THE EFFECTS OF LABOR ON THE BIOMECHANICAL PROPERTIES OF THE FEMORA AND THE HUMERI IN THE 19TH AND 20TH CENTURIES

by

Shelby Garza, B.S.

A thesis submitted to the Graduate Council of
Texas State University in partial fulfillment
of the requirements for the degree of
Master of Arts
with a Major in Anthropology
August 2019

Committee Members:

Daniel J. Wescott, Chair

Nicholas P. Herrmann

M. Kate Spradley

ACKNOWLEDGEMENTS

I would first like to thank all of the individuals, as well as their families, who have donated their remains to the willed body donation program at the Forensic Anthropology Center at Texas State University. Without these gracious donations, this research would not have been possible.

Thank you to my advisor, Dr. Daniel Wescott, for all of his assistance, guidance, and support, all of which helped me to successfully complete this research as well as the graduate program. I would also like to thank my committee members, Dr. Kate Spradley and Dr. Nicholas Herrmann, for all of the help they offered to successfully complete my thesis work. Thank you to the Grady Early Fellowship for the funding I received, which helped me in completion of this project.

I would also like to thank Dr. Deborah Cunningham and Devora Gleiber for all of their help with my data collection. Lastly, I would like to thank my family and my friends, especially my wonderful cohort, for their constant support and encouragement throughout the graduate program.

TABLE OF CONTENTS

Page

ACKNOWLEDGEMENTS iv

LIST OF TABLES vii

LIST OF FIGURES viii

LIST OF ABBREVIATIONS ix

ABSTRACT x

CHAPTER

I. INTRODUCTION 1

Research Questions 2
Background and Literature Review 4
Bone Structure and Adaptation 4
Biomechanical Modeling and Cross-Sectional Properties
Of Long Bones 6
Behavioral Interpretations of Long Bone CSG 8
Mobility 8
Sexual Dimorphism 9
Activity Patterns and Levels 10
Labor 12

II. MATERIALS AND METHODS 14

Study Sample 14
Defining Labor 15
Texas State University Donated Skeletal Collection 15
Robert J. Terry Anatomical Skeletal Collection Samples 16
Reconstruction of Cross-Sectional Properties 17
Preparation for Scanning 17
Fixturing and Scanning 20
Cortical Bone Analysis 22
Terry Collection CT Images 25

Statistical Analysis 26

III. RESULTS 28

Labor 30
Femur 30
Humerus 30
Femoral to Humeral Diaphyseal Strength Proportions 32
Secular Change 33
Femur 33
Humerus 35
Femoral to Humeral Diaphyseal Strength Proportions 36

IV. DISCUSSION AND CONCLUSION 38

Labor 38
Texas State University Donated Skeletal Collection 38
Terry Collection 43
Secular Change 44
Conclusion 46
Future Research 48

APPENDIX SECTION 49

REFERENCES 53

LIST OF TABLES

Table **Page**

1. Sample demographics 17

2. Cross-sectional properties of cortical bone 23

3. Descriptive statistics for the femoral properties 28

4. Descriptive statistics for the left humeral properties 29

5. Significantly different cross-sectional properties of the midshaft slice of the femur in comparisons between the TXSTDSC and Terry Collection 34

LIST OF FIGURES

Figure **Page**

1. Visual representation of the feedback loop associated with strain and the and the optimum customary strain level 4

2. Study sample size....................15

3. Elements ready to be scanned....................19

4. Fixtures for scanning....................20

5. Orientation of the femur and humerus for reconstruction 22

6. Labeled image of scanned femora 23

7. Cross-sections of the femur and humerus showing centroid and bending axes after analyzed in BoneJ....................24

8. Boxplots representing significant differences in the femur between the TXSTDSC manual labor workers and non-manual labor workers in CA, I_{min}, and J 31

9. Graphical depiction of the femoral-to-humeral ratio of the TXSTDSC manual and non-manual labor workers J of the femur and humerus....................33

10. Linear regression analysis showing significant correlation between year of birth and I_{max}, I_{min}, and J in the midshaft of the femur and shape in the proximal 20% of the femur....................35

11. Graphical depiction of the femoral-to-humeral ratio of the TXSTDSC and Terry Collection manual and non-manual labor workers J of the femur and humerus....................37

12. Linear regression analysis showing significant correlation between age and cortical area in the proximal 65% and midshaft slice of the humerus....................41

LIST OF ABBREVIATIONS

Abbreviation	Description
CSG	Cross-Sectional Geometry
HRXCT	High-Resolution X-Ray Computed Tomography
I	Second Moment of Area
J	Polar Second Moment of Area
I_{max}/I_{min}	Cross-Sectional Shape Ratio
I_{max}	Maximum Second Moment of Area
I_{min}	Minimum Second Moment of Area
TXSTDSC	Texas State University Donated Skeletal Collection
FACTS	Forensic Anthropology Center at Texas State
FARF	Forensic Anthropology Research Facility
AP	Anteroposterior
BBs	Ball Bearings
µm	Microns
kV	Voltage
µA	Current
CSA	Cross-Sectional Area
SMAs	Second Moments of Area
mA	
ANOVA	Analysis of Variance
YOB	Year of Birth
BMI	Body Mass Index
ML	Mediolateral

ABSTRACT

Bone is an adaptive tissue that can change in shape and size throughout the course of life due to loading regime through the modeling and remodeling process. Therefore, the cross-sectional geometry (CSG) of long bone shafts provides a generalized measure of the loading that occurred during life. The purpose of this study is to investigate differences in long bone strength and shape between manual and non-manual labor workers in the 19th and 20th centuries and examine if there is any secular change occurring between the 19th and 20th century individuals. This research was completed by taking high-resolution x-ray computed tomography (HRXCT) scans of the left femur and both humeri for each individual. The cross-sectional geometric properties were analyzed, and an ANOVA was run to test for significant differences between size, shape, and robusticity between the manual and non-manual labor workers. The results showed that the humeri of manual labor workers are significantly more robust than non-manual labor workers in the 20th century sample. However, the femora were significantly larger in the non-manual labor workers in the 20th century sample. In the 19th century sample, there were no significant differences in the size, shape, or robusticity of the humeri or femora between manual and non-manual labor workers. Secular change was also observed in the femur, with the 20th century sample having larger and more round femora in comparison to the 19th century individuals.

I. INTRODUCTION

Bone is an adaptive tissue that can change in shape and size throughout the course of life due to loading regime through the modeling and remodeling processes (Miller, Agarwal, Aristizabal, & Langebaek, 2018). Therefore, the cross-sectional geometry (CSG) of long bone shafts provides a generalized measure of the loading that occurred during life by providing information about the bone's shape and its ability to resist bending and torsional loading (Ruff, 2008). For that reason, biological anthropologists have long used loading patterns to analyze subsistence strategies and activity levels of current and past populations.

Numerous studies have examined loading patterns using CSG between groups with different subsistence economies and division of labor associated with the subsistence economies (Brock and Ruff, 1988; Marchi, Sparacello, Holt, & Formicola, 2006; Ogilvie & Hilton, 2011; Pearson, Peterson, Sparacello, Daneshvari, & Grine, 2014; Ruff, 1987). Additionally, several studies have investigated secular change in long bone length and biomechanical properties (Jantz & Jantz, 1999; Jantz, Jantz, & Devlin, 2016; Trotter, Peterson, & Wette, 1968; Wescott, Cunningham, & Hunt, 2014; Wescott & Zephro, 2016). However, no study has examined if differences in long bone CSG properties between laborers and non-laborers has changed in the United States from the 19th to 20th century due to advancing technology that reduces limb bone loading for manual labor.

The purpose of this study is to investigate if there are differences in long bone strength and shape between individuals with traditionally known manual and non-manual occupations and if the pattern of those differences, if any, has changed from the 19th to

20th centuries. This research will benefit anthropology by adding to research on the association between long bone mechanical properties and physical labor and the secular trends in long bone mechanical properties. The method used in this research can also be used in both forensic and bioarchaeological contexts. For bioarchaeology, the results of this research could lead to non-destructive methods that can help assess the activity levels of past populations. Looking at differences in long bone cross-sectional morphology between manual labor workers and non-manual labor workers may also help to narrow down a missing person's report if there is a consistent significant difference between structural properties. It will also provide information relating to the skeletal variation that occurs within and between populations.

RESEARCH QUESTIONS

This research examines the difference in diaphyseal strength and shape in the humerus and femur between individuals with occupations traditionally considered manual labor and non-manual labor. The study will also investigate if there is a secular change in CSG for laborers and non-laborers from the 19th to 20th centuries. Comparisons of CSG properties were made between individuals from the 19th and 20th centuries with known occupations. High-resolution x-ray computed tomography (HRXCT), which is a non-destructive method to investigate the internal bone structure, was used to obtain images of the bone diaphyseal cross-section. The images were then used to address the following research questions.

The first question addresses if there are significant differences in femur and/or humerus mechanical properties (bending (I), torsional (J) rigidity, and shaft shape

(I_{max}/I_{min})) between manual and non-manual laborers in the 19th or in the 20th centuries? The null hypothesis for this question is that there are no significant differences in bending rigidity, torsional rigidity, or the cross-sectional shape of long bones between manual and non-manual laborers in the 19th or in the 20th centuries. The alternative hypothesis states that there are significant differences in bending rigidity, torsional rigidity, or the cross-sectional shape of long bones between manual and non-manual laborers in the 19th or in the 20th centuries.

Second, are there significant differences in humeral and femoral mechanical properties between 19th and 20th century manual workers and between 19th and 20th century non-manual workers? The null hypothesis for this question is that there are no secular differences for manual laborers and for non-manual laborers. The alternative hypothesis is that there are secular differences for manual laborers and for non-manual laborers.

Third, if the results from research questions one and two reject the null hypothesis, the final research question will look to examine changes in relative strength of the upper and lower limbs between 19th and 20th century manual and non-manual labor workers. The null hypothesis for this question is that there are no differences between changes in relative strength of the upper and lower limbs. The alternative hypothesis is that there are differences between changes in relative strength of the upper and lower limbs.

BACKGROUND AND LITERATURE REVIEW

Bone Structure and Adaptation

The idea that mechanical loading affects bone structure and form has long been used by anthropologists to study the differences in behavior within and between both present and past populations. This idea is commonly known as bone functional adaptation, which states that bone will adapt to mechanical forces and, over time, the structure of the bone will change to reduce strain caused by those forces (Cowin, 2001; Martin, Burr, & Sharkey, 1998; Pearson & Lieberman, 2004; Ruff, Holt, & Trinkaus, 2006; Ruff, 2008). When bone is under an increased level of strain, osteoblastic activity will also increase until the strain is neutralized (Huiskes, Ruimerman, Van Lenthe, & Janssen, 2000). That is, bone deposition that occurs during time of increased strain will return the bone back to the optimum customary level, or the level that the bone can withstand the strain normally being applied (Lanyon, 1996; Ruff et al., 2006; Ruff, 2008). See Figure 1 for a visual representation of how the optimum customary strain level works.

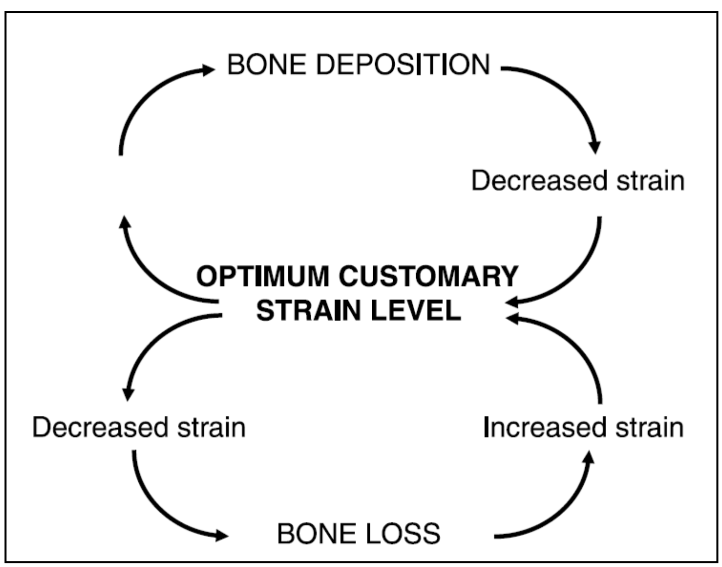

Figure 1. Visual representation of the feedback loop associated with strain and the optimum customary strain level. (From Ruff, 2008)

One of the primary conceptional models for bone functional adaptation, known as the mechanostat hypothesis, was first proposed by Frost in 1996 and later expanded on by him in 2003. Frost (1996, 2003) argues that the mass and architecture of bone structure will change in response to mechanical loading based on a feedback system. The mechanostat model states that there will be net formation with increased strain and net resorption with decreased strain through the processes of modeling and remodeling. The model predicts when and where bone should be deposited and/or resorbed in response to mechanical strain. It can be hypothesized that individuals who are working manual labor jobs are participating in activities that are regularly placing excess strain on their load-bearing bones. Based on the mechanostat model, it would then be expected that individuals who are working manual labor jobs would have more bone deposition than individuals who were working non-manual labor jobs, which will be reflected in the CSG biomechanical properties.

Another aspect of the mechanostat hypothesis (Frost, 1996; Frost, 2003) states that bone will only react to mechanical loading if it is an intentional and repetitive action. Therefore, only individuals that are repeatedly participating in actions that produce heavy loads on bone will have bone that will adapt to those loads. As a result, individuals conducting repetitive activities are expected to have elevated bending/torsional strength and cortical bone area compared to individuals that do not perform repetitive manual labor. There will also be greater deposition of bone in the plane of greatest strain resulting in shape differences.

Literature has also shown that bone response to mechanical loading is decreased in older individuals when compared to younger individuals. Bertram and Swartz (1991) noted that the modeling and remodeling associated with mechanical loading will also be affected by the growth and development process, with greater bone deposition associated with mechanical loading occurring in younger individuals compared to older individuals. Therefore, individuals that begin an activity earlier in life will exhibit greater changes in biomechanical properties compared to individuals that conduct the same activity but start later in life. Unfortunately, when comparing manual labor workers to non-manual labor workers, the documented occupation may not be the same job they were working at a younger age. This has the potential to skew the results of this project because if a non-manual labor worker had a manual labor job when they were younger the mechanical loading that occurred from their earlier jobs could be reflected in their biomechanical properties (Pearson & Lieberman, 2004).

Adaptive modeling, which occurs when there are various changes in structure or function of the bone at a cellular level due to bone-loading manipulations, has been shown to occur in experimental studies looking at orthopedic animal models (Goodship, Lanyon, & McFie, 1979; Lanyon, Hampson, Goodship, & Shah, 1975; Liskova & Hert, 1971). Using cross-sectional geometry (CSG) to analyze the dynamics of bone tissue modeling provides biological anthropologists the resources to investigate the cellular processes of adaptation and response rather than solely focusing on whole bone complexities (Brock & Ruff, 1988).

Biomechanical Modeling and Cross-Sectional Properties of Long Bones

Cross-sectional geometry can be useful when analyzing loading patterns and strength of a long bone from an individual. This is because long bones can be compared to hollow beam in engineering terms, meaning that long bones should follow the standard beam theory regarding stresses from loading and strength (Timoshenko & Gere, 1972; Ruff, 1983). One of the most important geometric characteristics analyzed from cross-section of bone is the second moment of area, or I, which serves as an estimate of bone rigidity (Ruff, 1983). This can further be separated into maximum (I_{max}) and minimum (I_{min}) second moment of area, which refers to the direction of the maximum and minimum bending load being applied, respectively. Torsional loading can also occur in long bones (Carter, 1978), and the polar second moment of area (J) can be used to evaluate torsional strength and rigidity, and recent research states that J provides the most accurate estimation of average bending rigidity in typical cross-sections of bone (Lieberman, Polk, & Demes, 2004).

Research has shown that bending and torsional rigidity are the most biomechanically relevant indicators of diaphyseal loading and provide an estimate of bone strength (Ruff, 2008). It has also been observed that taking external measurements does not provide an accurate estimation of the internal makeup of the bone and that cortical area can be used to evaluate the effect of mechanical forces on long bones (Ruff, Larsen, & Hayes, 1984; Wescott, 2006). Shaft shape (I_{max}/I_{min}) can also be used as an indicator of the direction of bending forces the bone has undergone (Lieberman et al., 2004). If the shaft shape ratio is equal to one, this indicates that the bone was experiencing equal levels of maximum and minimum or mediolateral and anteroposterior bending loads. However, if the ratio is greater than one, this indicates greater bending loads in the anteroposterior direction and if the ratio is less than one it indicates greater bending loads in the mediolateral direction for the femur midshaft (Ruff, 1987; Wescott, 2006). The opposite is true for the subtrochanteric (20%) region. Bone shape is also a better indicator of mobility and activity pattern when compared to relative bone size (Ruff & Larsen, 2014).

Prior to comparisons of the CSG, the geometric data must be size standardized. This is because body size can be considered a mechanical load that the lower limb bones are constantly supporting (Ruff, 2008). From this, it can be hypothesized that a larger individual will be placing more mechanical strain on their long bones than a smaller individual. Ruff (2008) also suggested that the best way to standardize cross-sectional properties is by dividing the geometric data by body mass times bone length squared. Research has shown that femoral head size can be used as a proxy for body mass (Auerbach & Ruff, 2004). Standardizing the geometric data helps to assure that the differences in CSG are related to activity patterns rather than body size.

Behavioral Interpretations of Long Bone CSG

<u>Mobility</u>

Studies have shown that long bone biomechanical properties or CSG can be used to interpret behavioral patterns, including terrestrial mobility, in human populations (Ruff, 2008). In addition, we know there has been a significant change in long bone size and shape over the past several centuries in the United States (Jantz & Jantz, 1999; Jantz et al., 2016; Wescott & Zephro, 2016). These studies have shown that there is an overall increase in long bone length and a decrease in mediolateral bending strength, or the bones resistance to bending (Moore, 2013), of the femora and tibiae over the past two centuries. The leading factor that could potentially explain these changes is the transition to a more sedentary lifestyle (Jantz et al., 2016; Wescott & Zephro, 2016).

There have been multiple studies conducted linking sedentariness to bone biology. Wescott and Zephro (2016) investigated secular changes in femoral biomechanical properties of individuals born between 1856 and 1978 and showed that an increase in sedentariness is associated with a decrease in mediolateral bending at midshaft. Scheffler and Hermanussen (2014) analyzed how the sedentary lifestyles associated with modern humans affects elbow breadth, pelvic breadth, and depth and breadth of the thorax. The results were analyzed as both absolute values and relative to height and showed a significant decrease in relative elbow breadth as well as relative pelvic breadth and pelvic absolute breadth. With non-manual labor workers presumably being more sedentary than manual labor workers, there would be an expected difference in bone biology between the two groups.

Sexual Dimorphism

Sexual dimorphism refers to any differences in the skeleton that are strictly associated with biological sex. While there are many differences that are present when no other factors are involved, labor and occupation can help to exacerbate these differences. A reason why this may be occurring is because of the cultural ideas that are put forth when considering who typically works jobs that involve heavy manual labor. The idea that sex difference occur in the cross-sectional geometry and shape of the long bones of individuals is supported by numerous studies (Pomeroy & Zakrzewski, 2009; Miller et al., 2018; Larson, 1997; Ruff, 1983).

Pomeroy and Zakrzewski (2009) used external diaphyseal long bone measurements to examine differences between two medieval European populations from different cultures. By looking at populations with different cultural norms, the authors looked for patterns to show if sexual dimorphism in cross-sectional shape of long bones was associated with cultural ideas of gender roles and occupation or activity level. The results of their study found few differences in cross-sectional shape of the upper limb bones compared to the lower limb bones. They did find significant differences between femoral and tibial midshaft shape as well as the shape at the nutrient foramen of the tibia. These results support previous research that states that there are behavioral differences based off gender roles in medieval Muslim Spain.

Miller and colleagues (2018) analyzed the remains from the Tibanica archaeological site to examine differences in activity patterns between males and females of different age cohorts. CSG of the femora and the humeri were used to analyze bone size, shape, and strength. The results from their study presented evidence of differences in labor based off sex, with females having more upper body strength and males having more lower body strength. They also showed that the diaphyseal shape of the femur in females decreased as age increased, indicating that individuals were less mobile as they aged.

Activity Patterns and Levels

There have also been multiple studies that have examined whether habitual activities affect the biomechanical properties of long bones. Stock and Pfeiffer (2001), for example, observed the postcranial robustness between two groups with different subsistence strategies and showed that foragers who relied on marine resources as the primary provider of food had significantly stronger humeri than foragers who used terrestrial resources, but the opposite was true for the femora. These results would be expected because individuals who are highly mobile are regularly placing strain on their lower limb bones. However, individuals that are mainly utilizing marine resources would have to either swim or use some form of water transportation to hunt these resources, which would lead to more loading on the upper limbs.

Similarly, Stock (2006) examined cross-sectional geometric properties of the tibia, femur, ulna, clavicle, and humerus to test if climate and habitual activities contribute to variation in robusticity of the skeletal elements. The results showed that torsional rigidity, or the bone's resistance to twisting (Moore, 2013), corresponds with activity levels at the distal ends of both the upper and lower limbs and strengthening of the femoral midshaft was significantly affected by increase in activity. These results show that habitual activities significantly affect the biomechanical properties of long bones.

Cameron and Pfeiffer (2014) used cross-sectional geometric properties from Later Stone Age foragers from different regions to look for differences in mobility patterns based off geographical regions. Their results showed that there was no statistical difference between different regions and CSG properties. These results provided evidence that, although they were living in different regions, all individuals participated in similar habitual activities.

Ledger, Holtzhausen, Constant, and Morris (2000) used computerized tomography scans to analyze the difference in biomechanical properties between three different populations. The first was an 18th century unmarked burial site in South Africa suggested to house remains of slaves or "free black" people with a low socioeconomic status, the second was a modern cadaver collection, and the third was a hunter-gatherer collection. The results showed that the hunter-gatherer group had higher tibial strength properties when compared to both the modern group and the South Africa sample. This provides evidence that the hunter-gatherer group was highly mobile when compared to the other groups. The results also showed that the males in the South Africa sample showed higher humeral strength properties when compared to both the modern sample and the hunter-gatherer sample, which supports the hypothesis that these individuals were manual laborers. While this research investigates the differences in cross-sectional geometry between modern and historic samples, it does not directly compare laborers from a modern population to laborers from a historical population.

Certain studies have also shown that directional asymmetry can occur in upper and lower limbs of the same individual due to biomechanical factors such as weight-loading and handedness. Auerbach and Ruff (2006) compared prevalence of asymmetry in upper and lower limbs amongst Holocene adults spanning six continents to provide a baseline for studying bilateral asymmetry in different populations. Their results showed that across all populations, upper limbs tend to have right biases in directional asymmetry and lower limbs have a significantly lower percentage of directional asymmetry. These results could be explained by the fact that lower limb bones are more affected by locomotion patterns when compared to upper limb bones that are more affected by activity patterns.

Labor

Studies also link labor to bone biology and the biomechanical properties of long bones. Ruff (1987) analyzed the cross-sectional geometric properties of the femora and the tibiae between males and females using population samples dated from recent to the Middle Paleolithic era. The results showed that as individuals became more sedentary and transitioned to agriculture, males experienced an increase in circular cross-sectional shape while females had little to no change in shape. These results provide evidence that manual labor affects the CSG of long bones because as individuals became more sedentary, the males were the only sample that had a significant difference in CSG. Ogilvie and Hilton (2011) examined CSG of the humeri from 92 adult foragers and farmers from the Lower Pecos region in Texas and the Pottery Mound pueblo from New Mexico. Their results showed that female farmers had the greatest humeral strength, indicating that they participated in activities that resulted in large amounts of upper limb work when compared to their male counterparts. However, with machines that are now capable of doing much of the manual labor for employees, there is a possibility that the biomechanical properties of manual labor workers would not significantly differ from non-manual labor workers in current populations.

Although there is plenty of literature on how behavioral patterns can affect the biomechanical properties of long bones, there is a lack of information regarding how technological advancements have affected the size, shape, and robusticity of long bones. There is also a lack of literature analyzing secular changes in biomechanical properties of long bones for individuals of known occupations. Therefore, this study seeks to fill in this gap by examining differences between male manual and non-manual laborers in the United States and if there has been a change in the differences between them over the past century due to technological advancements that may reduce strain on the bones of manual laborers. This research will benefit anthropology by providing information on the impact that industrial advancements has had on bone biology and by adding to research on the association between long bone mechanical properties and physical labor and the secular trends in long bone mechanical properties.

II. MATERIALS AND METHODS

STUDY SAMPLE

The study sample used for my thesis comes from the Robert J. Terry Anatomical Skeletal Collection (Hunt &Albanese, 2005) and the Texas State University Donated Skeletal Collection (TXSTDSC) (Wescott, 2018). The Terry collection represents 19^{th} and 20^{th} century individuals and the Texas State collection represents 20^{th} century individuals. My study sample consists of femora and humeri from American Black and American White male manual and non-manual labor workers (defined below). Females were not examined. See Figure 2 for a chart depicting sample sizes from both collections.

Both the left and right humeri were used for this study because research has shown that there is more asymmetry in the upper limb bones regarding diaphyseal shape due to handedness (Auerbach & Ruff, 2006; Plato, Fox, & Garruto, 1984). However, only the left femur was used because, although there is asymmetry in the lower limb bones, it tends to always favor the left side (Auerbach & Ruff, 2006). If individuals had any sort of medical intervention, a knee or hip replacement for example, then the femur was not used, and the right femur was not substituted for the left in these cases. Also, if there was severe pathology to any of the elements, those elements were excluded from the sample.

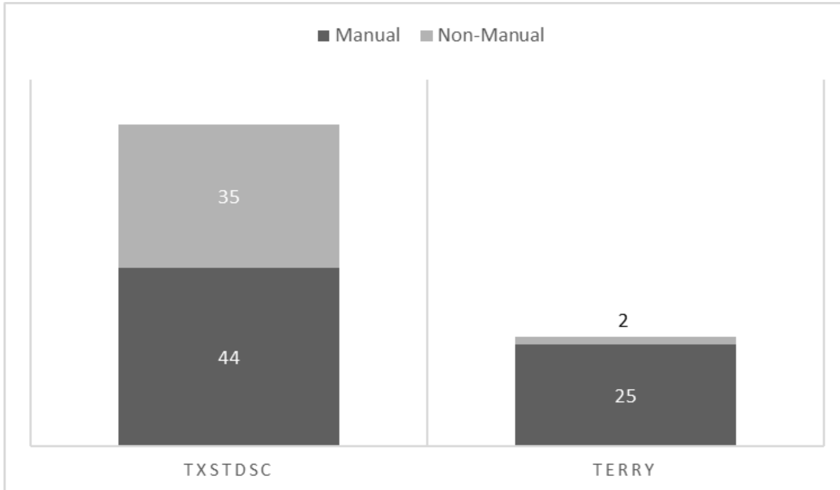

Figure 2. Study sample size.

Defining Labor

For this research, manual labor workers were defined as individuals whose jobs require mostly physical labor rather than being confined to a desk for most of the day, and the opposite defined non-manual labor workers. Individuals with occupations that were obviously either manual or non-manual were first chosen, but after the list had been exhausted occupations that were not so clear were also chosen, however an internet search was done to verify whether there was labor involved in the job. Individuals that had a job that required a mixture of manual and non-manual labor work were not included in the sample. Some examples of occupations that were classified as manual labor are: construction worker, mechanic, and oil field worker. Some examples of occupations that were classified as non-manual labor were: teacher, attorney, and secretary. A list of all occupations and their classifications can be found in Appendix A.

Texas State University Donated Skeletal Collection

The Forensic Anthropology Center at Texas State (FACTS) was started in 2006 and has a willed body donation program that began accepting donations in 2008 with the opening of the Forensic Anthropology Research Facility (FARF) (Wescott, 2018). Currently, FACTS receives between 65 and 80 donations a year, with the highest number being 79 donations in the year of 2017. Approximately 60.2 percent of donors are male and of those, 92 percent self-identify as white. Ages range from 0-103 years, with 79 percent of individuals between the ages of 41 and 80. The average age for males is 65 (Wescott, 2018).

There are a total 79 individuals included in the sample from the TXSTDSC. Of these 79 individuals, 44 are manual labor workers and 35 are non-manual labor workers. The average age of the individuals is 64 years, with the youngest individual being 20 years and the oldest individual being 91 years. From these 79 individuals, a total of 224 elements were scanned. Occupation was documented for all individuals as well as age, ancestry, stature, weight, and handedness. See Table 1 for a brief summary and Appendix B for a detailed summary table of the demographic data from the TXSTDSC.

Robert J. Terry Anatomical Skeletal Collection Samples

There are a total of 1,728 individuals in the Terry Collection today. These individuals were collected between the years of 1898 and 1967 and are representative of the US population during those years (Hunt & Albanese, 2005). Approximately 944 of the individuals in the Terry Collection are male and of those, 508 are American Black and 436 are American White. The mean age at death for males in the collection is 53, and the total age at death range is between 14 and 102.

Gaining access to the Siemens SOMATOM Emotion 6 CT Scanner and the Terry Collection was not permissible for the timeline required to complete this research. For this reason, data that was previously collected by Dr. Daniel Wescott was used for the

Terry Collection samples. This led to a decrease in sample size, resulting in 27 individuals from the Terry Collection. Of those 27 individuals, 25 were considered manual labor workers and 2 were considered non-manual labor workers. The average age of these individuals was 42 years, with the youngest individual being 27 and the oldest individual being 60 years. Only data from the left side was available, so a total of 52 scanned elements were used. Due to the limited sample size, especially in non-manual labor workers, the results will be interpreted with caution. See Table 1 for a brief summary and Appendix C detailed summary of the demographic data from the Terry Collection.

Table 1. Sample demographics. Brief summary of the TXSTDSC and Terry Collection demographics, including ranges and averages for age, stature, and BMI. Note BMI is blank for the Terry Collection because cadaver weight was not recorded.

	TXSTDSC				Terry			
	Manual		Non-Manual		Manual		Non-Manual	
	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.
Age	20 - 91	62	32-91	67	27-60	42	30-50	40
Stature	152.4 - 190.5	176.2	162.6 - 190.5	178.2	157.5 - 184	172.3	168.5	168.5
BMI	13.5 - 48.2	26.6	15.3 - 51.6	27.8				

<u>RECONSTRUCTION OF CROSS-SECTIONAL PROPERTIES</u>

Preparation for Scanning

To calculate I and J, a high-resolution x-ray computed tomography (HRXCT) scan was taken at midshaft and 20 percent of the femora and of the midshaft and 65 percent of the humeri. Slices from these scans were then analyzed in ImageJ (Schneider, Rasband, & Eliceiri, 2012) using the BoneJ (Doube et al., 2010) plug-in to calculate the mechanical properties. This plugin calculates multiple cross-sectional geometric properties by using the “slice geometry” feature. These are calculated by examining the sum of each pixel area and multiplying it by the squared distances from the neutral axes. The neutral axis is typically found in the medullary cavity of bone and is the area that does not experience any longitudinal stresses (Moore, 2013). The area around the primary axes equal I_{max} and I_{min}. To calculate J, I_{max} and I_{min} are added together. I_{max} is divided by I_{min} to calculate shaft shape.

Cross-sectional properties are sensitive to errors in bone positioning, so prior to scanning the elements, bone reference axes were defined following the methods described in Ruff and Hayes (1983) and Wescott (2001). The femur was placed on a table with the posterior edges of the condyles on the table. A small piece of clay was then placed under the proximal end of the femur to make the distal and proximal ends at the same level above the table. The coronal plane was then determined by finding the anteroposterior (AP) midpoint of the shaft near the proximal and distal ends of the bone using calipers. The sagittal plane lies perpendicular to the coronal plane and is defined by the mediolateral midpoint of the shaft inferior to the lesser trochanter and the deepest point of the intercondylar notch.

The methods to define the coronal and sagittal plane for the humerus were similar to those used for the femur (Ruff & Hayes, 1983; Wescott, 2001). The sagittal plane is defined by the mediolateral midpoint of the shaft just distal to the lesser tubercle and the proximal aspect of the olecranon fossa. The coronal plane is defined as the plane starting at the AP midpoint of the shaft and running along the long axis of the trochlea and capitulum.

After the coronal and sagittal planes were marked on the humerus and femur, midshaft was located for both the humerus and the femur as well as the proximal 20% of the femur and the proximal 65% of the humerus. These points were used because they are the areas that are most often used for biomechanical analysis. Although typically subtrochanteric is used for the femur, the proximal 20% was used for this study instead so that the measurements would be standardized because it can sometimes be difficult to locate the subtrochanteric landmark.

Once all points were marked on the humeri and femora, 0.12-gram green and brown plastic airsoft ball bearings (BBs), 6mm in diameter, were hot glued to the bone in the four locations determined (Figure 3). The BB's were glued because they can easily be seen in the reconstructed HRXCT scans, allowing for the proper slices to be analyzed.

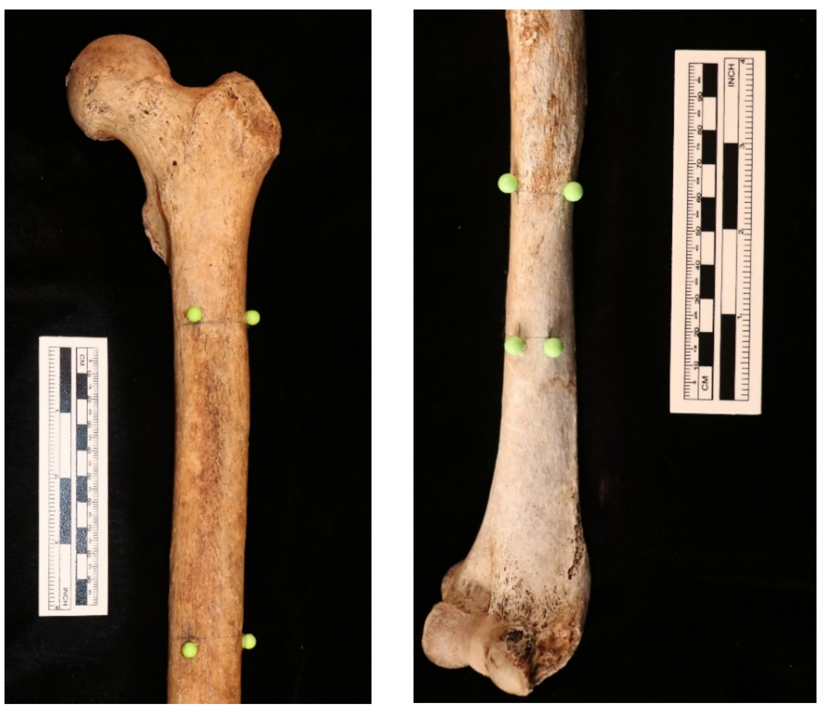

Figure 3. Elements ready to be scanned. Femur (left) with plastic BBs at 20% and midshaft and humerus (right) with plastic BBs at midshaft and 65%

Fixturing and Scanning

For scanning of both the humeri and femora, the elements were placed in a fixture made from green florist foam. This was done because the foam is low in density and can be filtered out of the HRXCT scan. To cut down on scanning time, multiple elements were scanned at once and clay was used to differentiate the individuals from each other. Four femora were scanned at the same time and were all placed with the distal end of the bone situated in the foam and six humeri were scanned at once and were all placed with the humeral head situated in the foam (Figure 4).

Figure 4. Fixtures for scanning. Femora (left) and humeri (right) in the fixtures used for scanning.

Each scan was obtained using a North Star Imaging, Inc. X5000 HRXCT system and the NSI efX$_{DR}$ software program (North Star Imaging, Inc.). For the purpose of this research, only a cross-sectional slice of cortical bone was needed, so the parameters were set for the scans with no frames averaged, which sped up scanning time severely. To cut down the low-energy photons, an aluminum filter was used for all scans. An example of some of the basic settings for the femoral scanning were as follows: focal spot of 7 microns (µm), 2500 - 2950 projections, no frames averaged, a continuous scan, voltage ranging from 130-145 kV, and a current range of 162-200 µA. An example of some of the basic settings for the humeral scanning were as follows: focal spot of 7 microns (µm), 2850 - 3000 projections, no frames averaged, a continuous scan, voltage ranging from 130-160 kV, and a current range of 155-200 µA.

If the imagining geometry was altered, calibration was run following the scanning of the elements. It is important to calibrate the image when conducting HRXCT scans because calibration establishes key parameters for the scan (North Star Imaging, Inc.). This calibration is crucial for accurately setting the voxel size during reconstruction. For all calibrations, a large 15mm calibration tool was used.

All scans were reconstructed using the NSI efX$_{CT}$ program (North Star Imaging, Inc.). When completing the reconstructions, the reconstruction box was used to ensure that the BBs were aligned along the coronal and sagittal planes (Figure 5). Doing this ensures that, when the reconstructed files are uploaded in ImageJ and the geometrical properties are obtained, an exact cross section is being analyzed. After reconstruction, images of the slices were exported into 8-bit tiff files.

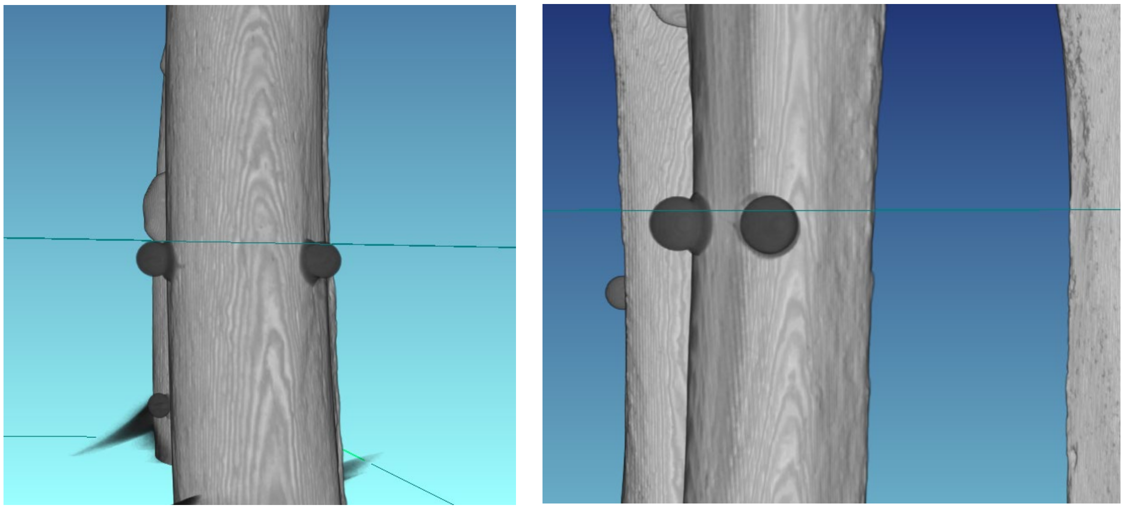

Figure 5. Orientation of the femur (left) and humerus (right) for reconstruction.

Cortical Bone Analysis

Prior to analysis of the CSG, the donation number for the element needed to be determined. To do this, the scan slices were visually assessed in sequential order and the number of clay pieces on the bone were counted. Once differentiation had occurred, a key was made to associate each cross-section with the proper donation number (Figure 6). This method was also used to locate the slice that would be analyzed for the geometric properties. For the femur, the slice located directly below the BBs at the proximal 20% slice and directly above the BBs at the midshaft slice were selected. For the humerus, the slice located directly below the BBs at the midshaft slice and directly above the BBs at the proximal 65% slice were selected.

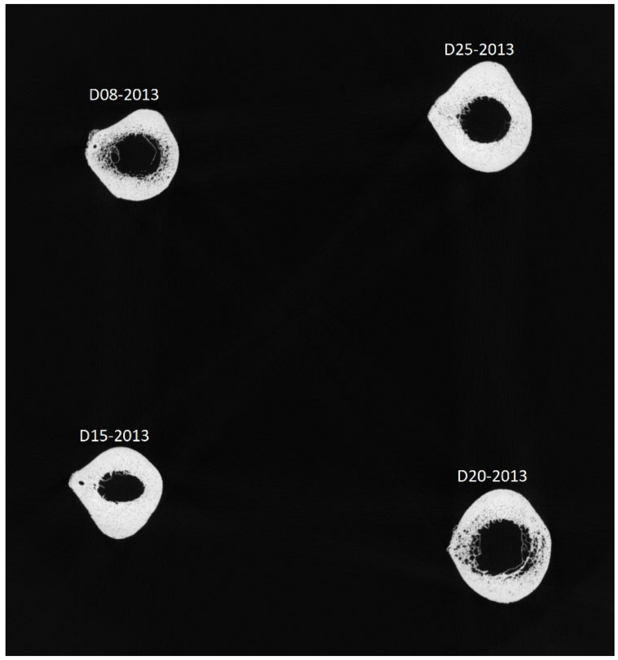

Figure 6. Labeled image of scanned femora.

Once the slice to be analyzed was determined, the tiff file was opened in the program ImageJ, a scale was set in pixels/mm based on the resolution of each scan, and the image was cropped so that only the cross-section of the element of interest was visible. The geometric properties were then analyzed with the BoneJ plug-in for ImageJ. The "Slice Geometry" tool was used to obtain maximum (I_{max}) and minimum (I_{min})

Table 2. Cross-sectional properties of cortical bone. (Ruff 2008)

Property	**Abbr.**	**Units**	**Definition**
Cortical Area	CA	mm^2	Compressive/tensile strength
Second moment of area around major axis	I_{max}	mm^4	Maximum bending rigidity
Second moment of area around minor axis	I_{min}	mm^4	Minimum bending rigidity
Polar second moment of area	J	mm^4	Torsional and (twice) average bending rigidity (Imin+Imax)

bending moments, then the two were added together to obtain the torsional rigidity (J) of the bone. I_{max} was divided by I_{min} to get the shape of the bone. Cross-sectional area (CSA) was also obtained from this tool. See Table 2 for definitions of all the CSG variables that were analyzed. The “Slice Geometry” macro allows the user to input an entire stack or a single slice. The macro then calculates the cross-sectional geometric properties of the shape and displays the results in a graph. When the slice is analyzed in BoneJ, the macro will also draw axes and centroids on a copy of the slice (Figure 7).

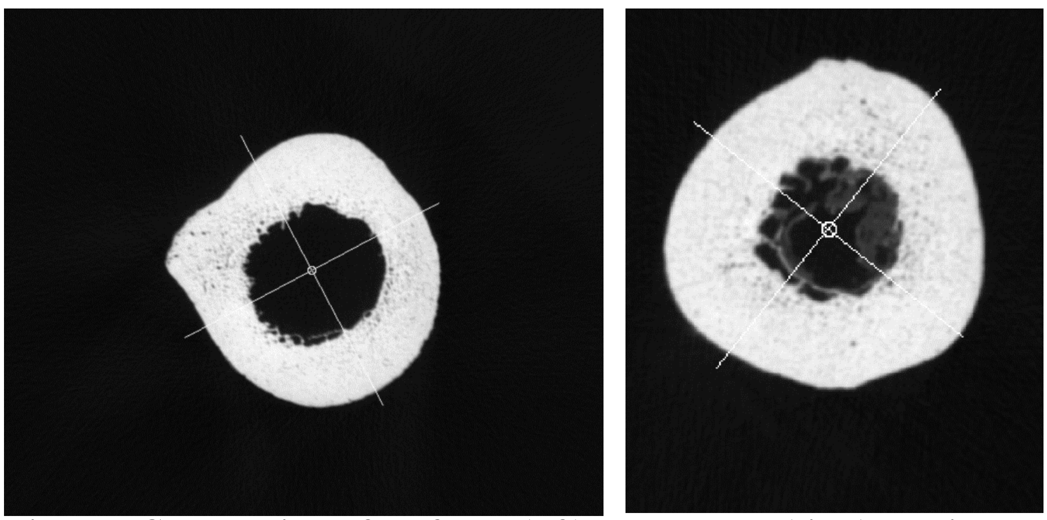

Figure 7. Cross-sections of the femur (left) and humerus (right) showing centroid and bending axes after analyzed in BoneJ.

When comparing bone structural properties between individuals, body size must be accounted for to complete an accurate comparison. This is because body size can be considered a mechanical load and it can also affect muscle size, and other factors that influence loading (Ruff, 2008). To standardize for body mass, the second moments of area (SMAs) were divided by body mass times bone length^2. For the femur, the femoral maximum length and the femoral head diameter was used. For the humerus, the humeral maximum length and the femoral head diameter was used. All measurements were taken following the descriptions outlined in Buikstra and Ubelaker (1994). In some cases, femoral head diameter could not be measured, in cases with double hip replacements for example, so humeral head diameter was used instead. The SMAs were then multiplied by 1000 so that more manageable numbers could be used for statistical comparison. To test for the effect of body size on CSG, both the standardized and unstandardized measurements were analyzed.

TERRY COLLECTION CT IMAGES

Bones from the Terry Collection were scanned using a Siemens medical CT system at the Smithsonian National Museum of Natural History. Bones were positioned in the proper orientation using the method described above so that the long access of the bone was at a right angle to the x-ray source. A single 0.5 mm image was acquired perpendicular to the coronal and sagittal planes at the midshaft and 65% length of the humerus and midshaft and 20% length of the femur. The CT parameters were set to 90 mAs, 110 kV, with a 1.5 second scan time. External measurements, including bone length and femur head diameter, were recorded for all individuals. Slice images were converted to 8-bit tiff files and cross-sectional properties were calculated using the Momentmacro macro in Image J. The biomechanical properties were then standardized using bone length^2 and femur head diameter as described above.

STATISTICAL ANALYSIS

Parametric statistical tests assume that the data is normally distributed and there is equal variance. A Shapiro-Wilk W test was first run to test for normal distribution, followed by a Levene's test to test for equal variance. The appropriate statistical test was then used to analyze the data depending on the results of the tests for distribution and variance. All statistical analyses were done in the program JMP Pro 14® and a significance level of $\alpha = 0.05$ was used.

The first test that was done was to test the general hypothesis of this study, which examines if there are differences in CSG between manual and non-manual labor workers in 19th and 20th century populations. A parametric analysis of variance (ANOVA) or a non-parametric Kruskal-Wallis test was run to test for differences in the cross-sectional properties within and between the study samples. ANOVA is used to analyze the differences among group means and the variation among and between groups. The assumptions of an ANOVA test are that the data is normally distributed, that it has equal variance, and that all the samples are independent of one another. A non-parametric Kruskal-Wallis one-way analysis of variance was done on the data that did not meet the requirements of an ANOVA. A Kruskal-Wallis test compares group medians rather than group means.

When comparing the humeri between the individuals, rather than comparing same side, the dominant arm was compared to the dominant arm and the non-dominant to the non-dominant. For the TXSTDSC, this data was in their donation paperwork. If handedness was not documented, it was assumed that the individual was right-handed because most people are right-handed rather than left-handed. For the Terry Collection, data was only collected on elements from the left side, so all the humeral data was compared to the non-dominant arm for the TXSTDSC.

A regression analysis was also run to test for secular change in mechanical variables between 19th and 20th century workers with year of birth (YOB) on the x-axis and CSG properties on the y-axis. The assumptions of linear regression are that there is a linear relationship, normality of the data with little or no multicollinearity, no autocorrelation and homoscedasticity. Tests for these assumptions will be conducted. If they fail, then a nonparametric test such as the Kendall rank correlation test will be used, or the mechanical variables can be log transformed.

III. RESULTS

The results of the Shapiro Wilks W test showed that many of the variables being analyzed were not normally distributed, resulting in a nonparametric statistical test being used to compare these variables among populations. Additionally, the results of the Levene's test also showed that many variables had unequal variance, also resulting in a nonparametric test being run.

When the standardized CSG properties were compared to the non-standardized properties there was a difference in significance for some variables. These results validate the importance of standardizing CSG for body size prior to analysis. For the remainder of the results and discussion sections, only the standardized CSG properties will be referenced. Descriptive statistics were run and are presented in Table 3 for the femur and 3 for the humerus.

Table 3. Descriptive statistics for the femoral properties. (mean ± standard deviation)

	Collection	Terry	Terry	TXSTDSC	TXSTDSC
Position	Occupation	Labor	Non-Labor	Labor	Non-Labor
20%	I_{max}	3.40 ± 0.58	3.10 ± 0.48	3.16 ± 0.57	3.26 ± 0.86
	I_{min}	2.42 ± 0.46	2.25 ± 0.9	2.47 ± 0.42	2.55 ± 0.62
	J	5.82 ± 0.93	5.34 ± 1.38	5.63 ± 0.91	5.81 ± 1.4
	CA	0.04 ± 0.005	0.04 ± 0.005	0.04 ± 0.006	0.04 ± 0.008
	Shape	1.43 ± 0.25	1.45 ± 0.37	1.29 ± 0.17	1.29 ± 0.2
Midshaft	I_{max}	2.74 ± 0.5	2.28 ± 0.71	3.78 ± 0.64	3.92 ± 1.13

Table 3. Continued.

	I_{min}	2 ± 0.33	1.73 ± 0.29	2.73 ± 0.49	2.84 ± 0.71
	J	4.74 ± 0.76	4.01 ± 1	6.51 ± 1.04	6.76 ± 1.77
	CA	0.04 ± 0.005	0.04 ± 0.005	0.04 ± 0.006	0.041 ± 0.008
	Shape	1.38 ± 0.19	1.3 ± 0.19	1.4 ± 0.19	1.39 ± 0.23

Table 4. Descriptive statistics for the left humeral properties.
(mean ± standard deviation)

	Collection	Terry	Terry	TXSTDSC	TXSTDSC
Position	Occupation	Labor	Non-Labor	Labor	Non-Labor
Midshaft	I_{max}	2.03 ± 0.73	1.5 ± 0.29	2.18 ± 0.58	1.88 ± 0.51
	I_{min}	1.36 ± 0.45	1.07 ± 0.18	1.41 ± 0.34	1.28 ± 0.34
	J	3.39 ± 1.16	2.57 ± 0.46	3.6 ± 0.89	3.16 ± 0.83
	CA	0.04 ± 0.007	0.04 ± 0.002	0.05 ± 0.008	0.04 ± 0.008
	Shape	1.49 ± 0.17	1.40 ± 0.04	1.56 ± 0.21	1.48 ± 0.17
65%	I_{max}	1.65 ± 0.53	1.38 ± 0.13	1.72 ± 0.38	1.54 ± 0.41
	I_{min}	1.27 ± 0.37	1.14 ± 0.03	1.41 ± 0.33	1.24 ± 0.32
	J	2.92 ± 0.89	2.51 ± 0.16	3.12 ± 0.69	2.78 ± 0.72
	CA	0.04 ± 0.006	0.04 ± 0.001	0.04 ± 0.008	0.04 ± 0.007
	Shape	1.29 ± 0.1	1.21 ± 0.08	1.23 ± 0.14	1.25 ± 0.13

LABOR

The first analysis that was run was to test to the relationship between CSG properties in both the humerus and the femur in manual labor and non-manual labor individuals. The results of the ANOVA and Kruskal-Wallace tests show that there were some significant differences, which will be discussed further below.

Femur

The results show that there are no significant differences in the CSG properties taken at the proximal 20% slice between manual labor workers and non-manual labor workers in both the TXSTDSC and Terry Collection. The same results can be seen for the midshaft of the femur.

Although there are no statistically significant differences, it should be noted that the non-manual labor workers in the TXSTDSC on average have larger CSG properties for all variables when compared to the manual labor workers in the collection for both the 20% and midshaft slices (Table 3). The opposite was observed for the Terry Collection however, where most of the properties were on average larger in manual labor workers rather than the non-manual labor workers (Table 3).

Humerus

The results of the comparisons between the non-dominant arm of the individuals show that there were no significant differences between manual labor workers and non-manual labor workers in the Terry collection at both the midshaft and proximal 65% slices. However, there was a significant difference in the proximal 65% between the TXST manual and non-manual labor workers in CSA ($p=0.0377$), Imin ($p=0.0120$), and J (p=0.0187), with the manual labor workers having larger averages for all three variables (Figure 3.1). There was also a significant difference between TXST manual labor workers and non-manual labor workers at the midshaft slice in I_{max} (p=0.0157) and J (p=0.0215).

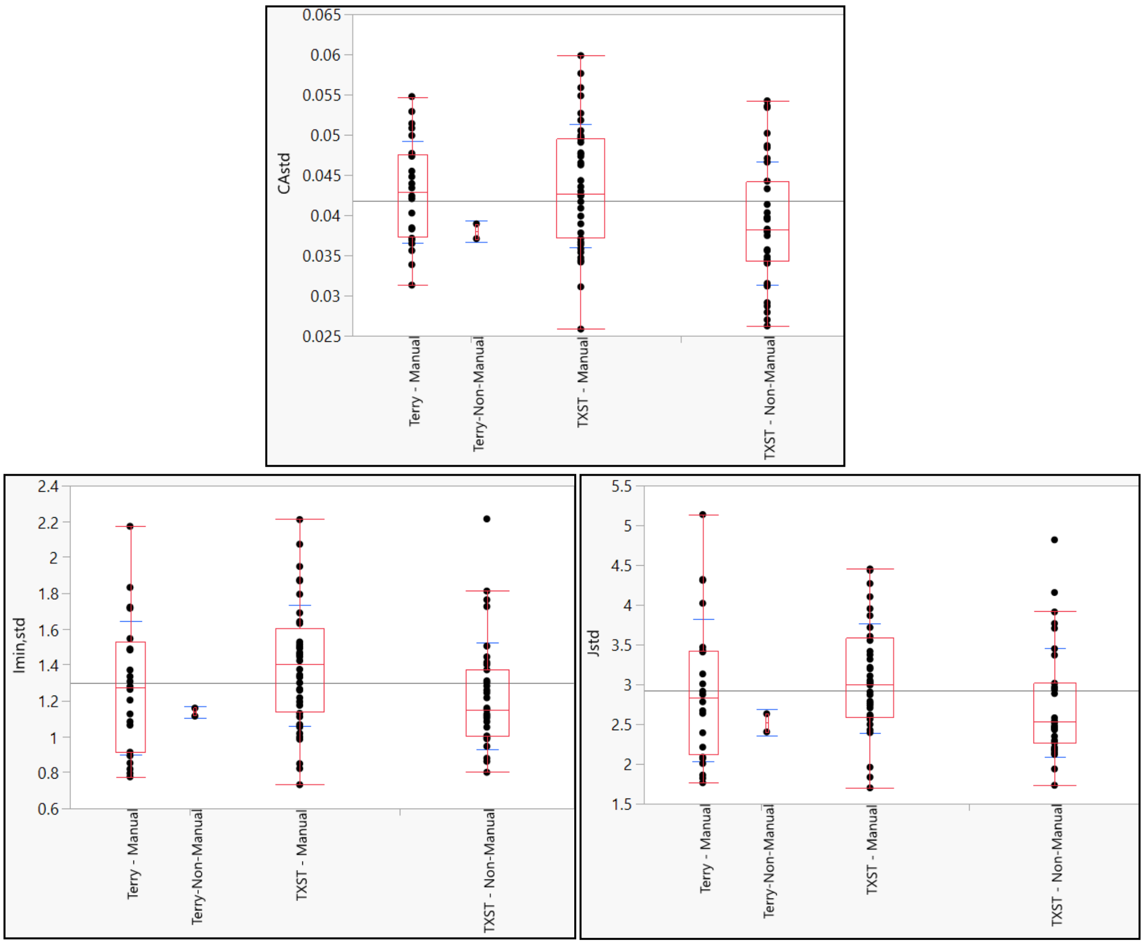

Figure 8. Boxplots representing significant differences in the femur between the TXSTDSC manual labor workers and non-manual labor workers in CA (top), I_{min} (left), and J (right).

Only the TXST collection was compared for the dominant arm because the Terry collection only had data from the left arm. The results of the comparisons between the dominant arm of the individuals show that there were no significant differences between manual labor workers and non-manual labor workers in the midshaft slice, although manual labor workers had larger CSG properties for all variables. Prior to analysis of the proximal 65% slice there were three outliers that were removed from the group. The results of the comparison show that there was a significant difference between Imin ($p=0.0282$) and J ($p=0.0459$), with the manual labor workers having larger CSG properties for all variables, not just those that were significant.

Femoral to Humeral Diaphyseal Strength Proportions

An analysis was also done to test for changes in relative strength of the upper and lower limbs between manual and non-manual labor workers. To do this, a femoral-to-humeral ratio was obtained using J from the proximal 65% of the humerus and the midshaft of the femur. If the resulting ratio was greater than one, than the femur was stronger than the humeri and if the ratio was less than one the humerus was larger than the femur.

Once this ratio was obtained for each individual in the TSXTDSC, a Shapiro-Wilk W test was run to test for normal distribution. The results showed that the data was not normally distributed, so a Kruskall-Wallis test was run to test for differences in the femoral-to-humeral ratio of J between manual and non-manual labor workers in the TXSTDSC.

The results showed that, although not significant, there was a difference in relative strength of the femur compared to the humerus, with non-manual labor workers having relatively stronger femora. A graphical depiction of this difference can be seen in Figure 3.2.

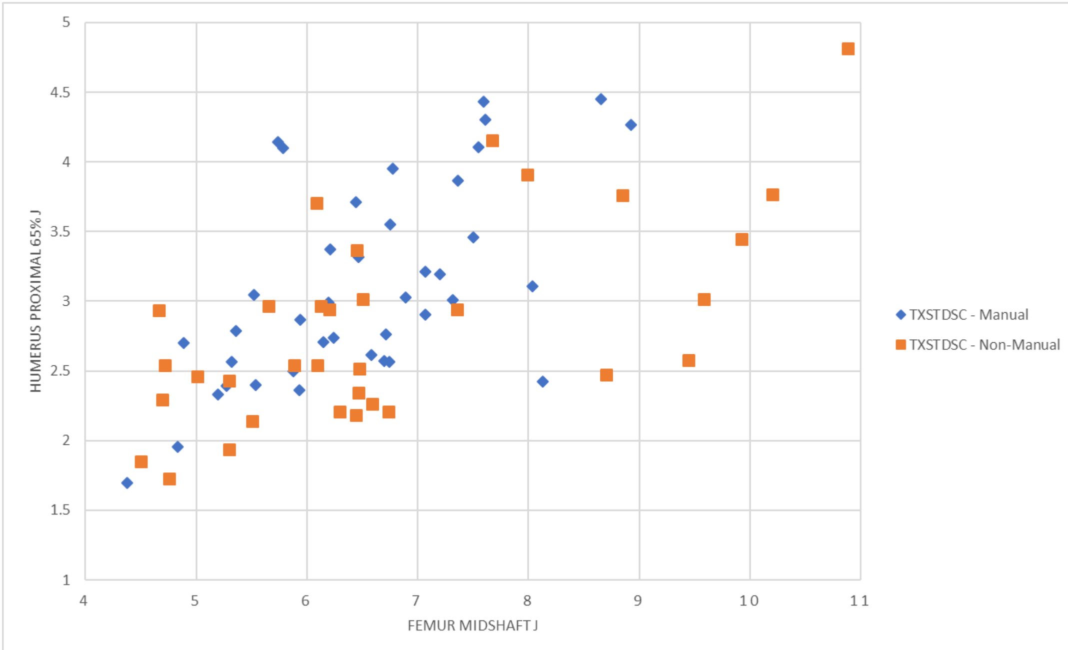

Figure 9. Graphical depiction of the femoral-to-humeral ratio of the TXSTDSC manual and non-manual labor workers J of the femur and humerus.

<u>SECULAR CHANGE</u>

The second analysis tested for a trend in secular changes between manual and non-manual labor workers in the 19th and 20th century. The results of the ANOVA and Kruskal-Wallace tests show that secular trends can be observed from the data, which will be discussed in detail below. The results of a linear regression analysis that shows how year of birth affects the cross-sectional geometry is also presented below.

Femur

The results from the comparison of the CSG properties in the proximal 20% slice of the femur show that there are no significant signs of secular change in the variables, however there is a significant difference between manual labor workers in the Terry collection and TXST manual ($p=0.0161$) and non-manual ($p=0.0206$) workers, with the

TXSTDSC sample having a more circular shaft shape.

However, a pattern of secular change can be seen in the comparisons of the midshaft slices for the femur, with the CSG properties becoming larger in the TXST collection in all variables. Significant differences were observed for all variables between manual labor workers in the TXSTDSC and both the manual and non-manual labor workers in the Terry Collection (Table 3.3). Significant differences were also observed between I_{max}, I_{min}, and J when the TXSTDSC non-manual labor workers were compared to the manual labor workers in the Terry Collection. Lastly, in the comparison between TXSTDSC non-manual labor workers and non-manual labor workers from the Terry Collection, significant differences were seen between I_{min} and J.

Table 5. Significantly different cross-sectional properties of the midshaft slice of the femur in comparisons between the TXSTDSC and Terry Collection.

Collection/Occupation	TXST Manual Labor	TXST non-manual labor
Terry Manual Labor	I_{max} (p=<.0001), I_{min} (p=<.0001), J (p=<.0001)	I_{max} (p=<.0001), I_{min} (p=<.0001), J (p=<.0001)
Terry non-manual labor	I_{max} (p=0.0227), I_{min} (p=0.0277), J (p=0.0277)	I_{min} (p=0.0302), J (p=0.0428)

The results of a linear regression analysis show that there are significant correlations between year of birth and I_{max}, I_{min}, and J of the midshaft (all with p-values of <.0001) (Figure 3.2). These values all increased as year of birth increased. There was also a significant correlation between year of birth and shape of the proximal 20% slice of the femur (p=0.0127) (Figure 3.3). These results indicate that the femur is getting stronger in all CSG properties and more circular in shape as year of birth increases. The slope of the regression line was 0.015 for I_{max}, 0.012 for I_{min}, and 0.026 for J. The slope for I_{max} is slightly larger than the slope for Imin, suggesting that the decrease in shape is being driven slightly more by I_{min}.

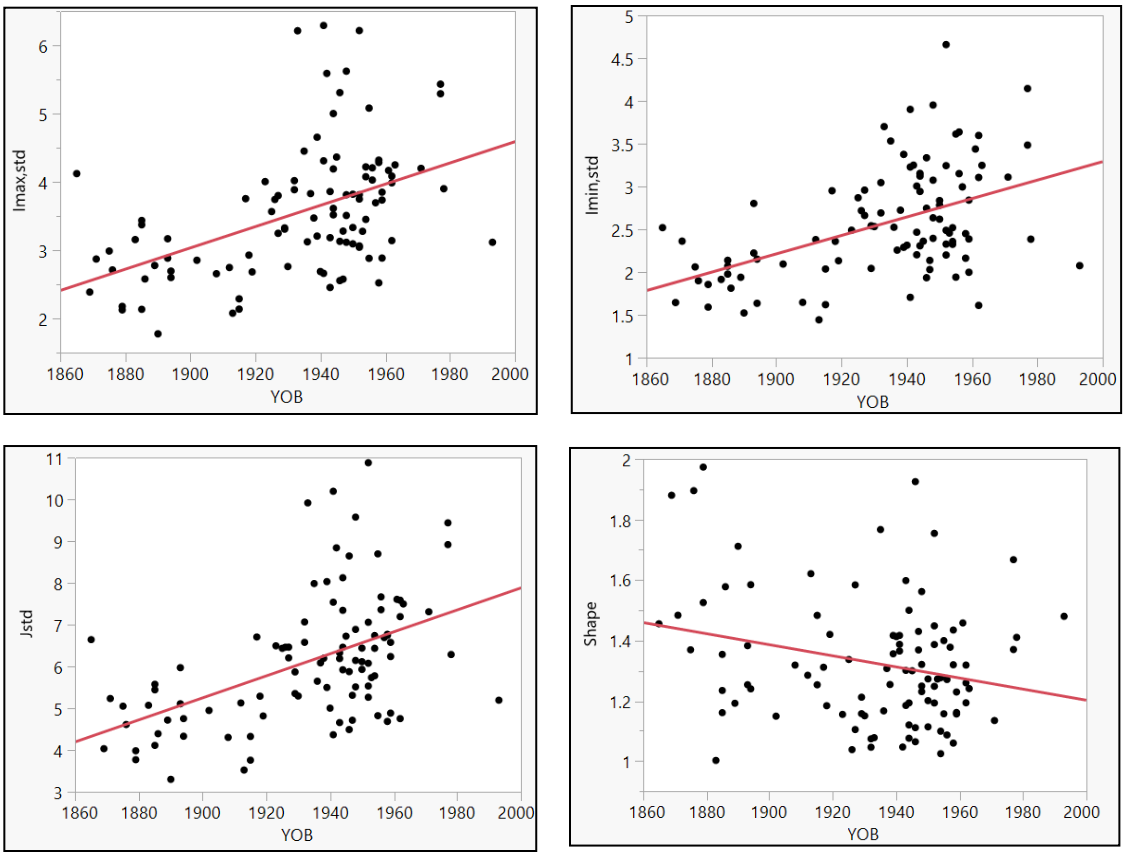

Figure 10. Linear regression analysis showing significant correlation between year of birth and I_{max} (top left), I_{min} (top right), and J (bottom left) in the midshaft of the femur and shape (bottom right) in the proximal 20% of the femur.

Humerus

Secular change in the dominant humerus could not be analyzed because in the Terry collection only data from the left side was available. However, the results of analysis of secular change in the non-dominant armed showed there is no significant patterns in secular change in both the midshaft and proximal 65% slices. The results of the linear regression analysis also showed no significant correlation between year of birth and the cross-sectional properties in the humerus.

Femoral to Humeral Diaphyseal Strength Proportions

An analysis was also done to test for changes in relative strength of the upper and lower limbs between manual and non-manual labor workers. To do this, a femoral-to-humeral ratio was obtained using J from the proximal 65% of the humerus and the midshaft of the femur. If the resulting ratio was greater than one, than the femur was stronger than the humeri and if the ratio was less than one the humerus was larger than the femur.

Once this ratio was obtained for each individual in the TSXTDSC and the Terry Collection, a Shapiro-Wilk W test was run to test for normal distribution. The results showed that the data was not normally distributed, so a Kruskall-Wallis test was run to test for differences in the femoral-to-humeral ratio of J between manual and non-manual labor workers in the TXSTDSC and Terry Collections.

The results show that there were significant differences between the TXSTDSC manual labor workers and the Terry Collection manual labor workers ($p=0.0006$) as well as the TXSTDSC non-manual labor workers and the Terry Collection manual labor workers ($p=0.0005$). The results also showed almost significant differences between the TXSTDSC manual ($p=0.0628$) and non-manual ($p=0.0700$) labor workers and the Terry Collection non-manual labor workers. All of these results showed that the TXSTDSC is relatively stronger than the Terry Collection. A graphical depiction of this can be seen in Figure 3.4.

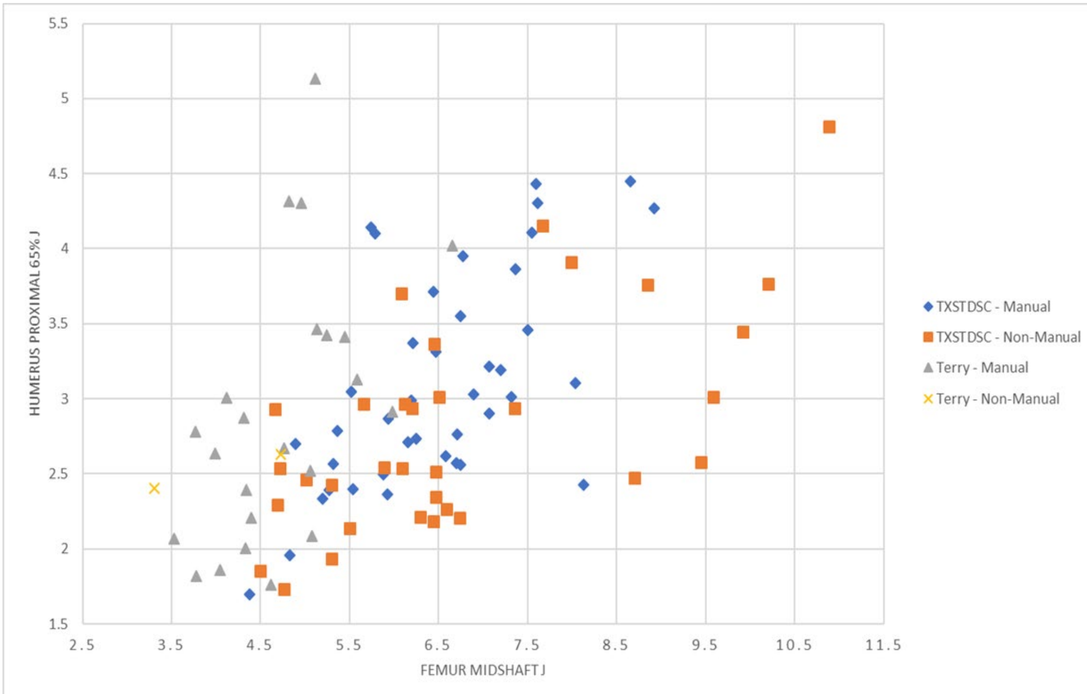

Figure 11. Graphical depiction of the femoral-to-humeral ratio of the TXSTDSC and Terry Collection manual and non-manual labor workers J of the femur and humerus.

IV. DISCUSSION AND CONCLUSION

The purpose of this research was to test for differences in the cross-sectional geometric properties between manual labor and non-manual labor workers within and between 19th and 20th century individuals, as well as to look for secular change. This research was completed by analyzing the geometric properties of cross-sections of the humeri and femora. The results of this study show that there are statistical differences observed in the humerus and the femur between manual labor workers and non-manual labor workers as well as a pattern of secular change. However, some of the comparisons produced results that were not to be expected.

LABOR

Texas State University Donated Skeletal Collection

In the humerus, the manual labor workers of the TXST Collection exhibited significantly larger cross-sectional properties for all variables, however in the femur the non-manual labor workers exhibited larger CSG properties. This indicates that manual labor affects the humerus more than the femur in a modern population, suggesting that a manual labor occupation involves more heavy lifting using the upper limb rather than an increase in walking, lifting with the legs, or activities that would affect the lower limbs. These results are supported by research that has been done discussing the cross-sectional properties of the lower limbs being more attributed to locomotion patterns whereas the CSG of the upper limbs tends to be more associated with mechanical loading from activity patterns (Pomeroy & Zakrzewski, 2009).

Furthermore, a study completed by Wescott (2008) compared external measurements and estimated SMAs of the humerus and femur between archaeological individuals from different subsistence groups. The results of this study showed that, in males, humeral head diameter, humeral midshaft area, and femoral midshaft shape differed significantly. Although these variables are not the same as the variables being used in this study, they do show a pattern that differences between manual labor and non-manual labor workers appears more on the upper limbs, which agrees with the results of this study.

The results of Stock's (2006) examination of cross-sectional geometric properties of the tibia, femur, ulna, clavicle, and humerus showed that torsional rigidity corresponds with activity levels at the distal ends of both the upper and lower limbs and strengthening of the femoral midshaft was significantly affected by increase in activity. These results correspond with the results that were observed in the humerus, however not in the femur. However, the femur did increase in strength between the 19^{th} and 20^{th} century, so the lack of significant differences in the femur between TXSTDSC manual and non-manual labor workers could once again be attributed to the idea that manual labor workers are participating more in activities that affect their upper limbs as opposed to their lower limbs. Also, the distal end of the femur was not observed for this study, so perhaps there is significant changes occurring at the lower end of the femur.

The results also show that there is a more significant difference in the non-dominant arm when compared to the dominant arm. This could be in relation to studies done on bilateral asymmetry (Auerbach & Ruff 2006), which show that the right humerus tends to be larger than the left humerus due to handedness. The results of this study would be expected then because the dominant arm is being exposed to more mechanical forces in both manual and non-manual labor workers due to constant use. However, the non-dominant arm tends to be used less in individuals that are not involved in manual labor.

The results also show that the proximal 65% of the humerus shows more significant differences than the midshaft of the humerus. These results may be explained by literature that states that the muscle attachment site of the deltoid on the humerus can sometimes be prominent at the midshaft, and if so, it will affect the cross-sectional properties (Ruff & Larsen 2001). Because the deltoid tuberosity only sometimes extends to the midshaft of the humerus, this can cause variation in the results, making it seem that the proximal 65% of the humerus is more affected by manual labor.

These results could also be influenced by age of individuals and how long individuals were working at their jobs. Research has shown that individuals of an older age tend to have less bone response to mechanical loading when compared to younger individuals (Lieberman, Pearson, Polk, Demes, & Crompton, 2003; Ruff et al., 2006). This may be explained by the fact that response to mechanical strain of surviving cells in an older individual is decreased (Pearson & Lieberman 2004). To support this claim, an experiment was conducted using male Dorset sheep of different ages (Lieberman & Crompton, 1998). The sheep were all exposed to different levels of activity and they were separated into three age cohorts: juveniles, subadults, and young adults. The results of this study showed that as the age cohort increased, there was less bone response to the mechanical strain of exercising.

The results of these studies have implications because the individuals that are completing the donation paperwork are later in life and they are placing the job they are currently working at the time in their paperwork. Potentially, the donors could have worked a job at a younger age in life that would have more of an effect on their CSG properties. Also, following the mechanostat theory, because of the extensive bone growth due to loading it can be hypothesized that manual labor workers will lose more bone than non-manual labor workers after retirement.

To test the effect that age has on the cross-sectional properties, a linear regression was run to test for a correlation with age. The results of this test showed that, in the humerus, as age increases all cross-sectional properties decrease at both the midshaft and 65% slices of the bone. However, of these properties, only cortical area decreased significantly, with a p-value of 0.0062 in the 65% slice and a p-value of 0.0084 in the midshaft slice (Figure 4.1).

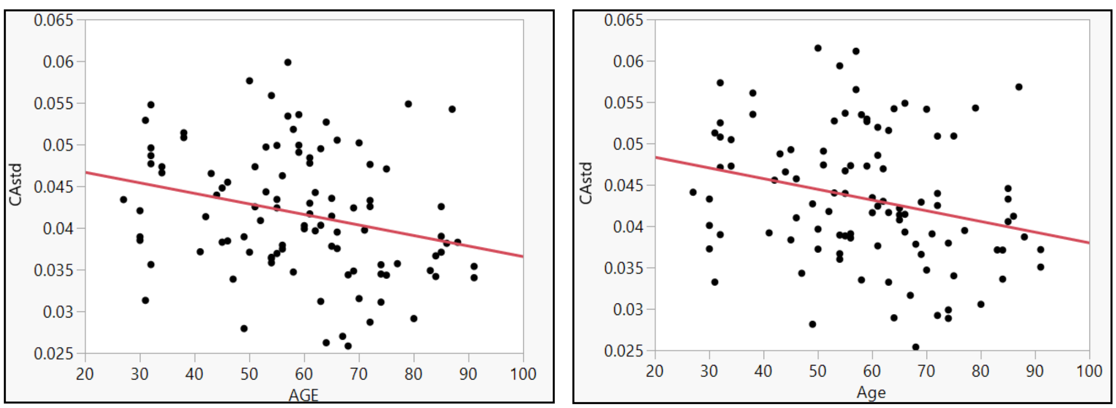

Figure 12. Linear regression analysis showing significant correlation between age and cortical area in the proximal 65% (left) and midshaft slice (right) of the humerus.

For the sample being used from the TXSTDSC, the average age for manual labor workers was 62 and the average age for non-manual labor workers was 66. Because there is only a four-year age difference in the averages of these two groups, it is hypothesized that the differences being observed are not being significantly affected by the age of the sample.

The results of the linear regression analysis for the femur differed from the results of the humerus, and the results of the midshaft and 20% slice differed also. For the 20% slice, both shape and cortical area significantly decreased with age, with a p-value of 0.0432 for cortical area and a p-value of 0.0129 for shape. I_{max} also decreased as age increased, but not significantly. For the midshaft slice, however, I_{max} (p=0.0034), I_{min} (p=0.0027), and J (p=0.0021) all increased significantly as age increased, but cortical area decreased, but not significantly. While these results were interesting, there is a low probability that the age differences are what are accounting for differences in the cross-sectional properties due to the close averages between the groups.

To test the hypothesis that individuals that worked manual labor jobs were losing more bone as their age increased, a linear regression to test for the age effect on the CSG properties were done on manual labor and non-manual labor workers separately. The results of the linear regression analyses showed that manual labor and non-manual labor workers have similar results with bone loss and increase in age. However, manual labor workers had a higher decrease in cortical area (p=0.0474) when compared to non-manual labor workers (p=0.0779). These results support the idea that manual labor workers are losing more bone with age when compared to non-manual labor workers, although the difference is not as severe as would be expected.

According to the mechanostat hypothesis (Frost, 1996; Frost, 2003), a decrease in mechanical loading can lead to a decrease in cortical bone. Many of the donors in our collection are older individuals and there is the possibility that they were retired for many years prior to being donated to our collection. The average age of retirement in the United

States is 65 (Diamond & Gruber, 1999), yet the average age for the sample was 64, with some people being over the age of 80. That is 10 plus years of possible decreased activity that could be resulting in a loss of cortical bone.

Lastly these results could be influenced by the job descriptions of the donors and the fact that many assumptions were made about what the job listed entailed. Habitual activities could also influence the results. In the donor paperwork we do ask they provide their habitual activities, but some individuals choose to leave this section blank. If the next of kin is donating the remains, they could also be leaving this blank because they did not know what their habitual activities were.

Terry Collection

The results of the comparison of the Terry manual labor workers to non-manual labor workers showed that there were no significant differences in the femur or the humerus. However, there were only two individuals that were classified as non-manual labor from this group, so these results should be taken lightly. These results are also showing that the properties were on average larger in the manual labor workers than the non-manual labor workers, although not significant. These results suggest that, although individuals in the 19th century that worked manual labor jobs tend to be more active throughout the day, all individuals in the 19th century had high activity levels when compared to each other.

These results can be expected when the history and demographics of the Terry Collection are taken into consideration. Many of the individuals that are in the Terry Collection were procured from anatomy departments once dissection was completed (Hunt & Albanese, 2005). The records also note that many of the individuals that are found in the Terry Collection were of a lower socioeconomic status, many of whom died during the Great Depression (Hunt & Albanese, 2005). With these individuals coming from lower socioeconomic status, it can be hypothesized that more of those individuals would be participating in manual labor activities during their daily activities, which can be explained by the results of the comparison of the Terry Collection manual and non-manual labor workers.

SECULAR CHANGE

Although the results did not show changes in CSG properties in the humerus between the 19th and 20th century collections, they did show changes in the CSG properties of the femur. The results showed that the CSG properties were larger in the TXSTDSC collection compared to the Terry Collection. They also showed that the shaft shape becomes more rounded as year of birth increases. These results could be due to the added body weight from the 19th to 20th centuries.

Although all the properties were standardized by body size, there could be a correlation between obesity and CSG properties. Brahmabhatt, Rho, Bernardis, Gillespie, and Ziv (1998) conducted research using male rats to test how obesity affects the cortical thickness, outer anteroposterior diameter, outer mediolateral diameter, as well as other biomechanical properties of the femur. Their results showed that weight gain and obesity can lead to improved biomechanics via bone adaptation. Previous studies have also shown that femur shape changes over time, however rather than becoming rounder, the shaft shape becomes elongated anteroposteriorly due to a decrease in mediolateral bending (Jantz et al., 2016; Wescott & Zephro, 2016).

However, research has shown that excessive weight gain can lead to the shape of the femur being more circular due to mediolateral expansion (Agostini & Ross, 2011; Harrington & Wescott, 2015). Gruss (2007) also conducted a study that tested the effect of limb bone length on the biomechanical properties. The results of this study showed that as limb bone length increases, there will also be an increase in anteroposterior bending. The results of these studies help to support the results of this project because there is an increase in both long bone limb length and weight between the 19th and 20th centuries. These increases will affect both the AP and ML bending strength of the femur, resulting in an overall increase in strength of the bone as well as a more circular shaft shape.

To test this a linear regression analysis was run to look for patterns between CSG and body mass index (BMI) using the TXSTDSC. To calculate BMI for the individuals included in the analysis, cadaver height and weight was used rather than the height and weight listed on the paperwork. This was done because sometimes the donation paperwork was completed years before the donation was received. Also, some of the paperwork was completed by next of kin and when it was completed the height and weight was just an estimate.

The results of the linear regression analysis showed that there is an increase at the midshaft of the femur in cortical area, I_{max}, J, and shape as BMI increases, although not significant. There is also a slight decrease in I_{min} as BMI increases, although not significant. These results support previous literature that states that with excessive weight gain, there will be an increase in ML bending (Agostini & Ross, 2011; Harrington & Wescott, 2015).

This increase would explain the differences being observed between the 19th and 20th century individuals. Also, this could explain why non-manual labor workers have stronger femora when compared to manual labor workers. It can be hypothesized that non-manual labor workers are on average more sedentary than manual labor workers, resulting in non-manual labor workers having a higher BMI. These results are supported by the results of a Kruskal-Wallis test. Although the results from this test were not significant, it does show that non-manual labor workers have a higher BMI on average.

These results support the idea that, even when cross-sectional properties are standardized for body size, BMI can have an effect on the CSG. They also support the statement mentioned previously, that an increase in BMI will have an effect on the mediolateral (ML) bending, and when that is paired with the increase in AP bending from longer limb bone lengths, an increase in strength of the femur as well as a more circular shaft shape is observed.

CONCLUSION

Cross-sectional geometry has long been used to interpret behaviors in both past and modern populations. For this reason, CSG properties of the humeri and femora were used to evaluate differences between manual labor workers and non-manual labor workers. Analysis was also done to test for secular change in the CSG properties between 19th and 20th century individuals to see how modern lifestyle and occupational activity have changed over time.

The results showed that labor does influence the biomechanical properties of the humerus, but it does not affect the CSG of the femur. Individuals who work manual labor jobs tend to have an increase in cortical area, I_{max}, I_{min}, and J in the TXSTDSC, although there are no differences between manual labor and non-manual labor workers in the Terry Collection. In the femur, while there were significant differences between manual labor workers and non-manual labor workers, those differences showed an increase in the CSG properties in the non-manual labor workers compared to the manual labor workers. These differences can potentially be explained by slightly higher averages in height and weight in the non-manual labor workers compared to the manual labor workers. There is also a pattern of secular change being observed in the femur, with an increase in both anteroposterior and mediolateral bending and a circular shaft shape in the 20th century population.

The results of the increase in strength and greater circularity of the femur provide evidence that the lifestyle of a modern population can have an effect on the biomechanical properties of the long bones. Also, on average a 20th century population will be taller and have a higher BMI than individuals from a 19th century population, which is reflected in the biomechanical properties of the femur.

These results also provided more research that can be added to literature stating that manual labor will have more of an effect on the CSG of the upper limbs when compared to the lower limbs. The lack of secular change in the humeri suggests that technological advancements have had little effect on the CSG properties of the humeri. The results of this research help to support this idea by showing that manual labor workers have more mechanical loading and strain being placed on their upper limbs.

Future Research

To expand upon this research, females can be added to the sample to test for differences in the cross-sectional properties of males and females that have documented that they have the same occupation. Furthermore, it would also be useful to gain information on not only how long the individual was working the manual labor job, but also on average how many hours a week that person was participating in increased activity as a direct result of their job.

APPENDIX SECTION

Appendix A. List of occupations and their classifications.

Occupation	Type of Labor	Occupation	Type of Labor
Accountant	Non-Manual	Handyman	Manual
Air Force	Manual	Insurance Examiner	Non-Manual
Archaeologist	Manual	Laborer	Manual
Army	Manual	Landscaper	Manual
Arts	Non-Manual	Lawyer	Non-Manual
Attorney	Non-Manual	Machinist	Manual
Auditor	Non-Manual	Manager	Non-Manual
Auto Mechanic	Manual	Manufacturing Laborer (Welder)	Manual
Brick Mason	Manual	Mechanic	Manual
Business	Non-Manual	Musician	Non-Manual
Carpenter	Manual	Newsman	Non-Manual
Changed Tires	Manual	Oil Field	Manual
Chef	Non-Manual	Painter	Manual
Computer Industry	Non-Manual	Paper Hanger	Manual
Computer Programmer	Non-Manual	Railroad Conductor	Manual
Computer Service Tech	Non-Manual	Rancher	Manual
Construction	Manual	Real Estate	Non-Manual
Cook	Non-Manual	Retail and Handyman	Manual
Dispatcher	Non-Manual	Sales	Non-Manual
Electrician	Manual	School Chair Director	Non-Manual
EMT	Manual	Steelworker	Manual
Farm hand	Manual	Systems Analyst	Non-Manual
Field Engineer	Manual	Tailor	Non-Manual
Furniture Refinisher	Manual	Teacher	Non-Manual
Gardener	Manual	Texas Railroad Com. (oil & gas div.)	Manual
General Labor	Manual	Tool and dye operator	Manual
Glazier	Manual	Uniform Rental/Self-Employed	Non-Manual
Graphic Arts	Non-Manual	Warehouse Work	Manual
Grocery	Non-Manual		

Appendix B. TXSTDSC sample demographics.

Donation Number	Ancestry	Age	BMI	Occupation
D01-2009	W	49	20.92	Mechanic
D10-2010	W	32	25.82	Handyman
D15-2010	H	64	27.12	Changed Tires
D19-2011	W	56	28.69	Carpentry
D02-2009	W	91	18.65	Mechanic
D08-2010	H	66	24.41	Steelworker
D12-2010	W	54	17.22	Handyman
D08-2011	W	53	25.97	Mechanic/Maintenance
D14-2011	W	51		Painter/general labor
D16-2011	B	84	13.47	Manufacturing Laborer (Welder)
D07-2015	W	53	48.17	Rancher
D46-2013	W	55	34.43	Oil Field
D05-2012	W	79	25.83	Carpenter
D06-2012	W	58	23.29	Construction
D33-2012	W	72		Landscaper
D38-2012	W	50	27.38	Mechanic
D41-2012	W	60	22.89	Warehouse Work
D45-2012	W	65	20.37	Auto Mechanic
D47-2012	W	68	32.98	Gardener
D05-2013	W	54	36.01	Handyman Remodeling
D13-2013	W	69	43.53	Carpenter
D14-2013	W	58	18.97	Army - Various Jobs
D23-2013	W	63	21.52	Handyman
D28-2013	W	85	27.12	General Labor
D53-2013	W	65	21.23	Glazier
D55-2013	W	57	32.28	Laborer
D57-2013	W	54	18.24	Laborer
D61-2013	W	61	21.11	Machinist
D65-2013	W	61	25.85	Retail and Handyman
D29-2014	W	72	21.96	Furniture Refinisher
D33-2014	W	20	34.66	EMT
D40-2014	W	84	19.58	Air Force
D48-2014	W	52	30.34	Electrician
D57-2014	W	59	45.61	Brick Mason
D65-2014	W	43	28.89	Construction
D03-2015	W	85	27.16	Texas Railroad Com. (oil & gas div.)
D08-2015	W	51	39.89	Construction
D20-2015	W	74	21.66	Army
D39-2015	W	85	20.60	Air Force

D05-2009	W	61	19.13	Field Engineer
D59-2014	W	60	21.70	Archaeologist
D42-2012	W	68	38.24	Railroad Conductor
D11-2013	W	64	22.96	Tool and dye operator
D26-2013	W	69	22.50	Oil Field Products
D03-2008	W	75	43.24	Graphic Arts
D03-2009	W	32	34.45	Police Dispatcher
D02-2010	W	71	20.09	Teacher
D11-2010	W	91	17.51	Attorney
D03-2011	W	66	37.53	Dispatcher
D13-2011	W	65	21.69	Arts
D15-2012	W	62	21.52	Sales
D18-2012	W	59	48.35	Attorney
D30-2012	W	74	31.18	Salesman
D20-2013	W	67	25.09	Sales/Marketing
D25-2013	W	62		Insurance Examiner
D27-2013	W	69	28.19	Lawyer/Judge
D30-2013	W	86	25.09	Accountant
D35-2013	W	77	26.38	Auditor
D36-2013	W	88	19.80	Lawyer
D44-2013	W	64	20.52	Computer Industry
D49-2013	W	61	20.67	Computer Programmer
D66-2013	W	72	35.87	Computer Service Tech
D08-2014	B	57		Manager
D09-2014	W	70	15.35	Musician
D26-2014	W	72	20.53	Law/advertising/banking
D49-2014	W	56	27.98	School Chair Director
D51-2014	W	74	25.10	Dispatcher/Various
D10-2015	W	66	44.11	Computer Program
D28-2016	W	83	24.42	Teacher
D09-2010	W	63	20.98	Systems Analyst
D13-2010	W	70	51.60	Business
D05-2011	W	80	22.96	Sales
D07-2011	W	87	38.60	Salesman
D10-2011	W	63	21.69	None (Disabled: psychiatric disease)
D15-2011	W	49	23.75	Grocery
D20-2012	W	34		Chef
D21-2012	W	42	20.80	Real Estate
D23-2012	W	56	30.69	Cook
D28-2012	W	75	24.67	Uniform Rental/Self-Employed

Appendix C. Terry Collection sample demographics.

Cat #	Ancestry	Age	Occupation
54	B	46	Laborer
145R	B	31	Laborer
201	W	55	Laborer
207	W	45	Paper Hanger
209	B	38	Laborer
216	W	45	Farm hand
221, L	W	47	Laborer
229	W	41	Painter
265	B	32	Laborer
288	B	59	Laborer
343	W	32	Laborer
3R	B	55	Laborer
7R	B	55	Laborer
31R	B	38	laborer
33R	B	54	Painter
34R	W	44	Laborer
35R, L	B	60	Laborer
49R	B	27	Laborer
88RR	B	31	Laborer
89R	B	32	Laborer
95R	B	30	Laborer
109	B	46	Mechanic
123	B	34	Laborer
261	W	50	Laborer
269	B	30	Laborer
84	B	30	Tailor
126R	B	50	Newsman

REFERENCES

Agostini, G. M. & Ross, A. H. (2011). The effect of weight on the femur: A cross-sectional analysis. *Journal of Forensic Sciences,* 56(2), 339-343.

Auerbach, B. M. & Ruff, C. B. (2004). Human body mass estimation: A comparison of “morphometric” and “mechanical” methods. *American Journal of Physical Anthropology,* 125(4), 331-342.

Auerbach, B. M. & Ruff, C. B. (2006). Limb bone bilateral asymmetry: variability and commonality among modern humans. *Journal of Human Elevation,* 50(2), 203-218.

Bertram, J. E. A. & Swartz, S. M. (1991). The ‘law of bone transformation’: A case of crying Wolff? *Biological Reviews,* 66(3), 245-273.

Brahmabhatt, V., Rho, J., Bernardis, L., Gillespie, R., & Ziv, I. (1998). The effects of dietary-induced obesity on the biomechanical properties of femora in male rats. *International Journal of Obesity,* 22(8), 813.

Brock, S. L. & Ruff, C. B. (1988). Diachronic patterns of change in structural properties of the femur in the prehistoric American Southwest. *American Journal of Physical Anthropology,* 75, 113-127.

Buikstra, J. E. & Ubelaker, D. H. (1994). *Standards for data collection from human skeletal remains. Arkansas archeological survey research series.* Fayetteville, AR: Arkansas Archeological Survey.

Cameron, M. E. & Pfeiffer S. (2014). Long bone cross-sectional geometric properties of Later Stone Age foragers and herder-foragers. *South African Journal of Science,* 110(9), 1-11.

Carter, D. R. & Spengler D. M. (1978). Mechanical properties and composition of cortical bone. *Clinical Orthopaedics and Related Research,* 135, 192-217.

Cowin, S. C. (2001). *Bone biomechanics handbook.* Boca Raton: CRC Press.

Diamond, P. & Gruber, J. (1999). Social security and retirement in the United States. In: *Social Security and Retirement Around the World* (pp. 437-473). University of Chicago Press.

Doube, M., Klosowski, M. M., Arganda-Carreras, I., Cordelières, F. P., Dougherty, R. P., Jackson, J. S., Schmid, B., Hutchinson, J. R., & Shefelbine, S. J. (2010). BoneJ: Free and extensible bone image analysis in ImageJ. *Bone,* 47(6), 1076-1079.

Frost, H. M. (1996). Perspectives: A proposed general model of the “mechanostat” (suggestions from a new skeletal-biologic paradigm). *The Anatomical Record,* 244(2), 139-147.

Frost, H. M. (2003). Bone’s mechanostat: A 2003 update. *The Anatomical Record,* 275(2), 1081-1101.

Goodship, A. E., Lanyon, L. E., & McFie, H. (1979). Functional adaptation of bone to increased stress. An experimental study. *The Journal of Bone and Joint Surgery,* 61(4), 539-546.

Gruss, L. T. (2007). Limb length and locomotor biomechanics in the genus Homo: An experimental study. *American Journal of Physical Anthropologists,* 134(1), 106-116.

Harrington, K. I. & Wescott, D. J. (2015). Size and shape differences in the distal femur and proximal tibia between normal weight and obese American whites. *Journal of Forensic Sciences,* 60, S32-S38.

Huiskes, R., Ruimerman, R., Van Lenthe, G. H., & Janssen, J. D. (2000). Effects of mechanical forces on maintenance and adaptation of form in trabecular bone. *Nature*, 405(6787), 704-706.

Hunt, D. R. & Albanese, J. (2005). History and demographic composition of the Robert J. Terry anatomical collection. *American Journal of Physical Anthropology*, 127(4), 406-417.

Jantz, L. M. & Jantz, R. L. (1999). Secular change in long bone length and proportion in the United States, 1800-1970. *American Journal of Physical Anthropology,* 110, 57-67.

Jantz, R. L., Jantz, L. M., & Devlin, J. L. (2016). Secular changes in the postcranial skeleton of American whites. *Human Biology,* 88(1), 65-75.

JMP®, Version 14. SAS Institute Inc., Cary, NC, 1989-2019.

Lanyon, L. E., Hampson, W. G. J., Goodship, A. E., & Shah, J. S. (1975). Bone deformation recorded in vivo from strain gauges attached to the human tibial shaft. *Acta Orthopaedica Scandinavica*, 46(2), 256-268.

Lanyon, L. E. (1996). Using functional loading to influence bone mass and architecture: Objectives, mechanisms, and relationship with estrogen of the mechanically adaptive process in bone. *Bone*, 18, S37-S43.

Ledger, M., Holtzhausen, L. M, Constant, D, & Morris, A. G. (2000). Biomechanical beam analysis of long bones from a late 18th century slave cemetery in Cape Town, South Africa. *American Journal of Physical Anthropology,* 112, 207-216.

Lieberman, D. E. & Crompton, A. W. (1998). Responses of bone to stress. *Principles of Biological Design: The Optimization and Symmorphosis Debate,* 78-86.

Lieberman, D. E., Pearson, O. M., Polk, J. D., Demes, B., & Crompton, A. W. (2003). Optimization of bone growth and remodeling in response to loading in tapered mammalian limbs. *Journal of Experimental Biology,* 206(18), 3125-3138.

Lieberman, D. E., Polk, J. D., & Demes, B. (2004). Predicting long bone loading from cross-sectional geometry. *American Journal of Physical Anthropology,* 123(2), 156-171.

Liskova, M., Hert, J. (1971). Reaction of bone to mechanical stimuli. *Folia Morphologica,* 19, 301-317.

Marchi, D., Sparacello, V. S., Holt, B. M., & Formicola, V. (2006). Biomechanical approach to the reconstruction of activity patterns in Neolithic western Liguria, Italy. *American Journal of Physical Anthropology,* 131, 447-455.

Martin, R. B., Burr, D. B., & Sharkey, N.A. (1998). *Skeletal tissue mechanics.* New York: Springer.

Miller, M. J., Agarwal, S. C., Aristizabal, L., & Langebaek, C. (2018). The daily grind: Sex- and age-related activity patterns inferred from cross-sectional geometry of long bones in a pre-Columbian muisca population from Tibanica, Colombia. *American Journal of Physical Anthropology,* 167, 311-326.

Moore, M. K. (2013). Functional morphology and medical imaging. In: E. A. DiGangi & M. K. Moore (Eds.), *Research Methods in Human Skeletal Biology* (pp. 397-424). Waltham: Academic Press.

North Star Imaging, Inc. efXCT: Computed Tomography Reconstruction and Visualization software version 1.7.97.0.

North Star Imaging, Inc. efXDR: Digital Radiography and CT Acquisition Software version 1.1.97.6.

Ogilvie, M. D. & Hilton, C. E. (2011). Cross-sectional geometry in the humeri of foragers and farmers from the prehispanic American Southwest: exploring patterns in the sexual division of labor. *American Journal of Physical Anthropology,* 144, 11-21.

Pearson, O. M., Lieberman, D. E. (2004). The aging of Wolff's "law": Ontogeny and responses to mechanical loading in cortical bone. *American Journal of Physical Anthropology,* 125(S39), 63-99.

Pearson, O. M., Peterson, T. R., Sparacello, V. S., Daneshvari, S. R., & Grine, F. E. (2014). Activity, "body shape," and cross-sectional geometry of the femur and tibia. In: K. J. Carlson & D. Marchi (Eds.), *Reconstructing mobility: Environmental, behavioral, and morphological determinants* (pp. 133-151). New York, NY: Springer.

Plato, C. C., Fox, K. M., & Garruto, R. M. (1984). Measures of lateral functional dominance: Hand dominance. *Human Biology,* 56, 259-275.

Pomeroy, E. & Zakrzewski, S. R. (2009). Sexual dimorphism in diaphyseal cross-sectional shape in the medieval Muslim population of Écija, Spain, and Anglo-Saxon Great Chesterford, UK. *International Journal of Osteoarchaeology,* 19(1), 50-65.

Ruff, C. B. & Hayes, W. C. (1983). Cross-sectional geometry of Pecos Pueblo femora and tibiae – A biomechanical investigation: I. Method and general patterns of variation. *American Journal of Physical Anthropology,* 60(3), 359-381.

Ruff, C. B., Larsen, C. S., & Hayes, W. C. (1984). Structural changes in the femur with the transition to agriculture on the Georgia coast. *American Journal of Physical Anthropology,* 64(2), 125-136.

Ruff, C. (1987). Sexual dimorphism in human lower limb bone structure: Relationship to subsistence strategy and sexual division of labor. *Journal of Human Evolution,* 16, 391-416.

Ruff, C. B. & Larsen, C. S. (2001). Reconstructing behavior in Spanish Florida: The biomechanical evidence. *Bioarchaeology of Spanish Florida: The Impact of Colonialism,* 113-145.

Ruff, C., Holt, B., Trinkaus, E. (2006). Who's afraid of the big bad Wolff?: "Wolff's law" and bone functional adaptation. *American Journal of Physical Anthropology,* 129(4), 484-498.

Ruff, C.B. (2008). Biomechanical analyses of archaeological human skeletons. In: M. A. Katzenberg & S. R. Saunders (Eds.), *Biological anthropology of the human skeleton* (2nd Ed., pp. 183-206). Hoboken, NJ: Wiley.

Ruff, C. B. & Larsen, C. S. (2014). Long bone structural analyses and the reconstruction of past mobility: A historical review. In: K. J. Carlson & D. Marchi (Eds.), *Reconstructing mobility: Environmental, behavioral, and morphological determinants* (pp. 13-29). New York, NY: Springer.

Scheffler C. & Hermanussen M. (2014). Is there an influence of modern life style on skeletal build? *American Journal of Human Biology,* 26(5), 590-597.

Schneider, C. A., Rasband, W. S., & Eliceiri, K. W. (2012). NIH image to ImageJ: 25 years of image analysis. *Nature Methods,* 9(7), 671.

Stock, J. & Pfeiffer, S. (2001). Linking structural variability in long bone diaphysis to habitual behaviors: Foragers from the southern African Later Stone Age and the Andaman Islands. *American Journal of Physical Anthropology,* 115(4), 337-348.

Stock, J. T. (2006). Hunter-gatherer postcranial robusticity relative to patterns of mobility, climatic adaptation, and selection for tissue economy. *American Journal of Physical Anthropology,* 131(2), 194-204.

Timoshenko, S. P. & Gere, J. M. (1972). *Mechanics of Materials.* New York: Van Nostrand Reinhold.

Trotter, M., Peterson, R. R., & Wette, R. (1968). The secular trend in the diameter of the femur of American whites and negroes. *American Journal of Physical Anthropology,* 28, 65-74.

Wescott, D. J. (2001). *Structural variation in the Humerus and Femur in the American Great Plains and adjacent regions: Differences in subsistence strategy and physical terrain* (Unpublished doctoral dissertation). University of Tennessee, Knoxville.

Wescott, D. J. (2006). Effect of mobility on femur midshaft external shape and robusticity. *American Journal of Physical Anthropology,* 130(2), 201-213.

Wescott, D. J. (2008). Biomechanical analysis of humeral and femoral structural variation in the Great Plains. *Plains Anthropologist,* 53(207), 333-355.

Wescott, D. J., Cunningham, D. L., & Hunt, D. R. (2014). Temporal trends in femoral diaphyseal torsional asymmetry among the Arikara associated with postural behavior. *American Journal of Physical Anthropology,* 154(4), 512-524.

Wescott, D. J. & Zephro, L. R. (2016). Secular change in the femur diaphyseal biomechanical properties of American whites. *Human Biology,* 88(1), 38-46.

Wescott, D. J. (2018). The Forensic Anthropology Research Facility at Texas State University: Factors affecting forensic case interpretation and forensic taphonomy research in central Texas. In: M. Sorg, W. Haglund, & Marden (Eds.), *Forensic Taphonomy* (2nd Ed., in press). Boca Raton: CRC Press.