANOVA for individuals of African ancestry. Note: Raw = unstandardized coefficients, Stand. = standardized coefficients, Struc. = structure coefficients.

To estimate the group centroids for the body mass groups, the sample bias scores were multiplied by the corresponding bias unstandardized discriminant function coefficients and then averaged across the samples. The means and standard deviations for each body mass group are in Table 102. An ANOVA with four levels in the IV was performed on the canonically derived bias score DV, and is statistically significant [$F(3, 11.255) = 11.109, p < 0.001$].

	n	Mean	S.D.
24.04-54.37kg	44	-1.096	1.180
54.38-66.10kg	85	-0.204	1.054
66.11-80.20kg	46	-0.130	0.824
80.21-99.79kg	28	0.085	0.812

Table 102: Means and Standard Deviations for the canonically derived variables for individuals of African ancestry.

The Cohen's d absolute values were as follows, from highest to lowest: Group 1 vs. Group 4 = 1.159; Group 1 vs. Group 3 = 0.967; Group 1 vs. Group 2 = 0.852; Group 2 vs. Group 4 = 0.290; Group 3 vs. Group 4 = 0.238; and Group 2 vs. Group 3 = 0.075. The differences between individuals of African ancestry in Groups 1 and 4, Groups 1 and 3, and Groups 1 and 2 are suggestive of a large effect size; the difference between individuals of African ancestry in Groups 2 and 4, and Groups 3 and 4 are suggestive of a small effect size. There is no discernible difference between individuals of African ancestry in Groups 2 and 3.

Table 103 shows the results from Tukey's b post-hoc tests for unequal sample sizes. There are no significant differences among the body mass group bias scores for individuals of African ancestry using any method except the İşcan et al. method. The İşcan et al. method under-ages individuals of African ancestry from Group 1 significantly compared to individuals of African ancestry in Groups 2, 3, and 4.

A DFA was applied to assess how well body mass could be predicted from the bias scores of the eight age estimation methods. The cross-validated classification shows that only 46.3% of individuals of African ancestry are correctly classified into their body mass group based on bias scores. individuals of African ancestry in Group 1 are classified correctly at a rate of 40.9%, Group 2 at a rate of 80.0%, Group 3 at a rate of 10.9%, and Group 4 at a rate of 10.7%.

The discriminant scores from Function 1 and Function 2 were used to plot the sample on the discriminant dimensions. Group 4 is associated with the largest group centroid (0.424), Group 3 is associated with the next largest group centroid (0.206), Group 2 is associated with the second smallest centroid (0.137) and, finally, Group 1 is associated with the smallest group centroid (-0.750) (see Figure 54).

Method	Body Mass	n	Subset (yrs)		
			1	2	3
Kunos et al.	Group 2	85	4.35		
	Group 4	28	6.21		
	Group 1	44	6.73		
	Group 3	46	8.78		
DiGangi et al.	Group 4	28	-10.89		
	Group 2	85	-9.98		
	Group 1	44	-8.81		
	Group 3	46	-7.24		
İşcan et al.	Group 1	44	-9.73		
	Group 2	85		0.60	
	Group 3	46		2.98	
	Group 4	28		4.54	
Passalacqua	Group 2	85	1.15		
	Group 1	44	1.68		
	Group 4	28	2.11		
	Group 3	46	4.98		
Lovejoy et al.	Group 1	44	-3.68		
	Group 4	28	-2.25		
	Group 2	85	-2.06		
	Group 3	46	-0.52		
Buckberry and Chamberlain	Group 2	85	7.48		
	Group 1	44	7.66		
	Group 4	28	9.50		
	Group 3	46	11.89		
Rougé-Maillart et al.	Group 1	44	-2.18		
	Group 4	28	-1.39		
	Group 2	85	-1.13		
	Group 3	46	1.65		
Suchey-Brooks	Group 1	44	-4.86		
	Group 2	85	-4.73		
	Group 3	46	-2.96		
	Group 4	28	-1.86		

Table 103: Tukey's *b* post-hoc test results for individuals of African ancestry bias scores separated by body mass. Note: alpha level = 0.05

Figure 54: Canonically derived centroids for the body mass groups for individuals of African ancestry.

3.5.3 Results Summary

3.5.3.1 Accuracy

For males and individuals of European ancestry, there are statistically significant differences among the body mass groups for accuracy scores. The MANOVA effect size is low at 4.1% and 4.2%, respectively. For females and individuals of African ancestry, there are no statistically significant differences among the body mass groups for accuracy scores.

Using the standardized coefficients from the MANOVA:

- Males have the highest contribution to the model from the Rougé-Maillart et al. and Suchey-Brooks methods, which have the most variance between body mass group accuracy scores. The Kunos et al., DiGangi et al., İşcan et al., Passalacqua, and Lovejoy et al. methods have moderate contributions to the model, indicating that there are

differences among the body mass group accuracy scores for these methods, but they are not as substantial as those from the Rougé-Maillart et al. and Suchey-Brooks methods. The Buckberry and Chamberlain method has little to no contribution to the model, and has the least amount of variance in its body mass group accuracy scores (see Table 86).

- Individuals of European ancestry have the highest contribution to the model from the DiGangi et al. and Rougé-Maillart et al. methods, and the greatest variance in the body mass group accuracy scores. All other methods have moderate contributions to the model, indicating that there are differences among the body mass group accuracy scores for these methods, but they are not as substantial as those from the DiGangi et al. and Rougé-Maillart et al. methods (see Table 95).

The differences in group centroid values generated from the MANOVA for the male and European accuracy scores are significant. Males and individuals of European ancestry in the heaviest body mass groups have significantly higher accuracy scores compared to males and individuals of European ancestry in the lightest body mass groups. The Cohen's d values indicate there is a medium effect size for males, and a strong effect size for individuals of European ancestry. These results are corroborated by the discriminant function canonical analyses results: lighter males and individuals of European ancestry have lower accuracy scores than heavier males and individuals of European ancestry, and the males and individuals of European ancestry in the lightest body mass groups cluster together, while the males in the heaviest body mass groups cluster together (see Figure 49 and Figure 52).

Table 104 shows the inaccuracy scores for males, females, individuals of European ancestry, and individuals of African ancestry separated by body mass. There are no differences in the body mass group accuracy scores for the Lovejoy et al. and Buckberry and Chamberlain methods. The Kunos et al. method accuracy scores for individuals of European ancestry in the lightest body mass group are lower compared to individuals of European ancestry in the heaviest body mass group. The DiGangi et al. method accuracy scores for males in the two lightest body mass groups are lower compared to males in heaviest body mass group, and individuals of European ancestry in the lightest body mass group have lower accuracy scores compared to individuals of European ancestry in the two heaviest body mass groups. The İşcan et al. method accuracy scores for

males, individuals of European ancestry, and individuals of African ancestry in the lightest body mass group are significantly lower compared to individuals in the heaviest body mass groups. The Passalacqua accuracy scores for the lightest males and individuals of African ancestry are significantly lower compared to the heaviest males and individuals of African ancestry. The Rougé-Maillart et al. method accuracy scores for males and individuals of European ancestry in the two lightest body mass groups are significantly lower compared to males and individuals of European ancestry in the two heaviest body mass groups. The Suchey-Brooks accuracy scores for males in the lightest body mass group are significantly lower than those in the heaviest body mass groups; and individuals of European ancestry in the second lightest group have lower accuracy scores compared to the two heaviest groups, and individuals of European ancestry in the lightest body mass group have lower accuracy scores compared to individuals of European ancestry in the second heaviest body mass group. For females, there are no significant differences among the body mass group accuracy scores. For both all individuals, the DiGangi et al. method performs poorly (see Figure 55, Figure 56, Figure 57, and Figure 58).

Body Mass (kg)		Kunos et al.	DiGangi et al.	İşcan et al.	Passal- acqua	Lovejoy et al.	Buckberry & Chamberlain	Rougé-Maillart et al.	Suchey- Brooks
Males	24.04-54.37	11.23	16.72	13.13	12.80	9.59	11.31	11.95	10.27
	54.38-66.10	10.85	17.14	11.57	11.64	9.48	11.39	12.20	11.21
	66.11-80.20	10.07	13.47	9.04	10.87	8.07	12.71	9.31	7.33
	80.21-99.79	9.03	11.71	10.02	10.04	7.75	11.54	8.39	8.65
Females	24.04-54.37	12.09	19.87	14.36	11.96	9.29	10.22	11.93	10.01
	54.38-66.10	9.62	14.68	11.14	11.80	7.13	10.65	8.49	7.95
	66.11-80.20	10.90	15.97	9.66	13.14	6.55	10.17	8.17	7.48
	80.21-99.79	8.38	14.19	10.94	11.00	9.56	10.94	7.31	8.94
European	24.04-54.37	11.20	19.78	12.88	11.67	10.14	9.66	12.77	10.91
	54.38-66.10	10.61	18.21	11.92	11.85	9.79	10.81	11.93	11.25
	66.11-80.20	9.75	15.04	9.63	11.46	8.25	11.53	9.37	7.53
	80.21-99.79	8.82	12.23	10.37	10.41	8.31	11.26	8.55	8.95
African	24.04-54.37	12.64	14.70	15.64	14.05	7.86	13.34	10.05	8.41
	54.38-66.10	10.05	12.82	10.53	11.44	6.62	11.69	9.01	7.93
	66.11-80.20	11.57	10.33	7.63	10.50	6.57	14.67	8.39	6.83
	80.21-99.79	9.43	11.11	9.18	9.18	6.61	12.29	7.18	7.64

Table 104: Inaccuracy scores (in years) for each age-at-death estimation method separated by body mass for males, females, individuals of European ancestry, and individuals of African ancestry. Significant differences are noted by boxes.

Figure 55: Mean inaccuracy scores for the age estimation methods categorized by body mass for males.

Figure 56: Mean inaccuracy scores for the age estimation methods categorized by body mass for females.

Figure 57: Mean inaccuracy scores for the age estimation methods categorized by body mass for individuals of European ancestry.

Figure 58: Mean inaccuracy scores for the age estimation methods categorized by body mass for individuals of African ancestry.

Discriminant function analyses show that accuracy scores are poor predictors of body mass. Light males (5.3%), heavy females (0%), light individuals of European ancestry (10%), and heavy individuals of African ancestry (0%) have the lowest classification scores. Males in the second heaviest body mass group (60.9%), females in the second lightest body mass group (81%), individuals of European ancestry in the second heaviest body mass group (51.1%), and individuals of African ancestry in the second lightest body mass group (87.1%) have the highest classification scores. These results indicate that accuracy scores cannot be used reliably to predict body mass groups, except for females and individuals of African ancestry in the second lightest body mass groups.

3.5.3.2 Bias

For males, females, individuals of European ancestry, and individuals of African ancestry there are statistically significant differences among the body mass groups for bias scores. The MANOVA effect size is 4.7% for males and 7.8% for females, suggesting that body mass has a larger effect for females than males using this model, though both have low effect sizes. Similarly, the MANOVA effect size is 5.7% for individuals of European ancestry and 7.6% for individuals of African ancestry, suggesting that body mass has a larger effect for individuals of African ancestry than individuals of European ancestry using this model, though both have low effect sizes. Similar to the BMI MANOVA results, although females and individuals of African ancestry have stronger differences among the mean bias scores of each body mass group according to the MANOVA, they are not as statistically significant as those of males and individuals of European ancestry because of small sample sizes in the heavier body mass groups.

Using the standardized coefficients from the MANOVA:

- Males have the highest contribution to the model from the Kunos et al. and Işcan et al. methods, which have the greatest variance in the body mass group bias scores. All other methods have moderate contributions to the model, indicating that there are differences among the body mass group bias scores for these methods, but they are not as substantial as those from the Kunos et al. and Işcan et al. methods (see Table 89).

- Females have the highest contribution to the model from the Kunos et al., DiGangi et al. and Işcan et al. methods, which have the greatest variance in the body mass group bias scores compared to the other methods. All other methods have moderate contributions to the model, indicating that there are differences among the body mass group bias scores for these methods, but they are not as substantial as those from the other three methods (see Table 92).
- Individuals of European ancestry have the highest contribution to the model from the Işcan et al. and Kunos et al. methods, which have the greatest variance in the body mass group bias scores compared to the other methods. All other methods have moderate contributions to the model, indicating that there are differences among the body mass group bias scores for these methods, but they are not as substantial as those from the Işcan et al. and Kunos et al. methods (see Table 98).
- Individuals of African ancestry have the highest contribution to the model from the Işcan et al. method, which has the greatest variance in the body mass group bias scores compared to all other methods. The Lovejoy et al., Buckberry and Chamberlain, Rougé-Maillart et al., and Suchey-Brooks methods have moderate contributions, indicating that there are differences among the body mass group bias scores for these methods, but they are not as substantial as those from the Işcan et al. method. The Kunos et al., DiGangi et al., and Passalacqua methods have the lowest bias scores for individuals of African ancestry using this model, and the least amount of variance in their body mass group bias scores (see Table 101).

The differences in group centroid values generated from the MANOVA for the male, female, European, and African bias scores are significant. Males, individuals of European ancestry, and individuals of African ancestry in the lightest body mass group have significantly higher negative bias scores compared to individuals in all other body mass groups, and the Cohen's *d* values indicate these are large effect sizes between the lightest and heaviest groups, and medium effect sizes for the other relationships. Females in the lightest body mass group have significantly higher negative bias scores compared to females in the heaviest body mass group, and the Cohen's *d* value indicates this is a medium effect size. The results from the DFA

corroborate these findings. These results are corroborated by the discriminant function canonical analyses results: males, females, individuals of European ancestry, and individuals of African ancestry in the lightest body mass group are under-aged more than individuals in the other body mass categories, with the greatest difference between lightest and heaviest groups (see Figure 50, Figure 51, Figure 53, and Figure 54).

Table 105 shows the bias scores for males, females, individuals of European ancestry, and individuals of African ancestry separated by body mass. For the Kunos et al. method, males and individuals of European ancestry in the two lightest body mass groups are under-aged compared to males and individuals of European ancestry in the two heaviest body mass groups. For the DiGangi et al. method, individuals of European ancestry in the two lightest body mass groups are under-aged compared to individuals of European ancestry in the two heaviest body mass groups. For the İşcan et al. method, all individuals in the lightest body mass group are under-aged compared to all other body mass groups. The Passalacqua, Lovejoy et al. Buckberry and Chamberlain, and Rougé-Maillart et al. methods significantly under-age males and individuals of European ancestry in the lightest body mass groups compared to males and individuals of European ancestry in the two heaviest body mass groups. The Suchey-Brooks method under-ages males in the two lightest body mass groups compared to the two heaviest groups; under-ages females in the lightest body mass group compared to females in the second heaviest group; and under-ages female individuals of European ancestry in the two lightest body mass groups compared to individuals of European ancestry in the two heaviest groups. For all individuals, the DiGangi et al. method performs poorly (see Figure 59, Figure 60, Figure 61, and Figure 62).

Body Mass (kg)		Kunos et al.	DiGangi et al.	İşcan et al.	Passal- acqua	Lovejoy et al.	Buckberry & Chamberlain	Rougé-Maillart et al.	Suchey- Brooks
Males	24.04-54.37	0.93	-13.12	-6.97	-4.35	-7.03	3.95	-7.15	-7.36
	54.38-66.10	1.74	-14.54	1.57	-3.02	-6.08	5.28	-5.96	-9.28
	66.11-80.20	5.34	-10.08	3.62	1.30	-3.72	8.53	-2.81	-4.90
	80.21-99.79	6.11	-10.34	1.75	0.94	-4.03	9.28	-2.71	-3.77
Females	24.04-54.37	-0.35	-18.33	-9.67	-1.43	-7.55	2.16	-8.28	-7.84
	54.38-66.10	2.21	-13.37	0.21	0.30	-3.77	5.68	-2.94	-5.00
	66.11-80.20	4.50	-12.17	-3.59	-0.86	-3.72	8.03	-3.34	-3.41
	80.21-99.79	5.79	-11.69	-7.69	-2.38	-8.44	6.31	-4.44	-4.19
European	24.04-54.37	-2.50	-18.70	-7.62	-4.99	-8.86	1.08	-10.11	-8.79
	54.38-66.10	0.52	-16.47	1.36	-3.53	-7.07	4.26	-7.01	-9.46
	66.11-80.20	5.16	-11.45	2.32	-0.37	-4.78	7.31	-4.40	-5.23
	80.21-99.79	4.99	-10.40	-0.37	0.15	-5.15	8.78	-3.31	-4.32
African	24.04-54.37	6.37	-8.61	-9.73	1.68	-3.68	7.66	-2.18	-4.86
	54.38-66.10	4.35	-9.98	0.60	1.15	-2.06	7.48	-1.13	-4.73
	66.11-80.20	8.78	-7.24	2.98	4.98	-0.52	11.89	-1.65	-2.96
	80.21-99.79	6.21	-10.89	4.54	2.11	-2.25	9.50	-1.39	-1.86

Table 105: Bias scores (in years) for each age-at-death estimation method separated by body mass for males, females, individuals of European ancestry, and individuals of African ancestry. Significant differences are noted by boxes.

Discriminant function analyses show that bias scores are poor predictors of body mass. Light males (3.6%), heavy females (0%), heavy individuals of European ancestry (24.1%), and heavy individuals of African ancestry (10.7%) have the lowest classification scores. Males in the second heaviest group (76.4%), females in the lightest body mass group (84.0%), and individuals of European ancestry and individuals of African ancestry in the second lightest body mass groups (48% and 80%, respectively) have the highest classification scores. These results indicate that bias cannot be used reliably to predict body mass groups, except for females in the lightest body mass group and individuals of African ancestry in the second lightest body mass group.

Figure 59: Mean bias scores for the age estimation methods categorized by body mass for males.

Figure 60: Mean bias scores for the age estimation methods categorized by body mass for females.

Figure 61: Mean bias scores for the age estimation methods categorized by body mass for individuals of European ancestry.

Figure 62: Mean bias scores for the age estimation methods categorized by body mass for individuals of African ancestry.

3.6 Research Question IV: Are there differences between non-weight-bearing and weight-bearing joint age estimations?

To test the differences between the non-weight-bearing rib age estimation methods (i.e. Kunos et al. and İşcan et al. methods) and the weight-bearing pelvic age estimation methods (i.e. Passalacqua, Lovejoy et al., Buckberry and Chamberlain, Rougé-Maillart et al., Suchey-Brooks methods), the accuracy and bias scores of each method were averaged into two groups: Non-Weight Bearing (NWB) and Weight-Bearing (WB). The DiGangi et al. method was removed from these analyses as it has the lowest accuracy and precision scores for all methods. Table 106 shows the averages for each method and loading group.

Method	Accuracy Score (yrs)	Bias Score (yrs)
Kunos et al.	10.43	3.11
İşcan et al.	11.17	-0.7
Non-Weight Bearing Joint Average	10.80	1.21
Passalacqua	11.45	-1.13
Lovejoy et al.	8.65	-5.42
Buckberry and Chamberlain	11.42	6.24
Rougé-Maillart et al.	10.34	-5.01
Suchey-Brooks	9.22	-6.26
Weight-Bearing Joint Average	10.22	-2.62

Table 106: Average accuracy and bias scores for the Non-Weight-Bearing and Weight-Bearing Joint groups.

The two weight-bearing joint groups were compared using paired sample t-tests to determine statistical significance between the two samples.

3.6.1 Sex

3.6.1.1 Accuracy

Males

Table 107 shows the average accuracy scores for each method as well as the average accuracy scores for the NWB and WB joint groups. A paired-sample t-test was conducted to compare NWB and WB joint accuracy scores to determine if there are differences between the group accuracy scores for males. There are no significant differences between the accuracy scores for NWB ($\bar{x} = 10.50$ years, $s.d. = 5.73$) and WB joints ($\bar{x} = 10.06$ years, $s.d. = 4.89$); $t(513) = 1.580$, $p = 0.115$.

Method	Accuracy Score (yrs)
Kunos et al.	10.33
İşcan et al.	10.76
Non-Weight Bearing Joint Average	10.50
Passalacqua	11.17
Lovejoy et al.	8.69
Buckberry and Chamberlain	11.94
Rougé-Maillart et al.	10.43
Suchey-Brooks	9.29
Weight-Bearing Joint Average	10.06

Table 107: Average accuracy scores for the Non-Weight-Bearing and Weight-Bearing Joint groups for males.

When separated by BMI, there are no differences between the NWB and WB joint accuracy scores for males. When separated by stature, there are significant differences between the accuracy scores of males in Group 4; there is more error associated with the NWB joint age estimations than the WB joint age estimations for males in the tallest stature group. When separated by body mass, there are significant differences between the accuracy scores of males in Group 1; there is more error associated with the NWB joint age estimations than the WB joint age estimations for males in the lightest body mass group (see Table 108).

	Group		n	Score (yrs)	s.d. (yrs)	t	df	Sig (2-tail)
BMI	Underweight	NWB Inaccuracy	80	12.16	7.55	1.029	79	0.307
		WB Inaccuracy	80	11.38	5.76			
	Normal	NWB Inaccuracy	290	10.43	5.43	1.200	289	0.231
		WB Inaccuracy	290	9.98	4.81			
	Overweight	NWB Inaccuracy	117	9.89	5.09	0.449	116	0.654
		WB Inaccuracy	117	9.63	4.60			
	Obese	NWB Inaccuracy	27	9.06	4.49	0.178	26	0.860
		WB Inaccuracy	27	8.84	3.54			
Stature	Group 1	NWB Inaccuracy	55	10.82	6.26	0.071	54	0.944
		WB Inaccuracy	55	10.76	5.08			
	Group 2	NWB Inaccuracy	136	10.76	5.33	0.735	135	0.464
		WB Inaccuracy	136	10.39	5.18			
	Group 3	NWB Inaccuracy	195	10.29	6.13	0.391	194	0.696
		WB Inaccuracy	195	10.09	5.16			
	Group 4	NWB Inaccuracy	128	10.43	5.31	2.150	127	0.033
		WB Inaccuracy	128	9.36	3.96			
Body Mass	Group 1	NWB Inaccuracy	75	12.18	7.16	2.023	74	0.047
		WB Inaccuracy	75	10.76	5.84			
	Group 2	NWB Inaccuracy	152	11.20	6.26	0.225	151	0.823
		WB Inaccuracy	152	11.07	4.82			
	Group 3	NWB Inaccuracy	162	9.73	5.06	0.416	161	0.678
		WB Inaccuracy	162	9.52	4.68			
	Group 4	NWB Inaccuracy	125	9.66	4.53	1.105	124	0.271
		WB Inaccuracy	125	0.09	4.37			

Table 108: Paired t-test results for male inaccuracy scores comparing NWB and WB joints separated by BMI, stature, and body mass.

Females

Table 109 shows the average accuracy scores for each method as well as the average accuracy scores for the NWB and WB joint groups. A paired-sample t-test was conducted to compare NWB and WB joint accuracy scores to determine if there are differences between the group accuracy scores for females. There are significant differences between the accuracy scores for NWB ($\bar{x} = 11.32$ years, $s.d. = 6.52$) and WB joints ($\bar{x} = 9.18$ years, $s.d. = 4.97$); $t(200) = 4.556$, $p < 0.001$.

Method	Accuracy Score (yrs)
Kunos et al.	10.66
İşcan et al.	12.22
Non-Weight Bearing Joint Average	11.32
Passalacqua	12.14
Lovejoy et al.	8.57
Buckberry and Chamberlain	10.19
Rougé-Maillart et al.	10.10
Suchey-Brooks	9.04
Weight-Bearing Joint Average	9.18

Table 109: Average accuracy scores for the Non-Weight-Bearing and Weight-Bearing Joint groups for females.

When separated by BMI, the accuracy scores are significantly different between NWB and WB joints for underweight, normal-sized, and overweight females, with the NWB joints showing the most error. When separated by stature, the accuracy scores are significantly different between NWB and WB joints for females in all stature groups, with the NWB joints showing the most error. When separated by body mass, there are significant differences between NWB and WB joint accuracy scores for females in Groups 1 and 2, with the NWB joints showing the most error (see Table 110).

	Group		n	Score (yrs)	s.d. (yrs)	t	df	Sig (2-tail)
BMI	Underweight	NWB Inaccuracy	38	13.12	6.71	4.891	37	≤0.001
		WB Inaccuracy	38	8.57	5.21			
	Normal	NWB Inaccuracy	103	11.48	6.71	2.685	102	0.008
		WB Inaccuracy	103	9.67	5.20			
	Overweight	NWB Inaccuracy	45	10.18	6.22	2.047	44	0.047
		WB Inaccuracy	45	8.09	3.93			
	Obese	NWB Inaccuracy	15	9.17	4.48	-0.959	14	0.352
		WB Inaccuracy	15	10.60	5.20			
Stature	Group 1	NWB Inaccuracy	107	11.54	6.72	3.289	106	0.001
		WB Inaccuracy	107	9.48	5.07			
	Group 2	NWB Inaccuracy	75	11.40	6.74	2.428	74	0.018
		WB Inaccuracy	75	9.38	5.01			
	Group 3	NWB Inaccuracy	17	9.79	4.22	2.283	16	0.036
		WB Inaccuracy	17	6.59	3.53			
Body Mass	Group 1	NWB Inaccuracy	70	13.16	7.00	3.703	69	≤0.001
		WB Inaccuracy	70	10.31	5.75			
	Group 2	NWB Inaccuracy	84	10.38	6.03	2.487	83	0.015
		WB Inaccuracy	84	8.56	4.65			
	Group 3	NWB Inaccuracy	29	10.28	6.58	1.711	28	0.098
		WB Inaccuracy	29	8.10	3.41			
	Group 4	NWB Inaccuracy	18	10.25	5.52	0.484	17	0.634
		WB Inaccuracy	18	9.42	4.72			

Table 110: Paired t-test results for female inaccuracy scores comparing NWB and WB joints separated by BMI, stature, and body mass.

3.6.1.2 Bias

Males

Table 111 shows the average bias scores for each method as well as the average accuracy scores for the NWB and WB joint groups. A paired-sample t-test was conducted to compare NWB and WB joint bias scores to determine if there are differences between the group bias scores for males. There are significant differences between the accuracy scores for NWB ($\bar{x} = 2.43$ years, $s.d. = 9.81$) and WB joints ($\bar{x} = -2.22$ years, $s.d. = 10.01$); $t(513) = 13.071$, $p < 0.001$.

Method	Bias Score (yrs)
Kunos et al.	4.02
İşcan et al.	0.83
Non-Weight Bearing Joint Average	2.46
Passalacqua	-0.87
Lovejoy et al.	-5.07
Buckberry and Chamberlain	7.04
Rougé-Maillart et al.	-4.60
Suchey-Brooks	-6.36
Weight-Bearing Joint Average	-2.28

Table 111: Average bias scores for the Non-Weight-Bearing and Weight-Bearing Joint groups for males.

When separated by BMI, there are differences between the NWB and WB joint bias scores of normal-sized, overweight, and obese males; males in the WB groups are significantly under-aged compared to males in the NWB groups. When separated by stature, there are significant differences between the bias scores of males in all groups; males in the WB groups are significantly under-aged compared to males in the NWB groups. When separated by body mass, there are significant differences among the bias scores of males in Groups 2, 3, and 4; males in the WB group are under-aged compared to males in the NWB groups (see Table 112).

	Group		n	Score (yrs)	s.d. (yrs)	t	df	Sig (2-tail)
BMI	Underweight	NWB Bias	80	-4.79	12.97	-0.311	79	0.757
		WB Bias	80	-4.52	11.32			
	Normal	NWB Bias	290	4.05	8.21	13.431	289	<0.001
		WB Bias	290	-2.11	9.96			
	Overweight	NWB Bias	117	3.13	9.35	5.989	116	<0.001
		WB Bias	117	-0.96	9.44			
	Obese	NWB Bias	27	3.28	7.37	3.527	26	0.002
		WB Bias	27	-1.99	7.90			
Stature	Group 1	NWB Bias	55	-1.58	9.85	4.045	54	<0.001
		WB Bias	55	-5.52	9.51			
	Group 2	NWB Bias	136	2.77	9.86	7.629	135	<0.001
		WB Bias	136	-2.56	10.45			
	Group 3	NWB Bias	195	2.36	9.75	9.156	194	<0.001
		WB Bias	195	-3.10	9.99			
	Group 4	NWB Bias	128	3.89	9.45	4.392	127	<0.001
		WB Bias	128	0.90	9.03			
Body Mass	Group 1	NWB Bias	75	-3.02	12.90	1.433	74	0.156
		WB Bias	75	-4.40	10.65			
	Group 2	NWB Bias	152	1.71	9.72	8.558	151	<0.001
		WB Bias	152	-3.96	10.62			
	Group 3	NWB Bias	162	4.79	7.84	9.205	161	<0.001
		WB Bias	162	-0.85	9.60			
	Group 4	NWB Bias	125	3.50	8.75	5.992	124	<0.001
		WB Bias	125	-0.57	8.81			

Table 112: Paired t-test results for male bias scores comparing NWB and WB joints separated by BMI, stature, and body mass.

Females

Table 113 shows the average bias scores for each method as well as the average bias scores for the NWB and WB joint groups. A paired-sample t-test was conducted to compare NWB and WB joint bias scores to determine if there are differences between the group bias scores for females. There are significant differences between the bias scores for NWB ($\bar{x} = -1.28$ years, $s.d. = 10.94$) and WB joints ($\bar{x} = -2.84$ years, $s.d. = 9.03$); $t(200) = 2.770$, $p = 0.006$.

Method	Bias Score (yrs)
Kunos et al.	0.93
İşcan et al.	-4.73
Non-Weight Bearing Joint Average	-1.90
Passalacqua	-1.76
Lovejoy et al.	-6.27
Buckberry and Chamberlain	4.31
Rougé-Maillart et al.	-5.98
Suchey-Brooks	-6.00
Weight-Bearing Joint Average	-3.44

Table 113: Average bias scores for the Non-Weight-Bearing and Weight-Bearing Joint groups for females.

When separated by BMI, there are significant differences between the NWB and WB joint bias scores for underweight and normal-sized females; underweight females are under-aged using the NWB joints compared to WB joints, and normal-sized females are under-aged using the WB joints compared to the NWB joints. When separated by stature, there are significant differences between the NWB and WB joint bias scores for females in Groups 1; the WB joints significantly under-age short females compared to the NWB joints. When separated by body mass, there are significant differences between NWB and WB joint bias scores for females in Group 2, with the WB joints significantly under-aging females compared to the NWB joints (see Table 114).

	Group		n	Score (yrs)	s.d. (yrs)	t	df	Sig (2-tail)
BMI	Underweight	NWB Bias	38	-5.99	11.27	-2.310	37	0.027
		WB Bias	38	-3.07	8.84			
	Normal	NWB Bias	103	-0.23	11.41	3.717	102	<0.001
		WB Bias	103	-3.24	9.57			
	Overweight	NWB Bias	45	0.02	9.28	1.566	44	0.124
		WB Bias	45	-1.56	7.73			
	Obese	NWB Bias	15	-0.50	9.03	1.768	14	0.099
		WB Bias	15	-3.37	9.92			
Stature	Group 1	NWB Bias	107	-2.41	11.76	2.281	106	0.025
		WB Bias	107	-4.25	9.06			
	Group 2	NWB Bias	75	-0.16	10.24	1.759	74	0.083
		WB Bias	75	-1.74	9.28			
	Group 3	NWB Bias	17	0.50	8.66	-0.088	16	0.931
		WB Bias	17	0.65	6.57			
Body Mass	Group 1	NWB Bias	70	-5.06	12.30	0.293	69	0.771
		WB Bias	70	-5.37	9.86			
	Group 2	NWB Bias	84	1.21	9.78	3.276	83	0.002
		WB Bias	84	-1.51	8.58			
	Group 3	NWB Bias	29	1.10	9.27	1.265	28	0.216
		WB Bias	29	-0.61	7.26			
	Group 4	NWB Bias	18	-2.08	9.25	0.438	17	0.667
		WB Bias	18	-2.81	8.71			

Table 114: Paired t-test results for female bias scores comparing NWB and WB joints separated by BMI, stature, and body mass.

3.6.2 Ancestry

3.6.2.1 Accuracy

European Ancestry

Table 115 shows the average accuracy scores for each method as well as the average accuracy scores for the NWB and WB joint groups. A paired-sample t-test was conducted to compare NWB and WB joint accuracy scores to determine if there are differences between the group accuracy scores for individuals of European ancestry. There are significant differences between the accuracy scores for NWB ($\bar{x} = 10.70$ years, $s.d. = 5.97$) and WB joints ($\bar{x} = 10.10$ years, $s.d. = 4.95$); $t(510) = 2.042, p = 0.042$.

Method	Accuracy Score (yrs)
Kunos et al.	10.19
İşcan et al.	11.30
Non-Weight Bearing Joint Average	10.70
Passalacqua	11.47
Lovejoy et al.	9.24
Buckberry and Chamberlain	10.87
Rougé-Maillart et al.	10.83
Suchey-Brooks	9.70
Weight-Bearing Joint Average	10.10

Table 115: Average accuracy scores for the Non-Weight-Bearing and Weight-Bearing Joint groups for individuals of European ancestry.

When separated by BMI, there are no significant differences among the accuracy scores between NWB and WB joints for individuals of European ancestry. When separated by stature, there are significant differences among the accuracy scores between NWB and WB joints for individuals of European ancestry in Group 1, with the NWB joints showing the most error for short individuals. When separated by body mass, there are significant differences between NWB and WB joints for individuals of European ancestry in Group 1, with the NWB joints showing the most error for individuals in the lightest body mass group (see Table 116).

	Group		n	Score (yrs)	s.d. (yrs)	t	df	Sig (2-tail)
BMI	Underweight	NWB Inaccuracy	69	11.35	7.27	0.014	68	0.989
		WB Inaccuracy	69	11.34	5.98			
	Normal	NWB Inaccuracy	276	11.00	5.97	1.970	275	0.050
		WB Inaccuracy	276	10.20	4.90			
	Overweight	NWB Inaccuracy	129	10.17	5.48	1.397	128	0.165
		WB Inaccuracy	129	9.34	4.48			
	Obese	NWB Inaccuracy	37	9.09	4.55	-0.565	36	0.575
		WB Inaccuracy	37	9.68	4.38			
Stature	Group 1	NWB Inaccuracy	121	11.64	6.75	1.987	120	0.049
		WB Inaccuracy	121	10.43	5.22			
	Group 2	NWB Inaccuracy	158	10.92	5.73	1.604	157	0.111
		WB Inaccuracy	158	10.09	5.28			
	Group 3	NWB Inaccuracy	150	9.81	5.68	-0.413	149	0.680
		WB Inaccuracy	150	10.05	4.79			
	Group 4	NWB Inaccuracy	82	10.49	5.56	1.193	81	0.236
		WB Inaccuracy	82	9.73	4.16			
Body Mass	Group 1	NWB Inaccuracy	101	12.01	6.94	2.059	100	0.042
		WB Inaccuracy	101	10.83	5.69			
	Group 2	NWB Inaccuracy	150	11.27	6.23	0.544	149	0.587
		WB Inaccuracy	150	10.94	5.11			
	Group 3	NWB Inaccuracy	145	9.88	5.55	0.923	144	0.358
		WB Inaccuracy	145	9.36	4.48			
	Group 4	NWB Inaccuracy	115	9.84	4.87	0.932	114	0.353
		WB Inaccuracy	115	9.30	4.35			

Table 116: Paired t-test results for European accuracy scores comparing NWB and WB joints separated by BMI, stature, and body mass.

African Ancestry

Table 117 shows the average accuracy scores for each method as well as the average accuracy scores for the NWB and WB joint groups. A paired-sample t-test was conducted to compare NWB and WB joint accuracy scores to determine if there are differences between the group accuracy scores for individuals of African ancestry. There are significant differences between the accuracy scores for NWB ($\bar{x} = 10.83$ years, $s.d. = 5.99$) and WB joints ($\bar{x} = 9.08$ years, $s.d. = 4.81$); $t(203) = 3.960$, $p < 0.001$.

Method	Accuracy Score (yrs)
Kunos et al.	11.03
İşcan et al.	10.85
Non-Weight Bearing Joint Average	10.94
Passalacqua	11.42
Lovejoy et al.	7.15
Buckberry and Chamberlain	12.85
Rougé-Maillart et al.	9.06
Suchey-Brooks	7.96
Weight-Bearing Joint Average	9.22

Table 117: Average accuracy scores for the Non-Weight-Bearing and Weight-Bearing Joint groups for individuals of African ancestry.

When separated by BMI, the accuracy scores are significantly different between NWB and WB joints for underweight individuals of African ancestry, with the NWB joints showing the most error. When separated by stature, the accuracy scores are significantly different between NWB and WB joints for individuals of African ancestry in Groups 3 and 4, with the NWB joints showing the most error for individuals in the tallest stature groups. When separated by body mass, there are significant differences between NWB and WB joints for individuals of African ancestry in Groups 1 and 2, with the NWB joints showing the most error for individuals in the lightest body mass groups (see Table 118).

	Group		n	Score (yrs)	s.d. (yrs)	t	df	Sig (2-tail)
BMI	Underweight	NWB Inaccuracy	49	14.04	7.06	5.400	48	<0.001
		WB Inaccuracy	49	9.27	5.16			
	Normal	NWB Inaccuracy	117	10.02	5.34	1.440	116	0.153
		WB Inaccuracy	117	9.17	4.86			
	Overweight	NWB Inaccuracy	33	9.18	5.12	0.601	32	0.552
		WB Inaccuracy	33	8.64	4.42			
	Obese	NWB Inaccuracy	5	9.10	3.85	0.566	4	0.602
		WB Inaccuracy	5	7.95	2.77			
Stature	Group 1	NWB Inaccuracy	41	10.27	5.90	1.940	40	0.059
		WB Inaccuracy	41	8.39	4.39			
	Group 2	NWB Inaccuracy	53	11.17	6.30	1.576	52	0.121
		WB Inaccuracy	53	9.85	4.72			
	Group 3	NWB Inaccuracy	62	11.31	6.63	2.290	61	0.025
		WB Inaccuracy	62	9.22	5.89			
	Group 4	NWB Inaccuracy	48	10.30	4.84	2.091	47	0.042
		WB Inaccuracy	48	8.63	3.52			
Body Mass	Group 1	NWB Inaccuracy	44	14.14	7.22	4.102	43	<0.001
		WB Inaccuracy	44	9.91	6.02			
	Group 2	NWB Inaccuracy	86	10.28	6.08	2.076	85	0.041
		WB Inaccuracy	86	8.84	4.21			
	Group 3	NWB Inaccuracy	46	9.60	4.50	0.572	45	0.570
		WB Inaccuracy	46	9.11	4.72			
	Group 4	NWB Inaccuracy	28	9.30	3.60	0.923	27	0.364
		WB Inaccuracy	28	8.43	4.62			

Table 118: Paired t-test results for individuals of African ancestry accuracy scores comparing NWB and WB joints separated by BMI, stature, and body mass.

3.6.2.2 Bias

European Ancestry

Table 119 shows the average bias scores for each method as well as the average bias scores for the NWB and WB joint groups. A paired-sample t-test was conducted to compare NWB and WB joint bias scores to determine if there are differences between the group bias scores for individuals of European ancestry. There are significant differences between the bias scores for

NWB ($\bar{x} = 0.81$ years, $s.d. = 10.43$) and WB joints ($\bar{x} = -3.55$ years, $s.d. = 9.62$); $t(510) = 12.259$, $p < 0.001$.

Method	Bias Score (yrs)
Kunos et al.	2.05
İşcan et al.	-0.74
Non-Weight Bearing Joint Average	0.82
Passalacqua	-2.37
Lovejoy et al.	-6.62
Buckberry and Chamberlain	5.28
Rougé-Maillart et al.	-6.49
Suchey-Brooks	-7.12
Weight-Bearing Joint Average	-3.73

Table 119: Average bias scores for the Non-Weight-Bearing and Weight-Bearing Joint groups for individuals of European ancestry.

When separated by BMI, there are significant differences between the NWB and WB joint bias scores for underweight, normal-sized, and obese individuals of European ancestry; the WB joints under-age individuals compared to the WB joints. When separated by stature, there are significant differences between the NWB and WB joint bias scores for all stature groups; the WB joints significantly under-age compared to the NWB joints. When separated by body mass, there are significant differences between NWB and WB joint bias scores for individuals of European ancestry in Groups 2, 3, and 4, with the WB joints significantly under-aging individuals compared to the NWB joints (see Table 120).

	Group		n	Score (yrs)	s.d. (yrs)	t	df	Sig (2-tail)
BMI	Underweight	NWB Bias	69	-6.88	11.09	-0.510	68	0.612
		WB Bias	69	-6.43	10.33			
	Normal	NWB Bias	276	2.30	10.04	12.425	275	<0.001
		WB Bias	276	-3.74	9.72			
	Overweight	NWB Bias	129	1.51	9.75	5.124	128	<0.001
		WB Bias	129	-1.84	8.90			
	Obese	NWB Bias	37	1.58	8.25	3.745	36	0.001
		WB Bias	37	-2.74	8.86			
Stature	Group 1	NWB Bias	121	-3.67	11.63	3.335	120	0.001
		WB Bias	121	-6.15	9.04			
	Group 2	NWB Bias	158	0.97	10.07	7.056	157	<0.001
		WB Bias	158	-3.58	9.69			
	Group 3	NWB Bias	150	2.18	8.92	9.440	149	<0.001
		WB Bias	150	-3.93	9.42			
	Group 4	NWB Bias	82	4.60	9.69	4.419	81	<0.001
		WB Bias	82	1.03	9.22			
Body Mass	Group 1	NWB Bias	101	-5.10	11.96	1.983	100	0.050
		WB Bias	101	-6.65	9.44			
	Group 2	NWB Bias	150	0.94	10.20	8.585	149	<0.001
		WB Bias	150	-4.82	10.17			
	Group 3	NWB Bias	145	3.71	8.65	8.573	144	<0.001
		WB Bias	145	-1.87	9.09			
	Group 4	NWB Bias	115	2.17	9.36	4.930	114	<0.001
		WB Bias	115	-1.30	8.79			

Table 120: Paired t-test results for European bias scores comparing NWB and WB joints separated by BMI, stature, and body mass.

African Ancestry

Table 121 shows the average bias scores for each method as well as the average bias scores for the NWB and WB joint groups. A paired-sample t-test was conducted to compare NWB and WB joint bias scores to determine if there are differences between the group bias scores for individuals of African ancestry. There are significant differences between the bias scores for NWB ($\bar{x} = 2.82$ years, $s.d. = 9.71$) and WB joints ($\bar{x} = 0.51$ years, $s.d. = 9.45$); $t(203) = 4.008$, $p < 0.001$.

Method	Bias Score (yrs)
Kunos et al.	5.82
İşcan et al.	-0.73
Non-Weight Bearing Joint Average	2.78
Passalacqua	2.05
Lovejoy et al.	-2.35
Buckberry and Chamberlain	8.74
Rougé-Maillart et al.	-1.17
Suchey-Brooks	-4.02
Weight-Bearing Joint Average	0.28

Table 121: Average bias scores for the Non-Weight-Bearing and Weight-Bearing Joint groups for individuals of African ancestry.

When separated by BMI, there are significant differences between the NWB and WB joint bias scores for normal-sized and overweight individuals of African ancestry; the WB joints under-age individuals compared to the NWB joints. When separated by stature, there are significant differences between the NWB and WB joint bias scores for individuals of African ancestry in Groups 1, 2, and 3; the WB joints significantly under-age individuals compared to the NWB joints. When separated by body mass, there are significant differences between NWB and WB joint bias scores for individuals of African ancestry in Groups 2, 3, and 4, with the WB joints significantly under-aging individuals compared to the NWB joints (see Table 122).

	Group		n	Score (yrs)	s.d. (yrs)	t	df	Sig (2-tail)
BMI	Underweight	NWB Bias	49	-2.78	13.83	-1.657	48	0.104
		WB Bias	49	-0.69	10.06			
	Normal	NWB Bias	117	4.41	7.21	5.157	116	<0.001
		WB Bias	117	0.74	9.50			
	Overweight	NWB Bias	33	5.24	7.29	2.993	32	0.005
		WB Bias	33	1.65	8.85			
	Obese	NWB Bias	5	4.50	7.16	1.136	4	0.319
		WB Bias	5	-0.55	6.49			
Stature	Group 1	NWB Bias	41	2.44	7.99	2.310	40	0.026
		WB Bias	41	-0.35	8.37			
	Group 2	NWB Bias	53	3.98	9.82	2.040	52	0.046
		WB Bias	53	1.67	10.12			
	Group 3	NWB Bias	62	2.27	11.34	2.098	61	0.040
		WB Bias	62	-0.06	10.24			
	Group 4	NWB Bias	48	2.57	8.80	1.585	47	0.120
		WB Bias	48	0.71	8.61			
Body Mass	Group 1	NWB Bias	44	-1.50	13.81	-0.497	43	0.622
		WB Bias	44	-0.77	10.97			
	Group 2	NWB Bias	86	2.56	8.79	3.261	85	0.002
		WB Bias	86	-0.07	8.97			
	Group 3	NWB Bias	46	5.88	6.16	2.969	45	0.005
		WB Bias	46	2.52	9.14			
	Group 4	NWB Bias	28	5.38	6.74	2.970	27	0.006
		WB Bias	28	1.00	8.75			

Table 122: Paired t-test results for individuals of African ancestry bias scores comparing NWB and WB joints separated by BMI, stature, and body mass.

3.6.3 Results Summary

3.6.3.1 Accuracy

There are no differences between the non-weight-bearing (NWB) and weight-bearing (WB) joint surface accuracy scores for males and individuals of European ancestry when separated by BMI, but there are for females and individuals of African ancestry. Underweight, normal-sized, and overweight females and underweight individuals of African ancestry have more error associated with their age estimations using NWB joints compared to WB joints. When separated by stature, there is significantly more error associated with the NWB joint age estimations for males in the tallest stature group and individuals of European ancestry in the shortest stature group compared to the WB joints. For females, there is significantly more error associated with NWB joint age estimations compared to WB joints for all stature groups. For individuals of African ancestry, there is significantly more error associated with the NWB joint stature age estimations for individuals in the two tallest groups. When separated by body mass, there is significantly more error associated with the NWB joint age estimations for males in the heaviest body mass group, individuals of European ancestry in the lightest body mass group, and females and individuals of African ancestry in the two lightest body mass groups compared to the WB joints. NWB joints have more error associated with their age estimations (between 1 and 5 years) compared to WB joints, and most of the error is associated with tall and light individuals.

3.6.3.2 Bias

When separated by BMI, normal-sized, overweight, and obese males and individuals of European ancestry are under-aged significantly when using WB joints compared to NWB joints. Underweight females are under-aged using NWB joints compared to WB joints, and normal-sized females are under-aged using WB joints compared to NWB joints. Underweight and normal-sized individuals of African ancestry are under-aged using the WB joints compared to the NWB joints. When separated by stature, males and individuals of European ancestry in all stature groups are under-aged using WB joints compared to NWB joints. Short females are under-aged using WB joints compared to NWB joints. Individuals of African ancestry in all stature groups except the tallest are under-aged using WB joints compared to NWB joints. When separated by body mass, all males, individuals of European ancestry, and individuals of African

ancestry except for those in the lightest body mass groups are under-aged using WB joints compared to NWB joints. Females in the second lightest body mass group are under-aged using WB joints compared to NWB joints. Overall, WB joints are under-aged compared to NWB joints by approximately 2 to 6 years.

3.7 Additional Analyses

For three of the methods used in the analysis—the Passalacqua sacrum method, the Buckberry and Chamberlain auricular surface method, and the Rougé-Maillart et al. auricular surface and acetabulum method—individual traits such as transverse organization, surface texture, porosity, and apical activity were assessed and scored separately. Further analyses were conducted on each of these features to ascertain whether there are different patterns among the BMI, stature, and body mass groups for these individual traits. One-way ANOVAs were used for these analyses.

There are seven features of the sacrum scored using the Passalacqua method: fusion between S2 and S3 on a scale of 1 to 2, fusion between S1 and S2 on a scale of 1 to 2, surface changes on a scale of 1 to 2, apical changes on a scale of 1 to 2, S1 ring fusion on a scale of 1 to 3, microporosity on a scale of 1 to 2, and macroporosity on a scale of 1 to 2. The lowest scores categorize early maturation stages while the highest scores categorize progressive degenerative changes. Fusion between S2 and S3 and fusion between S1 and S2 were not evaluated in the qualitative analysis. When separated by BMI, ANOVA tests show there are only statistically significant differences among the BMI groups for apical changes (Table 123). Tukey's *b* post-hoc tests show that the apical change scores for underweight and normal-sized individuals are significantly lower than those of obese individuals (see Table 124).

		Sum of Squares	df	Mean Square	F	Sig.
Surface Changes	Between Groups	0.020	3	0.007	0.850	0.467
	Within Groups	5.933	755	0.008		
	Total	5.953	758			
Apical Changes	Between Groups	1.580	3	0.527	3.548	0.014
	Within Groups	111.930	754	0.148		
	Total	113.511	757			
S1 Ring Fusion	Between Groups	1.119	3	0.373	1.429	0.233
	Within Groups	195.949	751	0.261		
	Total	197.068	754			
Microporosity	Between Groups	0.289	3	0.096	1.044	0.372
	Within Groups	69.684	754	0.092		
	Total	69.974	757			
Macroporosity	Between Groups	0.531	3	0.177	0.748	0.523
	Within Groups	178.283	754	0.236		
	Total	178.814	757			

Table 123: One-way ANOVA results for the Passalacqua sacrum method individual scoring features for BMI groups.

	BMI	n	Subset	
			1	2
Surface Changes	Normal	406	1.99	
	Overweight	170	1.99	
	Underweight	134	2.00	
	Obese	49	2.00	
Apical Changes	Underweight	134	1.78	
	Normal	406	1.80	
	Overweight	170	1.86	1.86
	Obese	49		1.94
S1 Ring Fusion	Underweight	134	2.35	
	Normal	406	2.41	
	Overweight	170	2.47	
	Obese	49	2.50	
Microporosity	Overweight	170	1.88	
	Normal	406	1.89	
	Underweight	134	1.91	
	Obese	49	1.96	
Macroporosity	Underweight	134	1.35	
	Overweight	170	1.37	
	Normal	406	1.39	
	Obese	49	1.47	

Table 124: Tukey's *b* post-hoc tests for the Passalacqua method individual scoring features for BMI.

Similarly, when separated by stature, there are only significant differences among the BMI groups for apical changes (Table 125). Tukey's *b* post-hoc tests show that the apical change scores for the Group 3 are significantly lower compared to individuals in Groups 1 and 2 (see Table 126).

		Sum of Squares	df	Mean Square	F	Sig.
Surface Changes	Between Groups	0.010	3	0.003	0.418	0.740
	Within Groups	5.943	755	0.008		
	Total	5.953	758			
Apical Changes	Between Groups	2.081	3	0.694	4.694	0.003
	Within Groups	111.430	754	0.148		
	Total	113.511	757			
S1 Ring Fusion	Between Groups	0.446	3	0.149	0.568	0.636
	Within Groups	196.621	751	0.262		
	Total	197.068	754			
Microporosity	Between Groups	0.512	3	0.171	1.854	0.136
	Within Groups	69.461	754	0.092		
	Total	69.974	757			
Macroporosity	Between Groups	0.896	3	0.299	1.266	0.285
	Within Groups	177.918	754	0.236		
	Total	178.814	757			

Table 125: One-way ANOVA results for the Passalacqua sacrum method individual scoring features for stature groups.

	Stature	n	Subset	
			1	2
Surface Changes	Group 4	137	1.99	
	Group 3	222	1.99	
	Group 1	181	1.99	
	Group 2	219	2.00	
Apical Changes	Group 3	222	1.74	
	Group 4	137	1.80	1.80
	Group 1	181		1.86
	Group 2	219		1.87
S1 Ring Fusion	Group 4	137	2.39	
	Group 1	181	2.40	
	Group 2	219	2.40	
	Group 3	222	2.45	
Microporosity	Group 1	181	1.86	
	Group 3	222	1.90	
	Group 4	137	1.92	
	Group 2	219	1.92	
Macroporosity	Group 3	222	1.33	
	Group 4	137	1.39	
	Group 2	219	1.41	
	Group 1	181	1.41	

Table 126: Tukey's *b* post-hoc tests for the Passalacqua method individual scoring features for stature.

When separated by body mass, there are no significant differences among the body mass group scoring features for the Passalacqua method (Table 127).

		Sum of Squares	df	Mean Square	F	Sig.
Surface Changes	Between Groups	0.016	3	0.005	0.696	0.555
	Within Groups	5.936	755	0.008		
	Total	5.953	758			
Apical Changes	Between Groups	0.660	3	0.220	1.470	0.221
	Within Groups	112.851	754	0.150		
	Total	113.511	757			
S1 Ring Fusion	Between Groups	1.060	3	0.353	1.354	0.256
	Within Groups	196.007	751	0.261		
	Total	197.068	754			
Microporosity	Between Groups	0.147	3	0.049	0.530	0.662
	Within Groups	69.826	754	0.093		
	Total	69.974	757			
Macroporosity	Between Groups	1.150	3	0.383	1.627	0.182
	Within Groups	177.664	754	0.236		
	Total	178.814	757			

Table 127: One-way ANOVA results for the Passalacqua sacrum method individual scoring features for body mass groups.

There are five features of the auricular surface scored using the Buckberry and Chamberlain method: transverse organization on a scale of 1 to 5, surface texture on a scale of 1 to 5, microporosity on a scale of 1 to 3, macroporosity on a scale of 1 to 3, and apical activity on a scale of 1 to 3. The lowest scores categorize early maturation stages while the highest scores categorize progressive degenerative changes. When separated by BMI, one-way ANOVA tests show there are statistically significant differences among the BMI groups for three of the five traits: surface texture, microporosity, and apical activity (Table 128). Tukey's *b* post-hoc tests show that obese individuals have significantly higher scores for surface texture compared to the individuals in the other BMI groups; obese individuals have significantly higher microporosity scores compared to normal-size and overweight individuals; and underweight individuals have significantly lower apical activity compared to all BMI groups, obese individuals have significantly higher apical activity scores compared to all BMI groups, and normal-sized and overweight individuals apical activity scores are significantly different from underweight and obese individuals. Although not significant in the ANOVA, there are differences in the macroporosity scores; underweight individuals have significantly higher macroporosity scores compared to obese individuals (see Table 129).

		Sum of Squares	df	Mean Square	F	Sig.
Transverse Organization	Between Groups	3.795	3	1.265	1.493	0.215
	Within Groups	641.960	758	0.847		
	Total	645.755	761			
Surface Texture	Between Groups	25.537	3	8.512	7.014	<0.001
	Within Groups	919.924	758	1.214		
	Total	945.461	761			
Microporosity	Between Groups	7.476	3	2.492	5.199	0.001
	Within Groups	363.318	758	0.479		
	Total	370.794	761			
Macroporosity	Between Groups	3.353	3	1.118	2.373	0.069
	Within Groups	356.958	758	0.471		
	Total	360.311	761			
Apical Activity	Between Groups	10.221	3	3.407	8.773	<0.001
	Within Groups	294.377	758	0.388		
	Total	304.598	761			

Table 128: One-way ANOVA results for the Buckberry and Chamberlain method individual scoring features for BMI groups.

	BMI	n	Subset		
			1	2	3
Transverse Organization	Normal	405	3.65		
	Underweight	136	3.66		
	Overweight	172	3.75		
	Obese	49	3.92		
Surface Texture	Underweight	136	3.40		
	Normal	405	3.75		
	Overweight	172	3.76		
	Obese	49		4.18	
Microporosity	Normal	405	2.31		
	Overweight	172	2.42		
	Underweight	136	2.47	2.47	
	Obese	49		2.67	
Macroporosity	Obese	49	1.37		
	Overweight	172	1.45	1.45	
	Normal	405	1.53	1.53	
	Underweight	136		1.62	
Apical Activity	Underweight	136	2.04		
	Normal	405		2.27	
	Overweight	172		2.27	
	Obese	49			2.53

Table 129: Tukey's *b* post-hoc tests for the Buckberry and Chamberlain method individual scoring features for BMI.

When separated by stature, one-way ANOVA tests show there are statistically significant differences among stature groups for four of the five traits: surface texture, microporosity, macroporosity, and apical activity (Table 130). Tukey's *b* post-hoc tests show that individuals in Group 2 have significantly higher surface texture scores compared to individuals in Group 1; individuals in Group 3 have significantly lower microporosity scores compared to individuals in Group 4; individuals in Group 1 have significantly higher macroporosity scores compared to individuals in all other stature groups; and individuals in Group 1 also have significantly lower apical activity scores compared to individuals in all other stature groups (see Table 131).

		Sum of Squares	df	Mean Square	F	Sig.
Transverse Organization	Between Groups	2.746	3	0.915	1.079	0.357
	Within Groups	643.009	758	0.848		
	Total	645.755	761			
Surface Texture	Between Groups	9.736	3	3.245	2.629	0.049
	Within Groups	935.724	758	1.234		
	Total	945.461	761			
Microporosity	Between Groups	4.042	3	1.347	2.785	0.040
	Within Groups	366.752	758	0.484		
	Total	370.794	761			
Macroporosity	Between Groups	9.040	3	3.013	6.502	<0.001
	Within Groups	351.271	758	0.463		
	Total	360.311	761			
Apical Activity	Between Groups	16.028	3	5.343	14.034	<0.001
	Within Groups	288.570	758	0.381		
	Total	304.598	761			

Table 130: One-way ANOVA results for the Buckberry and Chamberlain method individual scoring features for stature groups.

	Stature	n	Subset	
			1	2
Transverse Organization	Group 1	184	3.64	
	Group 3	223	3.66	
	Group 2	219	3.69	
	Group 4	136	3.82	
Surface Texture	Group 1	184	3.54	
	Group 3	223	3.72	3.72
	Group 4	136	3.78	3.78
	Group 2	219		3.84
Microporosity	Group 3	223	2.28	
	Group 1	184	2.39	2.39
	Group 2	219	2.43	2.43
	Group 4	136		2.48
Macroporosity	Group 3	230	1.39	
	Group 2	219	1.49	
	Group 4	136	1.52	
	Group 1	196		1.69
Apical Activity	Group 1	184	1.99	
	Group 3	223		2.30
	Group 2	219		2.32
	Group 4	136		2.36

Table 131: Tukey's *b* post-hoc tests for the Buckberry and Chamberlain method individual scoring features for stature.

When separated by body mass, one-way ANOVA tests show there are statistically significant differences among stature groups for three of the five traits: surface texture, macroporosity, and apical activity (Table 132). Tukey's *b* post-hoc tests show that individuals in Group 1 have significantly lower surface texture scores compared to individuals in Groups 3 and 4; individuals in Group 1 have significantly higher macroporosity scores compared to individuals in Groups 3

and 4; individuals in Groups 1 and 2 have significantly lower apical activity scores compared to individuals in Groups 3 and 4. Although not statistically significant in the ANOVA, there are differences for transverse organization; individuals in Group 2 have significantly lower scores compared to individuals in Group 4 (see Table 133).

		Sum of Squares	df	Mean Square	F	Sig.
Transverse Organization	Between Groups	6.541	3	2.180	2.585	0.052
	Within Groups	639.214	758	0.843		
	Total	645.755	761			
Surface Texture	Between Groups	17.918	3	5.973	4.881	0.002
	Within Groups	927.542	758	1.224		
	Total	945.461	761			
Microporosity	Between Groups	2.606	3	0.869	1.789	0.148
	Within Groups	368.188	758	0.486		
	Total	370.794	761			
Macroporosity	Between Groups	7.953	3	2.651	5.703	0.001
	Within Groups	352.358	758	0.465		
	Total	360.311	761			
Apical Activity	Between Groups	18.576	3	6.192	16.409	<0.001
	Within Groups	286.023	758	0.377		
	Total	304.598	761			

Table 132: One-way ANOVA results for the Buckberry and Chamberlain method individual scoring features for body mass groups.

	Body Mass	n	Subset	
			1	2
Transverse Organization	Group 2	240	3.58	
	Group 1	165	3.67	3.67
	Group 3	201	3.74	3.74
	Group 4	156		3.83
Surface Texture	Group 1	165	3.47	
	Group 2	240	3.71	3.71
	Group 3	201		3.77
	Group 4	156		3.94
Microporosity	Group 2	240	2.32	
	Group 3	201	2.37	
	Group 4	156	2.45	
	Group 1	165	2.46	
Macroporosity	Group 3	201	1.39	
	Group 4	156	1.44	
	Group 2	240	1.57	1.57
	Group 1	165		1.66
Apical Activity	Group 1	165	2.07	
	Group 2	240	2.13	
	Group 3	201		2.35
	Group 4	156		2.47

Table 133: Tukey's *b* post-hoc tests for the Buckberry and Chamberlain method individual scoring features for body mass.

There are four features of the auricular surface and three features of the acetabulum scored using the Rougé-Maillart et al. method: transverse organization on a scale of 1 to 7, surface texture on a scale of 1 to 5, porosity on a scale of 1 to 5, and apical activity on a scale of 1 to 3 for the auricular surface; the acetabular rim on a scale of 1 to 5, the acetabular fossa porosity on a scale of 1 to 4, and the apical activity of the posterior cornus on a scale of 1 to 3 for the acetabulum. The lowest scores categorize early maturation stages while the highest scores categorize progressive degenerative changes. When separated by BMI, one-way ANOVA tests show there are statistically significant differences among BMI groups for two of the seven traits: surface texture and auricular surface apical activity (Table 134). Tukey's *b* post-hoc tests show that obese individuals have higher surface texture scores compared to individuals in the other BMI groups; and underweight individuals have significantly lower auricular surface apical activity compared to all other BMI groups, obese individuals have significantly higher apical activity scores compared to all other BMI groups, and normal-sized and overweight individuals are significantly different from underweight and obese individuals (Table 135).

		Sum of Squares	df	Mean Square	F	Sig.
Transverse Organization	Between Groups	2.466	3	0.822	0.905	0.438
	Within Groups	687.792	757	0.909		
	Total	690.258	760			
Surface Texture	Between Groups	23.864	3	7.955	6.565	<0.001
	Within Groups	917.258	757	1.212		
	Total	941.122	760			
Porosity	Between Groups	9.764	3	3.255	2.604	0.051
	Within Groups	946.115	757	1.250		
	Total	955.879	760			
Apical Activity	Between Groups	10.141	3	3.380	8.615	<0.001
	Within Groups	297.429	758	0.392		
	Total	307.570	761			
Acetabular Rim	Between Groups	5.943	3	1.981	2.632	0.051
	Within Groups	570.446	758	0.753		
	Total	576.390	761			
Acetabular Fossa	Between Groups	2.153	3	0.718	1.134	0.334
	Within Groups	479.460	758	0.633		
	Total	481.613	761			
Acetabular Apical Activity	Between Groups	1.937	3	0.646	1.420	0.236
	Within Groups	344.668	758	0.455		
	Total	346.605	761			

Table 134: One-way ANOVA results for the Rougé-Maillart et al. method individual scoring features for BMI groups.

	BMI	n	Subset		
			1	2	3
Transverse Organization	Normal	405	3.69		
	Underweight	136	3.70		
	Overweight	171	3.74		
	Obese	49	3.92		
Surface Texture	Underweight	136	3.47		
	Normal	405	3.74		
	Overweight	171	3.75		
	Obese	49		4.18	
Porosity	Overweight	171	2.83		
	Normal	405	2.89		
	Obese	49	2.94		
	Underweight	144	3.16		
Apical Activity	Underweight	136	2.04		
	Normal	405		2.26	
	Overweight	171		2.27	
	Obese	49			2.53
Acetabular Rim	Overweight	171	2.96		
	Obese	49	2.97		
	Normal	405	3.15		
	Underweight	136	3.17		
Acetabular Fossa	Overweight	171	1.85		
	Underweight	136	1.88		
	Normal	405	1.88		
	Obese	49	2.10		
Acetabular Apical Activity	Underweight	136	2.10		
	Normal	405	2.10		
	Overweight	171	2.18		
	Obese	49	2.27		

Table 135: Tukey's *b* post-hoc tests for the Rougé-Maillart et al. method individual scoring features for BMI.

When separated by stature, one-way ANOVA tests show there are statistically significant differences among the stature groups for three of the seven traits: porosity, auricular surface apical activity, and acetabular rim (Table 136). Tukey's *b* post-hoc tests show individuals in Groups 1, 2 and 4 are scored significantly higher than individuals in Group 3 for porosity. For auricular surface apical activity individuals in Group 1 are scored significantly lower than individuals in all other stature groups. For acetabular rim scores, individuals in Group 1 are scored significantly higher than individuals in all other stature groups. Although not statistically significant in the ANOVA, there are significant differences among the stature groups for the acetabular fossa scores; individuals in Group 1 have significantly lower scores compared to individuals in Group 4 (see Table 137).

		Sum of Squares	df	Mean Square	F	Sig.
Transverse Organization	Between Groups	1.814	3	0.605	0.665	0.574
	Within Groups	688.444	757	0.909		
	Total	690.258	760			
Surface Texture	Between Groups	9.163	3	3.054	2.481	0.060
	Within Groups	931.960	757	1.231		
	Total	941.122	760			
Porosity	Between Groups	23.652	3	7.884	6.402	<0.001
	Within Groups	932.227	757	1.231		
	Total	955.879	760			
Apical Activity	Between Groups	14.360	3	4.787	12.375	<0.001
	Within Groups	293.209	758	0.387		
	Total	307.570	761			
Acetabular Rim	Between Groups	14.700	3	4.900	6.613	<0.001
	Within Groups	561.689	758	0.741		
	Total	576.390	761			
Acetabular Fossa	Between Groups	4.444	3	1.481	2.353	0.071
	Within Groups	477.168	758	0.630		
	Total	481.613	761			
Acetabular Apical Activity	Between Groups	1.694	3	0.565	1.241	0.294
	Within Groups	344.911	758	0.455		
	Total	346.605	761			

Table 136: One-way ANOVA results for the Rougé-Maillart et al. method individual scoring features for stature groups.

	Stature	n	Subset	
			1	2
Transverse Organization	Group 1	184	3.68	
	Group 3	223	3.69	
	Group 2	218	3.72	
	Group 4	136	3.82	
Surface Texture	Group 1	184	3.54	
	Group 3	223	3.70	
	Group 4	136	3.78	
	Group 2	218	3.83	
Porosity	Group 3	223	2.67	
	Group 2	218		2.94
	Group 4	136		3.06
	Group 1	184		3.12
Apical Activity	Group 1	184	2.00	
	Group 3	223		2.30
	Group 2	218		2.31
	Group 4	136		2.35
Acetabular Rim	Group 3	223	2.95	
	Group 4	136	3.08	
	Group 2	218	3.10	
	Group 1	184		3.33
Acetabular Fossa	Group 1	184	1.74	
	Group 3	223	1.88	1.88
	Group 2	218	1.90	1.90
	Group 4	136		1.96
Acetabular Apical Activity	Group 4	136	2.07	
	Group 1	184	2.07	
	Group 3	223	2.12	
	Group 2	218	2.18	

Table 137: Tukey's *b* post-hoc tests for the Rougé-Maillart et al. method individual scoring features for stature.

When separated by body mass, one-way ANOVA tests show there are statistically significant differences among the body mass groups for four of the seven traits: surface texture, porosity, auricular surface apical activity, and acetabular rim (Table 138). Tukey's *b* post-hoc tests show that individuals in Group 1 have significantly lower surface texture scores compared to individuals in Group 4; individuals in Group 1 have significantly higher porosity scores compared to individuals in Groups 3 and 4; individuals in Groups 1 and 2 have significantly lower auricular surface apical activity scores compared to individuals in Groups 3 and 4; and individuals in Group 1 have significantly higher acetabular rim scores compared to individuals in Group 4 (see Table 139).

		Sum of Squares	df	Mean Square	F	Sig.
Transverse Organization	Between Groups	4.364	3	1.455	1.606	0.187
	Within Groups	685.893	757	0.906		
	Total	690.258	760			
Surface Texture	Between Groups	15.257	3	5.086	4.158	0.006
	Within Groups	925.865	757	1.223		
	Total	941.122	760			
Porosity	Between Groups	14.214	3	4.738	3.809	0.010
	Within Groups	941.665	757	1.244		
	Total	955.879	760			
Apical Activity	Between Groups	16.599	3	5.533	14.414	<0.001
	Within Groups	290.971	758	0.384		
	Total	307.570	761			
Acetabular Rim	Between Groups	9.382	3	3.127	4.181	0.006
	Within Groups	567.008	758	0.748		
	Total	576.390	761			
Acetabular Fossa	Between Groups	2.420	3	0.807	1.276	0.282
	Within Groups	479.193	758	0.632		
	Total	481.613	761			
Acetabular Apical Activity	Between Groups	1.362	3	0.454	0.997	0.394
	Within Groups	345.243	758	0.455		
	Total	346.605	761			

Table 138: One-way ANOVA results for the Rougé-Maillart et al. method individual scoring features for body mass groups.

	Body Mass	n	Subset	
			1	2
Transverse Organization	Group 2	240	3.61	
	Group 1	165	3.73	
	Group 3	201	3.77	
	Group 4	155	3.81	
Surface Texture	Group 1	165	3.49	
	Group 2	240	3.70	3.70
	Group 3	201	3.75	3.75
	Group 4	155		3.92
Porosity	Group 3	201	2.80	
	Group 4	155	2.85	
	Group 2	240	2.92	2.92
	Group 1	165		3.17
Apical Activity	Group 1	165	2.08	
	Group 2	240	2.13	
	Group 3	201		2.34
	Group 4	155		2.46
Acetabular Rim	Group 4	155	2.92	
	Group 3	201	3.08	3.08
	Group 2	240	3.15	3.15
	Group 1	165		3.25
Acetabular Fossa	Group 1	165	1.79	
	Group 2	240	1.85	
	Group 3	201	1.88	
	Group 4	155	1.96	
Acetabular Apical Activity	Group 2	240	2.09	
	Group 3	201	2.09	
	Group 1	165	2.11	
	Group 4	155	2.20	

Table 139: Tukey's b post-hoc tests for the Rougé-Maillart et al. method individual scoring features for body mass.

Chapter 4: Discussion

In the early 1920's, T. Wingate Todd developed the first recognized methods of estimating adult age at death from skeletal remains based on changes to the pubic symphysis and stage of fusion in cranial sutures. Since these early publications, many researchers have tested, revised, and created new methods of macroscopic age estimation based not only on the pubic symphysis and cranial sutures, but on the ribs, sacrum, auricular surface, acetabulum, and teeth. The success of these methods depends on their ability to correlate chronological age at death to biological age at death, both within and between populations, as well as their ability to produce accurate and precise results.

Several dozen validation and population-specific studies have shown that, while most methods work well on the skeletal collection they were developed on, there is variability in the results produced by these methods on individuals from differing populations and skeletal collections of similar spatial and temporal affiliation (for example, Katz and Suchey, 1989; Saunders et al., 1992; Russell et al., 1993; Loth et al., 1994; Baccino et al., 1999; Aktas et al., 2004; Djurić et al., 2007; Chen et al., 2008; Hens et al., 2008; Kimmerle et al., 2008; Rissech et al., 2011; Hens and Belcastro, 2012). Often age estimation methods are revised to reflect population differences, but in an archaeological or forensic context, it is not always possible to know the population of origin, or whether methods developed on contemporary populations should be applied to past populations. Assessing microscopic age tends to yield more accurate and precise estimations of an individual's age at death, especially for older individuals (Crowder and Rosella, 2007). However, microscopic methods are destructive, and permissions to perform these types of analyses are difficult to attain for archaeological remains. Biological anthropologists, therefore, often rely on evaluating macroscopic skeletal age changes.

To understand these macroscopic surface changes, we need to understand the changes occurring at the microscopic level. Age changes at the microscopic level reflect a multitude of complex interactions occurring at the same time—osteoblasts decrease in numbers while osteoclasts increase in numbers; osteocyte apoptosis increases, causing a weakening of the bone; the breakdown of collagen cross-links triggers increased osteoclast activity; non-collagenous proteins decrease in numbers, influencing bone's response rate to mechanical and homeostatic

signals; BMD decreases; osteon size decreases—and, to complicate matters further, these interactions are influenced by health, diet, disease, physical activity, and genetics. These microscopic age changes translate into a breakdown of bone integrity on the surface—striae become granular, bone becomes porous, surface texture changes from billowed or ridged to amorphous and smooth, bone becomes lighter, osteophytic lipping occurs—and these changes are evaluated to estimate age at death.

My dissertation investigates the ways in which age-related skeletal surface changes are influenced by BMI, stature, and body mass through evaluating the age estimations generated from eight methods on 764 individuals with varying statures and body masses. Reliability was determined through accuracy and precision analyses. The results from this study demonstrate that body size does influence our age standards, and should be considered when estimating age at death, especially for individuals who are categorized in the underweight BMI group, short stature group, or light body mass group. The Kunos et al. first rib method, Lovejoy et al. auricular surface method, and Suchey-Brooks method are the least affected by body size, and in the absence of body size specific information, these more reliable methods should be used when possible.

Section 4.1 summarizes the findings for each method assessed. Section 4.2 analyzes whether BMI, stature, body mass, or joint surface have an influence on skeletal age estimation. Section 4.3 assesses the implications of this research for future work in paleodemography, paleoanthropology, and forensic anthropology.

4.1 Age Method Summaries

4.1.1 Kunos et al. First Rib Method

Accuracy

BMI

For males and individuals of African ancestry, there are differences among the BMI group accuracy scores using the Kunos et al. method; however, these relationships are not significant. Similarly, for females, there are differences among the BMI group accuracy scores, but they are not significant. This can most likely be attributed to low sample sizes in the obese female group; there are only 13 females in the obese BMI group, and although obese females had higher

accuracy scores (6.69 years) compared to underweight (10.42 years), overweight (10.93 years), and normal-sized females (10.95 years), the low sample sizes most likely contributed to this non-significant relationship. For individuals of European ancestry, individuals in the obese BMI group have higher accuracy scores (7.88 years) compared to underweight, normal-sized, and overweight individuals (range 9.25 years to 10.90 years). These results indicate that BMI is not a significant factor influencing the accuracy scores of the Kunos et al. method except for obese individuals of European ancestry.

Stature

For males, females, individuals of European ancestry, and individuals of African ancestry there are no differences in accuracy scores among stature groups. Therefore, stature is not a factor influencing the accuracy scores using the Kunos et al. method.

Body Mass

For males and individuals of European ancestry, there are differences among the body mass group accuracy scores using the Kunos et al. method. For males, these differences are not significant among the groups, but for individuals of European ancestry, individuals in the lightest body mass group have significantly lower accuracy scores (11.20 years) compared to individuals of European ancestry in the heaviest body mass group (8.82 years). For females and individuals of African ancestry, there are no differences in accuracy scores among body mass groups. These results indicate that accuracy scores are only significantly different for individuals of European ancestry in the lightest and heaviest body mass groups.

Bias

BMI

For males, females, individuals of European ancestry, and individuals of African ancestry, there are differences among the BMI groups for bias scores using the Kunos et al. method.

Underweight males have significantly lower bias scores (0.03 years) compared to obese males (5.96 years). For females and individuals of African ancestry, there are no significant differences among the BMI group bias scores; however, low sample sizes in the obese group likely affected these results. For females, overweight (4.23 years) and obese females (4.31 years) are over-aged by approximately 4 years compared to normal-sized females (0.42 years), and similarly, obese

individuals of African ancestry (8.40 years) are over-aged by approximately 3 years compared to underweight individuals of African ancestry (5.08 years). For individuals of European ancestry, underweight individuals of European ancestry (-1.99 years) are under-aged significantly compared to overweight (4.09 years) and obese individuals of European ancestry (4.94 years). These results show that underweight males and individuals of European ancestry are under-aged by 6 to 7 years, and underweight females and individuals of African ancestry are under-aged by 3 to 4 years, though not significant.

Stature

For males and individuals of European ancestry, there are differences among the stature group bias scores using the Kunos et al. method. Males in the shortest stature group (0.49 years) have significantly lower bias scores compared to males in the tallest stature group (5.82 years). For individuals of European ancestry, individuals in the shortest stature group (-1.93 years) under-aged significantly compared to individuals in all other stature groups (range 2.67 years to 5.92 years). For females and individuals of African ancestry, there are no significant differences among the bias scores for individuals of differing statures. These results show that stature does influence the bias scores of males and individuals of European ancestry for the Kunos et al. method; males and individuals of European ancestry in the shortest stature group are under-aged by approximately 5 to 7 years. Stature is not a factor influencing the bias scores for females and individuals of African ancestry.

Body Mass

For males, females, individuals of European ancestry, and individuals of African ancestry, there are differences among the body mass group bias scores using the Kunos et al. method. Males and individuals of European ancestry in the two lightest body mass groups (0.93 years and 1.74 years, and -2.50 years and 0.52 years) have significantly lower bias scores compared to males and individuals of European ancestry in the two heaviest body mass groups (5.34 years and 6.11 years, and 4.99 years and 5.16 years). Females in the lightest body mass group (-0.35 years) are under-aged compared to females in the two heaviest body mass groups (4.50 years and 5.79 years), but these differences are not significant due to small sample sizes. Similarly, for individuals of African ancestry, there are differences among the body mass group bias scores, but they are not significant. These results indicate that males and individuals of European ancestry in

the lightest body mass groups are under-aged by 6 to 7 years, while there are no significant differences in bias scores for females and individuals of African ancestry due to sample sizes.

	Accuracy	Bias
BMI	<ul style="list-style-type: none"> • BMI does not influence the accuracy scores among males, individuals of European ancestry, and individuals of African ancestry • Trends towards higher accuracy scores among obese females, but is not significant 	<ul style="list-style-type: none"> • Males and individuals of European ancestry in the underweight BMI group are under-aged by 6 to 7 years • Females and individuals of African ancestry in the underweight BMI group are under-aged by 3 to 4 years (though not significant)
Stature	<ul style="list-style-type: none"> • Stature does not affect accuracy scores for males, females, individuals of European ancestry, or individuals of African ancestry 	<ul style="list-style-type: none"> • Males and individuals of European ancestry in the shortest stature group are significantly under-aged by approximately 5 to 7 years • Stature does not affect bias scores for females and individuals of African ancestry
Body Mass	<ul style="list-style-type: none"> • Individuals of European ancestry in the lightest body mass group have significantly lower accuracy scores compared to individuals of European ancestry in the heaviest body mass group • Body mass does not affect accuracy scores for or males, females, and individuals of African ancestry 	<ul style="list-style-type: none"> • Males, females, and individuals of European ancestry in the lightest body mass groups are under-aged by 5 to 7 years • Body mass does not affect bias scores for individuals of African ancestry

Table 140: Summary of findings for the Kunos et al. method.

4.1.2 DiGangi et al. First Rib Method

Accuracy

BMI

For males, individuals of European ancestry, and individuals of African ancestry, there are differences among the BMI group accuracy scores using the DiGangi et al. method. Obese males have significantly higher accuracy scores (11.54 years) compared to normal-sized (15.10 years) and underweight males (16.99 years), and obese individuals of European ancestry (13.09 years) have significantly higher accuracy scores compared to underweight individuals of European ancestry (18.75 years). For individuals of African ancestry, obese individuals (5.60 years) show significantly higher accuracy scores than underweight individuals (14.57 years). For females, there are differences among the BMI group accuracy scores, but they are not significant. Again,

this can most likely be attributed to low sample sizes in the obese female group. Although obese females had higher accuracy scores (13.31 years) compared to underweight (17.08 years) and normal-sized females (17.36 years), the low sample sizes most likely contributed to this non-significant relationship. These results indicate that BMI only influences the accuracy scores of males, individuals of European ancestry, and individuals of African ancestry in the obese BMI group compared to males, individuals of European ancestry, and individuals of African ancestry in the underweight BMI group using the DiGangi et al. method; this pattern is similar for females, but not significant.

Stature

For males and individuals of European ancestry, there are differences among the stature group accuracy scores using the DiGangi et al. method. For males, these results are not significant. For individuals of European ancestry, individuals in the tallest stature group (13.76 years) have significantly higher accuracy scores compared to individuals in the shortest stature group (18.83 years). For females and individuals of African ancestry, there are no differences in stature group accuracy scores. Therefore, stature only affects the accuracy scores of individuals of European ancestry; tall individuals of European ancestry have higher accuracy scores compared to short individuals of European ancestry. Stature does not influence the accuracy scores of males, females, and individuals of African ancestry using the DiGangi et al. method.

Body Mass

For males and individuals of European ancestry, there are differences among the body mass group accuracy scores using the DiGangi et al. method. Males in the two heaviest body mass groups (11.71 years and 13.47 years) have significantly higher accuracy scores compared to males in the two lightest body mass groups (16.72 years and 17.14 years). For individuals of European ancestry, individuals in the heaviest body mass group have significantly higher accuracy scores (12.23 years) compared to individuals in the lightest body mass groups (18.21 years to 19.78 years). For females and individuals of African ancestry, there are no differences in body mass group accuracy scores. These results indicate that body mass only influences the accuracy scores of males and individuals of European ancestry in the heaviest body mass groups compared to males and individuals of European ancestry in the lightest body mass groups using the DiGangi et al. method.

Bias

BMI

For males and individuals of European ancestry, there are differences among the BMI groups for bias scores using the DiGangi et al. method. Underweight males are significantly under-aged (-14.49 years) compared to obese males (-8.23 years), and underweight individuals of European ancestry are significantly under-aged (-18.43 years) compared to overweight (-11.73 years) and obese individuals of European ancestry (-9.74 years). For females and individuals of African ancestry, there are differences among the BMI group bias scores, but they are not significant. Underweight females and individuals of African ancestry (-16.71 years and -10.65 years) are under-aged compared to obese individuals of African ancestry (-11.15 years and -5.60 years); however, due to small sample sizes, this relationship was not significant. These results show that males and individuals of European ancestry in the underweight BMI group are under-aged by 6 to 9 years compared to males and individuals of European ancestry in the obese BMI group, and females and individuals of African ancestry in the underweight BMI group are under-aged by 5 to 6 years compared to females and individuals of African ancestry in the obese BMI group, though they not significant.

Stature

For males, there are differences among the stature group bias scores using the DiGangi et al. method, but they are not significant. For individuals of European ancestry, there are differences in the bias scores, with individuals of European ancestry in the shortest stature group (-17.20 years) under-aged significantly compared to tall individuals of European ancestry (-10.86 years). For females and individuals of African ancestry, there are no significant differences among the bias scores for individuals of differing statures. These results indicate that stature only influences the bias scores of individuals of European ancestry; short individuals of European ancestry are under-aged compared to tall individuals of European ancestry by approximately 7 years. Stature does not affect the bias scores of males, females, and individuals of African ancestry for the DiGangi et al. method.

Body Mass

For males, there are differences among the body mass group bias scores using the DiGangi et al. method, but they are not significant. For individuals of European ancestry, there are differences

among the body mass group bias scores; individuals of European ancestry in the two lightest body mass groups (-19.70 years and -16.47 years) are significantly under-aged compared to individuals of European ancestry in the two heaviest body mass groups (-11.45 years and -10.40 years). For females, there are differences among the body mass group bias scores using the DiGangi et al. method, but they are not significant. Females in the lightest body mass group (-18.33 years) are under-aged by 5 to 7 years compared to females in all other body mass groups (-13.37 years and -11.69 years), but these differences are not significant due to small sample sizes. For individuals of African ancestry, there are no differences among the body mass group bias scores using the DiGangi et al. method. These results indicate that individuals of European ancestry and females in the lightest body mass groups are under-aged by 5 to 8 years (though not significant for females), while there are no differences for males and individuals of African ancestry for the DiGangi et al. method.

	Accuracy	Bias
BMI	<ul style="list-style-type: none"> • Males, individuals of European ancestry, and individuals of African ancestry in the obese BMI group have significantly higher accuracy scores compared to males, individuals of European ancestry, and individuals of African ancestry in the underweight BMI group • This pattern is similar for females, but not significant 	<ul style="list-style-type: none"> • Males and individuals of European ancestry in the underweight BMI group are under-aged by 6 to 9 years • Females and individuals of African ancestry in the underweight BMI group are under-aged by 5 to 6 years (though not significant)
Stature	<ul style="list-style-type: none"> • Tall individuals of European ancestry have higher accuracy scores compared to short individuals of European ancestry • Stature does not affect the accuracy scores of males, females, and individuals of African ancestry 	<ul style="list-style-type: none"> • Short individuals of European ancestry are under-aged compared to tall individuals of European ancestry by approximately 7 years • Stature does not affect the bias scores of males, females, and individuals of African ancestry
Body Mass	<ul style="list-style-type: none"> • Males and individuals of European ancestry in the heaviest body mass groups have higher accuracy scores compared to males and individuals of European ancestry in the lightest body mass groups • Body mass does not affect the accuracy scores of females and individuals of African ancestry 	<ul style="list-style-type: none"> • Individuals of European ancestry and females in the lightest body mass groups are under-aged by 5 to 8 years (though not significant for females) • Body mass does not affect the bias scores of males and individuals of African ancestry

Table 141: Summary of findings for the DiGangi et al. method.

4.1.3 İşcan et al. Fourth Rib Method

Accuracy

BMI

For males, females, and individuals of African ancestry, there are differences among the BMI group accuracy scores using the İşcan et al. method. Underweight males have significantly lower accuracy scores (13.74 years) compared to males in all other BMI groups (range 9.46 years to 10.18 years), underweight females (15.82 years) have lower accuracy scores compared to overweight (9.42 years) and obese females (9.85 years), and underweight individuals of African ancestry (16.18 years) have lower accuracy scores compared to overweight individuals of African ancestry (7.61 years). For individuals of European ancestry, there are no differences among the BMI group accuracy scores. These results indicate that BMI only influences the accuracy scores of males, females, and individuals of African ancestry in the underweight BMI

group compared to males, females, and individuals of African ancestry in the overweight and obese BMI groups using the İşcan et al. method.

Stature

For males, females, and individuals of African ancestry, there are no differences among the stature group BMI accuracy scores. For individuals of European ancestry, there are differences among the accuracy scores; individuals in the shortest stature group (13.31 years) have significantly lower accuracy scores compared to individuals in the tallest stature groups (range 10.17 years to 10.40 years). Therefore, stature only affects the accuracy scores of individuals of European ancestry for the İşcan et al. method.

Body Mass

For males and individuals of European ancestry, there are differences among the body mass group accuracy scores using the İşcan et al. method. Males in the lightest body mass group (13.13 years) have significantly lower accuracy scores compared to males in the two heaviest body mass groups (11.71 years and 13.47 years for males), and individuals of European ancestry in the lightest body mass group (12.88 years) have significantly lower accuracy scores compared to individuals of European ancestry in the second heaviest body mass group (9.63 years). For females and individuals of African ancestry, there are no differences in the body mass accuracy scores. These results show that body mass only influences the accuracy scores of males and individuals of European ancestry in the heaviest body mass groups compared to males and individuals of European ancestry in the lightest body mass groups for the İşcan et al. method.

Bias

BMI

For males and females, there are differences among the BMI groups for bias scores using the İşcan et al. method. Males and females in the underweight BMI group have significantly lower bias scores (-9.91 years and -14.87 years) compared to males and females in all other BMI groups (range 0.08 years to 3.68 years for males, range -4.27 years to -0.72 years for females). For individuals of European ancestry and individuals of African ancestry, there are differences among the BMI group bias scores. Individuals of European ancestry and individuals of African ancestry in the underweight BMI group have significantly lower bias scores (-11.78 years and -

10.63 years) compared to individuals in all other BMI groups (range -1.38 years to 2.50 years for individuals of European ancestry, -0.60 years to 3.18 years for individuals of African ancestry). These results show that males, females, individuals of European ancestry, and individuals of African ancestry in the underweight BMI group are under-aged by 10 to 15 years compared to individuals in all other BMI groups using the İşcan et al. method.

Stature

For males and individuals of European ancestry, there are differences among bias scores. Males and individuals of European ancestry in the short stature group are significantly under-aged (-3.65 years and -5.63 years) compared to males in all other stature groups (range 0.70 years to 2.30 years for males, -0.09 years to 3.47 years for individuals of European ancestry). For females and individuals of African ancestry, there are no significant differences among the stature group bias scores. These results indicate that stature only influences the bias scores of males and individuals of European ancestry in the shortest stature group, who are under-aged by approximately 3 to 5 years. Stature does not affect the bias scores of females and individuals of African ancestry for the İşcan et al. method.

Body Mass

For males, females, individuals of European ancestry, and individuals of African ancestry, there are differences among the body mass group bias scores using the İşcan et al. method. Males, individuals of European ancestry, and individuals of African ancestry in the lightest body mass group are significantly under-aged (-6.97 years, -7.62 years, and -9.73 years) compared to males in all other body mass groups (range 1.57 years to 3.62 years for males, -0.37 years to 2.32 for individuals of European ancestry, and 0.60 years to 4.54 years for individuals of African ancestry). Females in the lightest body mass group (-9.67 years) are under-aged compared to females in the second lightest body mass group (0.21 years). These results indicate that males, individuals of European ancestry, and individuals of African ancestry in the lightest body mass groups are under-aged by 7 to 15 years, while females in the lightest body mass group are under-aged by 9 years compared to females in the second lightest body mass group for the İşcan et al. method.

	Accuracy	Bias
BMI	<ul style="list-style-type: none"> • Males, females, and individuals of African ancestry in the underweight BMI group have significantly lower accuracy scores compared to individuals in the overweight and obese BMI groups • BMI does not affect the accuracy scores for individuals of European ancestry 	<ul style="list-style-type: none"> • Males, females, individuals of European ancestry, and individuals of African ancestry in the underweight BMI group are under-aged by 10 to 12 years compared to individuals in all other BMI groups
Stature	<ul style="list-style-type: none"> • Individuals of European ancestry in the short stature group have lower accuracy scores compared to individuals in the tall stature group • Stature does not affect the accuracy scores of males, females, and individuals of African ancestry 	<ul style="list-style-type: none"> • Males and individuals of European ancestry in the short stature group are under-aged by approximately 3 to 5 years • Stature does not affect the bias scores of females and individuals of African ancestry
Body Mass	<ul style="list-style-type: none"> • Males and individuals of European ancestry in the heaviest body mass groups have higher accuracy scores compared to males and individuals of European ancestry in the lightest body mass groups • Body mass does not affect the accuracy scores for females and individuals of African ancestry 	<ul style="list-style-type: none"> • Males, individuals of European ancestry, and individuals of African ancestry in the lightest body mass groups are under-aged by 7 to 15 years • Females in the lightest body mass group are under-aged by 9 years compared to females in the second lightest body mass group

Table 142: Summary of findings for the İşcan et al. method.

4.1.4 Passalacqua Sacrum Method

Accuracy

BMI

For males, females, individuals of European ancestry, and individuals of African ancestry, there are differences among the BMI group accuracy scores. Underweight males (13.74 years) have significantly lower accuracy compared to overweight males (9.46 years). For females, individuals of European ancestry, and individuals of African ancestry, the differences among BMI group accuracy scores are not significant. These results indicate that BMI only influences the accuracy scores between underweight and overweight males for the Passalacqua method.

Stature

For males, females, and individuals of African ancestry, there are no differences in accuracy scores among stature groups. For individuals of European ancestry, there are differences among

the accuracy scores among the stature groups, but they are not significant. Therefore, stature plays no role in determining accuracy scores using the Passalacqua method.

Body Mass

For males and individuals of European ancestry, there are differences among the body mass group accuracy scores. Males in the lightest body mass (12.80 years) group have significantly lower accuracy scores compared to males in the heaviest body mass group (10.04 years). For females and individuals of African ancestry, there are no differences in the body mass group accuracy scores. These results indicate that accuracy scores are only significantly different between males in the lightest and heaviest body mass groups for the Passalacqua method.

Bias

BMI

For males, females, individuals of European ancestry, and individuals of African ancestry, there are differences among the BMI group bias scores using the Passalacqua method. Males and individuals of European ancestry in the underweight BMI group are significantly under-aged (-5.85 years and -5.88 years) compared to males and individuals of European ancestry (1.36 years and 0.48 years) in the overweight BMI group. For females and individuals of African ancestry, the differences are not significant. These results show that males and individuals of European ancestry in the underweight BMI group are under-aged by 5 to 6 years compared to males and individuals of European ancestry in the overweight BMI group, and there are no differences in bias scores among BMI groups for females and individuals of African ancestry using the Passalacqua method.

Stature

For males and individuals of European ancestry, there are differences among the stature group bias scores, but these differences are not significant. For females and individuals of African ancestry, there are no significant differences among the stature group bias scores. These results indicate that stature does not influence bias scores for the Passalacqua method.

Body Mass

For males, females, and individuals of European ancestry, there are differences among the body mass group bias scores. Males and individuals of European ancestry in the lightest body mass

group (-4.35 years and -4.99 years) are significantly under-aged compared to males in the two heaviest body mass groups (0.94 years and 1.30 years for males, -0.37 years and 0.15 years for individuals of European ancestry). For females, there are no significant differences among the body mass group bias scores. For individuals of African ancestry, there are no differences among the body mass group bias scores. These results indicate that males and individuals of European ancestry in the lightest body mass groups are under-aged by 4 to 5 years compared to males and individuals of European ancestry in the two heaviest body mass groups, while there are no differences for females and individuals of African ancestry using the Passalacqua method.

	Accuracy	Bias
BMI	<ul style="list-style-type: none"> • Underweight males have lower accuracy scores for compared to overweight males • BMI does not influence the accuracy scores among females, individuals of European ancestry, and individuals of African ancestry 	<ul style="list-style-type: none"> • Males and individuals of European ancestry in the underweight BMI group are under-aged by 5 to 6 years • There are no differences in bias scores for females and individuals of African ancestry
Stature	<ul style="list-style-type: none"> • Stature does not influence accuracy scores 	<ul style="list-style-type: none"> • Stature does not influence bias scores
Body Mass	<ul style="list-style-type: none"> • Males in the lightest group have lower accuracy compared to males in the heaviest group • There are no differences among body mass group accuracy scores for females, individuals of European ancestry, or individuals of African ancestry 	<ul style="list-style-type: none"> • Males and individuals of European ancestry in the lightest body mass groups are under-aged by 4 to 5 years compared to males and individuals of European ancestry in the two heaviest body mass groups • There are no differences in bias scores for females and individuals of African ancestry

Table 143: Summary of findings for the Passalacqua method.

4.1.5 Lovejoy et al. Auricular Surface Method

Accuracy

BMI

For males, individuals of European and African ancestry, there are differences among the BMI group accuracy scores; however, these relationships are not significant. For females, there are differences among the BMI group accuracy scores. Obese females (11.62 years) have significantly lower accuracy scores compared to females in all other BMI groups (range 6.38

years to 8.48 years). These results indicate that BMI only influences the accuracy scores of obese females compared to females in the other BMI groups for the Lovejoy et al. method.

Stature

For males, females, and individuals of African ancestry there are no differences in accuracy scores among stature groups. For individuals of European ancestry, there are differences among the stature group accuracy scores, but they are not significant. Therefore, stature does not influence accuracy scores using the Lovejoy et al. method.

Body Mass

For males and individuals of European ancestry, there are differences among the body mass group accuracy scores; however, these differences are not significant among the groups. For females and individuals of African ancestry, there are no differences in accuracy scores among body mass groups. These results indicate that accuracy scores are not significantly different among the body mass groups using the Lovejoy et al. method.

Bias

BMI

For males, individuals of European ancestry, and individuals of African ancestry, there are differences among the BMI groups for bias scores; however, they are not significant. For females, there are no differences among the BMI group bias scores. These results indicate that BMI does not influence bias scores for the Lovejoy et al. method.

Stature

For males and individuals of European ancestry, there are differences among bias scores, with males and individuals of European ancestry in the shortest stature group (-7.62 years and -8.24 years) having significantly lower bias scores compared to males in the tallest stature group (-2.94 years and -3.17 years). For females and individuals of African ancestry, there are no significant differences among the bias scores for individuals of differing statures. These results indicate that stature influences the bias scores of males and individuals of European ancestry for the Lovejoy et al. method; males and individuals of European ancestry in the short stature group are significantly under-aged by approximately 4 to 5 years compared to males and individuals of

European ancestry in the tall stature group. Stature is not a factor that influences the bias scores of females and individuals of African ancestry.

Body Mass

For males, females, and individuals of European ancestry, there are differences among the body mass group bias scores. Males in the lightest body mass groups (-7.03 years) have significantly lower bias scores compared to males in the second heaviest body mass groups (-3.72 years). Females in the lightest body mass group (-8.44 years) have significantly lower bias scores compared to females in the two heaviest body mass groups (-3.77 years and -3.72 years), but these differences are not significant due to small sample sizes. Individuals of European ancestry in the lightest body mass group (-8.86 years) have significantly lower bias scores compared to individuals of European ancestry in the two heaviest body mass groups (-5.15 years and -4.78 years). For individuals of African ancestry, there are no significant differences among the body mass group bias scores. These results indicate that males, females, and individuals of European ancestry in the lightest body mass groups are under-aged by 3 to 5 years, while there are no differences among body mass bias scores for individuals of African ancestry using the Lovejoy et al. method.

	Accuracy	Bias
BMI	<ul style="list-style-type: none"> • Obese females have significantly lower accuracy scores compared females in the other BMI groups • BMI does not influence the accuracy scores among males, individuals of European ancestry, and individuals of African ancestry 	<ul style="list-style-type: none"> • BMI does not influence bias scores
Stature	<ul style="list-style-type: none"> • Stature does not influence accuracy scores 	<ul style="list-style-type: none"> • Males and individuals of European ancestry in the short stature group are significantly under-aged by 4 to 5 years compared to males and individuals of European ancestry in the tall stature group • Stature does not influence bias scores for females and individuals of African ancestry
Body Mass	<ul style="list-style-type: none"> • Individuals of European ancestry in the lightest body mass group have lower accuracy scores compared to individuals of European ancestry in the heaviest body mass group • Body mass does not influence accuracy scores for males, females, or individuals of African ancestry 	<ul style="list-style-type: none"> • Males, females, and individuals of European ancestry in the lightest body mass groups are under-aged by 3 to 5 years • Body mass does not influence bias scores for individuals of African ancestry

Table 144: Summary of findings for the Lovejoy et al. method.

4.1.6 Buckberry and Chamberlain Auricular Surface Method

Accuracy

BMI

For males, individuals of European ancestry, and individuals of African ancestry, there are no differences in accuracy scores among BMI groups. For females, there are differences among the BMI group accuracy scores; however, this relationship is not significant. These results indicate that BMI does not influence the accuracy scores for the Buckberry and Chamberlain method.

Stature

For males and individuals of European ancestry, there are differences among the stature group accuracy scores; males and individuals of European ancestry in the short stature groups (9.44 years and 8.85 years) have higher accuracy scores compared to males and individuals of European ancestry in the tall stature groups (12.94 years and 13.35 years). For females and

individuals of African ancestry, there are no differences in stature group accuracy scores. These results indicate that stature only influences the accuracy scores of males and individuals of European ancestry in the short stature group compared to males and individuals of European ancestry in the tall stature groups for the Buckberry and Chamberlain method.

Body Mass

For males and individuals of European ancestry, there are differences among the body mass group accuracy scores; however, these differences are not significant among the groups. For females and individuals of African ancestry, there are no differences among stature group accuracy scores. These results indicate that body mass does not influence the accuracy scores for the Buckberry and Chamberlain method.

Bias

BMI

For males, females, individuals of European ancestry, and individuals of African ancestry, there are differences among the BMI groups for bias scores; however, they are not significant except for individuals of European ancestry. Underweight individuals of European ancestry (1.46 years) have significantly lower bias scores compared to overweight (7.60 years) and obese individuals of European ancestry (7.79 years). These results indicate that BMI only affects bias scores of individuals of European ancestry; underweight individuals of European ancestry are under-aged by 6 years compared to overweight and obese individuals. BMI does not influence the bias scores for males, females, and individuals of African ancestry using the Buckberry and Chamberlain method.

Stature

For males and individuals of European ancestry, there are differences among stature group bias scores. Males in the shortest stature group (3.40 years) have significantly lower bias scores compared to males in the tallest stature group (10.84 years). Short individuals of European ancestry (1.38 years) have significantly lower bias scores compared to tall individuals of European ancestry (11.88 years) and individuals of European ancestry in the second shortest stature group (6.32 years). For females and individuals of African ancestry, there are no significant differences among the stature group bias scores. These results indicate that stature

influences the bias scores of males and individuals of European ancestry; short males and individuals of European ancestry are significantly under-aged by approximately 7 to 12 years compared to tall males and individuals of European ancestry. Stature does not influence the bias scores of females and individuals of African ancestry for the Buckberry and Chamberlain method.

Body Mass

For males, females, and individuals of European ancestry, there are significant differences among the body mass group bias scores. Males and individuals of European ancestry in the lightest body mass groups (3.95 years and 1.08 years) have significantly lower bias scores compared to males in the heaviest body mass groups (8.53 years and 9.28 years for males, 7.31 years and 8.78 years for individuals of European ancestry). Females in the lightest body mass group (2.16 years) have significantly lower bias scores compared to females in the two heaviest body mass groups (6.31 years and 8.03 years), but these differences are not significant due to small sample sizes. For individuals of African ancestry, there are no significant differences among the body mass group bias scores. These results indicate that males, females, and individuals of European ancestry in the lightest body mass groups are under-aged by 4 to 8 years, while there are no differences for individuals of African ancestry using the Buckberry and Chamberlain method.

	Accuracy	Bias
BMI	<ul style="list-style-type: none"> • BMI does not influence the accuracy scores 	<ul style="list-style-type: none"> • Underweight individuals of European ancestry are under-aged by 6 years compared to overweight and obese individuals of European ancestry • BMI does not influence the bias scores for males, females, and individuals of African ancestry
Stature	<ul style="list-style-type: none"> • Males and individuals of European ancestry in the short stature group have lower accuracy scores compared to males and individuals of European ancestry in the tall stature group • Stature does not influence accuracy scores of females and individuals of African ancestry 	<ul style="list-style-type: none"> • Males and individuals of European ancestry in the short stature group are significantly under-aged by approximately 7 to 12 years compared to males and individuals of European ancestry in the tall stature group • Stature does not influence the bias scores of females and individuals of African ancestry
Body Mass	<ul style="list-style-type: none"> • Body mass does not influence accuracy scores 	<ul style="list-style-type: none"> • Males, females, and individuals of European ancestry in the lightest body mass groups are under-aged by 4 to 8 years • Body mass does not influence the bias scores for individuals of African ancestry

Table 145: Summary of findings for the Buckberry and Chamberlain method.

4.1.7 Rougé-Maillart et al. Auricular Surface and Acetabulum Method

Accuracy

BMI

For males, and individuals of European ancestry there are differences among the BMI group accuracy scores. Obese males (7.27 years) have significantly higher accuracy scores compared to normal-sized (10.49 years) and underweight males (12.19 years). Obese individuals of European ancestry (8.38 years) have significantly higher accuracy scores compared to underweight individuals of European ancestry (12.84 years). For females and individuals of African ancestry, there are differences among the BMI group accuracy scores; however, they are not significant. These results indicate that BMI only influences the accuracy scores of underweight males and individuals of European ancestry, and it does not influence the accuracy scores for females and individuals of African ancestry for the Rougé-Maillart et al. method.

Stature

For males and individuals of European ancestry, there are differences in accuracy scores among stature groups. Tall males (8.71 years) have significantly higher accuracy scores compared to short males (12.09 years), and tall individuals of European ancestry (8.81 years) have significantly higher accuracy scores compared to short individuals of European ancestry (12.29 years) and individuals of European ancestry in the second tallest stature group (11.40 years). For females and individuals of African ancestry, there are no differences in stature group accuracy scores. These results indicate that stature only influences the accuracy scores of males and individuals of European ancestry in the short stature group compared to males and individuals of European ancestry in the tall stature group for the Rougé-Maillart et al. method.

Body Mass

For males and individuals of European ancestry, there are differences among the body mass group accuracy scores. Males and individuals of European ancestry in the two heaviest body mass groups (8.39 years and 9.31 years for males, 8.55 years and 9.37 years for individuals of European ancestry) have significantly higher accuracy scores compared to males and individuals of European ancestry in the two lightest body mass groups (11.95 years and 12.20 years for males, 11.93 years and 12.77 years for individuals of European ancestry). For females and individuals of African ancestry, there are no differences in stature group accuracy scores. These results indicate that body mass influences the accuracy scores of males and individuals of European ancestry in the lightest body mass groups for the Rougé-Maillart et al. method.

Bias

BMI

For males and individuals of African ancestry, there are differences among the BMI groups for bias scores; however, they are not significant. For individuals of European ancestry, there are differences among the BMI group bias scores; underweight individuals of European ancestry (-9.22 years) have significantly lower bias scores compared to overweight individuals of European ancestry (-1.14 years). For females, there are no differences among the BMI group bias scores. These results indicate that BMI only influences the bias scores of individuals of European ancestry; underweight individuals of European ancestry are under-aged by 8 years compared to

overweight individuals of European ancestry. BMI does not influence bias scores for males, females, and individuals of African ancestry using the Rougé-Maillart et al. method.

Stature

For males and individuals of European ancestry, stature provides a contribution to the differences among bias scores. Males in the shortest stature group (-8.67 years) have significantly lower bias scores compared to males in the tallest stature group (-0.37 years). Individuals of European ancestry in the shortest stature group (-9.61 years) have significantly lower bias scores compared to individuals of European ancestry in the tallest stature group (-0.47 years). For females and individuals of African ancestry, there are no significant differences among the bias scores for individuals of differing statures. These results indicate that stature only influences the bias scores of males and individuals of European ancestry for the Rougé-Maillart et al. method. Stature does not influence the bias scores for females and individuals of African ancestry.

Body Mass

For males, females, and individuals of European ancestry, there are differences among the body mass group bias scores. Males and individuals of European ancestry in the lightest body mass groups (-7.15 years and -10.11 years) have significantly lower bias scores compared to males in the heaviest body mass groups (-2.81 years and -2.71 years for males, and -4.40 years and -3.31 years). Females in the lightest body mass group (-8.28 years) have significantly lower bias scores compared to females in the two heaviest body mass groups (-3.34 years and -2.94 years), but these differences are not significant due to small sample sizes. For individuals of African ancestry, there are no significant differences among the body mass group bias scores. These results indicate that males, females, and individuals of European ancestry in the lightest body mass groups are under-aged by 5 to 6 years, while there are no differences for individuals of African ancestry using the Rougé-Maillart et al. method.

	Accuracy	Bias
BMI	<ul style="list-style-type: none"> • Males and individuals of European ancestry in the underweight BMI group have significantly lower accuracy scores compared males and individuals of European ancestry in the obese BMI group • BMI does not influence the accuracy scores for females and individuals of African ancestry 	<ul style="list-style-type: none"> • Underweight individuals of European ancestry are under-aged by 8 years compared to overweight individuals of European ancestry • BMI does not influence bias scores for males, females, and individuals of African ancestry
Stature	<ul style="list-style-type: none"> • Males and individuals of European ancestry in the short stature group have lower accuracy compared to males and individuals of European ancestry in the tall stature group • Stature does not influence the accuracy scores of females and individuals of African ancestry 	<ul style="list-style-type: none"> • Males and individuals of European ancestry in the short stature group are significantly under-aged by approximately 8 to 9 years compared to males and individuals of European ancestry in the tall stature group • Stature does not influence the bias scores for females and individuals of African ancestry
Body Mass	<ul style="list-style-type: none"> • Males and individuals of European ancestry in the lightest body mass groups have lower accuracy scores compared to males and individuals of European ancestry in the heaviest body mass groups • Body mass does not influence the accuracy scores for females and individuals of African ancestry 	<ul style="list-style-type: none"> • Males, females, and individuals of European ancestry in the lightest body mass groups are under-aged by 5 to 6 years • Body mass does not influence bias scores for individuals of African ancestry

Table 146: Summary of findings for the Rougé-Maillart et al. method.

4.1.8 Suchey-Brooks Pubic Symphysis Method

Accuracy

BMI

For males, females, and individuals of European ancestry there are differences among the BMI group accuracy scores. For females, individuals of European ancestry and individuals of African ancestry, these differences are not significant. Overweight males (8.73 years) have higher accuracy scores compared to underweight males (11.31 years). These results indicate that BMI only influences the accuracy scores of underweight males compared overweight males.

Stature

For males and individuals of European ancestry, there are differences in the accuracy scores among stature groups; however, these differences are not significant for individuals of European

ancestry. Tall males (7.82 years) have significantly higher accuracy scores compared to short males (11.18 years). For females and individuals of African ancestry, there are no differences in stature group accuracy scores. These results show that stature only influences the accuracy scores of short males compared to tall males for the Suchey-Brooks method.

Body Mass

For males and individuals of European ancestry, there are differences among the body mass group accuracy scores. Males in the two heaviest body mass groups have higher accuracy scores (7.33 years and 8.65 years for males) compared to males in the lightest body mass group (11.21 years). Individuals of European ancestry in the two heaviest body mass groups have higher accuracy scores (7.53 years and 8.95 years) compared to individuals of European ancestry in the second lightest body mass group (11.25 years). For females and individuals of African ancestry, there are no differences in body mass group accuracy scores. These results indicate that body mass only influences the accuracy scores of males and individuals of European ancestry in the lightest body mass groups compared to males and individuals of European ancestry in the heaviest body mass groups for the Suchey-Brooks method.

Bias

BMI

For males, females, and individuals of European ancestry, there are differences among the BMI group bias scores. For females, there are no significant differences among the BMI group bias scores. Underweight males (-8.86 years) have significantly lower bias scores compared to overweight males (-3.87 years). Underweight individuals of European ancestry (-9.86 years) have significantly lower bias scores compared to overweight individuals of European ancestry (-4.48 years). For individuals of African ancestry, there are no differences among the BMI group bias scores. These results indicate that BMI only influences the bias scores of males and individuals of European ancestry; underweight males and individuals of European ancestry are under-aged compared to overweight males and individuals of European ancestry by approximately 5 years. BMI does not influence bias scores for females and individuals of African ancestry using the Suchey-Brooks method.

Stature

For males and individuals of European ancestry, there are differences among bias scores. Males in the shortest stature group (-9.18 years) have significantly lower bias scores compared to males in the tallest stature group (-3.66 years). Individuals of European ancestry in the tallest stature group (-3.68 years) have significantly lower bias scores compared to individuals of European ancestry in all other stature groups (range -8.54 years to -7.23 years). For females and individuals of African ancestry, there are no significant differences among the stature group bias scores. These results indicate that stature only influences the bias scores of short males, who are under-aged by 6 years compared to tall males, and tall individuals of European ancestry, who are over-aged 3 to 4 years compared to individuals of European ancestry in all other stature groups. Stature does not influence the bias scores for females and individuals of African ancestry for the Suchey-Brooks method.

Body Mass

For males, females, and individuals of European ancestry, there are differences among the body mass group bias scores. Males in the two lightest body mass groups (-9.28 years and -7.36 years) have significantly lower bias scores compared to males in the heaviest body mass group (-3.77 years). Females in the lightest body mass group (-7.84 years) have significantly lower bias scores compared to females in the two heaviest body mass groups (-4.19 years and -3.41 years), but these differences are not significant due to small sample sizes. Individuals of European ancestry in the two lightest body mass groups (-9.46 years and -8.79 years) have significantly lower bias scores compared to individuals of European ancestry in the two heaviest body mass groups (-5.23 years and -4.32 years). For individuals of African ancestry, there are no significant differences among the body mass group bias scores. These results indicate that males, females, and individuals of European ancestry in the lightest body mass groups are under-aged by 4 to 6 years, while there are no differences for individuals of African ancestry using the Suchey-Brooks method.

	Accuracy	Bias
BMI	<ul style="list-style-type: none"> • Underweight males have significantly lower accuracy scores compared overweight males • BMI does not influence the accuracy scores for females, individuals of European ancestry, and individuals of African ancestry 	<ul style="list-style-type: none"> • Underweight males are under-aged compared to obese males by 5 years • Underweight individuals of European ancestry are under-aged compared to overweight individuals of European ancestry by 5 years • BMI does not influence bias scores for females and individuals of African ancestry
Stature	<ul style="list-style-type: none"> • Short males have lower accuracy scores compared to tall males • Stature does not influence the accuracy scores of females, individuals of European ancestry, and individuals of African ancestry 	<ul style="list-style-type: none"> • Short males in the shortest stature group are under-aged by 6 years compared to tall males • Individuals of European ancestry in the tallest stature group are over-aged 3 to 4 years compared to individuals of European ancestry in all other stature groups • Stature does not influence the bias scores for females and individuals of African ancestry
Body Mass	<ul style="list-style-type: none"> • Males and individuals of European ancestry in the lightest body mass groups have lower accuracy scores compared to males and individuals of European ancestry in the heaviest body mass groups • Body mass does not influence the accuracy scores for females and individuals of African ancestry 	<ul style="list-style-type: none"> • Males, females, and individuals of European ancestry in the lightest body mass groups are under-aged by 4 to 6 years • Body mass does not influence bias scores for individuals of African ancestry

Table 147: Summary of findings for the Suchey-Brooks method.

Table 148 summarizes these findings, and shows that for most methods, underweight and light-weight males, females, and individuals of European ancestry, and short males and individuals of European ancestry have the lowest accuracy and highest bias scores, but are generally reliable to estimate age, except for the DiGangi et al. method, which has the overall lowest accuracy and bias scores. All methods are reliable for individuals of African ancestry except for the İşcan et al. method accuracy and bias scores for underweight and low body mass groups. The term “reliable” for the purposes of this chart indicates that there are no significant differences among the accuracy and bias scores for the BMI, stature, and body mass groups.

[illegible]

		Kunos et al.	DiGangi et al.	İşcan et al.	Passalacqua	Lovejoy et al.	Buckberry & Chamberlain	Rougé-Maillart et al.	Suchey-Brooks
Body Mass	Male <i>Accuracy</i>	Reliable	Low body mass low accuracy	Low body mass low accuracy	Low body mass low accuracy	Reliable	Reliable	Low body mass low accuracy	Low body mass low accuracy
	<i>Bias</i>	Low body mass under-aged	Reliable	Low body mass under-aged	Low body mass under-aged	Low body mass under-aged	Low body mass under-aged	Low body mass under-aged	Low body mass under-aged
	Female <i>Accuracy</i>	Reliable	Reliable	Reliable	Reliable	Reliable	Reliable	Reliable	Reliable
	<i>Bias</i>	Reliable	Reliable	Low body mass under-aged	Reliable	Reliable	Reliable	Reliable	Low body mass under-aged
	European <i>Accuracy</i>	Low body mass low accuracy	Low body mass low accuracy	Low body mass low accuracy	Reliable	Reliable	Reliable	Low body mass low accuracy	Low body mass low accuracy
	<i>Bias</i>	Low body mass under-aged	Low body mass under-aged	Low body mass under-aged	Low body mass under-aged	Low body mass under-aged	Low body mass under-aged	Low body mass under-aged	Low body mass under-aged
	African <i>Accuracy</i>	Reliable	Reliable	Low body mass low accuracy	Low body mass low accuracy	Reliable	Reliable	Reliable	Reliable
	<i>Bias</i>	Reliable	Reliable	Low body mass under-aged	Reliable	Reliable	Reliable	Reliable	Reliable

Table 148: Summary of reliability for all age estimation methods separated by body size, sex, and ancestry.

4.2 BMI, Stature, and Body Mass Influence Skeletal Age Estimation

Three different patterns emerge from my data. First, individuals in the obese and underweight BMI groups, short and tall stature groups, and light and heavy body mass groups have significantly different reliability scores from each other. Second, individuals in the “middle” groups (i.e. individuals in the normal-sized and overweight BMI groups, second shortest and second tallest stature groups, and second lightest and second heaviest body mass groups) generally cluster together and have similar error and bias scores. Third, non-weight-bearing (NWB) joints have more error associated with their age estimations than weight-bearing (WB) joints, especially for individuals in the tall stature group and light body mass group, and WB joints are under-aged compared to NWB joints for individuals in the underweight BMI group, short stature group, and light body mass group. All of these patterns distinguish the individuals in the underweight BMI group, short stature group, and light body mass group from individuals in the other groups, especially individuals in the obese BMI group, tall stature group, and heavy weight group.

4.2.1 The Influence of Stature on Age Estimation

Stature does not have an influence on age estimations for most individuals, except males and individuals of European ancestry in the short stature group, who have lower accuracy scores and are under-aged compared to males and individuals of European ancestry in the tall stature group. There are few studies that consider stature in relation to skeletal aging except for those that identify short stature as an indicator of poor health, with the premise that short individuals have shorter life spans due to poor nutrition (Kemkes-Grottenthaler, 2005; Ferreira et al., 2008). The parsimonious explanation for the under-aging of short individuals in this study is that most individuals who were classified as short were also in the lightest body mass categories, especially for males and individuals of European ancestry.

Stature is most likely not a factor in skeletal aging because stature and body mass are expected to change in similar ratios (i.e. allometric scaling). The allometric relationship of stature to body mass is positive and linear (Heymsfield et al., 2007); my dissertation results suggest that the age-related changes occurring to bone as body mass increases or decreases are accommodated by

stature. As body mass increases or decreases, bone remodelling follows these principles of allometric scaling to accommodate these changes at the microscopic level, and these change appear to have little to no influence on skeletal aging except for males and individuals of European ancestry in the short stature group, who are under-aged.

4.2.2 The Influence of Body Mass on Age Estimation

Body mass influences skeletal age estimation for most methods and most individuals. Individuals in the lightest body mass group have more error associated with their age estimations compared to individuals in the heaviest body mass group. This relationship is significant for five of the eight methods for males and individuals of European ancestry, and two for individuals of African ancestry. There are no significant differences for females, but they do follow a similar pattern. Individuals in the lightest body mass group are under-aged compared to individuals in all other body mass groups. This relationship is significant for all eight methods for individuals of European ancestry, seven for males, two for females, and one for individuals of African ancestry. These results indicate that body mass has a stronger influence for males and individuals of European ancestry than females and individuals of African ancestry, but this may be a result of low sample sizes for females and individuals of African ancestry.

4.2.3 The Influence of BMI on Age Estimation

BMI is a combination of body mass and stature measurements. When considered separately, body mass has a stronger influence on skeletal age estimation than stature in this study. Although there are some differences in stature accuracy and bias scores among males and individuals of European ancestry, the low body mass groups demonstrate higher error and bias scores for all the age estimation methods, including females and individuals of African ancestry. This suggests that body mass is probably driving the BMI results, not stature, as the accuracy and bias scores between the body mass and BMI results are similar. Underweight individuals have more error associated with their age estimations and are under-aged compared to obese and/or overweight individuals. For males and individuals of European ancestry, these results are significant more often compared to females and individuals of African ancestry.

4.2.4 The Influence of Joint Surfaces on Age Estimation

This study also examined the differences between NWB and weight-bearing WB joint age estimations. The NWB rib joints were found to have more error (between 1 and 5 years) associated with their age estimations compared to WB pelvic joints, and most of the error is associated with individuals in the tall stature group and light body mass group. The WB pelvic joints were found to under-age individuals by approximately 2 to 6 years compared to NWB rib joints in almost all BMI, stature, and body mass groups except individuals in the lightest body mass group. This finding suggests that remodelling affects pelvic joints less than rib joints for most individuals except for those in the lightest body mass groups.

4.3 Factors that Affect Skeletal Aging

Individuals who have an underweight BMI and are in the low body mass groups in this study generally have the lowest accuracy and highest negative bias scores for most age estimation methods, suggesting that underweight individuals are subject to a decreased rate of skeletal aging. Conversely, males, females, individuals of European ancestry, and individuals of African ancestry in the obese BMI group and heavy body mass group have the highest accuracy scores and lowest negative bias scores, suggesting that obesity accelerates skeletal aging.

There are a variety of factors that may contribute to the differences in age estimations among BMI, stature, and body mass groups: bone remodelling rates and BMD, nutrition, physical activity and occupation, and hormone levels. This section will look at each of these factors as potential explanations for the trends observed in this study.

4.3.1 Bone Remodelling Rates and Bone Mineral Density (BMD)

As an individual ages, the rates of bone removal outpace the rates of bone formation (Cao et al., 2005, 2007; Pietschmann et al., 2007), especially in post-menopausal women who have decreased levels of estrogen, which is important in bone formation (Kaptoge et al., 2003). Studies have shown that older bone might be preferentially selected for osteoclast resorption, and compounded with the decrease in bone matrix deposited by osteoblasts, the rate of bone removal occurs faster than bone deposition as an individual ages (Lee et al., 2005; Szulc and Seeman, 2009). These changes in bone remodelling rates influence BMD scores; most individuals reach

their peak BMD around the age of 30 years, and after this time BMD begins to decrease in a predictable fashion (Lekamwasam et al., 2009). Coincidentally, these changes at the microscopic level also translate to changes at the macroscopic level. Between the ages of 30 and 40 years, when BMD is beginning to decline, the bone surface is beginning to show signs of aging—striae become dense and granular, billowing becomes smooth, microporosity begins to show on the surface—and these changes are evaluated by macroscopic age estimation methods. As an individual continues to age, and the rates of bone remodelling continue to outpace the rates of bone formation, BMD values decrease, and the surface of the bone reflects these changes—dense granularity becomes coarse, smooth surfaces become roughened and concave, macroporosity begins to replace microporosity, osteophytic activity occurs, and bone becomes more fragile. As demonstrated by this study, these surface changes are also influenced by body size; therefore, a greater understanding of how stature and body mass influence bone remodelling and BMD is required to explain these differences.

4.3.2 Sex and Ancestry Differences in BMD

Differences in BMD scores among males, females, individuals of European ancestry, and individuals of African ancestry are well established. On average, males generally have higher BMD than females (Nieves et al., 2005), and individuals of African ancestry have higher BMD compared to individuals of European ancestry (Finkelstein et al., 2002; Tracy et al., 2005). Though they follow the same pattern, the rates of bone remodelling have been shown to be faster in women compared to men, especially post-menopausal women (Kaptoge et al., 2003), and individuals of African ancestry have lower rates of bone remodelling compared to individuals of European ancestry (Han et al., 1997; Finkelstein et al., 2002). Similarly, European males have faster rates of bone remodelling compared to African males (Tracy et al., 2005), and European females have faster rates of modelling compared African females (Finkelstein et al., 2002). Most skeletal age estimation methods used in biological anthropology support these findings, and different rates of skeletal aging for sex and ancestry have been established (Işcan et al., 1984 a, 1985, 1987; Katz and Suchey, 1989; Brooks and Suchey, 1990; Yavuz et al., 1998). This study corroborates these findings, as males, females, individuals of European ancestry, and individuals of African ancestry have significantly different accuracy and bias scores from each other for most methods. As demonstrated in Section 3.2, females generally have higher negative bias

scores compared to males for each age estimation method, and individuals of African ancestry generally have higher accuracy and lower bias scores compared to individuals of European ancestry, as would be expected with females and individuals of African ancestry exhibiting differing rates of bone remodelling.

Most skeletal age estimation methods were developed on males of European ancestry, with modifications for females and individuals of African ancestry available. Therefore, it is not surprising that males in this study have higher accuracy and lower bias scores compared to females, especially since females have higher rates of bone remodelling. For individuals of European and African ancestry, since most methods were developed on individuals of European ancestry who have faster rates of bone remodelling compared to individuals of African ancestry, it was expected that individuals of African ancestry would have lower accuracy and higher negative bias scores. As shown in Section 3.2, generally there are few differences between the accuracy scores of Europeans and Africans, and individuals of African ancestry show higher negative bias scores for half the methods (i.e. the İşcan et al., Lovejoy et al., Rougé-Maillart et al., and Suchey-Brooks methods). The Kunos et al., DiGangi et al., Passalacqua, and Buckberry and Chamberlain methods over-age individuals of African ancestry compared to individuals of European ancestry. Two are first rib methods, and two are pelvic methods, indicating that there is no pattern for these differences, and further research to explain these differences is warranted.

4.3.3 Bone Remodelling and Body Size

When considering the rates of bone remodelling as measured by BMD on individuals of differing body sizes, individuals in the underweight BMI and low body mass group generally display lower BMD than individuals who are within the normal, overweight, and obese BMI range, or heavier body masses, and have an increased risk for osteoporosis (Shah et al., 2011). Examining the ways in which undernutrition and obesity affect bone remodelling and BMD may help explain the differences in skeletal aging observed in this study.

4.3.3.1 Undernutrition and BMD

Often, underweight individuals are under-nourished or in poor health with inadequate energy intake, thus influencing their rates of bone remodelling and BMD. The combination of poor nutrition and low amounts of fat tissue have been implicated in lower bone turnover rates for

underweight individuals (Coin et al., 2000, 2008). This low bone remodelling rate is protective to underweight individuals as the slower remodelling compensates for the lack of nutrients to support bone growth, but only to a certain extent. A lifetime of poor nutrition and low body mass will ultimately lead to low BMD, and increased risks of osteoporosis in older individuals (Coin et al., 2008). A recent study by Fernández-García and colleagues (2009) comparing “healthy” females with low body mass to “unhealthy” females with low body mass (i.e. females with anorexia nervosa) found no significant differences among BMD scores between the two groups, with both exhibiting lower than expected BMD compared to the control group of normal-sized females, indicating that nutrition may not be as important as body mass in skeletal health. This study has shown that low body mass is associated with the under-aging of individuals, suggesting the protective effect of low remodelling rates in underweight individuals is also seen on the bone surface and influences skeletal age estimations.

4.3.3.2 Obesity and BMD

When considering the rates of bone remodelling measured by BMD on obese individuals, the pattern of BMD is less clear. Obesity has been shown to both increase BMD and decrease BMD. Researchers who argue that obesity increases BMD have shown that as body mass increases, there is increased mechanical stress on bone, resulting in decreased bone resorption and higher BMD (Felson et al., 1993; Looker et al., 2001; Lim et al., 2004). Recently, however, studies have demonstrated a decrease in BMD for obese individuals. Researchers who argue that obesity decreases BMD do so based on the following evidence: First, obesity has been shown to decrease bone formation (i.e. osteoblastogenesis) while increasing fat formation (i.e. adipogenesis). Typically, mechanical loading promotes osteoblast differentiation and inhibits adipose formation; however, in obese individuals, the gene that promotes this action is down-regulated, leading to a decrease in osteoblast differentiation and an increase in adipocyte differentiation (Cao, 2011). Second, obesity has also been shown to increase bone resorption through the upregulation of pro-inflammatory genes, which stimulate osteoclast activity. There has also been evidence that bone marrow adipocytes might promote osteoclastogenesis (Cao, 2011). Third, obesity is associated with higher levels of leptin and decreased levels of adiponectin. Higher levels in leptin in obese animals have been found to be a negative regulator of bone mass, and decreased levels of adiponectin increase osteoclastogenesis and bone resorption (Cao, 2011).

The results from this study show that individuals in the obese BMI group and heavy body mass group are over-aged compared to individuals in the underweight BMI group and light body mass group, suggesting support for the second of these two observations—heavier individuals display increased rates of bone remodelling. Individuals in the obese BMI group and heavy body mass group in this study also show increased degenerative changes on the joint surfaces used in skeletal age estimation. For example, obese individuals have higher levels of apical activity on the sacrum and auricular surface, increased surface breakdown and porosity on the auricular surface, and increased activity on the acetabular rim compared to individuals in the underweight BMI group and lighter body mass group, resulting in higher age estimations in these heavily loaded areas.

Research on the ways in which visceral fat and muscle mass influence bone's remodelling might be one explanation for the over-aging of individuals in the obese BMI group and heavy body mass group compared to individuals in the underweight BMI group and light body mass group. Two studies have shown that differences in the ratio of visceral fat to lean muscle exhibit varied rates of bone loss (Gnudi et al., 2007; Bredella et al., 2011). Individuals with high body mass and more lean muscle, which decreases the pace of bone remodelling, had higher BMD values, and individuals with high body mass and more visceral fat, which increases the pace of bone remodelling, had lower BMD values. These results suggest that the accelerated skeletal aging of obese individuals observed in this study may be more dependent on the distribution and type of tissue (i.e. fat vs. muscle) rather than body mass or BMI group.

4.3.4 Physical Activity and Occupation

Another potential explanation for the pattern of under-aging individuals in the underweight BMI group and light body mass group observed in this study is physical activity. Most of the individuals in the underweight BMI group and light body mass group used in this study are from the Hamann-Todd collection (see Appendix 3 and Appendix 4), which is made up predominantly of European male migrant workers. The occupations recorded or found in census data for some individuals suggest that most worked labour intensive jobs (for example, bricklayer, iron worker, etc.: personal communication, Lyman Jellema, Cleveland Museum of Natural History). These labour intensive activities suggest high levels of mechanical loading on the bones, but the effect would be much less pronounced on underweight individuals compared to normal-sized and

overweight individuals. Underweight individuals have less body mass driving the impact of laborious activities on skeletal loading, but they also most likely had higher levels of lean muscle mass compared to fat mass than normal-sized and overweight individuals. High amounts of lean muscle mass appear to have a protective effect on bone remodelling, and lead to increased BMD (Lekamwasam et al., 2009). If underweight individuals are just as active as normal-sized and overweight individuals with similar amounts of lean muscle mass but less fat mass, the results from this study suggest the combination of decreased mechanical load from body mass and increased lean muscle influences BMD and skeletal aging in a positive way—underweight individuals are under-aged significantly compared to individuals in all other body mass groups, especially obese individuals—and provides a plausible explanation as to why lighter individuals experience slower rates of skeletal aging, especially compared to heavy individuals.

One study by Campanacho and colleagues (2012) examined the influence of occupation on age estimations of the pubic symphysis on a male sample from the Coimbra Collection in Portugal. The authors defined occupation as “manual labour” or “non-manual labour” based on recorded employment and femoral robusticity. Individuals in the “robust” group were from the manual labour group, while individuals in the “fragile” group were from the non-manual labour group. Fourteen aspects of the pubic symphysis were analyzed, and the results showed that only the ligamentous outgrowths on the ventral beveling were significantly different between the manual and non-manual labour groups. This study by Campanacho et al. was the first to suggest that occupation does not influence the rate of degeneration of the pubic symphysis; however, the study did not take body size into consideration, nor did they assess skeletal age markers from other areas of the body. In my dissertation, the pubic symphysis has been shown to display low error rates except for short and underweight males. Similarly, short males and underweight males, females, and individuals of European ancestry are under-aged significantly compared to all other groups, with fewer signs of degeneration. Without knowledge of the body mass of the Coimbra Collection, it is difficult to compare the results of these two studies. If the males in the Coimbra Collection were underweight and/or short, which is not an unreasonable assumption for this late-19th to mid-20th century collection, it could explain why there were fewer differences among the robust and fragile groups. Underweight males in my dissertation with labour intensive occupations did not display accelerated signs of skeletal aging, but rather obese individuals with

less labour intensive occupations experienced accelerated skeletal aging, suggesting that body size might play a bigger role in age estimation than physical activity.

Studies that have examined the physical activity levels of individuals of varying body masses have shown that individuals with high BMIs and body masses are less active than underweight, normal-sized, and overweight individuals, but they do perform small amounts of moderate and low-level activities (approximately 30 and 60 minutes each day) (Cooper et al., 2000; Davis et al., 2006). Although the amount of time heavier individuals spend being physically active is significantly lower than underweight, normal-sized, and overweight individuals, the increased weight-load of an obese individual would presumably have a larger impact on the skeletal system, causing increased degenerative changes on the pelvic joints not seen in underweight individuals, increasing their skeletal age estimations.

The NWB rib joints were found to have more error (between 1.5 and 5 years) associated with their age estimations compared to WB pelvic joints, and most of the error is associated with tall and light individuals. The WB pelvic joints were found to under-age individuals by approximately 2 to 6 years in almost all groups except the lightest body mass groups compared to NWB rib joints. BMD and the effect of mechanical loading and physical activity have been shown to be significantly different between WB and NWB joints (Tommerup et al., 1993; Nikander et al., 2006; Mikkola et al., 2008). It has been demonstrated that the WB tibia is affected by the environment significantly more than the NWB radius, indicating that there are bone remodelling differences between the two sites (Mikkola et al., 2008). The results of my dissertation show that there are differences in the accuracy and bias of the methods on NWB and WB joints, which might suggest that bone remodelling of the pelvis occurs more slowly than the ribs (i.e. the pelvis is under-aged compared to the ribs) in almost all groups except the underweight BMI group and light body mass group, indicating that the pelvis may be influenced more by external factors such as loading and activity. However, the rates of bone remodelling were not known or tested for the individuals in this study.

As previously shown, increases in lean muscle mass stimulate a protective effect in the weight-bearing joints of physically active and heavy individuals, and may provide an explanation for the decreased age estimations of WB joints for all stature groups and average to heavier individuals.

Weight-bearing exercise has been shown to be sufficient in stimulating periosteal bone formation in the femur, but not in the ribs, indicating that bone response to weight-bearing exercises is specific to the loaded, weight-bearing bones (Tommerup et al., 1993). Since the pelvis is heavily loaded and affected by physical activity more than the ribs, there would be an expected increase in BMD and decreased pace of bone remodelling, leading to younger age estimations of the pelvis. However, when the age methods are considered separately, this hypothesis breaks down as the Işcan et al. fourth rib method has the highest levels of inaccuracy and lowest bias scores, and is a NWB joint. Further research on how body mass influences skeletal aging at both NWB and WB joints is required to interpret these results.

4.3.5 Hormone Levels

Another potential explanation for the significantly different age estimations between underweight and obese individuals is hormones. Osteocyte apoptosis increases with tissue age causing a weakening of the bone independent of BMD, but not independent of fat content. Leptin, a protein hormone that plays a key role in regulating energy intake and expenditure, including appetite and hunger, metabolism, and behaviour, is one of the most important adipose-derived hormones. Increased levels of leptin have been linked to obesity and induce osteocyte apoptosis (Gordeladze et al., 2002), and decreases lamellar bone formation while increasing cortical bone formation (Hamrick and Ferrari, 2008). It has been suggested that this increasing cortical bone formation may represent a mechanism for coping with increased body mass on obese individuals (Hamrick and Ferrari, 2008), and would help explain the over-aging of obese individuals observed in this study. Underweight individuals have decreased levels of leptin, which can have a protective effect against osteocyte apoptosis, and may also play a role in explaining the under-aging of lighter individuals compared to heavier individuals. Conversely, decreased leptin levels have also been shown to decrease bone formation markers, though not in conjunction with BMD (Fernández-García et al., 2009); therefore, the role of leptin in the under-aging of underweight individuals requires further exploration.

4.4 Implications of Study Results for Paleodemography, Paleoanthropology, and Forensic Anthropology

For biological anthropologists, reliable age estimations form the basis of work that interprets health, disease, and adaptation in past populations and communities. The results of this study indicate that all methods are reliable for males, females, Europeans, and Africans with average statures and body masses, but the age estimations of underweight individuals are not. The Kunos et al. method is the most reliable rib method, and the Lovejoy et al. and Suchey-Brooks methods are the most reliable pelvic methods. The DiGangi et al. method is the least reliable method overall with the lowest accuracy and highest bias scores for this sample. The İşcan et al. method under-ages underweight individuals by the highest amount for all methods, and should be used with caution if a population is known to have low body mass. The Buckberry and Chamberlain method over-ages individuals for this sample, which is consistent with other studies (Mulhern and Jones, 2005; Hens and Belcastro, 2012).

Often, the archaeological record appears to lack older individuals, and it is generally believed that life expectancy in past populations was 20 to 35 years (Paine and Harpending, 1998; Roksandic and Armstrong, 2011). However, we know that the average stature of past populations was shorter and the average estimated body mass was lighter (see Table 3). The results of this study suggest that a reassessment of the age estimations that have been generated for past populations is warranted. The under-representation of infants and older adults can affect paleodemographic interpretations of fertility rates, death rates, mortality curves, and general health of past populations (see Cipriano-Bechtle et al., 1996; Guy et al., 1997; Paine and Harpending, 1998). If lighter and shorter individuals are under-aged between 5 to 15 years, as shown by this study, correcting this would significantly change our current understanding of past population life expectancy and population structure. By increasing the presence of older adults in the skeletal record, our interpretation of roles and dynamics within a group would change, as adult longevity is a measure of a population's success. Increasing the average age at death of a population by only 5 years shifts fertility and death rates significantly (Paine and Harpending, 1998), and would re-shape the ways we understand human longevity.

Some paleoanthropological studies focus on small-bodied human ancestors, and often researchers use current skeletal age estimation methods to infer ages at death of fossil specimens.

As seen in Table 3, the stature and body mass estimations for early hominids are significantly different from those of current human populations. If the age estimations derived from our current standards have significantly different accuracy and bias scores for underweight individuals, the divergence from fossil forms may be even more extreme. With new information on the ways body size affects our age standards, researchers will have opportunities to re-examine skeletal materials and more accurately determine age at death, with the possibility of refining our knowledge about the lifespan of past human and ancestral populations.

Forensic anthropologists rely on accurate age estimations to create biological profiles and to narrow searches for missing persons. Recently, forensic anthropologists have acknowledged that obesity affects several aspects of a biological profile, including stature estimations (Adams and Herrmann, 2009), and there have been attempts to characterize features of the obese skeleton (Agostini and Ross, 2011; Moore and Schaefer, 2011). According to Statistics Canada, there are approximately 4.7 million obese individuals in Canada, which represents almost 20% of the adult population (Statistics Canada, 2012). Similarly, in the United States, the Centers for Disease Control reports that 35.7% of U.S. adults are obese (Ogden et al., 2012). Understanding the relationship of obesity to skeletal aging will allow forensic anthropologists to better estimate the age at death of human remains. This study has shown that individuals with low body mass and high body mass have significantly different accuracy and bias scores for almost all age estimations methods, but this difference is especially seen among males and individuals of European ancestry. The development of sex- and ancestry-specific formulae to account for body size could create more accurate age estimations and help law enforcement officers narrow the scope of their investigations and improve their effectiveness.

4.5 Estimating Body Size of Skeletal Remains

In biological anthropology, studies on body size are generally associated with stature and body mass calculations, sexual dimorphic relationships, and ecogeographic and population differences in body proportions. Stature is an important variable in both paleodemographic and forensic case studies. Stature can be associated with health and disease in a population (Steckel et al., 2002; Kemkes-Grottenthaler, 2005), and knowing a person's stature can narrow individual identification in forensic cases (Adams and Herrmann, 2009). Several methods of stature estimation have been developed using measurements of long bones and linear regression

formulae. The most reliable are those using long bones directly associated with stature, such as the femur (Trotter and Gleser, 1952; Sjøvold, 1990; Ross and Konigsberg, 2002), while methods using other bones, including the upper limb (Mall et al., 2001; Celbis and Agritmis, 2006; Ozaslan et al., 2006), sternum (Menezes et al., 2011), sacrum (Karakas et al., 2010), metacarpals (Sagir, 2006), and metatarsals (Bidmos and Dayal, 2003; Bidmos, 2006; Cordeiro et al., 2009) have also been developed with some level of success. The Fully (Fully, 1956) and Revised Fully (Raxter et al., 2006, 2007) methods of stature estimation are the most accurate methods because they use all the elements comprised in vertical length—the cranium, vertebral column, sacrum, femur, tibia, talus, and calcaneus—and apply these measurements to a linear regression formula based on age and soft tissue (Maijanen, 2009; Auerbach, 2011). An interesting study by Adams and Hermann (2009) on stature reconstruction of dismembered, fleshed remains found that individuals with the highest BMI scores had the lowest correlations to known stature in life. Overall, stature is generally considered to be a reliable, measureable body size variable, and could be used in future calculations to determine which age methods are the most appropriate for individuals of differing statures. However, caution must be used when estimating stature of individuals with high BMIs.

Body mass is also important when considering health and disease, especially in relation to osteoporosis, as well as metabolic costs, mobility, brain size, longevity, thermoregulation, and so on (McHenry, 1992). The two most common methods of estimating body mass are from measurements of the maximum femoral head diameter and stature/ bi-iliac breadth (BIB). A test of both methods by Auerbach and Ruff (2004) demonstrate that they are both reliable with Pearson correlation values between 0.74 and 0.81 to known body mass. However, the femoral head diameter and BIB methods were not developed on individuals with high body masses or BMIs; therefore, these measurements and calculations do not consider heavier individuals. BIB body mass calculations are based on the assumption that human bodies can be compared to cylinders, and by applying surface area models to measurements of stature (length) and bi-iliac breadth (width), an estimation of body mass can be obtained (Ruff, 1994). As individuals become heavier, calculating the amount of subcutaneous fat surrounding the pelvis (or the width of the cylinder) based on skeletal measurements becomes more difficult, and the results less accurate. The method works well on elite athletes (Ruff, 2000) and distinguishing individuals from different ecogeographic regions based on body proportions (Ruff, 1994; Ruff et al., 2005;

Pomeroy and Stock, 2012), and it has been used to estimate body mass for past populations (Ruff et al., 1993, 2006; Rafferty et al., 1995; Sealy and Pfeiffer, 2006; Kurki et al., 2009), but it is not commonly used to estimate body mass in modern populations. Therefore, predicting body mass using femoral head diameter or BIB measurements for obese individuals may be a challenge in cases of unknown individuals, and would make it difficult to apply the results of the current study to obese individuals.

Recently, researchers have begun to investigate the influence of body size on skeletal features. For example, Agostini and Ross (2011) analyzed the femoral cross-sections of 121 males of varying BMIs from the William Bass Collection. Their results show that there is a significant difference in medial-lateral femoral measurements of obese individuals compared to normalized individuals. Obese individuals have larger medial-lateral cross-section diameters than individuals of normal BMIs, suggesting that an increase in body mass affects body mass-loading bones. The authors suggest the change in gait swing and increased loading on heel-toe impact in obese individuals may explain the increased bone deposition in the femur. The results of Agostini and Ross' study imply that it may be possible to determine obese individuals based on femoral shape, which would allow researchers to apply appropriate body-size adjusted age estimation methods in the future.

4.6 Study Limitations

There are several limitations of this study that should be considered. First, the body mass recorded for each individual is cadaver weight, which might not accurately reflect living weight. Second, as body mass for these individuals is only known at death, any fluctuations in weight throughout life are unknown. For example, if an individual gained or lost a substantial amount of weight before they died, only their weight at death is recorded, and it will not accurately reflect the life history of the individual. Third, BMD is not known for this population, but only inferred based on current studies of BMD. Fourth, the occupations, levels of physical activity, and general health are known for some, but not all of the individuals in this study. Fifth, the Hamann-Todd and William Bass Collections each have their own set of biases. The Hamann-Todd Collection mostly consists of unclaimed bodies of European male migrant workers from the early 20th century in Ohio, and the William Bass Collection consists mostly of donated bodies of males from the late 20th century in Tennessee. And sixth, the application of new body-size

adjusted age estimation parameters is limited because our current standards of estimating body mass are poor, especially for modern populations with high rates of obesity.

Chapter 5: Conclusion

When comparing the age estimation methods for this sample of 764 individuals, the İşcan et al. method consistently under-ages males, females, individuals of European ancestry, and individuals of African ancestry more than any other method, and the DiGangi et al. method is the most unreliable method with low accuracy (over 20 years in some cases) and high bias scores (under-aging individuals by almost 20 years). The Buckberry and Chamberlain method has comparable accuracy scores to the other methods, but over-ages individuals more than all other methods, which is consistent with findings from others who have tested this method (Falys et al., 2006; Hens and Belcastro, 2012). The Kunos et al., Lovejoy et al., and Suchey-Brooks methods are the most reliable age methods, as they have the highest accuracy and lowest bias scores among the BMI, stature, and body mass groups; the error rates for these three methods are between 8 years to 10 years, and typically underweight and short individuals are only under-aged by approximately 5 years compared to heavier and tall individuals.

Males and individuals of European ancestry, and females and individuals of African ancestry generally follow similar reliability trends. The age estimations of females and individuals of African ancestry are the least affected by BMI, stature, and body mass for this sample, and are most likely due to small sample sizes in the obese BMI group and heavy body mass group. Males and individuals of European ancestry in the underweight BMI group, short stature group, and lighter body mass group have between 3 years and 10 years of error associated with their age estimations, and they are typically under-aged between 5 years and 15 years.

Bone remodelling rates and BMD are influenced by body mass. Underweight individuals have lower rates of bone remodelling and lower BMD scores, and this study has shown that these lower remodelling rates translate to age-related changes at the surface of bone. Underweight individuals are under-aged compared to overweight and obese individuals, providing a protective effect against skeletal aging. Low amounts of fat tissue have been shown to lower rates of bone turnover in underweight individuals, and underweight individuals in this study were found to follow this trend as they were under-aged with all age estimation methods, and there was more error associated with their age estimations compared to individuals in the other body mass groups, especially those from the heaviest body mass group. The results of the current study

suggest that body mass and lean muscle mass might be more influential to BMD than nutritional status.

Obese individuals have been shown to display both low and high BMD scores. In this study, obese individuals are over-aged compared to underweight individuals, with increased degenerative changes on the joint surfaces used in skeletal age estimation. Lean muscle mass vs. fat muscle mass has been shown to influence bone remodelling rates in obese individuals. Obese individuals with higher amounts of muscle mass to fat mass have lower rates of bone turnover compared to obese individuals with higher amounts of fat mass to muscle mass. Obese individuals in this study were over-aged compared to underweight individuals, suggesting that they had high amounts of fat mass compared to muscle mass.

Physical activity and occupation are proposed as other ways to explain the differences in age estimations generated from individuals with differing body sizes. I argue that underweight individuals who are physically active with greater amounts of lean muscle mass are under-aged compared to obese individuals because of the lower bone remodelling rates associated with lean muscle mass. Conversely, obese individuals who are moderately active with increased amounts of visceral fat are over-aged compared to underweight individuals because of the higher bone remodelling rates associated with fat mass. The mechanical stress of physical activity is increased on obese individuals, and combined with high amounts of fat mass and low amounts of lean muscle mass, bone remodelling rates increase, resulting in increased osteophytic activity and more degeneration of the joint. The individuals with low body mass in this study were born in the late 19th century and were labourers who performed activities with high levels of mechanical loading, and presumably they had higher levels of lean muscle mass compared to the obese individuals in this study who were born in the mid-20th century and engaged in less physically demanding occupations. Low body mass decreases bone remodelling rates, increases BMD and therefore, decreases the markers of aging observed on the osseous materials. The mechanical stress of physical activity is decreased in individuals with low body mass, and combined with high amounts of lean muscle mass and low amounts of fat mass, bone remodelling rates decrease, resulting in less osteophytic activity, lower microporosity scores, and overall less degeneration to the joint.

This is the first study to show that body size influences skeletal age estimations, and the first study to show that skeletal age estimations are significantly different between weight-bearing and non-weight-bearing joints.

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Appendix 1

Hamann-Todd Collection	< 1.54m (< 5.0ft)	1.55–1.62m (5.1–5.3ft)	1.63–1.70m (5.4–5.6ft)	1.72–1.78m (5.7–5.9ft)	1.79–1.84m (5.10–6.0ft)	1.85–1.92m (6.1–6.3ft)	>1.93m (> 6.4ft)	Total
<45.0kg (< 100lbs)	49	99	162	147	44	8	0	514
45.4–56.5kg (100–124lbs)	34	114	215	245	100	22	1	731
56.7–67.6kg (125–149lbs)	22	89	346	380	152	32	4	1015
68.0–79.0kg (150–174lbs)	6	22	109	127	99	28	1	336
79.4–89.8kg (175–199lbs)	0	1	9	29	32	13	1	85
90.2–101.6kg (200–224lbs)	1	1	6	7	8	5	1	29
>102.0kg (>225lbs)	0	1	2	0	2	1	0	1
Total	112	327	841	930	402	96	8	2717

Appendix 1: Stature and body mass distribution of the Hamann-Todd Collection.

Appendix 2

William Bass Collection	< 1.54m (< 5.0ft)	1.55–1.62m (5.1–5.3ft)	1.63–1.70m (5.4–5.6ft)	1.72–1.78m (5.7–5.9ft)	1.79–1.84m (5.10–6.0ft)	1.85–1.92m (6.1–6.3ft)	>1.93m (> 6.4ft)	Total
<45.0kg (< 100lbs)	5	7	7	1	0	0	0	20
45.4–56.5kg (100–124lbs)	10	18	28	9	4	2	0	71
56.7–67.6kg (125–149lbs)	7	13	27	28	12	3	0	90
68.0–79.0kg (150–174lbs)	2	12	38	47	30	12	1	142
79.4–89.8kg (175–199lbs)	4	7	16	23	19	11	1	81
90.2–101.6kg (200–224lbs)	0	4	11	13	12	13	0	53
>102.0kg (>225lbs)	1	10	14	27	30	11	4	97
Total	29	71	141	148	107	52	6	554

Appendix 2: Stature and body mass distribution of the William Bass Collection.

Appendix 3

Hamann–Todd Collection	< 1.54m (< 5.0ft)	1.55–1.62m (5.1–5.3ft)	1.63–1.70m (5.4–5.6ft)	1.72–1.78m (5.7–5.9ft)	1.79–1.84m (5.10–6.0ft)	1.85–1.92m (6.1–6.3ft)	>1.93m (> 6.4ft)	Total
<45.0kg (< 100lbs)	19	42	0	0	0	0	0	61
45.4–56.5kg (100–124lbs)	19	27	26	28	26	0	0	126
56.7–67.6kg (125–149lbs)	18	28	28	30	29	13	0	146
68.0–79.0kg (150–174lbs)	5	15	26	30	28	9	0	113
79.4–89.8kg (175–199lbs)	0	0	8	25	25	12	0	70
90.2–101.6kg (200–224lbs)	0	0	6	6	5	3	0	20
>102.0kg (>225lbs)	0	0	0	0	0	0	0	0
Total	61	112	94	119	113	37	0	536

Appendix 3: Stature and body mass distribution of the final sample selected from the Hamann–Todd Collection.

Appendix 4

William Bass Collection	< 1.54m (< 5.0ft)	1.55–1.62m (5.1–5.3ft)	1.63–1.70m (5.4–5.6ft)	1.72–1.78m (5.7–5.9ft)	1.79–1.84m (5.10–6.0ft)	1.85–1.92m (6.1–6.3ft)	>1.93m (> 6.4ft)	Total
<45.0kg (< 100lbs)	5	5	0	0	0	0	0	10
45.4–56.5kg (100–124lbs)	7	10	15	8	3	0	0	43
56.7–67.6kg (125–149lbs)	2	9	15	16	9	0	0	51
68.0–79.0kg (150–174lbs)	0	8	18	12	16	10	0	64
79.4–89.8kg (175–199lbs)	0	6	11	15	13	9	0	54
90.2–101.6kg (200–224lbs)	0	0	9	9	10	10	0	44
>102.0kg (>225lbs)	0	0	0	0	0	0	0	0
Total	14	44	68	60	51	29	0	260

Appendix 4: Stature and body mass distribution of the final sample selected from the William Bass Collection.

Appendix 5

Age Categories (years)		Std.						Skewness		Kurtosis		K-S Z	Asymp. Sig. (2-tailed)
		n	Min	Max	Mean	Deviation	Variance	Statistic	Std. Error	Statistic	Std. Error		
Male	19-29	34	22	62	43.21	9.673	93.562	-0.533	0.403	-0.221	0.788	0.131	0.148
	30-39	94	32	66	49.28	7.047	49.665	0.170	0.249	-0.175	0.493	0.126	0.001
	40-49	114	36	70	54.97	6.737	45.389	-0.378	0.226	-0.512	0.449	0.112	0.001
	50-59	113	43	70	57.39	6.315	39.883	-0.492	0.227	-0.356	0.451	0.129	<0.001
	60-69	117	37	76	59.23	7.086	50.214	-0.412	0.224	0.915	0.444	0.093	0.014
	70-79	64	48	75	61.41	5.642	31.832	-0.260	0.299	-0.018	0.590	0.120	0.023
	80-89	11	54	71	64.73	5.061	25.618	-0.846	0.661	0.735	1.279	0.219	0.147
	Total	547	22	76	55.62	8.494	72.148	-0.609	0.104	0.573	0.209	0.101	<0.001
Female	19-29	18	24	44	36.89	6.570	43.163	-0.694	0.536	-0.609	1.038	0.178	0.135
	30-39	43	28	66	47.26	7.725	59.671	0.148	0.361	0.550	0.709	0.110	0.200
	40-49	43	28	70	51.28	8.452	71.444	-0.160	0.361	0.421	0.709	0.091	0.200
	50-59	37	40	67	55.70	7.516	56.492	-0.514	0.388	-0.423	0.759	0.138	0.071
	60-69	40	35	68	55.43	7.096	50.353	-0.588	0.374	0.809	0.733	0.115	0.200
	70-79	40	38	71	58.90	8.851	78.349	-0.958	0.374	0.206	0.733	0.149	0.025
	80-89	12	50	67	58.83	6.264	39.242	-0.155	0.637	-1.655	1.232	0.196	0.200
	Total	233	24	71	52.54	9.782	95.689	-0.404	0.159	-0.281	0.318	0.067	0.013
European	19-29	21	24	62	42.52	9.590	91.962	-0.097	0.501	-0.207	0.972	0.116	0.200
	30-39	73	37	66	49.88	6.342	40.221	0.418	0.281	-0.170	0.555	0.154	<0.001
	40-49	106	37	70	54.55	6.937	48.117	-0.222	0.235	-0.356	0.465	0.082	0.078
	50-59	123	43	70	57.50	6.122	37.482	-0.498	0.218	-0.333	0.433	0.114	<0.001
	60-69	132	35	76	58.52	7.325	53.656	-0.424	0.211	0.801	0.419	0.085	0.021
	70-79	82	38	75	60.54	7.189	51.684	-0.952	0.266	1.257	0.526	0.129	0.002
	80-89	19	50	71	61.89	6.632	43.988	-0.584	0.524	-0.820	1.014	0.198	0.049
	Total	556	24	76	56.21	8.119	65.911	-0.507	0.104	0.308	0.207	0.085	<0.001
African	19-29	29	22	56	39.52	8.963	80.330	-0.268	0.434	-0.621	0.845	0.099	0.200
	30-39	62	28	66	47.15	8.194	67.143	0.206	0.304	-0.098	0.599	0.106	0.082
	40-49	49	28	65	52.61	8.289	68.701	-0.543	0.340	0.110	0.668	0.113	0.151
	50-59	25	40	70	54.44	8.661	75.007	-0.187	0.464	-1.012	0.902	0.139	0.200
	60-69	24	40	72	56.96	7.012	49.172	-0.629	0.475	1.152	0.918	0.153	0.153
	70-79	22	40	70	60.09	6.989	48.848	-1.236	0.491	1.993	0.953	0.153	0.197
	80-89	3	54	67	60.00	6.557	43.000	0.670	1.225	-	-	0.277	-
	Total	214	22	72	50.83	10.108	102.162	-0.361	0.166	-0.332	0.331	0.083	0.001
Other Ancestry	19-29	2	44	50	47.00	4.243	18.000	-	-	-	-	0.260	-
	30-39	2	-	-	-	-	-	-	-	-	-	-	-
	40-49	2	50	62	56.55	8.485	72.000	-	-	-	-	0.260	-
	50-59	2	54	59	56.50	3.536	12.500	-	-	-	-	0.260	-
	60-69	1	-	-	-	-	-	-	-	-	-	-	-
	70-79	0	-	-	-	-	-	-	-	-	-	-	-
	80-89	1	-	-	-	-	-	-	-	-	-	-	-
	Total	10	44	62	53.60	5.929	35.156	0.183	0.687	-0.811	1.334	0.228	0.150
Total	19-29	52	22	62	41.02	9.173	84.137	-0.203	0.330	-0.398	0.650	0.083	0.200
	30-39	137	28	66	48.64	7.299	53.276	0.123	0.207	0.066	0.411	0.112	<0.001
	40-49	157	28	70	53.96	7.406	54.845	-0.416	0.194	0.038	0.385	0.089	0.004
	50-59	150	40	70	56.97	6.645	44.160	-0.540	0.198	-0.279	0.394	0.109	<0.001
	60-69	157	35	76	58.26	7.259	52.694	-0.426	0.194	0.796	0.385	0.085	0.008
	70-79	104	38	75	60.44	7.116	50.637	-0.986	0.237	1.269	0.469	0.135	<0.001
	80-89	23	50	71	61.65	6.350	40.328	-0.483	0.481	-0.865	0.935	0.174	0.069
	Total	780	22	76	54.70	9.003	81.063	-0.577	0.088	0.263	0.175	0.089	<0.001

Appendix 5: Descriptive statistics for the Kunos et al. method.

Appendix 6

Age Categories (years)		Std.						Skewness		Kurtosis		K-S Z	Asymp. Sig. (2-tailed)
		n	Min	Max	Mean	Deviation	Variance	Statistic	Std. Error	Statistic	Std. Error		
Male	19-29	33	12	57	27.52	10.826	117.195	0.692	0.409	0.667	0.798	0.218	<0.001
	30-39	92	15	57	32.80	9.229	85.170	1.103	0.251	0.935	0.498	0.317	<0.001
	40-49	111	25	66	38.65	9.024	81.430	0.849	0.229	0.070	0.455	0.292	<0.001
	50-59	112	25	61	41.91	8.819	77.776	0.145	0.228	-0.629	0.453	0.192	<0.001
	60-69	116	20	66	43.30	9.916	98.334	0.233	0.255	-0.515	0.446	0.179	<0.001
	70-79	62	25	66	45.52	9.498	90.221	-0.070	0.304	-0.673	0.599	0.162	<0.001
	80-89	11	32	61	49.09	8.526	72.691	-0.463	0.661	-0.008	1.279	0.187	0.200
	Total	537	12	66	39.66	10.681	114.077	0.181	0.105	-0.465	0.210	0.214	<0.001
Female	19-29	18	12	32	21.17	6.483	42.029	0.082	0.536	-1.246	1.038	0.278	0.001
	30-39	42	12	58	30.49	10.696	114.399	0.897	0.361	1.150	0.709	0.258	<0.001
	40-49	42	15	58	33.26	10.397	108.100	0.821	0.361	0.393	0.709	0.292	<0.001
	50-59	36	20	61	39.33	11.454	131.200	0.312	0.393	-1.038	0.768	0.239	<0.001
	60-69	39	25	50	36.69	7.991	63.850	0.296	0.378	-1.113	0.741	0.286	<0.001
	70-79	39	20	66	44.74	12.734	162.143	-0.122	0.378	-1.140	0.741	0.149	0.029
	80-89	11	25	61	42.36	13.567	184.055	0.218	0.661	-1.409	1.279	0.148	0.200
	Total	229	12	66	35.72	12.301	151.308	0.449	0.161	-0.483	0.320	0.235	<0.001
European	19-29	21	15	50	27.33	10.618	112.733	0.474	0.501	-0.565	0.972	0.194	0.039
	30-39	71	12	57	32.72	9.595	92.062	0.618	0.285	0.531	0.563	0.290	<0.001
	40-49	104	15	66	37.06	9.948	98.968	0.695	0.237	0.253	0.469	0.300	<0.001
	50-59	121	20	61	41.69	9.159	83.851	0.079	0.220	-0.585	0.437	0.189	<0.001
	60-69	130	20	66	42.03	9.899	97.999	0.308	0.212	-0.450	0.422	0.183	<0.001
	70-79	79	20	66	45.00	10.917	119.179	-0.081	0.271	-0.740	0.535	0.136	0.001
	80-89	19	25	61	45.32	12.202	148.895	-0.248	0.524	-1.178	1.014	0.147	0.200
	Total	545	12	66	39.77	10.928	119.431	0.179	0.105	-0.466	0.209	0.207	<0.001
African	19-29	29	12	57	23.79	9.500	90.241	1.306	0.434	4.051	0.845	0.208	0.002
	30-39	62	12	58	31.44	10.052	101.037	1.295	0.304	1.626	0.599	0.300	<0.001
	40-49	48	25	61	37.15	9.401	88.383	0.611	0.343	-0.315	0.674	0.270	<0.001
	50-59	25	25	61	39.60	11.475	131.667	0.390	0.464	-1.150	0.902	0.266	<0.001
	60-69	24	25	61	39.92	9.744	94.949	0.352	0.472	-0.614	0.918	0.250	<0.001
	70-79	22	25	61	46.00	10.614	112.667	-0.345	0.491	-0.943	0.953	0.168	0.107
	80-89	2	44	57	50.50	9.192	84.500	-	-	-	-	0.260	-
	Total	212	12	61	35.30	11.829	139.916	0.428	0.167	-0.482	0.333	0.247	<0.001
Other Ancestry	19-29	1	-	-	-	-	-	-	-	-	-	-	-
	30-39	2	25	32	28.50	4.950	24.500	-	-	-	-	0.260	-
	40-49	2	39	44	41.50	3.536	12.500	-	-	-	-	0.260	-
	50-59	2	32	44	38.00	8.485	72.000	-	-	-	-	0.260	-
	60-69	1	-	-	-	-	-	-	-	-	-	-	-
	70-79	0	-	-	-	-	-	-	-	-	-	-	-
	80-89	1	-	-	-	-	-	-	-	-	-	-	-
	Total	9	25	44	35.22	7.791	60.694	-0.052	0.717	-1.650	1.400	0.216	0.200
Total	19-29	51	12	57	25.27	9.934	98.683	0.897	0.333	1.253	0.656	0.171	0.001
	30-39	135	12	58	32.07	9.740	94.869	0.946	0.209	0.944	0.414	0.295	<0.001
	40-49	154	15	66	37.14	9.701	94.110	0.651	0.195	0.082	0.389	0.286	<0.001
	50-59	148	20	61	41.23	9.550	91.198	0.123	0.199	-0.738	0.396	0.193	<0.001
	60-69	155	20	66	41.64	9.872	97.466	0.324	0.195	-0.486	0.387	0.197	<0.001
	70-79	101	20	66	45.22	10.807	116.792	-0.133	0.240	-0.802	0.476	0.138	<0.001
	80-89	22	25	61	45.73	11.581	134.113	-0.308	0.491	-0.960	0.953	0.153	<0.001
	Total	766	12	66	38.48	11.326	128.273	0.211	0.088	-0.512	0.176	0.216	<0.001

Appendix 6: Descriptive statistics for the DiGangi et al. method.

Appendix 7

Age Categories (years)		Std.						Skewness		Kurtosis		K-S Z	Asymp. Sig. (2-tailed)
		n	Min	Max	Mean	Deviation	Variance	Statistic	Std. Error	Statistic	Std. Error		
Male	19-29	34	17	59	28.62	9.979	99.577	1.084	0.403	1.391	0.788	0.260	<0.001
	30-39	93	22	72	38.43	10.266	104.574	0.517	0.250	0.080	0.495	0.220	<0.001
	40-49	111	26	72	45.75	10.561	111.536	0.303	0.229	0.173	0.455	0.198	<0.001
	50-59	112	28	72	48.33	11.204	125.521	0.364	0.225	-0.305	0.453	0.208	<0.001
	60-69	116	26	72	51.12	12.321	151.811	0.122	0.225	-0.510	0.446	0.191	<0.001
	70-79	66	26	72	52.02	13.953	194.692	-0.032	0.295	-0.985	0.582	0.158	<0.001
	80-89	11	50	76	65.18	10.610	112.564	-0.774	0.661	-1.454	1.279	0.376	<0.001
	Total	534	17	76	46.26	13.309	177.133	0.209	0.105	-0.429	0.209	0.175	<0.001
Female	19-29	19	14	51	29.21	12.730	162.064	0.602	0.524	-0.867	1.014	0.222	0.014
	30-39	43	14	65	33.02	10.809	116.833	0.859	0.361	0.611	0.709	0.307	<0.001
	40-49	44	17	65	34.55	11.605	134.672	0.450	0.357	-0.496	0.702	0.214	<0.001
	50-59	34	17	65	42.68	10.968	120.286	0.135	0.403	0.364	0.788	0.243	<0.001
	60-69	35	17	76	44.66	16.381	268.350	0.295	0.398	-0.596	0.778	0.155	0.033
	70-79	32	17	76	48.19	16.630	276.544	0.278	0.414	-0.567	0.809	0.189	0.005
	80-89	11	23	65	43.91	13.262	175.891	-0.243	0.661	-0.371	1.279	0.202	0.200
	Total	218	14	76	39.15	14.530	211.112	0.553	0.165	-0.065	0.328	0.174	<0.001
European	19-29	21	17	51	30.95	10.176	103.548	0.492	0.501	-0.488	0.972	0.233	0.004
	30-39	73	17	72	39.64	10.612	112.621	0.258	0.281	0.007	0.555	0.188	<0.001
	40-49	103	17	72	44.41	11.140	124.107	0.219	0.238	0.472	0.472	0.187	<0.001
	50-59	119	28	72	47.80	11.025	121.552	0.301	0.222	-0.306	0.440	0.189	<0.001
	60-69	129	17	76	50.17	13.827	191.174	-0.015	0.213	-0.483	0.423	0.154	<0.001
	70-79	77	23	76	52.04	14.207	201.827	0.017	0.274	-0.817	0.541	0.152	<0.001
	80-89	18	23	72	55.11	15.091	227.752	-0.336	0.536	-0.749	1.038	0.202	0.051
	Total	540	17	76	46.81	13.304	177.004	.0210	0.105	-0.345	0.210	0.155	<0.001
African	19-29	30	14	59	27.40	11.714	137.214	1.128	0.427	0.753	0.833	0.246	<0.001
	30-39	61	14	65	33.36	9.871	97.434	0.974	0.306	1.088	0.604	0.297	<0.001
	40-49	50	17	65	38.30	12.593	158.582	0.251	0.337	-0.892	0.662	0.173	0.001
	50-59	25	17	72	42.60	11.446	131.000	0.307	0.464	1.191	0.902	0.230	0.001
	60-69	21	23	72	46.71	12.096	146.314	-0.070	0.501	0.104	0.972	0.226	0.006
	70-79	21	17	76	46.10	16.766	281.909	0.366	0.501	-0.653	0.972	0.166	0.136
	80-89	3	23	76	49.67	26.502	702.333	-0.057	1.225	-	-	0.176	-
	Total	211	14	76	37.61	13.672	186.935	0.577	0.167	-0.078	0.333	0.190	<0.001
Other Ancestry	19-29	2	-	-	-	-	-	-	-	-	-	-	-
	30-39	2	26	39	32.50	9.192	84.500	-	-	-	-	0.260	-
	40-49	2	50	59	54.50	6.364	40.500	-	-	-	-	0.260	-
	50-59	2	39	72	55.50	23.335	544.500	-	-	-	-	0.260	-
	60-69	1	-	-	-	-	-	-	-	-	-	-	-
	70-79	0	-	-	-	-	-	-	-	-	-	-	-
	80-89	1	-	-	-	-	-	-	-	-	-	-	-
	Total	10	26	72	44.00	15.535	241.333	0.540	0.687	-0.761	1.334	0.202	0.200
Total	19-29	53	14	59	28.83	10.926	119.374	0.838	0.327	0.150	0.644	0.247	<0.001
	30-39	136	14	72	36.72	10.676	113.981	0.534	0.208	0.021	0.413	0.219	<0.001
	40-49	155	17	72	42.57	11.956	142.948	0.100	0.195	-0.150	0.387	0.172	<0.001
	50-59	146	17	72	47.01	11.367	139.214	0.296	0.201	-0.110	0.399	0.197	<0.001
	60-69	151	17	76	49.62	13.591	184.703	0.016	0.197	-0.434	0.392	0.160	<0.001
	70-79	98	17	76	50.77	14.903	222.099	0.040	0.244	-0.813	0.483	0.153	<0.001
	80-89	22	23	76	54.55	15.996	255.879	-0.415	0.491	-0.632	0.953	0.181	<0.001
	Total	761	14	76	44.22	14.034	196.951	0.237	0.089	-0.417	0.177	0.152	<0.001

Appendix 7: Descriptive statistics for the İşcan et al. method.

Appendix 8

Age Categories (years)		Std.						Skewness		Kurtosis		K-S Z	Asymp. Sig. (2-tailed)
		n	Min	Max	Mean	Deviation	Variance	Statistic	Std. Error	Statistic	Std. Error		
Male	19-29	35	16	63	35.34	12.804	163.938	0.229	0.398	-0.695	0.778	0.260	<0.001
	30-39	95	28	63	44.32	10.324	106.580	0.090	0.247	-0.049	0.490	0.326	<0.001
	40-49	112	23	63	49.11	12.960	167.970	-0.379	0.228	-1.000	0.453	0.251	<0.001
	50-59	114	28	63	53.31	10.340	106.923	-0.476	0.226	-0.798	0.449	0.326	<0.001
	60-69	119	28	63	55.66	9.665	93.411	-0.818	0.222	-0.511	0.440	0.390	<0.001
	70-79	67	28	63	57.12	9.507	90.379	-1.306	0.293	0.683	0.578	0.433	<0.001
	80-89	11	45	63	58.09	8.408	70.691	-1.189	0.661	-0.764	1.279	0.448	<0.001
	Total	553	16	63	50.84	12.298	151.237	-0.574	0.104	-0.563	0.207	0.282	<0.001
Female	19-29	18	23	63	40.50	12.761	162.853	0.167	0.536	-0.928	1.038	0.249	0.004
	30-39	43	16	63	46.05	12.670	160.522	-0.250	0.361	-0.483	0.709	0.258	<0.001
	40-49	45	28	63	44.16	10.831	117.316	0.094	0.354	-0.252	0.695	0.309	<0.001
	50-59	37	28	63	50.86	9.470	89.676	0.230	0.388	-0.890	0.759	0.381	<0.001
	60-69	40	45	63	54.45	9.103	82.869	-0.104	0.374	-2.097	0.733	0.351	<0.001
	70-79	39	45	63	57.15	8.428	71.028	-0.768	0.378	-1.458	0.741	0.423	<0.001
	80-89	11	45	63	61.36	5.427	29.455	-3.317	0.661	11.000	1.279	0.528	<0.001
	Total	233	16	63	50.04	11.780	138.774	-0.411	0.159	-0.585	0.318	0.254	<0.001
European	19-29	22	16	51	36.23	10.980	120.565	-0.479	0.491	-1.256	0.953	0.333	<0.001
	30-39	74	28	63	45.04	11.046	122.012	0.074	0.279	-0.407	0.552	0.299	<0.001
	40-49	105	28	63	49.59	11.839	140.167	-0.305	0.236	-0.846	0.467	0.251	<0.001
	50-59	124	28	63	52.60	10.426	108.698	-0.367	0.217	-0.853	0.431	0.309	<0.001
	60-69	134	28	63	55.63	9.375	87.890	-0.657	0.209	-0.976	0.416	0.389	<0.001
	70-79	84	28	63	56.58	9.007	82.391	-0.864	0.263	-0.698	0.520	0.415	<0.001
	80-89	18	45	63	61.00	5.821	33.882	-2.706	0.536	5.977	1.038	0.523	<0.001
	Total	561	16	63	51.99	11.432	130.689	-0.565	0.103	-0.542	0.206	0.301	<0.001
African	19-29	29	16	63	36.59	13.847	191.751	0.422	0.434	-0.790	0.845	0.250	<0.001
	30-39	62	16	63	44.53	11.377	129.433	-0.091	0.304	-0.087	0.599	0.307	<0.001
	40-49	50	23	63	44.14	13.257	175.756	0.066	0.337	-1.100	0.662	0.226	<0.001
	50-59	25	45	63	53.16	8.980	80.640	0.213	0.464	-2.092	0.902	0.338	<0.001
	60-69	24	28	63	53.54	10.346	107.042	-0.546	0.472	-0.602	0.918	0.320	<0.001
	70-79	22	28	63	59.23	9.008	81.136	-2.566	0.491	6.546	0.953	0.481	<0.001
	80-89	3	45	63	51.00	120.392	108.00	1.732	1.225	-	-	0.385	-
	Total	215	16	63	46.97	13.227	174.943	-0.295	0.166	-0.829	0.330	0.231	<0.001
Other Ancestry	19-29	2	45	63	54.00	12.728	162.00	-	-	-	-	0.260	-
	30-39	2	45	51	48.00	4.243	18.000	-	-	-	-	0.260	-
	40-49	2	28	45	36.50	12.021	144.500	-	-	-	-	0.260	-
	50-59	2	45	63	54.00	12.728	162.000	-	-	-	-	0.260	-
	60-69	1	-	-	-	-	-	-	-	-	-	-	-
	70-79	0	-	-	-	-	-	-	-	-	-	-	-
	80-89	1	-	-	-	-	-	-	-	-	-	-	-
	Total	10	28	63	51.10	11.780	138.767	-0.552	0.687	-0.140	1.334	0.244	0.094
Total	19-29	53	16	63	37.09	12.904	166.510	0.188	0.327	-0.773	0.644	0.258	<0.001
	30-39	138	23	63	44.86	11.090	122.986	-0.018	0.206	-0.250	0.410	0.302	<0.001
	40-49	157	23	63	47.69	12.556	157.652	-0.203	0.194	-0.979	0.385	0.234	<0.001
	50-59	151	28	63	52.71	10.158	103.181	-0.310	0.197	-0.921	0.392	0.308	<0.001
	60-69	159	28	63	55.36	9.513	90.497	-0.651	0.192	-0.887	0.363	0.380	<0.001
	70-79	106	28	63	57.13	9.084	82.516	-1.146	0.235	0.139	0.465	0.430	<0.001
	80-89	22	45	63	59.73	7.106	50.494	-1.773	0.491	1.250	0.953	0.496	<0.001
	Total	786	16	63	50.60	12.145	147.493	-0.523	0.087	-0.580	0.174	0.273	<0.001

Appendix 8: Descriptive statistics for the Passalacqua method.

Appendix 9

Age Categories (years)		Descriptive Statistics						Skewness		Kurtosis		K-S Z	Asymp. Sig. (2-tailed)
		n	Min	Max	Mean	Std. Deviation	Variance	Statistic	Std. Error	Statistic	Std. Error		
Male	19-29	22	22	42	31.39	4.286	18.371	0.560	0.409	1.100	0.798	0.292	<0.001
	30-39	95	27	65	38.46	5.923	35.081	1.421	0.247	4.063	0.490	0.271	<0.001
	40-49	115	32	65	43.21	5.857	34.307	1.050	0.226	2.070	0.447	0.217	<0.001
	50-59	115	32	65	48.83	7.237	52.367	0.538	0.226	0.205	0.447	0.226	<0.001
	60-69	120	37	65	52.49	6.291	39.580	0.646	0.221	0.033	0.438	0.264	<0.001
	70-79	68	42	65	55.75	5.966	35.593	0.382	0.291	-0.466	0.574	0.365	<0.001
	80-89	11	47	65	60.36	6.712	45.055	-0.995	0.661	-0.550	1.279	0.391	<0.001
	Total	557	22	65	46.73	9.394	88.240	0.158	0.104	-0.424	0.207	0.136	<0.001
Female	19-29	19	27	37	29.89	3.035	9.211	0.498	0.524	-0.502	1.014	0.304	<0.001
	30-39	43	27	54	35.65	5.847	34.185	1.119	0.361	1.278	0.709	0.269	<0.001
	40-49	45	32	54	40.16	4.306	18.543	0.789	0.354	1.234	0.695	0.257	<0.001
	50-59	37	37	65	47.22	7.091	50.285	0.835	0.388	0.078	0.759	0.283	<0.001
	60-69	41	32	65	52.90	8.726	76.140	-0.141	0.369	-0.486	0.724	0.206	<0.001
	70-79	40	42	65	56.40	7.692	59.169	-0.305	0.374	-0.870	0.733	0.247	<0.001
	80-89	12	47	65	57.75	8.001	64.023	-0.340	0.637	-1.833	1.232	0.318	<0.001
	Total	237	27	65	45.46	11.138	124.054	0.313	0.158	-0.861	0.315	0.158	<0.001
European	19-29	21	27	42	31.05	4.068	16.548	0.996	0.501	1.192	0.972	0.265	<0.001
	30-39	74	27	54	37.53	5.341	28.527	0.961	0.279	1.118	0.552	0.269	<0.001
	40-49	108	32	65	42.54	5.873	34.494	1.139	0.233	2.735	0.461	0.222	<0.001
	50-59	125	32	65	48.46	7.384	54.525	0.653	0.217	0.050	0.430	0.211	<0.001
	60-69	135	37	65	52.83	6.679	44.605	0.404	0.209	-0.168	0.414	0.267	<0.001
	70-79	86	42	65	56.02	6.925	47.952	-0.045	0.260	-0.753	0.514	0.301	<0.001
	80-89	19	47	65	58.68	7.227	52.228	-0.474	0.524	-1.448	1.014	0.335	<0.001
	Total	568	27	65	47.79	9.585	91.869	0.144	0.103	-0.575	0.205	0.145	<0.001
African	19-29	30	22	42	30.67	3.925	15.402	0.524	0.427	1.529	0.833	0.267	<0.001
	30-39	62	27	65	37.44	6.745	45.496	1.464	0.304	4.017	0.599	0.235	<0.001
	40-49	50	37	54	41.96	5.103	26.039	0.930	0.337	0.256	0.662	0.237	<0.001
	50-59	25	37	65	48.44	6.733	45.340	0.114	0.464	0.240	0.902	0.196	0.015
	60-69	25	32	65	51.76	8.283	68.607	0.148	0.464	0.235	0.902	0.237	0.001
	70-79	22	47	65	55.86	5.462	29.838	0.747	0.491	-0.108	0.953	0.406	<0.001
	80-89	3	-	-	-	-	-	-	-	-	-	-	-
	Total	217	22	65	42.71	10.122	102.448	0.488	0.165	-0.389	0.329	0.156	<0.001
Other Ancestry	19-29	1	-	-	-	-	-	-	-	-	-	-	-
	30-39	2	42	47	44.50	3.536	12.500	-	-	-	-	0.260	-
	40-49	2	37	47	42.00	7.071	50.000	-	-	-	-	0.260	-
	50-59	2	-	-	-	-	-	-	-	-	-	-	-
	60-69	1	-	-	-	-	-	-	-	-	-	-	-
	70-79	0	-	-	-	-	-	-	-	-	-	-	-
	80-89	1	-	-	-	-	-	-	-	-	-	-	-
	Total	9	32	47	43.11	5.465	29.861	-1.289	0.717	0.770	1.400	0.317	0.009
Total	19-29	52	22	42	30.85	3.913	15.309	0.692	0.330	1.220	0.650	0.269	<0.001
	30-39	138	27	65	37.59	6.022	36.259	1.228	0.206	2.982	0.410	0.249	<0.001
	40-49	160	32	65	42.35	5.624	31.625	1.095	0.192	2.260	0.381	0.225	<0.001
	50-59	152	32	65	48.44	7.212	52.010	0.596	0.197	0.100	0.391	0.211	<0.001
	60-69	161	32	65	52.60	6.965	48.505	0.311	0.191	-0.049	0.380	0.252	<0.001
	70-79	108	42	65	55.99	6.630	43.953	0.041	0.233	-0.654	0.461	0.322	<0.001
	80-89	23	47	65	59.00	7.367	54.273	-0.604	0.481	-1.357	0.935	0.358	<0.001
	Total	794	22	65	46.35	9.956	99.128	0.193	0.087	-0.588	0.173	0.133	<0.001

Appendix 9: Descriptive statistics for the Lovejoy et al. method.

Appendix 10

Age Categories (years)		Std.						Skewness		Kurtosis		K-S Z	Asymp. Sig. (2-tailed)
		n	Min	Max	Mean	Deviation	Variance	Statistic	Std. Error	Statistic	Std. Error		
Male	19-29	33	17	72	40.55	12.096	146.318	0.517	0.409	-0.031	0.798	0.220	<0.001
	30-39	95	29	72	52.31	11.380	129.512	-0.456	0.247	-0.592	0.490	0.223	<0.001
	40-49	115	29	72	57.23	10.233	104.708	-0.802	0.226	0.000	0.447	0.233	<0.001
	50-59	115	38	72	62.59	8.094	65.507	-1.183	0.226	1.706	0.447	0.235	<0.001
	60-69	120	29	72	63.00	8.760	76.739	-1.449	0.221	2.506	0.438	0.224	<0.001
	70-79	68	51	72	64.97	7.295	53.223	-0.811	0.291	-0.555	0.574	0.257	<0.001
	80-89	11	60	72	69.55	3.908	15.273	-1.670	0.661	2.657	1.279	0.371	<0.001
	Total	557	17	72	58.94	11.381	129.523	-1.014	0.104	0.456	0.207	0.226	<0.001
Female	19-29	18	17	51	32.61	9.160	83.899	0.447	0.536	0.594	1.038	0.264	0.002
	30-39	43	17	72	45.12	15.190	230.724	0.156	0.361	-1.315	0.709	0.192	<0.001
	40-49	45	17	72	52.78	12.367	152.949	-0.711	0.354	0.052	0.695	0.209	<0.001
	50-59	37	29	72	61.43	10.474	109.697	-1.386	0.388	1.858	0.759	0.229	<0.001
	60-69	41	38	72	61.12	7.342	53.910	-1.347	0.369	2.736	0.724	0.238	<0.001
	70-79	40	51	75	66.68	5.903	34.840	-1.434	0.374	1.739	0.733	0.322	<0.001
	80-89	12	67	75	70.33	2.462	6.601	-0.812	0.637	-1.650	0.637	0.417	<0.001
	Total	236	17	72	56.42	14.813	219.419	-0.889	0.158	-0.363	0.316	0.235	<0.001
European	19-29	21	17	60	38.81	12.291	151.062	-0.126	0.501	-0.951	0.972	0.220	0.009
	30-39	74	29	67	49.22	12.820	164.364	-0.189	0.279	-1.211	0.552	0.190	<0.001
	40-49	108	29	72	56.69	10.243	104.928	-0.681	0.233	-0.153	0.461	0.201	<0.001
	50-59	125	29	72	62.76	8.468	71.700	-1.452	0.217	2.821	0.430	0.244	<0.001
	60-69	135	29	72	63.37	8.520	72.593	-1.509	0.209	2.772	0.414	0.235	<0.001
	70-79	86	51	72	65.66	6.693	44.791	-0.952	0.260	-0.059	0.514	0.265	<0.001
	80-89	19	60	72	70.05	3.308	10.942	-1.822	0.524	3.450	1.014	0.406	<0.001
	Total	568	17	72	59.78	11.519	132.678	-1.180	0.103	0.895	0.205	0.231	<0.001
African	19-29	29	17	72	36.97	11.617	134.963	1.266	0.434	1.885	0.845	0.258	<0.001
	30-39	62	17	72	50.79	13.442	180.693	-0.531	0.304	-0.539	0.599	0.232	<0.001
	40-49	50	17	72	54.16	12.556	157.647	-0.856	0.337	0.082	0.662	0.279	<0.001
	50-59	25	38	72	59.95	9.944	98.873	-0.740	0.464	-0.102	0.902	0.201	0.011
	60-69	25	38	72	62.68	8.102	65.643	-1.122	0.464	2.247	0.902	0.250	<0.001
	70-79	22	51	72	65.36	7.525	56.623	-1.219	0.491	0.172	0.953	0.359	<0.001
	80-89	3	67	72	68.67	2.887	8.333	1.732	1.225	-	-	0.385	-
	Total	216	17	72	53.88	14.141	199.954	-0.633	0.166	-0.635	0.330	0.209	<0.001
Other Ancestry	19-29	1	-	-	-	-	-	-	-	-	-	-	-
	30-39	2	51	67	59.00	11.314	128.00	-	-	-	-	0.260	-
	40-49	2	60	67	63.50	4.950	24.500	-	-	-	-	0.260	-
	50-59	2	60	67	63.50	4.950	24.500	-	-	-	-	0.260	-
	60-69	1	-	-	-	-	-	-	-	-	-	-	-
	70-79	0	-	-	-	-	-	-	-	-	-	-	-
	80-89	1	-	-	-	-	-	-	-	-	-	-	-
	Total	9	38	72	61.00	10.583	112.000	-1.488	0.717	2.041	1.400	0.270	0.057
Total	19-29	51	17	72	37.75	11.698	136.834	0.629	0.333	0.272	0.656	0.217	<0.001
	30-39	138	17	72	50.07	13.068	170.762	-0.353	0.206	-0.911	0.410	0.210	<0.001
	40-49	160	17	72	55.98	11.020	121.440	-0.828	0.192	0.203	0.381	0.230	<0.001
	50-59	152	29	75	62.31	8.710	75.857	-1.306	0.197	2.009	0.391	0.238	<0.001
	60-69	161	29	72	63.29	8.414	70.793	-1.452	0.191	2.632	0.380	0.223	<0.001
	70-79	108	51	72	65.60	6.834	46.709	-1.007	0.233	-0.034	0.461	0.285	<0.001
	80-89	23	60	72	69.69	3.183	10.134	-1.605	0.481	2.722	0.935	0.392	<0.001
	Total	793	17	72	58.19	12.544	157.364	-1.035	0.087	0.331	0.173	0.232	<0.001

Appendix 10: Descriptive statistics for the Buckberry and Chamberlain method.

Appendix 11

Age Categories (years)		Std.						Skewness		Kurtosis		K-S Z	Asymp. Sig. (2-tailed)
		n	Min	Max	Mean	Deviation	Variance	Statistic	Std. Error	Statistic	Std. Error		
Male	19-29	34	22	48	34.76	6.858	47.034	0.789	0.403	-0.165	0.788	0.315	<0.001
	30-39	94	22	59	40.26	7.949	63.181	0.489	0.249	0.353	0.493	0.303	<0.001
	40-49	115	30	59	45.45	7.558	57.127	0.034	0.226	-0.367	0.447	0.275	<0.001
	50-59	115	38	73	49.54	9.236	85.303	0.514	0.226	-0.154	0.447	0.244	<0.001
	60-69	120	90	73	51.55	8.217	67.527	0.158	0.221	0.177	0.438	0.267	<0.001
	70-79	68	38	73	53.35	9.048	81.874	0.212	0.291	-0.119	0.574	0.234	<0.001
	80-89	11	48	73	60.82	8.909	79.364	0.203	0.661	-0.670	1.279	0.308	0.004
	Total	557	22	73	47.35	10.002	100.044	0.224	0.104	-0.168	0.207	0.207	<0.001
Female	19-29	18	22	38	30.44	5.803	33.673	-0.086	0.536	-0.904	1.038	0.253	0.003
	30-39	43	30	59	37.70	8.002	64.025	0.657	0.361	-0.593	0.709	0.251	<0.001
	40-49	45	30	59	41.27	7.820	61.155	0.510	0.354	-0.147	0.695	0.284	<0.001
	50-59	37	30	59	48.78	8.597	73.901	-0.187	0.388	-1.017	0.759	0.210	<0.001
	60-69	41	38	73	53.27	9.872	97.451	0.278	0.369	-0.299	0.724	0.215	<0.001
	70-79	40	38	73	54.28	10.110	102.204	0.248	0.374	-0.396	0.733	0.208	<0.001
	80-89	12	48	73	59.50	7.574	57.364	0.472	0.637	0.823	1.232	0.360	<0.001
	Total	236	22	73	46.17	11.814	139.577	0.247	0.158	-0.520	0.316	0.171	<0.001
European	19-29	21	22	48	33.14	6.150	37.829	0.266	0.501	0.503	0.972	0.267	<0.001
	30-39	74	22	59	38.78	7.796	60.775	0.392	0.279	-0.378	0.552	0.243	<0.001
	40-49	108	30	59	44.56	7.902	62.436	0.217	0.233	-0.540	0.461	0.233	<0.001
	50-59	125	30	73	49.37	9.171	84.105	0.461	0.209	-0.070	0.430	0.247	<0.001
	60-69	135	30	73	51.77	8.430	71.059	0.121	0.209	0.032	0.414	0.250	<0.001
	70-79	86	38	73	53.84	8.893	79.079	0.271	0.260	-0.054	0.514	0.233	<0.001
	80-89	19	48	73	61.53	7.820	61.152	0.313	0.524	-0.375	1.014	0.364	<0.001
	Total	568	22	73	48.13	10.321	106.525	0.163	0.103	-0.243	0.205	0.200	<0.001
African	19-29	29	22	48	32.97	6.962	48.463	0.764	0.434	0.464	0.845	0.320	<0.001
	30-39	61	22	59	40.15	8.350	69.728	0.652	0.306	0.279	0.604	0.306	<0.001
	40-49	50	30	59	43.52	7.856	61.724	-0.023	0.337	-0.440	0.662	0.276	<0.001
	50-59	25	38	59	49.20	9.069	82.250	-0.112	0.464	-1.689	0.902	0.260	<0.001
	60-69	25	38	73	52.32	9.245	85.477	0.590	0.454	0.336	0.902	0.280	<0.001
	70-79	22	38	73	53.14	11.470	131.552	0.242	0.491	-0.759	0.953	0.195	0.028
	80-89	3	48	53	55.33	6.351	40.333	-1.732	1.225	-	-	0.385	-
	Total	215	22	73	43.97	10.702	114.532	0.403	0.166	-0.209	0.330	0.209	<0.001
Other Ancestry	19-29	2	30	48	39.00	12.728	162.00	-	-	-	-	0.260	-
	30-39	2	38	48	43.00	7.071	50.000	-	-	-	-	0.260	-
	40-49	2	-	-	-	-	-	-	-	-	-	-	-
	50-59	2	-	-	-	-	-	-	-	-	-	-	-
	60-69	1	-	-	-	-	-	-	-	-	-	-	-
	70-79	0	-	-	-	-	-	-	-	-	-	-	-
	80-89	1	-	-	-	-	-	-	-	-	-	-	-
	Total	10	30	73	47.70	10.791	116.456	1.076	0.687	3.976	1.334	0.389	<0.001
Total	19-29	52	22	48	33.27	6.780	45.965	0.620	0.330	0.225	0.650	0.301	<0.001
	30-39	137	22	59	39.45	8.025	64.397	0.515	0.207	-0.019	0.411	0.273	<0.001
	40-49	160	30	59	44.28	7.839	61.446	0.127	0.192	-0.485	0.381	0.251	<0.001
	50-59	152	30	73	49.32	9.065	82.167	0.381	0.197	-0.266	0.391	0.236	<0.001
	60-69	161	30	73	51.99	8.669	75.150	0.243	0.191	0.071	0.380	0.255	<0.001
	70-79	108	38	73	53.69	9.419	88.719	0.240	0.233	-0.253	0.461	0.223	<0.001
	80-89	23	48	73	60.13	8.075	65.209	0.331	0.481	-0.313	0.935	0.338	<0.001
	Total	793	22	73	47.00	10.580	111.941	0.209	0.087	-0.274	0.173	0.190	<0.001

Appendix 11: Descriptive statistics for the Rougé-Maillart et al. method.

Appendix 12

Age Categories (years)								Skewness		Kurtosis		K-S Z	Asymp. Sig. (2-tailed)
		n	Min	Max	Mean	Std. Deviation	Variance	Statistic	Std. Error	Statistic	Std. Error		
Male	19-29	35	18	35	27.46	6.657	44.314	-0.048	0.398	-1.596	0.778	0.243	<0.001
	30-39	95	23	46	36.06	5.565	30.975	0.675	0.247	-0.093	0.490	0.376	<0.001
	40-49	115	29	61	43.24	7.450	55.502	0.533	0.226	0.390	0.447	0.296	<0.001
	50-59	115	35	61	47.94	7.775	60.444	0.472	0.226	-0.244	0.447	0.372	<0.001
	60-69	120	35	61	50.58	7.822	61.180	0.301	0.221	-1.182	0.438	0.380	<0.001
	70-79	68	46	61	55.49	7.286	53.089	-0.561	0.291	-1.737	0.574	0.408	<0.001
	80-89	11	46	61	56.91	7.006	49.091	-1.189	0.661	-0.764	1.279	0.448	<0.001
	Total	559	18	61	45.38	10.510	110.468	-0.030	0.103	-0.481	0.206	0.247	<0.001
Female	19-29	19	19	38	29.32	5.991	35.895	-0.007	0.524	-0.710	1.014	0.190	0.071
	30-39	43	25	48	36.28	5.767	33.254	0.421	0.361	0.196	0.706	0.266	<0.001
	40-49	45	25	60	39.91	8.050	64.810	0.795	0.354	0.952	0.695	0.327	<0.001
	50-59	37	31	60	48.59	7.988	63.803	0.000	0.388	-0.501	0.759	0.286	<0.001
	60-69	40	38	60	53.00	7.646	58.462	-0.522	0.374	-0.966	0.733	0.320	<0.001
	70-79	38	48	60	56.21	5.653	31.954	-0.826	0.383	-1.395	0.750	0.433	<0.001
	80-89	12	48	60	57.00	5.427	29.455	-1.327	0.637	-0.326	1.232	0.460	<0.001
	Total	234	19	61	45.52	11.265	126.895	0-.097	0.159	-1.071	0.317	0.187	<0.001
European	19-29	22	18	38	28.00	6.655	44.286	-0.215	0.491	-1.401	0.953	0.183	0.054
	30-39	74	23	48	36.08	5.812	33.774	0.563	0.233	0.350	0.461	0.249	<0.001
	40-49	108	25	61	42.84	7.729	59.741	0.513	0.233	0.350	0.461	0.242	<0.001
	50-59	125	35	61	48.82	7.635	58.297	0.392	0.217	-0.503	0.430	0.295	<0.001
	60-69	135	35	61	51.98	7.735	59.828	0.023	0.209	-1.369	0.414	0.274	<0.001
	70-79	85	46	61	55.69	6.742	45.453	-0.637	0.261	-1.589	0.517	0.386	<0.001
	80-89	19	46	61	56.21	6.469	41.842	-0.875	0.524	-1.320	1.014	0.405	<0.001
	Total	568	18	61	47.24	10.287	105.814	-0.179	0.103	-0.614	0.205	0.195	<0.001
African	19-29	30	18	38	28.13	6.410	41.085	0.025	0.427	-1.209	0.833	0.188	0.009
	30-39	62	25	48	36.23	5.493	30.178	0.610	0.304	0.230	0.599	0.233	<0.001
	40-49	50	25	61	41.00	7.827	61.265	0.689	0.337	0.689	0.662	0.209	<0.001
	50-59	25	31	61	45.12	7.928	62.860	0.403	0.464	0.349	0.902	0.264	<0.001
	60-69	24	35	61	48.29	7.328	53.694	0.620	0.472	0.034	0.918	0.308	<0.001
	70-79	21	46	61	55.84	6.830	46.648	-0.771	0.501	-1.515	0.972	0.390	<0.001
	80-89	3	60	61	60.67	0.333	61.00	-1.732	1.225	-	-	0.385	<0.001
	Total	215	18	61	40.86	10.511	110.479	0.348	0.166	-0.306	0.330	0.165	<0.001
Other Ancestry	19-29	2	23	35	29.00	8.485	72.000	-	-	-	-	0.260	-
	30-39	2	-	-	-	-	-	-	-	-	-	-	-
	40-49	2	-	-	-	-	-	-	-	-	-	-	-
	50-59	2	35	46	40.50	7.778	60.500	-	-	-	-	0.260	-
	60-69	1	-	-	-	-	-	-	-	-	-	-	-
	70-79	0	-	-	-	-	-	-	-	-	-	-	-
	80-89	1	-	-	-	-	-	-	-	-	-	-	-
	Total	10	23	60	39.90	10.005	100.100	0.485	0.687	1.134	1.334	0.212	0.200
Total	19-29	54	18	38	28.11	6.436	41.421	-0.079	0.325	-1.298	0.639	0.173	<0.001
	30-39	138	23	48	36.13	5.609	31.457	0.587	0.206	-0.051	0.410	0.247	<0.001
	40-49	160	25	61	42.31	7.745	59.987	0.534	0.192	0.367	0.381	0.227	<0.001
	50-59	152	31	61	48.10	7.805	60.924	0.352	0.197	-0.364	0.391	0.281	<0.001
	60-69	160	35	61	51.34	7.814	61.055	0.102	0.192	-1.271	0.381	0.278	<0.001
	70-79	106	46	61	55.75	6.727	45.258	-0.653	0.235	-1.562	0.465	0.387	<0.001
	80-89	23	46	61	56.96	6.086	37.043	-1.174	0.481	-0.608	0.935	0.431	<0.001
	Total	793	18	61	45.42	10.732	115.165	-0.051	0.087	-0.683	0.173	0.179	<0.001

Appendix 12: Descriptive statistics for the Suchey-Brooks et al. method.

Appendix 13

BMI Categories		Kunos et al.	DiGangi et al.	İşcan et al.	Passalacqua	Lovejoy et al.	Buckberry & Chamberlain	Rougé-Maillart et al.	Suchey-Brooks
Underweight	Kunos et al.	46.374	20.919	28.178	12.137	12.115	19.698	22.650	4.413
	DiGangi et al.	20.919	128.418	76.794	33.734	46.660	-30.558	61.610	52.118
	İşcan et al.			125.28					
		28.178	76.794	5	32.032	37.331	1.793	51.759	31.058
	Passalacqua	12.137	33.734	32.032	76.430	18.389	-1.896	26.729	17.347
	Lovejoy et al.	12.115	46.660	37.331	18.389	59.673	1.334	50.972	29.940
	Buckberry & Chamberlain	19.698	-30.558	1.793	-1.896	1.334	83.975	17.338	-19.344
	Rougé-Maillart et al.	22.650	61.610	51.759	26.729	50.972	17.338	83.319	38.751
	Suchey-Brooks	4.413	52.118	31.058	17.347	29.940	-19.344	38.751	66.268
Normal	Kunos et al.	54.205	-2.422	5.403	12.143	1.356	29.061	6.824	0.152
	DiGangi et al.	-2.422	112.466	17.919	13.378	36.480	-26.716	38.871	43.699
	İşcan et al.	5.403	17.919	53.753	2.404	-0.337	-2.280	2.462	4.548
	Passalacqua	12.143	13.378	2.404	71.050	11.789	10.029	11.715	7.177
	Lovejoy et al.	1.356	36.480	-0.337	11.789	38.874	-2.829	28.415	23.091
	Buckberry & Chamberlain	29.061	-26.716	-2.280	10.029	-2.829	74.733	10.010	-13.379
	Rougé-Maillart et al.	6.824	38.871	2.462	11.715	28.415	10.010	60.651	23.675
	Suchey-Brooks	0.152	43.699	4.548	7.177	23.091	-13.379	23.675	50.383
Overweight	Kunos et al.	37.174	-3.302	-2.948	2.434	0.231	19.904	1.956	-2.876
	DiGangi et al.	-3.302	82.085	6.485	-4.268	21.369	-26.709	21.133	26.217
	İşcan et al.	-2.948	6.485	63.398	-2.608	-4.025	5.166	5.249	2.481
	Passalacqua	2.434	-4.268	-2.608	45.169	4.519	-0.641	9.068	0.935
	Lovejoy et al.	0.231	21.369	-4.025	4.519	49.367	-4.099	27.039	19.707
	Buckberry & Chamberlain	19.904	-26.709	5.166	-0.641	-4.099	78.650	0.055	-18.208
	Rougé-Maillart et al.	1.956	21.133	5.249	9.068	27.039	0.055	44.993	20.456
	Suchey-Brooks	-2.876	26.217	2.481	0.935	19.707	-18.208	20.456	50.310
Obese	Kunos et al.	41.454	-20.403	4.683	11.629	-14.708	18.505	-15.362	-21.948
	DiGangi et al.	-20.403	70.098	-4.938	7.065	26.286	-23.948	38.569	10.246
	İşcan et al.	4.683	-4.938	32.978	-4.265	-12.606	15.108	9.951	-3.606
	Passalacqua	11.629	7.065	-4.265	54.906	6.422	20.643	7.232	7.222
	Lovejoy et al.	-14.708	26.286	-12.606	6.422	52.375	-25.849	17.083	17.055
	Buckberry & Chamberlain	18.505	-23.948	15.108	20.643	-25.849	59.422	-5.434	-17.169
	Rougé-Maillart et al.	-15.362	38.569	9.951	7.232	17.083	-5.434	43.325	16.643
	Suchey-Brooks	-21.948	10.246	-3.606	7.222	17.055	-17.169	16.643	46.295

Appendix 13: Covariance matrix for males separated by BMI for accuracy scores.

Appendix 14

BMI Categories		Kunos et al.	DiGangi et al.	İşcan et al.	Passalacqua	Lovejoy et al.	Buckberry & Chamberlain	Rougé-Maillart et al.	Suchey-Brooks
Underweight	Kunos et al.	159.62	167.10	145.079	116.401	105.059	128.164	135.327	98.997
	DiGangi et al.	167.101	208.101	158.293	130.099	106.504	129.879	143.720	104.701
	İşcan et al.	145.079	158.293	222.823	108.815	102.729	133.555	137.567	87.351
	Passalacqua	116.401	130.099	108.815	213.572	93.075	121.096	114.911	88.536
	Lovejoy et al.	105.059	106.504	102.729	93.075	116.830	133.550	129.339	75.090
	Buckberry & Chamberlain	128.164	129.879	133.555	121.096	133.550	210.568	174.168	92.235
	Rougé-Maillart et al.	135.327	143.720	137.567	114.911	129.339	174.168	192.094	102.336
	Suchey-Brooks	98.997	104.701	87.351	88.536	75.090	92.235	102.336	116.323
Normal	Kunos et al.	151.709	151.586	-12.375	108.674	83.212	114.445	111.245	79.369
	DiGangi et al.	151.586	197.256	-38.269	109.291	83.638	113.714	112.330	83.204
	İşcan et al.	-12.375	-38.269	141.839	-4.859	7.474	3.263	6.653	8.710
	Passalacqua	108.674	109.291	-4.859	201.430	79.128	106.078	102.023	69.583
	Lovejoy et al.	83.212	83.638	7.474	79.128	87.012	92.288	90.729	57.532
	Buckberry & Chamberlain	114.445	113.714	3.263	106.078	92.288	170.114	140.456	74.212
	Rougé-Maillart et al.	111.245	112.330	6.653	102.023	90.729	140.456	152.926	76.364
	Suchey-Brooks	79.369	83.204	8.710	69.583	57.532	74.212	76.364	85.547
Overweight	Kunos et al.	94.384	82.125	27.012	62.215	54.466	65.307	66.193	70.041
	DiGangi et al.	82.125	120.120	2.504	41.087	46.831	52.105	53.560	60.621
	İşcan et al.	27.012	2.504	164.615	42.858	51.564	45.510	43.962	47.993
	Passalacqua	62.215	41.087	42.858	131.775	55.214	53.738	70.120	45.320
	Lovejoy et al.	54.466	46.831	51.564	55.214	102.454	78.398	87.434	53.186
	Buckberry & Chamberlain	65.307	52.105	45.510	53.738	78.398	129.389	104.432	64.018
	Rougé-Maillart et al.	66.193	53.560	43.962	70.120	87.434	104.432	123.480	71.029
	Suchey-Brooks	70.041	60.621	47.993	45.320	53.186	64.018	71.029	112.039
Obese	Kunos et al.	80.998	77.951	5.803	54.389	48.422	60.129	62.743	42.271
	DiGangi et al.	77.951	138.105	11.498	54.495	66.809	69.375	74.658	56.105
	İşcan et al.	5.803	11.498	126.074	45.742	22.957	5.262	20.154	-25.822
	Passalacqua	54.389	54.495	45.742	178.045	73.311	85.025	64.282	53.815
	Lovejoy et al.	48.422	66.809	22.957	73.311	85.378	56.791	44.077	39.129
	Buckberry & Chamberlain	60.129	69.375	5.262	85.025	56.791	107.865	72.382	69.655
	Rougé-Maillart et al.	62.743	74.658	20.154	64.282	44.077	72.382	77.934	47.618
	Suchey-Brooks	42.271	56.105	-25.822	53.815	39.129	69.655	47.618	106.745

Appendix 14: Covariance matrix for males separated by BMI for bias scores.

Appendix 15

BMI Categories		Kunos et al.	DiGangi et al.	İşcan et al.	Passalacqua	Lovejoy et al.	Buckberry & Chamberlain	Rougé-Maillart et al.	Suchey-Brooks
Underweight	Kunos et al.	147.502	113.653	99.393	124.879	66.020	78.024	112.364	79.780
	DiGangi et al.	113.653	148.319	72.339	84.785	56.310	48.021	89.688	50.410
	İşcan et al.	99.393	72.339	162.171	112.942	52.070	27.558	73.315	88.661
	Passalacqua	124.879	84.785	112.942	196.888	62.475	94.720	115.896	99.863
	Lovejoy et al.	66.020	56.310	52.070	62.475	70.060	49.181	74.633	39.690
	Buckberry & Chamberlain	78.024	48.021	27.558	94.720	49.181	143.283	107.469	55.600
	Rougé-Maillart et al.	112.364	89.688	73.315	115.896	74.633	107.469	134.063	78.799
	Suchey-Brooks	79.780	50.410	88.661	99.863	39.690	55.600	78.799	91.346
Normal	Kunos et al.	179.929	171.391	47.354	125.538	86.472	96.679	101.247	90.481
	DiGangi et al.	171.391	206.860	26.276	122.878	81.722	89.084	98.502	78.380
	İşcan et al.	47.354	26.276	247.809	77.240	56.043	63.215	81.523	45.459
	Passalacqua	125.538	122.878	77.240	215.176	86.971	97.209	107.548	89.762
	Lovejoy et al.	86.472	81.722	56.043	86.971	93.966	80.133	88.969	64.041
	Buckberry & Chamberlain	96.679	89.084	63.215	97.209	80.133	161.818	118.376	62.996
	Rougé-Maillart et al.	101.247	98.502	81.523	107.548	88.969	118.376	145.421	74.621
	Suchey-Brooks	90.481	78.380	45.459	89.762	64.041	62.996	74.621	98.513
Overweight	Kunos et al.	152.765	160.621	23.403	100.923	46.677	72.117	67.837	64.643
	DiGangi et al.	160.621	235.931	31.312	148.044	38.314	68.284	62.512	71.113
	İşcan et al.	23.403	31.312	144.609	52.124	28.991	36.452	38.117	45.403
	Passalacqua	100.923	148.044	52.124	226.362	60.195	36.090	62.478	68.976
	Lovejoy et al.	46.677	38.314	28.991	60.195	51.800	47.714	54.195	28.405
	Buckberry & Chamberlain	72.117	68.284	36.452	36.090	47.714	129.983	83.585	39.534
	Rougé-Maillart et al.	67.837	62.512	38.117	62.478	54.195	83.585	100.074	47.489
	Suchey-Brooks	64.643	71.113	45.403	68.976	28.405	39.534	47.489	71.295
Obese	Kunos et al.	48.859	71.788	7.551	62.526	32.122	29.019	17.218	34.449
	DiGangi et al.	71.788	164.808	56.410	58.538	71.474	54.571	50.410	42.673
	İşcan et al.	7.551	56.410	142.936	67.051	107.494	74.955	112.103	44.731
	Passalacqua	62.526	58.538	67.051	263.692	78.455	124.353	103.968	149.615
	Lovejoy et al.	32.122	71.474	107.494	78.455	126.308	97.487	120.410	49.256
	Buckberry & Chamberlain	29.019	54.571	74.955	124.353	97.487	174.077	126.705	53.628
	Rougé-Maillart et al.	17.218	50.410	112.103	103.968	120.410	126.705	146.603	58.814
	Suchey-Brooks	34.449	42.673	44.731	149.615	49.256	53.628	58.814	109.936

Appendix 15: Covariance matrix for females separated by BMI for bias scores.

Appendix 16

BMI Categories		Kunos et al.	DiGangi et al.	İşcan et al.	Passalacqua	Lovejoy et al.	Buckberry & Chamberlain	Rougé-Maillart et al.	Suchey-Brooks
Underweight	Kunos et al.	44.780	30.314	23.478	11.025	22.378	8.840	26.795	11.058
	DiGangi et al.	30.314	136.747	76.977	23.446	56.285	-17.932	68.857	46.817
	İşcan et al.	23.478	76.977	119.567	18.475	39.592	0.531	53.597	35.421
	Passalacqua	11.025	23.446	18.475	71.284	21.054	5.706	24.475	18.985
	Lovejoy et al.	22.378	56.285	39.592	21.054	67.974	10.527	57.282	27.820
	Buckberry & Chamberlain	8.840	-17.932	0.531	5.706	10.527	67.977	13.387	-8.073
	Rougé-Maillart et al.	26.795	68.857	53.597	24.475	57.282	13.387	78.077	42.884
	Suchey-Brooks	11.058	46.817	35.421	18.985	27.820	-8.073	42.884	69.931
Normal	Kunos et al.	56.772	12.278	5.335	14.957	4.123	22.034	10.641	4.029
	DiGangi et al.	12.278	134.723	25.520	13.829	42.287	-26.247	44.302	42.274
	İşcan et al.	5.335	25.520	76.483	9.715	3.813	-2.693	10.420	6.679
	Passalacqua	14.957	13.829	9.715	74.562	13.840	6.381	17.585	11.552
	Lovejoy et al.	4.123	42.287	3.813	13.840	45.280	-5.861	31.073	26.147
	Buckberry & Chamberlain	22.034	-26.247	-2.693	6.381	-5.861	66.283	6.045	-10.250
	Rougé-Maillart et al.	10.641	44.302	10.420	17.585	31.073	6.045	65.386	26.409
	Suchey-Brooks	4.029	42.274	6.679	11.552	26.147	-10.250	26.409	53.029
Overweight	Kunos et al.	43.827	0.465	0.847	3.299	-1.412	13.300	0.067	-3.391
	DiGangi et al.	0.465	103.815	13.130	2.337	16.724	-19.241	19.459	27.616
	İşcan et al.	0.847	13.130	68.259	4.577	-2.016	1.071	3.482	2.563
	Passalacqua	3.299	2.337	4.577	48.947	1.728	-5.735	10.484	1.309
	Lovejoy et al.	-1.412	16.724	-2.016	1.728	46.572	-2.925	27.221	18.092
	Buckberry & Chamberlain	13.300	-19.241	1.071	-5.735	-2.925	60.620	1.548	-14.986
	Rougé-Maillart et al.	0.067	19.459	3.482	10.484	27.221	1.548	45.966	19.817
	Suchey-Brooks	-3.391	27.616	2.563	1.309	18.092	-14.986	19.817	46.509
Obese	Kunos et al.	38.107	-20.838	-2.660	5.396	-17.123	11.815	-19.742	-19.296
	DiGangi et al.	-20.838	83.719	8.798	4.234	37.357	-14.694	44.208	16.525
	İşcan et al.	-2.660	8.798	39.830	-0.380	-0.332	17.320	23.477	-3.867
	Passalacqua	5.396	4.234	-0.380	71.701	14.330	14.023	18.305	17.014
	Lovejoy et al.	-17.123	37.357	-0.332	14.330	65.291	-22.675	33.013	23.304
	Buckberry & Chamberlain	11.815	-14.694	17.320	14.023	-22.675	62.575	1.830	-17.589
	Rougé-Maillart et al.	-19.742	44.208	23.477	18.305	33.013	1.830	60.910	26.780
	Suchey-Brooks	-19.296	16.525	-3.867	17.014	23.304	-17.589	26.780	44.557

Appendix 16: Covariance matrix for individuals of European ancestry separated by BMI for accuracy scores.

Appendix 17

BMI Categories		Kunos et al.	DiGangi et al.	İşcan et al.	Passalacqua	Lovejoy et al.	Buckberry & Chamberlain	Rougé-Maillart et al.	Suchey-Brooks
Underweight	Kunos et al.	133.338	120.712	102.364	99.601	88.649	95.376	114.341	79.086
	DiGangi et al.	120.712	148.779	99.919	80.360	78.464	82.455	102.904	59.946
	İşcan et al.	102.364	99.919	154.026	78.166	73.084	91.604	97.283	62.292
	Passalacqua	99.601	80.360	78.166	198.957	85.440	105.034	106.570	85.645
	Lovejoy et al.	88.649	78.464	73.084	85.440	110.398	107.525	111.901	60.355
	Buckberry & Chamberlain	95.376	82.455	91.604	105.034	107.525	175.370	140.264	69.726
	Rougé-Maillart et al.	114.341	102.904	97.283	106.570	111.901	140.264	159.173	86.400
	Suchey-Brooks	79.086	59.946	62.292	85.645	60.355	69.726	86.400	111.214
Normal	Kunos et al.	171.792	167.678	18.771	118.714	87.155	114.424	110.598	83.380
	DiGangi et al.	167.678	213.165	-6.542	114.267	84.438	109.537	107.141	81.205
	İşcan et al.	18.771	-6.542	193.122	34.162	27.699	28.347	35.963	25.271
	Passalacqua	118.714	114.267	34.162	203.458	79.282	102.570	102.664	72.828
	Lovejoy et al.	87.155	84.438	27.699	79.282	86.775	86.991	85.823	56.469
	Buckberry & Chamberlain	114.424	109.537	28.347	102.570	86.991	158.995	129.688	70.286
	Rougé-Maillart et al.	110.598	107.141	35.963	102.664	85.823	129.688	145.818	71.037
	Suchey-Brooks	83.380	81.205	25.271	72.828	56.469	70.286	71.037	88.184
Overweight	Kunos et al.	113.306	107.380	28.848	74.353	51.124	61.450	61.277	68.357
	DiGangi et al.	107.380	159.720	15.940	69.719	41.488	49.572	47.782	63.857
	İşcan et al.	28.848	15.940	180.901	47.157	48.864	56.263	47.973	50.387
	Passalacqua	74.353	69.719	47.157	150.698	53.816	48.634	65.622	52.686
	Lovejoy et al.	51.124	41.488	48.864	53.816	88.793	69.177	77.823	43.423
	Buckberry & Chamberlain	61.450	49.572	56.263	48.634	69.177	124.226	96.861	53.229
	Rougé-Maillart et al.	61.277	47.782	47.973	65.622	77.823	96.861	116.881	60.429
	Suchey-Brooks	68.357	63.857	50.387	52.686	43.423	53.229	60.429	101.855
Obese	Kunos et al.	76.966	83.561	5.340	61.449	48.699	59.169	52.847	37.845
	DiGangi et al.	83.561	162.564	32.862	64.070	77.507	75.844	75.402	46.910
	İşcan et al.	5.340	32.862	132.001	44.647	59.678	36.222	51.049	1.719
	Passalacqua	61.449	64.070	44.647	213.947	85.442	115.178	83.528	98.237
	Lovejoy et al.	48.699	77.507	59.678	85.442	112.878	80.188	77.213	41.775
	Buckberry & Chamberlain	59.169	75.844	36.222	115.178	80.188	123.987	94.479	67.791
	Rougé-Maillart et al.	52.847	75.402	51.049	83.528	77.213	94.479	107.242	55.650
	Suchey-Brooks	37.845	46.910	1.719	98.237	41.775	67.791	55.650	94.375

Appendix 17: Covariance matrix for individuals of European ancestry separated by BMI for bias scores.

Appendix 18

BMI Categories		Kunos et al.	DiGangi et al.	İşcan et al.	Passalacqua	Lovejoy et al.	Buckberry & Chamberlain	Rougé-Maillart et al.	Suchey-Brooks
Underweight	Kunos et al.	162.118	155.367	157.428	133.438	82.486	110.794	116.643	96.120
	DiGangi et al.	155.367	212.565	175.662	129.375	85.859	107.879	122.375	98.017
	İşcan et al.	157.428	175.662	287.571	130.271	98.480	108.916	136.176	110.239
	Passalacqua	133.438	129.375	130.271	230.792	71.333	101.021	105.417	97.583
	Lovejoy et al.	82.486	85.859	98.480	71.333	80.181	90.213	93.120	58.386
	Buckberry & Chamberlain	110.794	107.879	108.916	101.021	90.213	188.928	143.753	77.055
	Rougé-Maillart et al.	116.643	122.375	136.176	105.417	93.120	143.753	159.046	85.355
	Suchey-Brooks	96.120	98.017	110.239	97.583	58.386	77.055	85.355	95.259
Normal	Kunos et al.	126.990	122.998	-22.482	88.171	63.830	92.516	90.342	71.271
	DiGangi et al.	122.998	151.571	-45.880	90.219	59.840	90.068	90.687	71.034
	İşcan et al.	-22.482	-45.880	126.697	-20.287	4.694	2.165	6.601	2.317
	Passalacqua	88.171	90.219	-20.287	189.467	66.415	93.654	84.355	68.049
	Lovejoy et al.	63.830	59.840	4.694	66.415	74.810	80.820	80.004	54.527
	Buckberry & Chamberlain	92.516	90.068	2.165	93.654	80.820	180.807	132.089	65.429
	Rougé-Maillart et al.	90.342	90.687	6.601	84.355	80.004	132.089	140.339	74.984
	Suchey-Brooks	71.271	71.034	2.317	68.049	54.527	65.429	74.984	84.110
Overweight	Kunos et al.	95.155	88.610	8.756	60.481	48.575	83.936	76.973	62.234
	DiGangi et al.	88.610	125.633	-9.753	72.884	48.978	82.220	79.811	57.492
	İşcan et al.	8.756	-9.753	99.966	30.332	20.520	6.324	9.727	27.847
	Passalacqua	60.481	72.884	30.332	180.059	58.684	41.618	65.326	42.428
	Lovejoy et al.	48.575	48.978	20.520	58.684	77.309	63.400	68.576	49.678
	Buckberry & Chamberlain	83.936	82.220	6.324	41.618	63.400	157.371	95.820	65.312
	Rougé-Maillart et al.	76.973	79.811	9.727	65.326	68.576	95.820	103.797	70.408
	Suchey-Brooks	62.234	57.492	27.847	42.428	49.678	65.312	70.408	88.945
Obese	Kunos et al.	11.300	8.550	20.950	31.500	2.900	-6.850	5.100	21.700
	DiGangi et al.	8.550	16.300	-16.050	3.500	6.150	-2.100	-5.400	48.200
	İşcan et al.	20.950	-16.050	151.800	133.500	-2.150	-17.400	45.900	-70.700
	Passalacqua	31.500	3.500	133.500	141.500	4.000	-42.250	31.000	-20.000
	Lovejoy et al.	2.900	6.150	-2.150	4.000	5.700	10.450	4.300	16.600
	Buckberry & Chamberlain	-6.850	-2.100	-17.400	-42.250	10.450	177.700	63.800	48.350
	Rougé-Maillart et al.	5.100	-5.400	45.900	31.000	4.300	63.800	41.200	-3.600
	Suchey-Brooks	21.700	48.200	-70.700	-20.000	16.600	48.350	-3.600	169.300

Appendix 18: Covariance matrix for individuals of African ancestry separated by BMI for bias scores.

Appendix 19

Stature Categories		Kunos et al.	DiGangi et al.	İşcan et al.	Passalacqua	Lovejoy et al.	Buckberry & Chamberlain	Rougé-Maillart et al.	Suchey-Brooks
Group 1	Kunos et al.	29.237	13.341	20.170	7.311	-3.489	22.763	8.185	.852
	DiGangi et al.	13.341	106.662	28.211	13.613	29.931	-15.992	42.195	26.205
	İşcan et al.	20.170	28.211	86.991	12.413	3.807	28.084	15.460	7.919
	Passalacqua	7.311	13.613	12.413	63.341	21.998	10.616	24.569	2.805
	Lovejoy et al.	-3.489	29.931	3.807	21.998	55.810	-.471	37.897	21.332
	Buckberry & Chamberlain	22.763	-15.992	28.084	10.616	-.471	66.436	6.404	-2.062
	Rougé-Maillart et al.	8.185	42.195	15.460	24.569	37.897	6.404	66.973	25.761
	Suchey-Brooks	.852	26.205	7.919	2.805	21.332	-2.062	25.761	46.189
Group 2	Kunos et al.	48.924	1.340	.443	24.000	3.706	26.927	13.485	-1.714
	DiGangi et al.	1.340	116.844	21.854	33.503	43.984	-27.061	48.027	52.808
	İşcan et al.	.443	21.854	58.858	1.410	8.332	-1.760	18.317	10.248
	Passalacqua	24.000	33.503	1.410	86.229	28.491	12.918	30.482	26.676
	Lovejoy et al.	3.706	43.984	8.332	28.491	50.251	-8.459	35.067	34.103
	Buckberry & Chamberlain	26.927	-27.061	-1.760	12.918	-8.459	76.561	7.371	-23.708
	Rougé-Maillart et al.	13.485	48.027	18.317	30.482	35.067	7.371	62.782	31.523
	Suchey-Brooks	-1.714	52.808	10.248	26.676	34.103	-23.708	31.523	67.188
Group 3	Kunos et al.	53.851	7.714	11.008	7.198	4.236	23.318	7.625	-2.355
	DiGangi et al.	7.714	119.597	35.123	12.010	39.012	-19.013	45.561	44.754
	İşcan et al.	11.008	35.123	75.868	12.415	5.726	-6.579	12.539	9.414
	Passalacqua	7.198	12.010	12.415	64.281	3.782	2.241	6.632	2.972
	Lovejoy et al.	4.236	39.012	5.726	3.782	46.705	4.270	36.106	21.840
	Buckberry & Chamberlain	23.318	-19.013	-6.579	2.241	4.270	72.629	13.798	-9.676
	Rougé-Maillart et al.	7.625	45.561	12.539	6.632	36.106	13.798	68.166	27.627
	Suchey-Brooks	-2.355	44.754	9.414	2.972	21.840	-9.676	27.627	52.120
Group 4	Kunos et al.	51.096	-14.101	3.441	2.946	-.523	27.250	1.988	1.237
	DiGangi et al.	-14.101	82.943	10.983	-3.819	19.345	-41.670	20.644	24.036
	İşcan et al.	3.441	10.983	56.849	1.002	.647	4.183	4.377	6.873
	Passalacqua	2.946	-3.819	1.002	49.682	-.220	3.860	4.015	-2.274
	Lovejoy et al.	-.523	19.345	.647	-.220	31.404	-8.651	15.228	13.032
	Buckberry & Chamberlain	27.250	-41.670	4.183	3.860	-8.651	82.045	6.607	-18.735
	Rougé-Maillart et al.	1.988	20.644	4.377	4.015	15.228	6.607	40.826	12.525
	Suchey-Brooks	1.237	24.036	6.873	-2.274	13.032	-18.735	12.525	40.359

Appendix 19: Covariance matrix for males separated by stature for accuracy scores.

Appendix 20

Stature Categories		Kunos et al.	DiGangi et al.	İşcan et al.	Passalacqua	Lovejoy et al.	Buckberry & Chamberlain	Rougé-Maillart et al.	Suchey-Brooks
Group 1	Kunos et al.	44.739	29.062	8.701	8.186	7.292	3.423	14.810	7.109
	DiGangi et al.	29.062	136.056	40.867	-3.887	38.380	-10.445	49.049	28.817
	İşcan et al.	8.701	40.867	121.223	20.200	16.412	9.055	30.119	22.691
	Passalacqua	8.186	-3.887	20.200	69.213	7.832	4.753	17.980	8.627
	Lovejoy et al.	7.292	38.380	16.412	7.832	53.492	.840	38.019	23.306
	Buckberry & Chamberlain	3.423	-10.445	9.055	4.753	0.840	51.540	8.960	-0.125
	Rougé-Maillart et al.	14.810	49.049	30.119	17.980	38.019	8.960	73.839	34.287
	Suchey-Brooks	7.109	28.817	22.691	8.627	23.306	-0.125	34.287	50.454
Group 2	Kunos et al.	51.674	11.385	4.213	22.996	4.323	18.692	12.970	1.655
	DiGangi et al.	11.385	144.291	33.756	29.499	43.960	-23.767	50.405	51.943
	İşcan et al.	4.213	33.756	66.155	2.601	9.522	-4.372	18.077	5.202
	Passalacqua	22.996	29.499	2.601	77.880	26.156	9.269	27.976	21.337
	Lovejoy et al.	4.323	43.960	9.522	26.156	58.341	-6.799	40.055	34.395
	Buckberry & Chamberlain	18.692	-23.767	-4.372	9.269	-6.799	64.514	5.884	-16.376
	Rougé-Maillart et al.	12.970	50.405	18.077	27.976	40.055	5.884	65.625	31.973
	Suchey-Brooks	1.655	51.943	5.202	21.337	34.395	-16.376	31.973	63.074
Group 3	Kunos et al.	53.277	10.901	7.388	5.475	2.899	19.105	5.567	-2.267
	DiGangi et al.	10.901	117.717	24.900	13.652	39.807	-13.695	40.406	41.111
	İşcan et al.	7.388	24.900	60.950	8.277	-0.411	-5.627	3.733	5.089
	Passalacqua	5.475	13.652	8.277	64.641	6.329	-0.101	12.135	6.819
	Lovejoy et al.	2.899	39.807	-.411	6.329	46.190	-1.616	32.317	22.665
	Buckberry & Chamberlain	19.105	-13.695	-5.627	-0.101	-1.616	58.473	6.424	-10.843
	Rougé-Maillart et al.	5.567	40.406	3.733	12.135	32.317	6.424	58.913	25.172
	Suchey-Brooks	-2.267	41.111	5.089	6.819	22.665	-10.843	25.172	52.440
Group 4	Kunos et al.	56.465	-19.788	4.588	2.937	-0.422	31.810	0.951	0.508
	DiGangi et al.	-19.788	80.706	2.059	0.726	18.010	-43.655	20.147	16.581
	İşcan et al.	4.588	2.059	61.645	6.059	-0.187	13.159	10.610	2.816
	Passalacqua	2.937	.726	6.059	54.159	2.567	1.884	5.005	1.027
	Lovejoy et al.	-0.422	18.010	-0.187	2.567	35.870	-5.115	17.848	9.056
	Buckberry & Chamberlain	31.810	-43.655	13.159	1.884	-5.115	85.658	8.353	-15.988
	Rougé-Maillart et al.	.951	20.147	10.610	5.005	17.848	8.353	41.430	11.540
	Suchey-Brooks	.508	16.581	2.816	1.027	9.056	-15.988	11.540	41.102

Appendix 20: Covariance matrix for individuals of European ancestry separated by stature for accuracy scores.

Appendix 21

Body Mass Categories		Kunos et al.	DiGangi et al.	İşcan et al.	Passalacqua	Lovejoy et al.	Buckberry & Chamberlain	Rougé-Maillart et al.	Suchey-Brooks
Group 1	Kunos et al.	42.853	17.362	20.618	21.222	7.676	17.848	22.796	11.047
	DiGangi et al.	17.362	111.907	76.592	29.457	45.139	-15.697	59.904	39.941
	İşcan et al.	20.618	76.592	120.901	32.919	41.475	5.810	54.575	36.059
	Passalacqua	21.222	29.457	32.919	81.405	22.795	12.049	24.692	17.108
	Lovejoy et al.	7.676	45.139	41.475	22.795	51.381	7.304	47.640	24.882
	Buckberry & Chamberlain	17.848	-15.697	5.810	12.049	7.304	83.837	22.706	-4.542
	Rougé-Maillart et al.	22.796	59.904	54.575	24.692	47.640	22.706	83.970	36.217
	Suchey-Brooks	11.047	39.941	36.059	17.108	24.882	-4.542	36.217	58.793
Group 2	Kunos et al.	54.810	7.421	16.354	5.492	4.361	28.740	7.024	-0.661
	DiGangi et al.	7.421	129.934	27.034	28.237	41.366	-36.095	41.619	56.710
	İşcan et al.	16.354	27.034	70.460	8.338	1.383	-2.784	3.219	5.265
	Passalacqua	5.492	28.237	8.338	82.991	23.001	5.601	24.498	14.750
	Lovejoy et al.	4.361	41.366	1.383	23.001	49.998	-7.990	37.263	28.870
	Buckberry & Chamberlain	28.740	-36.095	-2.784	5.601	-7.990	69.400	3.589	-25.430
	Rougé-Maillart et al.	7.024	41.619	3.219	24.498	37.263	3.589	66.360	26.451
	Suchey-Brooks	-0.661	56.710	5.265	14.750	28.870	-25.430	26.451	62.275
Group 3	Kunos et al.	53.963	-12.382	-1.061	13.197	-1.624	35.898	3.204	-8.598
	DiGangi et al.	-12.382	96.328	9.091	-1.691	25.282	-26.124	27.731	26.725
	İşcan et al.	-1.061	9.091	45.147	-4.511	-4.977	-2.131	-1.812	-2.594
	Passalacqua	13.197	-1.691	-4.511	60.272	-0.049	7.767	2.784	-0.006
	Lovejoy et al.	-1.624	25.282	-4.977	-0.049	37.653	0.085	20.204	18.125
	Buckberry & Chamberlain	35.898	-26.124	-2.131	7.767	0.085	84.442	13.511	-7.740
	Rougé-Maillart et al.	3.204	27.731	-1.812	2.784	20.204	13.511	46.653	15.981
	Suchey-Brooks	-8.598	26.725	-2.594	-0.006	18.125	-7.740	15.981	39.385
Group 4	Kunos et al.	37.403	-5.631	-4.563	4.528	-1.658	11.869	0.478	-1.773
	DiGangi et al.	-5.631	75.318	0.719	-0.097	25.918	-20.765	27.367	25.468
	İşcan et al.	-4.563	0.719	53.075	-1.463	-3.853	9.604	8.246	3.981
	Passalacqua	4.528	-0.097	-1.463	42.192	2.229	3.011	4.538	1.351
	Lovejoy et al.	-1.658	25.918	-3.853	2.229	44.105	-8.275	24.359	19.021
	Buckberry & Chamberlain	11.869	-20.765	9.604	3.011	-8.275	68.469	1.282	-16.893
	Rougé-Maillart et al.	.478	27.367	8.246	4.538	24.359	1.282	48.257	21.021
	Suchey-Brooks	-1.773	25.468	3.981	1.351	19.021	-16.893	21.021	47.019

Appendix 21: Covariance matrix for males separated by body mass for accuracy scores.

Appendix 22

Body Mass Categories		Kunos et al.	DiGangi et al.	İşcan et al.	Passalacqua	Lovejoy et al.	Buckberry & Chamberlain	Rougé-Maillart et al.	Suchey-Brooks
Group 1	Kunos et al.	64.404	30.659	-5.841	24.416	16.504	7.687	30.051	9.572
	DiGangi et al.	30.659	171.086	47.607	-2.697	61.906	-20.765	74.652	51.943
	İşcan et al.	-5.841	47.607	144.823	9.560	27.511	-12.227	37.365	45.465
	Passalacqua	24.416	-2.697	9.560	79.454	10.160	14.333	29.997	16.633
	Lovejoy et al.	16.504	61.906	27.511	10.160	51.179	-1.461	48.168	29.863
	Buckberry & Chamberlain	7.687	-20.765	-12.227	14.333	-1.461	60.408	12.369	-8.709
	Rougé-Maillart et al.	30.051	74.652	37.365	29.997	48.168	12.369	98.156	48.751
	Suchey-Brooks	9.572	51.943	45.465	16.633	29.863	-8.709	48.751	66.338
Group 2	Kunos et al.	46.190	16.997	13.212	12.585	8.846	-0.121	3.562	6.982
	DiGangi et al.	16.997	109.667	23.673	0.561	27.693	-15.100	19.966	26.647
	İşcan et al.	13.212	23.673	72.919	14.885	8.812	7.652	12.484	2.935
	Passalacqua	12.585	.561	14.885	75.272	7.677	4.098	9.377	5.990
	Lovejoy et al.	8.846	27.693	8.812	7.677	46.284	-4.292	27.827	24.115
	Buckberry & Chamberlain	-0.121	-15.100	7.652	4.098	-4.292	68.759	4.652	-0.378
	Rougé-Maillart et al.	3.562	19.966	12.484	9.377	27.827	4.652	44.301	19.987
	Suchey-Brooks	6.982	26.647	2.935	5.990	24.115	-0.378	19.987	42.431
Group 3	Kunos et al.	50.953	-13.218	23.392	3.372	-5.869	29.197	-7.482	-1.448
	DiGangi et al.	-13.218	160.677	51.845	15.898	-0.087	-34.387	20.613	26.374
	İşcan et al.	23.392	51.845	75.591	43.549	7.590	-5.796	4.919	10.280
	Passalacqua	3.372	15.898	43.549	59.195	5.350	-13.275	3.654	1.038
	Lovejoy et al.	-5.869	-0.087	7.590	5.350	23.828	6.044	15.473	-1.597
	Buckberry & Chamberlain	29.197	-34.387	-5.796	-13.275	6.044	76.148	-4.995	-8.158
	Rougé-Maillart et al.	-7.482	20.613	4.919	3.654	15.473	-4.995	33.076	6.628
	Suchey-Brooks	-1.448	26.374	10.280	1.038	-1.597	-8.158	6.628	26.044
Group 4	Kunos et al.	19.050	-18.008	1.558	-5.267	-19.558	6.492	-13.725	-12.442
	DiGangi et al.	-18.008	106.829	42.079	-7.000	47.954	-8.054	33.004	21.413
	İşcan et al.	1.558	42.079	82.996	-13.933	19.371	-24.538	10.754	4.396
	Passalacqua	-5.267	-7.000	-13.933	66.000	27.867	-21.867	19.467	31.467
	Lovejoy et al.	-19.558	47.954	19.371	27.867	73.863	-16.029	53.346	26.904
	Buckberry & Chamberlain	6.492	-8.054	-24.538	-21.867	-16.029	40.863	-0.913	-7.204
	Rougé-Maillart et al.	-13.725	33.004	10.754	19.467	53.346	-0.913	61.029	28.421
	Suchey-Brooks	-12.442	21.413	4.396	31.467	26.904	-7.204	28.421	37.796

Appendix 22: Covariance matrix for females separated by body mass for accuracy scores.

Appendix 23

Body Mass Categories		Kunos et al.	DiGangi et al.	İşcan et al.	Passalacqua	Lovejoy et al.	Buckberry & Chamberlain	Rougé-Maillart et al.	Suchey-Brooks
Group 1	Kunos et al.	169.712	175.424	124.650	126.274	97.187	121.172	135.950	93.503
	DiGangi et al.	175.424	220.783	127.422	133.458	102.808	126.629	146.752	97.267
	İşcan et al.	124.650	127.422	246.432	110.523	80.798	115.907	115.896	82.185
	Passalacqua	126.274	133.458	110.523	228.311	96.072	112.630	109.003	92.711
	Lovejoy et al.	97.187	102.808	80.798	96.072	94.486	108.539	108.037	61.761
	Buckberry & Chamberlain	121.172	126.629	115.907	112.630	108.539	197.619	163.762	82.359
	Rougé-Maillart et al.	135.950	146.752	115.896	109.003	108.037	163.762	176.857	93.406
	Suchey-Brooks	93.503	97.267	82.185	92.711	61.761	82.359	93.406	110.720
Group 2	Kunos et al.	170.236	170.595	2.712	119.995	99.179	130.469	131.484	100.272
	DiGangi et al.	170.595	212.730	-26.989	122.522	98.783	126.216	128.282	103.108
	İşcan et al.	2.712	-26.989	202.727	12.238	27.306	24.823	24.631	24.799
	Passalacqua	119.995	122.522	12.238	210.260	92.385	123.886	121.014	76.828
	Lovejoy et al.	99.179	98.783	27.306	92.385	103.327	108.176	113.257	72.684
	Buckberry & Chamberlain	130.469	126.216	24.823	123.886	108.176	171.898	154.095	85.853
	Rougé-Maillart et al.	131.484	128.282	24.631	121.014	113.257	154.095	180.398	92.744
	Suchey-Brooks	100.272	103.108	24.799	76.828	72.684	85.853	92.744	102.162
Group 3	Kunos et al.	118.472	122.105	-5.409	84.186	69.860	97.929	83.372	53.492
	DiGangi et al.	122.105	176.859	-22.546	80.662	73.344	101.505	92.073	59.524
	İşcan et al.	-5.409	-22.546	114.212	-1.193	14.778	1.352	5.707	5.717
	Passalacqua	84.186	80.662	-1.193	177.386	65.149	84.608	77.845	53.388
	Lovejoy et al.	69.860	73.344	14.778	65.149	89.246	92.183	79.463	45.926
	Buckberry & Chamberlain	97.929	101.505	1.352	84.608	92.183	173.748	127.408	65.978
	Rougé-Maillart et al.	83.372	92.073	5.707	77.845	79.463	127.408	125.911	59.548
	Suchey-Brooks	53.492	59.524	5.717	53.388	45.926	65.978	59.548	69.370
Group 4	Kunos et al.	90.765	74.681	27.221	60.978	46.280	56.611	61.236	65.592
	DiGangi et al.	74.681	105.706	8.628	48.047	37.644	43.977	47.092	56.921
	İşcan et al.	27.221	8.628	151.164	41.700	35.227	35.078	38.023	36.235
	Passalacqua	60.978	48.047	41.700	142.980	51.175	60.117	68.034	48.518
	Lovejoy et al.	46.280	37.644	35.227	51.175	88.268	63.429	72.422	48.999
	Buckberry & Chamberlain	56.611	43.977	35.078	60.117	63.429	116.050	91.625	60.221
	Rougé-Maillart et al.	61.236	47.092	38.023	68.034	72.422	91.625	111.872	64.368
	Suchey-Brooks	65.592	56.921	36.235	48.518	48.999	60.221	64.368	108.164

Appendix 23: Covariance matrix for males separated by body mass for bias scores.

Appendix 24

Body Mass Categories		Kunos et al.	DiGangi et al.	İşcan et al.	Passalacqua	Lovejoy et al.	Buckberry & Chamberlain	Rougé-Maillart et al.	Suchey-Brooks
Group 1	Kunos et al.	54.404	35.651	8.287	18.855	16.436	7.564	32.602	17.523
	DiGangi et al.	35.651	147.264	59.771	15.300	57.162	-12.823	70.100	40.556
	İşcan et al.	8.287	59.771	123.460	22.172	34.148	-2.577	47.437	36.636
	Passalacqua	18.855	15.300	22.172	74.264	18.663	14.866	31.287	17.818
	Lovejoy et al.	16.436	57.162	34.148	18.663	53.192	4.977	44.921	23.336
	Buckberry & Chamberlain	7.564	-12.823	-2.577	14.866	4.977	58.004	16.386	-.324
	Rougé-Maillart et al.	32.602	70.100	47.437	31.287	44.921	16.386	87.431	41.706
	Suchey-Brooks	17.523	40.556	36.636	17.818	23.336	-.324	41.706	59.275
Group 2	Kunos et al.	50.870	20.007	11.895	6.887	8.649	13.797	5.287	3.512
	DiGangi et al.	20.007	140.125	34.587	21.623	42.769	-28.242	42.868	51.526
	İşcan et al.	11.895	34.587	80.799	15.276	4.614	-3.613	10.148	3.282
	Passalacqua	6.887	21.623	15.276	82.064	21.343	2.185	21.908	16.796
	Lovejoy et al.	8.649	42.769	4.614	21.343	58.867	-5.189	41.971	33.462
	Buckberry & Chamberlain	13.797	-28.242	-3.613	2.185	-5.189	63.029	1.798	-17.328
	Rougé-Maillart et al.	5.287	42.868	10.148	21.908	41.971	1.798	66.001	28.676
	Suchey-Brooks	3.512	51.526	3.282	16.796	33.462	-17.328	28.676	63.060
Group 3	Kunos et al.	57.088	-9.368	4.016	14.899	-4.661	33.959	-0.731	-10.198
	DiGangi et al.	-9.368	112.194	14.100	6.027	21.078	-25.418	24.124	25.089
	İşcan et al.	4.016	14.100	52.988	1.264	-4.755	.955	0.580	-3.180
	Passalacqua	14.899	6.027	1.264	63.497	1.354	-2.106	6.696	2.659
	Lovejoy et al.	-4.661	21.078	-4.755	1.354	37.291	-.691	20.354	15.785
	Buckberry & Chamberlain	33.959	-25.418	0.955	-2.106	-0.691	74.367	7.425	-6.840
	Rougé-Maillart et al.	-.731	24.124	0.580	6.696	20.354	7.425	42.526	15.031
	Suchey-Brooks	-10.198	25.089	-3.180	2.659	15.785	-6.840	15.031	38.338
Group 4	Kunos et al.	39.642	-9.473	-4.093	3.213	-6.271	12.298	-2.314	-4.709
	DiGangi et al.	-9.473	76.011	2.184	1.615	28.011	-14.453	24.956	22.730
	İşcan et al.	-4.093	2.184	60.591	-1.349	-2.239	9.118	8.600	1.662
	Passalacqua	3.213	1.615	-1.349	48.636	7.300	3.697	9.841	6.066
	Lovejoy et al.	-6.271	28.011	-2.239	7.300	50.442	-13.176	26.275	20.155
	Buckberry & Chamberlain	12.298	-14.453	9.118	3.697	-13.176	59.670	2.436	-17.371
	Rougé-Maillart et al.	-2.314	24.956	8.600	9.841	26.275	2.436	52.157	20.979
	Suchey-Brooks	-4.709	22.730	1.662	6.066	20.155	-17.371	20.979	45.577

Appendix 24: Covariance matrix for individuals of European ancestry separated by body mass for accuracy scores.

Appendix 25

Body Mass Categories		Kunos et al.	DiGangi et al.	İşcan et al.	Passalacqua	Lovejoy et al.	Buckberry & Chamberlain	Rougé-Maillart et al.	Suchey-Brooks
Group 1	Kunos et al.	49.493	3.727	5.237	28.691	3.577	20.918	14.459	-3.825
	DiGangi et al.	3.727	114.073	82.658	17.549	34.982	-19.920	49.874	47.821
	İşcan et al.	5.237	82.658	148.702	15.203	40.414	-11.734	49.110	54.245
	Passalacqua	28.691	17.549	15.203	91.347	16.378	3.728	22.510	19.121
	Lovejoy et al.	3.577	34.982	40.414	16.378	43.283	5.024	50.332	32.336
	Buckberry & Chamberlain	20.918	-19.920	-11.734	3.728	5.024	97.625	28.054	-14.073
	Rougé-Maillart et al.	14.459	49.874	49.110	22.510	50.332	28.054	93.161	38.562
	Suchey-Brooks	-3.825	47.821	54.245	19.121	32.336	-14.073	38.562	65.224
Group 2	Kunos et al.	54.045	-5.468	20.987	9.753	1.887	27.634	8.547	.849
	DiGangi et al.	-5.468	77.004	6.154	10.947	18.088	-25.031	13.740	29.821
	İşcan et al.	20.987	6.154	53.419	2.088	.797	9.997	-1.518	4.395
	Passalacqua	9.753	10.947	2.088	76.915	9.725	10.337	13.007	1.257
	Lovejoy et al.	1.887	18.088	.797	9.725	27.690	-6.378	19.243	14.175
	Buckberry & Chamberlain	27.634	-25.031	9.997	10.337	-6.378	79.905	11.242	-11.605
	Rougé-Maillart et al.	8.547	13.740	-1.518	13.007	19.243	11.242	48.559	17.644
	Suchey-Brooks	.849	29.821	4.395	1.257	14.175	-11.605	17.644	40.995
Group 3	Kunos et al.	40.340	-14.455	1.658	4.222	6.718	32.144	9.485	1.812
	DiGangi et al.	-14.455	74.047	13.923	-14.811	14.234	-25.469	29.270	29.169
	İşcan et al.	1.658	13.923	37.171	6.967	-.942	-9.879	-6.852	6.179
	Passalacqua	4.222	-14.811	6.967	51.811	-4.111	24.144	-10.800	-7.867
	Lovejoy et al.	6.718	14.234	-.942	-4.111	29.229	12.344	16.463	11.989
	Buckberry & Chamberlain	32.144	-25.469	-9.879	24.144	12.344	106.047	24.597	-9.258
	Rougé-Maillart et al.	9.485	29.270	-6.852	-10.800	16.463	24.597	50.821	12.447
	Suchey-Brooks	1.812	29.169	6.179	-7.867	11.989	-9.258	12.447	33.925
Group 4	Kunos et al.	18.254	2.434	-2.746	4.587	6.915	6.873	4.698	4.492
	DiGangi et al.	2.434	92.247	17.980	-10.612	30.636	-38.550	37.388	33.225
	İşcan et al.	-2.746	17.980	39.189	-9.589	1.851	-6.720	6.374	12.251
	Passalacqua	4.587	-10.612	-9.589	29.115	-4.446	-12.794	-10.107	-1.786
	Lovejoy et al.	6.915	30.636	1.851	-4.446	34.840	7.709	29.925	17.336
	Buckberry & Chamberlain	6.873	-38.550	-6.720	-12.794	7.709	87.323	-3.016	-8.598
	Rougé-Maillart et al.	4.698	37.388	6.374	-10.107	29.925	-3.016	38.967	23.659
	Suchey-Brooks	4.492	33.225	12.251	-1.786	17.336	-8.598	23.659	46.238

Appendix 25: Covariance matrix for individuals of African ancestry separated by body mass for accuracy scores.

Appendix 26

Body Mass Categories		Kunos et al.	DiGangi et al.	İşcan et al.	Passalacqua	Lovejoy et al.	Buckberry & Chamberlain	Rougé-Maillart et al.	Suchey-Brooks
Group 1	Kunos et al.	174.798	154.202	85.061	107.449	84.293	102.242	124.227	87.217
	DiGangi et al.	154.202	189.242	78.107	88.916	79.129	89.390	114.195	68.078
	İşcan et al.	85.061	78.107	232.379	92.946	52.037	78.787	88.325	70.334
	Passalacqua	107.449	88.916	92.946	186.677	73.029	93.312	104.456	80.402
	Lovejoy et al.	84.293	79.129	52.037	73.029	77.758	74.211	81.399	48.778
	Buckberry & Chamberlain	102.242	89.390	78.787	93.312	74.211	151.084	123.999	67.155
	Rougé-Maillart et al.	124.227	114.195	88.325	104.456	81.399	123.999	148.907	84.286
	Suchey-Brooks	87.217	68.078	70.334	80.402	48.778	67.155	84.286	101.461
Group 2	Kunos et al.	163.996	161.174	14.959	117.954	91.438	109.300	108.024	88.724
	DiGangi et al.	161.174	200.640	-15.426	116.125	85.331	102.278	101.554	86.647
	İşcan et al.	14.959	-15.426	221.977	43.553	41.299	41.040	46.177	33.328
	Passalacqua	117.954	116.125	43.553	210.828	93.602	111.279	115.231	81.998
	Lovejoy et al.	91.438	85.331	41.299	93.602	105.016	102.219	106.060	69.868
	Buckberry & Chamberlain	109.300	102.278	41.040	111.279	102.219	162.328	136.069	71.718
	Rougé-Maillart et al.	108.024	101.554	46.177	115.231	106.060	136.069	159.778	77.051
	Suchey-Brooks	88.724	86.647	33.328	81.998	69.868	71.718	77.051	100.304
Group 3	Kunos et al.	126.004	137.471	3.919	96.087	65.292	89.219	75.614	53.529
	DiGangi et al.	137.471	207.786	-9.374	101.028	68.903	93.206	81.138	60.859
	İşcan et al.	3.919	-9.374	141.018	6.670	22.075	12.298	15.433	8.365
	Passalacqua	96.087	101.028	6.670	195.654	63.493	69.911	69.296	56.937
	Lovejoy et al.	65.292	68.903	22.075	63.493	82.823	80.817	70.695	38.434
	Buckberry & Chamberlain	89.219	93.206	12.298	69.911	80.817	154.346	112.261	56.122
	Rougé-Maillart et al.	75.614	81.138	15.433	69.296	70.695	112.261	111.574	49.749
	Suchey-Brooks	53.529	60.859	8.365	56.937	38.434	56.122	49.749	67.932
Group 4	Kunos et al.	93.093	78.688	32.006	67.646	45.662	55.297	54.978	62.875
	DiGangi et al.	78.688	117.887	26.103	53.732	38.838	42.976	41.644	52.655
	İşcan et al.	32.006	26.103	169.002	48.672	46.739	51.524	46.147	42.440
	Passalacqua	67.646	53.732	48.672	157.940	56.480	77.127	72.560	62.151
	Lovejoy et al.	45.662	38.838	46.739	56.480	93.473	64.817	75.590	45.372
	Buckberry & Chamberlain	55.297	42.976	51.524	77.127	64.817	109.857	89.632	58.525
	Rougé-Maillart et al.	54.978	41.644	46.147	72.560	75.590	89.632	114.850	61.395
	Suchey-Brooks	62.875	52.655	42.440	62.151	45.372	58.525	61.395	107.623

Appendix 26: Covariance matrix for individuals of European ancestry separated by body mass for bias scores.

Appendix 27

Body Mass Categories		Kunos et al.	DiGangi et al.	İşcan et al.	Passalacqua	Lovejoy et al.	Buckberry & Chamberlain	Rougé-Maillart et al.	Suchey-Brooks
Group 1	Kunos et al.	166.575	179.015	147.076	152.400	93.810	118.277	133.786	100.061
	DiGangi et al.	179.015	259.405	170.148	152.312	102.293	131.344	151.839	107.527
	İşcan et al.	147.076	170.148	302.063	134.670	89.493	103.816	127.934	93.915
	Passalacqua	152.400	152.312	134.670	290.315	103.406	131.215	138.871	129.928
	Lovejoy et al.	93.810	102.293	89.493	103.406	92.687	105.227	114.245	69.630
	Buckberry & Chamberlain	118.277	131.344	103.816	131.215	105.227	219.718	173.774	87.164
	Rougé-Maillart et al.	133.786	151.839	127.934	138.871	114.245	173.774	191.548	104.002
	Suchey-Brooks	100.061	107.527	93.915	129.928	69.630	87.164	104.002	113.376
Group 2	Kunos et al.	137.017	124.801	4.083	100.553	63.366	91.018	86.261	77.582
	DiGangi et al.	124.801	142.690	-23.062	100.496	56.275	79.274	75.301	69.970
	İşcan et al.	4.083	-23.062	165.243	1.967	27.548	22.910	23.710	17.157
	Passalacqua	100.553	100.496	1.967	207.893	65.604	85.663	82.365	62.363
	Lovejoy et al.	63.366	56.275	27.548	65.604	67.794	67.517	72.076	48.111
	Buckberry & Chamberlain	91.018	79.274	22.910	85.663	67.517	161.634	114.908	58.701
	Rougé-Maillart et al.	86.261	75.301	23.710	82.365	72.076	114.908	129.447	68.166
	Suchey-Brooks	77.582	69.970	17.157	62.363	48.111	58.701	68.166	81.985
Group 3	Kunos et al.	98.218	93.814	-17.049	44.906	49.995	90.643	79.012	54.387
	DiGangi et al.	93.814	129.475	-15.405	56.372	47.495	95.151	90.337	60.988
	İşcan et al.	-17.049	-15.405	87.622	8.955	-5.300	-13.269	-9.541	3.979
	Passalacqua	44.906	56.372	8.955	139.177	51.677	85.353	65.437	48.490
	Lovejoy et al.	49.995	47.495	-5.300	51.677	73.011	81.520	66.548	47.023
	Buckberry & Chamberlain	90.643	95.151	-13.269	85.353	81.520	181.610	121.050	64.227
	Rougé-Maillart et al.	79.012	90.337	-9.541	65.437	66.548	121.050	120.010	64.660
	Suchey-Brooks	54.387	60.988	3.979	48.490	47.023	64.227	64.660	72.620
Group 4	Kunos et al.	70.397	67.384	3.177	45.939	43.722	50.667	60.606	58.228
	DiGangi et al.	67.384	97.136	-28.022	44.988	49.843	49.389	63.007	64.947
	İşcan et al.	3.177	-28.022	105.221	2.459	10.213	-9.07	14.070	8.402
	Passalacqua	45.939	44.988	2.459	111.877	28.102	-1.944	35.044	23.762
	Lovejoy et al.	43.722	49.843	10.213	28.102	74.861	65.019	65.343	52.556
	Buckberry & Chamberlain	50.667	49.389	-9.07	-1.944	65.019	150.259	93.944	63.148
	Rougé-Maillart et al.	60.606	63.007	14.070	35.044	65.343	93.944	90.396	62.614
	Suchey-Brooks	58.228	64.947	8.402	23.762	52.556	63.148	62.614	103.238

Appendix 27: Covariance matrix for individuals of African ancestry separated by body mass for bias scores.