ABSTRACT

AGOSTINI, GINA MARIE. The Relationship between Body Mass Index and Long Bone Morphology: A Multidirectional Analysis. (Under the direction of Ann Helen Ross, D. Troy Case and Scott M. Fitzpatrick).

Obesity has increased significantly during the last three decades in all ages and both sexes among European and African Americans, and Hispanic individuals of Mexican origin. Biomechanical literature is replete with evidence of compensatory adaptations made by overweight individuals to cope with adiposity in daily life, yet aside from correlations between weight and arthritis frequencies, little attention has been paid to the effect that obesity has on the human skeleton. Because a key goal of physical anthropology is to create a thorough and accurate biological profile of the individuals being analyzed, more research is needed to investigate implications of obesity, a condition which clearly affected how an individual appeared in life.

The goal of this project was twofold: [1] to assess differences in diaphyseal cross-sectional geometry of both humeri, the left femur and the left tibia on the basis of BMI; and [2] to test whether the expression of musculoskeletal stress markers (MSMs) of each bone were affected by weight. Both properties have been shown to be influenced by load and mechanical action resulting from stress-induced remodeling responses at the cellular level.

A sample of modern males of European ancestry was utilized for this research. After controlling for age, multivariate statistics show significant (*p-value* < 0.05) elongation of the mediolateral (ML) dimension of the proximal and midshaft femur in overweight individuals after controlling for age. T-tests of group means confirm that overweight individuals have significantly large ML dimensions in this region (*p-value* < 0.05), suggesting that femora of

overweight individuals undergo abnormally high rates of sagittal stress. These findings correlate well with biomechanical gait analyses, which show that overweight individuals display significant increases in step width and hip abduction, disproportionately large mediolateral ground reaction forces, and longer periods of stance during the walking cycle when compared to normal weight controls. All of these activities could explain abnormal sagittal stress of the proximal femur, especially when coupled with movement of excess mass.

A significant bilateral effect of BMI on the ML dimension of the proximal humerus was also found (p-value < 0.01) after controlling for age. T-tests confirmed that overweight individuals have significantly large dimensions in this region (p-value < 0.05), perhaps due to high loads transmitted through the shoulder when an individual uses his arms to rise from a seated position.

Despite their success in archaeological assessments of activity, MSMs were not found to be a suitable method of differentiating overweight individuals from normal or underweight individuals. This could be due to the presence of biological defense mechanisms at sites of muscle attachment due to the routinely high stresses associated with muscle pull. It is also possible that genetic influences of MSM expression or lack of significant activity differences between overweight and normal or underweight individuals could explain this result.

DEDICATION

To Shirley Amos-Palmer, for showing that inspiration can turn up in the oddest of places.

BIOGRAPHY

Gina Marie Agostini obtained her B.A. in anthropology and minor in French at the University of Arkansas. Within the field, her interests lie in modern applications of biological anthropology. With a specific focus on skeletal biology, she intends to study the theories and mechanisms which govern bone modeling and remodeling, and how these can highlight (or complicate) biomechanical inferences of behavior and locomotion across different disciplines. She is especially interested in the benefit that this research has for forensic and genetic-based analyses of skeletal material, perhaps on the basis of body weight.

ACKNOWLEDGEMENTS

Though somewhat misguided, I found the most poignant thing I learned while attending the required "Electronic Thesis and Dissertation" workshop last year was that while the Dedication was traditionally limited to one or two sentences, the Acknowledgements could be as many pages as I liked! This is most fortunate, as despite the slow realization that I am somewhat "quantitatively-minded," I have not *entirely* mastered the fine art of brevity. Couple this with my natural tendencies toward the sentimental, and the fact I have had no shortage influence and inspiration in my life, and you will see that not only do I have a lot of people to thank, but I will likely take a lot of time to thank them! I do not quite know where to begin, so I suppose I will start close to home.

To my parents, Michael and Tracey, who have generally encouraged me to be whatever I desired (no matter how outrageous the choice). I must also thank them for allowing me to move back home when those desires did not exactly function on a "real world" budget. I wholly credit my parents for my adaptability. Little did they know frequent childhood moves from state-to-state were, in fact, preparing me for future travels country-to-country. Thanks to mom and dad I can now claim "beneficial naiveté" as one of the many unique (and very anthropological) personality traits in my bizarre arsenal. I must also thank dad for his constant advice to "suck it up" and move on. While he *may* have been referring to scraped knees and broken arms, I have found this advice indispensible in my professional life, especially after the receipt of my first (and second and third) rejection letters. I also thank mom for forcing me to do my homework every day as soon as I got home from school, no matter how much my ADD-like tendencies hindered the process. While I may have despised it then, I feel that it made me aware that education was not only important, but worth working for. In this same vein, I must also thank mom and dad for instilling in me early a firm sense of morality and a strong work ethic. I would not have succeeded without them, and would never have been fit to even consider a career in either the medicolegal system or academia without the strong foundation on which I was raised.

I thank my little (yet taller) brother, Anthony, for always alleviating my PC-ineptness, dressing as a pirate with me and taking me to my first (and only) LAN party. I must apologize for the all of the times I dressed him as a girl, mocked him, stole his micro machines or otherwise acted as the stereotypically dominant older sibling. To that end, I must also acknowledge his generally forgiving nature! I congratulate him on choosing a career that would immediately settle him into the job market after four years of college. We were always perfect opposites.

To my extended family (and friends), who have always supported me unconditionally, I thank you for such kind generosity in allowing spare bedrooms, couches, air mattresses and free meals as I spent nomadic summers gathering data, working on my thesis, and stealing away to work. I have learned more from all of you than I can properly verbalize. I want to thank Grandma Jo and Grandpa Mario who would drive to visit Anthony and I every year, regardless of how far we lived, and always with a new Disney movie in tow. To Grandma Josephine, who is among the kindest, most patient, most non-judgmental, brightest, family-oriented, and most self-sacrificing people I have had in my life. And despite all of her amazing (often hidden) talents, she still remains one of the most humble people I have ever known. To Grandpa Mario, who always has the best stories, especially after a few glasses of wine, and who truly was the "stuff of movies." Were some aspiring director wanting to make an Italian-inspired, depression era dark comedy, I'm convinced the Agostini shenanigans would make a suitable mold. I am keeping my last name forever.

I want to thank Grandma Vi, who managed to maintain her sanity after raising five girls, and help with nine grandsons and one (very bull-headed) granddaughter! To Grandpa William for giving me my first set of calipers, and for not yelling at me when I broke his apple tree. I also need to thank all of my aunts, each of which is unique, kind, creative, incredibly generous and brilliant. I have never had to look very far for inspiration.

I thank Tim and Janice Truemper who are my family through and through, who so generously extend their home and their advice, and who are among some of the most incredible people I have known. It would be a lie if I said I did not sometimes regret leaving Veterinary medicine, solely for the purpose that it meant I was affirming a future in which I did not work under Dr. Truemper's brilliant and patient influence. The Truempers came into my life during a time in which I desperately needed variation, kindness and understanding. I feel that their influence helped to motivate and inspire me, and I hope to keep them all as my surrogate family forever.

Because the love of a pet is so often overlooked, I devote a special section for my pets—Shirley, Byrd, and Willoughby—who are the best cat, chinchilla, and fish a single girl could ask for. I appreciate their forgiving natures, especially during periods of long, school-related absences. To MayCee, who climbed the stairs everyday to happily greet us despite having hip dysplasia and severe arthritis. Once one gets past the neurotic tendencies that define all border collies, she truly is the best dog a family could ask for. And to round out the family acknowledgments, I must say a big thank you to Little Blue for not breaking down this summer.

I would not have been able to succeed were it not for the unwavering, generous support of my friends. Thank you to Joe, Jill, Vern, Justin, Carol, Lauren and Glen, my amazingly brilliant friends who have so kindly put up with me for the past eight years and beyond- your tolerance is inspiring. I thank the "coffee crew regulars" who were willing to visit with me en masse every Sunday. We were our own personal Bloomsbury Group, and I loved every debate, argument, neat find and conversation we shared, regardless of the depth or shallowness of topics discussed. In this respect, I should also thank Mike and the crew at the Global Village coffeehouse, as it was not only the source of my daily caffeine, but also the bulk of my productivity. I thank Emily, perhaps the only person with whom I could share a program, an office, two projects, an apartment, and "my feelings" without ending up in a fight. Go and be qualitative! To MedRobin, who always made me stronger and who gave me so many happy and crazy experiences. You taught me how to be confident and (gracefully) push the envelope. I still smile whenever I think of the experiences we have had together. To Thomas for his endless dramatics, and his constant reminders that not only will margarine give me cancer, staying in school is a sure fire way to end up penniless and ignorant. To Georgia, my favorite closet cynic and American-born French best friend. To Ashwynn, who shares my passion for the first, and with whom I hope to work in the future (though that would require us living in the same place). I thank Amanda, Melinda, Tony, Kat, Sarah, Jaime, Stacy, Elizabeth, and the crew at New Hope Animal Hospital who I feel so fortunate to have had in my life. I acknowledge the University of Arkansas for not only making me tough, but also remarkably well adept at standing up for myself.

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his gift for teaching, but in his ability to inspire renewed passion for a project that was so long in duration. I am in awe of his patience and his honesty, his work ethic and his dedication, and I hope to one day possess the level of stamina he has toward his research. I have not forgotten the extra research opportunities he gave to me so many years ago. It was one of the things that helped to drive my passion for this field, and made me determine to excel within it.

Finally, I must especially thank my mentor, Dr. Ross. It was she who first inspired my interest in anthropology and who continued to foster this interest even after I had transferred to another university. I thank her for advising and inspiring me, remaining candidly open, influencing me to have an opinion, including me in casework and forensic opportunities, and for providing me with the very grounded and realistic interpretation of forensic anthropology that I largely credit for my drive to succeed in this field. It was through her that I was first exposed to the “inner workings” of anthropology and academia, and I am exceptionally grateful to have had her guidance these past years. I have never been good at actively verbalizing the extent to which someone has influenced my life. For lack of a better phrase, she is my hero, and was long before I entered the anthropology graduate program at North Carolina State University.

TABLE OF CONTENTS

LISTS OF TABLES

LISTS OF FIGURES

APPENDIX IV

INTRODUCTION

Public health programs place heavy emphasis on obesity, which has increased steadily and rapidly during the last 20 years in all age and sex categories among white, black, and Hispanic people of Mexican origin in the United States (Lai et al., 2008; Flegal et al., 2002). Obesity is also becoming more prevalent in other developed parts of the world (Eckel, 1997) despite the fact that complications associated with it, such as diabetes (Mokdad et al., 2003) and heart disease (Eckel, 1997), are well documented. Currently, two-thirds of individuals in the United States are overweight, and only complications due to smoking cause more deaths than complications associated with obesity (Fontaine and Barofsky, 2001:173). This epidemic prompts many health officials to state that life expectancy is decreasing (Olsanshky et al., 2005). Furthermore, there is no indication that these rates are declining (Hedley et al., 2004). Weight has been a strong area of focus in biomechanics, with research showing correlations between obesity and altered walking gait (Spyropoulos et al., 1991; Wearing et al, 2006), altered sit-to-stand movements (Sibella et al., 1998), reduction in stature (Felix et al., 2005), and altered plantar pressures (Birtane, 2004, Hills, 2001).

Growing attention has been paid to the impact that obesity has on the skeletal system with regard to both increased mechanical load and compensatory behaviors made to cope with this increased load. However, aside from noting correlations between obesity and osteoarthritis (Wearing et al., 2006; Weiss, 2006), little attention has been paid to the observable effect that weight has on the human skeleton. As obesity is increasing in frequency (Flegal et al., 2002), any information which could be discerned from skeletal remains regarding its impact has great promise to aid in forensic investigations and identification efforts, as well as public health issues. Weight assessments made through skeletal material could also benefit archaeological interpretations of both health and culture. This is especially true in analyses of societies with differing or temporally changing levels of social stratification (and presumably, differential access to adequate nutrition), or societies where obesity was known to have been present (and even praised), such as in portions of sub-Saharan Africa (Renzaho, 2004).

The lack of skeletal-based research in obesity is especially troublesome in forensic anthropology. In a system where age, sex, stature and ancestry determinations are the first course of business when analyzing skeletal remains, it seems problematic that such little attention has been paid to a condition that clearly affects the way that a person would have appeared to others in life. Perhaps Kenneth Kennedy (1989:133) said it best in stating "[f]orensic anthropologists, who have the most to gain from a familiarity with markers of occupational stress in their medico-legal pursuits toward personal identification, have produced few published accounts of their case studies and laboratory observations."

Determining whether or not a person was obese is difficult, especially when there is a lack of soft tissue available for analysis. Though research in the area is scant, there have been numerous articles published that do show cross-sectional changes in the diaphyses of long bones correlated to mechanical load (Stock and Shaw, 2007; Drapeau and Streeter, 2005;

Ruff, 2005; Wescott and Cunningham, 2005; Lieberman et al., 2001; Ruff, 2000; Ruff et al., 1994; Trinkaus et al., 1994; Stirland, 1993; Ruff et al., 1991). There are also equations to estimate general body mass using various skeletal criteria (Grine et al., 1995; McHenry, 1992; Ruff et al., 1991): those devised by Ruff appear to be the most reliable (Auerbach, 2004). However, it is worth noting that of the small number of individuals evaluated by Ruff (1991), the formulae were *least* successful in predicting the body mass of a severely overweight individual, suggesting that additional characteristics need to be assessed in order to discern obesity.

Because obese people would likely exhibit characteristics of having carried increased mechanical load (evident via cross-sectional analyses or other remodeling patterns), it is possible that obese individuals could have increased MSM robusticity as a result of having to support and move additional weight mass. However, there is a general assumption of inactivity associated with obesity (Kitagawa and Miyashita, 1978), which may suggest that evidence of muscle use would be less pronounced in the overweight. Although overweight individuals still engage in many habitual activities (e.g., walking, rising from a chair or bed), Turner et al. (1998) have described bone remodeling as specifically related to abnormal stresses, not habitual ones. As such, one aspect of this project focuses on determining whether overweight and obese individuals exemplify increased MSM robusticity as a result of carrying their weight in normal daily functions (i.e., are these functions abnormal enough to elicit a remodeling change), or whether they exemplify little to no MSM robusticity as a result of inactivity.

Because bone remodeling is responsive in large part due to stress and pressure (Turner and Pavalko, 1998), and because obese people compensate for their weight by altering their movements, this study assumes that there will be altered patterns on skeletal material of the overweight as a direct result of long term, abnormal mechanical compensation. If MSMs can be used as a means of distinguishing overweight from normal and underweight individuals, then further research into the remodeling characteristics of bone made by these compensatory and protective behaviors could be more fully investigated.

The goals of this research were two-fold: [1] to test whether there are any statistically significant differences in the diaphyseal morphology of arm and leg bones when analyzed on the basis of weight; and [2] to test the suitability of musculoskeletal stress marker severity for differentiating between overweight, normal weight or underweight individuals (as determined by BMI calculations)

To discern whether there are any differences in the diaphyseal morphology of arm and leg bones when analyzed on the basis of weight (after controlling for age), diaphyseal cross-sectional geometry was chosen to quantitatively evaluate morphology of the diaphysis, an area which has a long recorded history of correlation to mechanical load. Diaphyseal anteroposterior (AP) dimensions and mediolateral (ML) dimensions of both humerii, the left femur and left tibia were evaluated, as well as a ratio of the two.

The second goal involved use of MSMs to qualitatively evaluate whether there are any overall differences in muscle use on the basis of weight, and whether patterns of MSM severity could be a suitable proxy for distinguishing overweight individuals from other weight groups at different stages in life. Patterns of MSM severity were evaluated by age to discern any effect that age might have on MSM expression and subsequent interpretations.

PRINCIPLES OF BONE REMODELING

a. Wolff's Law

The first major attempt to understand the principles governing bone remodeling arose from German anatomist Julius Wolff, who in the late 19th century proposed that the trabecular structures in the proximal femur originated during development to cope with the different types of strain which most impacted it (largely those strains associated with supporting the trunk of the body). In his volume "The law of bone remodeling," Wolff describes three main trabecular systems in the sagittal plane of the proximal femur: [1] a series of linear trabecular struts, commencing at the medial compact bone of the femoral shaft and terminating at the lateral wall of the greater trochanter and the superior femoral head; [2] a second series commencing at the lateral aspect of the proximal femoral shaft and terminating at the medial femoral neck and head; and [3] a final system commencing at the superior-most aspect of the femur between the greater trochanter and the femoral head, with trabecular struts fanning both laterally and medially, tracing the superior contour. The intersection of the first two trabecular systems, he states, are mostly perpendicular, and form an arch-like support structure at the midsection of the proximal femur.

Wolff states that these three systems are consistent through all coronal longitudinal sections, regardless of how anteriorally or posterioally displaced the sectioning cuts were made. Figure 1 is the schematic devised by Wolff. The properties of these systems (i.e., the right-angle intersections and arch-like appearance) were later used by Wolff to create mathematically and engineering based formulae with which to predict bone modeling on the basis of the types of forces experienced by these systems.

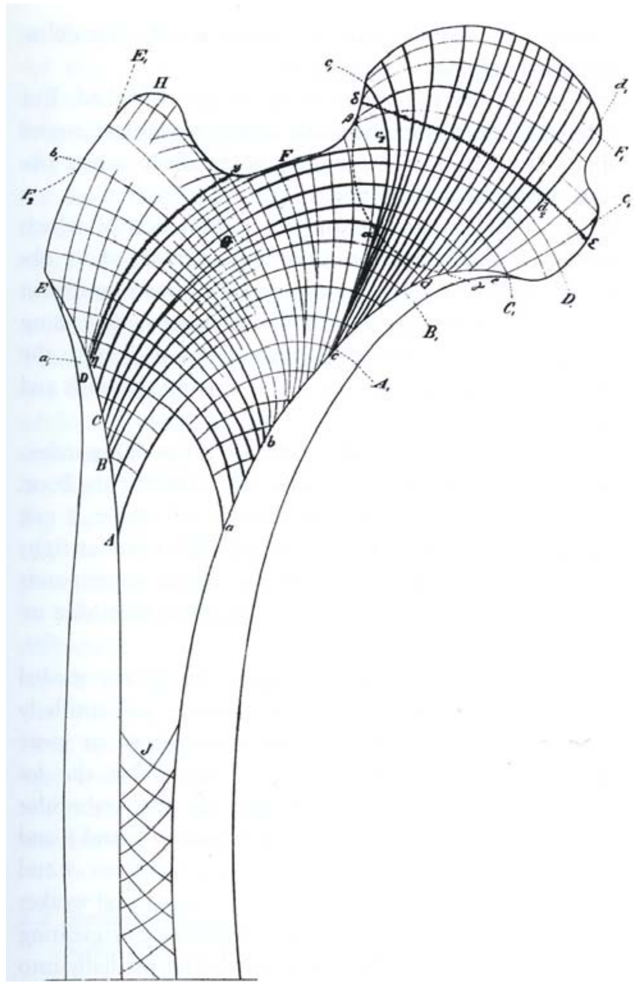

Figure 1. *Orientation of the trabecular structures of the proximal femur (Wolff, 1892).*

Over time, however, there have been many different criticisms of Wolff's law, especially with regard to the mathematic and engineering-based principles used in its formulation.

b. The Evolution of Wolff's Law

One of the main complaints against Wolff's Law is that it does not account for the type of forces impacting bone, i.e., whether bone responds in different ways to habitual stresses versus abnormal ones. Carter (1984) hypothesized that abnormal forces most greatly impact bone remodeling, and that the slow accumulation of bone microdamage actually stimulates remodeling to occur in a "site specific" fashion. Turner and Pavalko (1998) agree that bone remodeling is error driven, responding more rapidly to abnormal pressures, but Turner (1998) but does not attribute remodeling to microdamage. Relying heavily on studies using live animals, he states that remodeling follows three main rules, all of which are governed by abnormal stresses: [1] remodeling is affected by dynamic loads; [2] it begins very quickly after a mechanical stimulus; and [3] it eventually stabilizes itself, becoming "less responsive to routine loading signals" (Carter, 1984:399). He also states that loading frequency has as much of an impact on triggering the remodeling process as does the type of strain.

Turner's (1998) three rules appear to be in line with the hypotheses of Carter (1984:S20), who states "there exists…a physiologic 'band' of activity wherein bone tissue is fairly unresponsive to changes in loading history," meaning bone remodels less actively when faced with slight deviations of habitual activity. However, he does go on to state that "changes in bone mass are affected with increasing intensity as the bone strain history deviates further from the center of the physiologic band," again illustrating the increasingly strong response of bone remodeling to intensifying *abnormal* stresses, which could include a very high mechanical load, or an altered biomechanical movement coupled with a high mechanical load.

Another critique of Wolff's Law relates to interpretation, and some believe that the term is taken far too specifically, actually evolving away from its original meaning to encompass an entire realm of bone remodeling principles. Pearson and Leiberman (2004:65) provide a concrete explanation of this phenomenon, stating:

> "Although Wolff's law is frequently invoked, it is neither a law, nor completely true. [T]he concept has grown into a more general, organizing principle that seeks to provide a means for understanding the gross shapes and adaptations of bones. It is now common to use Wolff's "law" as a catch-all concept to denote the adaptation of bone to mechanical stimuli. In this more generalized role, the "law" has evolved into a black-box axiom of functional morphology to relate skeletal form and function. However, the many flaws and exceptions to Wolff's "law" have rendered the term somewhat useless."

Ruff et al. (2006) also address this issue, but do not feel that the claims made by Wolff were entirely false. Rather, they state that much of the criticism behind the law pertains to confusion regarding whether to use a strict or a general interpretation of it. They state that it is now common knowledge that the mathematic principles driving Wolff's conclusion were not accurate, so it is not logical to adopt a strict interpretation of his work. Rather, they advocate using the phrase "bone functional adaptation (BFA)" to refer to a general, remodeling-focused interpretation of Wolff's Law which avoids the incorrect assumptions encountered in strict interpretations.

c. Research in Bone Functional Adaptation

While it is generally acknowledged that BFA does occur, there is still much argument regarding the specific mechanisms that are in place to accommodate this process. Some researchers feel that cells within the bone matrix can register pressure and communicate via a "connected cellular network (CCN)" to trigger a localized remodeling response (Pearson and Lieberman, 2004:68). Others feel that continual microtrauma at specific sites of stress trigger remodeling (Carter, 1984). And others feel that bone only remodels as a result of non-habitual stresses (Carter, 1984; Turner and Pavalko, 1998), though there is still much argument regarding how soon after an abnormal force occurs that bone will begin to remodel, as well as what constitutes an "abnormal" pressure. Studies using live animals have provided differing results on the matter (Zumwalt, 1998), though they generally support Turner and Pavalko (1998). For example, research using roosters and mice supports the hypothesis that bone responds more strongly to abnormal stresses, and that there is a point (or threshold) at which bone remodeling ceases (Umemura, 1997; Rubin and Lanyon, 1985).

Threshold principles seem logical if one believes that the goal of BFA is to strengthen bone against specific abnormal stresses (thereby preventing fracture). Given this, there would eventually be a point (or threshold) at which BFA has resulted in a perfectly designed morphology that meets the highest level of function for the specific force enacted upon it. At this point, BFA has resulted in a bone shape which has transformed "abnormal" stresses into "habitual" ones. If BFA does work in this manner, then it would seem probable that the forces associated with the long-term mechanical compensations of obese people would be reflected in the adult long bone morphology.

LITERATURE REVIEW

a. Musculoskeletal Stress Markers

Musculoskeletal stress markers are areas of roughness found at muscle, ligament, or tendon insertion sites on long bones (Weiss 2002). According to Hawkey and Merbs (1995), when muscles are regularly exercised in a repetitive manner, blood flow to these attachment sites increases, triggering osteon development and bone remodeling. Drapeau and Streeter (2005) state that "[t]here is accumulating evidence that some remodeling targets damaged bone, more specifically microcracks resulting from accumulated mechanical stress" (Drapeau and Streeter, 2005:404) which supports Hawkey and Merb's (1995) assertion. However, Lanyon (1984:S57) states that it is actually repetitive strain that triggers the remodeling process, and not "tissue damage or increased profusion." This is further corroborated by Turner et al. (1998), who suggest that the strain of bone under daily activity strains dormant osteocytes as well, which in turn signal osteoclast and osteoblast activity directly to the area of attachment. Regardless of the mechanisms behind bone remodeling, the result is a robust, thickened projection of bone that, due to its varying severity of expression, has been used in the past as a direct indication of specific muscle use (Rodrigues, 2005; Chapman, 1997; Hawkey and Merbs, 1995; Hawkey, 1988).

MSMs have chiefly served as a way to interpret different habitual activities in archaeological populations. Hawkey (1988) devised a classification system to be used with MSMs in which there are four categories based on increasing robusticity: O- Absent, R1-

Faint, R2- Moderate, and R3- Strong. Similar classifications were also used to score stress lesions and *ossific extosis* at insertion sites.

In her pioneering standardization research project using these MSM severity scores, Hawkey (1988) evaluated prehistoric populations of Thule Eskimo and Gran Quivira Pueblo. She found that MSM severity between left and right humerii were strongly correlated to modern rates of handedness, MSM severity was greater on the side of the jaw opposite the most severe dental pathology (likely due to avoidance of chewing on the affected side), and that attachment sites of specific muscles could be used to indicate culture-specific activities (such as holding animal hides during manufacture, wrestling, or harpooning). This same scoring system was used by Hawkey and Merbs (1995), who were able to conclude that the use of different muscle groups over time could indicate changes in activity patterns among Hudson Bay Eskimos as well as provide insight into the differing tasks associated with division of labor.

Use of MSMs to discern small and large scale cultural trends is commonplace. Lai and Lovell (1992) used MSMs to gain insight into the activities of three Native American admixed individuals recovered at a trade post site in Alberta, Canada. In this study, MSM severity scores were combined with other indicators of lifelong habitual stress, including Schmorl's nodes, osteoarthritis, and accessory facet locations and frequencies. It was concluded that all three individuals engaged in activities that heavily-loaded the spinal column and all major upper and lower joint areas. MSM evaluation showed highly robust enthesial development at locations associated with shoulder and elbow musculature, consistent with a life of boat paddling and navigation, and heavy lifting. Chapman (1997) combined MSM robusticity analyses to activities associated with Spanish-favored goods to discern whether activity patterns in a Pueble population changed as a result of Spanish influence. Specific MSM locations for a pre-contact population were compared to a post-contact population, indicating changes in muscle use between these two time periods that were generally consistent with known maize and log processing techniques.

MSMs have also been used to evaluate changes in subsistence strategy. Eshed et al. (2003) used Hawkey's (1988) scoring system to study muscle use differences of the arms between Natufian hunter-gatherers and Neolithic agriculturalists on the basis of sex. It was discovered that while both populations exhibited similar patterns of muscle use between the sexes, the MSM expression of the agriculturalists was much more pronounced, suggesting heavier physical demands with this lifestyle. It was found that women tended to have greater MSM expression for muscles associated with the distal arms, such as might be required for "more delicate and precise movements of the hand" (Eshed et al., 2003:312), and that agriculturalist women exhibited evidence of grain processing as well. Males also showed increased mean MSM score in the shift to agriculturalism. However, increased physical demand with the shift to agriculturalism is not supported in all subsistence-based MSM analyses (Larsen, 1995).

Use of MSMs to make inferences about non-activity behaviors has also been undertaken by Hawkey (1998), who combined MSMs, muscle attachment lesion studies and joint erosion analyses to make inferences into a Pueblo man's failing mobility. Her assertion is that this individual could not have continued to thrive had it not been for the aid (or compassion) of other members of his group.

As MSMs are the direct result of bone remodeling at a site of stress, it is important to recognize that it is muscle *use* that may result in increased MSM robusticity. Therefore, it is possible that those attachment sites of muscles that are not routinely used will not be robust. In fact, research by Burr (1997) found that muscle disuse leads to rapid loss of bone mass much faster than muscle use leads to an increase in bone mass. Burr (1997:1547) also states that the "forces applied to bone are primarily the result of muscular contraction" and "muscle forces place greater loads on bones than do gravitational forces associated with weight."

b. Diaphyseal Cross-Sectional Geometry

As previously stated, the main purpose in assessing MSMs in this project is so that research conducted using properties of bone cross-section can be applied as a mechanism for obesity determination. Many studies have been performed which correlate differences in cross-sectional geometry to differences in physical activity (Sladek et al., 2006; Brock and Ruff, 2005; Ruff, 2005; Stock and Pfieffer, 2001; Mays, 1999; Jantz and Ousley, 1984; Ruff et al., 1984; Ruff and Hayes, 1983).

While physical activity should not be discarded from these analyses, research has also found strong correlations between current body mass and cross-sectional geometry. When studying the impact of mass on cortical area, Ruff et al. (1991:407) state that their research "indicates that cortical area 'tracks' body weight more closely [than articular surfaces]: relatively heavy or light subjects do have relatively thicker or thinner cortices, respectively."

In research which focused on the structural changes of long bones over the course of evolutionary history, Ruff (2005) found that long bone strength has decreased over time, especially recently. He also states that this change is likely the result of activity reductions due to increased reliance upon technology. Similar findings were also made by Holt (2003) who evaluated the cross-sectional properties of the femur and tibia of Eurpoean males and females across three temporal periods: the Early and Late Paleolithic and Mesolithic eras. Holt discovered that the midshaft region of the femur in the latter two time periods was more circular, suggesting decreased mobility through time, consistent with environmental change.

Recent research presented by Wescott (2006a:7) using femoral midshaft cross-sectional geometry has found that:

> "Femur midshaft shape (FMS) has increased significantly through time, especially in females, due to a decrease in the midshaft mediolateral diameter (MLM) rather than an increase in anteroposterior diameter (APM) (Rockhold 1998, Wescott, 2001). If FMS truly reflects differences in mobility, then these results are difficult to explain. Because of modern transportation, one would expect the femoral midshafts of modern Americans to become more circular through time as a result of decreased a-p bending strength. Since this is not the case, researchers should use caution when using femur shape, at least when it is derived from external measurements, to interpret mobility patterns"

In this same study, researchers compared the cross-sectional geometry of nine prehistoric and historic populations with differing activity levels and found that "inferred mobility levels do not correspond consistently with femur midshaft structure in either males or females" (Wescott, 2006a:1). This suggests that there are other underlying factors which prompt changes in cross-sectional geometry aside from activity patterns or alterations caused by terrain complexities.

Research on secular changes of the femora of American black and white males and females in the Terry collection found no significant anteroposterior elongation of the femur at midshaft (Rockhold, 1998). However, there was a significant reduction of the mediolateral dimension which resulted in a decreased femoral circumference. Results also showed an overall decrease in robusticity across all groups, and that there were secular similarities between black and white females, and between black and white males. Rockhold also states that the mediolateral reduction could be associated with mechanical load, and that these findings could be due to lifestyle differences in the 1900s. However, she was not able to discern why this trend did not carry into the anteroposterior dimension.

MATERIALS AND METHODS

I. Sample Information

Because bone density (and presumably, cross-sectional geometry) is known to be influenced by many factors, including age, sex, pathology, pregnancy, nutritional deficiencies, genetics, and activity level (Stodder, 2008), it was necessary to restrict the sample to avoid as many of these biases as possible (Weiss, 2003). Therefore, only males of European ancestry were examined as they were best represented in the skeletal collections utilized, allowing for large samples from which to draw data. Additionally, studies of secular trends show that males of European ancestry display the most significant changes in long bone shape and size over time, which “may reflect [greater] sensitivity to environmental changes” (Jantz and Jantz, 1999:65). Skeletons displaying any type of pathology beyond knee or hip osteoarthritis were not included in this analysis, and each BMI category contained equal numbers of individuals, with equal age distributions. The Hamann-Todd collection was selected due to the large number of individuals represented for which both weight and stature were recorded, allowing calculation of BMI.

The Hamann-Todd collection is currently housed at the Cleveland Museum of Natural History in Cleveland, Ohio. According to Quigley (2001), the collection dates from 1912 to 1938 and is composed of unclaimed individuals from city morgues and hospitals around the Cleveland area. Each decedent in the collection is well-documented, often with photographs, medical information and descriptions available, as well as a full biological profile.

There are 3309 skeletons in this collection for which weights are recorded. Of these, 2702 individuals are male and 1997 are of European ancestry. Body Mass Index (BMI) was calculated using a standard equation provided by the Center for Disease Control: BMI= Weight in kg / (Height in m)^2 (http://www.cdc.gov/nccdphp/dnpa/bmi/index.htm). In this collection, there are 1371 individuals whose BMI classification is less than 18.5 (underweight), 1672 individuals whose BMI classification is between 18.5 and 24.9 (normal weight), 237 individuals who have a BMI between 25 and 29.9 (overweight), and only 39 individuals who have a BMI that exceeds 30 (obese).

To maintain sample sizes large enough for statistical analysis, the obese and overweight categories were combined. Because BMI scores occur on a continuous scale, and because of questions regarding the validity of BMI for use in determination of fitness, individuals given either the highest and lowest BMI scores of each classification were not used in this study to ensure that sample groups were as distinct as possible. Therefore, the designation “overweight” was used for any individual with a calculated BMI greater than or equal to 26.5. Individuals with a BMI between 19.5 and 24.5 were classified as “normal weight.” The “underweight” classification was used for any individual with a calculated BMI less than 17.5. All three BMI categories were age-matched to within one year, resulting in samples containing similar age distribution so that the effect of age on diaphyseal morphology and MSM severity could also be assessed. The above restrictions, coupled with the inability to measure some individual specimens due to degradation or absence, reduced the overall sample size to 184 individuals, 67 of whom were overweight, 59 normal weight, and 58 underweight. See Table 8.1 in the Appendix I for a complete inventory of all individuals utilized for this study.

II. General Methods

To avoid any morphological differences which might be related to handedness (Wescott, 2006), both the left and right humeri were used to analyze non-weight bearing bones. Because similar complications of bilateral asymmetry are not present in the legs (Ruff and Jones, 1981), only the left femur and left tibia were chosen to represent weight bearing bones. Standard maximum length measurements were taken for all bones using previously established guidelines (Moore-Jansen et al., 1994). Only external cross-sectional measurements were taken for this project. Although past analysis of cross-sectional properties required invasive sectioning of the bone, research has shown a high correlation between external diaphyseal geometry and results obtained through invasive sectioning (Wescott 2006; Pearson 2000; Rockhold 1998). Anteroposterior (AP) and mediolateral (ML) cross-sectional measurements were taken using Mitutuyo digital sliding calipers at regular intervals of bone shaft length established by Ruff (1981): 20%, 35%, 50%, 65% and 80%, measuring proximally from the distal-most point (such that 20% of the diaphyseal length is the distal-most measurement taken). A six inch triangle ruler was used on an osteometric board to mark the above locations on the diaphysis to reduce any observer error that might arise from differences in anterior diaphyseal bending between bones of different individuals. The calipers were equipped with a small, triangular level to ensure proper AP or ML alignment, thereby reducing error due to fluctuations in the angle of the calipers. All measurements were entered automatically into Microsoft Excel where the AP/ML ratio was calculated.

III. Cross Sectional Methods

a. Humerus

The orientation of the humerus and determination of cross-sectional locations was accomplished using guidelines outlined by Rhodes and Knusel (2005:538) who state:

> "the humeri were marked at a point perpendicular to the long axis at 20%, 35%, 50%, 65%, and 80% of the maximum humeral length. This was taken as a point measured previously from the inferior margin of the medial trochlear crest to the superiormost point on the humeral head, with 20% reflecting the most distal slice and 80% being the most proximal. The humeri were oriented on the gantry table in a standardized anteroposterior position, parallel to the longitudinal axis of the positioning beam. This beam was oriented such that it bisected the humerus into equal medial and lateral halves, as determined by the proximal and distal articular surfaces."

The humerus was oriented onto of the osteometric board so that the long axis of the diaphysis was parallel to the board surface. In order to ensure replicable measures between humeri, the bone was also oriented such that when observing the distal surface, the lateral-most and medial-most points were oriented parallel to the surface of the osteometric board as well.

Plasticine clay was used to prop both medial and distal ends, ensuring proper alignment and steadying the bone while measurements were taken.

Once the humerus was properly positioned, the length of the bone was measured and marked at 20%, 35%, 50%, 65%, and 80% of the total length, when measuring from the distal end. Percentages of the total length were used as they were sufficient to avoid the complexities of the distal-most and proximal-most ends, and because they were not based on variable morphological characteristics (as would have would have been the case if trying to discern only bone shaft length), thus making them more replicable from humerus to humerus.

b. Femur

The femur was positioned according to Ruff (1983) directly onto the osteometric board on the dorsal surface, with the posterior aspects of both condyles resting on the surface of the board, and the distal-most aspect of the medial condyle making contact with the stationary arm. The long axis of the diaphysis was aligned to be as perpendicular to the arm of the osteometric board as possible. The area just distal to the attachment of the lesser trochanter and the area immediately proximal to the attachment of the femoral condyles were marked on the medial aspect of the diaphysis. Using plasticine clay, the proximal aspect of the femur was raised until such point that the two marked locations on the diaphysis were parallel to the surface of the osteometric board.

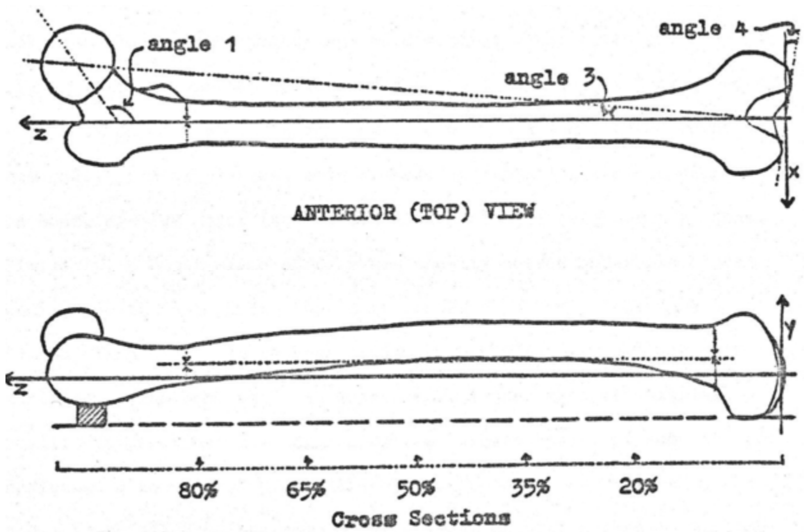

Figure 2: *Proper orientation of the femur (Ruff, 1983)*

For the determination of diaphyseal length, Ruff required that a portion of the distal and the proximal ends be disregarded. In the interest of truly reproducible measures, an alternate method of determining length was devised in order to reduce operator error. For the purpose of this project, the bone shaft was determined to run from the distal-most point of the femur to the site at which the femoral neck contacts the greater trochanter. Because length does not include the femoral head and neck, the 20% and 80% cross-sectional locations avoided the complexities of the proximal-most and distal-most ends, and the remaining cross-sectional measures maintained good coverage of the femoral diaphysis.

c. Tibia

Maximum length was recorded, as well as the length measured from the center of the talar facet to between the proximal epicondyles using spreading calipers. The latter measurement was used to establish the locations of the percentages at which cross-sectional measurements were taken.

The tibia was oriented according to Ruff (1981) such that the anterior-most margins of the superior articular facets were in the same plane (Ruff and Hayes, 1983). For this project, the superior-most point of the medial epicondyle and the laterodistal-most point of the medial malleolus were used as reference points in the determination of the axis. Using plasticine clay, the bone was oriented such that the medial epicondyle reference point and the medial malleolus reference point were in the same plane, all the while ensuring that the anterior margins of the articular facets were still parallel to the surface of the osteometric board. Additional clay was used to secure the tibia in this position while the AP and ML measurements were taken.

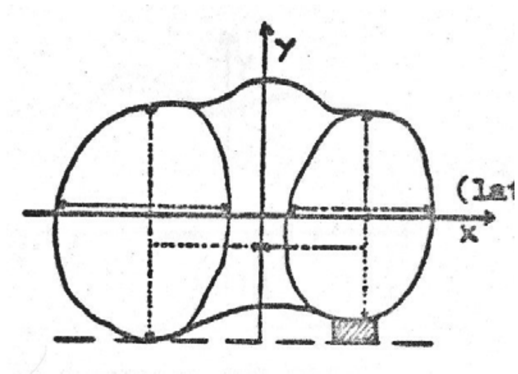

Figure 3: *Proximal orientation of the tibia (Ruff, 1983)*

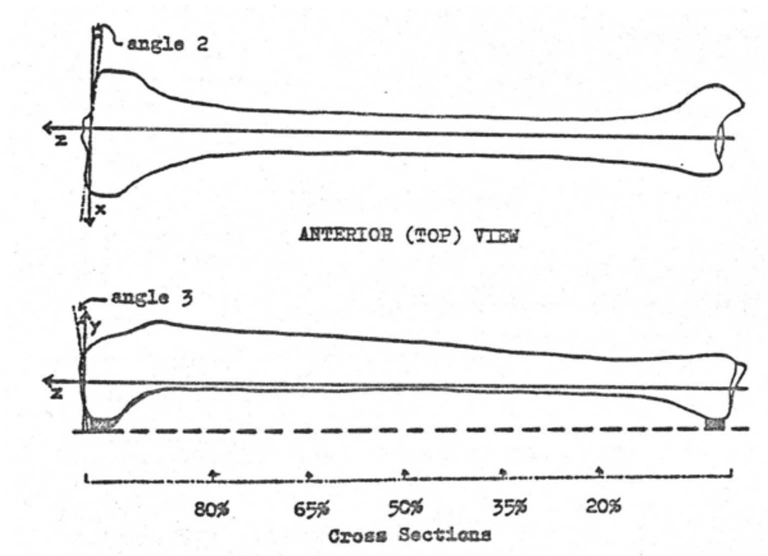

Figure 4: *Proper orientation of the tibia (Ruff, 1983)*

IV. <u>Musculoskeletal Stress Marker Methods</u>

Fifteen total MSMs for four bones were evaluated (Table 4.1). Standardization criteria established by Mariotti et al. (2006, 2007) was used to score thirteen of these: three for the femur, two for the tibia, and four for each humerus. According to these criteria, each site was given one of five scores based on the severity of expression: 1A, 1B, 1C, 2, and 3, with 3 being the most severe. Upon recommendation of the researchers, these five scores were compiled into three, with 1A, 1B and 1C being combined into a score of 1. Scores were also recorded for two additional sites of the femur, the linea aspera, and the intertrochanteric line. MSM severity scores were used to run statistical analyses. For photographs which demonstrate some MSM scores used, please refer to Appendix IV.

TABLE 4.1. MSM features used and muscles analyzed.

Bone	Muscle	Muscle Action	Corresponding Feature
Humerus	*M. latissimus dorsi major teres major*	Medial rotation of arm	Medial bicipital groove
	M. pectoralis major	Flexion, adduction, medial rotation of arm	Lateral bicipital groove
	M. deltoideus	Abduction of arm	Deltoid tubercle
	M. brachioradialis	Rotation of forearm	Distolateral aspect
Femur	*G. maximus*	Extension and lateral rotation of thigh, adduction of hip joint, flexion of trunk	Gluteal line
	M. vastus medialis	Extension of knee	Spiral line
	M. vastus	Adduction of Hip	Linea aspera
	Iliofemoral Ligament	Stabilization of Hip Joint	Intertrochanteric line
	M. iliopsoas	Flexion of thigh	Lesser trochanter
Tibia	Quadruceps tendon	Extension of leg at knee	Tibial tuberosity
	M. soleus	Flexion of ankle	Soleal line

Definition of muscle actions taken from White (2000) and Bowden & Bowden (2002)

a. Humerus

Table 4.2. Summary of humeral MSM sites, scores and descriptions

Feature	Muscles	Score	Description
Med. Bicipital Groove	*M. latissimus dorsi major teres major*	1 2 3	Lesser tubercle is smooth or has mild irregularity Lesser tubercle has raised crest, sulcus may be present Lesser tubercle has prominent crest, rough surface
Lat. Bicipital Groove	*M. pectoralis major*	1 2 3	Greater tubercle is smooth or has mild irregularity Greater tubercle has raised crest with marked rugosity Greater tubercle has prominent crest, oblong fossa
Deltoid Tubercle	*M. deltoideus*	1 2 3	Deltoid attachment is smooth, or only slightly raised Attachment is raised and can alter the diaphseal profile Prominent cresting present, diaphyseal profile altered
Distolateral Aspect	*M. brachioradialis*	1 2 3	Area is smooth, or has an “inverted ‘v’” or “lipping” Area displays a noticeable crest Area displays prominent, almost “sail-like” crest

Scores and descriptions adapted from Mariotti et al., 2007

b. Femur

Table 4.3. Summary of femoral MSM sites, scores and descriptions

Feature	Muscles	Score	Description
Gluteal Line	*Gluteus maximus*	1 2 3	Attachment is smooth or just slightly roughened Attachment is raised with pronounced roughness Attachment displays crest, fossa may be present
Spiral Line	*M. vastus medialis*	1 2 3	Unraised line present (continuous or discontinuous) Line clearly raised Line displays ridging or cresting
Lesser Trochanter (LT)	*M. iliopsoas*	1 2 3	LT has low, rounded margins, may display striations "Sharply angled" medial margin, may show rugosity Marked "lipping" of medial margin, flattened profile
Intertrochan-teric Crest	Iliofemoral ligament	1 2 3	Attachment is smooth or slightly irregular, not raised Attachment is rough, may have slight cresting Attachment is prominently raised, often has cresting
Linea Aspera	*M. vastus*	1 2 3	Area is smooth, or displays slight (< 1mm) raising Area is clearly raised, but has smooth margins Area is very raised, irregular margins, rough surface

Scores and descriptions for gluteal line, spiral line and LT adapted from Mariotti et al., 2007

c. Tibia

Table 4.4. Summary of tibial MSM sites, scores and descriptions

Feature	Muscles	Score	Description
Soleal Line	*M. soleus*	1 2 3	Attachment is smooth or slightly roughened Rough line with continuous or discontinuous crest Raised line with prominent crest, may be fossa
Tibial Tuberosity	Quadriceps tendon	1 2 3	Smooth surface, shallow groove may be present Crest present at "proximal end of inferior" tuberosity Prominent crest that runs across the tuberosity

Scores and descriptions adapted from Mariotti et al., 2007

V. Statistical Analysis

A Pearson's Product-Moment Correlation Coefficient test was conducted to discern whether weight, stature, maximum bone length, and diaphyseal cross-sectional geometry were correlated. A multivariate analysis of variance (MANOVA) was performed to test whether age and BMI had a significant effect on diaphyseal cross-sectional geometry. A separate MANOVA was performed to test whether age or BMI had a significant effect on the severity of MSM expression. Statistical analyses were performed using Statistical Analysis Software (SAS), Version 9.4.1.

RESULTS

I. <u>Overall Population Means</u>

The diaphyseal dimension means and ranges by BMI classification are presented in Tables 5.1 – 5.3 and Figures 9 - 20 (See Appendix II).

a. Diaphyseal Dimension Means by Weight

Table 5.1. *Mean AP dimension (mm) by BMI classification*

Cross-Section	Overweight		Normal Weight		Underweight	
	Mean	**Range**	**Mean**	**Range**	**Mean**	**Range**
Right Humerus						
20%	19.66	16.00 - 18.65	18.92	16.00 - 23.12	19.19	16.46 - 23.68
35%	22.08	17.43 - 20.86	21.37	17.43 - 24.12	21.40	18.56 - 25.50
50%	23.31	19.00 - 22.29	22.79	19.85 - 26.79	22.74	19.00 - 24.40
65%	24.30	19.30 - 23.40	23.50	19.80 - 27.70	23.90	19.90 - 30.40
80%	24.92	17.54 - 23.87	24.19	19.74 - 27.37	24.52	20.19 - 30.29
Left Humerus						
20%	19.80	15.84 - 24.86	19.36	15.94 - 22.82	19.28	16.39 - 23.40
35%	21.96	18.49 - 25.71	21.51	17.48 - 24.18	21.42	18.35 - 25.10
50%	22.55	18.58 - 27.44	22.21	19.55 - 26.53	22.12	17.98 - 26.93
65%	23.39	18.45 - 28.96	23.16	19.12 - 27.12	23.38	18.82 - 28.80
80%	24.12	19.23 - 29.22	23.75	18.43 - 27.11	23.87	19.26 - 26.74
Left Femur						
20%	33.16	27.03 - 37.40	32.65	27.46 - 37.45	32.53	25.77 - 39.61
35%	29.86	25.18 - 34.08	29.56	24.42 - 34.35	29.68	24.39 - 35.32
50%	29.36	23.46 - 33.65	28.66	23.64 - 34.67	28.92	22.95 - 34.01
65%	29.15	23.91 - 35.09	28.46	23.67 - 35.41	28.56	22.70 - 32.87
80%	29.74	23.59 - 36.25	28.89	23.89 - 35.61	29.22	23.80 - 34.44
Left Tibia						
20%	23.89	20.42 - 37.45	23.93	20.09 - 27.94	23.57	19.60 - 27.45
35%	24.28	20.20 - 34.35	24.11	19.89 - 29.07	23.89	20.30 - 30.17
50%	28.39	23.35 - 34.67	28.26	23.14 - 33.64	27.88	24.35 - 34.82
65%	33.07	26.92 - 39.74	32.45	27.02 - 38.89	32.21	27.97 - 38.13
80%	39.47	33.63 - 44.36	39.15	31.44 - 47.62	38.75	31.51 - 44.89

Table 5.2. *Mean ML dimension (mm) by BMI classification*

Cross-Section	Overweight		Normal Weight		Underweight	
	Mean	**Range**	**Mean**	**Range**	**Mean**	**Range**
Right Humerus						
20%	27.88	19.89 - 35.38	26.76	20.82 - 33.05	26.83	21.19 - 33.41
35%	20.66	16.76 - 24.91	20.06	16.93 - 24.47	20.12	17.03 - 24.57
50%	22.57	16.74 - 26.95	21.70	18.34 - 26.25	21.95	18.33 - 27.69
65%	23.10	18.58 - 28.14	22.12	18.63 - 26.57	22.45	18.73 - 28.97
80%	25.27	19.98 - 32.82	23.85	19.83 - 28.21	24.26	20.01 - 30.67
Left Humerus						
20%	26.90	20.19 - 34.85	26.36	21.42 - 34.33	26.49	22.16 - 32.89
35%	19.86	16.20 - 22.90	19.63	16.88 - 24.27	19.46	16.92 - 23.73
50%	21.73	16.46 - 26.74	21.20	17.67 - 26.82	21.34	17.79 - 25.54
65%	22.18	16.79 - 27.07	21.43	18.61 - 25.23	21.56	18.41 - 27.76
80%	24.54	19.23 - 32.67	23.25	19.35 - 28.28	23.80	19.57 - 29.34
Left Femur						
20%	41.20	32.95 - 50.89	39.75	33.76 - 48.53	40.13	28.91 - 50.39
35%	32.19	26.48 - 37.61	30.77	26.93 - 37.26	31.02	24.65 - 36.63
50%	30.03	25.24 - 35.88	28.97	25.40 - 33.18	28.67	23.65 - 32.79
65%	31.12	26.33 - 36.89	30.09	26.37 - 33.90	29.55	23.33 - 34.91
80%	32.96	28.57 - 38.51	31.88	27.91 - 36.13	31.54	27.16 - 34.96
Left Tibia						
20%	25.32	19.65 - 29.10	25.36	22.22 - 29.10	24.86	19.65 - 31.54
35%	23.27	18.71 - 26.67	23.25	19.92 - 28.53	22.57	16.93 - 26.85
50%	23.89	19.14 - 28.01	23.9	19.84 - 29.89	23.26	17.06 - 27.44
65%	25.90	20.78 - 31.58	25.52	22.06 - 33.27	25.20	17.94 - 30.96
80%	32.64	25.25 - 39.07	32.40	27.77 - 41.49	32.03	21.36 - 42.39

Table 5.3. *Mean AP/ML ratio by BMI classification*

Cross-Section	Overweight		Normal Weight		Underweight	
	Mean	**Range**	**Mean**	**Range**	**Mean**	**Range**
Right Humerus						
20%	0.71	0.57 - 0.96	0.71	0.57 - 0.90	0.72	0.57 - 0.86
35%	1.07	0.90 - 1.36	1.07	0.89 - 1.21	1.07	0.86 - 1.17
50%	1.04	0.89 - 1.25	1.05	0.90 - 1.21	1.04	0.92 - 1.17
65%	1.05	0.91 - 1.27	1.06	0.95 - 1.23	1.07	0.92 - 1.24
80%	0.99	0.73 - 1.18	1.02	0.86 - 1.19	1.01	0.89 - 1.19
Left Humerus						
20%	0.74	0.56 - 1.03	0.74	0.54 - 0.91	0.73	0.59 - 0.92
35%	1.11	0.98 - 1.33	1.1	0.89 - 1.22	1.1	0.99 - 1.23
50%	1.04	0.86 - 1.19	1.05	0.91 - 1.22	1.04	0.87 - 1.25
65%	1.06	0.82 - 1.25	1.08	0.94 - 1.30	1.09	0.93 - 1.27
80%	0.98	0.84 - 1.14	1.02	0.83 - 1.17	1.01	0.81 - 1.18
Left Femur						
20%	0.81	0.71 - 0.99	0.82	0.71 - 0.97	0.81	0.70 - 1.01
35%	0.93	0.83 - 1.09	0.96	0.83 - 1.19	0.96	0.81 - 1.18
50%	0.98	0.77 - 1.17	0.99	0.83 - 1.22	1.01	0.85 - 1.22
65%	0.94	0.75 - 1.14	0.95	0.78 - 1.20	0.97	0.79 - 1.24
80%	0.90	0.71 - 1.11	0.91	0.69 - 1.14	0.93	0.76 - 1.05
Left Tibia						
20%	0.95	0.83 - 1.12	0.94	0.77 - 1.14	0.95	0.86 - 1.09
35%	1.05	0.80 - 1.31	1.02	0.81 - 1.21	1.06	0.90 - 1.35
50%	1.20	0.87 - 1.48	1.19	0.92 - 1.44	1.21	1.01 - 1.60
65%	1.29	1.00 - 1.55	1.28	1.19 - 1.51	1.29	1.07 - 1.72
80%	1.22	1.00 - 1.43	1.22	1.19 - 1.47	1.22	1.02 - 1.73

b. Diaphyseal Dimension Means by Age

The diaphyseal dimension means and ranges by age classification are presented in Tables 5.4 – 5.6 and Figures 21 - 32 (See Appendix II).

Table 5.4. *Mean AP dimension (mm) by age classification*

Cross-Section	Young (20-40 yrs)		Middle (41-60 yrs)		Old (61+ yrs)	
	Mean	Range	Mean	Range	Mean	Range
Right Humerus						
20%	19.35	16.69 - 23.68	19.23	16.00 - 23.54	19.35	16.46 - 22.61
35%	21.39	18.56 - 26.35	21.55	17.43 - 24.93	22.18	19.42 - 25.72
50%	22.42	19.00 - 27.81	22.81	19.27 - 27.86	23.96	20.86 - 28.28
65%	23.30	19.75 - 30.37	23.80	19.30 - 29.39	24.90	19.88 - 29.92
80%	24.02	19.20 - 30.29	24.44	17.54 - 29.57	25.52	21.19 - 29.03
Left Humerus						
20%	18.92	15.84 - 23.40	19.59	16.44 - 24.86	19.90	15.94 - 23.28
35%	21.33	18.35 - 25.10	21.58	17.48 - 24.93	22.15	19.36 - 25.71
50%	21.88	17.98 - 26.93	22.26	18.58 - 26.29	22.91	19.95 - 27.44
65%	22.90	18.82 - 28.80	23.20	18.45 - 28.09	24.10	20.14 - 28.96
80%	23.48	18.43 - 27.17	23.84	19.23 - 29.22	24.64	19.93 - 28.62
Left Femur						
20%	31.97	25.77 - 38.13	33.05	27.03 - 39.61	33.05	29.09 - 37.37
35%	29.09	24.39 - 35.32	29.86	24.42 - 35.27	30.03	27.40 - 33.84
50%	28.27	22.95 - 33.33	29.10	23.46 - 34.01	29.50	25.72 - 34.67
65%	28.00	22.70 - 32.38	28.80	23.67 - 32.95	29.40	25.09 - 35.41
80%	28.56	23.59 - 33.53	29.39	23.89 - 36.25	30.16	25.82 - 35.61
Left Tibia						
20%	23.34	19.60 - 27.35	23.91	20.03 - 28.30	24.02	20.89 - 27.94
35%	23.74	20.20 - 29.07	24.25	19.89 - 30.17	24.12	21.29 - 27.41
50%	27.75	23.35 - 33.64	28.35	23.14 - 34.82	28.22	24.95 - 32.17
65%	32.11	26.92 - 38.89	32.81	27.02 - 39.74	32.61	28.95 - 37.64
80%	38.17	31.51 - 45.74	39.29	31.44 - 44.89	39.85	33.63 - 47.62

Table 5.5. *Mean ML dimension (mm) by age classification*

Cross-Section	Young (20-40 yrs)		Middle (41-60 yrs)		Old (61+ yrs)	
	Mean	Range	Mean	Range	Mean	Range
Right Humerus						
20%	26.54	19.89 - 31.79	27.19	20.82 - 35.38	27.96	22.31 - 33.05
35%	19.82	16.76 - 23.48	20.31	16.79 - 24.57	20.80	18.02 - 24.91
50%	21.64	16.74 - 25.70	22.07	18.33 - 27.69	22.69	19.45 - 26.25
65%	22.18	18.58 - 28.97	22.60	18.63 - 27.43	23.03	19.83 - 28.14
80%	24.15	20.01 - 30.67	24.48	19.83 - 32.82	25.01	21.47 - 30.03
Left Humerus						
20%	26.26	21.52 - 33.91	26.41	20.19 - 32.37	27.46	21.96 - 34.85
35%	19.39	17.23 - 23.26	19.57	16.20 - 23.73	20.19	17.48 - 24.27
50%	20.85	16.46 - 24.11	21.38	16.88 - 26.74	22.27	18.67 - 26.82
65%	21.43	18.27 - 27.76	21.73	16.79 - 27.07	22.16	18.94 - 26.52
80%	23.57	19.57 - 29.34	23.87	19.23 - 32.67	24.38	21.04 - 28.64
Left Femur						
20%	39.43	28.91 - 50.39	40.42	33.76 - 50.89	41.18	35.00 - 48.53
35%	30.55	24.65 - 36.55	31.40	25.92 - 37.61	31.88	26.67 - 37.26
50%	28.56	24.19 - 31.56	29.47	23.65 - 35.88	29.20	25.16 - 32.66
65%	29.56	24.88 - 33.29	30.58	23.33 - 36.89	30.06	25.68 - 33.56
80%	31.64	27.16 - 36.13	32.36	27.33 - 38.51	31.98	28.70 - 35.59
Left Tibia						
20%	24.98	19.65 – 31.54	25.07	19.65 - 29.10	25.71	22.87 - 29.08
35%	22.58	16.93 – 26.85	23.01	18.71 - 27.68	23.64	20.98 - 28.53
50%	22.87	17.06 – 26.96	23.78	19.18 - 29.89	24.38	21.98 - 29.43
65%	24.79	17.94 – 30.89	25.66	20.78 - 33.27	26.18	22.44 - 31.28
80%	31.26	21.36 – 42.39	32.46	25.22 - 41.49	33.40	28.54 - 40.97

Table 5.6. *Mean AP/ML ratio by age classification*

Cross-Section	Young (20-40 yrs)		Middle (41-60 yrs)		Old (61+ yrs)	
	Mean	Range	Mean	Range	Mean	Range
Right Humerus						
20%	0.73	0.58 - 0.90	0.71	0.57 - 0.96	0.70	0.57 - 0.86
35%	1.08	0.96 - 1.20	1.06	0.86 - 1.36	1.07	0.89 - 1.19
50%	1.04	0.92 - 1.22	1.04	0.89 - 1.21	1.06	0.93 - 1.25
65%	1.05	0.92 - 1.27	1.06	0.91 - 1.23	1.09	0.91 - 1.25
80%	0.99	0.86 - 1.16	1.00	0.73 - 1.19	1.02	0.91 - 1.19
Left Humerus						
20%	0.73	0.56 - 0.91	0.75	0.59 - 1.03	0.73	0/54 - 0.92
35%	1.10	0.96 - 1.21	1.10	0.97 - 1.33	1.10	0.89 - 1.19
50%	1.05	0.90 - 1.25	1.04	0.87 - 1.22	1.03	0.86 - 1.16
65%	1.07	0.93 - 1.20	1.07	0.92 - 1.30	1.09	0.82 - 1.27
80%	0.99	0.83 - 1.15	1.00	0.81 - 1.18	1.01	0.90 - 1.17
Left Femur						
20%	0.82	0.70 - 1.01	0.82	0.71 - 0.99	0.80	0.73 - 0.90
35%	0.96	0.81 - 1.19	0.95	0.83 - 1.16	0.95	0.85 - 1.10
50%	1.00	0.83 - 1.22	0.99	0.77 - 1.22	1.01	0.88 - 1.22
65%	0.95	0.79 - 1.14	0.94	0.75 - 1.24	0.98	0.85 - 1.20
80%	0.91	0.69 - 1.04	0.91	0.74 - 1.11	0.94	0.81 - 1.14
Left Tibia						
20%	0.94	0.86 - 1.02	0.96	0.77 - 1.14	0.93	0.84 - 1.03
35%	1.03	0.81 - 1.35	1.06	0.81 - 1.31	1.02	0.87 - 1.21
50%	1.22	0.87 - 1.60	1.20	0.92 - 1.48	1.16	0.95 - 1.34
65%	1.30	1.08 - 1.72	1.29	1.00 - 1.55	1.25	1.07 - 1.45
80%	1.24	1.02 - 1.73	1.22	1.00 - 1.47	1.19	1.05 - 1.34

c. Musculoskeletal Stress Marker Means

The MSM means and ranges by BMI and age classification are presented in Tables 5.7 and 5.8 respectively.

Table 5.7. *Mean MSM expression by BMI classification*

Cross-Section	Overweight		Normal Weight		Underweight	
	Mean	Range	Mean	Range	Mean	Range
Right Humerus						
Lateral B.G.	2.05	1 - 3	1.90	1 - 3	2.07	1 - 3
Medial B.G.	1.47	1 - 3	1.19	1 - 3	1.53	1 - 3
Deltoid	1.40	1 - 3	1.31	1 - 3	1.52	1 - 3
Distolateral	1.12	1 - 3	1.25	1 - 3	1.22	1 - 2
Left Humerus						
Lateral B.G.	1.78	1 - 3	1.63	1 - 3	1.80	1 - 3
Medial B.G.	1.53	1 - 3	1.17	1 - 3	1.51	1 - 3
Deltoid	1.52	1 - 3	1.38	1 - 3	1.51	1 - 3
Distolateral	1.13	1 - 3	1.21	1 - 3	1.22	1 - 2
Left Femur						
Intertroc. Line	1.42	1 - 3	1.63	1 - 3	1.46	1 - 3
Linea Aspera	1.40	1 - 3	1.29	1 - 3	1.26	1 - 3
Gluteal	1.70	1 - 3	1.88	1 - 3	1.70	1 - 3
Spiral Line	1.30	1 - 3	1.25	1 - 3	1.25	1 - 3
Lesser Troc.	1.31	1 - 3	1.22	1 - 3	1.36	1 - 3
Left Tibia						
Tibial Tub.	1.40	1 - 3	1.63	1 - 3	1.43	1 - 3
Soleal Line	1.31	1 - 3	1.15	1 - 3	1.37	1 - 3

Table 5.8. *Mean MSM expression by age classification*

Cross-Section	Young (20-40 yrs)		Middle (41-60 yrs)		Old (61+ yrs)	
	Mean	Range	Mean	Range	Mean	Range
Right Humerus						
Lateral B.G.	1.90	1 - 3	1.94	1 - 3	2.31	1 - 3
Medial B.G.	1.49	1 - 3	1.38	1 - 3	1.37	1 - 3
Deltoid	1.23	1 - 3	1.40	1 - 3	1.66	1 - 3
Distolateral	1.28	1 - 3	1.20	1 - 3	1.06	1 - 2
Left Humerus						
Lateral B.G.	1.59	1 - 3	1.75	1 - 3	1.89	1 - 3
Medial B.G.	1.31	1 - 3	1.47	1 - 3	1.43	1 - 3
Deltoid	1.21	1 - 3	1.48	1 - 3	1.74	1 - 3
Distolateral	1.26	1 - 3	1.16	1 - 3	1.17	1 - 2
Left Femur						
Intertroc. Line	1.30	1 - 3	1.54	1 - 3	1.55	1 - 3
Linea Aspera	1.25	1 - 3	1.30	1 - 2	1.42	1 - 3
Gluteal	1.57	1 - 3	1.83	1 - 3	1.79	1 - 3
Spiral Line	1.06	1 - 2	1.33	1 - 3	1.24	1 - 3
Lesser Troc.	1.30	1 - 3	1.30	1 - 3	1.39	1 - 3
Left Tibia						
Tibial Tub.	1.33	1 - 3	1.54	1 - 3	1.49	1 - 3
Soleal Line	1.15	1 - 3	1.31	1 - 3	1.34	1 - 3

II. Pearson's Product-Moment Correlation Coefficients

a. Weight to Age and Stature Correlations

A Pearson's Product-Moment Correlation Coefficient test was used to determine whether there was any correlation between age and stature, weight, or BMI. Results indicate that there is no significant correlation between age and weight (r = -0.001, *p-value* = 0.985) or age and BMI (r = 0.01, *p-value* = 0.898). There was a weak positive correlation between weight and stature (r = 0.252, *p-value* = 0.001).

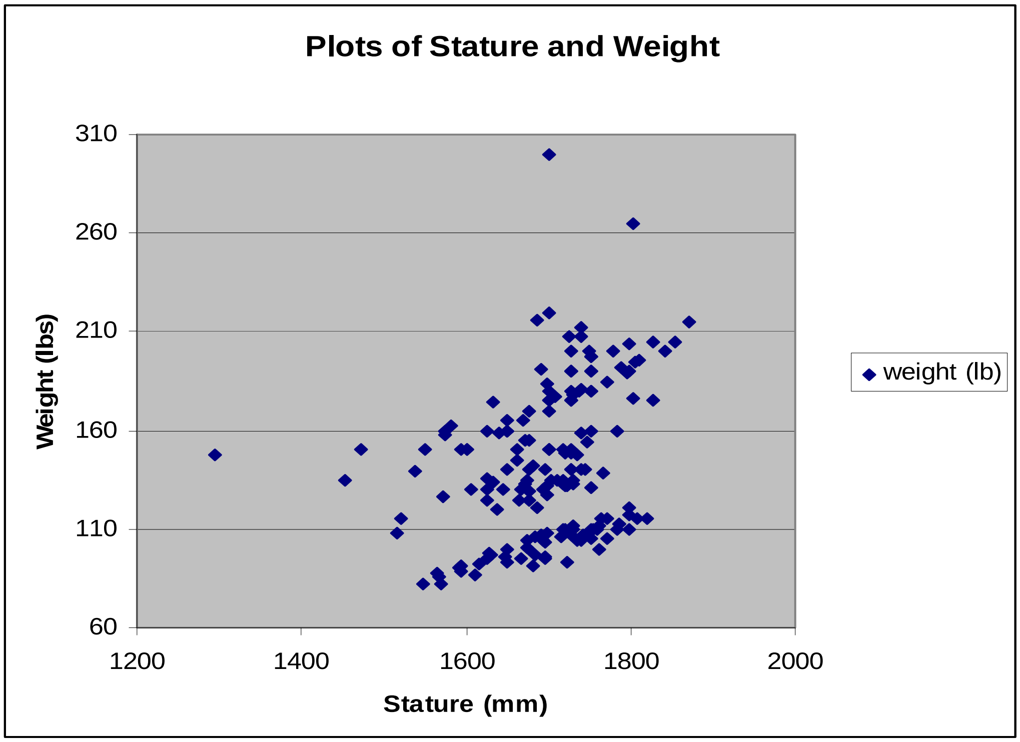

FIGURE 5. *Scatterplot of stature and weight in males of European ancestry.*

b. Cross-Sectional Geometry to BMI and Stature

A Pearson's Product-Moment Correlation Coefficient test was used to determine whether there was any correlation between stature and AP/ML cross-sectional ratio**.** Results for the right humerus showed no significant correlation between stature and cross-sectional geometry at 20% (r = 0.055, *p-value* = 0.488), 35% (r = 0.034, *p-value* = 0.667), 50% (r = -0.0714, *p-value* = 0.365), 65% (r = -0.039, *p-value* = 0.617) or 80% (r = -0.146, *p-value* = 0.063). In the left humerus there was no significant correlation at 20% (r = 0.060, *p-value* = 0.44), 35% (r = -0.019, *p-value* = 0.807), 50% (r = -0.084, *p-value* = 0.281) or 65% (r = -

0.158, *p-value* = 0.087), but there was a weak negative correlation at 80% (*r* = -0.158, *p-value* = 0.041).

Results for the left femur showed no significant correlation between stature and cross-sectional geometry at 20% (*r* = -0.049, *p-value* = 0.517), 35% (*r* = -0.079, *p-value* = 0.295), 50% (*r* = 0.037, *p-value* = 0.623), 65% (*r* = 0.044, *p-value* = 0.559), or 80% (*r* = 0.009, *p-value* = 0.234). In the left tibia, there was no significant correlation at 20% (*r* = -0.093, *p-value* = 0.222), 50% (*r* = -0.114, *p-value* = 0.133), 65% (*r* = -0.069, *p-value* = 0.368) or 80% (*r* = -0.003, *p-value* = 0.971), but there was a weak negative correlation between stature and cross-sectional geometry at 35% (*r* = -0.147, *p-value* = 0.053).

Correlations between BMI and AP/ML ratio were also evaluated using a Pearson's Product-Moment Correlation Coefficient statistic, which showed that there was no significant correlation between BMI and cross-sectional ratio at any location of the arm and leg bones evaluated. There was no significant correlation in the right humerus at 20% (*r* = -0.083, *p-value* = 0.292), 35% (*r* = 0.016, *p-value* = 0.838), 50% (*r* = -0.0187, *p-value* = 0.813), 65% (*r* = -0.072, *p-value* = 0.363) or 80% (*r* = -0.124, *p-value* = 0.063). Results also showed no significant correlation between BMI and cross-sectional geometry of the left humerus at 20% (*r* = 0.034, *p-value* = 0.660), 35% (*r* = 0.005, *p-value* = 0.952), 50% (*r* = 0.014, *p-value* = 0.864), 65% (*r* = -0.125, *p-value* = 0.107) or 80% (*r* = -0.099, *p-value* = 0.202).

In the leg, there was no significant correlation between BMI and cross-sectional geometry of the femur at 20% (*r* = 0.004, *p-value* = 0.96), 35% (*r* = -0.103, *p-value* = 0.172), 50% (r = -0.12, *p-value* = 0.111), 65% (r = -0.115, *p-value* = 0.125) or 80% (r = -0.084, *p-value* = 0.263). Results for the tibia also showed no significant correlation at 20% (r = 0.005, *p-value* = 0.951), 35% (r = 0.007, *p-value* = 0.927), 50% (r = 0.027, *p-value* = 0.72), 65% (r = 0.06, *p-value* = 0.436), or 80% (r = 0.042, *p-value* = 0.58).

Table 5.9. *Pearson's product moment coefficient correlation results for stature, BMI, and cross-sectional geometry of males of European ancestry*

X-Sec		Right Humerus BMI	Right Humerus Stature	Left Humerus BMI	Left Humerus Stature	Femur BMI	Femur Stature	Tibia BMI	Tibia Stature
20%	**r**	-0.083	0.055	0.034	0.060	0.004	-0.049	0.005	-0.093
	p	0.292	0.488	0.660	0.440	0.960	0.517	0.951	0.222
35%	**r**	0.016	0.034	0.005	-0.019	-0.103	-0.079	0.007	-0.147
	p	0.838	0.667	0.952	0.807	0.172	0.295	0.927	0.053
50%	**r**	-0.019	-0.071	0.014	-0.084	-0.120	0.037	0.027	-0.114
	p	0.813	0.365	0.862	0.281	0.111	0.623	0.720	0.133
65%	**r**	-0.072	-0.039	-0.125	-0.133	-0.115	0.044	0.060	-0.069
	p	0.363	0.617	0.107	0.087	0.125	0.559	0.436	0.368
80%	**r**	-0.124	-0.146	-0.099	-0.158	-0.084	0.090	0.042	-0.003
	p	0.114	0.063	0.202	***0.041**	0.263	0.234	0.580	0.971

n=163 *n= 163* *n=178* *n=174*

**indicates significant result (p-value < 0.05)*

c. AP Dimension to Maximum Length

A Pearson's product moment correlation coefficient showed a significant correlation between maximum bone length and the AP cross-sectional dimension at all locations for all bones evaluated.

There was a weak-to-moderate positive correlation between AP dimensions and maximum length at all locations for all bones evaluated. In the arm, correlations for the right humerus were as follows: 20% (r = 0.280, *p-value* < 0.01), 35% (r = 0.362, *p-value* = < 0.01), 50% (r = 0.298, *p-value* < 0.01), 65% (r = 0.271, *p-value* < 0.01) and 80% (r = 0.258, *p-value* < 0.01). The positive correlations for the left humerus were: 20% (*r* = 0.302, *p-value* < 0.01), 35% (*r* = 0.443, *p-value* < 0.01), 50% (*r* = 0.379, *p-value* < 0.01), 65% (*r* = 0.285, *p-value* < 0.01) and 80% (*r* = 0.308, *p-value* < .01).

In the leg, results for the femur showed stronger correlations between maximum length and AP dimension, with significant results at 20% (*r* = 0.610, *p-value* < .01), 35% (*r* = 0.589, *p-value* < .01), 50% (*r* = 0.573, *p-value* < .01), 65% (*r* = 0.563, *p-value* < .01) and 80% (*r* = 0.416, *p-value* < 0.01). Results for the tibia showed moderate positive correlations at 20% (*r* = 0.357, *p-value* < 0.01), 35% (*r* = 0.410, *p-value* < 0.01), 50% (*r* = 0.460, *p-value* < 0.01), and stronger correlations at 65% (*r* = .537, *p-value* < 0.01) and 80% (*r* = 0.553, *p-value* < .01).

Table 5.10. *Pearson's product moment coefficient correlation results for maximum bone length and AP dimension of males of European ancestry*

AP		R Humerus	L Humerus	Femur	Tibia
20%	**r**	0.2800	0.3015	0.6104	0.3574
	p	***0.0003**	***< 0.0001**	***< 0.0001**	***< 0.0001**
35%	**r**	0.3615	0.4431	0.5894	0.4095
	p	***< 0.0001**	***< 0.0001**	***< 0.0001**	***< 0.0001**
50%	**r**	0.2982	0.3786	0.5730	0.4604
	p	***0.0001**	***< 0.0001**	***< 0.0001**	***< 0.0001**
65%	**r**	0.2705	0.2846	0.5630	0.5373
	p	***0.0005**	***0.0002**	***< 0.0001**	***< 0.0001**
80%	**r**	0.2577	0.3083	0.4162	0.5532
	p	***0.0009**	***< 0.0001**	***< 0.0001**	***< 0.0001**
		n=163	*n=163*	*n=169*	*n=159*

**indicates significant result (p-value < 0.01)*

d. ML Dimension to Maximum Length.

There was a weak-to-moderate positive correlation between ML dimensions and maximum length at all locations on all bones evaluated. In the arms, the right humerus was significant at 20% ($r = 0.295$, *p-value* < 0.01), 35% ($r = 0.359$, *p-value* < 0.01), 50% ($r = 0.401$, *p-value* < 0.01), 65% ($r = 0.36$, *p-value* < 0.01) and 80% ($r = 0.369$, *p-value* < 0.01). The left humerus was significant at 20% ($r = 0.249$, *p-value* < 0.01), 35% ($r = 0.385$, *p-value* < 0.01), 50% ($r = 0.437$, *p-value* < 0.01), 65% ($r = 0.364$, *p-value* < 0.01) and 80% ($r = 0.363$, *p-value* < 0.01).

Significant correlations in the leg were also weak-to-moderate. The femur was significant at 20% ($r = 0.479$, *p-value* < 0.01), 35% ($r = 0.513$, *p-value* < 0.01), 50% ($r = 0.427$, *p-value* < 0.01), 65% ($r = 0.359$, *p-value* < 0.01) and 80% ($r = 0.366$, *p-value* < 0.01) and the tibia was significant at 20% ($r = 0.342$, *p-value* < 0.01), 35% ($r = 0.439$, *p-value* < 0.01), 50% ($r = 0.404$, *p-value* < 0.01), 65% ($r = 0.419$, *p-value* < 0.01), and 80% ($r = 0.266$, *p-value* < 0.01).

Table 5.11. *Pearson's product moment coefficient correlation results for maximum bone length and ML dimension of males of European ancestry*

ML		R Humerus	L Humerus	Femur	Tibia
20%	**r**	0.2944	0.2486	0.4793	0.3425
	p	***0.0001**	***0.0014**	***< 0.0001**	***< 0.0001**
35%	**r**	0.3592	0.3851	0.5127	0.4388
	p	***< 0.0001**	***< 0.0001**	***< 0.0001**	***< 0.0001**
50%	**r**	0.4013	0.4368	0.4272	0.4037
	p	***< 0.0001**	***< 0.0001**	***< 0.0001**	***< 0.0001**
65%	**r**	0.3600	0.3641	0.3593	0.4193
	p	***< 0.0001**	***< 0.0001**	***< 0.0001**	***< 0.0001**
80%	**r**	0.3688	0.3634	0.3663	0.2659
	p	***< 0.0001**	***< 0.0001**	***< 0.0001**	***< 0.0001**
		n=163	*n=163*	*n=169*	*n=159*

**indicates significant result (p-value < 0.01)*

e. AP/ML to Maximum Length

The correlations between maximum length and AP/ML cross-sectional ratio differed greatly from the correlations between maximum length and either AP or ML dimension. The results for the right humerus showed no significant correlation between maximum bone length and cross-section geometry at 20% (r = -0.0978, *p-value* = 0.214), 35% (r = -0.08, *p-value* = 0.311), 65% (r = -0.137, *p-value* = 0.081) or 80% (r = -0.141, *p-value* = 0.072). There was a weak negative correlation at 50% (r = -0.211, *p-value* < 0.01). For the left humerus, there was no significant correlation between maximum length and cross-sectional geometry at any of the locations measured: 20% (r = -0.017, *p-value* = 0.834), 35% (r = 0.022, *p-value* = 0.783), 50% (r = -0.106, *p-value* = .177), 65% (r = -0.119, *p-value* = 0.131) and 80% (r = -0.070, *p-value* = 0.374).

In the leg, there was no significant correlation between maximum bone length and cross-sectional geometry of the femur at 20% (r = 0.113, *p-value* = 0.145) or 35% (r = 0.064, *p-value* = 0.412). There were weak positive correlations at 50% (r = 0.19, *p-value* < 0.05) and 65% (r = 0.187, *p-value* < 0.05). There was no significant correlation at 80% (r = 0.127, *p-value* = 0.1). In the tibia, there was no correlation between maximum bone length and cross-sectional geometry at 20% (r = -0.001, *p-value* = 0.989), 35% (r = -0.098, *p-value* = 0.221), 50% (r = -0.058, p = 0.464), or 65% (r = -0.013, *p-value* = 0.869). There was a weak positive correlation at 80% (r = 0.160, *p-value* < 0.05).

Table 5.12. *Pearson's product moment correlation coefficient results for maximum bone length and AP/ML ratio of males of European ancestry*

AP/ML		R Humerus	L Humerus	Femur	Tibia
20%	**r**	-0.0978	-0.0166	0.1125	-0.0011
	p	0.2144	0.8336	0.1453	0.9891
35%	**r**	-0.0798	0.0218	0.0635	-0.0977
	p	0.3110	0.7827	0.4118	0.2208
50%	**r**	-0.2112	-0.1063	0.1921	-0.0585
	p	****0.0068**	0.1770	***0.0132**	0.4640
65%	**r**	-0.1371	-0.1187	0.1871	-0.0132
	p	0.0811	0.1314	***0.0149**	0.8690
80%	r	-0.1412	-0.0701	0.1268	0.1604
	p	0.0722	0.3740	0.1004	***0.0434**
		n=163	*n=163*	*n=169*	*n=159*

**significant at p-value < 0.05, ** significant at p-value < 0.01*

III. <u>Multivariate Analysis of Variance (MANOVA) Results</u>

The MANOVA results show no significant age*BMI interaction or BMI effect on the AP dimension of any of the bones evaluated, but there is a significant age effect (Wilks' Λ = 0.8404, d.f. = 10,300; p > F = 0.0032) on the right humerus.

Table 5.13. Overall *MANOVA for age, BMI, and AP dimension in males of European ancestry.*

Bone	Effect	Wilks' Λ	F	d.f.	p > F
R Humerus	**Age**	0.8404	2.72	10, 300	***0.0032**
n = 163	**BMI**	0.9242	1.21	10, 300	0.2866
	Age*BMI	0.9003	0.80	20, 498.44	0.7119
L Humerus	**Age**	0.8978	1.66	10, 300	0.0893
n = 163	**BMI**	0.9324	1.07	10, 300	0.3859
	Age*BMI	0.8874	0.91	20, 498.44	0.5687
Femur	**Age**	0.8998	1.79	10, 330	0.0616
n = 178	**BMI**	0.9471	0.91	10, 330	0.5255
	Age*BMI	0.8571	1.30	20, 548.19	0.1690
Tibia	**Age**	0.9441	0.85	10, 292	0.5782
n = 174	**BMI**	0.9560	0.66	10, 292	0.7573
	Age*BMI	0.8962	0.82	20, 485.18	0.6956

** indicates significant result (p-value < .01)*

There is no significant age*BMI interaction or age effect on the diaphyseal ML dimension, but there was a significant BMI effect on the left humerus (Wilks' Λ = 0.8652, d.f. = 10, 300; p > F = 0.0151).

TABLE 5.14. Overall *MANOVA for age, BMI, and ML dimension in males of European ancestry.*

Bone	Effect	Wilks' Λ	F	d.f.	p < F
R. Humerus	**Age**	09571	0.67	10, 300	0.7562
n = 163	**BMI**	0.0883	2.52	10, 300	0.1775
	Age*BMI	0.8850	0.93	20, 498.44	0.5424
L. Humerus	**Age**	0.8993	1.63	10, 300	0.0960
n = 163	**BMI**	0.8652	2.25	10, 300	***.0151**
	Age*BMI	0.8686	1.08	20, 498.44	0.3652
Femur	**Age**	0.9225	1.36	10, 330	0.1982
n = 178	**BMI**	0.9371	1.09	10, 330	0.3687
	Age*BMI	0.9197	0.70	20, 548.19	0.8271
Tibia	**Age**	0.9040	1.51	10, 292	0.1338
n = 174	**BMI**	0.9532	0.71	10, 292	0.7162
	Age*BMI	0.9223	0.60	20, 485.18	0.9141

** indicates significant result (p-value < 0.05)*

No significant age*BMI interaction , age or BMI effect was found on the AP/ML cross-sectional ratio of the humerii or femur. However, a significant age*BMI interaction was found for the tibia (Wilks' Λ = 0.7516, d.f. = 20, 498.44, p < F = 0.0017)

TABLE 5.15. Overall *MANOVA for age, BMI, and AP/ML ratio in males of European ancestry.*

Bone	Effect	Wilks' Λ	F	d.f.	p < F
R. Humerus	**Age**	0.9298	1.11	10, 300	0.3533
n = 163	**BMI**	0.9531	.73	10, 300	0.6961
	Age*BMI	0.8763	1.01	20, 498.44	0.4457
L. Humerus	**Age**	0.9290	1.13	10, 300	0.3421
n = 163	**BMI**	0.9032	1.57	10, 300	0.1157
	Age*BMI	0.8806	.97	20, 498.44	0.4924
Femur	**Age**	0.9182	1.44	10, 330	0.1621
n = 178	**BMI**	0.9601	.68	10, 330	0.7446
	Age*BMI	0.8714	1.16	20, 548.19	0.2832
Tibia	**Age**	0.8171	3.19	10, 300	***0.0007**
n = 174	**BMI**	0.8370	2.79	10, 300	***0.0026**
	Age*BMI	0.7516	2.24	20, 498.44	***0.0017**

** indicates significant result (p-value < 0.01)*

The MANOVA results show that there was no significant age*BMI interaction or effect of BMI for MSM severity of any of the bones evaluated, but there was a significant age effect on the right and left humerii (Wilks' Λ = 0.8450, d.f. = 8, 300; p < F = 0.0013) and (Wilks' Λ = 0.8993, d.f. = 8, 296; p < F = 0.0442), respectively.

TABLE 5.16. Overall *MANOVA for age, BMI, and MSM severity in males of European ancestry.*

Bone	Effect	Wilks' Λ	F	d.f.	p < F
R. Humerus	**Age**	0.8450	3.30	8, 300	****0.0013**
n = 163	**BMI**	0.9367	1.25	8, 300	0.2718
	Age*BMI	0.9120	.88	16, 458.9	0.5946
L. Humerus	**Age**	0.8993	2.02	8, 296	***0.0442**
n = 163	**BMI**	0.9434	1.09	8, 296	0.3678
	Age*BMI	0.9541	.44	16, 452.79	0.9719
Femur	**Age**	0.9016	1.71	10, 322	0.0771
n = 178	**BMI**	0.9514	.81	10, 322	0.6174
	Age*BMI	0.8907	.95	20, 534.93	0.5233
Tibia	**Age**	0.9743	.98	4, 300	0.4169
n = 174	**BMI**	0.9842	.60	4, 300	0.6625
	Age*BMI	0.9765	.45	8, 300	0.8904

**significant at p-value < 0.05, ** significant at p-value < 0.01*

IV. <u>Analysis of Variance (ANOVA) Results</u>

To evaluate specific MSMs or areas of diaphyseal cross-section which might be affected by BMI or age, ANOVAs were also conducted for each location.

a. AP Dimension to BMI and Age.

The ANOVA for BMI showed a significant BMI effect at the most-proximal (20%) location (F = 3.11, *p-value* < 0.05) and the second-most-proximal (35%) location (F = 3.74, *p-value* < 0.05). The ANOVA for age was significant at the midpoint (50%) location (F = 8.02, *p-value* < 0.01), second-most-proximal (65%) (F = 6.26, *p-value* < 0.01) and most-proximal (80%) location (F = 4.56, *p-value* < 0.05).

The ANOVA did not detect any significant age*BMI interaction or BMI effect on AP dimension of the left humerus. Age was significant at the distal-most (20%) location (F =

3.22, *p-value* < 0.05) and the second-most-proximal (65%) location (F = 3.97, *p-value* < 0.05).

In the leg, there was no statistically significant age*BMI interaction or BMI effect at any cross-sectional location measured on the femur. Age was significant at the four proximal locations measured: 35% (F = 3.08, *p-value* < 0.05), 50% (F = 5.01, *p-value* < 0.01), 65% (F = 5.78, *p-value* < 0.01) and 80% (F = 7.07, *p-value* < 0.01). Age and BMI were not significant on the AP Dimension at any location of the tibia.

Table 5.17. *ANOVAs for age, BMI, and AP dimension in males of European ancestry.*

			R. Humerus		L. Humerus		Femur		Tibia	
AP	**Variable**	**d.f.**	**F**	**p**	**F**	**p**	**F**	**p**	**F**	**p**
20%	**Age**	2	0.10	0.904	3.22	***0.043**	2.93	0.056	1.42	0.246
	BMI	2	3.11	***0.047**	2.85	0.061	1.50	0.225	1.23	0.296
	Age*BMI	4	0.40	0.807	1.37	0.248	2.22	0.068	0.81	0.524
35%	**Age**	2	2.54	0.082	2.47	0.088	3.08	***0.049**	0.90	0.407
	BMI	2	3.74	***0.026**	2.70	0.071	0.29	0.749	0.87	0.421
	Age*BMI	4	0.81	0.520	1.13	0.346	1.49	0.207	0.71	0.589
50%	**Age**	2	8.02	****0.001**	2.98	0.054	5.01	***0.008**	1.06	0.348
	BMI	2	2.42	0.092	1.29	0.277	0.25	0.778	1.23	0.297
	Age*BMI	4	0.91	0.462	0.72	0.578	2.02	0.093	0.52	0.723
65%	**Age**	2	6.26	****0.002**	3.97	****0.021**	5.78	****0.004**	1.03	0.358
	BMI	2	2.23	0.111	0.36	0.701	0.67	0.511	1.67	0.191
	Age*BMI	4	1.48	0.211	1.10	0.360	1.32	0.264	0.83	0.511
80%	**Age**	2	4.56	****0.012**	2.87	0.060	7.07	****0.001**	2.76	0.067
	BMI	2	1.64	0.198	0.90	0.411	1.30	0.275	1.28	0.282
	Age*BMI	4	1.08	0.369	1.53	0.198	1.19	0.315	0.85	0.494

n = 163 *n = 163* *n = 178* *n = 174*

**significant at p-value < 0.05, ** significant at p-value < 0.01*

b. ML Dimension to BMI and Age.

Age*BMI interaction and age were not significant on the ML dimension of the right humerus. BMI was significant at the most-proximal (80%) location (F = 5.04, *p-value* < 0.01). For the left humerus, age was significant only at the midpoint (50%) location (F =

5.46, *p-value* < 0.01) and BMI was significant at the proximal-most (80%) location (F = 5.94, *p-value* < 0.01).

Age was significant at the four distal femoral locations: 20% (F = 3.30, *p-value* < 0.05), 35% (F = 3.70, *p-value* < 0.05), 50% (F = 3.55, *p-value* < 0.05) and 65% (F = 3.59, *p-value* = 0.05). BMI was significant at the midpoint (50%) location (F = 4.12, *p-value* < 0.05), the second-most-proximal (65%) location (F = 4.60, p < 0.05), and the most-proximal (80%) location (F = 3.51, *p-value* < 0.05).

Results for the tibia showed no significant age*BMI interaction or BMI effect on the ML dimension at any location. Age was significant at the most-proximal (80%) location (F = 4.25, *p-value* < 0.05), the second-most-proximal (65%) location (F = 3.10, *p-value* < .05), and the midpoint (50%) location (F = 4.41, *p-value* < .05).

Table 5.18. *ANOVAs for age, BMI, and ML dimension in males of European ancestry.*

			R. Humerus		L. Humerus		Femur		Tibia	
ML	**Variable**	**d.f.**	**F**	**p**	**F**	**p**	**F**	**p**	**F**	**p**
20%	**Age**	2	1.90	0.153	2.06	0.131	3.30	***0.039**	1.29	0.278
	BMI	2	2.69	0.071	.48	0.618	1.51	0.223	1.13	0.326
	Age*BMI	4	0.24	0.913	.25	0.911	0.86	0.490	0.28	0.889
35%	**Age**	2	2.60	0.078	3.04	0.051	3.70	***0.027**	2.44	0.091
	BMI	2	1.79	0.170	1.30	0.277	2.63	0.075	2.49	0.086
	Age*BMI	4	1.07	0.375	1.28	0.281	0.57	0.684	1.10	0.358
50%	**Age**	2	2.67	0.072	5.46	****0.005**	3.55	***0.031**	4.41	***0.014**
	BMI	2	2.03	0.134	1.11	0.332	4.12	***0.018**	1.99	0.140
	Age*BMI	4	0.99	0.417	.65	0.625	0.43	0.784	1.30	0.274
65%	**Age**	2	1.36	0.259	1.22	0.299	3.59	***0.030**	3.10	***0.048**
	BMI	2	2.42	0.093	2.81	0.063	4.60	****0.011**	1.44	0.239
	Age*BMI	4	0.59	0.667	1.15	0.337	0.32	0.868	1.22	0.305
80%	**Age**	2	1.16	0.316	1.09	0.338	1.96	0.145	4.25	***0.016**
	BMI	2	5.04	****0.008**	5.94	****0.003**	3.51	***0.032**	1.08	0.341
	Age*BMI	4	0.26	0.906	1.21	0.309	0.94	0.443	1.63	0.169
				n = 163		*n = 163*		*n = 178*		*n = 174*

**significant at p-value < 0.05, ** significant at p-value < 0.01*

c. AP/ML Ratio to BMI and Age

Age*BMI interaction, age or BMI were not significant on the cross-sectional ratio at any location of the right humerus. In the left humerus, BMI was significant only at the most proximal location of 80% (F = 3.22, *p-value* < 0.05).

In the femur, age*BMI interaction or BMI were not significant on the cross-sectional properties at any location. Age was significant at only the proximal-most location measured: 80% (F = 3.34, *p-value* < 0.05). Results for the tibia showed no significance for age on the cross-sectional ratio at any of the locations measured. There was an effect of an age*BMI interaction at only the second-most-distal (35%) location (F = 3.36, *p-value* < 0.05).

Table 5.19. *ANOVAs for age, BMI, and AP/ML ratio in males of European ancestry.*

			R. Humerus		L. Humerus		Femur		Tibia	
AP	**Variable**	**d.f.**	**F**	**p**	**F**	**p**	**F**	**p**	**F**	**p**
20%	**Age**	2	2.22	0.113	0.68	0.508	1.02	0.365	2.65	0.074
	BMI	2	0.15	0.862	0.48	0.617	0.88	0.415	0.01	0.992
	Age*BMI	4	0.28	0.888	0.95	0.438	0.88	0.480	0.29	0.882
35%	**Age**	2	0.48	0.622	0.31	0.218	0.28	0.759	2.79	0.065
	BMI	2	0.23	0.794	1.54	0.728	1.46	0.236	3.65	***0.028**
	Age*BMI	4	1.12	0.349	1.58	0.181	0.79	0.534	3.36	****0.011**
50%	**Age**	2	0.92	0.401	0.60	0.549	1.27	0.284	2.18	0.116
	BMI	2	0.33	0.719	0.13	0.591	1.16	0.315	0.39	0.677
	Age*BMI	4	1.94	0.107	1.03	0.396	1.22	0.306	1.70	0.152
65%	**Age**	2	2.70	0.071	1.48	0.231	2.37	0.096	2.15	0.120
	BMI	2	0.20	0.822	2.09	0.127	0.78	0.461	0.10	0.906
	Age*BMI	4	2.29	0.062	1.78	0.136	0.69	0.597	1.45	0.221
80%	**Age**	2	2.24	0.110	1.32	0.270	3.34	***0.038**	1.67	0.193
	BMI	2	1.62	0.201	3.22	***0.043**	0.31	0.734	0.25	0.783
	Age*BMI	4	1.35	0.255	1.62	0.172	0.98	0.418	2.35	0.056
			n = 163		*n = 163*		*n = 178*		*n = 174*	

**significant at p-value < 0.05, ** significant at p-value < 0.01*

d. MSMs to BMI and Age

BMI was not significant on musculoskeletal stress marker severity of the right humerus. Age was significant on only the deltoid tubercle (F = 4.45, *p-value* < 0.05). BMI was significant on the crest of the medial bicipital groove (F = 4.20, *p-value* < 0.05), and age on the deltoid tubercle (F = 5.49, *p-value* < 0.01).

Table 5.20. *ANOVAs for age, BMI, and MSM severity of the right and left humerii of males of European ancestry*

			Right		Left	
MSM	**Effect**	**d.f.**	**F**	**P**	**F**	**P**
Lateral BG	**Age**	2	2.81	0.063	1.41	0.395
	BMI	2	0.67	0.512	0.93	0.395
	Age*BMI	4	0.47	0.760	0.87	0.482
Medial BG	**Age**	2	0.25	0.758	0.67	0.515
	BMI	2	1.65	0.195	4.20	***0.017**
	Age*BMI	4	0.92	0.454	0.44	0.782
Deltoid	**Age**	2	4.45	****0.013**	5.49	****0.005**
	BMI	2	2.04	0.133	0.49	0.616
	Age*BMI	4	0.70	0.592	0.23	0.921
Distolat. End	**Age**	2	2.78	0.065	0.93	0.398
	BMI	2	1.05	0.354	0.23	0.795
	Age*BMI	4	0.96	0.430	0.30	0.879
				n = 163		*n = 163*

**significant at p-value < 0.05, ** significant at p-value < 0.01*

There was no effect of BMI on any of the five MSM sites evaluated for the femur. There was a significant effect of age on the severity of the gluteal line (F = 3.21, *p-value* < 0.05) and the spiral line (F = 4.14, *p-value* < 0.05).

Table 5.21. *ANOVAs for age, BMI, and MSM severity of the left femur of males of European ancestry.*

MSM	Effect	F	d.f.	p-value
Intertrochanteric	**Age**	1.93	2	0.149
	BMI	1.76	2	0.176
	Age*BMI	0.22	4	0.927
Linea Aspera	**Age**	0.73	2	0.484
	BMI	0.28	2	0.754
	Age*BMI	0.74	4	0.568
Gluteal	**Age**	3.21	2	***0.043**
	BMI	0.76	2	0.468
	Age*BMI	0.65	4	0.631
Spiral Line	**Age**	4.14	2	***0.018**
	BMI	0.65	2	0.526
	Age*BMI	2.17	4	0.075
Lesser Trochanter	**Age**	0.53	2	0.592
	BMI	0.20	2	0.818
	Age*BMI	1.65	4	0.164

n = 178

**indicates significant result (p-value < 0.05)*

In the tibia, age and BMI were not significant**.**

Table 5.22. *ANOVAs for age, BMI, and MSM severity of the left tibia of males of European ancestry.*

MSM	Effect	F	d.f.	p
Tibial Tub.	Age	1.47	2	0.233
	BMI	0.88	2	0.417
	Age*BMI	0.48	4	0.750
Soleal Line	Age	0.44	2	0.645
	BMI	0.34	2	0.711
	Age*BMI	0.44	4	0.779

n = 174

V. <u>T-tests</u>

A t-test using a Fisher's protected LSD correction (for uneven sample sizes) was used to evaluate the areas for which a significant effect was found. Results are presented in tables 5.23 and 5.24.

At the 20% location of the distal right humerus, a significant difference was found between normal weight and overweight AP means. At the 35% location, a significant difference was found between normal weight and overweight AP means, and between underweight and overweight AP means. This pattern is consistent with that of Figure 9 (see Appendix). At the 80% location of the proximal right humerus, a significant difference was found between overweight and normal weight ML means and between overweight and underweight ML means. At the 80% location of the proximal left humerus, a significant difference was found between overweight and normal weight ML means. At the 50%, 65% and 80% locations of the mid-to-proximal femur, a significant difference was found between overweight and normal weight ML means and between overweight and underweight ML means. At the 80% location of the proximal left humerus, a significant difference between normal weight and overweight individuals only. All of the above patterns are consistent with those of figures 9-20 (see Appendix).

At the 80% location of the proximal right humerus, there was no significant difference found between the ML means of any age group. At the 50% location of the midshaft of the left humerus, a significant difference was found between old and middle age

ML means and old and young age means. Middle and young ML means did not significantly differ. At the 20% of the distal femur, a significant difference was found between old and young ML means. At the 35% location, a significant difference was found between old and young means and the middle and young means, and at the 50% and 65% locations, a significant difference middle and young means. At the 50% midshaft location of the tibia, a significant difference was found between old and young means, and between middle and young means. At the 65% location, a significant difference was found between old and young means only, and at the 80% proximal location, between old and young means and between middle and young means. All of the above patterns are consistent with graphical depictions of these means (Figures 21-32, see Appendix II). At the proximal-most location of the femur, t-tests show that there was a significant difference between mean scores of old and young individuals only.

T-tests showed that the mean deltoid attachment scores of the left humerus were significantly different between young and old individuals, and between young and middle-aged individuals. The mean deltoid attachment scores of the right humerus were significantly different between old and young individuals, and between middle-aged and old individuals. For the gluteal line of the femur, t-tests show that mean attachment scores were significantly different between the middle-aged and old groups only, while linea aspera mean attachment scores were significantly different between the young and middle-age groups.

Table 5.23. *Summary showing significant t-tests between age categories.*

Bone Cross-Section	Location	Young-Middle	Young-Old	Middle-Old
R. Humerus	AP 50%		X	X
	AP 65%		X	X
	AP 80%		X	X
L. Humerus	AP 20%	X	X	
	AP 65%		X	X
	ML 50%		X	X
Femur	AP 35%	X	X	
	AP 50%	X	X	
	AP 65%	X	X	
	AP 80%	X	X	
	ML 20%		X	
	ML 35%	X	X	
	ML 50%	X		
	ML 65%	X		
	AP/ML 80%		X	
Tibia	ML 50%	X	X	
	ML 65%		X	
	ML 80%	X	X	
MSMs				
R. Humerus	Deltoid		X	X
L. Humerus	Deltiod	X	X	
Femur	Gluteal Line	X		
	Spiral Line	X		

"X"- *indicates age ranges for which mean measures were significantly different* (*p-value* < 0.05)

Table 5.24. *Summary showing significant t-tests between BMI categories*

Bone	Location	Under-Normal	Under-Over	Normal-Over
Cross-Section				
R. Humerus	AP 20%			**X**
	AP 35%		**X**	**X**
	ML 80%		**X**	**X**
L. Humerus	ML 80%			**X**
	AP/ML 80%			**X**
Femur	ML 50%		**X**	**X**
	ML 65%		**X**	**X**
	ML 80%		**X**	**X**
MSMs				
L. Humerus	Lateral B.G.			

"X"- *indicates BMI categories for which mean measures were significantly different* (*p-value* < 0.05)

DISCUSSION

I. Cross-sectional dimensions and age

Literature regarding the effect of age on morphological and histological properties of long bones is prevalent, and research shows that there is an increase in diaphyseal dimensions due to age in both males and post-menopausal females (Riggs et al, 2004; Lu et al., 1996; Glynn et al., 1995; Ruff and Hayes, 1984; Lindahl and Lindgren, 1967), but that the opposite is true for bone mineral density. Increased endosteal resportion coupled with subperiosteal expansion results in increased cross-sectional diameter with greater increases in medullary space (Ruff and Hayes, 1988; Lindahl and Lindgren, 1967). This pattern, coupled with life-long resorption of trabecular and endosteal bone (Ruff and Hayes, 1988) beginning roughly at mid-life (Riggs et al., 2004) results in increased diaphyseal dimensions but decreased overall bone mineral density, with women losing more trabecular and cortical bone density than men (Riggs et al., 2004; Yano et al., 1984).

Martin and Atkinson (1977) and Ruff and Hayes (1988) found that while rates of reduction in bone mineral density were similar between men and women, only men displayed subperiosteal apposition at a rate that maintained bone strength, placing women at an increased risk of failure (e.g., fracture). Several researchers (Pearson and Lieberman, 2004; Ruff and Hayes, 1982; Martin et al., 1980; Martin and Atkinson, 1977) state that this age-related dimensional increase compensates for the reduction of bone mineral density by providing a larger area for load displacement, as "bone area distributed further from the center of the section will result in much greater bending and torsional rigidity and strength" (Ruff, 2008:186). This allows men to maintain resistance to both torsional and bending stresses as they age while women show a reduction in resistance to these same forces.

These findings correlate well with the Hamann-Todd data, which show significant or near significant associations between age and AP dimension at every cross-sectional location of the humeri and femur, with the exception of the distal-most aspect of the right humerus. Significant associations are also seen at the ML dimension of every cross-sectional location of the femur and tibia, with the exception of the proximal location of the femur and distal location of the tibia. At all AP locations for which a significant age effect was found, the association between age and AP dimension was always positive, with t-tests confirming significant differences between old and young individuals. With only two exceptions (the 50% and 65% ML dimensions of the femur), old individuals have the largest mean AP and ML measurements of all three age groups.

It is interesting to note that there is an overall lack of significant age effect on the AP dimension of the tibia. These results disagree with Ruff and Hayes (1988) who found that subperiosteal area of all male leg bones increased as age increased, with tibial cross-section increasing by 2-4% during each decade of life. Ruff and Hayes (1988) also found that the distal dimensions of the tibia increased at a faster rate than did the midshaft or proximal locations. According to them, these increases caused the tibia to maintain or increase resistance to both torsional and bending stresses throughout adult life. The Hamann-Todd data differ in several significant ways. First, in evaluating mean AP/ML ratios between age categories, older individuals consistently have the smallest means (Figure 32, see Appendix II). Because the ratio for the proximal four locations were greater than 1.0 for all three age groups, these findings suggest that the oldest age category had either abnormally small AP dimensions, abnormally large ML dimensions, or both when compared to the other two age groups.

In evaluating the AP and ML dimensions separately, the old age category had the largest ML dimension at every location on the tibia (with significantly larger ML means at the midshaft and proximal two locations), and no significant elongation of the AP dimension (Tables 5.4 and 5.5, see Results). So while there are definite increases in the ML dimension of the tibia with age, these changes are not as extreme as one would expect to see if overall subperiostal area was increasing 2-4% for every decade. One possible explanation for this difference is sample bias, though sample composition between these two studies were similar, including only modern white U.S. adults. Also possible is that the small number of individuals represented in Ruff and Hayes' analysis (1 to 6 individuals per decade) was insufficient for extrapolating age-related trends to larger populations. One final explanation for this deviation is that the individuals comprised in the Hamann-Todd collection participated in different biomechanical activities as they aged, rendering them with tibiae stronger in sagittal rigidity than those of younger individuals.

Both humeri were largely unaffected by age in the ML dimension, showing no significant effect of age except for the midshaft location of the left humerus. This is in contrast to the leg bones, both of which showed significant ML elongation with age as confirmed by t-tests. Perhaps the most simplistic explanation of this difference is that weight-bearing and non-weight bearing bones respond differently to age-related remodeling in the ML (or sagittal) plane. Localized differences in bone remodeling trends were found by Stock (2006), who concluded that not only did arm and leg bones differ in their response to climate and mechanical action, but proximal and distal elements differed in response as well. Although he specifically referred to biomechanical effects, these findings do raise question as to whether there is differential remodeling of load-bearing and non-load-bearing skeletal elements with age.

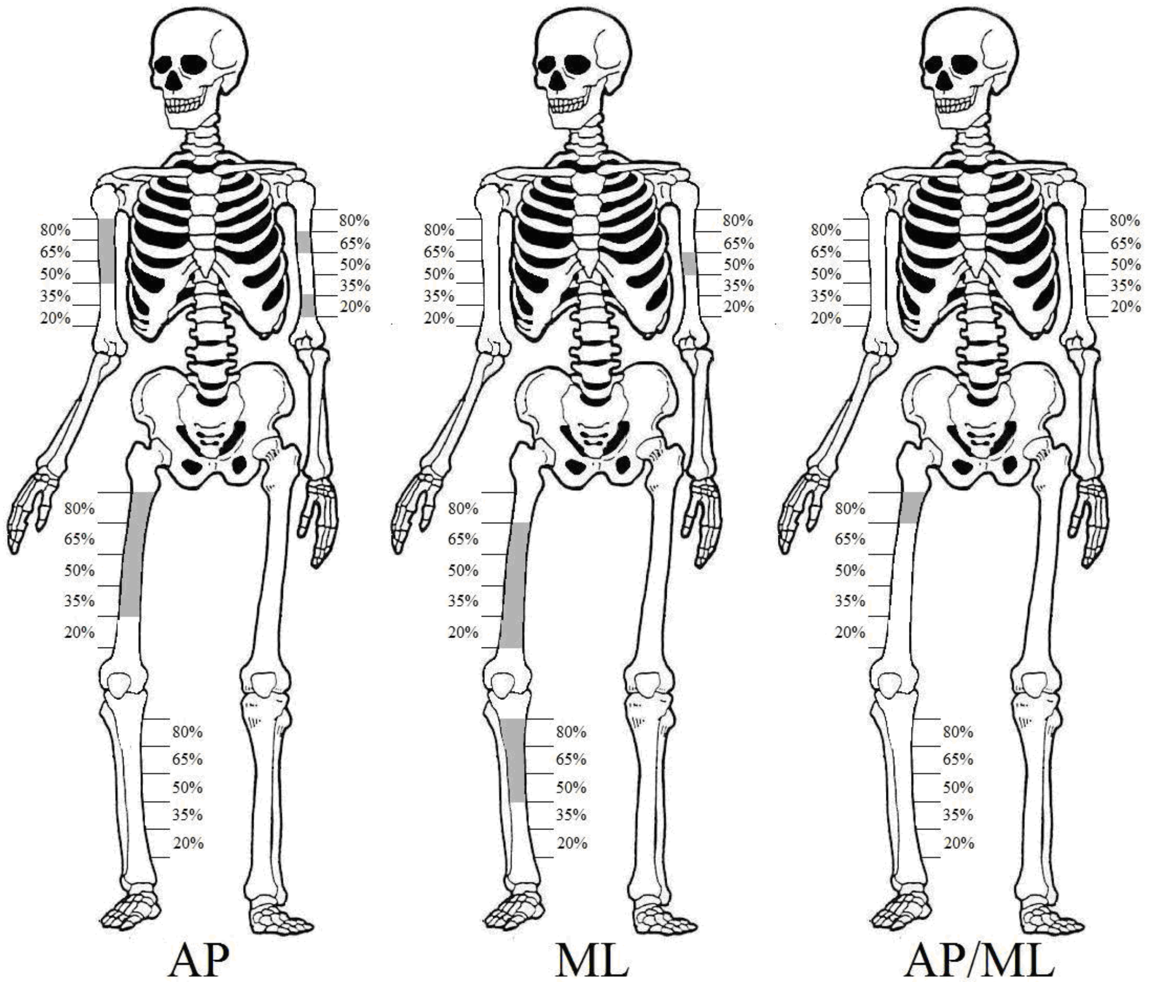

Figure 6: *Diagram of locations for which a significant age effect was reported. Image modified from Killgrave (www.killgrove.org/ANTH48/)*
Dark grey- p<.05

II. Cross-sectional dimensions and BMI

Studies have shown that differences in BMI positively correlate to bone mineral density (BMD), and that weight appears to slow the resorption process that occurs naturally with age, thereby maintaining or increasing BMD in overweight individuals (Stein et al., 1998; Yano et al., 1984). The effect of weight on BMD is so important that the National Institute of Health considers underweight BMI to be a predisposition to osteoporosis (Hassager and Christiansen, 1989). The direct mechanisms behind the maintenance of bone mineral in overweight individuals are still unknown, but some have speculated that it is a response to kinetic and kinematic differences. Because of the differential effects of load on weight-bearing and non-weight-bearing bones (Felson et al., 1993), the femur and tibia were evaluated separately from the humeri. Also, although there are a host of different forces which impact bone design (e.g., muscle and tendon pull, bone mineral content and bone elemental content), a simplified biomechanical approach was used to explore differences between overweight skeletal structure and under and normal weight skeletal structure using mainly kinematic and kinetic studies (Nordin and Frankel, 2001). For a concise discussion of current arguments regarding treatment of bone as a static mechanical unit, refer to Ruff et al. (2006).

a. Femur and Tibia Analysis

With regard to the Hamann-Todd data, the AP dimension was entirely unaffected by BMI. The ML dimension, however, showed significant effects of BMI at the two most proximal locations and midshaft regions of the femur, with the mean ML dimension for the overweight category being significantly larger than both the normal and underweight group means. The Pearson’s product moment correlation coefficient results showed a moderate positive correlation between maximum femoral bone length and ML dimension, but that correlations between stature and weight were weak ($r = 0.252$, $p = 0.001$).

These results are similar to those achieved by Stein et al. (1998), who found that after controlling for height, only the ML dimension of the femoral midshaft displayed significant weight effects. Ruff (2005) also found ML increases in the proximal femora of females, presumably due to alterations of the femur to compensate for increased pelvic width. Interestingly, research has also shown elongation of the proximal ML dimension of the femur in pregnant females (Ruff, 2008). As ML diameter measures resistance to sagittal bending, these results suggest that as weight increases, alterations to femoral angle results in greater sagittal pressures, forcing the femur to adapt or risk failure. This site specific remodeling could result simply from added mass, or could represent a more complex, biomechanically-induced remodeling due to compensatory behaviors made to cope with added mass. To investigate the latter hypothesis, research from biomechanical studies was evaluated to discern alterations made by overweight individuals, specifically targeting those behaviors which might result in increased sagittal loading of the proximal femur.

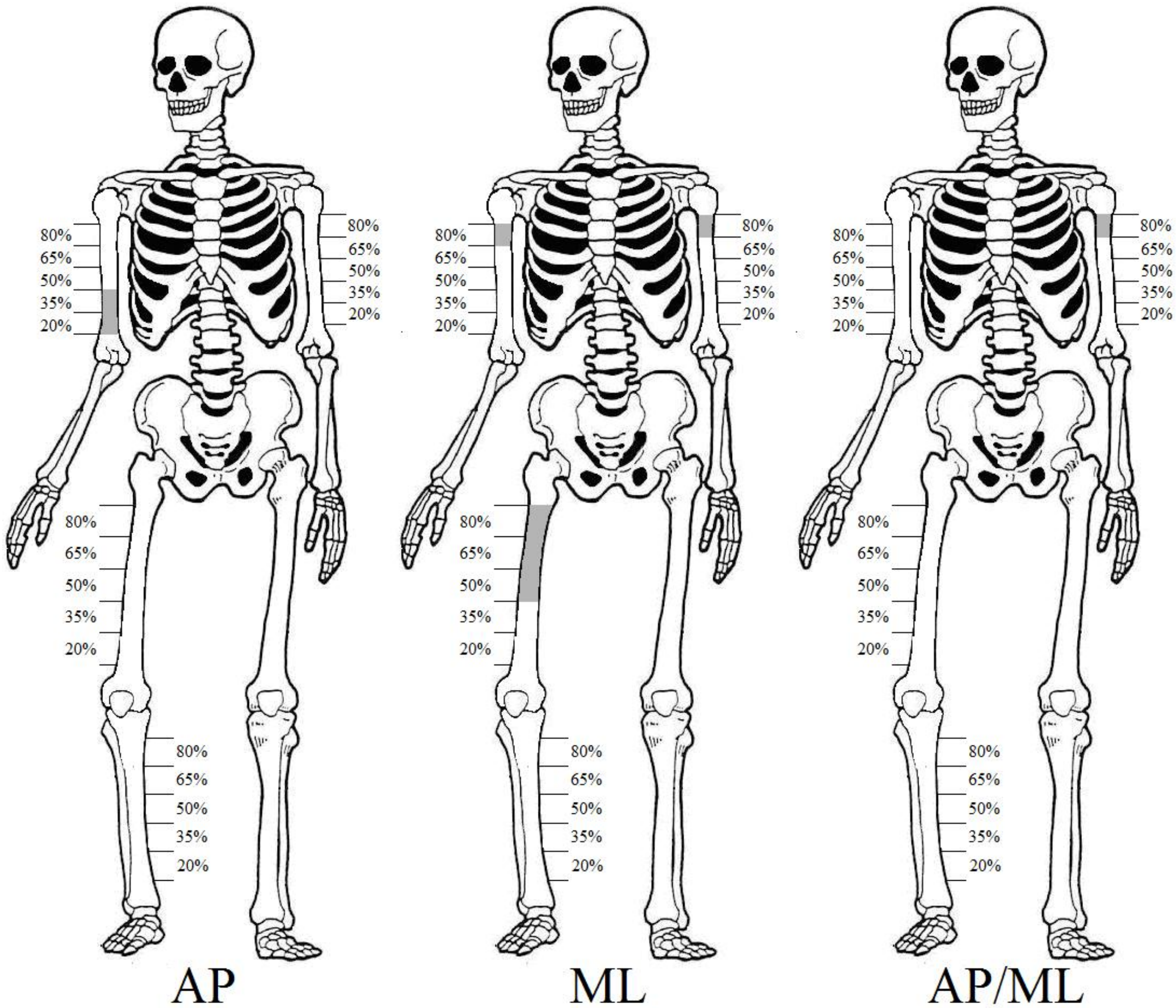

Figure 7: *Diagram of locations for which a significant BMI effect was reported.*
Image modified from Killgrave (www.killgrove.org/ANTH48/)
Dark grey- p<.05

b. Compensatory Behaviors Associated with Sit-to-Stand Movements

A wealth of biomechanical research exists which analyzes sit-to-stand (STS) movements, some of which focus explicitly on obesity. This analysis involves placement of reflective markers at major joint locations (hip, knee, ankle) and bone landmarks (e.g., along the spine), which are used as reference points while study participants are videotaped rising from a chair in different situations (e.g., with or without use of arms, with high seats or low seats). Researchers evaluate movement of the reflective markers in order to assess any kinematic or kinetic alterations made between groups in different situations, and to assess torque on different joints. Table 8.2 contains biomechanical terms and definitions utilized in this section (see Appendix III).

In evaluating the differences in STS motions of obese individuals without use of arms, researchers found that overweight individuals slide their feet dorsally before rising in order to reduce flexion of the torso and lighten the load on the lower back (Sibella et al., 2003; Bertocco et al. 2002; Galli et al., 2000). This is in contrast to normal weight individuals, who decreased the angle of the torso and refrained from moving their feet. Because higher trunk flexion correlates with higher forces of the hip joint (Sibella et al., 2003), the tendency of obese individuals to decrease the trunk angle actually reduces hip torque when compared to normal weight individuals, making BMI-related remodeling of the proximal femur difficult to explain, at least as related to standing from a seated position.

c. Compensatory Behaviors Associated with Gait

In an analysis of gait in normal and overweight men, Spyropoulos et al. (1991) found that overweight individuals displayed several key differences in walking strategy. For example, obese individuals had a step width twice that of normal weight individuals, resulting from greater abduction of the hip throughout all stages of the walking cycle. Increased step width in the obese was also found in gait-speed analyses (Browning and Kram, 2007). Increased hip abduction is presumably done to cope with excess adipose tissue of the inner thigh, and/or to maintain balance (Browning and Kram, 2007; Jadelis et al., 2001; Spyropoulos et al.,1991).

Gait analyses have also found that ground reaction forces (GRF) in obese individuals were greater than normal controls in both vertical, AP, and ML directions, with the largest differences in the latter (Browning and Kram, 2007). While increase in the AP plane of obese individuals is expected due to greater forces impacting the heel as it strikes, and required of the toe for pushing off, changes in the ML direction are more difficult to explain on the basis of normal action alone. An increase in the ML plane suggests that obese individuals strike the ground in an entirely different manner than do normal weight individuals. An increase in ML force could be associated with increased step width and/or a foot strike in which more stress is placed on either the medioplantar or lateroplantar sides of the foot, resulting in increased ML GRF responses. In fact, Lai et al. (2008) found that obese individuals had increased ankle eversion at many stages throughout the walking cycle, resulting in greater loads on the medial side of the foot.

Studies have also found that obese individuals spend more time in stance and less time in swing motion than did normal weight controls (Lai et al., 2008; DeVita and Hortobagyi, 2003), therefore exposing lower limb bones to longer periods of abnormal stress.

Browning and Kram (2007) found that while vertical and AP GRF increased linearly with weight, ML exceeded this proportion, with obese individuals having ML GRF forces over 80% greater than those observed in normal weight controls. This drastic increase in ML GRF force due to adiposity, coupled with associated kinematic alterations of step width, knee torque, increased stance length and ankle eversion could explain the ML-restricted remodeling of the proximal femur.

Although research shows that obese individuals alter the angles of joint placement in order to cope with obesity (Lai et al., 2008), gait analyses also show that while walking, knee and hip flexion/extension is not as strong in obese individuals as it is in normal weight individuals (DeVita and Hortobagyi, 2003). While it would seem acceptable to assume that greater muscular contraction (resulting in more forceful joint movements) would result in more rapidly-pronounced changes to bone structure, past research in bone remodeling shows that very little change is required to begin the remodeling process. In fact, Rubin and Lanyon (1984) found that as few as four cycles per day of under-average, abnormal load was sufficient to maintain bone mineral rates, and that 36 cycles was sufficient to enact peak bone remodeling rates of the periosteum in rooster ulnae. The influence of abnormal loads and stress-induced remodeling thresholds is also addressed in other bone remodeling research (Turner and Pavalko, 1998; Carter, 1984). Therefore, because obese people display abnormally-high rates of hip abduction due to increased step width, it is possible that even sub-average levels of mechanical action (as might be expected due to assumptions of inactivity) with associated “buffering” compensations to torque might be strong enough to elicit a remodeling response in the proximal femora- the only lower bone evaluated for which force does not run longitudinally through the diaphyseal axis. This might also explain the lack of response in the distal femur and proximal tibia, as knee joint angle and torque did not significantly differ between obese and normal weight individuals (DeVita and Hortobagya, 2003).

Another interesting aspect is the overall lack of BMI effect on the tibia which, aside from bones of the feet, carries more load than does any other skeletal element. Research in upper and lower limb cross-sectional robusticity found differential effects between proximal and distal limb segments, and between upper and lower limbs (Stock, 2006). Furthermore, Stock (2006) found that while the AP and ML bending strengths of the tibia correlated to terrain type (and therefore suspected mobility levels), this association was much stronger in the midshaft region of the femur. Stock concluded that “factors other than mobility may be more important in determining the shape of the tibial shaft” (Stock,2006:201). This is corroborated at the cellular level which showed that different locations of the skeleton remodeled at different rates and in different ways, and that stress was not always the main aggravator (Pearson and Leiberman, 2004).

d. Arm

Both humeri showed a significant effect of BMI at the proximal-most (80%) ML location. In both cases, the overweight category had the highest mean dimension. Similar results were not found in the literature. A possible explanation for this pattern is that overweight individuals more often use arms to push themselves up from a sitting or laying position, placing greater stress on the shoulder joint, though no biomechanical literature could be found which tested this hypothesis. Although the use of arms did not affect the range of motion (i.e., angles) of the legs when rising from a chair, it was found use of arms significantly decreased the amount of force upon the knee joint (Anglin and Wyss, 2000), from seven times body weight without use of arms to three times body weight with use of arms (Ellis et al., 1983). Because the force carried by the arms in rising from a chair reduces forces of the knee, it is possible that significant stress upon the shoulder joint would be experienced by individuals with a high BMI, explaining the positive effect of BMI on the proximal aspect of both humeri, though more research in this area is necessary.

III. BMI and Biomechanics of Osteoarthritis

Also of interest in this study is the overall lack of BMI effect on areas closest to the knee- distal femur and proximal tibia. Given the well-recorded associated between obesity and knee osteoarthritis (OA) in both sexes and all ancestries (Messier et al., 2005; Powell et al., 2005; Manek et al., 2003; Coggin et al., 2001; Cooper et al., 2000; Lau et al., 2000; Gelber et al., 1999; Hart et al., 1999; Cicuttini, 1996; Messier, 1994; Hartz et al., 1986; Leach, 1973), one would expect to see related structural differences of the femur and tibia. However, in an investigation into knee osteoarthritis, Andriacchi and Mundermann (2006) state that change in kinetics (malalignment) which alters load distribution is highly correlated to knee OA. Felson et al. (2004) concluded that obesity only affected OA in individuals with knee malalignment, and Sharma et al. (2000) similarly concluded that medial or lateral displacement of the knee greatly impacted the effect of obesity on OA. In the latter study, it was found that BMI significantly affected knee osteoarthritis only in individuals with varus (or lateral) displacement of the leg, a condition which results in higher rates of stress being placed upon the medial aspect of the knee joint (Figure 8). However, it remains uncertain whether obesity is the primary or secondary cause of knee OA in this study- i.e., “whether the influence of obesity on knee OA progression acts largely through malalignment” (Doherty, 2001). Rates of obese individuals with varus knee displacement were not reported.

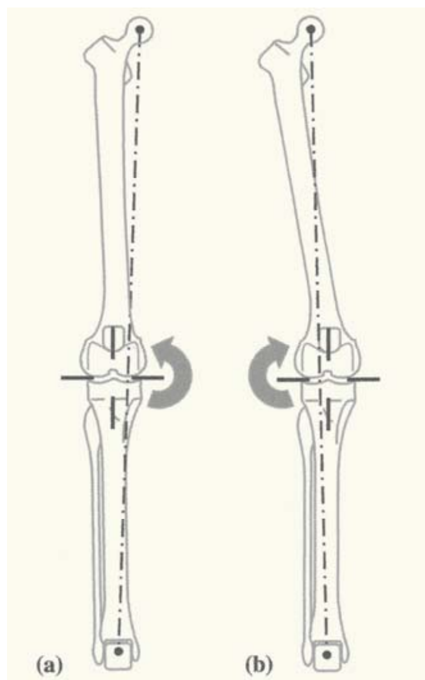

FIGURE 8. *Normal (right) and varus (lateral) displacement of the distal femur. Dashed line represents load-induced force (Sharma et al., 2000). Figure reproduced from Wearing et al. (2006)*

Although there is some argument over whether there is a correlation between obesity and hip OA, Cooper et al. (1998) found that while both hip injury and BMI were correlated to hip OA in British elderly males, hip injury was more often associated with unilateral hip OA while BMI correlated to bilateral OA (Cooper et al., 1998).

IV. Utility of MSMs in Biomechanical Analyses

MSMs did not show a significant BMI effect at any of the sites evaluated, though significant effects of age were found at the left and right attachments for the deltoid muscles, and the gluteal line and spiral line of the femur. A significant effect of age on MSM severity is not unique in the literature. In fact, Weiss (2004:236) states that age is the "best predictor of muscle scars."

Interesting is the overall lack of BMI effect (either positive or negative) on MSM expression, especially given the general assumptions of inactivity associated with overweight individuals (Kitagawa and Miyashita, 1978). There is general disagreement in the literature regarding whether overweight individuals are stronger or weaker than their normal weight contemporaries (Rolland et al., 2003; Hulens et al., 2002; Miyatake et al., 2000; Smelenda et al., 1998; Larsson et al., 1979; Kitagawa and Miyashita, 1978), however, the point may be moot. In fact, research shows that increased muscle strength does not prevent the likelihood of bone fracture (Hassager and Christiansen, 1989), suggesting that muscle action alone does not increase BMD, and may have less bearing on MSM expression than has been believed.

Some researchers argue that bone remodeling is both localized and selective, and furthermore that it occurs everywhere except for areas of muscle attachment. Hoyte and Enlow (1966), for example, state that active bone remodeling at sites of muscle attachment would be problematic by virtue of the fact that remodeling is synchronized deposition *and* resorption. Were resorption to occur at muscle attachment sites without any other anchoring mechanism, then the integrity of the surface to which muscle and tendon attach would be compromised, increasing the probability that muscle would tear from bone during use. Rather, Hoyte and Enlow state that "fibers within the generalized matrix of the bone…are directly continuous with the connective tissue framework of contiguous muscles [and] are exempt from this resorptive destruction" (Hoyte and Enlow, 1966; 208). The idea that bone and muscle are "contiguous" is increasingly supported through embryological and fetal developmental biology which emphasizes the fact that bone shares an embryological origin with muscle, tendon, and connective tissues, all of which arise from mesoderm (Kardong, 2009). This has led some anthropologists to advocate a stance in which bone is treated not as a distinct entity, but as part of a larger system subject to the same biological and genetic constraints as other organ systems of the body (Lovejoy, 2003).

Animal research appears to corroborate this belief. In a study comparing adult sheep exercised with added load to sedentary controls, Zumwalt (2006) found that muscle mass increased significantly for every muscle evaluated (even the masseter, which was not exposed to increased stress), but laser scan analysis of muscle attachment sites showed no significant morphological differences, even in clear instances of hypertrophy. At 90 days, the project was short in duration, however, it does raise question as to the reliability of MSM expression in activity assessments. Zumwalt (2006) argues that the body has biological defense mechanisms in place such that the continual microtrauma hypothesized to increase MSM robusticity is prevented. Like Hoyte and Enlow (1966), Zumwalt (2006) states that there is some evidence that bone remodeling thresholds differ by location, and that because MSMs are routinely subject to high stress, the threshold at these regions may be exceptionally high. Both suggestions are possible, especially as other animal research shows definite changes in other properties of bone (cross-sectional dimensions and cortical area) due to activity (Woo et al., 1981). Zumwalt (2006) advocates a skeptical approach to using MSM sites to infer activity, stating that past researchers may have neglected the biological mechanisms that serve to reduce the effect of muscle strain on bone, thereby combating any morphological change of the bone surface.

There are anthropologists and bioarchaoelogists who argue that although MSM severity is not straightforward, it is still a promising avenue for activity assessments. Weiss directly addresses Zumwalt's findings and states that animal bone remodeling might not be equitable to remodeling in humans due to lack of secondary osteons in animals (Weiss, 2003). In her study using an aggregation method (standardized averaging of many different attachment sites within a particular region), Weiss (2003) found that aggregated MSM expression of the arm correlated to cross-sectional robusticity, another indicator of activity.

However, aggregated MSM scores correlated more strongly to age, sex, and humeral size. Results were similar in the leg (Weiss, 2004). Interestingly, when evaluating MSMs singly, no correlation was found between any specific MSM site and age, sex, robusticity or bone size. Aggregation analyses, as well as evaluation of patterns rather than specific MSM sites (Robb, 1998) appear to be a progression in MSM methodology, and may partially address concerns regarding synergistic muscle use as expressed by Stirland (1998). According to Weiss (2004), pooling many observations in this manner reduces error variances, and increases the strength of the analysis. Therefore, it is possible that the lack of BMI significance in the Hamann-Todd data is the result of error associated with evaluation of single sites, as opposed to evaluating each element as a pooled dataset. However, it is worth noting that results of the MANOVA for MSM sites together still did not yield a significant effect of BMI.

Despite MSM ambiguity in anthropological contexts, there is research that shows generalized increased bone thickness due to activity, as exemplified in bilateral differences in the humeri of tennis players (Jones et al., 1977) and weight lifters (Karlsson et al., 2005). However, as pointed out by Lovejoy et al. (2003), many of these studies include individuals who have been practicing their sport since childhood and adolescence, a time at which bone remodeling occurs at a very high rate. However, it is also possible that the threshold theory of bone remodeling (Ruff et al., 2006; Rubin and Lanyon, 1985; Carter, 1984) is also applicable to sites of muscle attachement, and that despite any biological "defense mechanisms" which may be in place to avoid MSM increases, extreme muscle use associated with intense physical activity (i.e., weight lifting and/or prolonged athletic training) still elicits an increase in bone remodeling at the attachment site due to chronic overextension of the remodeling thresholds. This may occur until the bone has sufficiently bolstered the muscular attachment against these stresses. This hypothesis may partially explain and justify the utility of MSM analyses in archaeological contexts.

CONCLUSION

This research project has shown that weight does have an effect on sagittal loads of the midshaft and proximal femur in white males, eliciting a remodeling response which serves to bolster the ML dimension of overweight individuals in this region. It is possible that biomechanical alterations of gait, including increased step width, longer stance phase, and increased mediolateral ground reaction forces coupled with increased weight all impact the way that movement forces travel through the leg. Due to this abnormal force movement, localized remodeling thresholds of the proximal femur are exceeded, eliciting a remodeling response which increases the mediolateral dimension.

Bilateral BMI effects were also found in the most proximal ML dimension of the humeri. Limited research in shoulder joint biomechanics limit the interpretative power of this result, however, research does show that pushing oneself up from a seated position, greatly reduces loads on the knee joint, and may be a potential cause of mediolateral strengthening of the proximal humerus. Not surprisingly, age was correlated to increases in both AP and ML dimensions of most of the bones evaluated, a notable exception being the AP dimension of the tibia.

Musculoskeletal stress markers were not found to be a good method of differentiating between overweight and normal or underweight individuals due to the high variability of expression within each BMI class and the significant effect of age. Lack of significant BMI effect on MSM expression could be due to misclassification of heavily muscled individuals into the overweight category, genetic influences, ambiguity in MSM scoring, or differing levels and types of activity among individuals of the same BMI class. Also possible is that, due to their nature, sites of muscle attachment follow different rules of remodeling, requiring localized stresses to exceed a much higher threshold than do non-attachment site locations. This may explain why MSMs have been so successful in archaeological interpretations of activity, but have shown limited interpretive power when applied to modern populations with drastically reduced activity loads and cycles.

Results of this research are a positive step toward differentiation of overweight individuals through use of skeletal material. Significant differences between weight groups were uncovered, prompting need for further investigation with regard to sex and ancestry using larger, more recent collections with additional individual background information (such as occupation).

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APPENDICES

APPENDIX I

Table 8.1. *Inventory and biological profile of European males included in this project*

628	24	young	162	29.4	over	1581	Y	Y	Y	Y
653	26	young	185	26.8	over	1771	Y	Y	Y	Y
247	30	young	190	28.8	over	1727	Y	Y	Y	Y
338	30	young	175	26.5	over	1727	Y	Y	Y	Y
456	30	young	160	26.7	over	1651	Y	Y	Y	Y
1474	32	young	191	30.3	over	1691	Y	Y	Y	Y
428	35	young	150	28.3	over	1549	Y	Y	Y	Y
500	35	young	180	27.3	over	1727	Y	Y	Y	Y
714	35	young	189	26.6	over	1796	Y	Y	Y	Y
328	38	young	200	26.8	over	1841	Y	Y	Y	Y
380	38	young	180	26.7	over	1752	Y	Y	Y	Y
581	38	young	197	29.1	over	1752	Y	Y	Y	Y
626	38	young	159	26.8	over	1640	Y	Y	Y	Y
1080	38	young	178	27	over	1730	Y	Y	Y	Y
279	40	middle	190	28.1	over	1752	Y	Y	Y	Y
347	40	middle	180	28.3	over	1701	Y	Y	Y	Y
359	40	middle	300	47.1	over	1701	Y	Y	Y	Y
429	40	middle	165	27.5	over	1651	Y	Y	Y	Y
431	40	middle	200	28.6	over	1778	Y	Y	Y	Y
587	40	middle	181	27.1	over	1739	Y	Y	Y	Y
615	40	middle	265	37	over	1803	Y	Y	Y	Y
314	42	middle	150	26.6	over	1600	Y	Y	Y	Y
194	44	middle	208	31.2	over	1739	Y	Y	Y	Y
2441	44	middle	120	26.5	over	1638	Y	Y	Y	Y
257	45	middle	200	30.3	over	1727	Y	Y	Y	Y
532	45	middle	158	29.1	over	1574	Y	Y	Y	Y
1234	45	middle	174	29.6	over	1634	Y	Y	Y	Y
214	47	middle	150	26.6	over	1600	**N**	**N**	Y	**N**
745	48	middle	192	27.2	over	1788	Y	Y	Y	Y
1371	48	middle	215	27.8	over	1872	Y	Y	Y	Y
398	50	middle	160	27.3	over	1625	Y	Y	Y	Y
432	50	middle	170	27.3	over	1676	Y	Y	Y	Y

Table 8.1 Continued

832	50	middle	165	26.8	over	1670	Y	Y	Y	Y
966	50	middle	200	29.6	over	1750	Y	Y	Y	Y
1667	50	middle	204	28.7	over	1797	Y	Y	Y	Y
468	51	middle	180	26.7	over	1752	**N**	**N**	Y	**N**
2151	52	middle	135	29	over	1452	Y	Y	Y	Y
2189	52	middle	150	26.7	over	1595	Y	Y	Y	Y
1531	54	middle	197	29.1	over	1751	**N**	**N**	Y	**N**
2239	54	middle	190	26.6	over	1799	Y	Y	Y	Y
309	55	middle	160	29.4	over	1574	Y	Y	Y	Y
396	55	middle	170	26.7	over	1701	Y	Y	Y	Y
477	55	middle	160	26.7	over	1651	Y	Y	Y	Y
505	55	middle	175	27.5	over	1701	Y	Y	Y	Y
611	55	middle	205	27.8	over	1828	Y	Y	Y	Y
1381	55	middle	195	27.1	over	1805	Y	Y	Y	Y
1472	55	middle	148	40	over	1295	**N**	**N**	Y	**N**
1495	55	middle	180	27.1	over	1737	Y	Y	Y	Y
2577	56	middle	184	28.9	over	1698	Y	Y	Y	Y
869	58	middle	196	27.1	over	1810	Y	Y	Y	Y
556	60	old	212	31.8	over	1739	Y	Y	Y	Y
651	60	old	220	34.5	over	1701	Y	Y	Y	Y
1486	61	old	208	28.3	over	1726	Y	Y	Y	Y
899	64	old	139	26.6	over	1539	Y	Y	Y	Y
483	67	old	175	26.5	over	1727	Y	Y	Y	Y
405	68	old	190	28.8	over	1727	Y	Y	Y	Y
353	68	old	190	28.1	over	1752	Y	Y	Y	Y
2273	68	old	216	34.5	over	1686	Y	Y	Y	Y
216	70	old	175	27.5	over	1701	Y	Y	Y	Y
1292	71	old	205	27	over	1855	Y	Y	Y	Y
323	74	old	150	31.5	over	1473	Y	Y	Y	Y
1017	77	old	177	27.6	over	1707	Y	Y	Y	Y
203	80	old	160	29.4	over	1574	Y	Y	Y	Y
381	82	old	160	26.7	over	1651	Y	Y	Y	Y
688	24	young	145	23.8	normal	1663	Y	Y	Y	Y
394	26	young	140	22.5	normal	1676	Y	Y	Y	Y
310	30	young	140	21.2	normal	1727	Y	Y	Y	Y
142	30	young	125	21.3	normal	1625	**N**	**N**	Y	**N**

Table 8.1 Continued

484	30	young	125	20.1	normal	1676	Y	Y	Y	Y
1541	32	young	121	22.8	normal	1687	Y	Y	Y	Y
470	35	young	140	21.2	normal	1727	**N**	**N**	Y	**N**
491	35	young	130	22.2	normal	1625	Y	Y	Y	Y
750	35	young	133	21.6	normal	1672	Y	Y	Y	Y
389	38	young	150	23.5	normal	1701	Y	Y	Y	Y
481	38	young	150	23.5	normal	1701	Y	Y	Y	Y
706	38	young	155	24.7	normal	1672	Y	Y	Y	Y
801	38	young	154	22.9	normal	1746	**N**	**N**	Y	**N**
1079	38	young	135	20.7	normal	1719	Y	Y	Y	Y
443	40	middle	150	23.5	normal	1701	Y	Y	Y	Y
449	40	middle	175	23.7	normal	1828	Y	Y	Y	Y
459	40	middle	140	23.3	normal	1651	Y	Y	Y	Y
586	40	middle	159	23.8	normal	1739	Y	Y	Y	Y
601	40	middle	129	20.8	normal	1676	Y	Y	Y	Y
723	42	middle	127	20	normal	1699	Y	Y	Y	Y
962	44	middle	134	22.8	normal	1634	Y	Y	Y	Y
1330	44	middle	130	21.8	normal	1645	Y	Y	Y	Y
531	45	middle	150	23.3	normal	1717	Y	Y	Y	Y
1304	45	middle	108	21.3	normal	1515	**N**	**N**	Y	**N**
570	47	middle	129	20.8	normal	1676	Y	Y	Y	Y
843	48	middle	176	24.6	normal	1802	Y	Y	Y	Y
1395	48	middle	148	22.3	normal	1735	Y	Y	Y	Y
440	50	middle	150	22.7	normal	1727	Y	Y	Y	Y
465	50	middle	150	24.7	normal	1663	Y	Y	Y	Y
836	50	middle	132	20.7	normal	1699	Y	Y	Y	Y
993	50	middle	126	23.2	normal	1571	**N**	**N**	Y	**N**
1645	50	middle	140	20.9	normal	1745	Y	Y	Y	Y
1881	51	middle	138	20.1	normal	1766	Y	Y	Y	Y
2508	52	middle	133	20.5	normal	1717	**N**	**N**	Y	**N**
1808	54	middle	149	22.6	normal	1728	Y	Y	Y	Y
2222	54	middle	130	22.8	normal	1607	Y	Y	Y	Y
303	55	middle	160	23.7	normal	1752	Y	Y	Y	Y
499	55	middle	140	21	normal	1739	Y	Y	Y	Y
865	55	middle	142	22.8	normal	1682	Y	Y	Y	Y
1386	55	middle	125	20.5	normal	1664	Y	Y	Y	Y
1492	55	middle	132	20.2	normal	1720	Y	Y	Y	Y

Table 8.1 Continued

1764	55	middle	130	20.6	normal	1693	Y	Y	Y	Y
2631	56	middle	132	20.1	normal	1724	Y	Y	Y	Y
1956	58	middle	130	21.2	normal	1667	Y	Y	Y	Y
660	60	old	131	19.4	normal	1752	Y	Y	Y	Y
1561	61	old	135	21.1	normal	1703	**N**	**N**	Y	**N**
1588	64	old	140	22.1	normal	1696	Y	Y	Y	Y
720	67	old	135	20.9	normal	1711	Y	Y	Y	Y
534	68	old	135.5	23.1	normal	1625	Y	Y	Y	Y
828	68	old	135	21.8	normal	1675	Y	Y	Y	Y
3042	68	old	160	22.8	normal	1784	Y	Y	Y	Y
838	70	old	149	22.8	normal	1720	Y	Y	Y	Y
1644	71	old	135	20.5	normal	1729	Y	Y	Y	Y
114	74	old	125	20.1	normal	1676	Y	Y	Y	Y
1034	77	old	155	20.1	normal	1676	**N**	**N**	Y	**N**
3219	80	old	133	20.2	normal	1730	Y	Y	Y	Y
1307	82	old	115	22.6	normal	1520	**N**	**N**	Y	**N**
1769	24	young	110	16.9	under	1718	Y	Y	Y	Y
296	25	young	100	16.7	under	1651	Y	Y	Y	Y
1873	30	young	110	15.4	under	1798	Y	Y	Y	Y
2305	30	young	86	15.9	under	1567	Y	Y	Y	Y
2806	30	young	107	16	under	1743	Y	Y	Y	Y
1355	32	young	98	16.8	under	1629	Y	Y	Y	Y
790	34	young	90	16.1	under	1592	Y	Y	Y	Y
1336	35	young	95	15	under	1695	Y	Y	Y	Y
799	36	young	101	16.3	under	1674	Y	Y	Y	Y
826	38	young	104	16.5	under	1693	Y	Y	Y	Y
2532	38	young	100	14.6	under	1761	Y	Y	Y	Y
2689	38	young	108	15.8	under	441	Y	Y	Y	Y
2729	37	young	107	16.3	under	1728	Y	Y	Y	Y
1246	39	young	110	16.7	under	1730	Y	Y	Y	Y
1158	40	middle	121	17	under	1797	Y	Y	Y	Y
1362	40	middle	115	16	under	1807	Y	Y	Y	Y
2580	40	middle	89	15.9	under	1593	Y	Y	Y	Y
2778	40	middle	104	16.8	under	1675	Y	Y	Y	Y
2919	40	middle	112	16.4	under	1762	**N**	**N**	Y	**N**
3191	40	middle	96	15.2	under	1695	Y	Y	Y	Y
2223	42	middle	105	15.2	under	1771	Y	Y	Y	Y

Table 8.1 Continued

819	44	middle	104	15.6	under	1739	Y	Y	Y	Y
2384	44	middle	88	16.3	under	1564	Y	Y	Y	Y
1212	45	middle	113	16.1	under	1787	Y	Y	Y	Y
1359	45	middle	95	15.5	under	1666	Y	Y	Y	Y
833	46	middle	115	15.8	under	1819	Y	Y	Y	Y
1090	47	middle	82	15.1	under	1570	Y	Y	Y	Y
771	48	middle	82.5	15.6	under	1547	Y	Y	Y	Y
2618	48	middle	93	14.2	under	1723	Y	Y	Y	Y
218	50	middle	100	16.1	under	1676	Y	Y	Y	Y
769	50	middle	107	17	under	1691	Y	Y	Y	Y
841	50	middle	110	16.9	under	1720	Y	Y	Y	Y
1018	50	middle	117	16.4	under	1799	Y	Y	Y	Y
1132	51	middle	108	17	under	1698	Y	Y	Y	Y
1065	52	middle	97	15.5	under	1684	Y	Y	Y	Y
2425	52	middle	112	17	under	1731	Y	Y	Y	Y
1322	54	middle	115	16.8	under	1763	Y	Y	Y	Y
2559	54	middle	92	16	under	1615	Y	Y	Y	Y
3203	55	middle	91	14.6	under	1681	Y	Y	Y	Y
3073	55	middle	110	16.1	under	1760	Y	Y	Y	Y
2950	55	middle	96	16	under	1648	Y	Y	Y	Y
1503	55	middle	110	16.2	under	1753	Y	Y	Y	Y
2766	55	middle	115	16.6	under	1771	**N**	**N**	Y	**N**
2918	55	middle	97	16.6	under	1630	Y	Y	Y	Y
2710	56	middle	104	15.7	under	1734	Y	Y	Y	Y
2466	58	middle	110	16.2	under	1754	Y	Y	Y	Y
996	60	old	105	15.5	under	1752	Y	Y	Y	Y
1048	60	old	106	16.3	under	1715	Y	Y	Y	Y
1210	64	old	107	16.4	under	1718	Y	Y	Y	Y
1341	67	old	95	16.3	under	1625	Y	Y	Y	Y
992	68	old	87	15.2	under	1610	Y	Y	Y	Y
2297	68	old	113	16.1	under	1786	Y	Y	Y	Y
752	70	old	93	15.5	under	1649	Y	Y	Y	Y
2647	71	old	110	15.7	under	1784	Y	Y	Y	Y
810	74	old	106	16.9	under	1685	Y	Y	Y	Y
1068	77	old	103	16.2	under	1697	Y	Y	Y	Y
1021	81	old	91	16.2	under	1594	Y	Y	Y	Y

"N" *indicates bone for which data were not collected.*

APPENDIX II

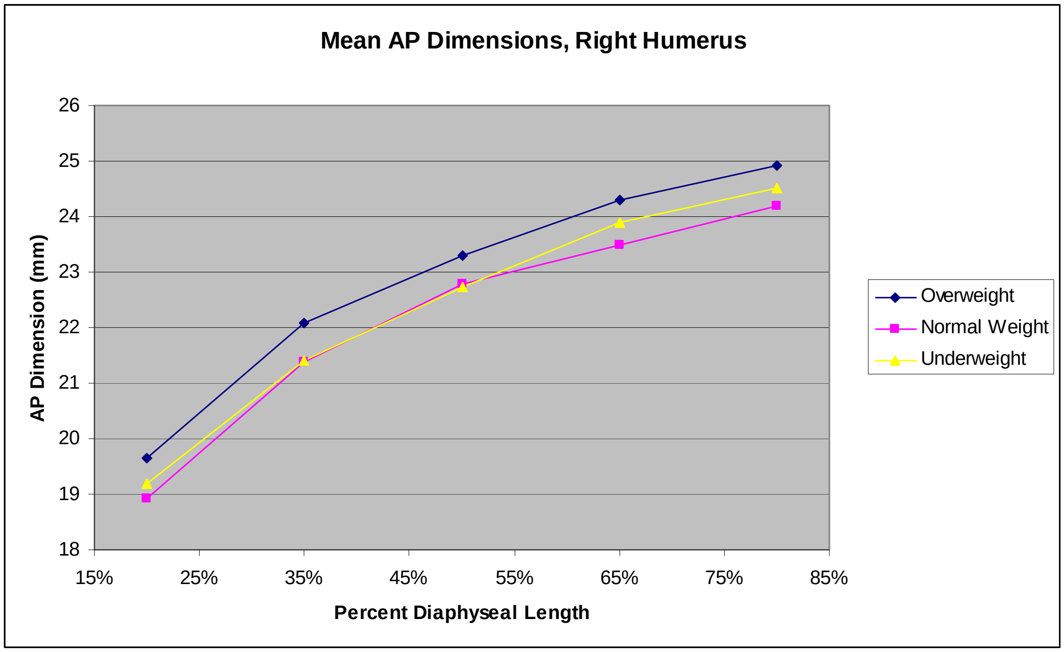

Figure 9. *Line plot of mean AP dimension by BMI classification in right humerus*

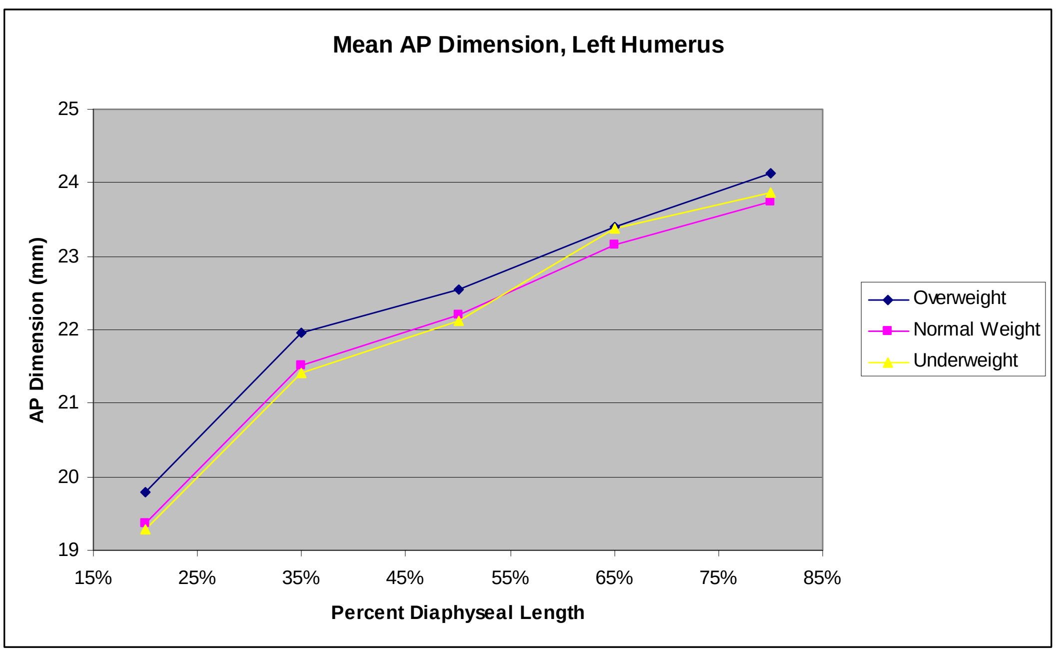

Figure 10: *Line plot of mean AP dimension by BMI classification in left humerus*

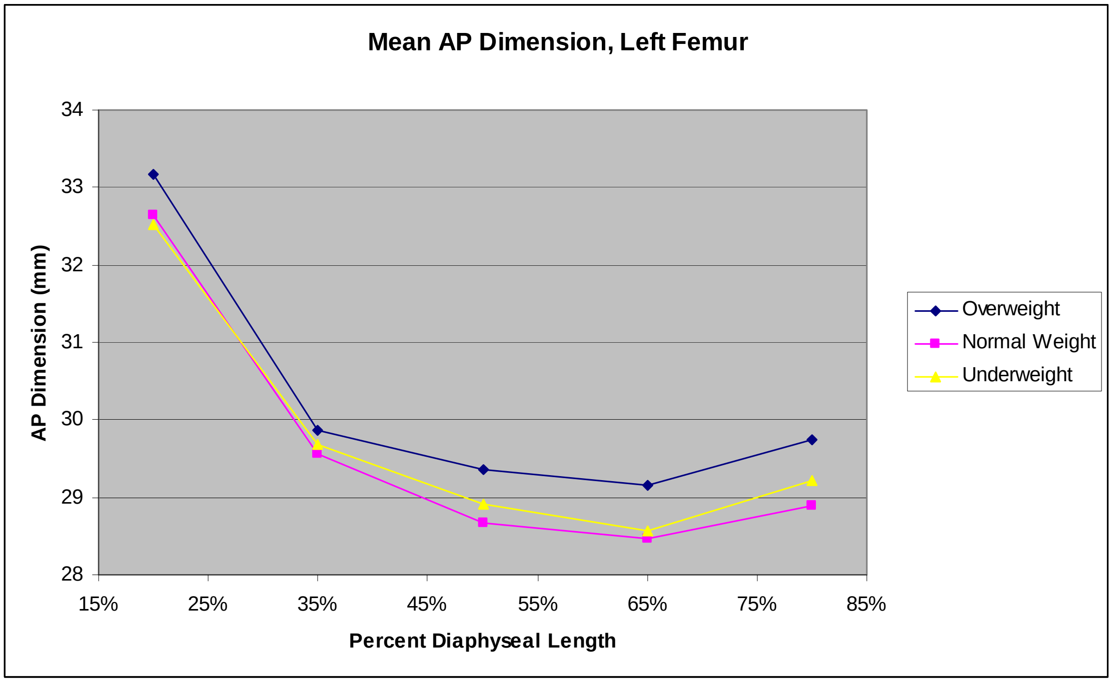

Figure 11. *Line plot of mean AP dimension by BMI classification in left femur*

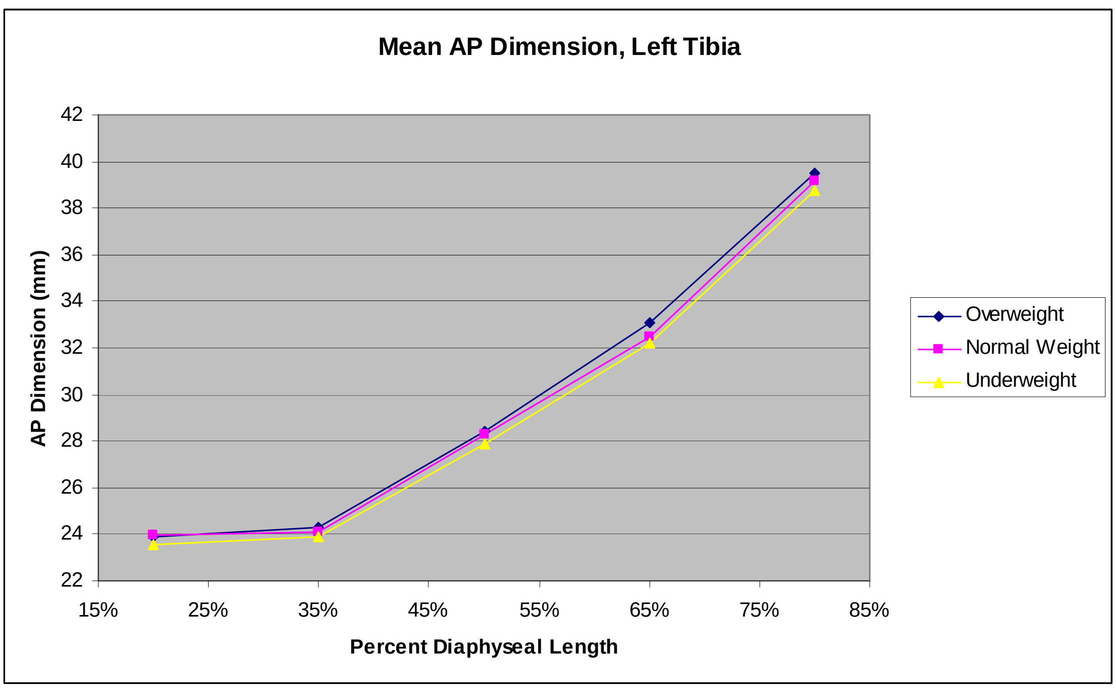

Figure 12. *Line plot of mean AP dimension by BMI classification in left tibia*

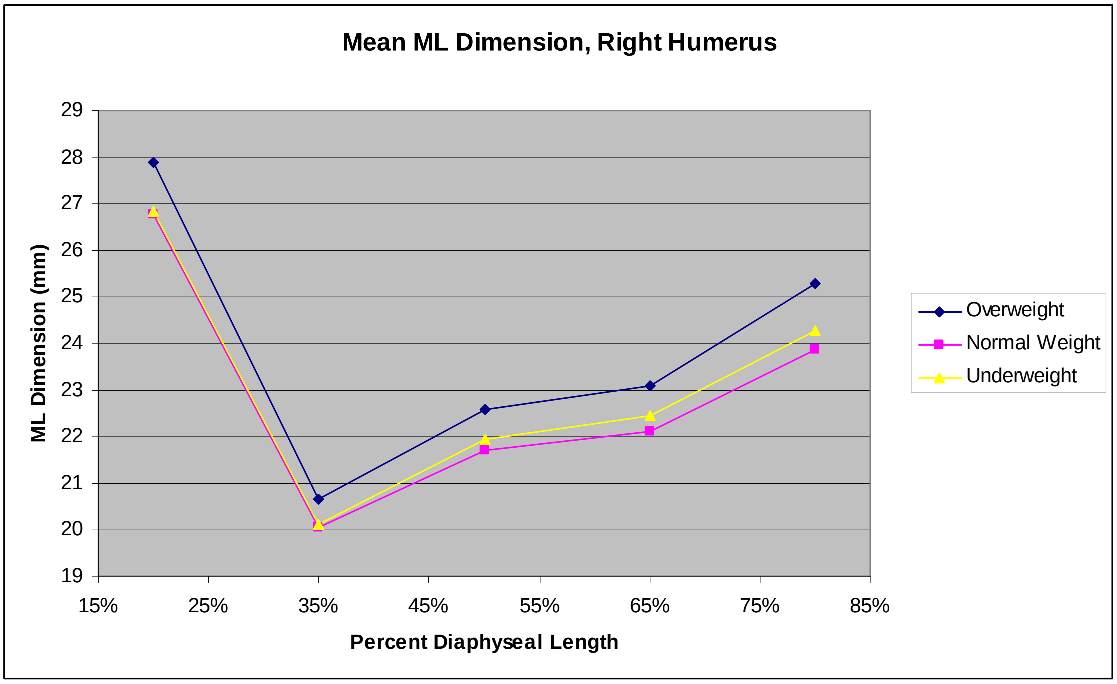

Figure 13. *Line plot of mean ML dimension by BMI classification in right humerus*

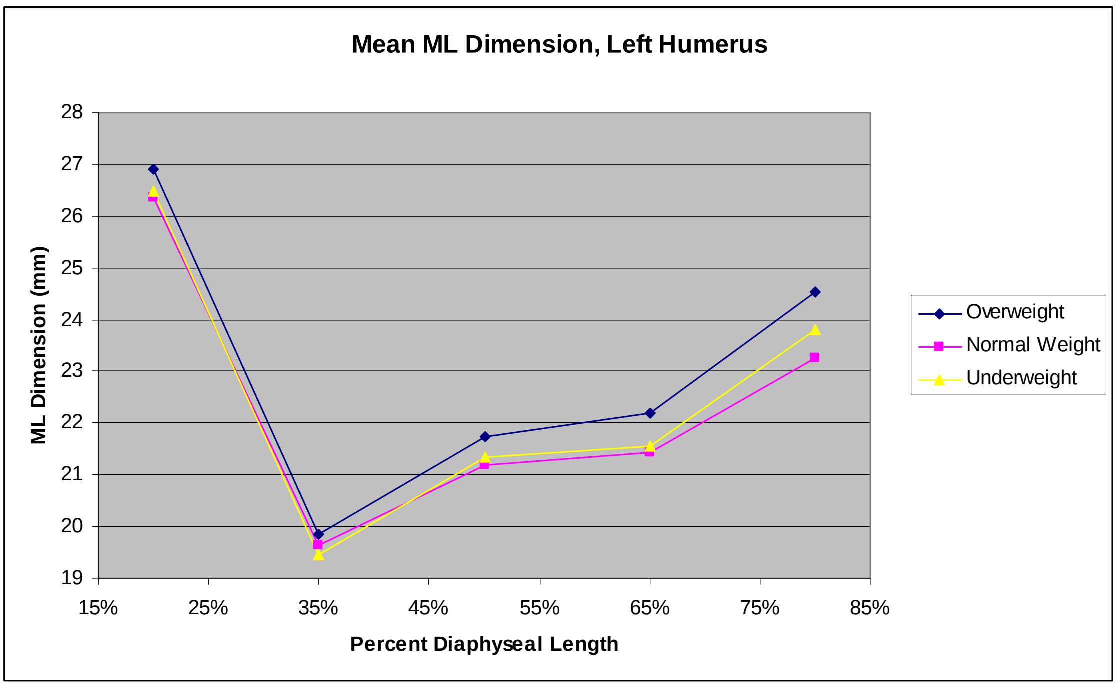

Figure 14. *Line plot of mean ML dimension by BMI classification in left humerus*

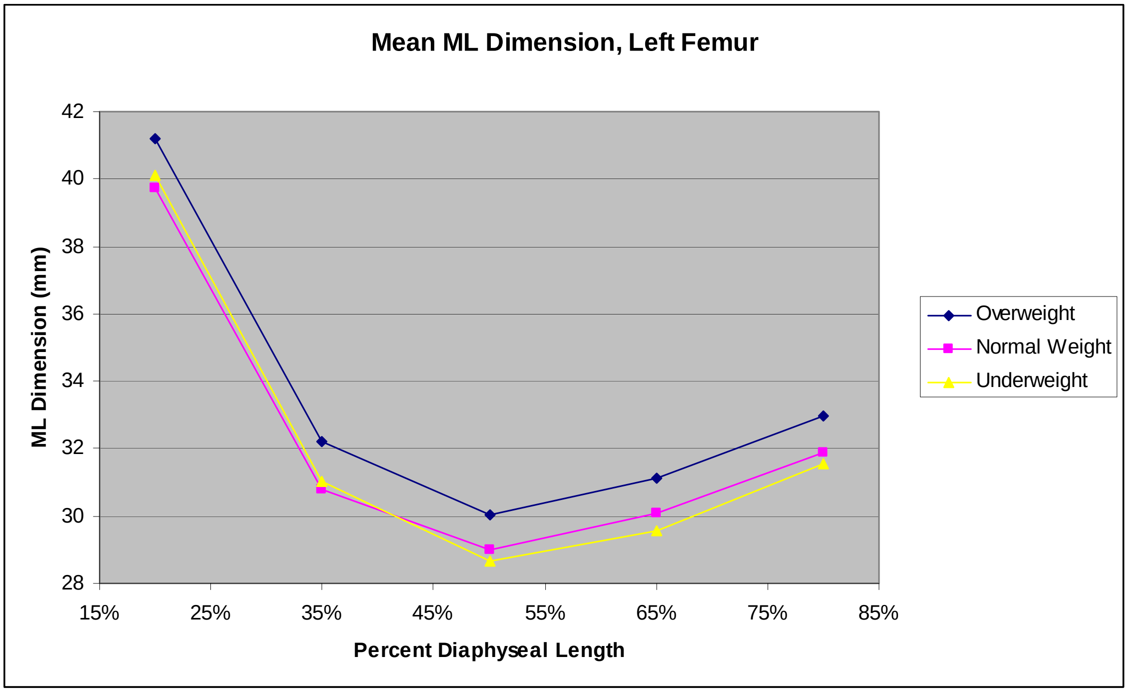

Figure 15. *Line plot of mean ML dimension by BMI classification in left femur*

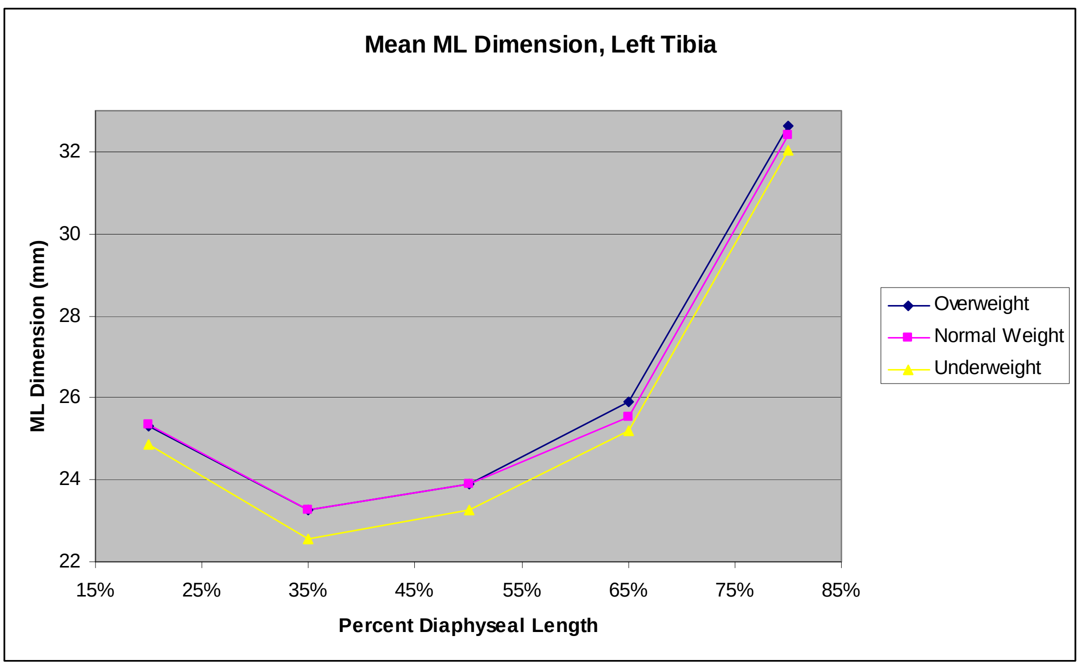

Figure 16. *Line plot of mean ML dimension by BMI classification in left tibia*

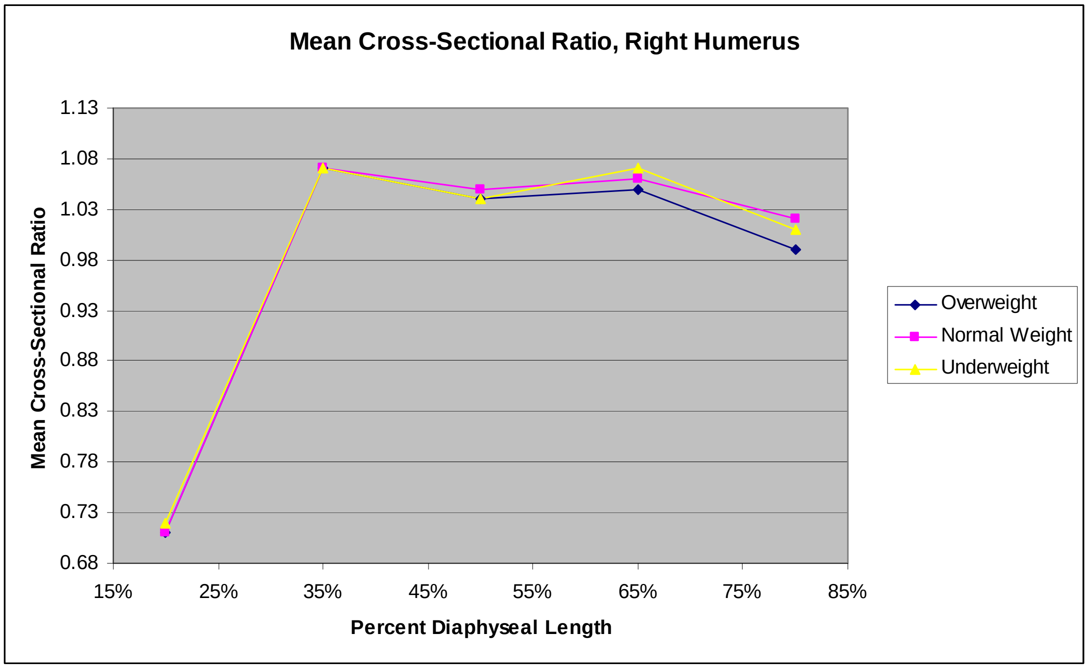

Figure 17. *Line plot of mean cross-section by BMI classification in right humerus*

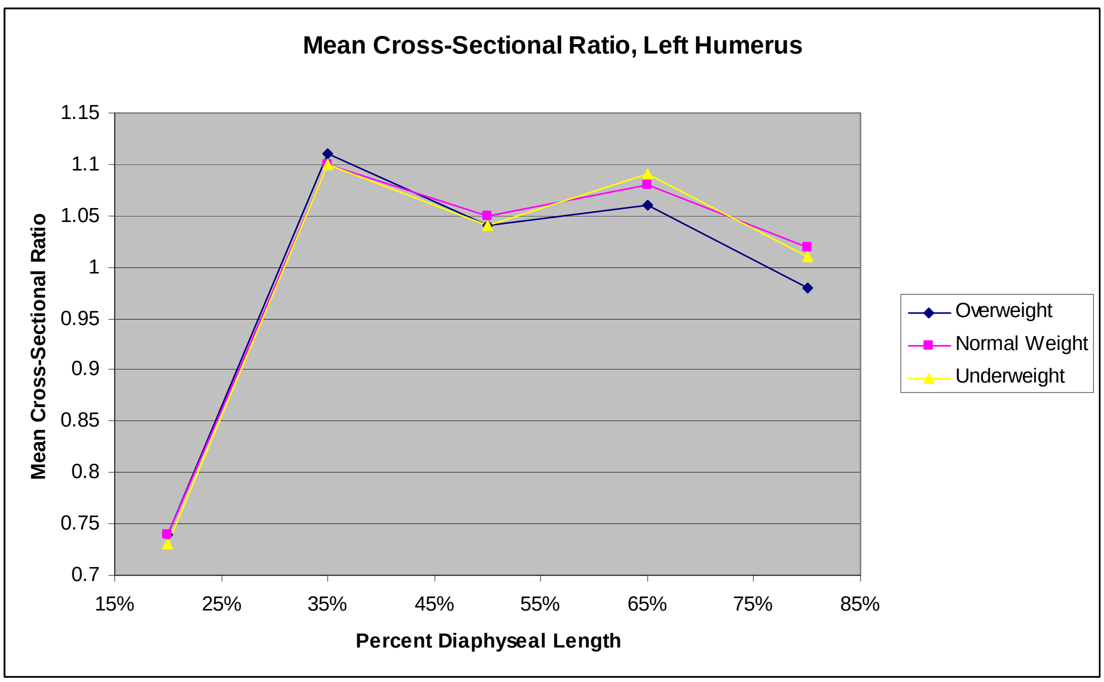

Figure 18. *Line plot of mean cross-section by BMI classification in left humerus*

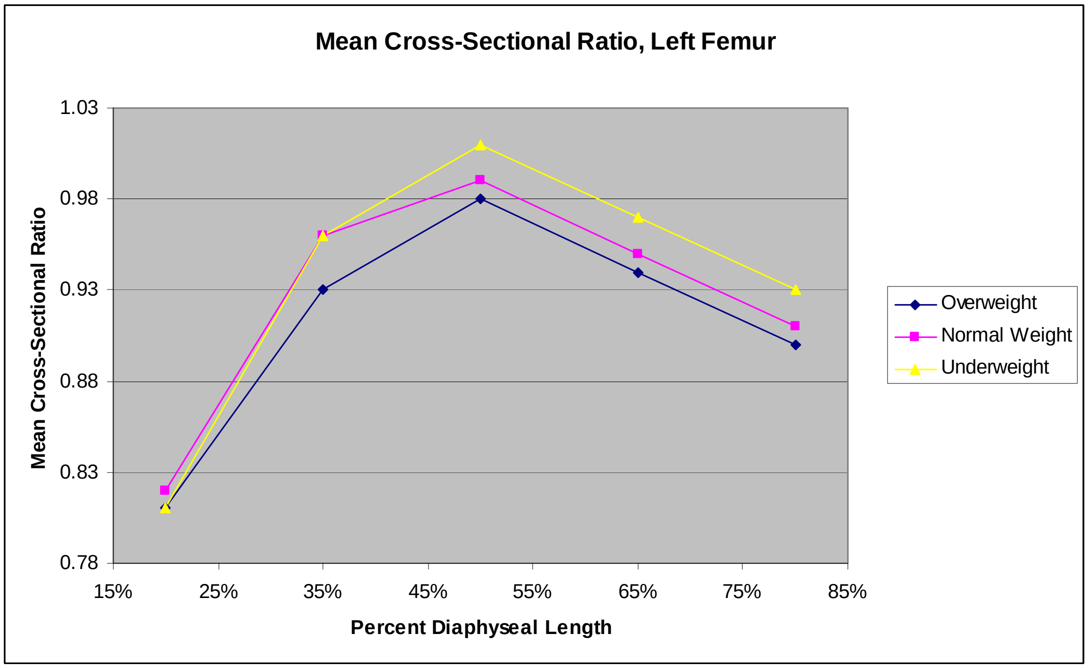

Figure 19. *Line plot of mean cross-section by BMI classification in left femur*

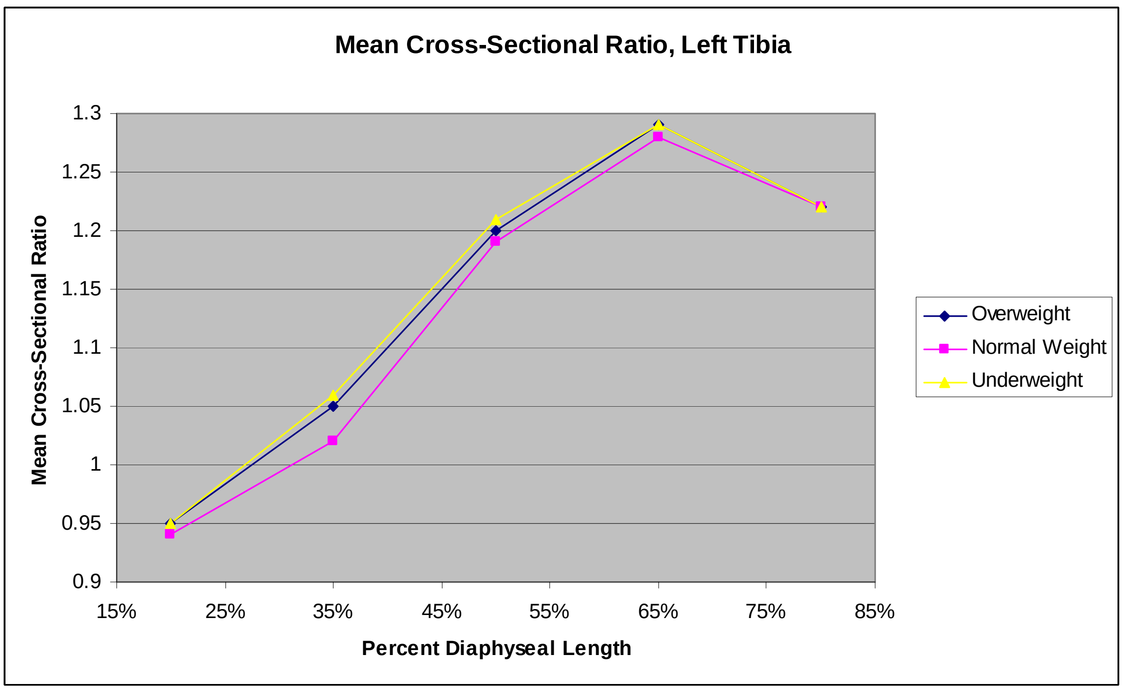

Figure 20. *Line plot of mean cross-section by BMI classification in left tibia*

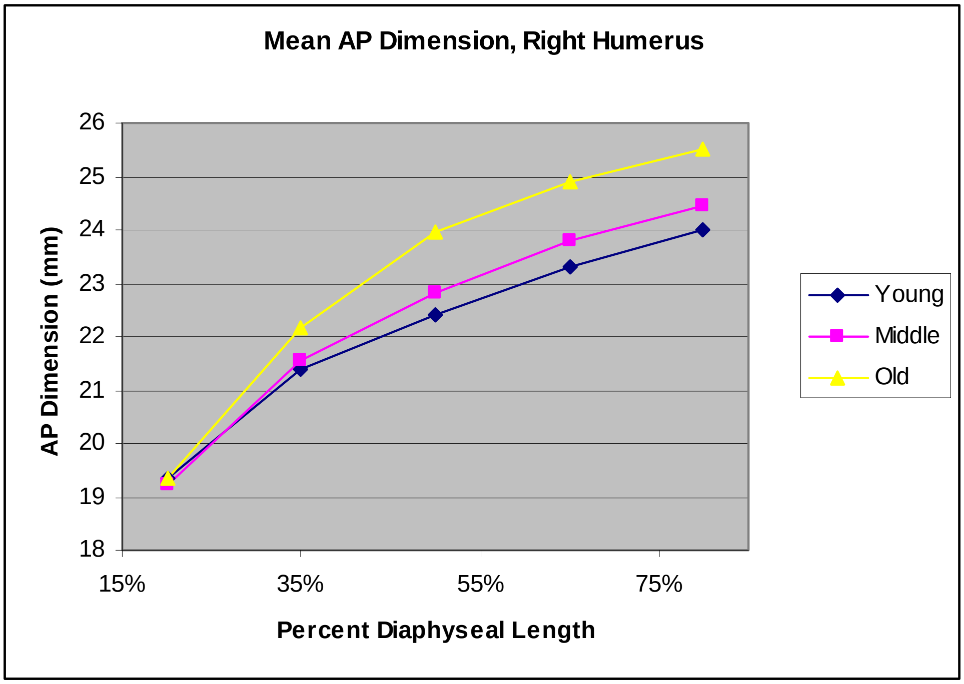

Figure 21. *Line plot of mean AP dimension by age classification in right humerus*

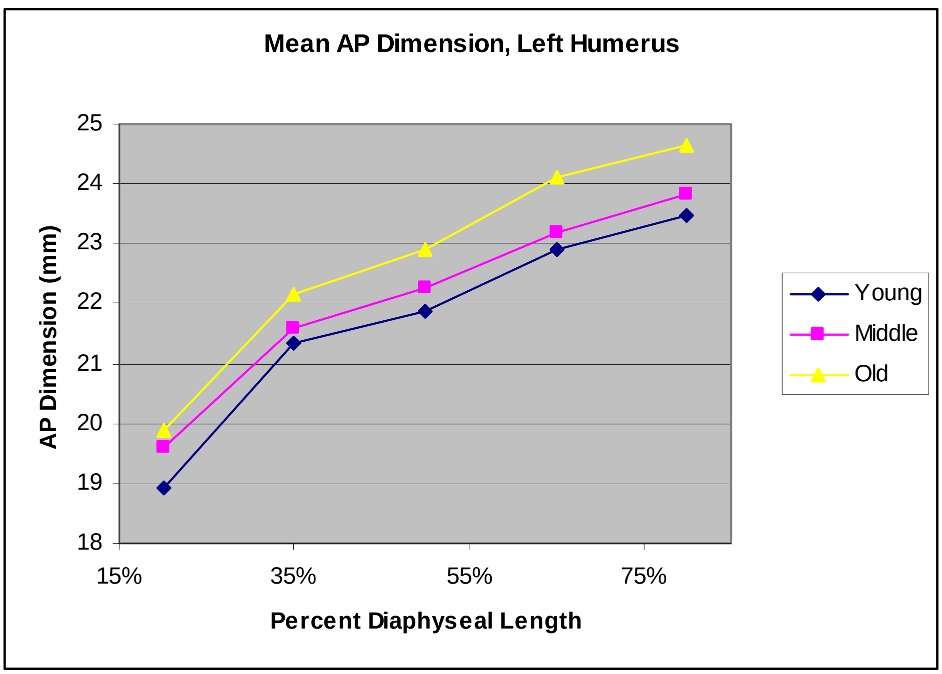

Figure 22. *Line plot of mean AP dimension by age classification in left humerus*

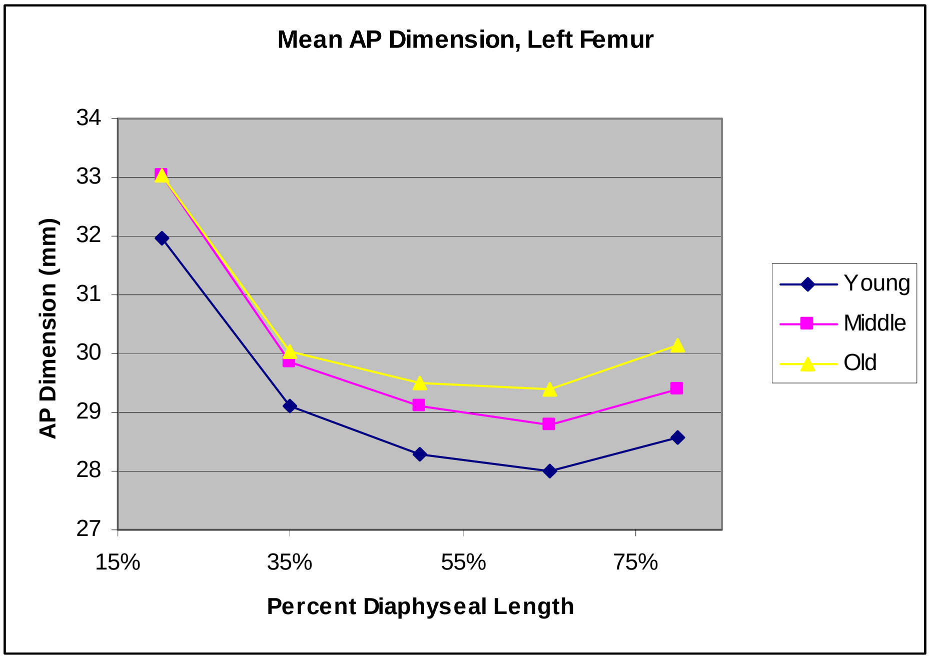

Figure 23. *Line plot of mean AP dimension by age classification in left femur*

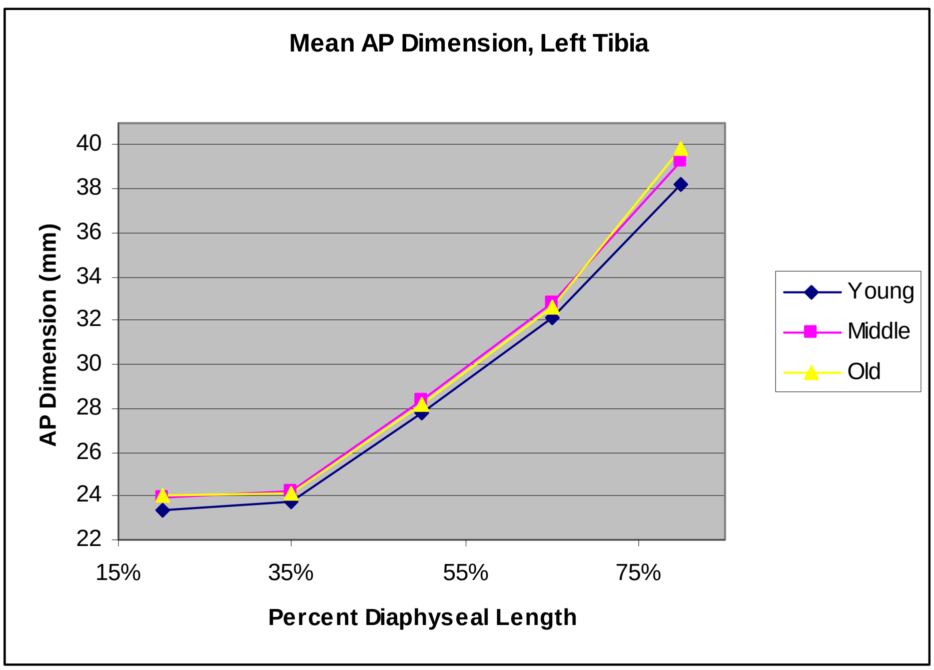

Figure 24. *Line plot of mean AP dimension by age classification in left tibia*

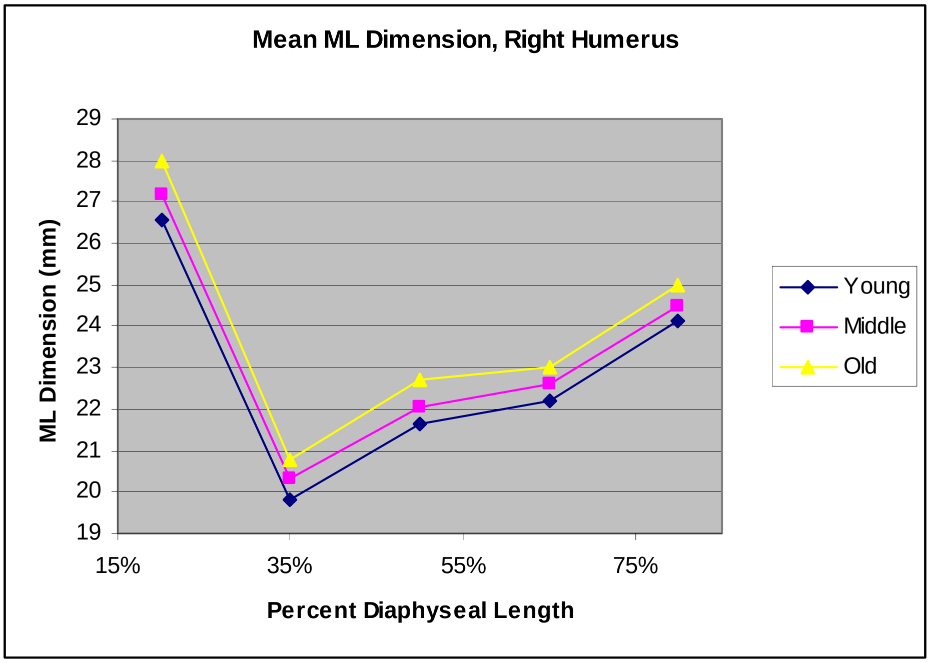

Figure 25. *Line plot of mean ML dimension by age classification in right humerus*

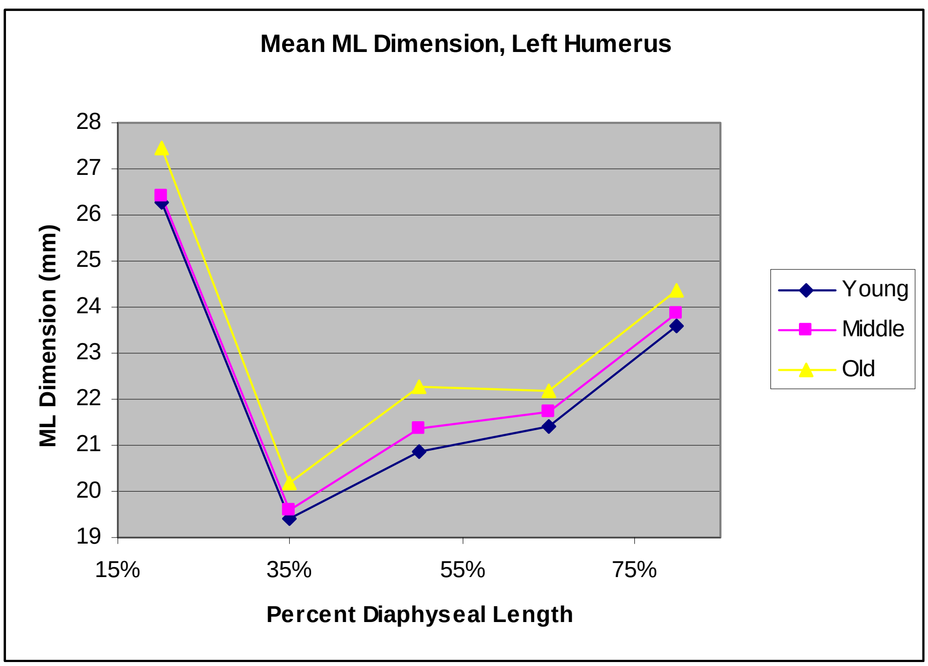

Figure 26. *Line plot of mean ML dimension by age classification in left humerus*

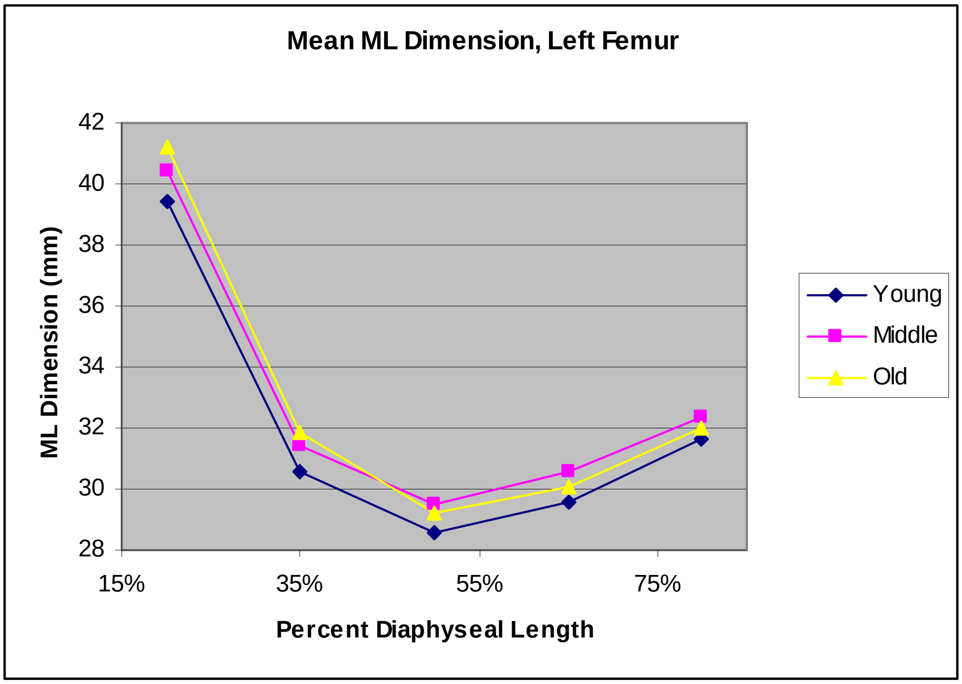

Figure 27. *Line plot of mean ML dimension by age classification in left femur*

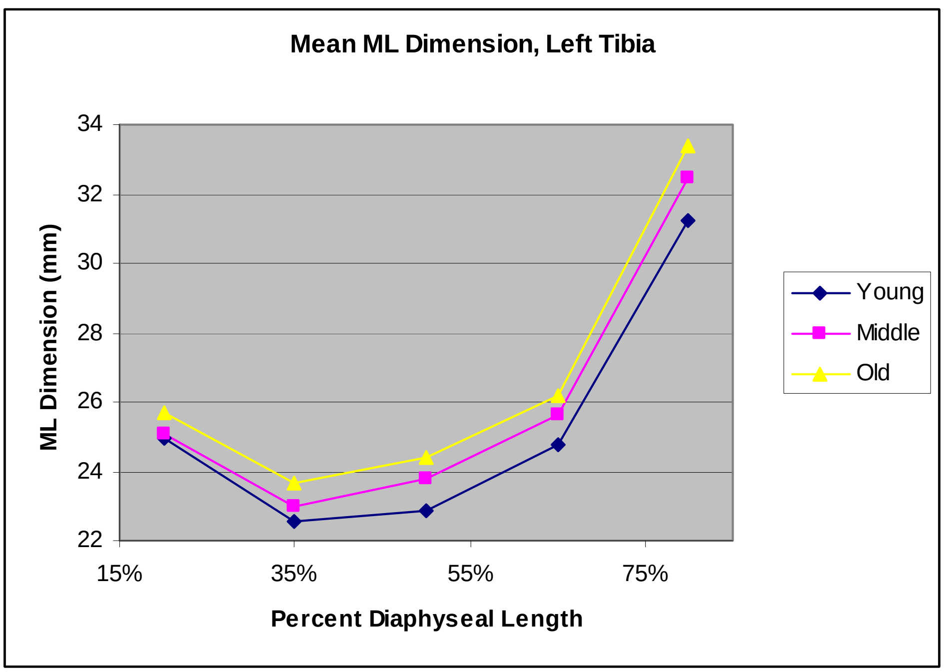

Figure 28. *Line plot of mean ML dimension by age classification in left tibia*

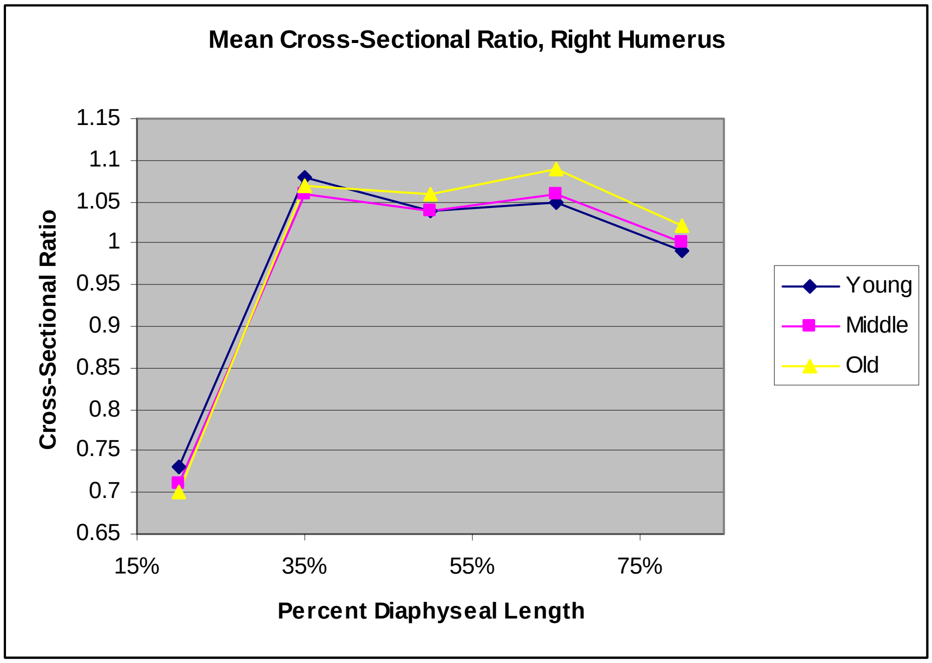

Figure 29. *Line plot of mean cross-sectional ratio by age classification in right humerus*

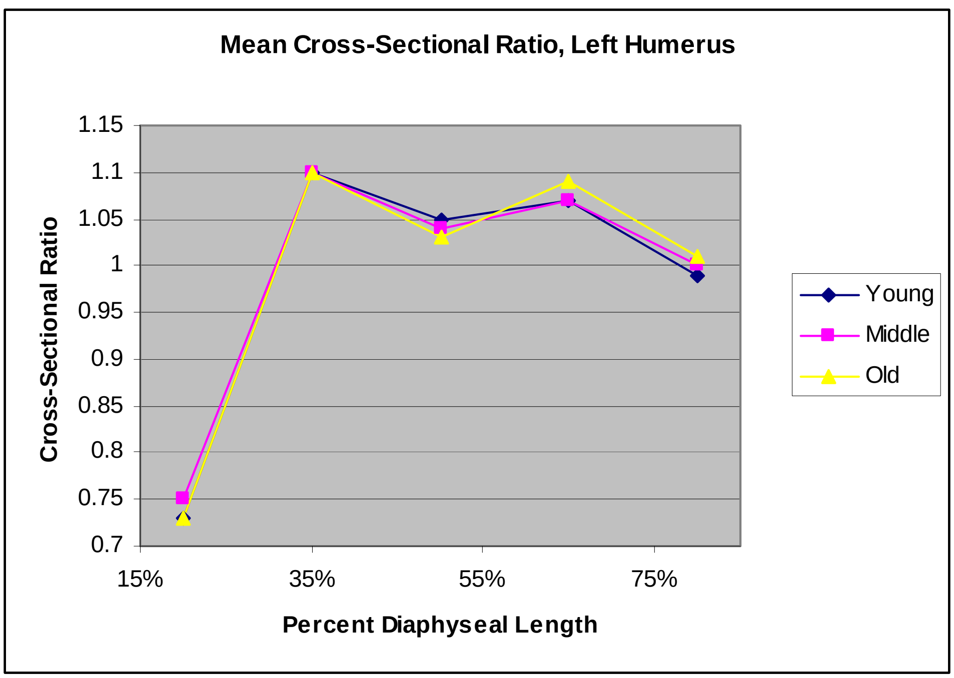

Figure 30. *Line plot of mean cross-sectional ratio by age classification in left humerus*

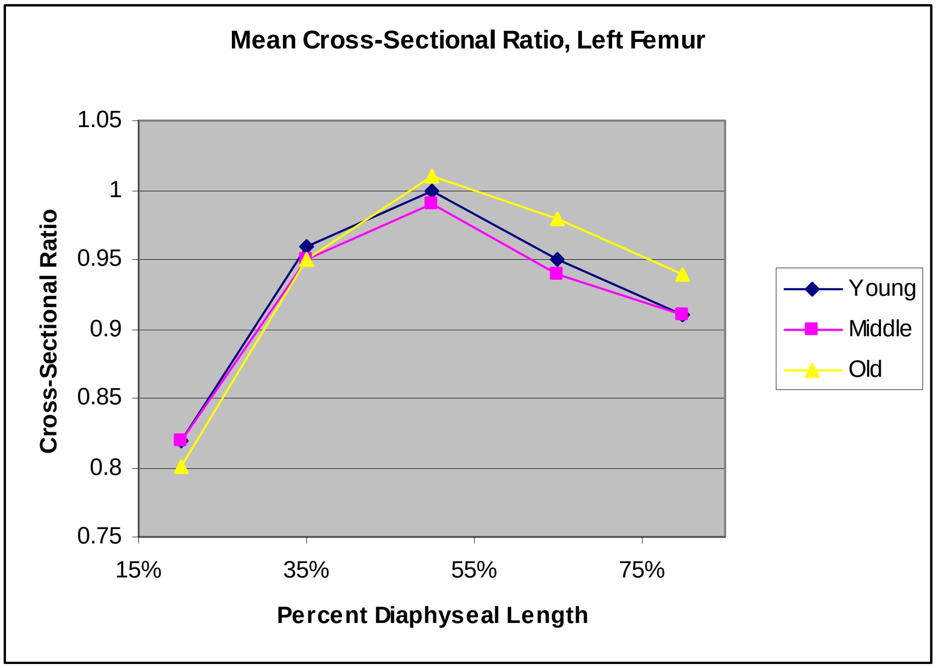

Figure 31. *Line plot of mean cross-sectional ratio by age classification in left femur*

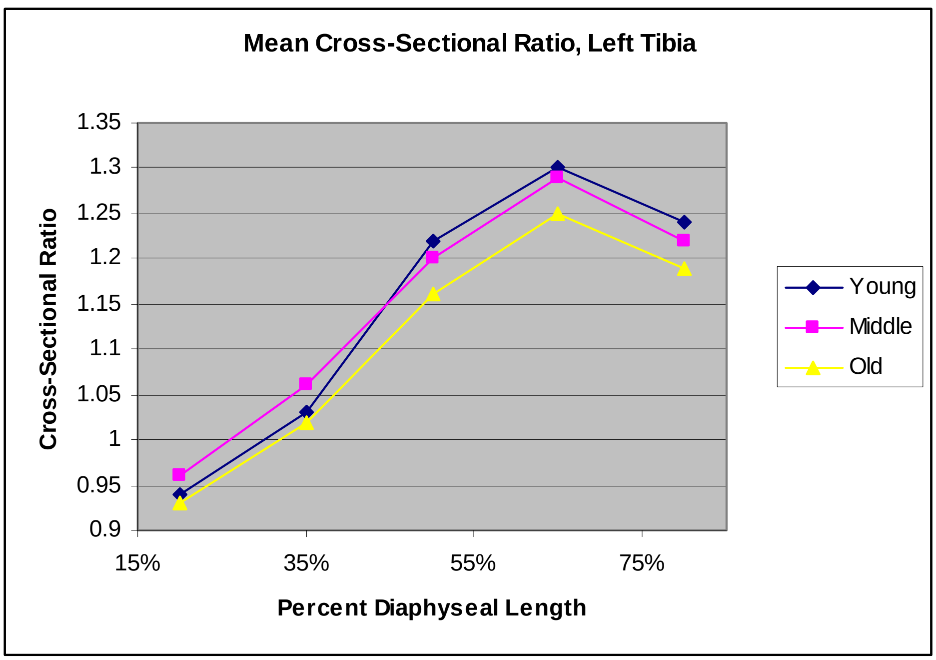

Figure 32. *Line plot of mean cross-sectional ratio by age classification in left tibia*

APPENDIX III

Table 8.2. *Summary of biomechanical terminology*

Biomechanical Term	Definition
Kinetics	The biomechanical study of forces associated with body movement.
Kinematics	The biomechanical study of geometrical principles (e.g., joint angle alterations) of body movement.
Moment	"Moment of force," often associated with bending forces.
Torque	Force associated with torsion or rotation.
AP GRF (x)	Ground reaction force moving in a horizontal anteroposterior direction. Equal and opposite of the force exerted on the ground by the body.
ML GRF (z)	Ground reaction force moving in a horizontal mediolateral direction. Equal and opposite of the force exerted on the ground by the body.
Vertical Force (y)	Ground reaction force moving in a vertical direction. Equal and opposite of the force exerted into the ground by the body.
Rigidity	Resistance of an object to deformation
Vector	A force that has both magnitude and direction (e.g., moment and torque).

Definitions from Ruff (2008), Nigg and Herzog (2007), and Nordin and Frankel (2001).

APPENDIX IV

Figure 33. *Scale of deltoid tubercle of the humerus. Scores are presented from left to right (1A, 1B, 1C, 2 and 3).*

Figure 34. *Scale of distolateral aspect of the humerus. Scores are presented from left to right (1A, 1B, 1C, 2 and 3).*

Figure 35. *Scale of the gluteal line of the femur. Scores are presented from left to right (1A, 1B, 1C, 2 and 3).*

Figure 36. *Scale of intertrochanteric crest of the femur. Scores are presented from top left to bottom right (1A, 1B, 1C, 2 and 3)*

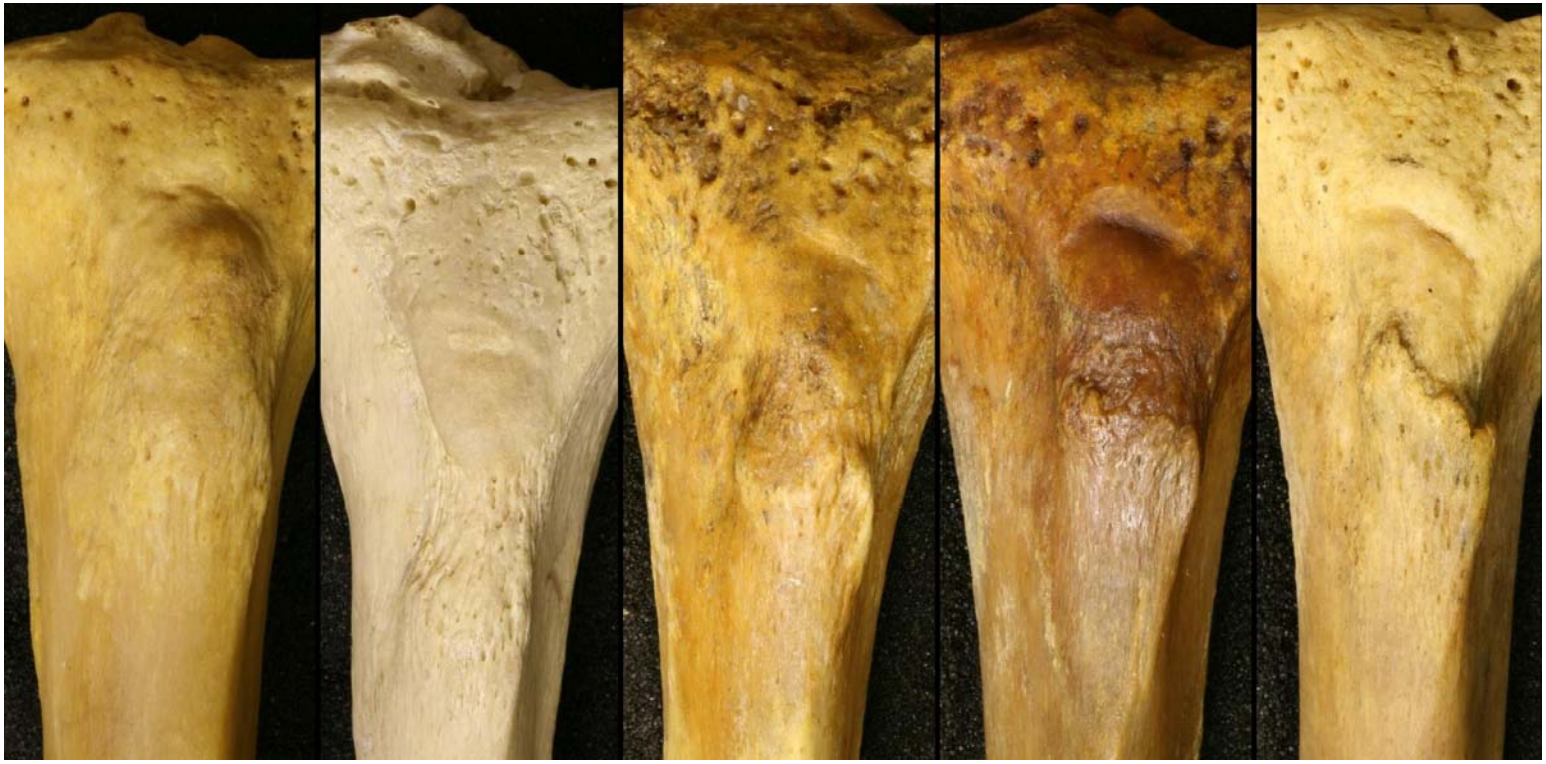

Figure 37. *Scale of tibial tuberosity of the tibia. Scores are presented from left to right (1A, 1B, 1C, 2 and 3).*

Figure 38. *Scale of soleal line of the tibia. Scores are presented from left to right (1A, 1B, 1C, 2 and 3).*