Health and Aging in Medieval and Post-medieval Denmark

By

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A thesis submitted to the Faculty of Graduate Studies of

The University of Manitoba

in partial fulfillment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

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Abstract

Using traditional and innovative osteological methods, skeletal degeneration and bone strength were assessed. The aims of the research were to analyze patterns of aging and differences in the manifestation of degeneration by sex, body size, and lifestyle. Two skeletal samples from medieval and post-medieval Denmark were analyzed for disorders associated with aging and increased body mass, the rural cemetery of Tirup (12th – 14th C.) and the urban cemetery of Black Friars (13th – 17th C.). This was a time of significant socioeconomic, environmental, and residential transition. During the medieval period Christianity replaced the old Viking Pagan religions, urbanization increased, the climatic downturn of the Little Ice Age affected crop yields and food security, and infectious disease, specifically the Black Death epidemic, decimated the population. Recognizing the effects of age, sex, and socioeconomic status on the health experience of Danes as they lived through these changes is important to understanding life in medieval and post-medieval Denmark. By analyzing trends in stature, body mass, femoral robusticity, and indulgence- and age-related degeneration, the results suggest that individuals living in the rural area were healthier than those living in the urban area. The results also present a temporal trend towards decreasing health from the medieval to the post-medieval period. The Protestant Reformation (1536 CE) seems to have affected urban females more significantly than males. Post-medieval female femoral strength increased significantly while male femoral strength remained constant. In an attempt to gain economic freedom in increasingly difficult times, many females sought employment in unconventional and physically demanding positions.

Age-related health patterns are complex and multi-faceted. Using conventional methods for age-estimation may obscure patterns of aging in the oldest individuals. Using the more precise age-at-death estimates from transition analysis (Milner and Boldsen 2012a), the current research indicates that stature increased in older age categories (70 years-at-death), but tall stature was detrimental to extended longevity (past 70 years of age). This trend was paralleled by several age- and indulgence related disorders. This research provides a comprehensive examination of health and aging in medieval and post-medieval Denmark with specific reference to the burgeoning urbanization revolution and changing political, religious, and environmental climate.

Acknowledgements

Having your PhD supervisor call you and tell you that she has accepted a position at another university and that you must either continue your degree with a new supervisor of begin you PhD again at a new university is not a pleasant experience. For me, however, it ended up being a wonderful opportunity as Dr. Rob Hoppa became my supervisor. I am so thankful to have had Rob as a mentor. Having Rob as a supervisor is like joining a large academic family. Being in Winnipeg felt less lonely and attending conferences became fun instead of a chore. Without his support and guidance, I would likely not have completed this degree. Thank you, Rob. I would also like to thank my PhD committee, Dr. Linda Larcombe and Dr. Heidi Marx for their guidance and support. It was wonderful to have such a knowledgeable and positive committee.

I would like to extend a special thank you to the Odense City Museums and Horsens Museum for access to the skeletal collections and to the ADBOU team in Odense, Denmark, Bodil Thelaide, Jesper Boldsen, Svenja Weiss, Dorthe Dangvard Pedersen, Peter Tarp, and Vicki Lillegård Kristensen. I greatly appreciate your openness and willingness to help (and for all the cake). I would specifically like to thank Bodil for her time spent answering my emails, helping me find accommodations in Odense, and taking me on excursions! Thank you also to the department of forensics at SDU for access to the CT scanner and to the technicians who trained me on how to use it.

I would also like to thank my funding sources – SSHRC Doctoral Fellowship (#752-2018-2041), SSHRC Insight Grant (#435-2017-729) awarded to R. Hoppa, University of Manitoba Graduate Fellowship, and the J.G. Fletcher Argue Award – and the Department of Anthropology at the University of Manitoba, the Faculty of Arts, and the Faculty of Graduate

Studies. Thank you for the opportunity to continue learning. Without your support I would not have been able to complete this research. I am honoured and humbled to have been chosen as a PhD candidate at the University of Manitoba.

Finally, I would like to take the time to thank my family and friends. I am proud and gratified to have such a strong support network. Thank you. Neil, thank you for staying by my side and calming me down from my countless mental and emotional breakdowns throughout this process. I love you and I am so thankful to have such a wonderful supporting husband by my side. To my mother, I cannot thank you strongly enough. If I could award you an honourary doctorate, I would. I am so appreciative of the countless hours you spent reading and editing this thesis, painstakingly removing the commas that I had sprinkled throughout the document. Thank you also for babysitting Theo so that I could get work done. Thank you to my father and sister who have supported me throughout my academic journey. Thank you to the new friends I made in Winnipeg, LS, AS, JA, SD, and DW. I am grateful to be able to call you part of my academic family. To my longtime friends, HE, AS, KS, and MP, thank you for believing in me, expressing interest in my research, never tiring of listening to me vent about academia, and for being able to take my mind off school when I needed it (and sometimes when I didn't). I love you all. THANK YOU!

For Theo.

Never stop learning.

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Chapter 1: Introduction

Studying the skeleton is an important avenue for understanding health in past ages. The examination of archaeological bone can elucidate biological and physical influences to which individuals were exposed. Written in bone is much of an individual's life history. As such, health research has been a central focus for bioarchaeologists. Understanding skeletal degeneration in the past can aid in comprehending the life and health of prehistoric populations as well as examine claims made in the historical literature. Skeletal health patterns can be used to understand the impacts of larger biocultural events as well as speak to differences in the historical and contemporary aging process. Skeletal analyses should recognize the broader implications of the interplay between biology, culture, and the environment. In this research skeletal indicators of overall health, namely stature, body mass, and degeneration (both indulgence- and age-related) are used to assess the impact of political, social, and environmental transitions in medieval and post-medieval Denmark.

The current research analyzes aspects of Danish medieval and post-medieval health in the rural sample of Tirup (ca. 1150 – 1350 CE) and the urban sample of Black Friars (ca. 1240 – 1607 CE). Differences in health patterns will be discussed in terms of location (rural versus urban), time period (medieval versus post-medieval), age-at-death, sex, and body size. Within these categories, trends in stature, body mass, indulgence-/body size-related disorders and degeneration, osteoporosis, and femoral robusticity will be assessed, placing this research within the plethora of bioarchaeological health research. Analyzing health patterns in the oldest individuals in a skeletal population is crucial to understanding archaeological health experience. The oldest individuals survived periods of ill health and, thus, can be understood as the healthiest individuals in the skeletal sample (Wood et al. 1992). It has been suggested that archaeological populations maintain bone strength more readily into older age due to more physically demanding lifestyles (Agarwal et al. 2004; Brickley 2002; Ruff and Hayes 1983). With more precise estimates of age in older adults, a greater understanding of age-related degeneration is explored.

1.1 Purpose and Significance

The current research analyzes trends in degeneration and robusticity in medieval (1000 – 1536 CE) and post-medieval (1536 –1660 CE) skeletal samples from Denmark. This period presents an excellent opportunity for analyzing the different influences in health patterns, as Denmark underwent significant socioeconomic, environmental, and residential transition during this time. This period saw Christianity replace the old Viking Pagan religions, an increase in urbanization, the climatic downturn of the Little Ice Age which affected crop yields and food security, and infectious disease, specifically the Black Death epidemic, decimate the population. Recognizing the effects of age, sex, and socioeconomic status on the health experience of Danes as they lived through these changes is important to understanding life in medieval and post-medieval Denmark. For many, the transition to Christianity led to an improvement in health. With the abolishment of slavery and revenge killings of the Viking age (Sawyer and Sawyer 1993), life expectancy increased (Benedictow 2003). The "urbanization revolution" that took place between the 12th and 13th centuries (Hybel and Poulsen 2007) affected the overall health of medieval Europeans (Boldsen 1990; Dyer 2002; Lewis 2002; Lewis and Gowland 2007; Judd and Roberts 1999; Palubeckaite et al. 2002; Petersen et al. 2006; Rasmussen et al. 2015; Sundman and Kjellstrom 2013; Werdelin et al. 2002). Health is often described as poorer in urban than in rural samples, associated with overcrowding, poor air quality, lower physical activity, and increased indulgence among urbanites (Dyer 2002; Lewis and Gowland 2007;

Pounds 2005). Recent research has questioned this analysis as it pertains to medieval and post-medieval Denmark, suggesting that the rural-urban dichotomy is too simplistic for understanding Danish health (Kelmelis and Dangvard Pedersen 2019).

Even with the mass relocation to urban areas in the 12th and 13th centuries, towns in medieval Denmark remained small into the post-medieval period (ca. 1350 CE) (Benedictow 2003). As such, temporal patterns may be more telling than spatial impact. Life expectancy increased in the post-medieval period as a result of improved hygiene and sanitation practices as well as the abolishment of strict fasting rituals with the Protestant Reformation (Benedictow 2003). The post-medieval sample, having survived the Black Death epidemic (1349 – 1350 CE), exhibited better survivorship over the pre-Black Death sample (DeWitte and Wood 2008). Comparing the two samples illustrated some interesting and unexpected results. For example, females in the urban and post-medieval sample were much more robust than the rural medieval women, almost on par with post-medieval urban males.

The oldest individuals can be understood as the healthiest, strongest members of a skeletal sample as they did not succumb to death at an earlier age (Wood et al. 1992). Studying age-related degeneration, namely osteoporosis and osteoarthritis, can, therefore, be very informative. Clinically, skeletal degeneration is considered to be a universal byproduct of aging (Tung and Iqbal 2007). Some bioarchaeological research has concluded the same (Ericksen 1976 (in females); Rewekant 1994), other researchers have found no such universality (Curate 2014; Poulsen et al. 2001; Robb et al. 2012). Agarwal et al. (2004) found that, while bone loss was noted in females by middle age, which they associated with parity and breastfeeding, no significant bone loss was seen in older individuals in a medieval British sample. Archaeological populations also demonstrate comparatively few osteoporotic hip fractures (Brickley 2002). It has been suggested that this is due to a maintenance of bone's biomechanical properties even as bone mass is lost (Ruff and Hayes 1983). The data presented in the following chapters suggests that males who died at an older age were healthier, taller, and more robust than younger males.

1.2 Research Objectives

The main objective of this research is to understand health, aging, and skeletal degeneration in medieval and post-medieval Denmark, exploring the following questions: 1) Does age-related degeneration follow a consistent pattern in medieval and post-medieval Denmark? 2) What physical influences affect skeletal degeneration? 3) Is there a relationship between body mass and indulgence-related disorders (such as diffuse idiopathic skeletal hyperostosis, gout, and plantar calcaneal spurs) and skeletal degeneration? 4) Is the lived experience of degeneration the same for both males and females?

Using stature, body mass, and degenerative and indulgence-related disorders, skeletal health will be analyzed. Within the context discussed above the following hypotheses were tested:

Hypothesis 1 – The rural sample will be healthier than the urban sample in that the rural sample will be taller and lighter, exhibit a lower prevalence of indulgence-related disorders and degeneration in the weight bearing joints and a lower frequency of osteoporosis and osteoporotic fracturing. Additionally, femoral size and strength will be greater among the rural sample than the urban sample.

Hypothesis 2 – A temporal trend towards decreasing health will be seen between the medieval and post-medieval period. The medieval sample will be taller and lighter, will exhibit fewer indulgence-related disorders and degeneration in the weight bearing joints as well as a lower prevalence of osteoporosis and osteoporotic fracturing. A decrease in femoral robusticity will be noted between the medieval and post-medieval period.

Hypothesis 3: Older individuals will be healthier than younger individuals but will present more non-life-threatening degeneration. Individuals that died in older age categories will be taller and lighter than those who died young. However, older individuals will present more instances of indulgence-related disorders and degeneration in the weight bearing joints as well as more osteoporosis. Individuals who died in older age categories will present smaller, weaker bones but fewer osteoporotic fractures than those who died in younger age-categories.

Hypothesis 4: Sex will affect health outcomes and lived experience. Males will be taller and heavier and exhibit less osteoporosis and osteoporotic fracturing than their female contemporaries. However, males will present more indulgence-related disorders and degeneration in the weight bearing joints. Finally, males will exhibit more robust, stronger femora than females.

Hypothesis 5: Underweight and overweight individuals will be less healthy than "normal" weight individuals in that "normal" weight individuals will be taller, present fewer indulgence-related disorders and degeneration in the weight bearing joints, exhibit less osteoporosis and fewer osteoporotic fractures than lighter individuals (but more than heavier individuals), and, as body mass increases, individuals will present larger, stronger femora.

The research is presented as follows: Chapters 2 and 3 present a review of the literature relevant to the current research. Chapter 2 is a review of historical literature that pertains to

Denmark in the periods of interest. The chapter presents a historical overview of the medieval and post-medieval periods, focusing on political struggles, demographic crises (i.e., the Great Famine and the Black Death), and the transformation of the Danish diet and living space with the "urbanization revolution". The focus of Chapter 3 shifts to present significant osteological research. The chapter begins with a discussion of different methods for estimating body size (i.e., body mass, stature, and robusticity) and the specific benefits and weaknesses of each method. The chapter then presents an overview of disorders related to aging and body mass (namely osteoporosis, degenerative joint disease, diffuse idiopathic skeletal hyperostosis, gout, and calcaneal spurs), exploring different approaches to diagnosing and recording each disorder in the bioarchaeological literature. The chapter closes with a discussion of the osteological paradox and the issues inherent in palaeopathological health research, specifically demographic non-stationarity, hidden heterogeneity, and selective mortality. Demographic non-stationarity is the idea that a population does not exist in a vacuum and, thus, changing birth, death, and immigration rates will affect the demographic profile of a skeletal populations through the generations. Hidden heterogeneity of risk implies that all individuals in a population have differing underlying frailty and susceptibility to disease which, in many cases, cannot be identified. Selective mortality refers to the concept that individuals with the highest frailty are most likely to die at a given age but in an archaeological sample we can only tell which individuals died, not which were at risk of death. This skews palaeopathological analyses in favour of the diseases that increase the likelihood of dying, making them seem more frequent than was likely the case in the living population. Chapter 4 presents the materials and methods used in this research. The chapter discusses the methods employed to estimate the temporal period, sex, age, stature, body mass, and robusticity for the two cemetery collections used, Tirup and Black Friars. Robusticity and osteoporosis prevalence were estimated using biomechanical properties of the femoral shaft and neck as well as maximum intensity projections (MIPs) of the proximal femur’s trabecular bone and, as such, Chapter 4 also discusses the method for scanning, processing, and analyzing computer tomography (CT) scans. The chapter then presents the techniques used to diagnose each age- and indulgence-related disorder. Chapter 5 provides the results and statistical analyses for the current research with Chapter 6 discussing the results. The results are discussed in terms of the hypotheses presented in this chapter and analyzed in terms of location of residence (i.e., rural or urban), time period, sex, age, and body size. The chapter focuses on specific shifts in the political, economic, and social landscape that may have triggered the trends seen in the results. Chapter 7 presents the conclusions of the current research, summarizing the project and discussing possible future directions of investigation.

Chapter 2: Literature Review – Historical Context

2.1 Introduction

This chapter will focus on the broad historical context of Denmark in the medieval and post-medieval periods. The skeletal populations of interest, the urban Black Friars (*Sørtebrodre*) cemetery in Odense and the rural cemetery of Tirup, can be contextualized within these historical periods. Understanding the historical context of skeletal material used in an analysis allows for a greater understanding of the biocultural processes at play. Human health and wellbeing are strongly tied to individual lived experience. Recognizing the interplay of culture, environment, and biology on health is important for a broader understanding of patterns seen in archaeological skeletal populations. In the following chapter, considerations associated with health, diet, and climate will be presented in terms of historical significance and impact on the rural and urban populations. The following chapter is separated by time period, as the distinction between the medieval and post-medieval periods is important for Denmark. As discussed below, the changing political and religious climate, paralleled by an environmental downturn, affected the health of Danes living in these periods.

2.2 Brief timeline

The relevant timeline ranges over two broad historical periods, the medieval and post-medieval (Table 2.1). The medieval period in Denmark began with the culmination of the Viking period and the introduction of Christianity around 1050 CE and concluded with the Protestant Reformation of the mid-16th century (Hybel and Poulsen 2007; Randsborg 2009). The period broadly defined as the medieval period or Middle Ages can be divided into two smaller sub-periods, the early medieval and the late medieval. The early medieval period dates from the end of the Viking Age to the middle of the fourteenth century when the Danish population was catastrophically decimated by the Great Famine (1315 – 1322 CE) and the Black Death (1349 – 1350 CE) (Hybel and Poulsen 2007). The late medieval period began with the conclusion of the Black Death epidemic and continued until the Protestant Reformation of 1536 CE (Hybel and Poulsen 2007). The post-medieval period (also referred to as the early modern period) began with the Protestant Reformation and ended with the peace of 1660 CE, which followed several battles between Denmark and Sweden (1611 – 1659 CE) (Randsborg 2009). It should be noted that depending on the source and area of Denmark being discussed, the dates connected to each period differ slightly (e.g. Oakley 1972) but the large geopolitical events associated with each transition are generally agreed upon.

Table 2.1 - Historical Periods of Interest

Historical Period	**Date**
Early Medieval	1050 – 1350 CE
Late Medieval	1350 – 1536 CE
Post-medieval	1536 – 1660 CE

2.3 The Early and Late Medieval Period (1050 – 1536 CE)

2.3.1 Unification of Denmark and the Rise of Christianity

Denmark was first mentioned as an autonomous kingdom on a Viking rune stone erected by Gorm the Old (ca. 958 CE) dating to ca. 950 CE (Lauring 1995; Nationalmuseet 2017). The Vikings, having seen the wealth associated with Western European Christian churches, brought Christianity back to Denmark at the end of the Viking Age (Lauring 1995). The first mention of Denmark as a Christian state is seen on a Viking rune stone (ca. 965 CE) (Nationalmuseet 2017) erected by Harald "Bluetooth" Gormsson (ca. 958 – 985 CE) (Lauring 1995). It took approximately one century for Christianity to take the place of the old Viking pagan religion

(Randsborg 2009). Knud the Great (1014 – 1035 CE), one of the last Viking kings, sent several English monks to Denmark with the aim of solidifying Christianity's hold but was unable to organize a lasting Church (Lauring 1995).

It was under Sven Estridsen (1047 – 1074 CE) that Denmark was unified and Christianity became commonplace in Denmark (Hybel and Poulsen 2007; Lauring 1995). The Church was reorganized (ca. 1060 CE) and an archbishopric was established (Hybel and Poulsen 2007; Lauring 1995). After his death, Estridsen was succeeded by his five sons in turn (Harald Hén, Knud the Holy, Oluf Hunger, Eric Egode, and Neils) (Lauring 1995; Oakley 1972). During Harald's short reign (1074 – 1080 CE) Christianity's hold in Denmark was tenuous (Lauring 1995). Knud (1080 – 1086 CE), having spent his youth as a Viking raider, was expected by medieval Danes to revert to earlier Pagan practices however, upon ascending the throne, he converted to Christianity, even introducing a tithe for the benefit of the Church. During his reign, Knud led an expedition against England's King, William the Conqueror, leaving a peasant army in charge of Denmark's borders. The peasantry eventually became impatient and demanded the king's return (Lauring 1995). In retaliation for the peasant insurgence, Knud toured Denmark inflicting heavy fines on peasants who had "interfered with the King's war" (Lauring 1995: 65). The tour culminated in a rebellion in Jutland forcing King Knud to flee south into Odense on the island of Funen. Knud was slain by the rebelling peasants in the Odense Cathedral (Lauring 1995). With the death of Knud the canon of Christianity was solidified in Denmark. During the reign of Oluf (1086 – 1095 CE), Denmark was plagued with repeated crop failure and resulting famine. Meanwhile, rumours of miracles occurring at Knud's grave led to the belief that the peasants had slain "*Guds Drot*" (God's King) and that the crop failures were divine punishment for their sin.

In 1157 CE, Denmark entered the Age of the Valdemars (1157 – 1241 CE) (Lauring 1995; Oakley 1972). The true unification of Denmark is said to have taken place under Valdemar I, or Valdemar the Great, (1157 – 1182 CE) (Hybel and Poulsen 2007). Under Valdemar I's rule order was restored, trade increased, and war was waged against pagans (Lauring 1995; Oakley 1972). During the early part of the Age of the Valdemars, important advances in agriculture were made, many new villages and farms were established, trade flourished, shipping increased, and several new churches were built.

Towards the end of the early medieval and into the late the medieval period tensions between the Church and Crown rose. The nobility feared the loss of wealth and prestige at the hands of the Church. The late medieval period saw an end to this feuding as it became common practice to appoint noblemen into high ecclesiastic positions, resulting in increased religious leniency (Lauring 1995). With this increased leniency the Church prospered, accumulating holdings and wealth throughout Denmark. While Christianity was well established by the late medieval period, the old pagan views still lingered, especially among the peasantry (Lauring 1995).

The transition to Christianity led to an overall improvement in health and life expectancy (Benedictow 2003). The Christian church abolished thralls (Viking slaves) (Benedictow 2003) and put an end to the revenge killings that were common practice among Vikings (Sawyer and Sawyer 1993). However, the Church also curtailed much of freedom enjoyed by Viking women (Sawyer and Sawyer 1993).

2.3.2 Health in Medieval Denmark

During the early medieval period, average stature indicates that health was generally good (Steckel 2004). However, studies from around Europe suggest that medieval health was strongly tied to socioeconomic status. Sutherland (2005) examined the frequency of anemia (diagnosed based on the presence of cribra orbitalia and porotic hyperostosis) in the medieval Gilbertine priory of St. Andrew, Fishergate, York (1200 – 1538 CE). The analysis illustrated that there was a significant association between status and anemia. Decreased status led to an increased prevalence of cribra orbitalia and porotic hyperostosis. Analyses of mortality patterns from the same cemetery collection illustrated that religious males enjoyed the longest lives (Sullivan 2004). These individuals likely had access to the widest range of economic and social resources, as well as greater quantity and quality of food, general living conditions and sanitation, and decreased work- and activity-related danger in medieval monasteries (DeWitte et al. 2013).

Mortality rates were high in the medieval period. Life expectancy at birth was around twenty to twenty-five years of age (Benedictow 2003). This is not to say that people did not live to senility; the prevailing cause of lowered life expectancy was that of high infant and child mortality (Benedictow 2003). Estimates from other medieval communities suggest that as many as forty percent of infants died within the first month of life (Wrigley 1968). Upon reaching maturity, females, given the dangers of pregnancy and childbirth, were much more susceptible to dying between the ages of twenty and forty (Benedictow 2003). The decreased female life expectancy could also be affected by the marriages of young adolescent women whose bodies were unprepared, both physiologically and anatomically, for pregnancy; marriages could take place for females as young as twelve years of age however fourteen to sixteen years was more common (Benedictow 2003). Kjellstrom et al. (2005) noted a trend towards worsening health in Sigunta, Sweden as time progresses (980 – 1537 CE). The authors suggested that the deterioration of health in later periods could be linked to increased population density. While health may have been generally good during the early medieval period, urbanization, poverty, and famine, as well as poor hygiene and sanitation practices may have led to a decline in overall health by the late medieval period.

Infectious diseases, leprosy, tuberculosis, and treponemal disease, were problematic during the medieval period in Denmark. A 2018 study by Schuenemann et al., suggested that leprosy, a degenerative disease caused by an infection of *Mycobacterium leprae*, may actually have originated in Europe instead of East Africa and Asia as was previously believed, although other evidence refutes this claim (Spigelman and Rubini 2016). In Scandinavia, leprosy became common by the tenth century, after which the stigmatizing effects of the disease can be seen in Danish cemeteries. When infected individuals were granted burial within regular (non-leprosaria) cemeteries, they were segregated to the least prestigious areas around the cemetery outskirts (Arcini 1999). Leprosy was eradicated by the 15th century in Denmark, making it one of the first European countries to eliminate the disease (Boldsen 2009; Lauring 1995). In Danish towns leprosy was eradicated by ca. 1350 CE (Boldsen 2009). The creation of the leprosaria, leper hospitals designed for segregating the infected, is credited with this decline in urban centers (Arcini 1999; Boldsen 2009). Without the strict segregation of lepers in rural Denmark the disease persisted (Boldsen 2009). In rural areas it has been speculated that increased contact with cattle, and thus the pathogen *Mycobacterium bovis* (associated with tuberculosis), provided individuals with a "natural vaccine" against leprosy (Boldsen 2009). According to Boldsen (2009), everyone interred in the medieval cemeteries in Tirup and Odense, Denmark (1150 – 1350 CE), would have been infected with (although not suffering from) leprosy between 1000 and 1300 CE.

Tuberculosis is caused by the pathogens *Mycobacterium tuberculosis* and *Mycobacterium bovis.* Mays et al. (2001) suggested that *M. tuberculosis* was responsible most of the medieval tuberculosis although others have argued that in rural areas *M. bovis* would have been more prominent due to the proximity of cattle (Kelmelis and Dangvard Pedersen 2019). Tuberculosis is associated with high levels of urbanization, population mobility, and socioeconomic inequality (Hargreaves et al. 2011). Lowered immune function leaves the host open to Mycobacterium-infection. Without compromised immunity, the host will mount a normal immune response and destroy the tuberculosis pathogen. However, tuberculosis pathogens become significantly more problematic in immune compromised populations (Flynn and Chan 2001). In skeletal material from Ribe (800 – 1800 CE), lesions associated with tuberculosis were found in Viking, medieval, and post-medieval skeletal material. It was calculated that approximately fifty percent of the medieval and post-medieval individuals buried in the cemetery would have had tuberculosis at the time of their death (although the skeletal population is not directly comparable to the living population). As expected, a significantly higher number of tuberculosis lesions were associated with socially disadvantaged burials (Dangvard Pedersen 2016). Poor quality of housing and hygiene practices in the medieval period would have exacerbated crowded and unsanitary living conditions and increased the spread of disease and ill health (Benedictow 2003).

Treponemal disease, namely syphilis, was also of concern in medieval Denmark. Venereal syphilis likely did not evolve until after the late 15th or early 16th centuries (Schwarz et al. 2013). The treponemal disease of the medieval period might have been a less aggressive form or perhaps non-venereal syphilis (Schwarz et al. 2013). In direct relation to the rise in syphilitic infections, mercury poisoning would have contributed to ill health during the medieval period, as large portions of individuals with syphilis were treated with mercury. Mercury-based medicines, administered as a vapour or, more often, a skin tonic, are well documented in the medieval literature as cures for skin disorders. Mercury was also administered to leprosy patients (Rassmussen et al. 2008).

The Black Death, or bubonic plague, described as the most catastrophic natural event in European history, claimed the lives of up to fifty percent of the European population in five years (Benedictow 2004; Bos et al. 2011). Very little direct evidence of mortality associated with the Black Death exists and the size of the medieval Danish population is not known. Using estimates of mortality rates from contemporaneous medieval populations it has been suggested that between thirty to fifty percent of the Danish population died as a result of the bubonic plague (Benedictow 2004). The Black Death is associated with the gram-negative bacillus, *Yersina pestis.* The high mortality associated with Black Death was due to the environment, host susceptibility, social conditions, climate, and vector dynamics, not bacterial phenotype (Bos et al. 2011). The rat-flea vector for the dissemination of the plague has been generally agreed upon (Benedictow 2004; Scott and Duncan 2001; Zeigler 1969). Rats are the natural hosts for the *Y. pestis* bacilli; humans (and other animals) are accidental hosts (Scott and Duncan 2001). The name “Black Death” (*Sorte død* in Danish) is associated with the putrefaction of the flesh which, within hours of death, will turn black (Zeigler 1969). Medieval documentation suggests that the Black Death generally killed within five to six days but could proceed more rapidly in certain cases. Several references refer to death within hours of perceived infection (Zeigler 1969).

It is believed that the *Y. pestis* bacilli reached Europe from the Asian continent on flea-infested rats traveling on merchant ships (Benedictow 2004). The plague is estimated to have reached Scandinavia in 1349 CE (Sawyer and Sawyer 1993), entering Denmark in the summer or early autumn, either from Southern Norway or directly from England (Benedictow 2004). Based on a likely rate of transmission, Black Death was probably not rampant in many areas of Denmark until 1350 CE (Benedictow 2004).

Increased population size followed by years of famine left most of Europe malnourished, exhausted, and highly susceptible to infectious disease (Zeigler 1969). DeWitte (2014) illustrated the decline in survivorship and paralleling increase in risk of mortality in the 13th century, prior to the Black Death epidemic (when compared to the 11th and 12th centuries). The decrease is linked to the change in climate and the resulting food shortages of the 13th and 14th centuries. These changes made the population extremely vulnerable to the devastating effects of the Black Death (DeWitte 2014). Until recently, Black Death was believed to have killed indiscriminately; however, by comparing indicators of stress, DeWitte and Wood (2008) illustrated that the plague preferentially killed frail, unhealthy individuals, especially males (DeWitte 2010). Individuals who survived the plague epidemic exhibited improved survivorship and decreased mortality when compared to pre-Black Death samples (DeWitte 2014).

Infectious diseases, urbanization, social stratification, proximity to animals, and religious expectations, would have significantly affected the health experience of medieval Danes. Health is also strongly tied to diet. Undernutrition and malnutrition have been linked to stunting (Fikadu et al. 2014) and increased susceptibility to disease (DeWitte 2014). Understanding the diet of medieval Danes, presented below, can help to understand medieval health in a broader sense.

2.3.3 Diet in Medieval Denmark

Socioeconomic status in Denmark dictated the diet of individuals. As the agricultural practices suggest, grain and grain products formed a significant part of the Danish medieval diet. It has been estimated that up to three quarters of the food produced and consumed by the medieval Dane came from grain (Hybel and Poulsen 2007; Poulsen 2013). Boldsen (2005a) found that dental attrition increased significantly by the 14th century in the medieval Danish cemetery at Tirup (1150 – 1350 CE), which he associated with increased reliance on grain between the 12th and 14th centuries. Grain played an important role in the Danish medieval diet regardless of class, however the type of grain available for consumption depended heavily on social situation. As in much of medieval Europe, white bread made of wheat was considered best and thus was eaten almost exclusively by the upper class. The middle class ate bread made from mixed barley, rye, and beans, while the poor ate corn-mixed or gruel bread (Dyer 1989; Poulsen 2013). Stable isotopic analyses have also illustrated that the Danish higher classes were able to access marine and terrestrial protein sources unavailable to peasants (Yoder 2012). The wealthiest of society would have had access to wine, spices, venison, and other rare animals (e.g., whale) (Poulsen 2013).

Poulsen (2013) exemplified the difference in food availability by quoting *Rigsthula*, a Nordic poem of unknown origin. According to the poet, on the peasant's table there was bread and soup. The bread was "weighty and thick [and] wedged with grain" (Poulsen 2013: 339). Poulsen (2013) noted the distinct lack of any mention of meat. On the table of the landowner (or middle-class member of Danish medieval society), the bread was "brown of barley meal" (Poulsen 2013: 340) and served with veal, a sign of elevated status. The poem goes on to describe the "patterned cloth, white, of thick linen" (Poulsen 2013: 340) of a lord's table. On this table white wheat bread served alongside several meat dishes and wine in silver cups is found (Poulsen 2013).

In the mid-14th century Danes consumed significantly less marine food. This period was in peak plague time and the decline in marine foods likely stemmed from the belief that fish could cause the plague (Yoder 2010). Consumption of animal products increased significantly after plague years when Denmark's secondary cattle-based economy reemerged (Poulsen 2013).

Religious fasting was required by the church. The most important fast was during Lent, however Christians were also expected to fast on certain Saturdays and Wednesdays. This could account for up to 150 days per year (Albala 2011). During these fasts, healthy adults were expected to abstain from the flesh of all animals as well as any product derived from them (i.e., butter, cheese, eggs). During Lent, it was expected that parishioners would abstain entirely from solid food during the day, breaking their fast for one meal at sundown (Albala 2011). For most parishioners, morality was interpreted not through the everyday acts but by observing the ritual behaviours commanded by the Church. As such, ritual fasting was paramount for most Christians (Albala 2011).

A mendicant friar, such as the Black Friars, having taken a vow of poverty, would likely have had a diet similar to that of the peasant. Stable isotopic analyses illustrate that, in the early medieval period in Denmark, the monastic diet was similar to that of the peasantry however they consumed more terrestrial animal and/or freshwater fish protein. In the mid-14th century, monastic diets shifted to include more freshwater fish and terrestrial protein, a diet more akin to that of the Danish elite (Yoder 2012). Yoder (2012) speculated that this transition in diet is due to a loosening of dietary proscriptions.

Dietary differences between urban and rural populations also existed in medieval Denmark suggesting either food preferences or "fashions" were distinct between rural and urban communities. For example, in the rural cemetery of Øm Kloster (1172 – mid-16th century CE) stable isotopic analyses suggested that the rural population subsisted mainly on grains, beans, vegetable grasses, and terrestrial animals (and perhaps freshwater fish), while the isotopic signature of individuals interred in the urban cemetery in Ribe (1250 – early 15th century CE) illustrated a greater reliance on marine foods (Yoder 2010). Climatic changes in the medieval period significantly affected the availability of food and the overall health of the medieval Dane.

2.3.4 The Changing Climate at the End of the Early Medieval Period

From the end of the Viking Period into the early medieval period (ca. 800 – 1300 CE), Europe experienced a climatic warming (Fagan 2000). This period has become known as the Medieval Warming Period. During this time, Scandinavians experienced stable weather patterns and temperatures approximately 2.0º – 3.0º C above that recorded a few centuries later and approximately 0.7º – 1.0º C above the modern average (Fagan 2000). Fagan (2000: 21) described this period as the "climatic golden age." Annual harvests flourished. The poor were able to survive off the land and the rich hunted for sport (Fagan 2000). May frosts, which can be troublesome for harvests, were uncommon between 1100 and 1300 CE (Fagan 2000). Images of abundant harvests and long-lasting summers can be seen depicted in several medieval paintings (Fagan 2000). Despite wars and crusades, the Medieval Warming Period is considered a time of abundance. During the early medieval period, the average male height was tall (173 cm) even by today's standards. Stature, which has long been used as a proxy for health, suggests that, while the early medieval period had its hardships, generally overall health was quite good (Steckel 2004).

Due to a change in the oceanic and atmospheric currents of the North Atlantic (known as the North Atlantic Oscillation, an atmospheric pressure system that governs the storm track and rainfall over Europe), the climate around Europe saw a dramatic transition in the late 13th century (Fagan 2000). After the turn of the 14th century the change in atmospheric pressure triggered a downturn in the European weather. Not only was there a significant cooling effect around the

European continent, but the area was affected by flooding, droughts, and heavy winds (Grove 1988; Jones and Mann 2004; Jordan 1996; Pfsiter 2005). This change in weather has been named the Little Ice Age (Fagan 2000). This climatic shift led to lowered food production, economic isolation, decline in health, and several consecutive years of crop failure and poor harvest yields (Fagan 2000). The series of failed harvests have been named "The Great Famine" (1315 – 1322 CE), as they were accompanied by widespread starvation among European populations (Jordan 1996). Famine was a common hazard for rural agrarian societies however, prior to 1315 CE, famines hit sporadically and were usually short lived. While strategies to combat harvest failures were in place, the preparations were not extensive enough to deal with the several consecutive harvest failures of "The Great Famine" (Jordan 1996). Near the end of the medieval period, Steckel (2004) noted a decrease in average male height (167 cm), which continued until the end of the Little Ice Age in the 19th century. According to Steckel (2004) this decline in height parallels the onset of the Little Ice Age, where increased poverty, urbanization, conflict, and global spread of disease were commonplace. While this cooling trend continued into the 19th century, climatic fluctuations throughout the period allowed for a tenuous balance to be regained in Europe (Fagan 2000).

As a direct result of the famine, many rural towns were abandoned. An increase in urbanization, as well as a rise in "rural beggars" (Jordan 1996: 97) and rural poor flocking to urban centers for alms, was seen across much of the European continent (Jordan 1996). Food shortages and inflated prices led to poverty, starvation, and increased disease susceptibility in both rural and urban settings (Jordan 1996).

2.3.5 Rural Settings

Population growth in the early medieval period led to an expansion of rural communities across Denmark (Orrman 2003a). New farming technologies, such as the heavy mouldboard plough, the bow sickle, and large-scale mills (Hybel and Poulsen 2007) allowed for development into previously untenable areas (Orrman 2003a). Rural villages, consisting of a central village based around a manor house surrounded by, on average, ten (but up to thirty or forty) farms predominated in medieval Denmark (Orrman 2003a). Danish villages have been termed the "migrating rural village" (Orrman 2003a: 291) as, throughout the first millennium CE farms around villages were constantly moving to more harvestable areas (Orrman 2003a). During the medieval period, farm locations became fixed (Hybel and Poulsen 2007).

Agriculture, in some form or another, has existed in Denmark since ca. 4000 BCE (Hybel and Poulsen 2007; Randsborg 2009). After reaching Jutland in Northern Denmark in the early New Stone Age (ca. 2700 BCE), the agricultural practices shifted more toward cattle breeding, and there was a reemergence in the importance of hunting (Oakley 1972; Randsborg 2009). Since this time, the Danes have come to rely heavily on agricultural practices, constantly balancing grain- and cattle-based agricultural production (Hybel and Poulsen 2007). Grain-based agriculture began to expand around the beginning of the medieval period (ca. 900 – 1100 CE), while cattle husbandry declined steadily from the end of the Viking and into the early medieval periods (Hybel and Poulsen 2007).

In the late medieval period, after the demographic crisis caused by the bubonic plague, the remaining Danish rural peasantry saw economic improvements (although not necessarily improvements in their political or social condition) (Hybel and Poulsen 2007; Orrman 2003c). For instance, the cost of renting land dropped in 1370 CE. This was the outcome of a widespread desertion of farmable land across the Danish countryside resulting from the bubonic plague and the high cost of rent between ca. 1350 and 1370 CE (Orrman 2003c). The crisis significantly affected the noble and ecclesiastic landowners who lost substantial income from the desertion and were required to pay increasingly high wages for hired labour (Orrman 2003c). For lease holding farmers, the economic crisis was a boon. Hired farm labourers could expect higher wages and farmers could keep more of the wealth they gained from their land. Freehold farmers benefited from the overall economic trend but did not benefit directly from the drop in rent (Orrman 2003c). This led to a reconfiguration of the Danish rural landscape in the late medieval period. Landowners could no longer afford large scale farming enterprises and instead leased portions of land to tenants. Considering the large-scale desertion of the area, tenants were able to lease considerable holdings for minimal rent and labourers could afford to rent small cottages (Orrman 2003c). This resulted in an equalization of the Danish peasantry in the late medieval period. A large portion of the peasantry became tenants with the ability to hire labourers of their own to work their larger land plots (Orrman 2003c).

After the population devastation of the late 14th century previously tended fields went unharvested leaving ample space for grazing animals (Poulsen 2013). The increasing land plot sizes lead to the exponential increase in the number of cows, sheep, and goats that farmsteads could accommodate and drove the reemergence of a secondary economy based on animal husbandry (Hybel and Poulsen 2007; Ormann 2003c; Poulsen 2013). Dairy production, mainly for butter, was already a significant source of income by the 14th century (Poulsen 2013). During the late medieval period the focus shifted from dairy to meat production. Raising cattle and oxen for beef soon outstripped the production of dairy (Poulsen 2013). Commercial activities allowed many of the farmers to accumulate wealth (Orrman 2003c). While there was a general trend towards increasing economic stability for the Danish rural peasantry in the late medieval period, tenants and farmers in areas where grain-based agriculture predominated had fewer opportunities to exploit than those practicing cattle husbandry (Orrman 2003c).

2.3.6 Urban Communities

The medieval period was a time of population influx into urban centers. Beginning in the seventh, eighth, and ninth centuries small rural settlements began to specialize in crafts, becoming centres for trade and exchange (Hybel and Poulsen 2007; Pounds 2005). While urban towns were economic entities generated for market production, they are juxtaposed with rural villages in that they were more densely populated and urbanites paid special taxes (Hybel and Poulsen 2007). At the end of the 12th century urban development in Denmark flourished and the number of towns increased exponentially (Benedictow 2003). For instance, during the Viking Age (before ca. 1000 CE) only four documented towns existed in Denmark (although the actual number is likely slightly higher) (Petersen et al. 2006). Around 1200 CE, Denmark experienced a wave of urbanization (Andersson 2003). By the end of the medieval period the number of documented towns increased to sixty-three, fifty of which were founded before 1300 CE (Petersen et al. 2006). While there was an increase in townships in the medieval period the size of towns remained relatively small, staying in the hundreds to low thousands, and the population living in towns did not exceed about five percent of the total population until the late medieval period (Benedictow 2003). Commercial expansion was the major driving force for the development of urban centres (Andersson 2003).

Individuals living in rural Denmark were almost exclusively farmers. Little else was available in rural areas by way of employment (Milner et al. 2015). Alternatively, urbanites had many more occupations available to them. For males, early craft specialization included potters, smiths, ship builders, carpenters, shoemakers, skinners, bakers, and butchers (Hybel and Poulsen 2007). Throughout the medieval period, as trade routes expanded, guilds were formed, and males were able to amass a great deal of wealth as merchants, drapers, artisans, and mercers. Many women moved to urban centers in order to gain economic freedom (Jacobsen 1983). Jacobsen (1983) documented female employment as laundresses, builders, and ferry workers (among other occupations). However, these positions were limited as was the availability of domestic positions. Even positions that fell traditionally under the purview of 'women's work', such as weaving, baking, spinning, brewing, cooking, etc., often employed males (Jacobsen 1983). Fortunate women could gain employment as drapers, artisans, or medical professionals, however the majority of women were employed in low level retail positions and distribution trades. Many women were forced to turn to increasingly physical and/or illegal positions in order to survive (Jacobsen 1983).

As urban centres expanded centralized governments were installed. Town councils were created in major urban centres (Andersson 2003). Paralleling the installation of town council representatives, there was an increase in social stratification with the urban elite being given more and more power (Andersson 2003).

2.3.7 Urban versus Rural Health

As is generally the case, the picture of health in medieval Denmark, painted by both historical and archaeological documentation, is that of healthier rural than urban life. Petersen et al. (2006), documenting mortality patterns between rural and urban communities in medieval Denmark, illustrated that between the urban cemetery of Sct. Mikkel (1100 – 1529 CE) and the rural cemetery at Tirup (12^{th} – 14^{th} century CE) urban adolescents and young adults had lower survivorship than their rural peers. It is important to note that Sct. Mikkel is believed to be a migrant cemetery and thus the decreased survivorship may be due to the stigmatizing effect of migration. Palubeckaite et al. (2002) found that individuals at the rural cemetery at Tirup (12th – 14th century CE) presented relatively few examples of linear enamel hypoplasia, an osteological indicator of stress during development, when compared to medieval sites in Lithuania, suggesting that stress associated with rural living in Denmark was likely acute and that ill health occurred periodically leading to death of the weaker children. Those who survived had a better resistance to stress. While health in many rural villages in Europe seems to have been better than in their urban contemporaries, individuals living in a rural setting, practicing subsistence agriculture, would have been highly susceptible to zoonoses (diseases transmitted by animals), allergies, and parasitic infections (Lewis 2002), as well as increased infections associated with the high trauma incidence of farming (Judd and Roberts 1999). Interestingly, Kelmelis and Dangvard Pedersen (2019) found that prevalence of rural and urban leprosy and tuberculosis did not necessarily support the notion that medieval rural Danes were healthier than their urban contemporaries. In fact, a significantly higher prevalence of tuberculosis was noted in the medieval rural cemetery of Sejet when compared to the urban cemeteries of Ole Wormsgale and Ribe Grey Friars. The authors posited that the difference in lesions could be explained by different disease strains but caution against using an overly simplistic rural versus urban dichotomy to explain health in medieval Denmark.

With increased urbanization and limited separation between living spaces in the late medieval period, health declined. Ill health in urban centres could, in part, be linked to the increase in trade specialization prior to industrialization. In their analysis of males interred at the urban cemetery in Sigtuna, Sweden (970 – 1530 CE), Sundman and Kjellstrom (2013) noted an elevated rate of chronic maxillary sinusitis, which the authors suggested could be linked to smoke inhalation in workshops. In urban centers, brewing, smithing, tanning, and salt boiling were common trade processes that added to the air pollution (Dyer 2002).

Additionally, urbanites, generally wealthier than their rural contemporaries, exhibited higher levels of lead poisoning than rural Danes. Rasmussen et al. (2015) examined lead poisoning in four medieval Danish cemeteries: Tirup, Ole Wormsgade, Nybøl, and Skt. Albert. Urban areas were more susceptible to lead poisoning as the wealthier sectors of society had access to luxuries unattainable by the poor. Wealthy families habitually ate and drank from lead oxide-glazed pottery. In rural communities lead poisoning was by no means unheard of; water collected from rooves was often contaminated with lead and, although glazed pottery was a rarity, unglazed pottery was also a significant source of lead (Rassmussen et al. 2015).

Evidence from medieval British data suggests that infant mortality was highest in medieval urban areas and that infant deaths in rural areas resulted mainly from endogenous factors (i.e., as a result of maternal influences). In urban areas, post-neonatal deaths outweighed neonatal ones suggesting exogenous factors (such as disease, poor nutrition, poisonings, accidents, etc.) (Lewis and Gowland 2007).

2.3.8 Monastic Communities

A large portion of the medieval segment of the Black Friars cemetery would have been comprised of the Black Friars themselves. Recognizing that lay people and monks would have experienced life very differently is important to understanding the skeletal populations analyzed in the current research. After the 11th century, Danish kings, magnates, and bishops extensively built churches across Denmark (Orrman 2003b). The introduction of the tithe in the early 12th century aided the rapid parish formation (Orrman 2003b). Early parishes in Denmark were small and closely situated, usually with no more than six kilometers between parishes (and only two kilometers between parishes in Funen) (Orrman 2003b). Early clerics in Scandinavia were predominantly foreign Benedictine monks from Germany and England (Orrman 2003b). In the 12th century, Augustinian, Cistercian, and Premonstratensian monasteries were founded across Denmark (Orrman 2003b). After the establishment of the Christian church, the clergy became a social class of its own, often on par with the privileged elite (Benedictow 2003). Several Benedictine and Cistercian monasteries became very affluent, owning and operating large estates (Hybel and Poulsen 2007: Jakobsen 2008; Orrman 2003b). Likely in direct contradiction to the increasing wealth of the clergy, the 13th century saw a proliferation of mendicant, or begging, orders such as the Franciscans and Dominicans (Orrman 2003b).

2.3.5.1 The Dominican Order

As the Black Friars form a significant part of the medieval skeletal sample from the Black Friars cemetery, the analysis of the historical literature must include an understanding of the Black Friars themselves. The Black Friars were an order of Dominican preachers. The Dominican Order, a branch of the Augustinian Order, was instituted to combat the rising heresy of medieval times (Bennett 1937; Hinnebusch 1985). The order was founded by Dominic de Guzman (later St. Dominic), a priest born into the lower nobility in Spain (Ashley 1990; Hinnebusch 1985). While on a mission in Southern France with his bishop, Diego de Azevedo, Dominic stayed at an inn owned by Catharit heretics (believing in a two-god system) (Ashley 1990). Dominic remained awake all night debating spirituality with the innkeeper who, upon daybreak, reformed to the Catholic Church (Ashley 1990; Bennett 1937; Hinnebusch 1985; Jakobsen 2008). Realizing that the existing Catholic priests were failing to meet the spiritual needs of the lay people, Dominic resolved to create an order to battle the growing spiritual degeneration (Jakobsen 2008). Thus, in 1216 CE, he obtained the Pope’s blessing to found an

Ordo Praedicatorum, or 'Order of Preachers' (Bennett 1937; Hinnebusch 1985; Jakobsen 2008). The Dominicans have been colloquially named the Black Friars (*Sørtebrodre* or "Black Brothers" in Danish) for the black cloaks that they wore over their white habits (Bennett 1937; Jakobsen 2008). The order was founded on the tenets of poverty and learning, as well as morality and discipline (Bennett 1937; Hinnebusch 1985). The two fundamental tenets of the order, poverty and learning, were crucial to the success of the Dominicans. Through their vow of poverty, which in medieval Europe was the predominant condition of the people, the brothers were seen as credible and trustworthy by those they were seeking to convert (Ashley 1990; Jakobsen 2008). As a mendicant order, vows were taken not to own any property, leaving the friars dependent on the goodwill of lay people (Jakobsen 2008).

The second tenet was that Dominican preachers must be learned (Bennett 1937; Hinnebusch 1985). In order to successfully preach the word of God, Dominican friars were rigorously educated (Ashley 1990; Bennett 1937; Hinnebusch 1985); some of the brothers would get degrees in Paris, Oxford, or Cambridge (Hinnebusch 1985) and then would return to their cloisters, providing mandatory lectures for the others (Ashley 1990). Unlike other clerics, who were predominantly lay people, Dominicans actively recruited well-educated young men, usually from the nobility (Bennett 1937). While most of their studies were biblical or theological in nature, medieval Dominican friars also published texts on history, pastoral theology, and botany, as well works of literature (Hinnebusch 1985).

The Black Friars spent their lives preaching, constantly in pursuit of conversion to the Catholic faith (Bennett 1937). Breaking with clerical tradition, Dominican friars would leave the cloisters and move to pastoral communities, preaching the benefits of living a pious and poor life (of which the brothers led by example) (Jakobsen 2008). In addition to preaching, the brothers would visit the sick and poor to give comfort and supply herbal remedies (Jakobsen 2008). The Dominican friars arrived in Scandinavia in early 1223 CE and remained there for the next 300 years (Jakobsen 2008; Orrman 2003b). By 1238 CE, the Dominican Order had fifteen monasteries across Denmark (Jakobsen 2008). In the post-Black death era, signs of decay can be seen in the order. This decay can be perceived in the relaxing of religious discipline as well as increased leniency towards vows of poverty (Hinnebusch 1985).

By the end of the late medieval period the escalating moral corruption, greed, and abuse of position by the Roman Catholic Church had reached unprecedented levels (Anderson 2011). The Roman Catholic Church had amassed a large amount of wealth and held a great deal of political power. One third of Danish lands were controlled by the Catholic Church (Lockhart 2007). While the transformation of the church did not legally take place until after Fredrick I's (1523 – 1533 CE) death in 1533 CE, the seeds of dissention and unhappiness with the current Catholic order had been sewn (Lauring 1995).

2.4 The Post-medieval Period (1536 – 1660 CE)

2.4.1 The Changing Religious and Political Climate

In large part, the Reformation in Denmark was spearheaded by Hans Tausen, often referred to as the "Danish Luther" (Anderson 2011; Oxford University Press 2009). Tausen was born in Birkende on the Island of Funen and studied at the Universities of Rostock, Copenhagen, and Louvain before traveling to Germany to study under Martin Luther in 1523 CE (Credo Reference 2016). In 1525 CE, upon returning to Denmark, Tausen was imprisoned for preaching his heretical Lutheran beliefs (Anderson 2011). However, en masse Danes would flock to Tausen's cell to hear him preach, eventually compelling his release (Anderson 2011). After being released, Tausen established the first Lutheran congregation in Viborg (Credo Reference

2016). In 1526 CE, Fredrick I made Tausen his chaplain and by 1528 CE Tausen was appointed bishop of Ribe (Anderson 2011: Credo Reference 2016).

Upon Fredrick I's death, internal battle raged within Denmark (1533 – 1536 CE) with the Catholic nobles supporting the claim of Christian II and the Protestant nobles backing Christian III. Eventually, the battle was decided and Christian III (1535 – 1559 CE) was crowned King, leading to the relatively peaceable Protestant Reformation of Denmark in 1536 CE (Lauring 1995; Randsborg 2009).

The Crown confiscated Church holdings after the Reformation, dramatically increasing the wealth and power of the Crown and nobility. They gained almost complete control over cultivatable land and, thus, agricultural production (Jespersen 2019). Lavish renaissance palaces and expansive manor houses were built in Denmark at this time. Christian IV's (1588 – 1648 CE) architectural accomplishments are still considered some of the finest examples of renaissance culture by Danes living today (Randsborg 2009). In addition to his architectural accomplishments, Christian IV solidified the defense of Norway, acquired lands in India, and reopened Copenhagen University as a Protestant institution (Randsborg 2009). It was under Christian IV that Denmark reached the peak of its European power (Lockhart 2007). In an attempt to make Denmark self-sufficient, Christian IV took steps toward (proto-)industrializing Denmark, building Denmark's largest naval arsenal (Lauring 1995; Lockhart 2007). The post-medieval period closed with a series of battles fought between Sweden and Denmark. Beginning in 1611 CE, Denmark attempted (unsuccessfully) to invade Sweden in a battle known as the Kalmar War (1611 – 1613 CE). The battle at Lutter Barenberg (1627 CE) culminated with Swedish (Catholic) inhabitation of Jutland. After the Thirty-Years' War (1618 – 1648 CE), a wounded and beaten Christian IV was forced to cede control of much of his land (both in

Denmark and Norway) to Sweden for thirty years (Randsborg 2009). Upon his death Christian IV was succeeded by Fredrick III (1648 – 1670 CE) (Lauring 1995). Fredrick III declared war on Sweden in 1657 CE. In the winter of 1658 CE, Swedish troops crossed over an ice bridge to the Danish islands, again defeating the Danish army (Randsborg 2009). Following the battle, the Peace of Roskilde was signed and Denmark was forced to yield all of its eastern provinces as well as some of its Norwegian holdings to the Swedes (Randsborg 2009). Later in 1658 CE, the Swedish King, Karl Gustaf, laid siege to several fortifications around Denmark simultaneously in an attempt to gain total control of the entire area. Dutch militia joined the Danish army in Copenhagen and defeated the Swedes in 1659 CE. In a new peace (1660 CE) with Sweden, the Danes regained control of much of the land they had lost (Randsborg 2009) and the post-medieval period ended.

2.4.4 Health in Post-medieval Denmark

The changing religious and political climate would likely have significantly affected the health of post-medieval Danes. The Black Death had killed a large proportion of the population, leaving behind healthier, less frail individuals (DeWitte and Wood 2008). Increasing urbanization and crowding along with early attempts at (proto-)industrialization may have led to a worsened health experience in the post-medieval period than that experienced in the medieval period.

Scott (2015), in her examination of pathology and stress indicators in the Black Friars cemetery in Odense, illustrated that the adult frequency of pathological conditions remains relatively constant between the medieval and post-medieval periods. Alternatively, those interred in the Black Friars cemetery demonstrated increased levels of stress in the post-medieval period when compared to the medieval sample. This was especially true among the female skeletal material (Scott 2015). Dangvard Pedersen (2016) found that the prevalence of tuberculosis remained relatively consistent between the medieval and post-medieval periods in Denmark. According to Benedictow (2003), life expectancy in Denmark increased in the post-medieval period, with life expectancy at birth rising to about thirty-five years. These changes may reflect an improvement in hygiene and sanitation and, in part, the abolishment of strict fasting rituals with the Reformation. Religious fasting practices would have undermined the already poor health of the more susceptible strata of society, those who were very poor, very young, pregnant and nursing mothers, or very old (Benedictow 2003).

2.4.3 Diet in Post-medieval Denmark

Pope Alexander VI began loosening dietary fasting proscriptions in 1491 CE, a trend that continued into the post-medieval period (Albala 2011). Luther's opinion that food restrictions were absurd and could not be used as a means to attain grace has been documented (Albala 2011). The pious ideals of abstaining from certain foods were dissolved outside of the family setting after the Protestant Reformation. However, as a staple of the earlier Christian faith, fasting rituals around Europe were often maintained in private. This continued for several centuries after the Reformation (Albala 2011).

The growth of Scandinavian capital cities throughout the medieval period allowed for cattle and grain trade in Scandinavian counties to shift from a more open trade to trade predominantly within Nordic countries. From the 13th century, with an increasing proportion of the population living in towns, trade between the town and countryside became important. In response to the increased localized market trade, Danish diets shifted to include more meat and dairy (Hybel and Poulsen 2007).

Specialized commodities were still traded internationally (Poulsen 2013). In fact, the international trade networks of the late medieval period allowed for the introduction of several new foods into the European diet. Potatoes, tomatoes, sweet potatoes, maize, chili peppers, asparagus, kidney beans, etc. were introduced from the New World (Anderson 2011). At first many of the imports (such as potatoes and kidney beans) were eaten exclusively by the poor. Once it was realized that these foods were resistant to most diseases and could grow in almost any soil, they became popular among all social strata. Sizeable market fairs were held in many large European cities where new exotic spices, such as saffron, cloves, cinnamon, and ginger, as well as sugar and dried fruit, could be purchased (Anderson 2011). As the availability of spices increased their cost went down, meaning that they became accessible to the middle classes as well as to the elite (Anderson 2011).

Bread was still an important staple of the European diet with the wealthiest eating the finely ground white flour bread and the bread becoming courser and darker for the poorer socioeconomic strata. Some of the very poorest individuals supplemented their rye or barley bread with grass (Anderson 2011).

Major famine, caused by weather, poor harvests, population increase, disease, and war, as well as people trying to profit from the increased demand for limited supplies, swept the European continent between 1594 and 1597 CE (Anderson 2011). Peasants, already living on the brink of disaster, lost the ability to feed themselves. Many of the urban poor were forced to turn to begging while rural peasants subsisted on carrion (Anderson 2011). The situation worsened leading to European-wide bread riots in 1628 CE (Anderson 2011).

2.4.2 Social stratification in the Post-medieval Period

As previously discussed social status significantly affects health. Social stratification in Denmark reached an unprecedented high in the post-medieval period. The post-medieval period saw a peak in the wealth and political power of the nobility. Proportionally, the nobility made up a rather small part of the Danish population. In Denmark around the time of the Reformation there were approximately 250 noble families (approximately 3000 people). These families made up 0.5% of the population and owned about forty percent of the Danish land (Lockhart 2007). Due to favour from the King, the Danish nobility were exempt from most taxes, held chief government positions, were excused from paying import dues on luxury items for personal use, and more (Lockhart 2007). Even within the nobility there was a sharp social distinction (Lockhart 2007). Throughout the post-medieval period wealth and power became increasingly concentrated at the highest echelons of society. In 1558 CE, one third of the nobility owned two thirds of the nobly owned land; by 1635 CE, one third of the nobility owned seventy-five percent of the nobly owned land. Partly due to royal politics and in part because the Danish nobility avidly partook in risky speculations on land (and partially simply due to a lack of procreation in some family lines), the number of land-owning noble families in Denmark decreased throughout the post-medieval period (Lockhart 2007). In 1536 CE, Denmark had 249 documented noble families. This number dropped to 222 and eventually 197 in 1560 and 1600 CE, respectively (Lockhart 2007). With grain prices rising in the last two thirds of the 16th century, as a response to the growing demand for bread in Western Europe, the land-owning nobility benefitted significantly. Lesser nobility, many of whom did not own land or whose families owned very little land, were required to take military or naval positions where available or serve as town bailiffs, a position usually occupied by a wealthy member of the peasantry (Lockhart 2007).

This upsurge in wealth did not trickle down to the peasantry, who made up eighty to eighty-five percent of the population during the post-medieval period (Lockhart 2007). The peasant class exhibited high variation in affluence in Denmark during this time, from near slave to relatively wealthy landowners (Anderson 2011). The peasantry were divided into: landowners, who owned their land, leaseholders, who rented land plots from the Danish nobility or Crown, cottagers, who worked small plots of land owned by others, and weekday labourers, who were required to provide labour for the lands they lived on or near. Landowners made up the minority of peasants in Denmark during the post-medieval period and were found mostly in Jutland. Landowners would have profited marginally from the rising grain prices but not in same way as the wealthy nobility as they were expected to pay heavy taxes to the Crown. Most of the peasants were leaseholders. Some leaseholders would have had large enough land plots to acquire capital. With cattle prices rising nearly 600% in the 16th century, peasants were able to profit from the secondary cattle industry. By the mid-16th century, Denmark was exporting 35,000 to 45,000 cattle per year, a number that grew until the beginning of the Thirty Years' War. The cottagers would have spent most of their time doing hired labour. At the beginning of the post-medieval period cottagers made up about five percent of the peasantry, a number that rose substantially over the next century, likely due to severe taxation by the Crown (Lockhart 2007). Peasants were considered "unfree" in Denmark, meaning that, unlike the nobility, they paid high taxes and had no privileges and very few rights (Lockhart 2007). One of the few privileges of the Danish peasantry was the right to sell their surplus grain, fish, butter, cattle, etc. to whomever they chose. Peasants residing near forests or coastlines would have been able to supplement their income with other non-agrarian pursuits, most often cattle raising, fishing, or charcoal burning (Lockhart 2007).

The Danish urban population remained small into the post-medieval period. Only approximately ten percent of the Danish population resided in urban areas. Most urban centers would have housed no more than 1000 people. Copenhagen was one of the few exceptions providing housing for over 5000 people (Lockhart 2007). After the Reformation, foreign merchants, mainly from Germany and the Netherlands flocked to Demark to capitalize on the thriving Danish trade economy. As in the late medieval period, towns were mostly self-governed. Town councils, made up predominantly of merchants, were the authority in the towns. Townspeople were required to pay annual taxes to the Crown; however, taxation was not nearly as extreme as it was for the peasantry (Lockhart 2007).

2.5 Chapter Synopsis: The Medieval and Post-medieval Periods

The early medieval period, beginning with the introduction of Christianity and culminating with the Black Death epidemic, was characterized by agricultural development, population expansion, stable weather patterns, and urbanization (Hybel and Poulsen 2007). The burgeoning agricultural economy triggered a shift in Danish dietary patterns to include more grain and grain products (Hybel and Poulsen 2007). According to historical record, health was generally quite good during the early medieval period as even the poorest peasants could subsist off of the land (Andersson 2011). Towards the end of the early medieval period, the climatic downturn led to a decline in overall health. The lack of available food (caused by consecutive harvest failures), resulted in a decrease in overall health and an increase in the population's susceptibility to disease (DeWitte and Wood 2008). The urbanization 'revolution' began in the early medieval period, with several new towns being formed. While the percentage of the population living in towns remained relatively small, the distinction between urban and rural started to become important. The period closed with the demographic crisis caused by the Black Death, which decimated the Danish population (Bos et al. 2011).

The late medieval period, beginning at the end of the Black Death epidemic and continuing until the Protestant Reformation, was characterized by expanding urbanization. It has been argued that with urbanization and increasingly overcrowded, unsanitary living spaces, infectious diseases became progressively more problematic (Lewis 2002). This assessment has, however, been questioned for medieval Denmark (Kelmelis and Dangvard Pedersen 2019). Health in both rural and urban communities was tied to social status. Social stratification increased throughout the medieval period, especially as urbanization increased and a merchant class emerged.

Throughout the medieval period, the wealth and power of the clergy increased substantially (Benedictow 2003). The population's dissatisfaction with the power of the Catholic Church spread and the teachings of Luther became more popular until the Reformation in 1536 CE, when the post-medieval period began.

The post-medieval period, from the Protestant Reformation until the peace of 1660 CE, was characterized by internal Scandinavian turmoil. Rising tensions between Sweden and Denmark erupted into a series of battles (Lockhart 2007). Urban expansion continued throughout the post-medieval period. The nobility and Crown's power were at an unprecedented high. However, for the peasantry, poverty was rampant (Lockhart 2007). For the poor, food availability was scarce and many peasants turned to begging or carrion to survive (Anderson 2011). While life expectancy increased in the post-medieval period (Benedictow 2003), the health experience of the population remained relatively constant, and, in some cases, worsened (Dangvard Pedersen 2016; Scott 2015).

2.6 Summary

In conjunction with the relevant osteological literature, discussed in the following chapter, Danish medieval and post-medieval history will form the basis for understanding the results garnered in the forthcoming analysis on the rural cemetery at Tirup and the urban cemetery of Black Friars.

Chapter 3: Literature Review – Osteological Context

3.1 Introduction

The following chapter will review the methods reported on in the anthropological literature to estimate body proportions (body mass, stature, and robusticity), as well as the pathology associated with increased body mass and age. Additionally, theoretical concerns presented by the "Osteological Paradox" (Wood et al. 1992) will be considered.

3.2 Estimating Body Mass from Skeletal Material

Several techniques for estimating body mass (BM) have been created, mostly derived to estimate body mass of hominid species. Techniques have been developed to estimate body mass based on cranial features (e.g., Aiello and Wood 1994) and on stature (e.g., Porter 1995). The most widely used techniques can be broken into two categories: mechanical and morphometric (Auerbach and Ruff 2004). Mechanical methods are based on the body's response to load bearing. Morphometric methods use an individual's stature and breadth to estimate body mass. Recently, the biomechanical properties of long bones have also been applied to the estimation of body mass.

3.2.1 Mechanical Body Mass Estimates

Mechanical methods are based on properties associated with mechanical loading and, thus, use the dimensions of weight bearing bones, most commonly the femoral head, to estimate body mass. The three most commonly used equations are those presented by Ruff et al. (1991), McHenry (1992), and Grine et al. (1995). These equations are based on femoral head diameter. As articular surfaces are less affected by activity level and muscular loading during life than diaphyseal dimensions (Auerbach and Ruff 2004), the femoral head diameter equations are seen as particularly useful. The femoral head also produces highly reproducible measurements

(Auerbach and Ruff 2004). Additionally, the femoral head is frequently present in archaeological material (Auerbach and Ruff 2004).

Ruff et al. (1991) devised several sex- and population-specific equations for the femur, as well as combined-sex equations. Their equations using femoral head diameter (FHD) are most commonly replicated in the literature. The equations are:

$$\text{Female BM} = 2.426 \times \text{FHD} - 35.1$$

$$\text{Male BM} = 2.741 \times \text{FHD} - 54.9$$

$$\text{Combined BM} = 2.160 \times \text{FHD} - 24.8$$

Interestingly, the results of the analysis by Ruff and colleagues (1991) suggest that, when estimating body mass, shaft dimensions, particularly cortical area and second moment of area in the medio-lateral plane (discussed later), were more highly correlated to current body mass than femoral head diameter. They found femoral head diameter to be more related to an individual's body mass at 18 years of age. Additionally, as the equations were created from a modern sample from the United States, they systematically tended to overestimate body mass when tested on an archaeological sample from the Pecos Pueblo. As such, the authors suggest making a 10% downward adjustment in body weight when calculations are done on early (preindustrial) archaeological populations (Ruff et al. 1991).

When measured against the gold standard, the stature/bi-iliac breadth equation (discussed below), which Auerbach and Ruff (2004) consider relatively unbiased, the Ruff et al. (1991) equation provided close body mass estimates. Pomeroy and Stock (2012), however, found that the equations overestimated body mass in the smaller individuals and underestimated it in larger individuals. When Elliot et al. (2016) tested the equation on CT scans of modern humans of known weight, they found that the male equation worked relatively well, while the female equation failed to meet acceptable error and accuracy criteria. Ruff et al. (2012) revised the original equations by including data from high-latitude populations into their analysis. The argument was that the new data made the equation more applicable worldwide. While they argued that their new formulae were superior to those previously created, Elliot et al. (2016) found that the female equation still failed to estimate body mass with any real accuracy.

Another equation commonly employed in the literature is that created by McHenry (1992). The author created the formula based on North Americans of both European and African descent as well as Khoisan and African Pygmies. The aim of the research was to create an equation that worked more reliably for hominids of smaller body size. The body mass estimation equation is a combined-sex equation:

$$BM = 2.239 \times FHD - 39.9$$ [1]

Auerbach and Ruff (2004) found that McHenry's (1992) equation consistently underestimated body mass in larger and "average" individuals, however was the most accurate technique using femoral head diameter for estimating the body mass of small individuals (see also Pomeroy and Stock 2012). By contrast, Elliot et al. (2016) found the equation created by McHenry (1992) to exceed expectation. The equation estimated mass within acceptable limits for males and when sex was combined, however failed to estimate female body mass reliably.

Grine et al. (1995) devised an equation using data from modern African and African American samples. This equation created is generally believed to be more accurate for larger bodied individuals (Auerbach and Ruff 2004):

$$BM = 2.268 \times FHD - 36.5$$

[1] Equation taken from Ruff et al. 1997 which they derived from raw unpublished data.

Auerbach and Ruff (2004) noted that the equation created by Grine et al. (1995) consistently overestimated body weight (see also Pomeroy and Stock 2012), however worked well for the largest individuals in the sample. As with the equation created by McHenry (1992), Elliot et al. (2016) found that the Grine et al. (1995) equation estimated body mass well for males and when sex was combined but female estimates were less reliable.

General limitations associated with body mass estimates using femoral head diameter include errors associated with extrapolating body mass (including unpreserved soft tissue) from a small part of the body (Ruff 2000a) as well as mismatching target and reference samples. The body mass estimation equations are created based on a (or several) specific population(s) or time period(s). Mismatching of body proportions between reference and target samples, whether by region or time period, can introduce significant bias into an analysis (Ruff et al. 2012). Body proportions vary based on genetics, sex, activity, nutrition, and hormones (Feldesman and Fountain 1996; Moro et al. 1996; Robbins 2007; Ruff 2000b, 2003; Ruff and Walker 1993; van der Meulen et al. 1993; Wallace et al. 2012).

Many argue that, in the absence of a full skeleton (or a reliable stature estimate), averaging the body mass estimates from the formulae created by Ruff et al. (1991), McHenry (1992), and Grine et al. (1995) provides the most accurate body mass approximation (Auerbach and Ruff 2004; Elliot et al. 2016 – although not for females; Pomeroy and Stock 2012).

3.2.2 Morphometric Body Mass Estimates

In an attempt to increase accuracy and reliability of body mass analyses, a morphometric body mass estimation method was generated. The morphometric method was created by Ruff (1994) by modeling the body as a cylinder (see also Ruff et al. 1997). The height of the cylinder is the stature (ST) component, while the diameter of the cylinder is estimated by measuring bi-iliac, or hip-to-hip, breadth (BIB). As it encompasses both height and width, this method is generally considered to be the most accurate and is often used as the standard to which the accuracy of mechanical methods is judged (Auerbach and Ruff 2004; Pomeroy and Stock, 2012). However, when Elliot et al. (2016) tested this statement using individuals of known weight, it only proved true for females. In the males of their sample, neither morphometric nor mechanical methods proved more reliable or accurate. It also must be noted that the accuracy of the morphometric method depends strongly on precise estimation of stature (Auerbach and Ruff 2004; Moore 2008; Ruff et al. 2012). Ruff and colleagues (2012) caution that estimating stature introduces error and, even when stature is known, some error is associated with the equation. Ruff (1994) created sex-specific and combined-sex equations to account for differences in the male and female physique, as well as for individuals where sex is indeterminate. These equations were shown to work well for "normal" individuals (Ruff et al. 1997) and relatively well in elite athletes (Ruff 2000a). The body mass of heavyweight wrestlers, however, was consistently underestimated due to the large difference between the width of their hips and shoulders. This trend was seen in all males but to a lesser degree. According to Moore (2008), by including a measurement of the clavicle this issue can be mitigated.

In 2005, Ruff and colleagues updated their equations to include high-latitude populations, namely the Alaskan Inupiat and Finnish individuals. The results were the creation of two "world-wide" sex-specific equations for body mass:

$$\text{Male BM} = 0.422 \times \text{ST} + 3.126 \times \text{BIB} - 92.9$$

$$\text{Female BM} = 0.504 \times \text{ST} + 1.804 \times \text{BIB} - 72.6$$

When the morphometric equations devised by Ruff (1994) and Ruff et al. (2005) were analyzed by Elliot et al. (2016), both equations were found to meet acceptable standards for reliability.

However, they did not consistently prove to be more reliable than the mechanical methods. In 2012, Ruff et al. updated the femoral head diameter equations using a hybrid approach based on body mass estimated by the Ruff et al. (2005) morphometric methods.

The main issues surrounding morphometric estimates of body mass center around their disregard for robusticity and adiposity. Moore (2008) stated that by calculating male and female body mass using separate equations or by using the length of the clavicle as a control for sex, the issue of robusticity could be substantially minimized. As previously stated, the equation also relies on the accurate estimation of stature. When stature must be estimated substantial error can be introduced.

Regardless of the method used, body mass must be adjusted for height. Clinically and archaeologically, this is often done using the Body Mass Index calculation (Canadian Diabetes Association 2018).

$BMI = kg/m^2$, where kg is the estimated body mass and m is the estimated height.

According to the National Heart, Blood, and Lung Institute (NIH) (2018), a BMI of less than 18.5 classifies an individual as underweight. A BMI of between 18.5 and 24.9 is considered normal. An overweight individual’s BMI falls between 25 and 29.9 whereas those with a BMI of over 30 are classified as obese (NIH 2018).

Several issues surrounding the use of BMI have arisen in the literature, of which the calculation’s inability to differentiate between weight increases due to increased muscle, bone mass, and/or fat, while interpreting the results as indicating increased body fat levels is considered the most problematic. Additionally, factors such as age, sex, and ethnicity have been shown to greatly affect BMI (Department of Health and Human Services and Centers for Disease

Control and Prevention 2018). While issues surround the use of BMI in both clinical and archaeological research, it presents the best available calculation to adjust body mass for height.

3.2.3 Biomechanical Body Mass Estimates

Biomechanical methods are based on principles of load bearing on the long bones and articulations of weight-bearing joints of the lower limbs (Moore 2008). Moore (2008) posited that due to decreased knee flexion, higher body mass will cause an increase in cross-sectional area without an increase in area moments of inertia or torsional strength (discussed later), leading to a more circular shaft ($I_{max} = I_{min}$). While Moore (2008) did not find any biomechanical properties helpful in predicting body mass, Kacki et al. (2019) found that body mass was highly correlated with medullary breadth at 50%, 65%, and 80% of the femoral shaft. Moore et al. (2007) and Moro et al. (1996) also found that cross-sectional area of the femur correlated strongly with body mass. The main issues surrounding biomechanical models for estimating body mass are the confounding effects of activity patterns and robusticity, as well as accounting for lifetime weight fluctuations (Moore 2008).

Moments of area and polar moments of area reflect the bone's bending and torsional (twisting) rigidity, respectively. Greater bending rigidity in one direction is due to more force being applied in that direction. A higher I_{max} to I_{min} (bending strength) ratio correlates to increased activity. According to Moore (2008), controlling for activity can be accomplished by an analysis of femoral cross-sectional shape. Between two individuals experiencing heavy loads, one being obese and one being active, the active individual will have a higher I_{max}/I_{min} ratio due to higher knee flexion causing antero-posterior elongation of the shaft. In the overweight individual a more circular cross-section would be expected ($I_{max} = I_{min}$). Agostini et al. (2011) found that, as body mass increases, the femur adapts to more medio-lateral pressure resulting in an increase of medio-lateral diameter. Moore (2008) and Moore and Schaefer (2011) did not find a clear correlation between cross-sectional shape and body weight.

3.2.4 Body Mass Estimation Summary

All body mass estimation methods described have benefits and drawbacks. In many cases the appropriate method is case specific depending on study sample. For the current analysis, a combination of methods was used. Initially, the morphometric methods, using bi-iliac breadth to estimate body mass, was deemed the most accurate and reliable. Due to preservation issues, the mechanical method, employing femoral head diameter to estimate body mass, was also employed as it provided a larger sample for analysis. The specific methods for body mass estimation used in the current analysis are discussed in Chapter 4.

3.3 Estimating Stature from Skeletal Material

Researchers have been attempting to accurately estimate living stature from skeletal material since the 19th century (E.g., Pearson 1899). Stature is the product of a combination of genetic and environmental factors. Genetic heritability will provide an individual's maximum achievable height. Environmental pressures (such as poor nutrition, physiological stress, disease, climate, etc.) mitigate whether individuals will reach this stature (Radu and Keleman 2015). Thus, estimating living stature can help researchers understand genetic and environmental (and social) pressures that may lead to sub-optimal growth patterns. The issue for researchers is to differentiate genetic and environmental contributions.

Stature estimation techniques can be separated into four categories. The first and simplest method is to measure the skeletal length in the grave. The individual must be in a supine position and the cranium and at least one talus must be undisturbed (See Boldsen 1984a; Petersen 2005, 2011). Stature is measured from just above the most distal point of the crania to a point just above the most distal point of the talus (Petersen 2005). Petersen (2005, 2011) found that measuring stature in this fashion underestimated height by approximately 2.5 cm. He concluded that when 2.5 cm are added to the measured height, measuring the skeletal length in grave is highly accurate in estimating living stature (only slightly less accurate than the "gold standard" for stature reconstruction, the anatomical method). The major drawback of this method is that it cannot be applied to significantly disturbed burials or burials where multiple individuals are interred (Radu and Keleman 2015). It can also be quite time consuming and requires a bioarchaeologist to be present at the dig site. For these reasons this method is rarely employed.

A second method, the anatomical method, created by Fully (1956) and updated by Fully and Pineau (1960) and Raxter et al. (2006, 2007), involves summing cranial, vertebral (including the 1st sacral vertebra), femoral, tibial, and talo-calcaneal height and adding a soft tissue correction. The anatomical method (presented by Raxter et al. 2006) with an age correction update (Raxter et al. 2007) is considered the most accurate method for reconstructing stature from skeletal material and is often used as a comparison for estimating the accuracy of other methods (Auerbach 2011). The anatomical method equations are:

ST (with age correction) = 1.009 x Skeletal Height – 0.0426 x age + 12.1

ST (without age correction) = 0.996 x Skeletal Height + 11.7

The major impediment to the universal use of the anatomical method is its requirement of a largely complete skeleton. As this is usually not the case in archaeological analyses, the anatomical method (Raxter et al. 2006, 2007) cannot often be employed. There are several methods for estimating the dimensions of missing elements, allowing researchers to employ the anatomical method on incomplete skeletal material. (For examples see Auerbach 2011 and

Sciulli et al. 1990). It should be noted, however, that with each estimation of element dimension, error is introduced (Auerbach 2011).

The third and most commonly used method for estimating stature is the mathematical model. This method relies on the correlation between stature and long bone lengths. Regression equations are created for one or more bones and, thus, do not require the complete preservation of a skeleton. A plethora of equations exist. At an international level, the most widely used regression equations are those developed by Trotter and Gleser in 1952 and 1958 (Jantz 1992; Radu and Kelemen 2015). Feldesman and Fountain (1996) found that population differences exist between femur to stature ratios and concluded that population-specific equations should be employed wherever possible. Significant discussion has taken place surrounding the most accurate equation for specific populations. Several researchers have devised population-specific regression equations (For examples see Auerbach and Ruff 2010; De Mendonça 2000; Genoves 1967; Maijanen and Niskanen 2010). Certain populations, such as the Ancient Maya, require specific formulae due to cultural practices (such as artificial cranial modification) that affect height (Pomeroy and Stock 2012). According to Boldsen (1984a), Danish skeletal material deviates from other population in the limb proportions, rendering estimates of stature from long bone length difficult. He posited that this is possibly due to catch-up growth after episodes of ill health (Boldsen 1998a). Boldsen (1984a) suggested using raw long bone length as a proxy for stature instead of calculating stature from long bone length. Population-specific stature estimation equations have been created for Scandinavian populations by Maijanen and Niskanen (2010). Population-specific stature estimation equations are often created from average statures of modern (thus genetically similar) populations from an analogous geographic area. Ruff et al.

(2012) devised several sex-specific formulae for European Holocene populations, which have been shown to perform well (Ruff et al. 2019). The formulae are:

Using the femur and tibia:

Male ST = 1.49(femur length + tibia length) + 43.55

Female ST = 1.42(femur length + tibia length) + 48.59

Combined sex ST = 1.49(femur length + tibia length) + 43.53

Using the femur alone:

Male ST = 2.72 (femur length) + 42.85

Female ST = 2.69(femur length) + 43.56

Combined sex ST = 2.77(femur length) + 40.50

In their 2008 article, Raxter and colleagues concluded that general standard of living due to changing climate, diet, and sanitation made modern and archaeological populations too dissimilar for accurate stature estimation.

For this reason, many of the more recently published articles employ a fourth method. The fourth method, the “hybrid” model, employs the anatomical method (Raxter et al. 2006, 2007) and the creation of population-specific regression formulae. The anatomical method is employed on the well-preserved material in order to get accurate average height estimates for the population in question. Using these averages, mathematical regression formulae are created. (For examples see Raxter et al. 2008; Ruff et al. 2012; Ruff et al. 2019). On top of population-specificity, it has been shown that male and female skeletons follow different growth patterns (Raxter et al. 2006). As such, many argue that sex-specific equations should be employed whenever possible. (For examples see Fully 1956; Pearson 1899; Ruff et al. 2012).

3.3.1 Stature Estimation Summary

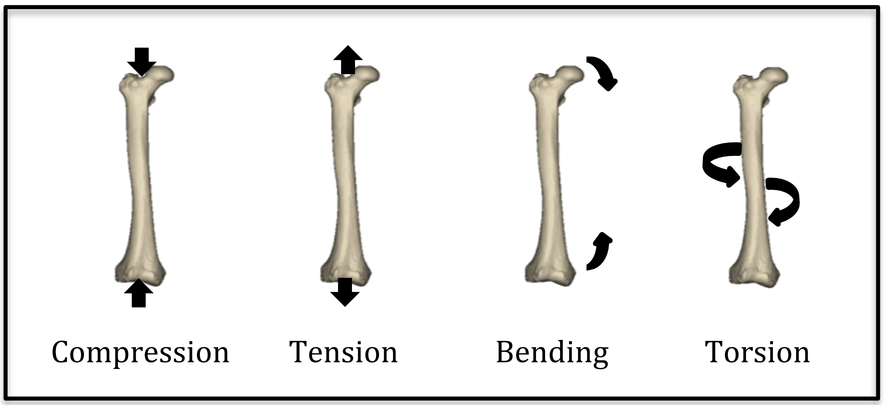
The most effective way to estimate stature from skeletal remains has been a topic of bioarchaeological research for over a century. Most researchers agree that the anatomical method first describe by Fully (1956) and updated by Raxter et al. (2006, 2007) is the most accurate. For the current research the anatomically estimated stature was used where possible. However, as previously discussed, the anatomical stature estimation method requires a relatively complete skeleton for analysis. In cases where only fragmentary material was available, a mathematical regression equation created by Ruff et al. (2012) for Holocene Europe and the skeletal length measured in grave (Boldsen 1984a) were used to supplement the anatomical method for stature estimation. Specifics on the stature estimation methods employed in the current research are presented in Chapter 4.

3.4 Estimating Robusticity from Skeletal Material

Robusticity, in general terms, refers to the overall strengthening of a skeletal element through the addition of bone tissue (Stock and Pfeiffer 2004). It is studied in the literature by applying engineering beam theory and other biomechanical analyses to long bones. The idea is based on “Wolff’s Law” or, as it has been more recently (and more aptly) named, “bone functional adaptation”. Generally, the principles of bone functional adaptation are (1) that organisms possess the ability to adapt to new living conditions and (2) that bone cells are capable of responding to local mechanical stresses (Ruff et al. 2006). Bone remodeling is based on strain (the physical deformation of bone tissue), acting through a feedback loop by which increased strain leads to bone deposition and decreased strain leads to bone resorption (Ruff et al. 2006). Systemic factors (such as age, disease, hormones, and genetics) also affect the feedback loop (Ruff et al. 2006).

The external loads applied to bone can be calculated by examining bone's cross-sectional geometric properties (Ruff 2008). A bone's ability to resist failure (fracturing) is referred to as strength; its ability to resist bending prior to failure is known as rigidity. Figure 3.1 illustrates the forces that act on bone during normal physical loading situations. Cross sectional or cortical bone area (CA), or the cross-sectional area of a long bone's diaphysis (shaft), is a measure of rigidity and strength in axial (upward and downward) compression and tension. As bone is rarely subjected to compression and tension alone, second moments of area (also known as area moments of inertia) can measure bending rigidity. Second moments of area are calculated by multiplying a small unit area of bone by the squared distance to an axis. Second moments of area are often measured through the antero-posterior (I_y) and medio-lateral (I_x) axes or as minimum (I_{min}) and maximum (I_{max}) values. Torsional (twisting) rigidity is measured as a polar second moment of area (J), which is a second moment of area measured through the centroid (central point). Minimum and maximum section moduli (Z_{min} and Z_{max}) are measures or bones bending strength along minimum and maximum axes. Torsional strength is approximated using a polar section modulus (Z_p). Polar section moduli are calculated through the centroid. Bending and torsional strengths are different from rigidities as the stress occurs at the outermost surface of a cross section. Bending and torsional strengths are calculated by dividing second moments of area by the distance of the outermost surface to the appropriate axis or centroid. Total cross-sectional area (TA), the total area of a cross section, including cortical area (CA) and medullary area (MA), the area of the medullary canal, can aid in understanding bone distribution. Percent cortical area (%CA), calculated as [(CA/TA) x 100], is used as a measure of relative cortical thickness or area (Ruff 2008). By examining the biomechanical distribution of bone, a skeletal sample's bone strength and rigidity can be estimated and compared. In order to compare the biomechanical properties between samples, the geometric properties must be adjusted for size, as body size is a mechanical load. According to Ruff (2008) the most effective way to standardize for size when measuring cross-sectional areas is using body mass. For section moduli, standardization is done by dividing a section modulus by body mass x relevant limb length. For second moments of area, using body mass x relevant limb length^2 will effectively achieve standardization.

Figure 3.1 Forces applied to bone



The major limitations to biomechanical cross-sectional analyses of bone are that material properties of bone, such as bone density and quality, also affect rigidity and strength. Bone quality is a combination of material properties such as mineralization, composition, and bone turnover and the structural properties of architecture, connectivity, and turnover (Agarwal 2008). Due to diagenic, or post-depositional, changes in archaeological bone, bone density and quality are often difficult to determine. Diagenesis is as likely to occur in random bones as in the entire skeletal sample. Additionally, it is not possible to determine the extent of diagenesis without invasive or chemical analyses (Agarwal 2008). Also of note, is that mechanical loading situations experienced in life are much more complex that those modeled in beam analysis. Forces applied during body movement are complex; multiple forces act simultaneously on bone.

The cross-sectional properties discussed here present the best available properties for evaluating the mechanical performance of bone (Liebermann et al. 2001, Ruff et al. 2006, Ruff 2008).

Using geometric cross-sectional properties, bone biomechanics has been applied to understanding subsistence strategies (Ruff 1987; Stock and Pfeiffer 2004; Wescott 2006), mobility patterns (Stock 2006; Weiss 2003; Wescott 2006), activity patterns (Bridges 1989; Rhodes and Knüsel 2005), behavioural patterns (Ruff 1999; Ruff and Larsen 2001), and the sexual division of labour (Ogilvie and Hilton 2011; Ruff 1987; Wescott 2006). Stock (2006) even found that climate is correlated with bone robusticity, especially in the upper limb. Hunter-gatherers from colder climates were shown to have stronger, more robust long bone shafts than hunter-gatherers from warmer climates.

While biomechanical analyses on bone can elucidate information about archaeological populations, there is still much that is unknown about bone's response to mechanical loading. Systemic factors such as age, disease, hormones, diet, and genetics all affect bone remodeling (Ruff et al. 2006). The extent to which genetics affects skeletal plasticity is still misunderstood (Pearson 2000). According to Ruff and colleagues (2006) genetics may determine bone shape, both directly (through osteoblastic and osteoclastic activity) and indirectly (through body weight, muscle strength, and activity level). Genetics may also influence bone's responsiveness to mechanical loading (Ruff et al. 2006). Multi-factorial explanations of bone robusticity are often overlooked in favour of activity-based explanations (Jurmain 1999). Another limitation to understanding bone geometry is that it is unclear as to what extent in vivo analyses using animal proxies (see Lieberman et al. 2001; Woo et al. 1981) or those performed on elite athletes (see Daly et al. 2004; Eckstein et al. 2002), which have been used to create many of the current biomechanical hypotheses, reflect real-life archaeological situations. In fact, in many cases, these experiments by nature reflect abnormal situations (Trinkaus et al. 1994). Activities undertaken by elite tennis players, for example, are "hardly … representative of a 'normal' subsistence-oriented population, they provide an extreme but nonpathological example of the nature of responses in humeral diaphyseal dimensions to marked unilateral activity patterns" (Trinkaus et al. 1994: 2). Additionally, different activities can produce similar bone manifestations (Jurmain 1999). Finally, bone mass decrease has been noted when rigorous activity ends, which could confound archaeological interpretation, especially in elderly individuals (Jurmain 1999). For these reasons, Jurmain and Roberts (2008) caution against the search for specific activity/behavioural patterns in skeletal material. Yet, there are a plethora of examples in the literature where skeletal robusticity (especially bilateral asymmetry of the humeri) has been linked to specific activities. (For examples see Hawkey and Merbs 1985; Lai and Lovell 1992).

Another bioarchaeological technique for assessing robusticity and muscularity is to examine musculoskeletal markers (MSM) (often termed occupational markers in the literature). MSM are "distinct skeletal marks that occur where a muscle, tendon, or ligament inserts onto the periosteum and into the underlying bony cortex" (Hawkey and Merbs 1995: 324). When force is applied (through action of the muscles) a local boney response is instigated (Hawkey and Merbs 1995). The use of MSM has come into question as there is evidence that they are not necessarily associated with strenuous activity and that genetics play an important role in the skeletal response to activity (Jurmain and Roberts 2008). While many researchers caution against using MSM to divine occupation (at least without other specific artefactual evidence) (Jurmain and Roberts 2008; Mariotti et al. 2007), their presence has been used extensively to intuit activity patterns. According to Weiss (2004), if body size and age are controlled for, sexual division of labour can be ascertained from MSM. Vilotte et al. (2010) argued that fibrous insertions should be avoided. The authors stated that fibrocartilaginous insertions are relevant indicators of general level of physical activity (at least in males). They were able to reconstruct general occupational types (non-manual workers, light manual workers, manual workers carrying heavy loads, and manual workers who use forceful tasks) with very little error (<10%).

3.4.1 Robusticity Estimation Summary

In the current analysis, femora were CT scanned, processed, and cross sections along the shaft and neck of the femora were analyzed for relevant geometric properties. As discussed, the strength of a bone is tied to both quantity (areas) and quality. Unfortunately, an assessment of bone quality is outside the purview of the current analysis. Musculoskeletal markers were excluded from the analysis as there is still a significant amount of contention surrounding their use to assess robusticity. Specifics on the estimation of robusticity for the current analysis are presented in Chapter 4.

3.5 Skeletal Disorders Associated with Aging and Body Mass

As individuals age the skeletal system starts to degenerate. In palaeopathological analyses this degeneration is seen inside the bones as: thinning of the cortical bone or loss of connectivity in the trabecular bone, in osteopenia or osteoporosis, bone remodeling and/or erosion at the joints, in degenerative joint diseases (osteoarthritis and vertebral osteophytosis), and excessive bone growth seen in disorders like diffuse idiopathic skeletal hyperostosis (Aufderheide and Rodriguez-Martin 2008). Many degenerative diseases are exacerbated by increased body mass in life, of which osteoarthritis, vertebral osteophytosis (especially in the lumbar region), and diffuse idiopathic skeletal hyperostosis are the most commonly studied. Other ailments associated with increased body mass that manifests as a skeletal response include plantar calcaneal spurs and gout. The following is a brief overview of age- and size- related disorders and the methodological techniques for assessing them in archaeological skeletal material.

3.5.1 Osteoporosis

Osteoporosis (OP) affects more than 75 million people in the United States, Europe, and Japan, causing 8.9 million (potentially life-threatening) fractures worldwide (World Health Organization 2004). OP is characterized by a decrease in bone mass and quality where bone resorption exceeds bone formation leading to increased bone fragility and susceptibility to fracturing (Agarwal and Grynpas 1996). This imbalance in bone remodeling occurs as a result of old age and certain medical conditions (e.g., scurvy) (Brickley 2000). OP is often linked to estrogen imbalance in menopausal women as well as genetics, nutrition, physical activity, and certain reproductive factors (Curate 2014). The World Health Organization (2004) defines OP as a bone mineral density (BMD) in the femoral neck that falls at least 2.5 standard deviations below the average of a young female (20 – 29 years); individuals are considered osteopenic when BMD lies between 1 and 2.5 standard deviations below the young female adult mean. This definition has been used to assess OP in archaeological populations as well. As OP has become such an important clinical issue, osteoarchaeologists have begun examining the disease in ancient skeletal collections in order to elucidate its universality and antiquity. Some researchers have concluded that OP is a universal phenomenon that occurs as individuals age (Eriksen 1976 (for females); Rewant et al. 1994); others have found no such universality (Curate 2014; Poulsen et al. 2001; Robb et al. 2012). Riggs et al. (2009) found that, while age was a significant factor in cortical bone loss, particularly in females, trabecular bone loss began in early adulthood in both sexes.

3.5.1.1 Evaluating Osteoporosis

Several methods exist for analyzing OP in archaeological bone including both invasive and non-invasive techniques. Problematically, many of the different technologies used are incompatible and thus direct comparison of results using different technology is impossible. However general trends can be related (Brickley and Agarwal 2003). The simplest method for diagnosing OP in skeletal remains is to examine bone for the presence of fracturing (Brickley 2000; Brickley and Agarwal 2003). Fractures related to OP include femoral neck fracturing, Colles' fractures of the wrist, and vertebral crush fractures (Brickley 2002; Lovell 1997). The difficulties associated with this type of analysis include differentiating peri- and post-mortem trauma, identifying exactly when a fracture occurred in an individual's life, and the fact that several pathological conditions (such as scurvy and leprosy) can lead to osteopenia and fracturing (Brickley and Agarwal 2003). Additionally, osteoporosis in bone prior to fracturing is overlooked. (For examples of this technique see Curate et al. 2010; Djuric et al. 2006; Domett and Tayles 2006; Mensforth and Latimer 1989).

Other techniques include assessing bone robusticity and size through biomechanical analyses of cortical bone. Many early studies (see Armelagos et al. 1972; Carlson et al. 1976; Dewey et al. 1969; Drusini et al. 2000; Martin and Armelagos 1979; Richman et al. 1979; Ruff and Hayes 1982, 1983) took cortical measurements directly from a cross section of cut bone. Due to their destructive nature, invasive techniques are increasingly avoided in archaeological analyses. Additionally, these methods tell researchers nothing about bone density or quality and only provide results on the amount of cortical bone present. Bone quality can affect bone strength and rigidity in many ways. For example, strain on the femoral neck will cause microfracturing if the load exceeds the yield stress (the maximum stress the femoral neck can withstand). In brittle bone, it is much more likely that the yield stress will cause a complete fracture (Thomas et al. 2009). Osteoporotic bone More recently researchers have turned to different technologies to assess cortical dimensions without destroying the bone itself.

Another technique, cortical histomorphometry, allows for the measurement of osteonal dimensions and bone turnover rate by microscopically analyzing thin sections of bone. (For examples see Cho and Stout 2003, 2011; Ericksen 1980; Foldes et al. 1995; Mulhern and Van Gerven 1997; Stout and Lueck 1995). Issues associated with cortical histomorphometry surround the difficulty in differentiating the affecting factors: age, metabolic disturbances, and/or biomechanical features. Furthermore, measurements of activation frequency and bone turnover rely on chronological age which is unreliable and inexact in archaeological samples. This technique is also invasive and destructive (Brickley and Agarwal 2003).

Optical densitometry or stereometry allows for the 3-D analysis of trabecular bone using stereo-pair photographs and a stereocompactor for analysis (Brickley and Agarwal 2003). Optical densitometry allows for the ‘optical density’ to be calculated from a radiograph with an aluminum step wedge (where translucency can be compared). Optical densitometry can be used to assess both compact and trabecular bone however it is most commonly used on trabecular bone where a digital stereocomparator allows the length of trabeculae to be measured in 3-D (Brickley and Agarwal 2003). Analysis using optical densitometry has been shown to produce good results (Brickley 2000). The main issues include the destructive nature of the technique and the need for specialized equipment. Due to the absence of soft tissue, results from archaeological bone will not be comparable to contemporary results. Diagenesis is a major concern as changes may influence the results and diagenic change is difficult to assess using this technique.

Although cheaper and more available than other technologies, the equipment is still relatively expensive and not widely available (Brickley 2000).

It has been argued that while long bone cortical robusticity is important in analyzing bone strength, in osteoporosis trabecular bone analyses are equally, if not more, important. Trabecular bone plays an important role in the load transmission and energy absorption (Keaveny et al. 1994; Harada et al. 1988; Hvid 1988; Wang et al. 2015). According to Eswara et al. (2006), trabecular bone holds in excess of 75% of the vertebral load. The strength and rigidity of bone is affected by bone architecture, or trabecular thickness, connectivity, orientation, spacing and anisotropy of trabecular bone (Fields et al. 2011; Liu et al. 2006, 2009; Shi et al. 2010). More recent clinical research has noted the importance of different types of trabecular bone, namely plates and rods, in determining bone strength (Liu et al. 2009; Stauber et al. 2006; Wang et al. 2013, 2015). Plate-like trabeculae, or flatter regions of trabecular bone, can withstand higher loads than elongated, cylindrical rod-like trabeculae (Salmon et al. 2015). It has been argued that as bone is lost, plate-like trabeculae transform into rods leading to a loss in bone mass as well a decrease in ability to withstand stress (Hidelbrand et al. 1999; Wang et al. 2013; Wehrli 2009), although more recent clinical research suggests that the plate to rod transition may be more complex than previous research suggests (Salmon et al. 2015; Wang et al. 2013)

Simple visual inspections of trabecular bone can indicate bone loss and bone quality. Trabecular bone is usually analyzed in the lower lumbar vertebrae or femoral neck. It is also possible to observe trabecular bone loss and cortical thinning by examining free-ending trabecular struts and micro-callus formation (Brickley and Agarwal 2003). In their analysis of microfractures, Roberts and Wakely (1992) noted that senile OP involved the loss of centrally situated trabeculae before those at the periphery. Additionally, horizontal trabeculae are lost prior to vertical ones. Thus, weight bearing structures are conserved and vertebral collapse will only occur in advanced cases. Roberts and Wakely (1992) suggested that the diagnosis of OP include the presence of microfracture calluses in the vertebrae even in the absence of external signs of OP, and not simply be limited to bone mineral density measurements.

As with much of bioarchaeological analysis, non-destructive methods are becoming more prevalent in palaeopathological analyses, allowing for the examination of bone while maintaining its integrity for future analysis. Non-destructive techniques for assessing bone density include radiogrammetry, dual energy x-ray absorptiometry, energy dispersive low angle x-ray scattering, and computed tomography.

Radiogrammetry allows for the morphometric analysis of bone from a radiograph. Metacarpal radiogrammetry has been used extensively in the analysis of OP in the archaeological literature (See Beauchesne and Agarwal 2014; Dequeker et al. 1997; Domett and Tayles 2006; Glencross and Agarwal 2011; Ives and Brickley 2004; Lazenby 1995, 1998; Mays 1996, 2000a, 2001, 2006; Rewekant 2001). Prior to dual energy X-ray absorptiometry (DEXA), metacarpal radiogrammetry was the clinical standard, and thus comparative data from modern samples are available (Brickley and Agarwal 2003). Radial (Ekenman et al. 1995) and humeral (Ericksen 1976) radiogrammetry have also been used. A limitation of radiography is that post-depositional bone changes such as severe soil infiltration may prevent the production of useful radiographs and in some cases may obscure the whole picture. However, the radiographic images from archaeological populations (if of good quality) can be compared to those of living individuals (Brickley and Agarwal 2003) and thus can be very useful for understanding the universality of OP.

Dual energy X-ray absorptiometry (DEXA) is widely used in palaeopathology as it is currently the clinical standard (Mays 2008) (but will not be used in this research). (For examples see Foldes et al. 1995; González-Reimers et al. 2002; Holck 2007; Lees et al. 1993; Mafart et al. 2008; Mays et al. 1998; Poulsen et al. 2001; Zaki et al. 2009). DEXA utilizes a stable X-ray source to measure bone mineral content and can be used for both trabecular and cortical bone density. DEXA scans measure areal BMD not volumetric BMD, and thus must be normalized for body or element size. Due to hardware and software differences between DEXA scanners, comparison between different studies is an issue. Additionally, archaeological specimens, due to a lack of soft tissue, cannot be compared to living subjects as computer software accounts for soft tissue when calculating BMD. This issue can be somewhat mediated by placing the element being scanned into a material with roughly the same density as soft tissue, such as dry rice or water. While this does not allow for direct comparisons with living populations, it does allow for a comparison of age-related patterns (Mays 2008).

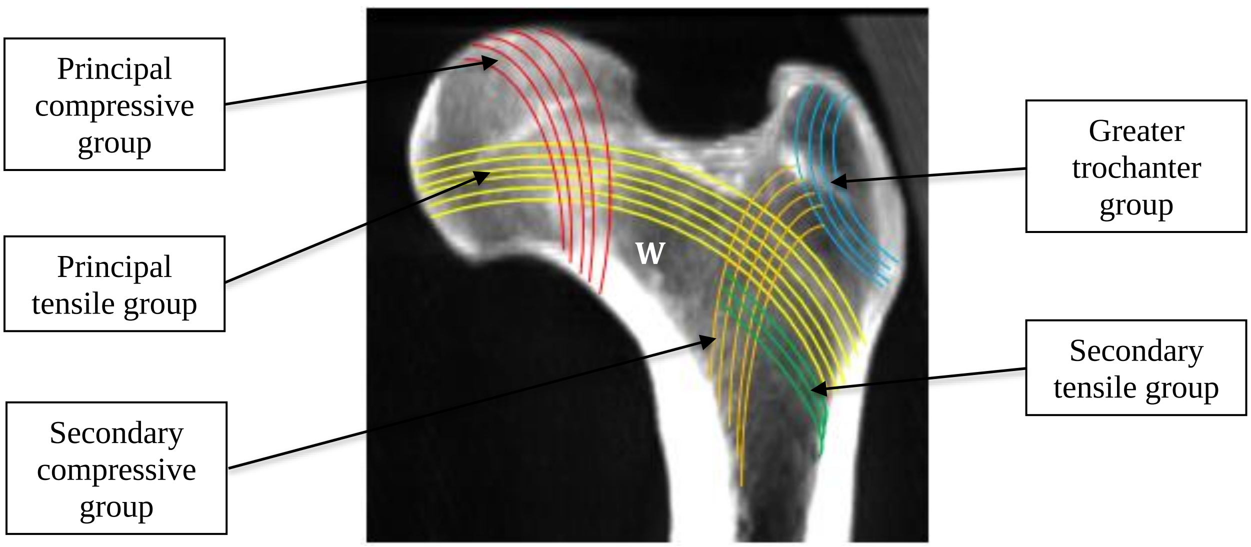
Perhaps the most significant problem associated with DEXA scanning is the possibility of diagenetic change in density due to physical or chemical contamination from the burial environment (Mays 2008). In their analysis of DEXA's usefulness in evaluating BMD in archaeological bone, González-Reimers et al. (2002) stated that, while DEXA seems to work well for archaeological bone, diagenesis, air pockets within cancellous bone, and the lack of bone marrow may distort DEXA-assessed BMD. They caution against using living individuals as a control for "normal" BMD for these reasons.

Energy-Dispersive Low Angle X-ray Scattering (EDLAXS) uses an energy sensitive detector that detects scattered photons from an object at a fixed angle. EDLAXS scanners can also identify different minerals in bone and thus are extremely useful in identifying diagenic change (Brickley and Agarwal 2003). EDLAXS produces a true estimate of volumetric BMD for both cortical and trabecular bone (rather than areal BMD such as in DEXA scans). This means that scanned archaeological bone can be directly compared to living individuals (Mays 2008). The technique has been shown to be an extremely accurate and reliable technique for archaeological bone density analysis. As the radiation dose is high, use in clinical settings is limited. Thus, inadequate scanner availability will likely leave this technique in relative obscurity in archaeological analyses (Brickley and Agarwal 2003). (For examples see Brickley and Waldron 1998; Farquharson and Speller 1997).

Quantitative computed tomography (qCT) is widely used for measuring BMD in clinical settings. It also provides an estimate of volumetric BMD, allowing for the isolation of specific bone area so that exclusively trabecular bone and/or cortical bone density can be measured. As with DEXA, the lack of soft tissue in archaeological bone means that bones must be placed in a soft-tissue equivalent for scanning and results are not directly comparable to living subjects. Ultimately, the high cost and radiation output limits qCTs availability for archaeological analyses (Mays 2008). González-Reimers et al. (2007) found a significant correlation between trabecular bone mass computed using histomorphometric analysis and qCT values, however accurate estimates of trabecular bone mass using qCT are not possible in ancient samples. Issues associated with qCT include the lack of marrow and fat in archaeological bone which distort qCT values and the relative contents of marrow which vary with age (meaning that qCT standard error increases as age-at-death increases). The authors also noted that distortion can be caused by trapped air bubbles and soil in bone. Suby et al. (2009) argue that by applying peripheral CT scanning methods, which allows for the exclusion of empty spaces in bone and the comparison of archaeological bone to a stable hydroxy-apatite control of known density, these issues can be mediated. (For bioarchaeological examples of qCT see Beauchesne 2012; Beauchesne and Agarwal 2017; Borrè et al. 2015; Bridges 1989; González-Reimers et al. 2007; Hardwood-Nash 1979; Hoffman et al. 2002; Jansen et al. 2002; Lewin and Hardwood-Nash 1977; Lynnerup 2008; Mountain 2019; Pickering et al. 1990; Rühli et al. 2002; Suby et al. 2009; Vahey and Brown 1984). Additionally, the development of micro- and nano-tomography has opened up unprecedented levels of analysis. The visualization of microcracks, microfractures, and the properties of osteocyte lacunae are now possible (Morgan 2014; Stauber and Müller 2008). Using micro-CT trabecular architecture can be analyzed. Bone volume (BV/TV), degree of anisotropy (DA), trabecular thickness (Tb.Th) trabecular spectrum (Tb.SP), trabecular number (Tb.N), and connective density (Conn.D) can be ascertained (Beauchesne and Agarwal 2017). Using technologies, such as microFTIR and scanning-SAXS imaging, diagenic change can be quantified (Reiche et al. 2011). (See Booth et al. 2016; Reiche et al. 2011; Ryan and Shaw 2015 for examples of the use of micro- and nano-CT in bioarchaeology). In the current analysis, CT scanning of the cortical and trabecular bone was undertaken. Bone mass was estimated visually from qCT scans (as describe in Chapter 4). Bone mass outputs estimated by the scanner software were not included in the analysis.

Regardless of the technique employed, Brickley and Agarwal (2003) state that, for an analysis of OP to be meaningful, some method must be employed for quantifying bone change. One index that has been used for archaeological research is the Singh Index, which simply requires the researcher to order radiographic images of bone loss into six categories based on the loss of major trabecular bone groups in the proximal femur (Figure 3.2) (Singh et al. 1970). Singh et al. (1970) identified six grades of bone loss based on the involution of trabecular bone in a predictable pattern, from Grade VI, where all types of trabecular bone are visible, to Grade I, where only compressive trabecular bone remains but is greatly reduced. Inter-observer error and repeatability has been shown to severely affect results garnered using this technique, especially in the middle scores (Brickley and Agarwal 2003). Brickley (2000) advised against using the Singh Index. However, in the absence of DEXA or EDLAX, the Singh Index is still considered useful in the analysis of femoral radiographs (Julka et al. 2012).

Figure 3.2 Major trabecular bone groups in the femoral head and neck



(Modified from Singh et al. 1970; used with permission)

Increased body mass is generally considered protective against OP. Cho and Stout (2011) found a positive linear relationship between increasing body mass and bone diameter and cortical thickness. In contrast, recent clinical literature has linked obesity to a decrease in BMD and increased prevalence of OP, especially in postmenopausal women (Cao 2011; Cobayashi et al. 2005; Goulding et al. 2000; Kim et al. 2010).

3.5.2 Degenerative Joint Disease

Osteoarthritis in synovial joints and vertebral osteophytosis in fibrocartilaginous joints, hereafter referred to collectively as degenerative joint disease (DJD), are linked to increased age (Bourke 1972; Jurmain 1977, 1980; Richards 1990; Richards and Brown 1981; Weiss 2006, 2007; Whittaker et al. 1985, 1990), genetics (Crubezy et al. 2002; Jurmain 1977; Ortner 1968), trauma (Aufderheide and Rodriguez-Martin 1998; Bourke 1972; Bridges 1992; Crubezy et al. 2002), and repeated sustained mechanical (occupational) stress (Bridges 1992, Jurmain 1977; Jurmain and Kilgore 1995; Kahl and Smith 2000; Klauss et al. 2009; Knüsel et al. 1997; Lai and Lovell 1992; Lovell 1994; Merbs 1983; Ortner 1968; Waldron 1995; Webb 1995; Wentz 2010). Clinically, obesity is referenced as significant factor in osteoarthritis in the weight-bearing joints (Coggon et al. 2001; Lementowski and Zelicof 2008; Pi-Sunyer 1991; Powell et al. 2005; van Saase et al. 1988). A higher body mass increases the biomechanical strain on weight-bearing joints and thus the likelihood of developing degenerative joint disease in the weight-bearing joints (Ortner 2003). DJD and OP are usually considered to have an inverse relationship. Individuals with DJD generally have higher BMD than those without (Dai 1996; Dequaker et al. 1996). However, Brickley and Waldron (1998) found that in their analysis of individuals with DJD from St. Bride's Parish, London, males with and without DJD showed no significant difference in BMD, and the BMD of females with DJD appeared lower than those without.

DJD occurs with the loss of cartilage in the joint. The pressure and eventual bone-on-bone rubbing leads to bone formation at joint margins (osteophytes and lipping), small cysts and surrounding sclerosis (diagnosed radiographically), eburnation (smooth, shiny, polished texture of the joint surface), and, in late stages, fibrotic thickened capsules (Aufderheide and Rodriguez-Martin 1998). The skeletal sites commonly affected by DJD include the temporo-mandibular joint, especially in cultures that use their teeth as tools, the shoulder, which is almost universally affected in the elderly and is one of the most commonly affected joints, the spine, the knee, the hip, the ankle (in trauma cases), and the foot (almost exclusively in the first toe) (Waldron 2008). Clinically, body mass has been demonstrated to increase the risk of DJD in the weight bearing joints, especially the knees (Zheng and Chen 2015) and hips (Jiang et al. 2011). However, when Weiss (2006, 2007) and Jurmain (1980) analyzed the effects of increased body mass on DJD in archaeological skeletons, they found a negative relationship, with DJD seen more frequently in lighter individuals than in heavier ones.

Overwhelmingly DJD is examined macroscopically in archaeological populations, however there are examples of radiographic analysis being undertaken to complement the gross morphological analysis (See Rogers et al. 1987, 1991; Rando and Waldron 2012).

3.5.2.1 Evaluating Degenerative Joint Disease

Several issues surround the diagnosis of DJD in synovial joints (i.e., osteoarthritis). Firstly, it is very difficult to correlate clinical and palaeopathological evidence of DJD (Jurmain and Kilgore 1995). Clinically, DJD is commonly diagnosed using pain and joint immobility. However, major arthritic boney changes can occur with little or no pain or joint immobility (Cockburn et al. 1979). Secondly, as coding of DJD relies on visual inspection, it will always remain somewhat subjective. Thirdly, methods for scoring DJD are distinct in many articles making them difficult or impossible to compare (Bridges 1992). Probably the most significant issue associated with DJD diagnosis, however, is the lack of standardization of diagnostic criteria in the palaeopathological literature.

Several diagnostic criteria have been employed in diagnosing DJD. Studies diagnose DJD as present or absent (See Brickley and Waldron 1998; Debono et al. 2004; Klaus et al. 2009; Rando and Waldron 2012; Waldron 1997a, b), in other cases as absent, slight, moderate, or severe (See Bourke 1972; Jurmain 1977, 1980; Jurmain and Kilgore 1995; Kahl and Smith 2000; Merbs 1983; Weiss 2006, 2007), and in other cases according to grading scales such as those proposed by Chapman (1963), Stewart (1958, as cited in Aufderheide and Rodriguez-Martin, 1998), Buikstra and Ubelaker (1994), etc. (See Crubezy et al. 2002; Eversole et al. 1985; Knüsel et al. 1997; Richards and Brown 1981; Wentz 2010; Whittaker et al. 1985, 1990). In studies that employ a grading scale, a decision must be made as to whether the joint components with different levels of DJD (such as the patellofemoral and medial and lateral tibiofemoral components of the knee joint) will be lumped into one composite score (such as in Crubezy et al. 2002; Knüsel et al. 1997; Wentz 2010) or whether each section will be scored separately (such as in Bridges 1992; Eversole et al. 1985; Richards and Brown 1981). The two methods cannot be compared. According to Bridges (1992) scoring each joint area separately is more accurate and allows for more meaningful statistical analyses.

In terms of specific boney changes used to diagnose DJD in synovial joints, eburnation is sometimes used exclusively (Brickley and Waldron 1998; Waldron 1997a) or researchers use the presence of either eburnation on the joint surface or gross remodeling of the articular area (Waldron 1997b). Marginal lipping (or osteophytes) and articular surface changes (or both) have been used as diagnostic criteria (Cruzeby et al. 2002; Jurmain 1990; Weiss 2006); it has been argued that a combination is more accurate (Jurmain and Kilgore 1995). According to Cockburn (1979), definitive diagnostic criteria for DJD should include eburnation and grooving on the articular surface of bone and, in cases where these features are not seen, thickening where bones are in direct contact, marginal osteophytes, and pseudocyst formation can be used. Rogers et al. (1987) classify DJD in skeletal material by marginal osteophytes, subchondral bone reaction (eburnation, sclerosis, or cysts), pitting of joint surfaces, and/or alteration of the joint surface. However, in the absence of marginal osteophytes and a subchondral bone reaction, joint changes cannot be classified as DJD. Other diagnostic criteria include any one or combination of periarticular lipping, subchondral bone resorption, and/or eburnation observed on at least one articular surface of the joint (Debono et al. 2004; Klaus et al. 2009) and eburnation, or at least two of the following: marginal osteophytes, new bone formation on the joint surface, pitting on the joint surface, and alteration in the joint contour (Rogers and Waldron 1995; Waldron 2008). Adding to the lack of standardization is the issue that many articles do not identify the diagnostic criteria used, making comparison between samples extremely problematic.

DJD in fibrocartilaginous joints, such as those in the spine, are almost exclusively diagnosed using marginal osteophytes, or bony outgrowths at the margin of the vertebral bodies. In general, DJD in the vertebral column is allocated a number grade based on severity (e.g., 0 = none, 1 = mild, 2 = moderate, 3 = severe, 4 = fused). While grading scales differ and grading remains somewhat subjective, the overall consensus on spinal degeneration makes spinal DJD analysis simpler and, for the most part, results are comparable (Aufderheide and Rodriguez-Martin 1998).

3.5.3 Diffuse Idiopathic Skeletal Hyperostosis (DISH)

Diffuse idiopathic skeletal hyperostosis (DISH) was first described by Forestier and Rotes-Querol (1950). For this reason it is sometimes referred to as Forestier's disease. A distinction is occasionally made between Forestier's diseases (where the spine is fused) and DISH (where spinal fusion is accompanied by extra-spinal enthesopathies) (Waldron 2008). Hypotheses surrounding the aetiology of DISH are numerous, including hypervitaminosis A, insufficient vitamin A, predisposition caused by immobilization of the thoracic spine, genetics, endocrinological factors such as type II diabetes or hyperinsulinemia, alterations in lipid metabolism, hyperuricemia (excess uric acid), dyslipidemia (excess lipids in the blood), or greater body lipid index (Bombak 2012). While the biological mechanisms resulting in DISH are still misunderstood, many researchers connect the development of DISH with a high body mass index, type II diabetes, and/or issues processing glucose and insulin (Cammisa et al. 1998; Daragon et al. 1995; Kiss et al. 2002; Resnick et al. 1978; Rogers and Waldron 2001; Verlaan et al. 2007). DISH is correlated to advanced age, male sex, and high caloric intake/increased weight (Rogers and Waldron 2001).

DISH occurs when the anterior longitudinal ligament begins to ossify in the thoracic region of the spine. Ossification occurs solely on the right side of the thoracic spine (Aufderheide and Rodrigues-Martin 1998; Waldron 2008); however, there is a rare exception where ossification occurs on the left side when DISH occurs in an individual with situs invertus (where the heart is on the right side) (Ciocci 1987). The skeletal manifestation of this spinal anomaly has been described as dripping candle-wax-like in appearance (Waldron 2008).

3.5.3.1 Evaluating Diffuse Idiopathic Skeletal Hyperostosis (DISH)

As one of the most obvious skeletal pathologies, it would stand to reason that the diagnosis of DISH would be straightforward, however several differing diagnostic criteria exist. Certain researchers require fusion of the anterior longitudinal ligament with no specification of number of fused vertebra (Arriaza 1993; Arriaza et al. 1993; Maat et al. 1995). Other requirements include two boney bridges in the spine (Mays 2000b), three continuously fused vertebrae (Rogers and Waldron 2001), or at least four continuously fused vertebrae (Rogers et al. 1985; Waldron 1991). Jankauskas (2003) requires only spinal entheses or extra-spinal ligament ossification. According to Rogers et al. (1987), DISH may be present where extra-spinal manifestations occur with only minimal changes in the spine (which they state could possibly represent an early stage of the disease). Paja et al. (2010) differentiate between DISH and early DISH (eDISH), where eDISH is diagnosed in the presence of extra-spinal enthesis ossification.

van der Merwe et al. (2012) stress that entheses used to diagnose DISH should be affected symmetrically before DISH can be considered.

The two most commonly used diagnostic criteria in paleopathology are those created by Resnick and Niwayama (1976) and Rogers and Waldron (2001). Resnick and Niwayama (1976) diagnosed DISH in the presence of flowing ossification of the anterior longitudinal ligament on the right side of at least four contiguous vertebrae. The authors require intervertebral disc space to be well preserved without evidence of DJD of the spine (Resnick and Niwayama 1976). According to van der Merwe et al. (2012), Resnick and Niwayama's (1976) choice to include four contiguous vertebrae as the diagnostic criteria was arbitrary and was made only to prevent the misdiagnosis of spondylosis deformans as DISH. Rogers and Waldron (2001), on the other hand, state that without the following three conditions DISH cannot be diagnosed: hyperostosis of the spine affecting at least three vertebrae (with or without ankylosis/fusion), changes confined to the right side of the thoracic vertebrae, and evidence of calcification or ossification in extraspinal ligaments. They state that preservation of inter-vertebral disc space and lack of involvement of the facet joints should not be diagnostic criteria but may be used to confirm diagnoses.

3.5.4 Gout

Gout occurs in the body when the production of uric acid increases or excretion by the kidneys is compromised (Waldron 2008). Clinical research indicates that healthy kidneys filter nearly 100% of urate, excreting between 5% and 10%. The kidneys of individuals suffering from gout excrete between 3% and 5% (Igel et al. 2017). The excess uric acid leads to the formation of uric acid crystals in the synovial fluid (Martinon 2010). Gout seldom manifests before the age of 40 and nine out of ten patients with gout are males (Ortner 2003). Clinically, gout has been linked to obesity, however caution is taken archaeologically as high body mass is not the only associated factor. Genetics also play a role in gout manifestation (Aufderheide and Rodriguez-Martin 1998; Ragab et al. 2017) as does alcohol consumption and diet (Swinson et al. 2010). The Health Professional Follow-up Study indicated that a purine-rich diet (such as those including a high proportion of meat) as well as an increased intake of alcohol, soft drinks, and fructose significantly increased the risk of gout (Choi et al. 2004, 2008a,b). Body mass has also been linked to increased gout incidence. Maynard et al. (2012) found that the incidence of gout was 11.8% in females greater than 70 years with a BMI of 35 or greater. This is juxtaposed to a gout incidence of 1.9% in females of the same age with a BMI less than 25 (Maynard et al. 2012). In archaeology, gout diagnoses are often linked to affluence. Wells (1973) described a case of gout from the Romano-British period in England (150 CE) in a 45 to 65-year-old male. The male was buried in a relatively affluent grave which led the author to wonder as to "whether his gout was causally related to a well-lined pocket and over-indulged belly" (Wells 1973: 400).

Gout has also been identified as a risk factor for the development of DISH. However, it is still unclear as to whether the presence of gout directly triggers the development of DISH or whether the relationship between the two disorders is associated with shared risk factors (which for both include a raised body mass index and metabolic disturbances) (Topless et al. 2018). According to Topless et al. (2018), while DISH is more common in patients with gout, genetic analyses do not support the causal relationship between gout and DISH. The authors argue that it is more likely that shared risk factors link the two conditions in a parallel relationship (Topless et al. 2018).

3.5.4.1 Evaluating Gout

Diagnosis of gout in archaeological literature is minimal, although a few diagnostic criteria have been created. According to Cockburn (1979) crystals in the joints are the most accurate indicator of gout in archaeological specimens. In the absence of these crystals, joint erosion in a few joints (usually asymmetrically) can be used. Bone erosion is also occasionally noted away from the joint, as well as non-specific, degenerative joint changes. Waldron (2008) suggests diagnosing gout archaeologically using asymmetrical erosion in articular or para-articular tissue in conjunction with overhanging margins (also known as Martel hooks). In the absence of technology to identify urate crystallization, gout identification should be done with care (Swinson et al. 2010). Ordi (2006) confirmed a gout diagnosis in Holy Roman Emperor Charles V using Energy Dispersive Analysis by x-ray, where sodium (from monosodium urate) was detected. Swinson et al. (2010) employed High Performance Liquid Chromatography (HPLC) in investigating gout.

3.5.5 Plantar Calcaneal Spurs

Boney spurs on the dorsal aspect of the calcaneus, at the attachment site of the Achilles or calcaneal tendon, have been associated with certain physical activities, such as running and ballet (Weiss 2012). Plantar calcaneal spurs, or boney outgrowths on the plantar aspect of the calcaneus at the insertion of the long plantar ligament and are believed to be associated with vertical compression and have been linked to obesity, age, and osteoarthritis (Menz et al. 2008). Contemporarily plantar spurs are more common (Weiss 2012). Weiss (2012) examined the aetiology of plantar and dorsal calcaneal spurs using the skeletal material from 121 hunter-gatherers from California (2180 – 250 BP). Weiss (2012) concluded that there is genetic and age-related component to heel spurs and that, as dorsal spurs are significantly more common than plantar spurs among hunter-gatherers, they are associated with physical activity. Plantar spurs, on the other hand, are a more modern phenomena resulting from excess weight and long periods of standing (Weiss 2012).

3.5.5.1 Evaluating Plantar Calcaneal Spurs

Spurs at the attachment of the Achilles tendon (dorsal calcaneal spurs) and at the attachment site of long plantar ligament (plantar calcaneal spurs) are recorded as present, if a palpable ridge can be detected, or absent (Weiss 2012).

3.6 Theoretical Consideration: The Osteological Paradox

In 1992, Wood, Milner, Harpending, and Weiss published their seminal paper entitled "The Osteological Paradox: Problems of Inferring Prehistoric Health from Skeletal Samples." In the article, Wood and colleagues (1992) consider three conceptual issues inherent in palaeopathological analyses: demographic non-stationarity, hidden heterogeneity, and selective mortality.

Demographic non-stationarity occurs when a population deviates from stationarity. Stationarity implies that the population is closed to migration, maintains a constant rate of mortality and fertility, has a zero growth rate, and equilibrium of age distribution. Most populations are not closed to migration and mortality and fertility rates change from one generation to the next, leading to a non-stable age distribution and a changing growth rate. Age-at-death distributions are more strongly affected by a change in fertility than mortality rate (Wood et al. 1992). DeWitte (2006) explained the issue, stating that as fertility increases, the number of infants in a population increase. This increase will result in a rise in the number of infants in the skeletal sample (even if the mortality risk remains constant) leading to a drop in average age-at-death. According to DeWitte (2006) the issue of demographic non-stationarity can be mediated by modeling a population as stable. A stable population meets all of the criteria of a stationary population except for the requirement of zero population growth (DeWitte 2006).

Selective mortality refers to the concept that, as individuals with the highest frailty are the most likely to die at a given age, and which individuals were at risk of death cannot be known from a skeletal sample, individuals in a skeletal sample are not representative of a living population's risk of death at that age. For instance, in a skeletal sample, we cannot know which individuals were at risk of dying at age 20; we can only observe the individuals who actually died at age 20. This means that the skeletal sample is selective for lesions associated with pathology that increase the risk of death. In other words, using lesion frequency from a skeletal sample to estimate disease frequency will overestimate the living population's disease prevalence (Wood et al. 1992). Boldsen and Milner (2012) use the analogy of a hospital waiting room. If one were to wait in a hospital reception area and monitor the conditions suffered by the members of a community, the range of severe conditions could be estimated. However, using that sample to estimate the general population prevalence of a certain condition would be problematic. In order to form an opinion on prevalence one would need to know the population's risk of developing the condition of interest as well as understand the population's risk dynamics. To add to the confusion, when mortality is high a larger fraction of the skeletal sample from that period will appear healthy. Conversely, if mortality stress is less only the frail will die, meaning that the skeletal sample will appear less healthy for that period of time (Wood et al. 1992). According to the definition of selective mortality, the oldest individuals in a skeletal sample should have been the least frail, 'healthiest' individuals of the population. They are the individuals who did not succumb to selective pressures such as disease, infections, malnutrition, etc. As they survived their stress experiences, the elderly in a sample should present indicators of a lifetime of different stress. Thus, indicators of frailty in older individuals can be used as gauges of the different selective pressures associated with gender, socioeconomic status, environment, social inequalities, and, more indirectly, time period. Bioarchaeologists are in a unique position to examine disparities in biocultural risk. As bone morphology is not tied solely to biological factors (Agarwal 2012), by examining the age-related bone loss in archaeological populations, researchers can better understand possible risks associated with different cultural settings. Sex-specific risks could include differential access to nutrition and resources (Muldner and Richards 2007), systematic violence (Martin 1997; Wilkinson 1997), accident-related trauma (Judd and Roberts 1999), and reproductive risks (Sutherland 2005) to mention a few.

The term hidden heterogeneity implies that a population is made up of individuals with a mixture of underlying frailty and susceptibility to disease. The differences in frailty may result from (but are not limited to) genetic heritability, socioeconomic inequality, environmental variability, or changes in time period. Many of these differences cannot be identified and thus are not measurable; the issue of measuring hidden heterogeneity of risk becomes infinitely more difficult in archaeological populations (Wood et al. 1992). It is possible that examining the oldest old in a population may elucidate some of these hidden risk factors. Consider osteoporosis; individuals reach their peak bone mass in young adulthood and from this point on bone mass is decreasing. Bone loss can be mediated by biocultural factors such as physical activity, increased breastfeeding time, and proper nutrition (Curate 2014). While it may not be possible to estimate all aspects of hidden heterogeneity of risk, by examining the individuals who exhibit the most and least amount of bone loss in the elderly, a better understanding of the cultural, environmental, social, and sex-based differences in risk can be gained. It may also be possible to use markers of increased body mass as indicators of increased socioeconomic status in some archaeological populations. Increased body mass may be indicative of decreased risk in certain aspects of life (such as nutrition and sanitation). However, these lesions may also be indicators of frailty and thus can be used to theorize about other heterogeneous risks. Regardless, care must be taken when making this association, as these disorders are not restricted to individuals of increased body size or high socioeconomic status.

Wood and colleagues (1992) made four recommendations to combat the issues presented. First, the authors tasked researchers to gain a deeper insight into the sources of hidden heterogeneity. Second, they stated that understanding of how frailty distributions are related to risk of death is required to comprehend palaeopathological disease processes. Third, researchers must better understand pathological processes. According to Wood and colleagues (1992) the first three tasks were addressed to researchers in biomedical fields. However, understanding pathological processes is not outside of the bioarchaeological purview. While it is likely that the majority of advancements in this area will come from clinical research, it is important to study and understand differences in the archaeological manifestation of diseases and degeneration. With the more precise age-at-death estimates, such as those developed by Milner and Boldsen (2012a), unprecedented levels of analysis are possible in the oldest old of archaeological samples. Our current understanding of archaeological patterns of degeneration may be related to limitations in earlier osteological age-at-death estimation techniques which could only broadly age older adults (i.e. >50 years). Additionally, using technologies, such as dual energy x-ray absorptiometry (DEXA), energy dispersive low angle x-ray scattering (EDLAXS), optical densitometry, and computer tomography (CT), all of which allow bioarchaeologists to examine internal bone pathology, can lead to a better understanding of archaeological pathological processes. It is especially important to research how clinical and archaeological manifestations of disease and degenerative processes may differ, and what causes these differences. The fourth task suggested in the osteological paradox was to understand the role of cultural context in determining heterogeneous frailty and level of selective mortality. In analyzing the paleopathology of aging and body size bioarchaeologists can better understand aspects of frailty and risks associated with environment, social inequalities, sex-based differences, cultural disparities, etc. It is in its unique ability to understand cultural and social risk factors that bioarchaeology can make progress in overcoming the osteological paradox. If a better understanding of the biocultural risk factors can be gained, a specific risk term could be added to mortality statistics that may bring osteology one step closer to understanding mortality profiles and through them, archaeological health.

3.7 Chapter Synopsis: Estimating Body Proportions and Pathology

Understanding the biological profile of an individual or the general trends seen in a population can aid in understanding health, behaviour, and environment. Through the use of specific equations, body mass, stature, and robusticity can be estimated. There are limitations and benefits to the use of all equations and researchers must choose equations based on research design and aims. Biomechanical principles employed in engineering beam theory can aid in understanding physical activity, general activity patterns, sexual division of labour, climate, and body mass. Each aspect of a biological profile will aid in elucidating risks to which an archaeological population was subjected and can help in reconstructing lifestyles of past populations.

Issues of bias are inherent in archaeological skeletal samples. Even more frustrating is not knowing what bias is present in each skeletal sample. Perhaps it is for this reason that, for the most part, the issues addressed in the osteological paradox have been ignored in palaeopathological research for the last two decades (DeWitte and Stojanowski 2015). Selective mortality and hidden heterogeneity of risk make disease prevalence analysis in archaeological populations difficult. Through using more precise aging techniques to assess pathology related to individual frailty, such as those associated with increased age and size, a better understanding of the biocultural risk factors associated with differing environment, social status, sex, location, and time period can be approached.

3.8 Summary

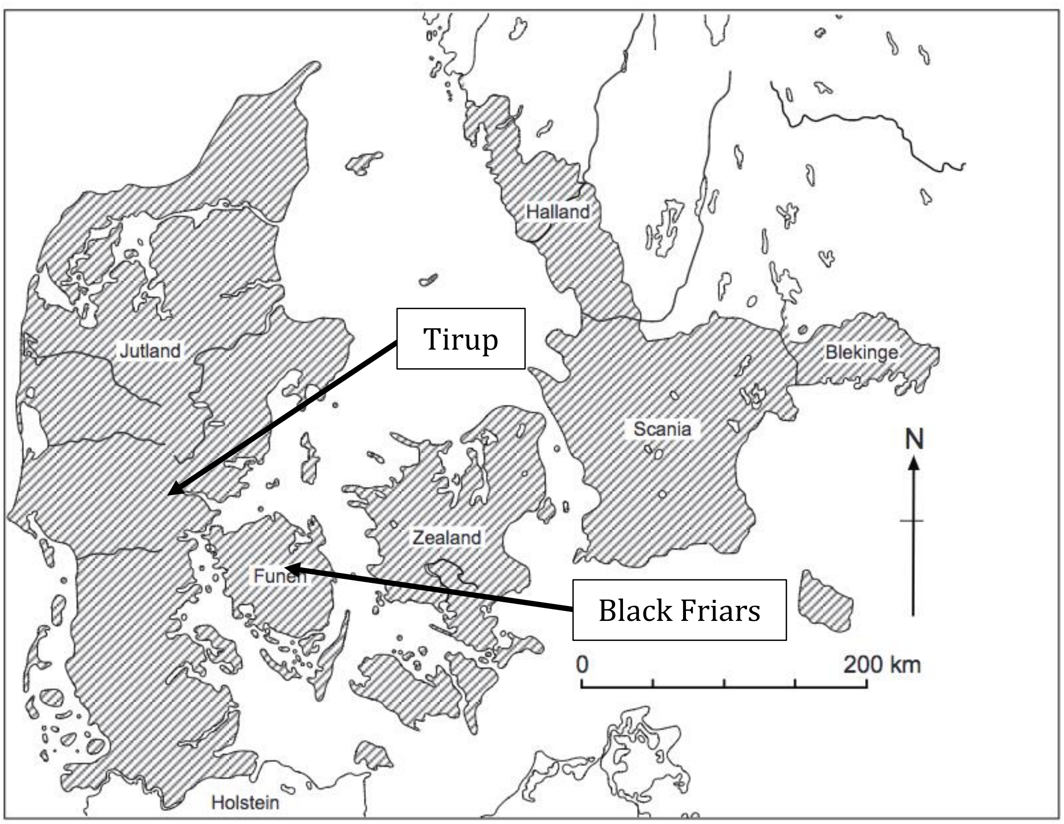
Methods for estimating body proportions and diagnosing paleopathological disease abound. Several of the techniques have been presented and critiqued in the previous chapter. The following chapter will present the materials and methods chosen for the current project, describing the techniques in detail.

Chapter 4: Materials and Methods

4.1 Skeletal Research Samples

The skeletal samples analyzed in this study comprised two cemetery collections curated by the Southern Denmark University (SDU) at the ADBOU lab. Adult skeletal material (≥ 18 years of age at time of death) was selected from the rural cemetery of Tirup and the urban Black Friars cemetery. A total number of 532 skeletons were assessed (n_{Tirup} = 139, $n_{Black\ Friars}$ = 393). Highly fragmentary material and subadult skeletal material (< 18 years) was excluded from the analysis. Additionally, complete, well-preserved right femora and fourth lumbar vertebrae were scanned for geometric analysis. Figure 4.1 presents a map of Denmark in medieval times, illustrating the locations of the two cemeteries used in this study.

Figure 4.1. Map of Denmark indicating site locations

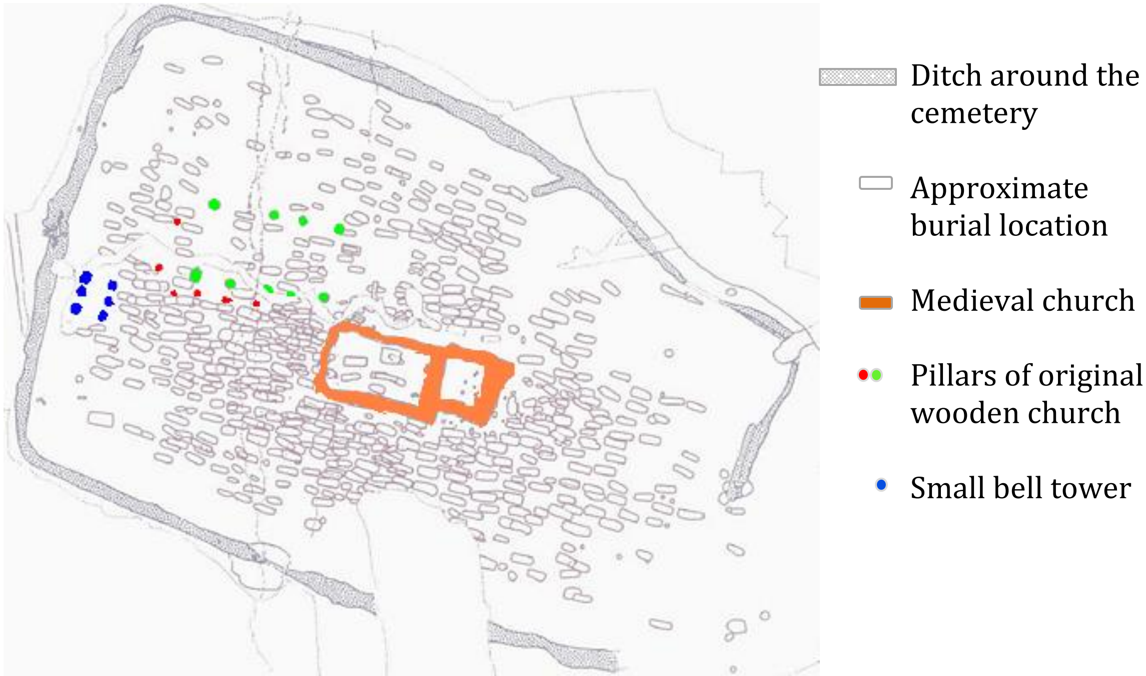


(Hybel and Poulsen 2007; used with permission)

4.1.1 The Cemetery of Tirup

The cemetery of Tirup (Figure 4.2) lies immediately west of the medieval town of Horsens in eastern Jutland (Kieffer-Olsen 1993). The cemetery's name is known only from the name of the field that, for a time in the middle ages, was controlled by the nearby royal castle of Bygholm. The cemetery would have been used by members of a rural village (Milner et al. 2015). Most of the individuals buried in the cemetery would have been agricultural workers as there was little alternative by way of employment in rural medieval Denmark. Both men and women would have had to undertake strenuous physical activity (Milner et al. 2015). The cemetery was in use from ca. 1150 to 1350 CE when it was abandoned (Boldsen 1998 a,b; Kieffer-Olsen 1993; Milner et al. 2015). It was not uncommon for towns and cemeteries to be abandoned during this time period (Hybel and Poulsen 2007). Of note is that the cemetery of Tirup was completely excavated which significantly limits the bias associated with analyses of the cemetery collection (Boldsen 2011, 1998a,b). The cemetery was excavated in 1984 by the National Museum and Vejle Museum of Cultural History (Kieffer-Olsen 1993). Of the 622 graves excavated from the Tirup cemetery, 139 skeletons were analyzed, 52 of which presented preserved right femora for geometric analysis. Skeletal material was excluded due to preservation – in some cases only fragments of crania were preserved – and age. More than 50% of the individuals recovered from the excavation died before the age of 20 (Boldsen 1988).

Figure 4.2. Site map of the cemetery of Tirup



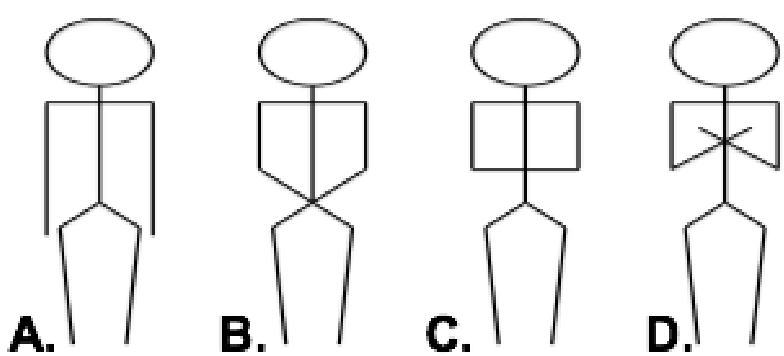
(From Boldsen 2011; used with permission)

4.1.2 Archaeological dating of the Tirup Populations

4.1.2.1 Arm Position

As no historical data exists pertaining to the cemetery of Tirup, dating was done exclusively using arm positions. In Danish medieval cemeteries arm position can be used to estimate general burial date as consistent temporal trends in arm position at burial exist (Kieffer-Olsen 1993). Four distinct arm positions (presented in Figure 4.3), based on the forearm's position relative to the body and upper arm (Boldsen 1984b), have been recorded: arm positions A, B, C, and D. Arm position A describes a burial with the forearms positioned along the sides of the body. This burial type predominates into the first half of the 13th century, between ca. 1050 and 1250 CE. Arm position B, where the forearms are placed over the pelvis, became more prominent until ca. 1350/1375 CE, when burials exhibiting arm position C became more common. Arm position C describes burials where the forearms are placed over the stomach at approximately right angles to the upper arm. Arm position D denotes burials where the forearms are crossed over the chest at approximately 45 degrees to the upper arm. The transition to arm position D occurs in the mid-1400s (Kieffer-Olsen 1993; Jantzen et al. 1994). Arm position D was mainly used after the Protestant Reformation (Mollerup and Boldsen 2010). Dating using arm positions must be undertaken with caution however, as the temporal trends are not exclusive and vary slightly between cemetery populations; burials presenting arm position A exist throughout the medieval period (Kieffer-Olsen 1993; Jantzen et al. 1994). The arm positions present in the skeletal material from Tirup include arm position A, B, and occasionally C (Boldsen 1988; Kieffer-Olsen 1993). Anomalies in arm position within a skeleton can be caused by body movement during decomposition (Kieffer-Olsen 1993). In such cases, when arm position A is combined with another arm position, the other arm position is designated. Alternatively, arm position C, when combined with any other arm position takes precedence and if arm position D is combined with A or B, it will take precedence (Kieffer-Olsen 1993). Arm position A and B were recorded in the current analysis. The Tirup cemetery also included burials exhibiting arm position C however, due to their fragmentary nature, none were included in this analysis. Table 4.1 identifies the breakdown of arm positions in the current Tirup sample.

Figure 4.3. Burial arm positions



(Modified from Keiffer-Olsen 1993; used with permission)

Table 4.1. Break down of arm positions from the cemetery of Tirup

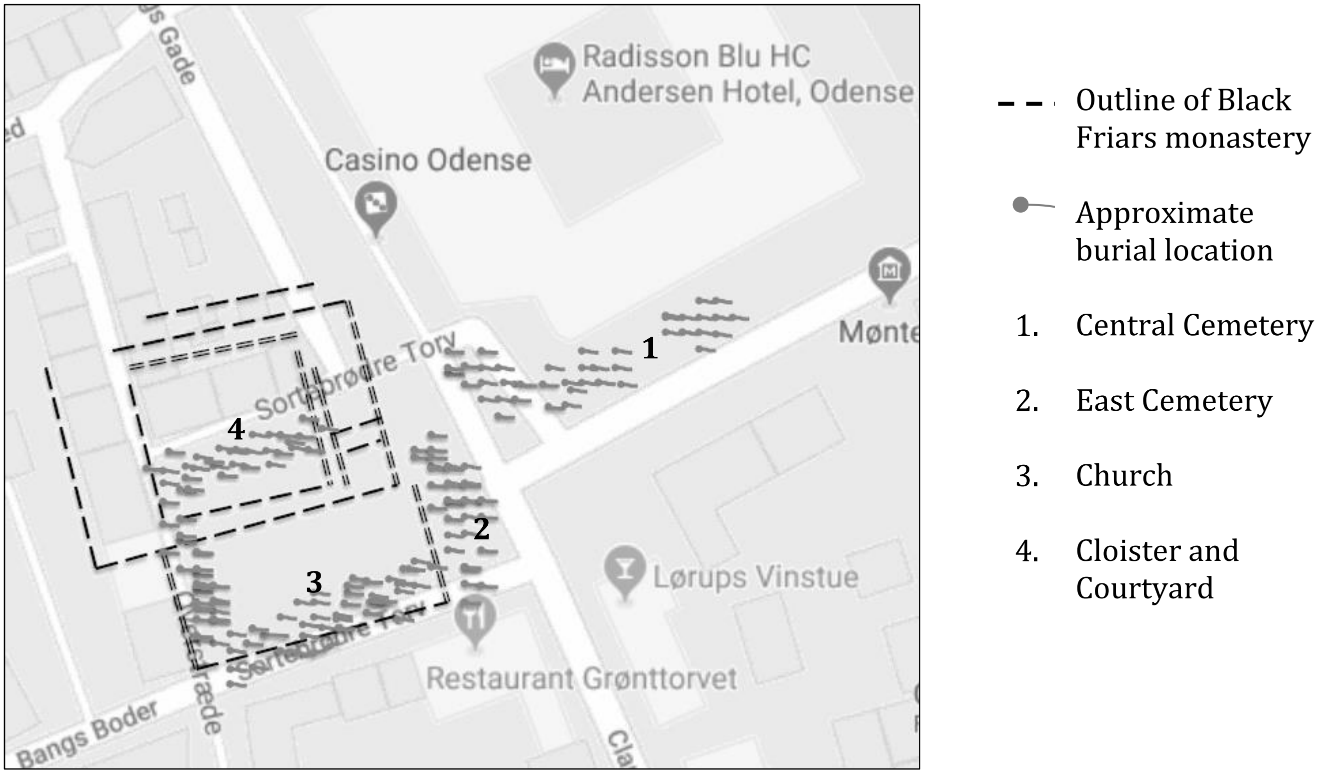
Time Period	Arm position					
	A (ca. 1050-1250 CE) N (%)	**B (ca. 1250-1375 CE) N (%)**	**C (ca. 1400-1450 CE) N (%)**	**D (ca. 1400-1536 CE) N (%)**	**Unknown N (%)**	**Total**
Medieval	101 (73)	23 (17)	0 (0)	0 (0)	15 (11)	139
Post-Medieval	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0
Total	101	23	0	0	15	139

4.1.3 The Black Friars Cemetery in Odense

The Black Friars Cemetery in Odense Denmark dates from circa 1240 to 1607 CE (Boldsen and Mollerup 2010). The cemetery is located on the periphery of the medieval town of Odense, currently Black Friars Square (Figure 4.4). No written records exist pertaining to the foundation of the monastery. Using the foundation of cathedrals in other major Danish cities as a guide, the foundation of the church likely dates to around 1240 CE (Becher 1999). The earliest records date to 1252 CE when the Odense monastery became the regional chapter for the Dominican order (Becher 1999). Archaeological evidence suggests that the Odense Black Friars took over an existing building and expanded it into the excavated monastery (Christensen 1988). The cemetery's use spanned two distinct interment phases, the medieval or monastic phase (ca. 1240 – 1536 CE) and the post-medieval or public phase (1536 – 1607 CE). During the medieval phase the existing structure was expanded to include a second church structure (Christensen 1988). Interment in the cemetery is likely predominantly that of the friars and, in certain sections, members of the middle class (Jakobsen 2008). The public interment phase began with the Protestant Reformation and the closing of the Black Friars monastery (Mollerup and Boldsen 2010). After the Reformation rights around the ecclesiastic ownership of property changed resulting in the closing of several churches and their cemeteries. Of the eleven cemeteries in use during the medieval period in Odense only five remained open after the Reformation (Mollerup and Boldsen 2010). Due to the lack of cemeteries, coupled with the expanding population in post-medieval urban centers, the cemeteries that remained open were much more commonly used (Christensen 1988). Mollerup and Boldsen (2010) estimated that 71% of the burials in the Black Friars cemetery could be dated to the post-medieval period. The church was demolished in 1542 CE and the cemetery was turned over to the city in 1551 CE (Christensen 1988, Mollerup and Boldsen 2010). As a public cemetery after the Reformation, the burials in the post-medieval period are predominantly those of the lower class (Becher 1999) although, as burial options became increasingly limited after the closing of the churches, the Black Friars cemetery likely houses individuals of all social strata (Mollerup and Boldsen 2010). The cemetery remained open until 1607 CE when the remaining structure was demolished (Christensen 1988).

Excavation of Black Friars Square began in 1972 and continued until 1997. Skeletal material was unearthed in 1978, 1979, and 1981 (Urth 1978, Nielsen 1982a,b). The excavation located the cloister and the monastic precinct (Mollerup and Boldsen 2010). The northern and western boundaries of the Black Friars monastery were not located as dwellings currently reside on the site (Christensen 1988) therefore, the cemetery was not completely excavated. According to the excavation report 680 burials were unearthed but not all produced viable skeletons for analysis (Nielsen 1982b) For the current research only 393 skeletons fit the selection criteria for analysis.

Figure 4.4 Site map of the cemetery of Black Friars



(Modified from Becher 1999 and Maps data ©2018 Google; used with permission)

4.1.4 Archaeological dating of Black Friars

4.1.4.1 Arm Position

In much the same way as the Tirup cemetery, arm position was used as a guide to aid in the temporal classification of skeletal remains. After the Reformation, arm position dating becomes less accurate as no one arm position dominated burial practice (Mollerup and Boldsen 2010). Arm position was recorded for burials excavated in 1979 and 1981 (Nielsen 1982a,b). As the Black Friars excavation took place prior to the publication of Kieffer-Olsen's dissertation in 1993 only three arm positions were recorded (1. arms along the sides, 2. arms over the abdomen, and 3. arms over the chest) (Nielsen 1982a,b). Scott (2015) posited that the subtle differences between arm positions B and C were not perceived, suggesting that the arm position recorded as “over stomach” likely encompasses both the arm positions B and C described by Keiffer-Olsen (1993). Table 4.2 presents the breakdown of arm positions from the current Black Friars sample.

Table 4.2. Break down of arm positions from the cemetery of Black Friars

Time Period	Arm position				
	1 (ca. 1050-1250 CE) N (%)	2 (ca. 1250-1450 CE) N (%)	3 (ca. 1450-1607 CE) N (%)	Unknown N (%)	Total
Medieval	54 (28)	60 (31)	1 (0.5)	79 (41)	194
Post-Medieval	14 (7)	110 (55)	38 (19)	37 (19)	199
Total	68 (17)	170 (43)	39 (10)	116 (30)	393

4.1.4.2 Burial Location

Burial location was also used to aid in the temporal classification of skeletal remains as arm position cannot be relied upon to accurately estimate burial date after the Reformation (Boldsen and Mollerup 2006). Interment differed based on time period. The church and adjacent cemetery to the east were predominantly used during the medieval period, while interment in the cloister and courtyard and the central cemetery was almost exclusively post-Reformation (Mollerup and Boldsen 2010). Following Scott (2015), individual burials were classified as medieval or post-medieval based on arm position and burial location (Table 4.3). The dating breakdown of the current study reasonably resembles that estimated by Mollerup and Boldsen (2010) (Table 4.4). Differences can be accounted for in the use of different selection criteria as well as the difficulty identifying monastic area boundaries from the site map.

Table 4.3 Burial date breakdown by location estimated in the current study

Burial Location	Number of medieval burials N (%)	Number of post-medieval burials N (%)
Church	131 (85)	23 (15)
Cloister and courtyard	4 (7)	51 (93)
Cemetery to the east of the church	33 (55)	27 (45)
Central cemetery	2 (2)	122 (98)

Table 4.4 Burial date breakdown by location estimated in Mollerup and Boldsen (2010)

Burial Location	Number of medieval burials N (%)	Number of post-medieval burials N (%)
Church	108 (77)	32 (23)
Cloister and courtyard	14 (17)	70 (83)
Cemetery to the east of the church	70 (55)	58 (45)
Central cemetery	16 (19)	67 (81)

4.1.3.3 Relative dating

The excavation reports from 1979 and 1981 include relative dating techniques to temporally classify burials (Nielsen 1982a,b). Church structures and grave goods of known age were used to date adjacent and stratigraphically connected burials as relatively older or younger than the associated archaeological finds. In cases where the relative dating disagreed with the arm position and burial location, the temporal classification identified by the relative dating took precedence. Disagreement leading to reclassification occurred in seven cases, six burials were reassigned as post-medieval and one burial was reclassified as medieval. While arm positions are beneficial for dating it is important to note that overlap exists between the phases and thus reclassification does not contradict arm position dating (Kieffer-Olsen 1993).

Skeletal material excavated in 1978, where no arm position data was recorded, could be generally dated based on stratigraphic position relative to burials providing dateable goods (Urth

1978). Ten burials were dated to around the time of the Reformation. All 10 were classified as medieval based on Mollerup and Boldsen's (2010) assessment that the majority of burials in the cemetery to the east of the church, where the 1978 excavation took place, were medieval. Table 4.5 presents the final breakdown of medieval and post-medieval burials identified in the current sample from the Black Friars cemetery.

Table 4.5 Final archaeological dating breakdown for the Black Friars cemetery

	Medieval graves N (%)	Post-medieval graves N (%)	Total graves
Black Friars Cemetery	170 (43)	223 (57)	393

4.2 Sex Determination and Age Estimation

Age and sex were estimated using standard osteological techniques. Sex was estimated based on pelvic and cranial dimensions. Pelvic dimensions used include the ventral arc, the subpubic concavity, the ischiopubic ramus ridge (Phenice 1969), the greater sciatic notch, and the preauricular sulcus (although the latter was allocated less weight) (Buikstra and Ubelaker 1994). Cranial dimensions used in the estimation of sex included the presence and robusticity of the nuchal crest, mastoid process, supraorbital margin, glabella, and mental eminence (Buikstra and Ubelaker 1994). In cases where the sex estimated using pelvic and cranial material differed, determination based on pelvic traits was weighted more significantly. The pelvis is considered more accurate as the female pelvis has adapted to childbirth (White and Folkens 2005). Overall size and robusticity were also factored into the final sex estimation. Initially, skeletal material was identified as male (m), likely male (m?), unknown (?), likely female (f?), or female (f). For individuals designated as likely male (n_{Tirup} = 3; $n_{Black\ Friars}$ = 8), likely female (n_{Tirup} = 1; $n_{Black\ Friars}$ = 17), or unknown (n_{Tirup} = 0; $n_{Black\ Friars}$ = 10) femoral head diameter, if available, was entered into a sex determination sigma calculator created by Milner and Boldsen (2012b) and sex was verified or identified. If sex was identified as likely female (n_{Tirup} = 0; $n_{Black\ Friars}$ = 8) or likely male (n_{Tirup} = 2; $n_{Black\ Friars}$ = 13) and no femoral head was available, a final classification of female or male was recorded. Table 4.6 and 4.7 identify the breakdown of sex in samples from Tirup and Black Friars respectively.

Table 4.6 Sex estimation for the cemetery of Tirup

Time Period	Male N (%)	Female N (%)	Unknown N (%)	Total
Medieval	87 (63)	52 (37)	0 (0)	139
Post-medieval	0 (0)	0 (0)	0 (0)	0
Total	87 (63)	52 (37)	0 (0)	139

Table 4.7 Sex Estimation for the cemetery of Black Friars

Time Period	Male N (%)	Female N (%)	Unknown N (%)	Total
Medieval	100 (59)	64 (37)	6 (4)	170
Post-medieval	112 (50)	107 (48)	4 (2)	223
Total	212 (54)	171 (44)	10 (3)	393

Age at death was estimated using several conventional osteological methods. Initially age was estimated using the pubic symphysis (Brooks and Suchey 1990; Todd 1921), the auricular surface (Lovejoy et al. 1985), and, where other areas were unavailable, the cranial sutures (Buikstra and Ubekaker 1994). As conventional methods are only able to broadly age the oldest individuals in a skeletal sample (as ≥ 50 or ≥ 60 years at death), and the purpose of the research presented here is to assess degeneration, an age-at-death estimation method that could more precisely age older individuals was required. As such, transition analysis, developed by Milner and Boldsen (2002) and refined in Milner and Boldsen (2012a), was used. Transition analysis relies on the premise that skeletal changes associated with aging are unidirectional and that by employing statistical methods (logistic regression and Bayes' Theorum) age-at-death can be more precisely estimated. Specific age-related boney changes of the pelvis (pubic symphysis and auricular surface) and cranial sutures are scored and entered into a statistical program. The age-at-death estimate is given as a point age estimate with a 95% confidence interval (Milner and Boldsen 2012a). In some instances, limited skeletal information, especially in individuals where the pelvis was damaged, rendered very broad ranges. Finally, age was estimated using a preliminary (and currently unpublished) version of the calibrated expert inference (CEI) method developed by the collaborative effort of researchers at Southern Denmark University, the Max Planck Institute of Demographic Research, and Pennsylvania State University (ADBOU 2015). Using the data available older skeletal material could only be classified as ≥ 50 years-at-death. The CEI method relies on age-related changes across a wide range of skeletal elements. Boney changes in skeletal elements that are less prone to degeneration than the pelvis and more accurate than cranial sutures are used for CEI aging (ADBOU 2015). For statistical analyses, age estimated using transition analysis was used. Table 4.8 and 4.9 identify the breakdown of age in samples from Tirup and Black Friars respectively. Table 4.10 illustrates the age breakdown for Black Friars by time period using transition analysis.

Table 4.8 Age distribution of the Tirup cemetery sample

Sex	Age Range	Conventional Methods N (%)	Transition Analysis N (%)	CEI N (%)
Male	Young Adult (18 – 30)	17 (20)	44 (53)	8 (11)
	Middle Adult (31 – 50)	44 (51)	26 (31)	55 (74)
	Old adult (51-70)	26 (30)	5 (6)	11 (15)
	Oldest-old adult (>70)	NA**	8 (10)	NA**
Female	Young Adult (18 – 30)	13 (25)	21 (45)	8 (20)
	Middle Adult (31 – 50)	26 (51)	22 (47)	29 (73)
	Old adult (51-70)	12 (24)	2 (4)	3 (8)
	Oldest-old adult (>70)	NA**	2 (4)	NA**

** As there is no way to separate the old adult and oldest-old adults using conventional methods, individuals that would fall into the oldest-old category are combined with the old adults.

Table 4.9 Age distribution of the Black Friars cemetery Sample

Sex	Age Range	Conventional Methods N (%)	Transition Analysis N (%)	CEI N (%)
Male	Young Adult (18 – 30)	49 (27)	76 (41)	38 (17)
	Middle Adult (31 – 50)	118 (64)	88 (47)	116 (53)
	Old adult (51-70)	17 (9)	6 (3)	66 (30)
	Oldest-old adult (>70)	NA**	17 (9)	NA**
Female	Young Adult (18 – 30)	41 (26)	80 (52)	46 (26)
	Middle Adult (31 – 50)	106 (68)	59 (38)	104 (59)
	Old adult (51-70)	9 (6%)	12 (8)	25 (14)
	Oldest-old adult (>70)	NA**	3 (2)	NA**
Unknown	Young Adult (18 – 30)	1 (100)	1 (100)	1 (100)
	Middle Adult (31 – 50)	0 (0)	0 (0)	0 (0)
	Old adult (51-70)	0 (0)	0 (0)	0 (0)
	Oldest-old adult (>70)	NA*	0 (0)	NA*

** As there is no way to separate the old adult and oldest-old adults using conventional methods, individuals that would fall into the oldest-old category are combined with the old adults.

Table 4.10 Age distribution by time period for the cemetery of Black Friars (using transition analysis)

Sex	Age Range	Medieval N (%)	Post-medieval N (%)	Total
Male	Young Adult (18 – 30)	38 (20)	38 (20)	76
	Middle Adult (31 – 50)	40 (21)	48 (26)	88
	Old adult (51-70)	2 (1)	4 (2)	6
	Oldest-old adult (>70)	6 (3)	11 (6)	17
Female	Young Adult (18 – 30)	33 (21)	47 (31)	80
	Middle Adult (31 – 50)	13 (8)	46 (30)	59
	Old adult (51-70)	6 (4)	6 (4)	12
	Oldest-old adult (>70)	2 (1)	1 (1)	3

4.3 Body Proportion Estimation

4.3.1 Stature Estimation

Stature was estimated using a modified hybrid technique that employed the anatomical method (Raxter et al. 2006) (n_{Tirup} = 28; $n_{Black\ Friars}$ = 66), European mathematical regression formulae created by Ruff et al. (2012)(n_{Tirup} = 64; $n_{Black\ Friars}$ = 236), and the skeletal length measured in grave (Boldsen 1984a) (n_{Tirup} = 36; $n_{Black\ Friars}$ = 13), with the living stature correction of 2.5 cm developed by Petersen (2005, 2011). The anatomical method without the age correction (Raxter et al. 2006) was more comparable to the skeletal length in the grave and was therefore used for further analysis. For the current study, regression formulae to reconstruct stature were based on the femora and tibiae, where possible, and the femora alone, in cases where the tibiae were damaged or unavailable. As anatomically reconstructed stature is considered the most accurate (Auerbach 2011, Radu and Keleman 2015), it was given precedence over the Ruff et al. (2012) regression equation. While Boldsen (1984a) suggested that stature calculated from regression equations was inaccurate for Danish medieval populations, the stature estimates calculated using the Ruff et al. (2012) equation were not significantly different from those calculated using the standard anatomical method in this analysis. However, analyses on the raw femoral length were undertaken as well, as Boldsen (1984a) suggested. Due to some anomalies in skeletal length measured in grave, it was only employed in cases where stature estimated using the other techniques was unavailable. For 16 cases (n_{Tirup} = 6, $n_{Black\ Friars}$ = 10), Auerbach's (2011) equations for estimating missing elements (most commonly vertebrae) were employed in the anatomical method calculation. Stature was also estimated using Scandinavian-specific regression formulae created by Maijanen and Niskanen (2010) and a newer method developed by Ruff et al. (2019). The former's estimates were rejected as they consistently produced statistically significantly higher stature outputs than all other methods. The latter estimates were discarded as the equations did not perform as well as those created by Ruff et al. (2012).

4.3.2 Body Mass Estimation

Body mass was estimated using both mechanical methods, the femoral head diameter (using an average of the equations described by Grine et al. 1995, McHenry 1992, Ruff et al. 1991 including the 10% decrease in body mass suggested by Ruff et al. 1991), and the morphometric method, bi-iliac breadth (as described by Ruff et al. 2005). Body mass was also estimated using the Ruff et al. (2012) equation for the femoral head but the results were discounted as they were less comparable to those estimated using bi-iliac breadth than the previously mention formulae. Due to preservation issues, the morphometric method could only be applied to 157 skeletons (n_{Tirup} = 40, $n_{Black\ Friars}$ = 117). Alternatively, the mechanical method could be applied to 427 skeletons (n_{Tirup} = 107; $n_{Black\ Friars}$ = 320). A statistically significant difference (p=0.001) was found between body mass estimated using the two methods. Results from both methods will be presented. In order to adjust for height, body mass was further analyzed as a BMI (BMI=kg/m^2). Body mass was compared using BMI categories described according to the National Heart, Blood, and Lung Institute (NIH 2018) as underweight (BMI <18.5), "normal" weight (BMI between 18.5 and 24.9), overweight (BMI between 25 and 29.9) and obese (BMI >30).

4.4 Robusticity: Computer Imaging and Analysis

Robusticity was estimated using geometric properties of right femora. Individuals were excluded if they exhibited skeletal evidence of infectious pathology. Skeletal changes associated with syphilis, leprosy, and tuberculosis were noted in both cemetery collections. Femora were also excluded from the biomechanical analysis if periostitis was present on the femur. In total 52 right femora from Tirup (36 males, 16 females) and 160 from Black friars (95 males, 65 females) were included in the analysis. In order to analyze the geometric properties, femora were CT scanned. Tables 4.11 and 4.12 illustrate the breakdown of age, sex and time period for CT scanned right femora from Tirup and Black Friars respectively.

Table 4.11 Breakdown of age, sex, and time period for scanned right femora for Tirup

Sex	Age Range	Medieval N (%)	Post-medieval N (%)	Total N (%)
Male	Young Adult (18 – 30)	18 (50)	0 (0)	18 (50)
	Middle Adult (31 – 50)	14 (39)	0 (0)	14 (14)
	Old adult (51-70)	1 (3)	0 (0)	1 (3)
	Oldest-old adult (>70	3 (8)	0 (0)	3 (8)
	Total Male	36	0	36
Female	Young Adult (18 – 30)	8 (50)	0 (0)	32
	Middle Adult (31 – 50)	8 (50)	0 (0)	26
	Old adult (51-70)	0 (0)	0 (0)	5
	Oldest-old adult (>70)	0 (0)	0 (0)	0
	Total Female	16	0	16

Table 4.12 Breakdown of age, sex, and time period for scanned right femora for Black Friars

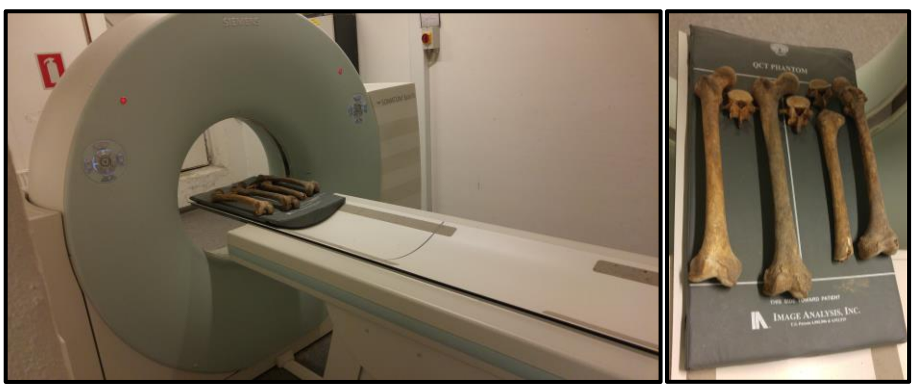
Sex	Age Range	Medieval N (%)	Post-medieval N (%)	Total N (%)
Male	Young Adult (18 – 30)	16 (17)	22 (23)	38 (40)
	Middle Adult (31 – 50)	22 (23)	23 (24)	45 (47)
	Old adult (51-70)	0 (0)	1 (1)	1 (1)
	Oldest-old adult (>70)	2 (2)	5 (5)	7 (7)
	Unknown	2 (2)	2 (2)	4 (4)
	Total Male	42	53	95
Female	Young Adult (18 – 30)	9 (14)	23 (35)	32 (49)
	Middle Adult (31 – 50)	5 (8)	21 (32)	26 (40)
	Old adult (51-70)	2 (3)	3 (5)	5 (8)
	Oldest-old adult (>70)	0 (0)	0 (0)	0 (0)
	Unknown	2 (3)	0 (0)	2 (3)
	Total Female	18	47	65

4.4.2 CT Data Collection

CT scans were undertaken using a Siemens SOMOTOM Spirit® Computed Tomography Scanner. The scanner was housed at The Institute of Forensic Medicine at SDU (although is currently housed in the ADBOU facility).

Complete, well-preserved femora and fourth lumbar vertebrae were scanned. Scans were undertaken on the proximal femora and fourth lumbar vertebrae for bone density analysis pertaining to osteoporosis (discussed later). Femora were scanned in an antero-posterior position (as they appear in standard anatomical position). Due to the shape of the fourth lumbar vertebrae, it was placed in a supero-inferior position and was scanned from the ventral to dorsal aspect. Bones were placed in the scanner bed in such a way as not to touch one another (Figure 4.5). All femora were scanned twice. One scan was taken at a lower resolution in order to analyze the full length of the bone. An additional scan at a higher resolution was taken of the proximal femora and fourth lumbar vertebrae in order to analyze trabecular structure.

Figure 4.5 Image of orientation for femora and fourth lumbar vertebra in CT scanner bed.



4.5.2.1 CT Specifications:

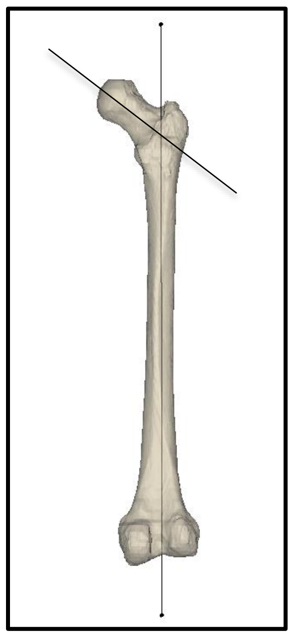
To attain the best possible scans for the project, scan specifications were set as follows. For scans of the femoral shaft, resolution trade-offs had to be made in order to capture the entire shaft in a single scan. Slices were taken at 3mm increments. Pitch, the movement of the table in each rotation divided by the spread of the radio waves, was set at 2.0. A smaller pitch leads to a higher resolution scan. The effective mAs refers to the amount of radiation used in a scan; higher radiation leads to a better quality scan but is limited by scan time and pitch (Bebbington 2017, Siemens Medical Solutions 2005). For the femoral scans, effective mAs was set at 30. For the higher resolution scans slices were taken at 1mm increments with a pitch of 0.8 and an effective mAs of 78.

4.4.3 Image Segmentation, Model Creation, and Image Reslice

Completed scans, saved as a DICOM stack, were analyzed using Materialise's Interactive Medical Imaging Control System© version 19.0, hereafter referred to as MIMICS (Materialise 2018). Three-dimensional models of the scanned femora were then created. In order to create a 3D model, the uploaded DICOM stack must be segmented, a process through which structures of interest are indicated based on set grey scale (Hounsfield units) threshold values. The grey values correspond with the density of structures, where denser material (for example cortical bone) will appear light grey or white and less dense structures (such as soft tissue and trabecular bone) will appear darker grey. This process can also be done manually, slice by slice (Materialise 2018), however manual segmentation is time consuming and was unnecessary for this project. Once the thresholds are selected and adjustments for unwanted structures are made – in the current project the scanner table had to be manually removed from the selection at superior and inferior points where the bones touched the table – MIMICS will render a 3D model.

Repeatability and accuracy require reference axes to be created. Creating reference axes for the femur is difficult due to the bone's curved shaft (Ruff 1981). Two reference axes were created for further analysis of the femur, a femoral shaft axis and the femoral neck or cervical axis (Figure 4.6). The neck axis runs through the centre of the femoral head and neck. The "shaft axis" is slightly more complicated as there are two potential axes. The "true" axis is a curved axis that follows the centerline of the bone shaft. For analysis purposes an "ideal" straight axis is more useful (Ruff 1981). Ruff (1981) created a method for generating an ideal axis on bone by constructing a straight axis though selected superior and inferior points. Ruff's (1981) method has become standard for this type of analysis. For this project, a centerline was generated in MIMICS, which simulates the "true" femoral axis and two points along the centerline were chosen; a point just distal to the lesser trochanter served as the superior point and a point where the centerline curves laterally (due to the asymmetrical flaring of the distal femur) served as the inferior point for the longitudinal femoral shaft axis. This axis serves as the z axis for further analysis. The x and y axes were generated in the MIMICS program.

Figure 4.6 Neck and shaft axis for femoral geometric analysis



In order to ensure that the cross-sectional measurements were being taken at the same angle on each bone, the DICOM image stack was resliced along the neck axis (in order to analyze Ward's triangle) and the longitudinal reference (z) axis (for analysis of the femoral shaft) generating a new stack of DICOM images.

4.4.4 Cross Section Selection

Three-dimensional models were then exported into MIMICS' sister program Materialise 3-MATIC© (Materialise 2018), where the length of the shaft was measured from the most proximal point of the greater trochanter (Figure 4.7) to an average point between the most distal points of the femoral condyles (Figure 4.8). Cross sectional points along the shaft at 20%, 35%, 50%, 65%, and 80%, with 20% being distal and 80% being proximal, were calculated (Figure 4.9). These points are standard in the literature as the central 60% of the shaft is considered the most accurate. The proximal and distal ends of the femoral shaft consist of a significant amount of trabecular bone (Moore 2008). Once the slice locations were ascertained, the DICOM image closest to the cross-section was selected for measurement. In cases where the slice fell directly between two images, the image closest to the epiphysis (distal for the 20%, 35%, and 50% cross sections and proximal for the 65% and 80% slices) was selected. In cases where the 80% slice intersected the distal aspect of the lesser trochanter ($n_{\text{Black friars}}$=3), the most proximal slice that did not transect the lesser trochanter was analyzed. The DICOM image intersecting Ward's triangle was ascertained qualitatively from the resliced femoral neck (Figure 4.9).

Figure 4.7 Location for proximal measurement of shaft length

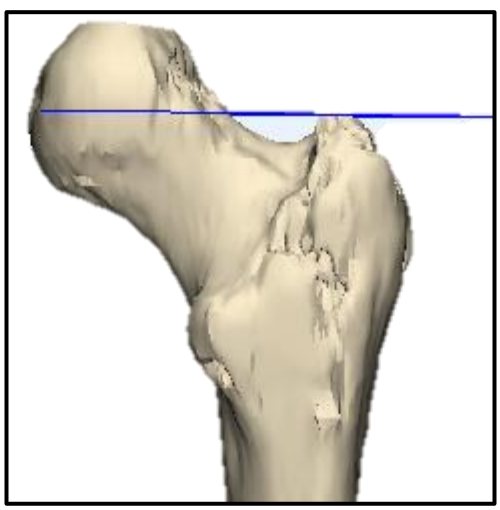


Figure 4.8 Location for distal measurement of shaft length

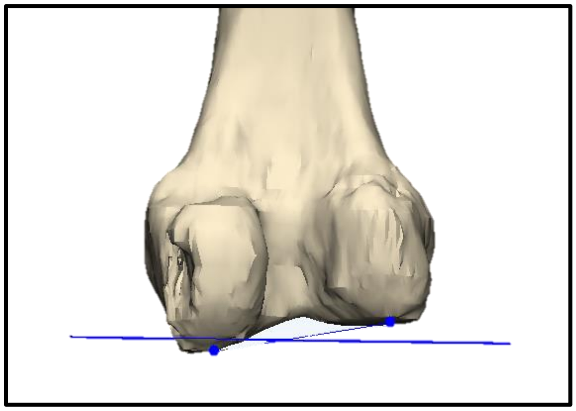
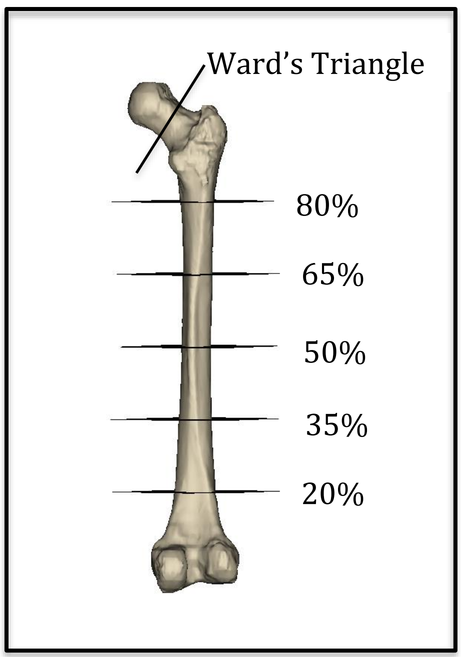


Figure 4.9 Location of cross sections for geometric analysis



4.5.5 Cross-sectional Measurements

Cross sectional geometric analysis was done using the open source image analysis software, ImageJ, using the BoneJ plugin (Doube et al. 2010). The selected DICOM images (at 20%, 35%, 50%, 65% and 80%) were imported into ImageJ and converted into binary 8-bit images. The program calculates cross-sectional geometric properties from a slice of bone. Using ImageJ the cortical area (CA), total area (TA), average cortical thickness, minimum second moment of area (I_{min}), maximum second moment of area (I_{max}), polar second moment of area (*J*), minimum section modulus (Z_{min}), maximum section modulus (Z_{max}), and polar section modulus (Z_p) were calculated. In order to calculate total area the medullary cavity was filled before running the analysis a second time. Following Ruff (2008), size was standardized for cross sectional areas using body mass, for section moduli using body mass by limb length, and for second moments of area using body mass by limb length^2. In order to avoid incredibly small numbers, size-standardized areas were multiplied by 10^2, section moduli by 10^4, and second moments of area by 10^5 (Ruff 2018). A shape ratio, in order to assess the circularity of bone, was also calculated (I_{max}/I_{min}). Table 4.13 provides definitions for the biomechanical properties listed above.

Table 4.13 Biomechanical measures and definitions

Measurement	Units	Definition
Cortical Area (CA)	mm^2	The area of cortical bone present in a slice. Cross sectional area is a measure of strength in compression and tension.
Total Area (TA)	mm^2	The total area of a slice including both the cortical bone and the medullary cavity. Total area is useful in identifying where bone loss is occurring.
Percent Cortical Area (%CA)	%	A measure of relative cortical thickness or area. This is important in assessing where bone is boing lost %CA = (CA/TA)*100
Average cortical thickness	mm	The average thickness of cortical bone in a given slice.
Minimum Second Moment of Area (I_{min})	mm^4	A measure of bone's bending rigidity, or ability to resist bending, along a minimum axis.
Maximum Second Moment of Area (I_{max})	mm^4	A measure of bone's bending rigidity, or ability to resist bending, along a maximum axis.

Polar Second Moment of Area (*J*)	mm^4	A measure of bone's torsional (twisting) rigidity, or ability to resist bending while under torsion.
Minimum Section Modulus (Z_{min})	mm^3	A measure of bone's bending strength, or ability to resist fracture, along a minimum axis.
Maximum Section Modulus (Z_{max})	mm^3	A measure of bone's bending strength, or ability to resist fracture, along a maximum axis.
Polar Section Modulus (Z_p)	mm^3	A measure of bone's torsional strength, or ability to resist fracture while under torsion (Ruff 2008).
I_{max}/I_{min}	NA	A shape ratio for bone which allows for the analysis of the distribution of bone along the major and minor axes (Macintosh et al. 2015).

4.5 Pathological Analysis

Age- and body size-related pathology, including DJD, DISH, gout, plantar calcaneal spurs, and osteoporosis, were recorded. Pathology, with the exception of osteoporosis, was examined macroscopically and recorded as present, absent, or unobservable. Infectious disease was rampant during the medieval and post-medieval periods in Denmark and would have affected the health of Danes during living these periods. The purpose of this research was, however, to analyze the effects of lifestyle on aging and degeneration. As such, an analysis of morbidity and mortality was outside the purview of the current research. Infectious disease has previously been researched for the cemetery of Tirup (Boldsen 1984b, 2001, 2005b, 2009; Schwarz et al. 2003) and for Black Friars (Boldsen and Mollerup 2006; Scott 2015).

4.5.1 Degenerative Joint Disease (DJD)

DJD was recorded for the weight bearing joints of the hips and knees and the lumbar vertebrae. DJD or osteoarthritis in the hip and knee joint was considered present if eburnation and at least two of the following were present: marginal osteophytes, new bone formation on the joint surface, pitting on the joint surface, and alteration in the joint contour (Rogers and Waldron 1995; Waldron 2008). Additionally, following Bridges (1992), osteoarthritic changes in the hip and knee joint were scored separately for each surface of the joint. Joint surface changes were recorded based on severity (0 = absent, 1 = slight, with initial osteophytes and joint surface degeneration, 2 = moderate, with major osteophytes and/or destruction of the joint surface, and 3 = severe, with joint fusion or near immobilization). The most severe osteoarthritic joint surface was recorded for final analysis.

DJD of the spine or vertebral osteophytosis, when present, was also scored based on severity. Vertebrae were scored from 1 – 4. Slight lipping of the vertebra's inferior or superior margin was recorded as a 1. Pronounced marginal lipping and extensive lipping with boney spurs were designated 2 and 3 respectively. Lipping that fused two or more vertebra was recorded as a 4 (Aufderheide and Rodriguez-Martin 1998). Tables 4.14 and 4.15 illustrate the age, sex, and time period breakdown for degenerative joint disease for Tirup and Black Friars respectively.

Table 4.14 Breakdown of age and sex for degenerative joint disease in the weight bearing joints for Tirup

Sex	**Age Range**	**OA Hip (Present/Total)**	**OA Knee (Present/Total)**	**VO Lumbar Spine (Present/Total)**
Male	Young Adult (18 – 30)	0/42	0/36	7/20
	Middle Adult (31 – 50)	3/24	0/24	15/17
	Old adult (51-70)	0/4	0/5	1/1
	Oldest-old adult (>70)	0/6	0/6	2/3
	Total Male	3/76	0/71	25/41
Female	Young Adult (18 – 30)	0/18	0/19	2/7
	Middle Adult (31 – 50)	0/21	0/19	4/9
	Old adult (51-70)	0/2	0/2	1/1
	Oldest-old adult (>70)	0/0	0/1	0/0
	Total Female	0/41	0/41	7/17

Table 4.15 Breakdown of age, sex, and time period for degenerative joint disease in the weight bearing joints for Black Friars

Sex	Age Range	OA Hip (Present/Total)		OA Knee (Present/Total)		VO Lumbar Spine (Present/Total)	
		Med.	Post-med.	Med.	Post-med.	Med	Post-med
Male	Young Adult (18 – 30)	0/36	2/38	0/33	0/36	9/20	10/17
	Middle Adult (31 – 50)	4/37	5/47	1/35	5/44	16/24	31/41
	Old adult (51-70)	0/1	0/4	0/1	1/4	1/1	2/2
	Oldest-old adult (>70)	0/4	0/10	0/5	0/9	0/0	5/7
	Total Male	4/78	7/99	1/74	6/93	26/45	78/67
Female	Young Adult (18 – 30)	0/27	0/42	1/25	0/40	4/14	15/37
	Middle Adult (31 – 50)	0/10	3/43	0/10	1/43	6/6	26/37
	Old adult (51-70)	0/5	1/6	1/5	0/6	3/3	6/6
	Oldest-old adult (>70)	0/1	0/0	0/2	0/0	0/0	1/1
	Total Female	0/43	4/91	2/42	1/89	13/23	48/81

4.5.2 Diffuse Idiopathic Skeletal Hyperostosis

DISH was diagnosed in the presence of ossification of the anterior longitudinal ligament on the right side of the thoracic region of the spine with at least 3 vertebrae affected as well as calcification or ossification of extra spinal ligaments (Rogers and Waldron 2001). Following Paja et al. (2010), where boney fusion was incomplete but the pathognomonic boney growth resembling the dripping of a candle was noted in conjunction with extraspinal entheses, a diagnosis of early DISH (eDISH) was made. See Tables 4.16 and 4.17 for the age, sex, and time period breakdown of DISH for Tirup and Black Friars respectively.

4.5.3 Gout

Gout was diagnosed based on asymmetrical erosion in the articular or para-articular tissue coupled with Martel hooks (or overhanging margins) (Waldron 2008). In several cases white crystallization was observed inside the eroded areas (Waldron 2008). As discussed earlier, in the absence of chemical analyses, gout can only be tentatively diagnosed. See Tables 4.16 and 4.17 for the age, sex, and time period breakdown of gout for Tirup and Black Friars respectively.

Table 4.16 Breakdown of age and sex for DISH and gout for Tirup

Sex	Age Range	DISH/eDISH (Present/Total)	Gout (Present/Total)
Male	Young Adult (18 – 30)	0/29	2/29
	Middle Adult (31 – 50)	2/19	1/22
	Old adult (51-70)	0/3	1/3
	Oldest-old adult (>70)	1/4	0/4
	Total Male	3/55	4/58
Female	Young Adult (18 – 30)	0/14	0/16
	Middle Adult (31 – 50)	0/16	2/14
	Old adult (51-70)	0/2	0/2
	Oldest-old adult (<70)	0/0	0/1
	Total Female	0/32	2/33

Table 4.17 Breakdown of age, sex, and time period for DISH and gout for Black Friars

Sex	Age Range	DISH/eDISH (Present/Total)		Gout (Present/Total)	
		Med.	**Post-med.**	**Med.**	**Post-med.**
Male	Young Adult (18 – 30)	2/22	0/29	1/19	1/28
	Middle Adult (31 – 50)	0/23	6/39	4/21	4/34
	Old adult (51-70)	1/1	0/3	0/0	0/3
	Oldest-old adult (>70)	0/2	2/6	0/4	1/9
	Total Male	3/49	8/77	5/44	6/75
Female	Young Adult (18 – 30)	0/17	0/40	0/14	1/31
	Middle Adult (31 – 50)	0/4	2/34	0/4	2/38
	Old adult (51-70)	0/3	0/6	0/1	0/4
	Oldest-old adult (>70)	0/0	0/1	0/1	0/0
	Total Female	0/27	2/81	0/23	3/73

4.5.4 Plantar Calcaneal Spurs

Boney outgrowths on the plantar surface of right and left calcanei were recorded. Calcaneal spurs were considered present if evidence of a palpable boney outgrowth existed (Weiss 2012). Dorsal spurring, at the attachment of the calcaneal tendon, was also recorded for comparison purposes. See Tables 4.18 and 4.19 for the age, sex, and time period breakdown of plantar and dorsal calcaneal spurs for Tirup and Black Friars respectively.

Table 4.18 Breakdown of age and sex for plantar and dorsal calcaneal joints for Tirup

Sex	Age Range	Plantar Spurs (Present/Total)	Dorsal Spurs (Present/Total)
Male	Young Adult (18 – 30)	1/26	13/27
	Middle Adult (31 – 50)	3/20	17/22
	Old adult (51-70)	0/3	2/3
	Oldest-old adult (>70)	0/5	1/4
	Total Male	4/54	33/56
Female	Young Adult (18 – 30)	0/14	4/13
	Middle Adult (31 – 50)	0/11	6/12
	Old adult (51-70)	0/2	1/2
	Oldest-old adult (>70)	0/1	1/1
	Total Female	0/28	12/28

Table 4.19 Breakdown of age, sex, and time period plantar and dorsal calcaneal joints for Black Friars

Sex	Age Range	Plantar Spurs (Present/Total)		Dorsal Spurs (Present/Total)	
		Med.	Post-med.	Med.	Post-med.
Male	Young Adult (18 – 30)	1/14	4/21	8/16	6/26
	Middle Adult (31 – 50)	6/18	6/28	14/17	26/33
	Old adult (51-70)	0/0	1/3	0/0	3/4
	Oldest-old adult (>70)	1/1	2/8	4/4	7/8
	Total Male	8/34	13/64	26/37	42/71
Female	Young Adult (18 – 30)	2/12	2/26	6/12	15/26
	Middle Adult (31 – 50)	1/8	4/30	3/6	16/30
	Old adult (51-70)	0/2	0/2	0/2	3/3
	Oldest-old adult (>70)	0/0	0/0	1/1	0/0
	Total Female	3/22	6/58	10/21	34/59

4.5.5 Bone Density and Osteoporosis

4.5.5.1 Fragility Fractures

Fragility fractures, including Colles' fracture, vertebral crush fractures, and femoral neck fractures were assessed as present, absent, or unobservable. No perimortem fractures were observed. Tables 4.20 and 4.21 illustrate the breakdown of age, sex, and time period of fragility fractures for Tirup and Black Friars respectively.

Table 4.20 Breakdown of age and sex for osteoporotic fracturing joints for Tirup

Sex	Age Range	Colles' (Present/Total)	Vertebral (Present/Total)	Femoral Neck (Present/Total)
Male	Young Adult (18 – 30)	0/20	4/24	0/36
	Middle Adult (31 – 50)	0/18	4/19	0/23
	Old adult (51-70)	0/2	0/3	0/4
	Oldest-old adult (>70)	0/2	0/2	0/8
	Total Male	0/42	8/48	0/68
Female	Young Adult (18 – 30)	2/12	0/9	0/16
	Middle Adult (31 – 50)	2/12	1/10	0/21
	Old adult (51-70)	0/2	0/2	0/2
	Oldest-old adult (>70)	1/1	0/0	0/1
	Total Female	5/27	1/21	0/40

Table 4.21 Breakdown of age, sex, and time period for osteoporotic fracturing for Black Friars

Sex	Age Range	Colles' (Present/Total)		Vertebral (Present/Total)		Femoral Neck (Present/Total)	
		Med.	Post-med.	Med.	Post-med.	Med	Post-med
Male	Young Adult (18 – 30)	1/18	1/24	6/23	4/29	0/34	0/36
	Middle Adult (31 – 50)	0/22	1/37	6/28	12/40	2/37	1/43
	Old adult (51-70)	0/2	0/3	0/2	0/2	0/1	0/4
	Oldest-old adult (>70)	0/2	0/4	0/0	1/6	0/4	0/10
	Total Male	1/44	2/68	12/53	17/77	2/76	1/92
Female	Young Adult (18 – 30)	0/16	2/33	2/20	3/31	0/25	0/42
	Middle Adult (31 – 50)	1/8	4/30	2/6	3/36	0/10	0/43
	Old adult (51-70)	0/2	1/5	0/3	1/6	0/6	0/6
	Oldest-old adult (70)	0/0	0/0	0/0	0/1	0/2	0/1
	Total Female	1/26	7/70	4/29	7/77	0/43	0/91

4.5.5.2 Bone Density

High resolution scans of the proximal femora and fourth lumbar vertebrae were imported into Dragonfly Object Research Systems Inc. Imaging Software©. Image segmentation was, again, done automatically by selecting set greyscale threshold settings of -1024 to 400 HU for the femora and -900 to 200 HU for the vertebral bodies. Once the threshold was set, the image was cropped and realigned along a repeatable oblique plane. For the femora, the plane was chosen to intersect the center of the femoral head, femoral neck, and femoral shaft directly below the lesser trochanter (Figure 4.10). Vertebrae were realigned along a plane that intersected the centre of the superior and inferior surfaces of the vertebral bodies (Figure 4.11).

Figure 4.10 Oblique plane created for femoral trabecular bone analysis

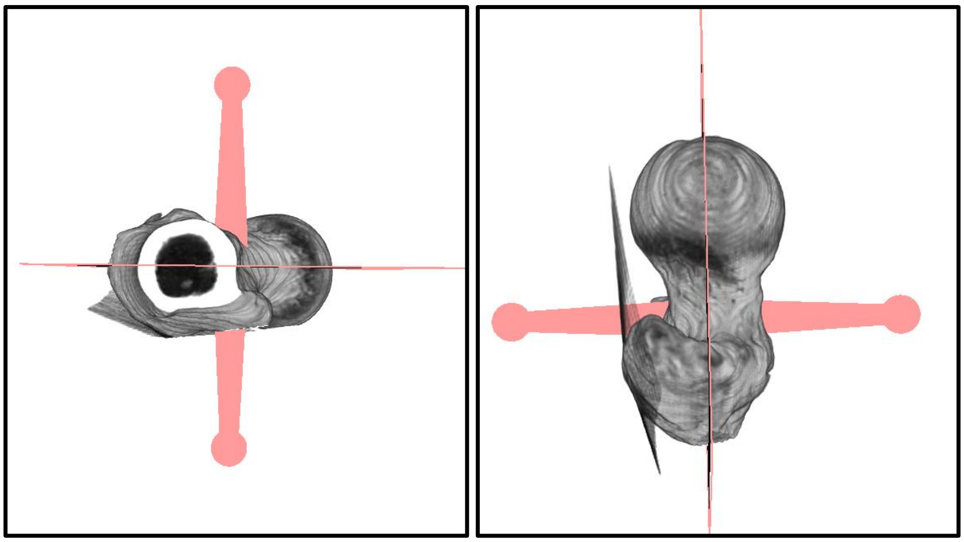
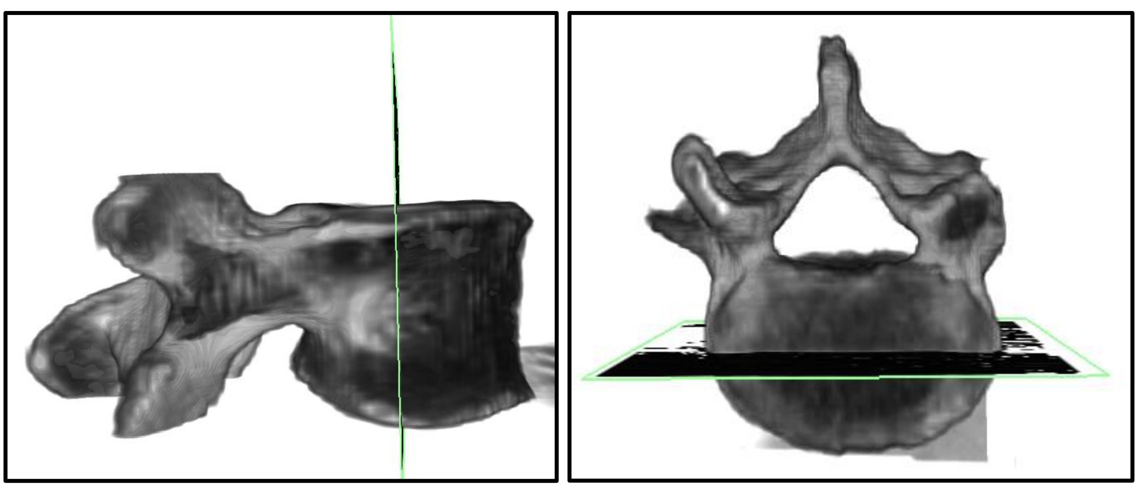


Figure 4.11 Oblique plane created for vertebral trabecular bone analysis



Using the coronal view of the newly oriented femoral DICOM stack, a slab maximum intensity projection (MIP) was created. A slab MIP is generated by overlaying the maximum voxels of every DICOM image within a set width to create a 2D image similar to an x-ray. The chosen width of the slab was 1/3 of the diameter of the femoral neck. Once the slab MIPs were created the images were separated into 6 categories. Categories were based on those created by Singh et al. (1970) using the predictable resorption pattern of the major groups of trabecular bone in the femoral head and neck. Grades I through III are considered osteoporotic and grade IV is considered osteopenic (Singh et al. 1970). A total of 293 proximal femora were categorized, 76 from Tirup (51 males, 25 females) and 217 from Black Friars (127 males, 90 females).

Grade VI – All normal trabecular bone groups are present; trabecular bone covers the entire femoral head.

Grade V – Secondary tensile and compressive trabecular bone are diminished and Ward's triangle becomes prominent.

Grade IV – Principle tensile trabecular bone is reduced but can still be traced from the lateral cortex of bone to the femoral neck.

Grade III – The continuity of principle tensile trabecular bone is broken opposite the greater trochanter.

Grade II – Only principle compressive trabeculae are prominent; tensile trabeculae have been resorbed.

Grade 1 – Principle compressive trabeculae are significantly reduced.

For the fourth lumbar vertebrae, the central coronal DICOM image created by reorienting the vertebral bodies was analyzed. 244 vertebrae, 60 from Tirup (42 males, 18 females) and 184 from Black Friars (90 males, 94 females) were scanned and classified into six categories. Grades 1 through III represent severe to mild osteoporosis while grade IV represents osteopenia.

Grade VI – Trabecular bone is tightly packed. Both horizontal and vertical trabeculae are regular in length.

Grade V – Trabecular bone appears reduced. Horizontal and vertebral struts remain intact but appear thinner.

Grade IV – Trabecular bone struts are thin. Bone appears increasingly porous.

Grade III – Intertrabecular connectivity is reduced with loss of horizontal trabecular struts.

Grade II – Increased number of free ending struts. Trabecular bone appears sparse with little horizontal connectivity.

Grade I – Limited intertrabecular connectivity remains. Horizontal trabecular struts appear completely resorbed. Only vertebral struts remain.

4.6 Summary

This chapter has presented the materials chosen and methods employed for the analysis of degeneration related aging and body mass in the rural site of Tirup and the urban site of Black Friars during the medieval and post-medieval periods. The next chapter will present the results of the analyses undertaken using the previously mentioned techniques.

Chapter 5: Results

5.1 Introduction

This chapter outlines the results for the analyses of this research. Results include an intra-observer error assessment for the biomechanical analysis, followed by comparisons between the rural and urban samples, time periods, age categories, sexes, and body size. Each comparison is evaluated based on stature, body mass, and indulgence-related and degenerative disorders, as well as a biomechanical analysis of the femora. As the two methods for estimating body mass, bi-iliac breadth and femoral head diameter, provided significantly different body mass outputs when compared using a paired samples t-test ($t=-3.497$; $df=137$; $p=0.001$), body mass was analyzed twice using the different body mass estimation methods.

5.2 Intra-observer error for biomechanical analysis

The biomechanical properties were reanalyzed for ten individuals in order to test for intra-observer error. Paired t-tests were run on the original and reanalyzed ImageJ outputs. All samples were highly correlated with r^2-values in excess of 80.8% and $p<0.005$ with the exception of percent cortical area at 65% ($r^2= 0.693$; $p=0.026$) and average cortical thickness at Ward's triangle ($r^2= 0.612$; $p=0.060$). Paired sample t-tests between runs showed no significant difference for most variables though maximum section modulus at 50% ($t=2.928$; $df=9$; $p=0.017$) and total area at 80% ($t=-2.460$; $d=9$; $p=0.036$) are somewhat more sensitive to repeated measures.

5.3 Rural to Urban Comparison

It was hypothesized (Hypothesis 1) that the rural sample would be healthier than the urban sample in that the rural sample would be taller and lighter, exhibit a lower frequency of indulgence-related disorders and degeneration in the weight bearing joints and a lower frequency of osteoporosis and osteoporotic fracturing. Additionally, femoral size and strength was expected to be greater among the rural sample than the urban sample. The following results relate to Hypothesis 1.

5.3.1 Stature

The calculated stature illustrated that the rural sample, Tirup, is slightly taller than the urban Black Friars sample, however only the differences in mean femoral length were significant (Figures 5.1 and 5.2). Differences in mean stature and femoral length were compared by site using independent samples t-tests. While no significant difference in stature existed by site for either between males (n_{rural}= 80; n_{urban} = 177) or females (n_{rural}= 48; n_{urban}= 141), mean femoral length was significantly longer in both rural males (n= 61; t=2.464; df= 228; p=0.014) and rural females (n= 32; t=1.977; df=167; p= 0.050) than in their urban counterparts (n_{males} = 169; $n_{females}$ = 137).

Figure 5.1 Mean stature by site

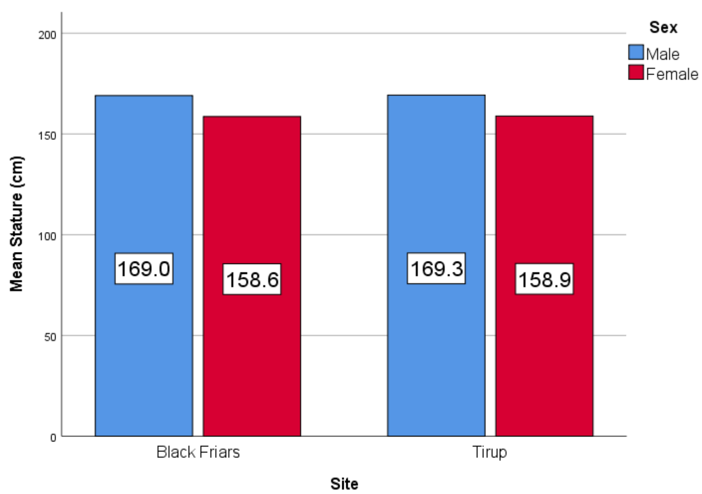
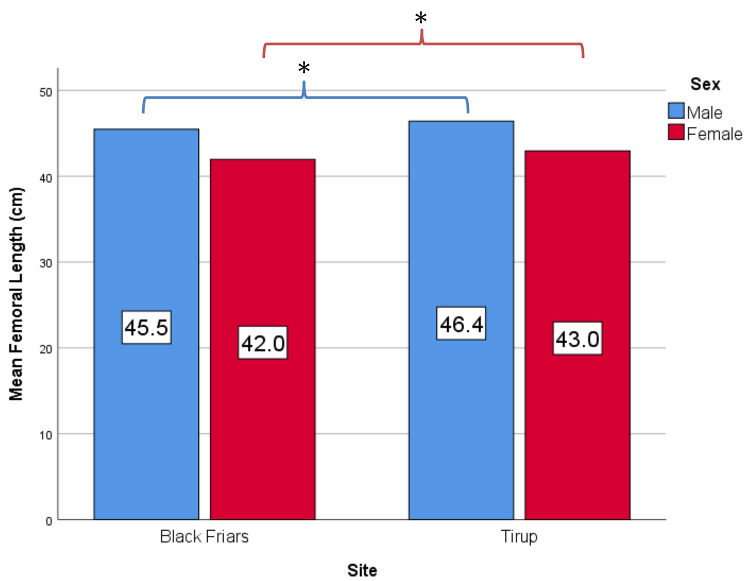


Figure 5.2 Mean femoral length by site



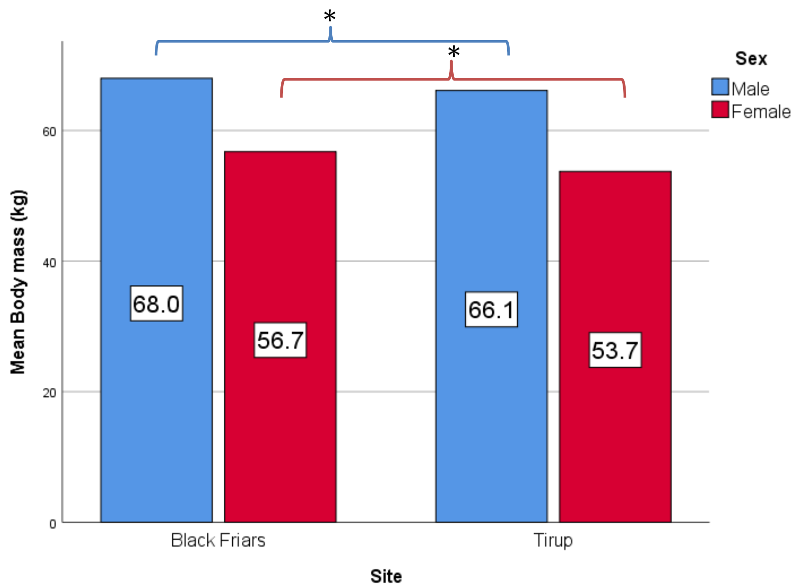
* significant at p<0.05

5.3.2 Body Mass

When using femoral head diameter to calculate body mass, a significant increase in body mass was noted between the rural and urban samples for both males (n_{rural}= 69; n_{urban}= 176; t=-2.231; df=243; p=0.027) and females (n_{rural}= 39; n_{urban}= 145;t=-3.318; df=182; p=0.001). Differences in mean body mass by site were compared using independent samples t-tests. No significant differences in mean body mass were noted for males or females using the bi-iliac breadth body mass estimation technique. The results for body mass differences by site, calculated using femoral head diameter, are presented in Figure 5.3.

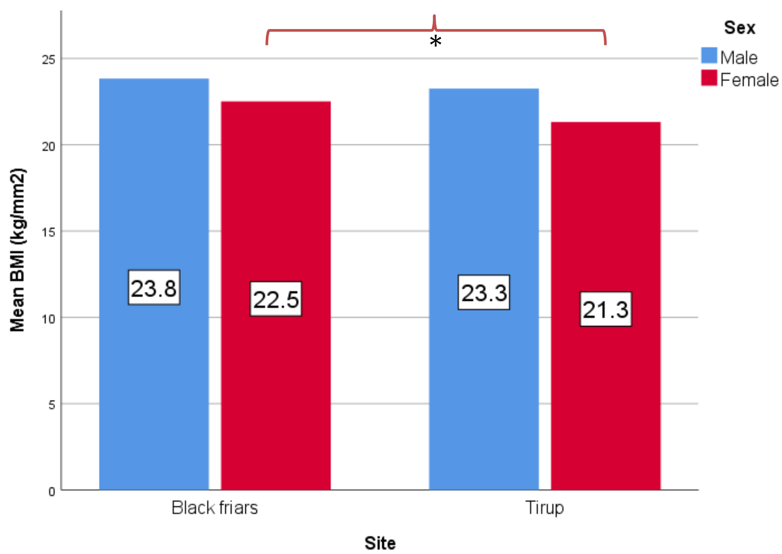
No significant differences in BMI were noted for males or females when using the bi-iliac breadth body mass estimation technique. When using the femoral head diameter to estimate BMI, a significant increase in the urban sample was noted for females (n_{Tirup}=36; $n_{Blackfriars}$=139; t=3.442; df=173; p=0.001) but not for males (Figure 5.4). Differences in body mass index (BMI) were also compared by site using independent samples t-tests. Figures 5.5 and 5.6 illustrate the distribution of body mass index in Tirup and Black Friars respectively.

Figure 5.3 Mean body mass (FHD) by site



*significant at $p<0.05$

Figure 5.4 Mean Body Mass Index (FHD) by site



*significant at $p<0.05$

Figure 5.5 Distribution of BMI categories (FHD) for the Tirup sample

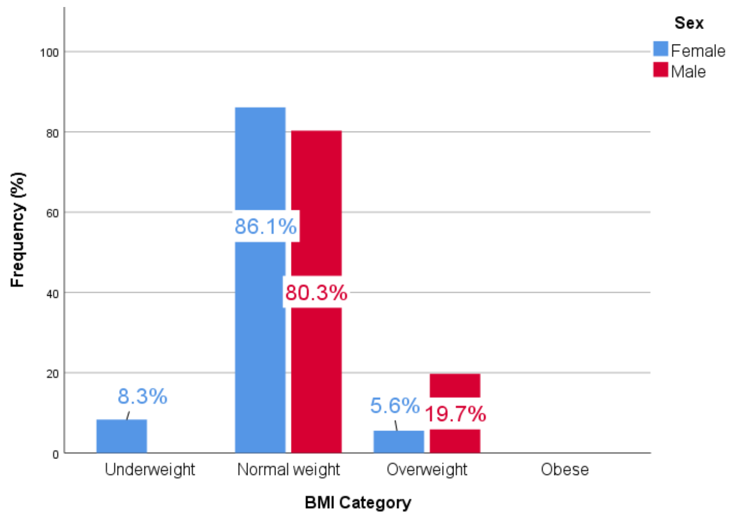
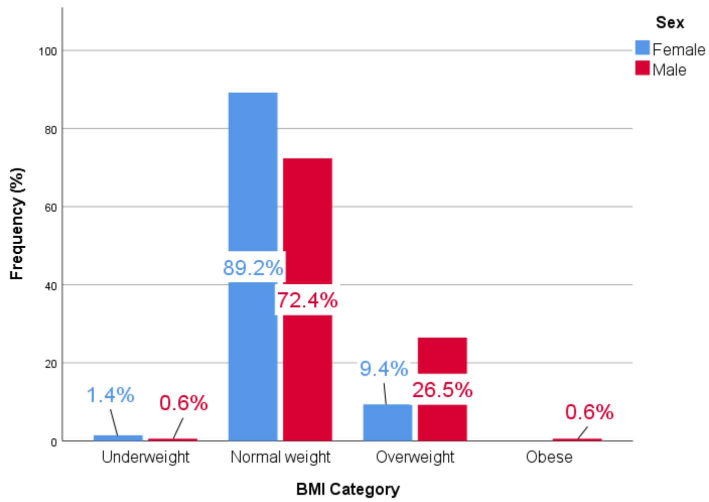


Figure 5.6 Distribution of BMI categories (FHD) for the Black Friars sample



5.3.3 Indulgence-Related Disorders and Degeneration

No significant differences were noted for any indulgence-related disorder with the exception of plantar calcaneal spurs which were significantly more common in the urban males (χ^2=5.291; df=1; p=0.015). The frequency of having any indulgence-related disorder also increased significantly between the rural and urban samples for males (χ^2=8.050; df=1; p=0.005). While the pattern for DISH is not statistically significant it is interesting to note that all cases of true DISH and the majority of eDISH were from the urban sample, Black Friars, and a similar pattern is seen for gout in males. No significant change in the prevalence of dorsal spurs was noted between the urban and rural sites. Chi-square tests (χ^2) were used to assess differences in the frequency of indulgence-related disorders (DISH, gout, and plantar calcaneal spurs) between the rural and urban samples. The frequency of plantar calcaneal spurs and indulgence-related disorders in males and combined sexes are presented in Tables 5.1 through 5.4. Figures 5.7 through 5.10 illustrate the frequency of indulgence-related disorders and dorsal calcaneal spurs between Black Friars and Tirup.

Table 5.1 Frequency of plantar calcaneal spurs by site in males

Site		Plantar Spurs		Total
		Absent	Present	
Black Friars	Count – N (%)	84 (78.5)	23 (21.5)	107
	Standardized residuals	-0.5	1.2	
Tirup	Count – N (%)	51 (92.7)	4 (7.3)	55
	Standardized residuals	0.8	-1.7	
Total	Count	135	27	162

Table 5.2 Frequency of plantar calcaneal spurs by site when sexes are combined

Site		Plantar calcaneal spurs		Total
		Absent	Present	
Black Friars	Count – N (%)	167 (83.9)	32 (16.1)	199
	Standardized residuals	-0.5	1.2	
Tirup	Count – N (%)	81 (94.2)	5 (5.8)	86
	Standardized residuals	0.7	-1.8	
Total	Count	248	37	285

Table 5.3 Frequency of combined indulgence-related disorders by site in males

Site		Indulgence-related disorder		Total
		Absent	Present	
Black Friars	Count – N (%)	45 (52.3)	41 (47.7)	86
	Standardized residuals	-1.0	1.3	
Tirup	Count – N (%)	35 (77.8)	10 (22.2)	45
	Standardized residuals	1.4	-1.8	
Total	Count	80	51	131

Table 5.4 Frequency of combined indulgence-related disorders by site when sexes are combined

Site		Indulgence-related disorder		Total
		Absent	Present	
Black Friars	Count – N (%)	91 (62.8)	54 (37.2)	145
	Standardized residuals	-0.9	1.3	
Tirup	Count – N (%)	56 (81.2)	13 (18.8)	69
	Standardized residuals	1.2	-1.9	
Total	Count	147	67	214

Figure 5.7 Distribution of DISH by site

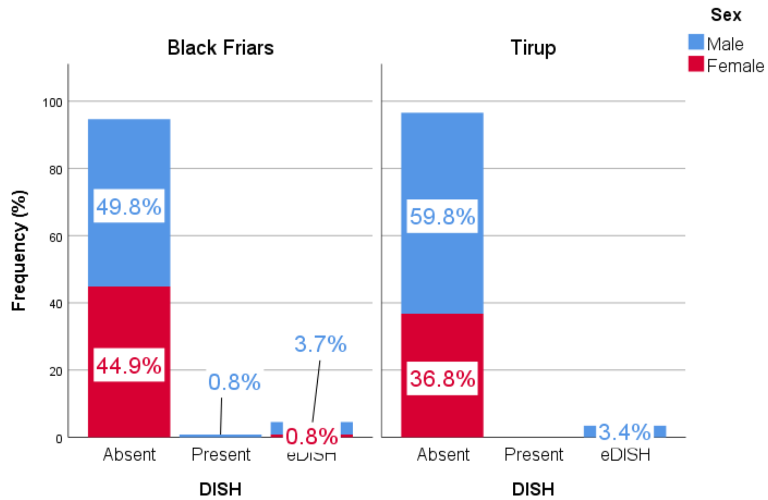


Figure 5.8 Distribution of gout by site

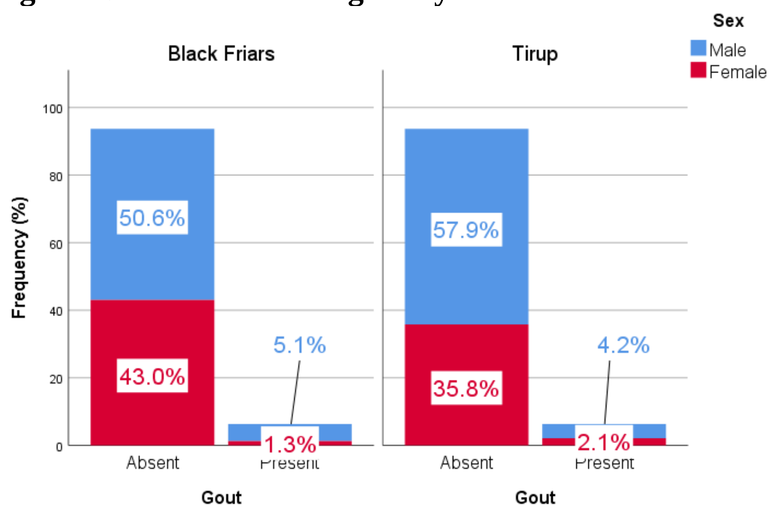
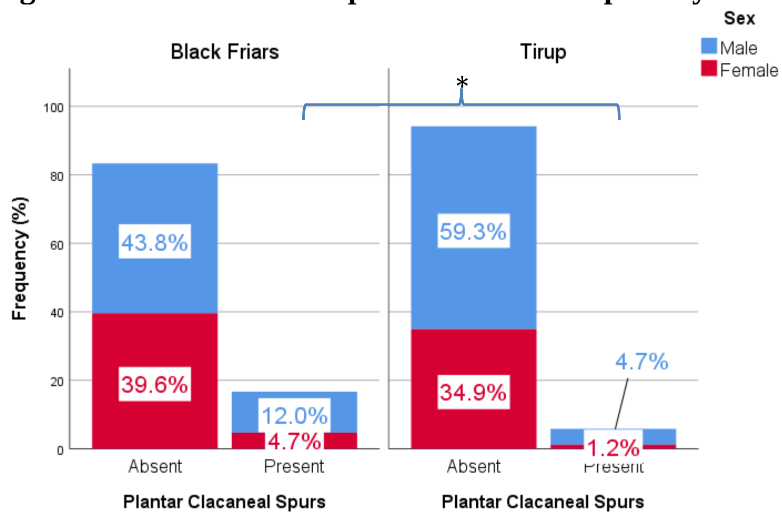
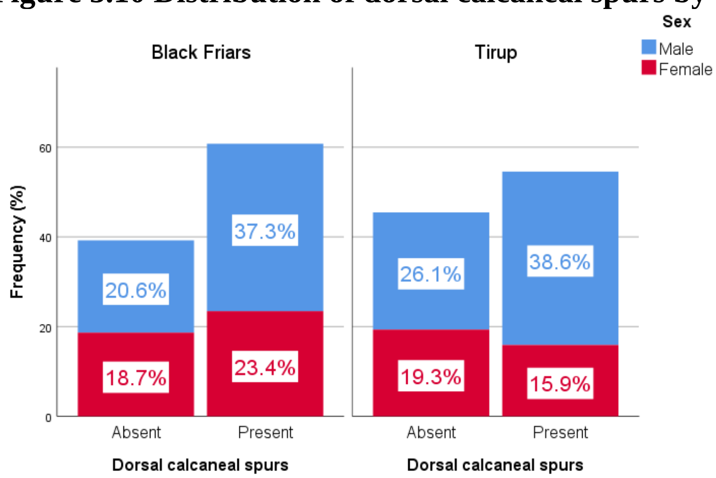


Figure 5.9 Distribution of plantar calcaneal spurs by site



*significant at p<0.05 (for males)

Figure 5.10 Distribution of dorsal calcaneal spurs by site



While an increase in the frequency of degenerative joint disease in the hips, knees, and lumbar spine exists in the urban sample when compared to the rural sample, no significant difference in degeneration was noted for any joint in either males or females. When sexes are combined the frequency of knee osteoarthritis is significantly higher in the urban sample (n=339; χ^2=4.326; df=1; p=0.026) than the rural sample (n=119). Table 5.5 displays the frequency of knee osteoarthritis between the rural and urban sites. Figures 5.11 through 5.13 present the distribution of degenerative joint disease severity by site.

Table 5.5 Frequency of degenerative joint disease of the knees by site (sexes combined)

Site		Knee OA		Total
		Absent	Present	
Black Friars	Count – N (%)	327 (96.5)	12 (3.5)	339
	Standardized residuals	-0.2	1.0	
Tirup	Count – N (%)	119 (100)	0 (0)	119
	Standardized residuals	0.3	-1.8	
Total	Count	446	12	458

Figure 5.11 Distribution of degenerative joint disease in the hips by site

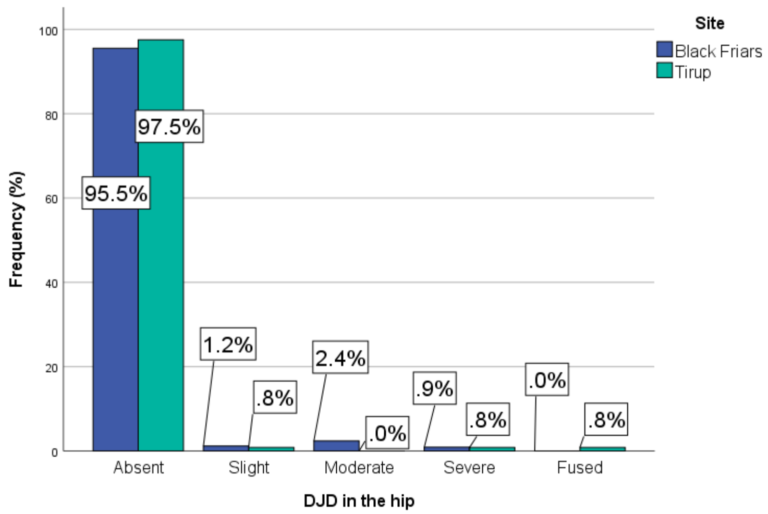


Figure 5.12 Distribution of degenerative joint disease in the knees by site

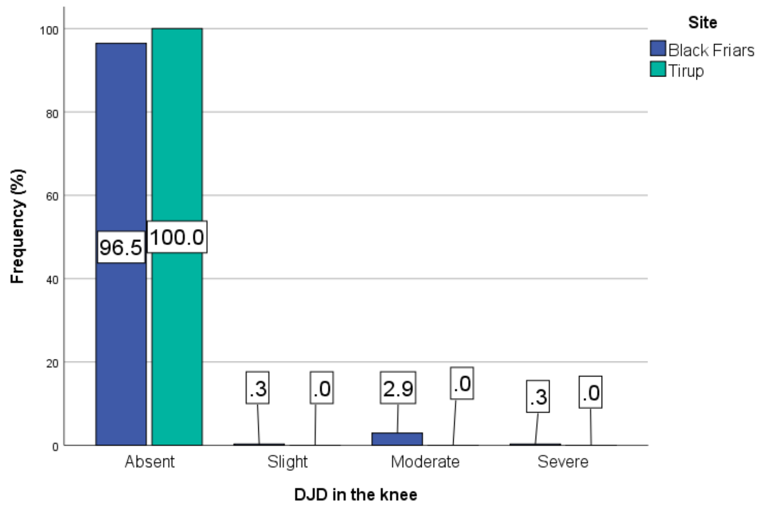
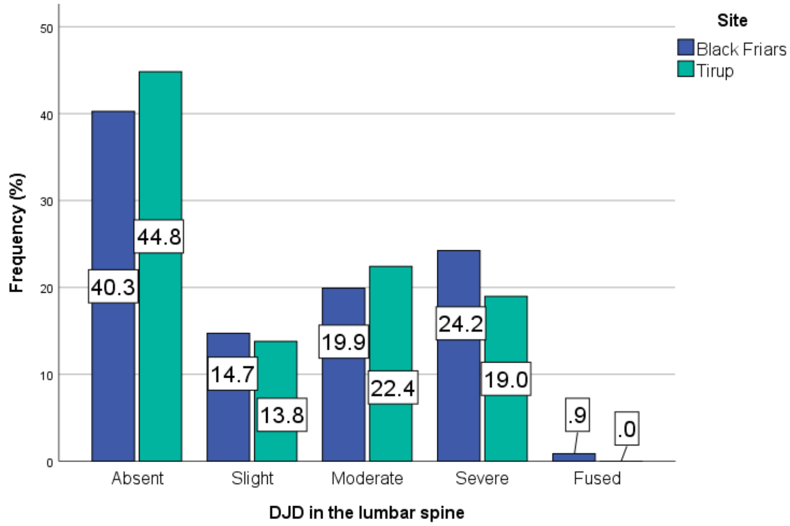


Figure 5.13 Distribution of degenerative joint in the lumbar spine by site



5.3.4 Degenerative Disorders - Osteoporosis

The frequency of osteoporosis was slightly higher in the rural cemetery of Tirup however the cases of moderate and severe osteoporosis were higher in the Black Friars cemetery. Figures 5.14 and 5.15 illustrate the distribution of trabecular bone loss in the femoral neck and fourth lumbar vertebrae by site. Trabecular bone loss was compared by site using chi-square tests (χ^2). The observed differences were not statistically significant.

Figure 5.14 Trabecular bone classification in the femoral neck by site

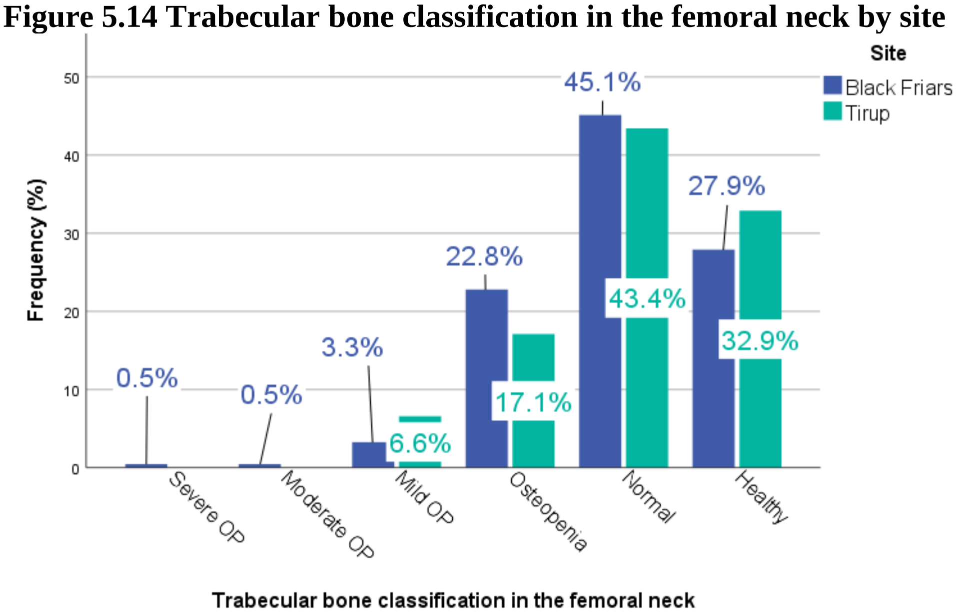
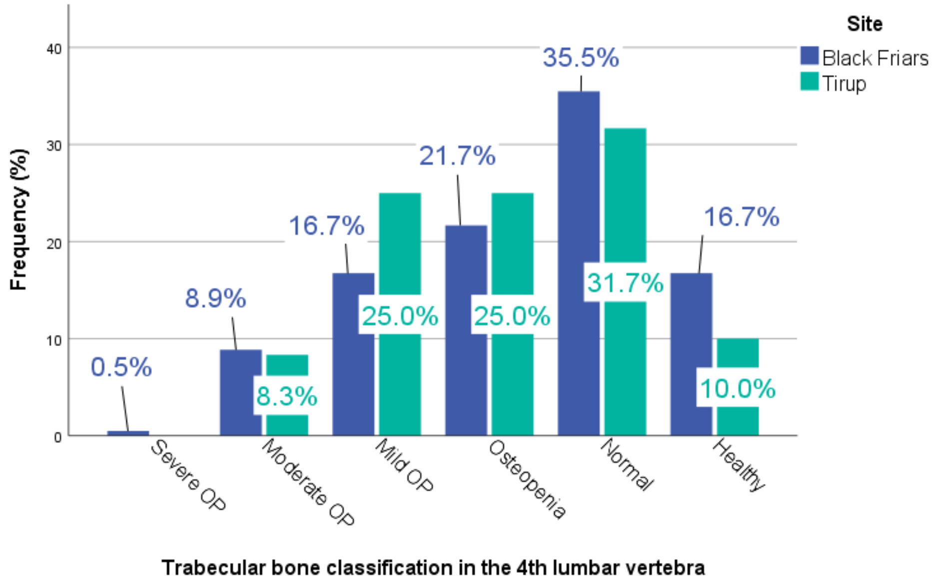


Figure 5.15 Trabecular bone classification in the fourth lumbar vertebra by site



While the urban sample, Black Friars, had a higher frequency of femoral neck fractures, Colles' fracture, and lumbar crush fractures, none of the differences were statistically significant. Figures 5.16 through 5.18 illustrate the frequency of osteoporotic fractures by site. The frequency of osteoporotic fractures was compared between the rural and urban samples using chi square tests (χ^2).

Figure 5.16 Femoral neck fractures by site

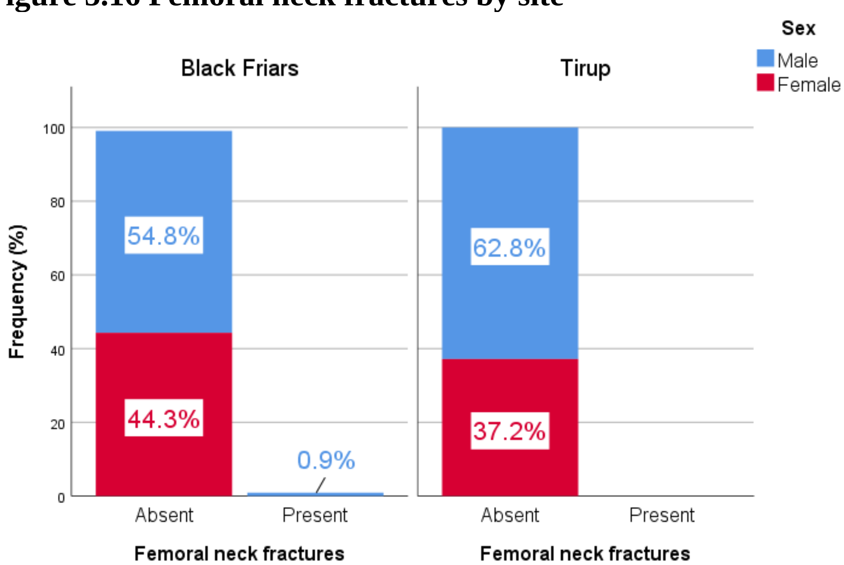


Figure 5.17 Colles' fractures by site

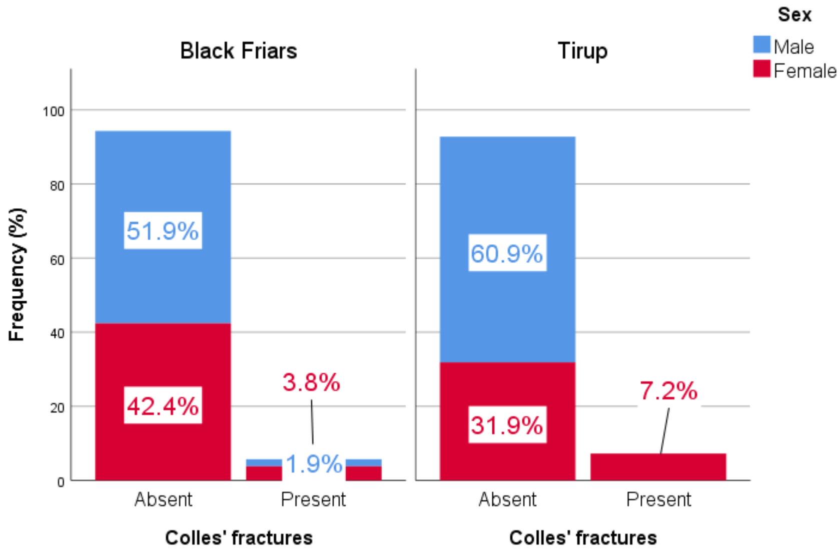
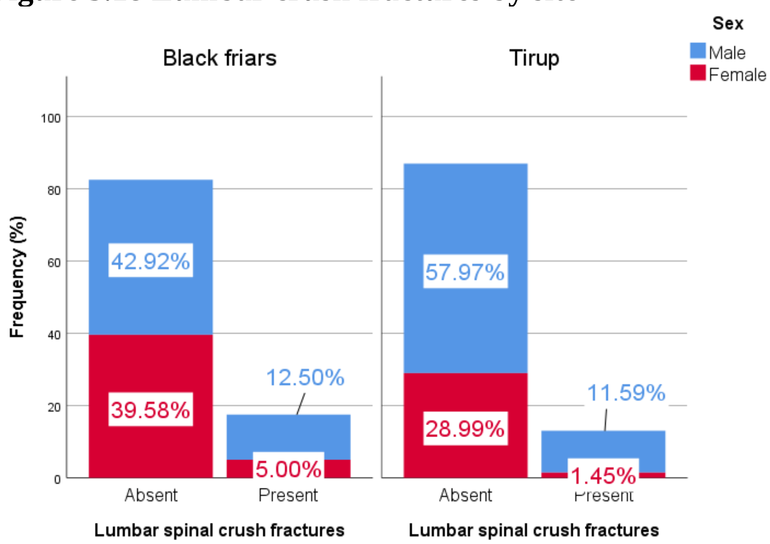


Figure 5.18 Lumbar crush fractures by site



5.3.5 Biomechanics

A general trend towards increased size and strength is seen in the urban sample of Black Friars, however cortical area, percent cortical area, and average cortical thickness are larger in the rural sample, Tirup. Independent samples t-tests were used to compare mean differences in cortical area (CA), total area (TA), percent cortical area (%CA), minimum second moment of area (I_{min}), maximum second moment of area (I_{max}), polar second moment of area (J), maximum section modulus (Z_{max}), minimum section modulus (Z_{min}), polar section modulus (Z_p), average cortical thickness, and a shape ratio (I_{max}/I_{min}) along the femoral shaft at 20%, 35%, 50%, 65%, and 80%, and at Ward's triangle between the rural and urban samples. The results of the independent samples t-tests for males and females are provided below in Table 5. 6 and 5.7. Figures 5.19 through 5.34 present relevant size-standardized results for differences in the biomechanical properties by site.

Table 5.6 Comparison of biomechanical properties between the urban (n=95) and rural (n=36) samples for males

Biomechanical property	Slice	t	df	p-value
CA (mm^2)	20%	-0.471	129	0.639
	35%	0.162	129	0.872
	50%	0.342	129	0.733
	65%	-0.613	129	0.541
	80%	-0.070	129	0.944
	Ward's	-0.788	124	0.432
TA (mm^2)	20%	3.248	129	0.001*
	35%	1.951	129	0.053
	50%	0.964	129	0.337
	65%	0.486	49.501	0.629
	80%	0.890	129	0.375
	Ward's	0.130	111.988	0.897
%CA	20%	-2.421	129	0.017*
	35%	-1.565	129	0.120
	50%	-0.768	129	0.444
	65%	-0.162	129	0.872
	80%	-0.663	129	0.508
	Ward's	-1.302	124	0.195
I_{min} (mm^4)	20%	4.464	129	0.001*
	35%	3.704	129	<0.001*
	50%	3.609	129	<0.001*
	65%	3.564	129	0.001*
	80%	3.858	129	<0.001*
	Ward's	2.391	123.871	0.018*
I_{max} (mm^4)	20%	3.590	129	<0.001*
	35%	3.402	129	<0.001*
	50%	3.212	129	0.002*
	65%	1.068	129	0.287

	80%	0.891	129	0.375
	Ward's	0.403	124	0.688
***J* (mm⁴)**	20%	4.235	129	<0.001*
	35%	2.275	129	0.025*
	50%	3.579	129	<0.001*
	65%	3.579	129	<0.001*
	80%	2.144	129	0.034*
	Ward's	1.017	122.706	0.311
Z_{max} (mm^3)	20%	3.074	129	0.003*
	35%	2.696	129	0.008*
	50%	1.397	129	0.165
	65%	0.667	49.426	0.508
	80%	0.753	129	0.453
	Ward's	0.006	124	0.995
Z_{min} (mm^3)	20%	2.647	129	0.009*
	35%	3.115	129	0.002*
	50%	2.567	129	0.011*
	65%	2.649	129	0.009*
	80%	2.652	129	0.009*
	Ward's	1.444	114.257	0.151
Z_p (mm^3)	20%	3.304	129	0.001*
	35%	3.012	129	0.003*
	50%	1.707	129	0.090
	65%	1.810	51.425	0.076
	80%	2.292	129	0.024*
	Ward's	0.660	116.509	0.511
Avg. cortical thickness (mm)	20%	-1.273	129	0.205
	35%	-0.634	129	0.527
	50%	-0.396	129	0.693
	65%	-1.673	129	0.097
	80%	-0.896	129	0.372
	Ward's	-1.241	124	0.217
I_{max}/I_{min}	20%	-1.131	129	0.260
	35%	-1.216	129	0.226
	50%	-0.391	129	0.696
	65%	-3.363	129	0.001*
	80%	-4.145	129	<0.001*
	Ward's	4.503	129	<0.001*

*significant at a 95% confidence interval

All values except % cortical area, avg. cortical thickness, and I_{max}/I_{min} are size- standardized; CA_{STD} = CA/BM; TA_{STD} = TA/BM; I_{STD} = I/(BM*Fem Length^2); J_{STD} = J/(BM*Fem Length^2); Z_{STD} = Z/(BM*Fem Length)

Table 5.7 Comparison of biomechanical properties between the urban (n=65) and rural (n=16) samples for females

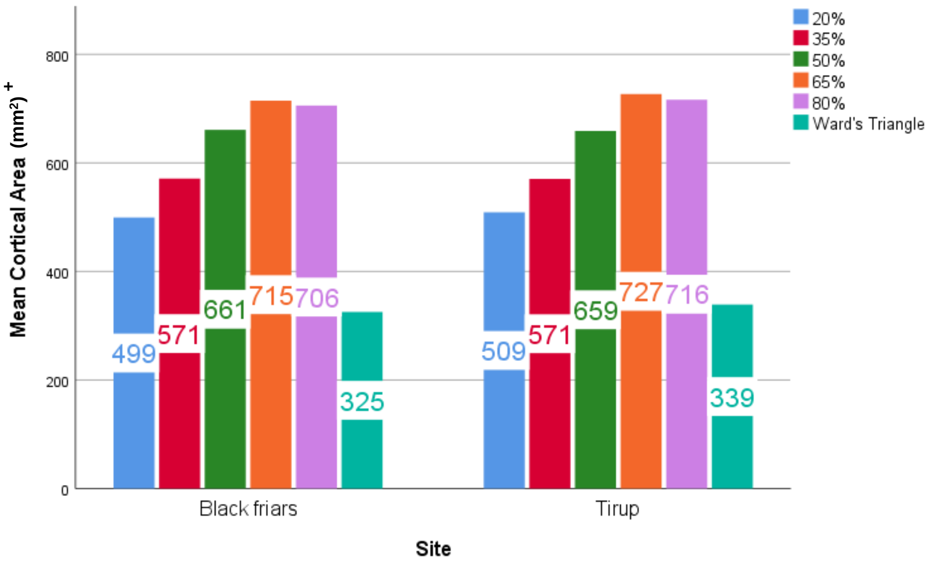
Biomechanical property	Slice	t	df	p-value
CA (mm^2)	20%	-0.542	79	0.589
	35%	0.908	79	0.367
	50%	0.930	79	0.355
	65%	0.625	79	0.534
	80%	0.759	79	0.450
	Ward's	-1.037	77	0.303
TA (mm^2)	20%	4.303	79	<0.001*
	35%	2.940	79	0.004*
	50%	1.821	79	0.072
	65%	0.062	79	0.951
	80%	2.293	79	0.025*
	Ward's	-0.838	77	0.405
%CA	20%	-4.262	79	<0.001*
	35%	-1.788	79	0.078
	50%	-1.003	79	0.319
	65%	0.108	16.488	0.915
	80%	-1.717	79	0.090
	Ward's	-0.144	77	0.886
I_{min} (mm^4)	20%	4.662	79	<0.001*
	35%	3.657	79	<0.001*
	50%	3.449	79	0.001*
	65%	3.941	79	<0.001
	80%	3.794	79	<0.001
	Ward's	0.531	77	0.597
I_{max} (mm^4)	20%	6.954	49.605	<0.001*
	35%	4.622	79	<0.001*
	50%	3.070	79	0.003*
	65%	2.605	79	0.011*
	80%	2.487	79	0.015*
	Ward's	0.072	77	0.943
J (mm^4)	20%	7.248	44.990	<0.001*
	35%	3.303	79	0.001*
	50%	3.821	79	<0.001*
	65%	3.821	79	<0.001*
	80%	3.046	79	<0.001*
	Ward's	0.188	77	0.851
Z_{max} (mm^3)	20%	3.830	79	<0.001*
	35%	3.680	79	<0.001*
	50%	3.128	79	0.002*
	65%	2.756	79	0.007*

	80%	2.756	79	0.007*
	Ward's	-0.483	77	0.630
Z_{min} (mm^3)	20%	3.349	79	0.001*
	35%	3.675	79	<0.001*
	50%	3.124	79	0.002*
	65%	2.991	79	0.004*
	80%	-0.017	79	0.986
	Ward's	0.138	77	0.890
Z_p (mm^3)	20%	4.037	79	<0.001*
	35%	3.872	79	<0.001*
	50%	2.624	79	0.010*
	65%	2.963	79	0.004*
	80%	3.486	79	0.001*
	Ward's	-0.377	77	0.708
Avg. cortical thickness (mm)	20%	-2.076	79	0.041*
	35%	0.257	79	0.798
	50%	0.386	79	0.701
	65%	0.819	79	0.415
	80%	0.078	79	0.938
	Ward's	0.547	77	0.586
I_{max}/I_{min}	20%	-0.566	79	0.573
	35%	-1.398	79	0.166
	50%	1.933	79	0.057
	65%	-2.283	17.293	0.035*
	80%	-1.701	79	0.093
	Ward's	-2.096	77	0.039*

*significant at a 95% confidence interval

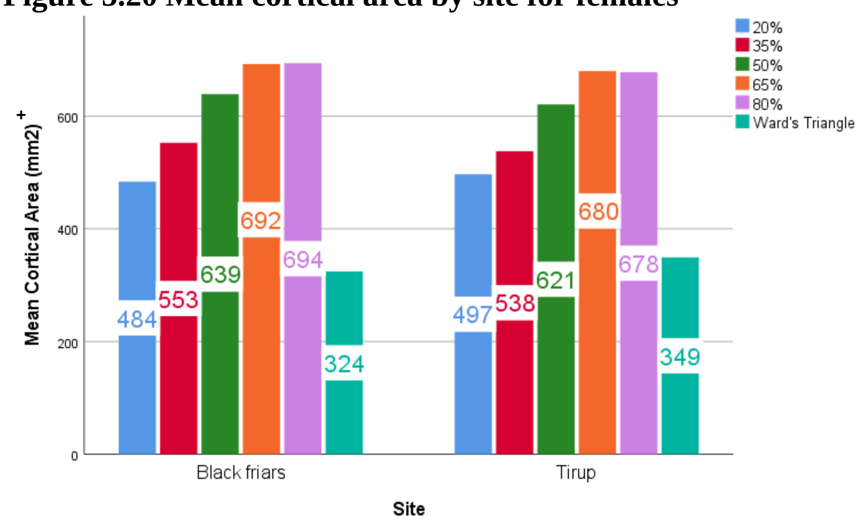
All values except % cortical area, avg. cortical thickness, and I_{max}/I_{min} are size- standardized; CA_{STD} = CA/BM; TA_{STD} = TA/BM; I_{STD} = I/(BM*Fem Length^2); J_{STD} = J/(BM*Fem Length^2); Z_{STD} = Z/(BM*Fem Length)

Figure 5.19 Mean cortical area by site for males



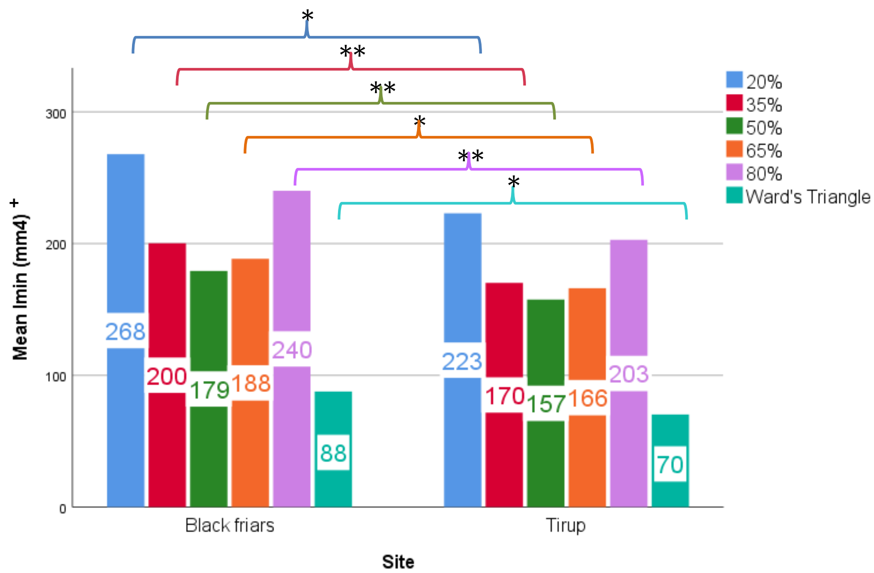
+CA values except are size- standardized; $CA_{STD} = CA/BM$

Figure 5.20 Mean cortical area by site for females



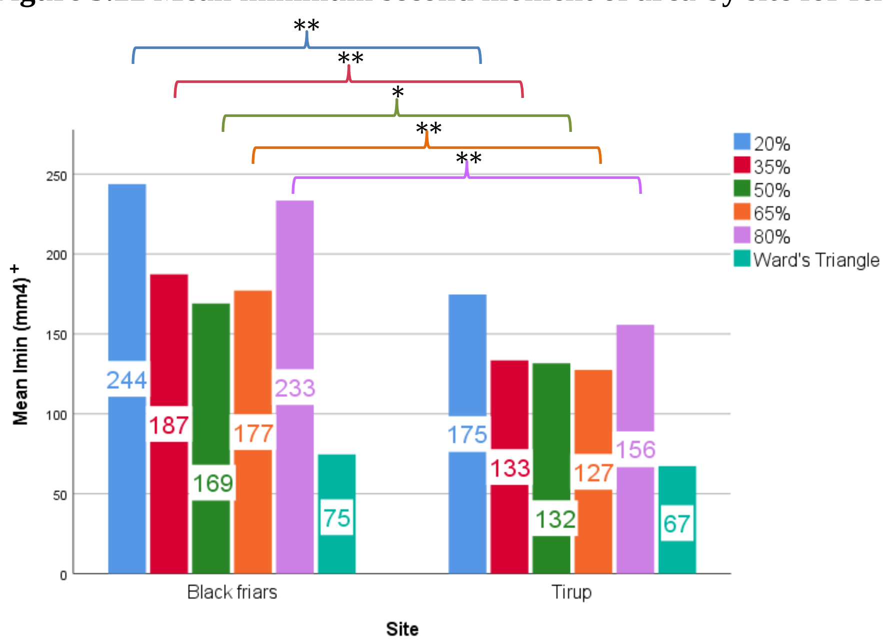
+CA values except are size- standardized; $CA_{STD} = CA/BM$

Figure 5.21 Mean minimum second moment of area by site for males



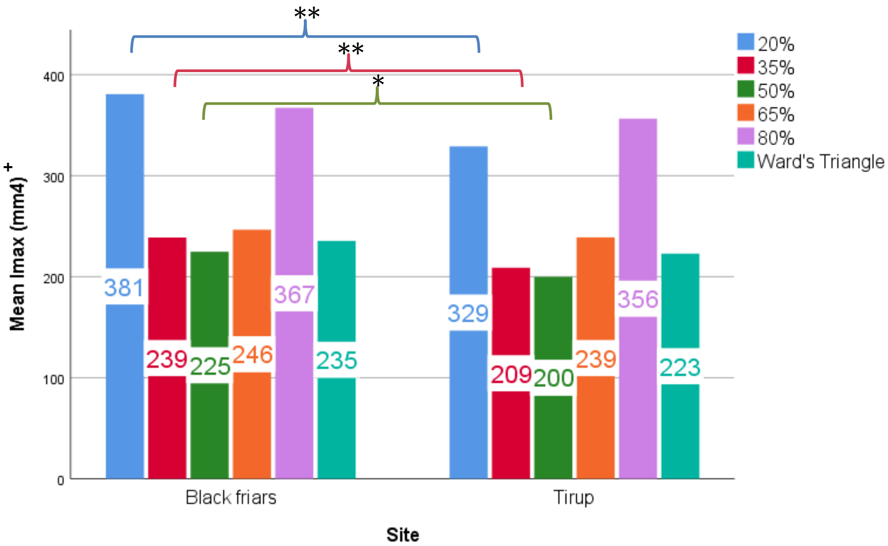
*significant at p<0.05; ** significant at p<0.001
+ I_{min} values are size-standardized: $I_{minSTD} = I_{min}/(BM*Fem\ Length^2)$

Figure 5.22 Mean minimum second moment of area by site for females



*significant at p<0.05; ** significant at p<0.001
+ I_{min} values are size-standardized: $I_{minSTD} = I_{min}/(BM*Fem\ Length^2)$

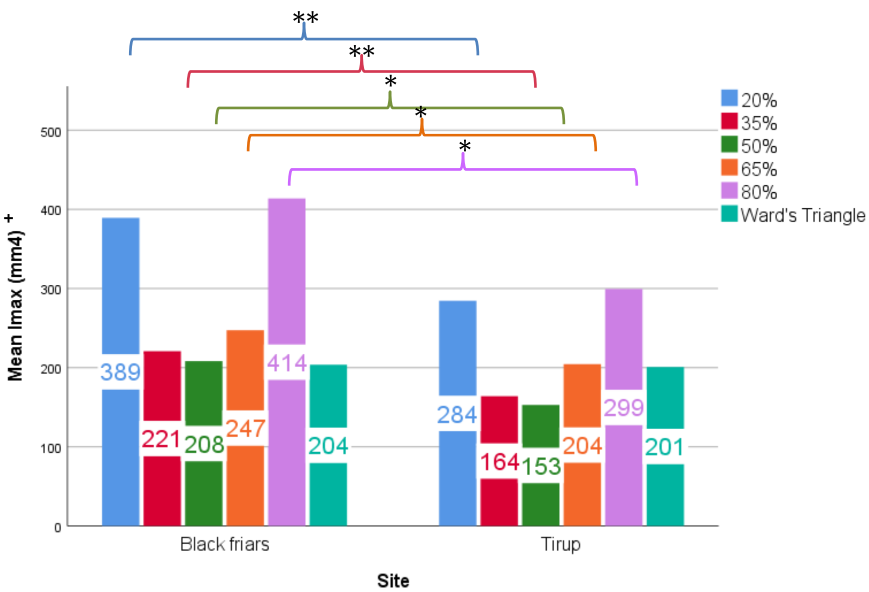
Figure 5.23 Mean maximum second moment of area by site for males



*significant at p<0.05; ** significant at p<0.001

+ I_{max} values are size-standardized: $I_{maxSTD} = I_{max}/(BM*Fem\ Length^2)$

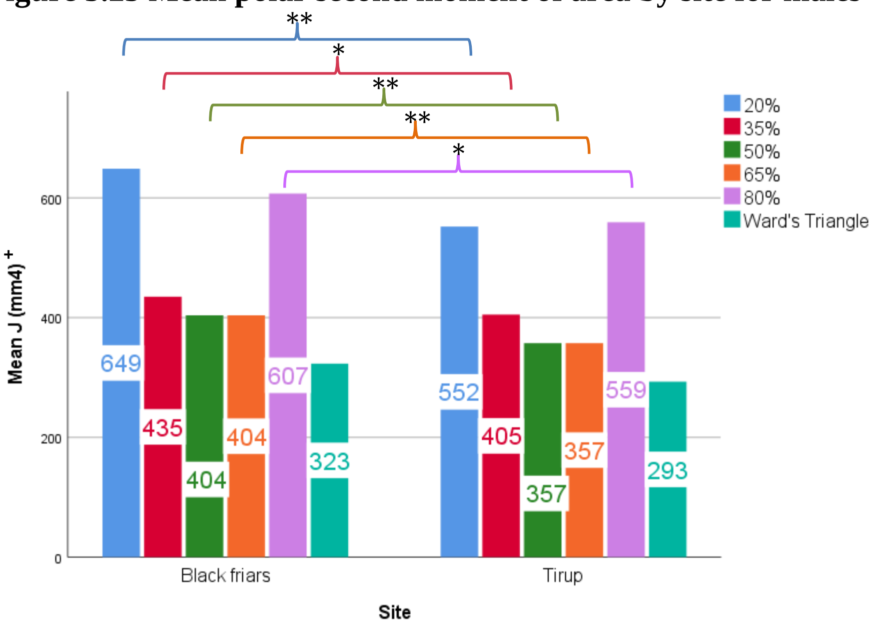
Figure 5.24 Mean maximum second moment of area by site for females



*significant at p<0.05; ** significant at p<0.001

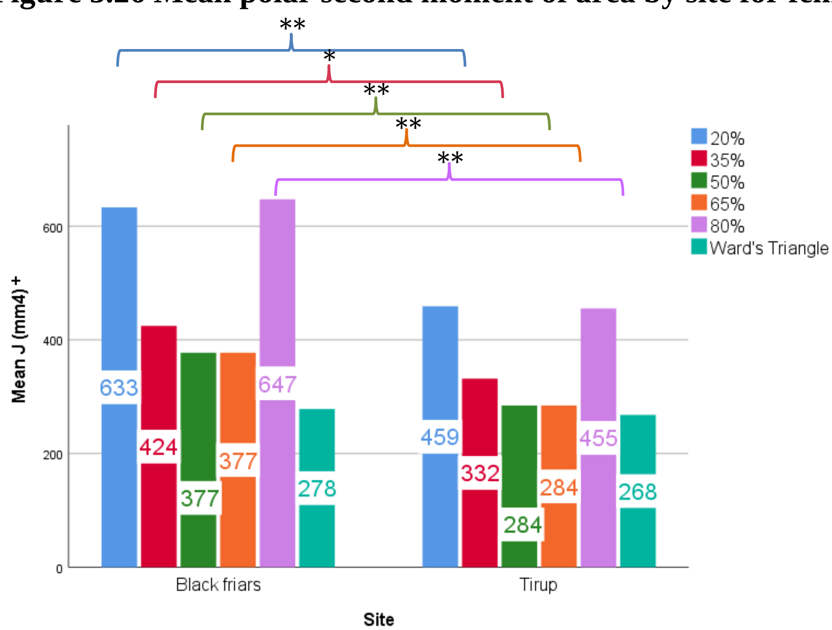
+ I_{max} values are size-standardized: $I_{maxSTD} = I_{max}/(BM*Fem\ Length^2)$

Figure 5.25 Mean polar second moment of area by site for males



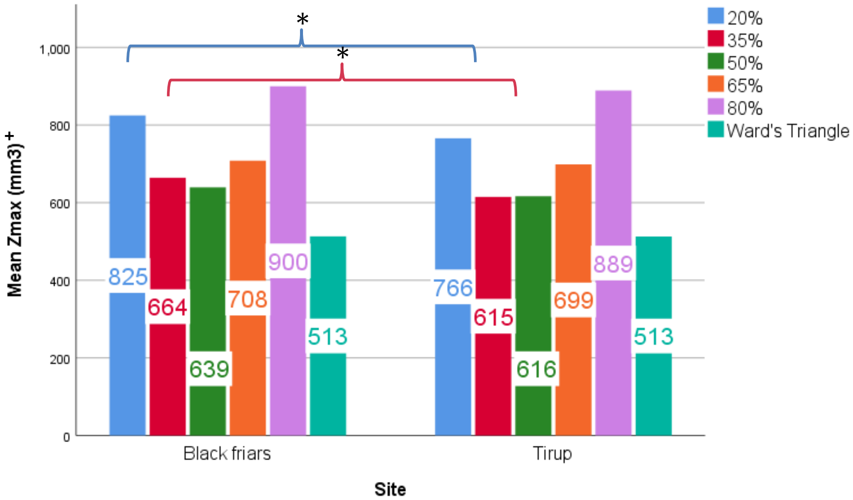
*significant at p<0.05; ** significant at p<0.001
$^{+}$ J values are size-standardized: $J_{STD} = J/(BM*Fem\ Length^2)$

Figure 5.26 Mean polar second moment of area by site for females



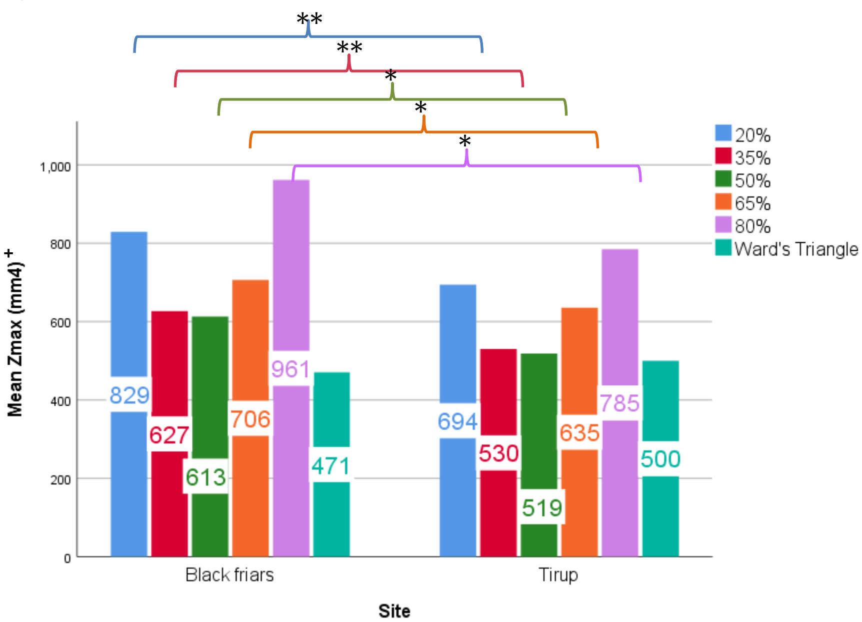
*significant at p<0.05; ** significant at p<0.001
$^{+}$ J values are size-standardized: $J_{STD} = J/(BM*Fem\ Length^2)$

Figure 5.27 Mean maximum section modulus by site for males



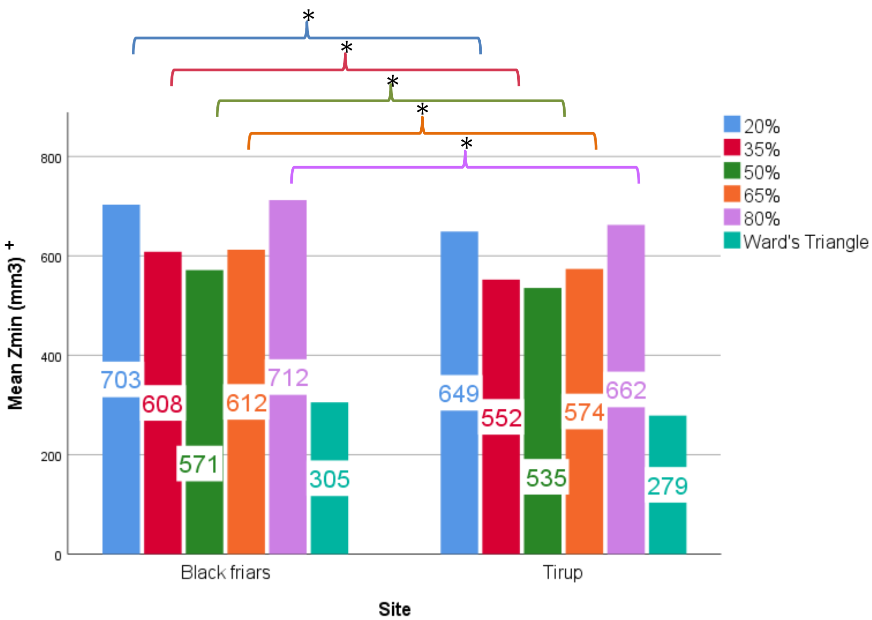
*significant at p<0.05
+ Z_{max} values are size-standardized: $Z_{maxSTD} = Z_{max}/(BM*Fem\ Length)$

Figure 5.28 Mean maximum section modulus by site for females



*significant at p<0.05; ** significant at p<0.001
+ Z_{max} values are size-standardized: $Z_{maxSTD} = Z_{max}/(BM*Fem\ Length)$

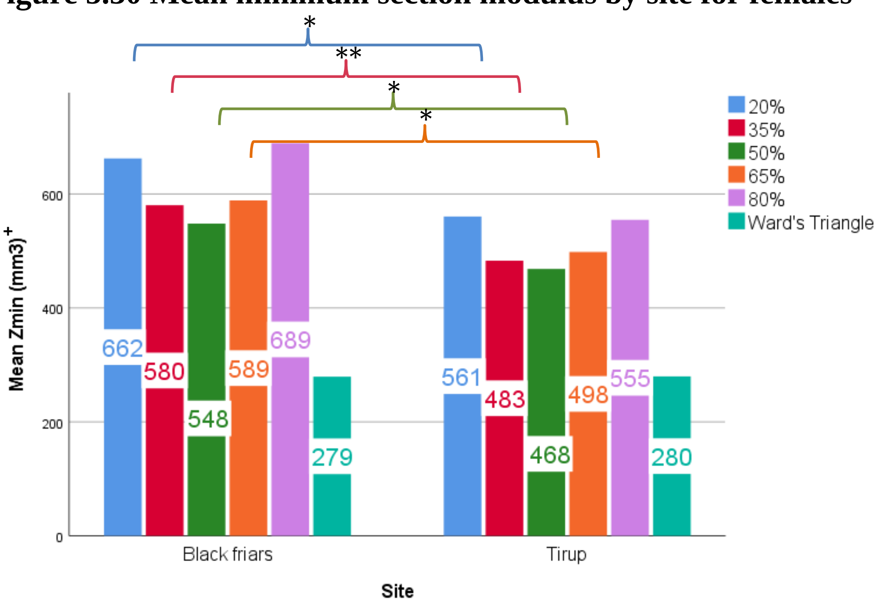
Figure 5.29 Mean minimum section modulus by site for males



*significant at $p<0.05$

$^{+}$ Z_{min} values are size-standardized: $Z_{minSTD} = Z_{min}/(BM*Fem\ Length)$

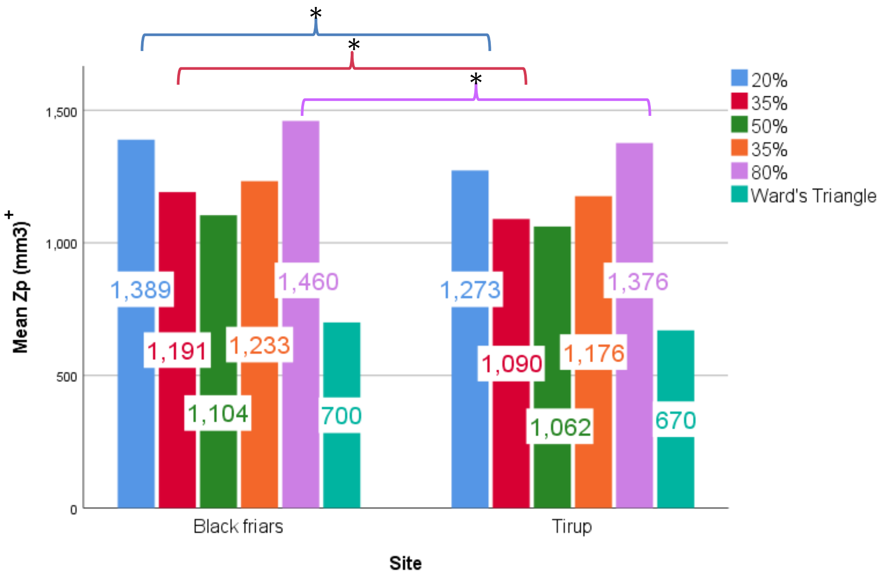
Figure 5.30 Mean minimum section modulus by site for females



*significant at $p<0.05$; ** significant at $p<0.001$

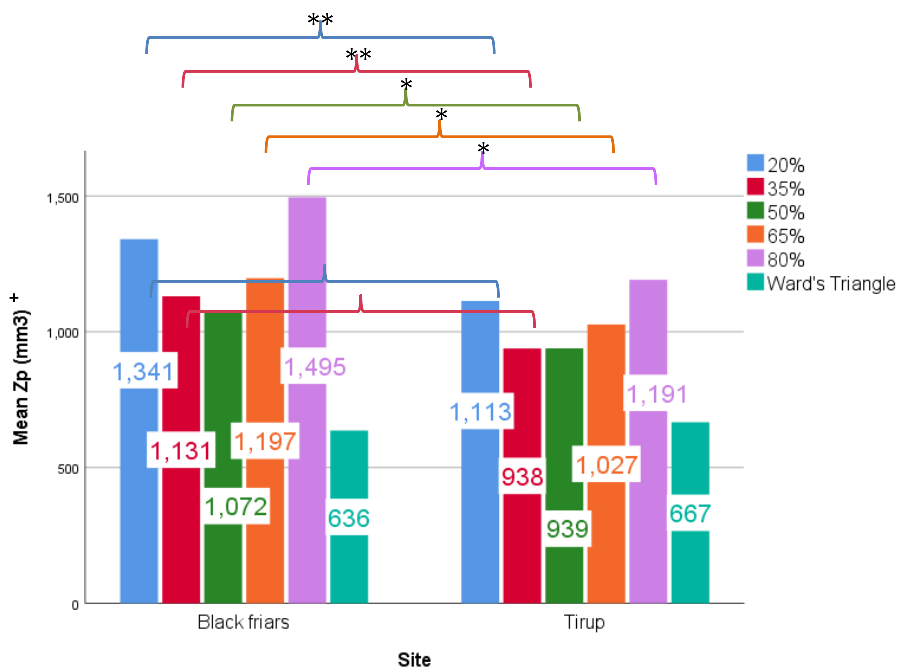
$^{+}$ Z_{min} values are size-standardized: $Z_{minSTD} = Z_{min}/(BM*Fem\ Length)$

Figure 5.30 Mean polar section modulus by site for males



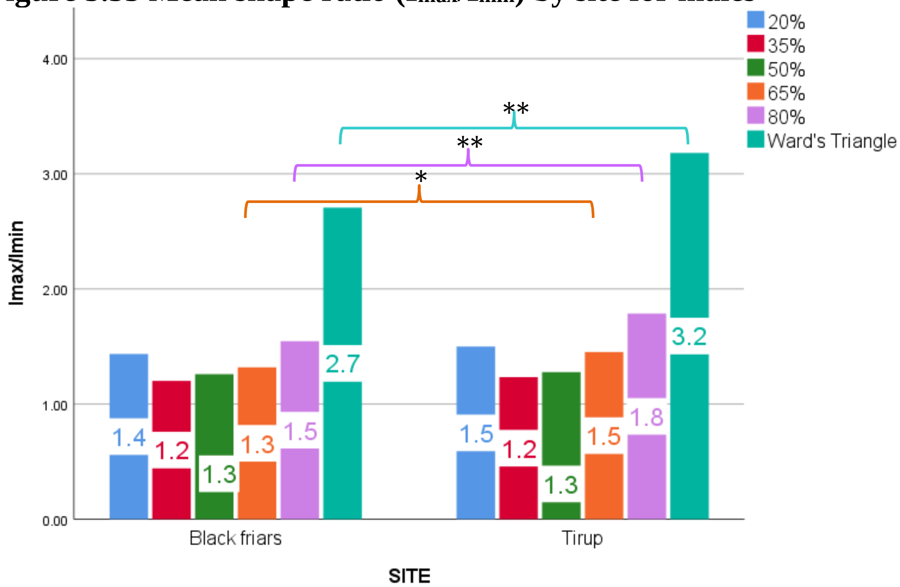
*significant at p<0.05
+ Z_p values are size-standardized: $Z_{pSTD} = Z_p/(BM*Fem\ Length)$

Figure 5.32 Mean polar section modulus by site for females



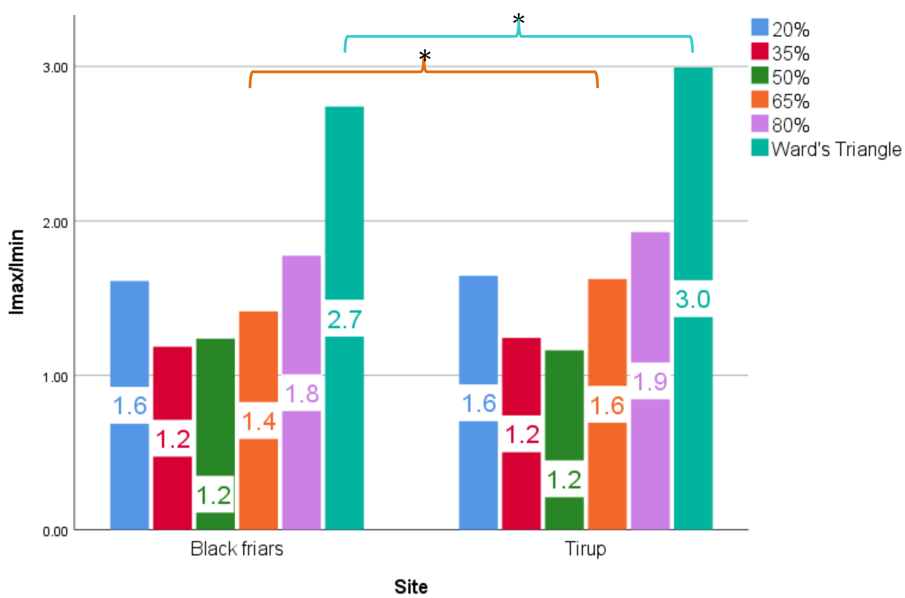
*significant at p<0.05; ** significant at p<0.001
+ Z_p values are size-standardized: $Z_{pSTD} = Z_p/(BM*Fem\ Length)$

Figure 5.33 Mean shape ratio (I_{max}/I_{min}) by site for males



*significant at p<0.05; ** significant at p<0.001

Figure 5.34 Mean shape ratio (I_{max}/I_{min}) by site for females



*significant at p<0.05

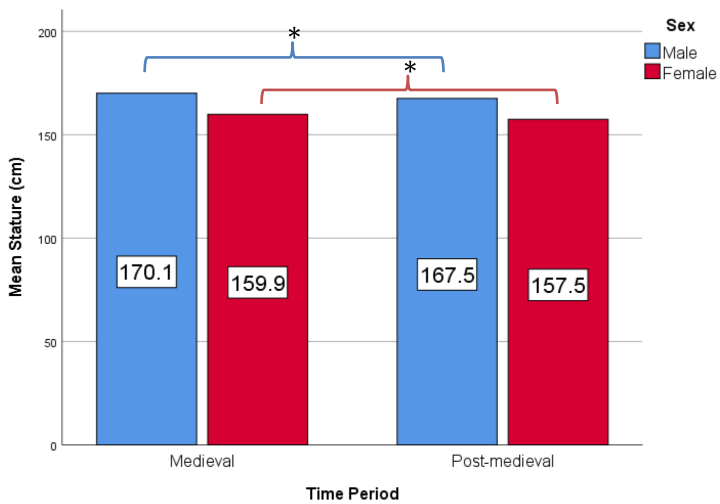
5.4 Time Period Comparison

Hypothesis 2 stated that a temporal trend towards decreasing health would be seen between the medieval and post-medieval period. It was expected that the medieval sample would be taller and lighter, would exhibit fewer indulgence-related disorders and degeneration in the weight bearing joints as well as a lower prevalence of osteoporosis and osteoporotic fracturing. A decrease in femoral robusticity was expected between the medieval and post-medieval period. The following results pertain directly to hypothesis 2.

5.4.1 Stature

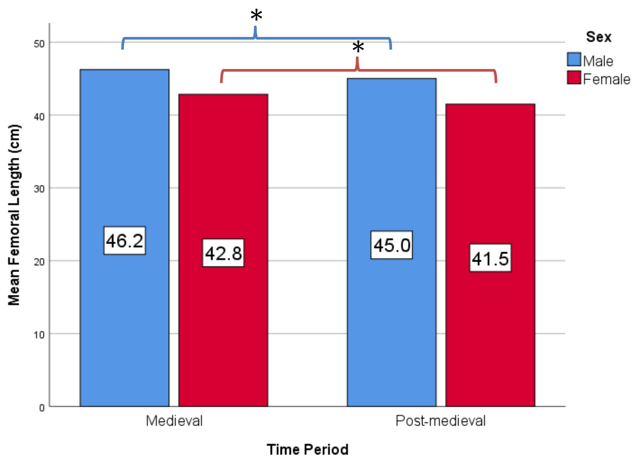
Significant decreases in mean stature from the medieval to the post-medieval periods were noted for both males ($n_{medeival}$= 159; $n_{post\text{-}medieval}$= 98; t=2.982; df=255; p=0.003) and females ($n_{medeival}$= 97; $n_{post\text{-}medieval}$= 92; t=2.503; df=177.748; p=0.013) (Fig. 5.35). Significant decreases in mean femoral length were also seen between time periods for both males ($n_{medeival}$= 78; $n_{post\text{-}medieval}$= 53; t=3.557; df=228; p<0.001) and females ($n_{medeival}$= 34; $n_{post\text{-}medieval}$= 47; t=3.465; df=150.032; p=0.001) (Fig. 5.36).

Figure 5.35 Mean stature by time period



*significant at p<0.05

Figure 5.36 Mean femoral length by time period



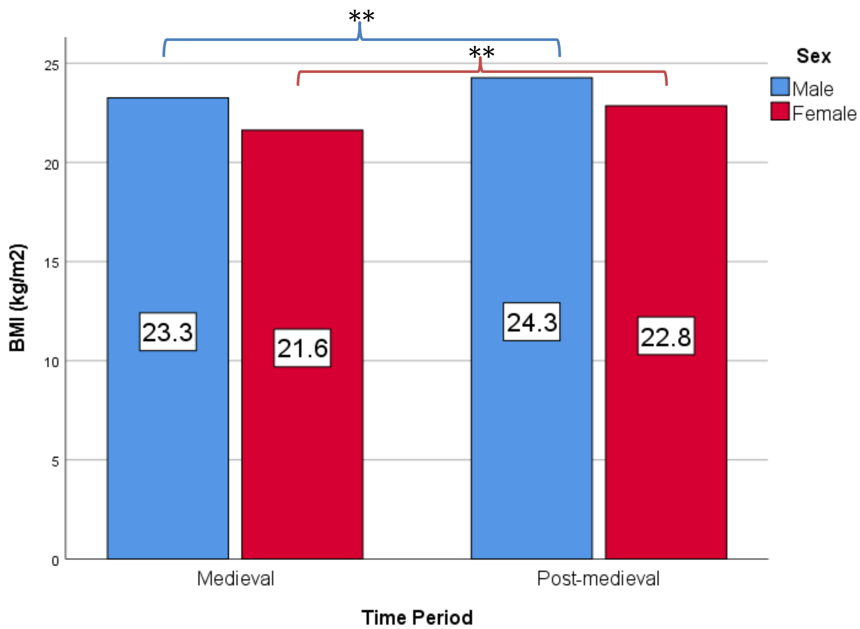
*significant at p<0.05

5.4.2 Body Mass

Differences in mean body mass by time period were compared using independent samples t-tests. No significant differences in mean body mass by time period were noted for males or females using either body mass estimation methods.

No significant differences in BMI were observed for either males or females when using the bi-iliac breadth body mass estimation method. When using the femoral head diameter to estimate BMI a significant increase in the post-medieval period was noted for both males ($n_{medieval}$= 139; $n_{post\text{-}medieval}$= 97; t=-3.652; df=234; p<0.001) and females ($n_{medieval}$= 83; $n_{post\text{-}medieval}$= 92; t= -4.439; df=173; p<0.001) (Fig. 5.37). Figures 5.38 and 5.39 present the distribution of BMI categories in each time period.

Figure 5.37 Mean body mass index (FHD) by time period



**significant at p<0.01

Figure 5.38 Distribution of BMI categories (FHD) in the medieval period

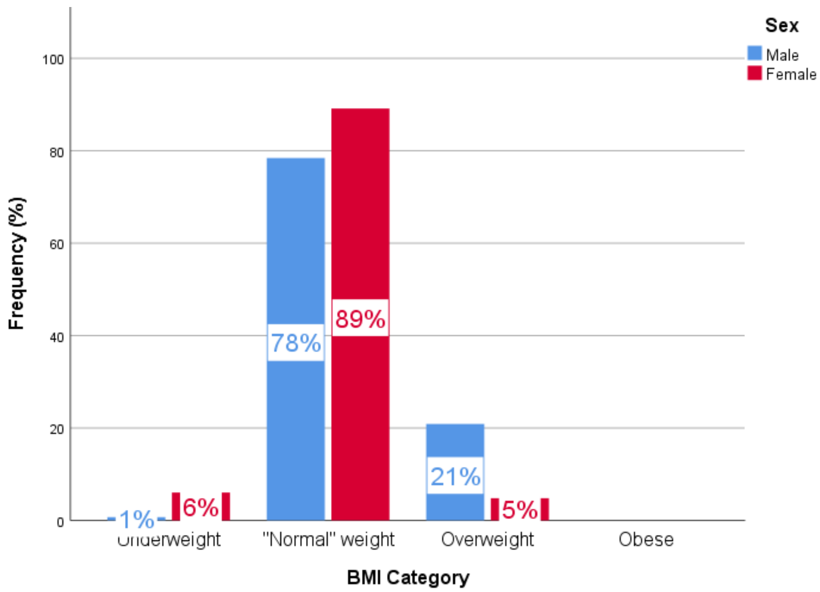
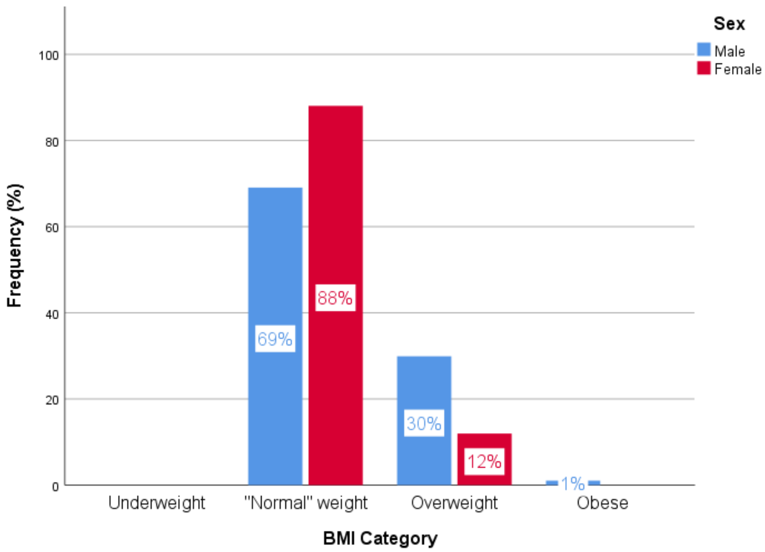


Figure 5.39 Distribution of BMI categories (FHD) in the post-medieval period



5.4.3 Indulgence-Related Disorders and Degeneration

The results indicate a minor increase in indulgence-related disorders between the medieval and post-medieval periods, although no significant differences were noted for any indulgence-related disorder in either sex or when the sexes were combined. Chi-square tests (χ^2) were used to assess differences in indulgence-related disorders (DISH, gout, and plantar calcaneal spurs) between the time periods. Figures 5.40 through 5.43 present the frequency of indulgence-related disorders, as well as dorsal calcaneal spurs, by time period.

Figure 5.40 Distribution of DISH by time period

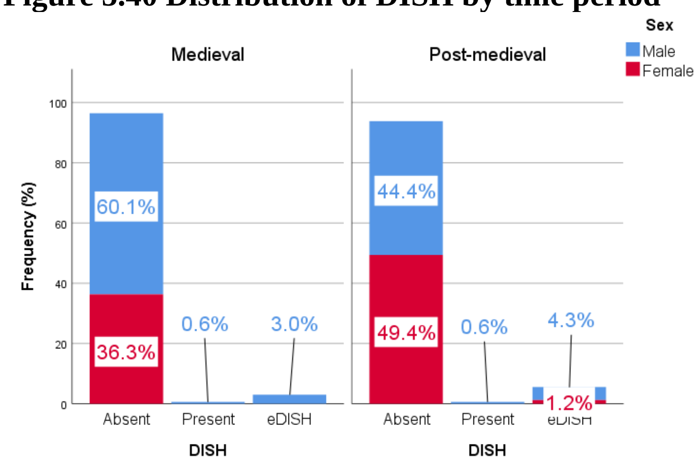


Figure 5.41 Distribution of gout by time period

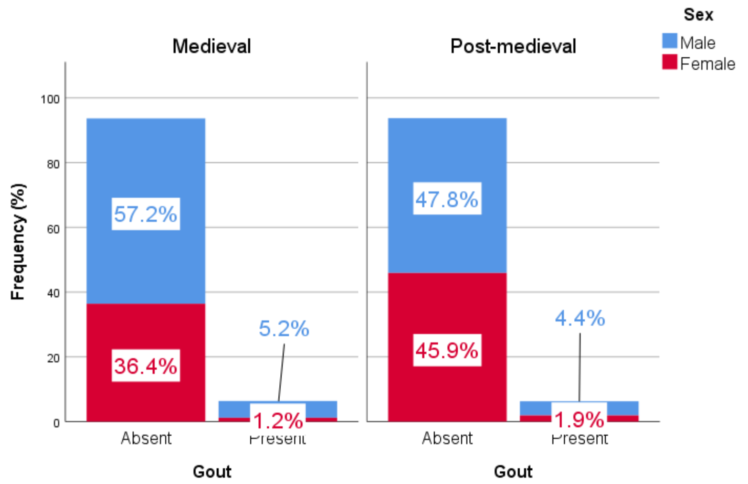


Figure 5.42 Distribution of plantar calcaneal spurs by time period

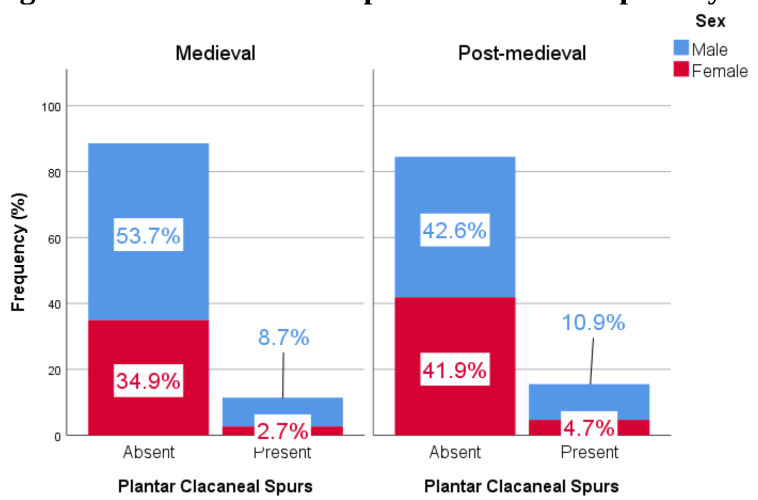
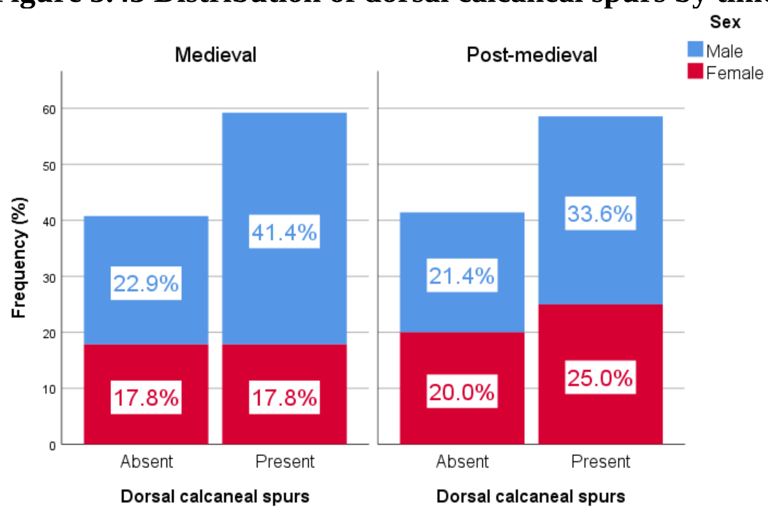


Figure 5.43 Distribution of dorsal calcaneal spurs by time period



In general, an increase in the frequency of degenerative joint disease was seen from the medieval to the post-medieval period. Tables 5.8 and 5.9 present the frequencies of knee osteoarthritis and severity in males. Figures 5.44 through 5.46 illustrate the distribution of degenerative joint disease by time period. A comparison of degenerative joint disease in the weight bearing joints between the medieval and post-medieval periods was undertaken using chi-square tests (χ^2). No significant differences in the frequency of degenerative joint disease was noted in any weight-bearing joint with the exception of osteoarthritis in the knee for males (χ^2=6.341; df=1; p=0.017), specifically the frequency of moderate osteoarthritis (χ^2=6.185; df=3; p=0.021).

Table 5.8 Frequency of knee osteoarthritis between the medieval and post-medieval period in males

Time Period		Knee OA		Total
		Absent	Present	
Medieval	Count – N (%)	155 (99.4)	1 (0.6)	156
	Standardized residuals	0.3	-1.6	
Post-medieval	Count – N (%)	97 (94.2)	6 (5.8)	103
	Standardized residuals	-0.3	1.9	
Total	Count	252	7	259

Table 5.9 Frequency of knee osteoarthritis severity between the medieval and post-medieval period in males

Time Period		Knee OA				Total
		Absent	Slight	Moderate	Severe	
Medieval	Count – N (%)	155 (99.4)	0 (0)	1 (0.6)	0 (0)	156
	Stand. residuals	3.2	-0.6	-2.0	-0.6	
Post-medieval	Count – N (%)	97 (94.2)	1 (1.0)	4 (3.9)	1 (1.0)	103
	Stand. residuals	-3.2	0.6	2.0	0.6	
Total	Count	252	1	5	1	259

Figure 5.44 Distribution of degenerative joint disease in the hips by time period

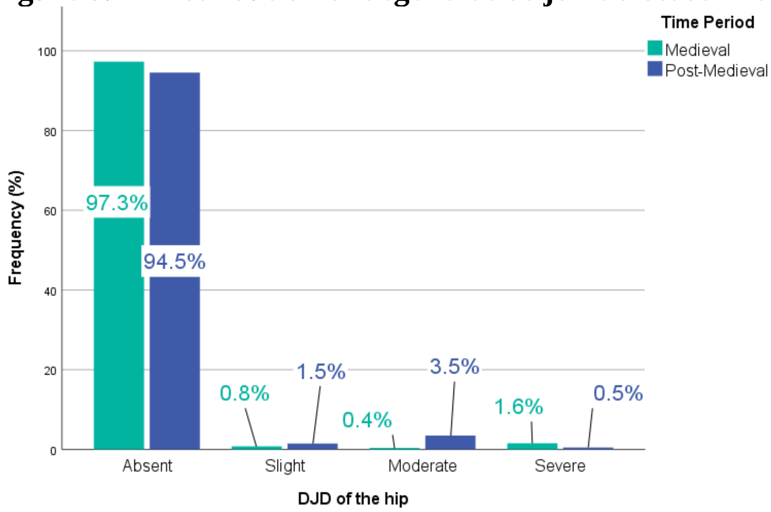


Figure 5.45 Distribution of degenerative joint disease in the knees by time period

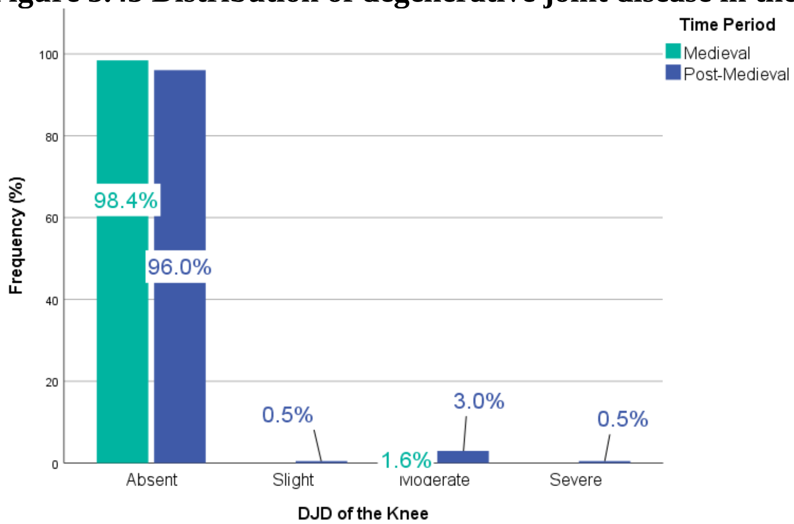
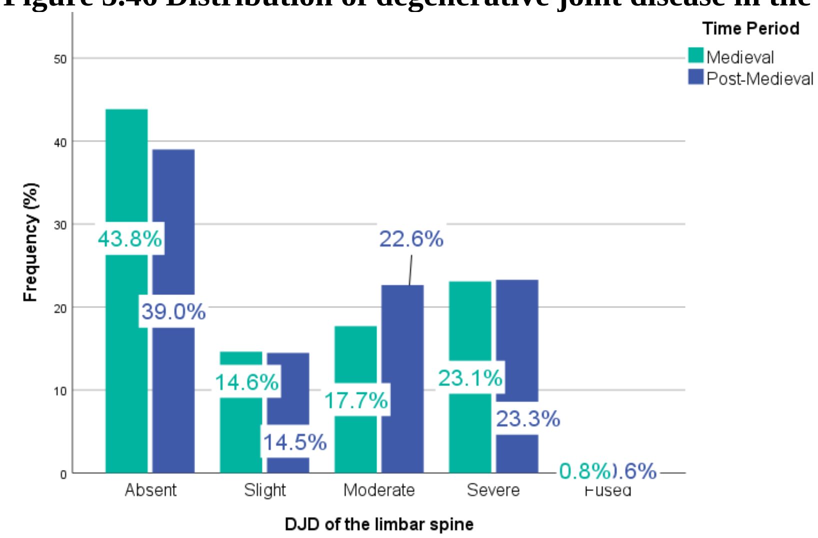


Figure 5.46 Distribution of degenerative joint disease in the lumbar spine by time period



5.4.4 Degenerative Disorders - Osteoporosis

When analyzed using the fourth lumbar vertebrae, the prevalence of osteoporosis is slightly higher in the medieval period however the severity is still greater in the post-medieval period. Figures 5.47 and 5.48 illustrate the distribution of trabecular bone loss by time period. The frequency of osteoporosis in the femoral neck was higher in the post-medieval period as was the severity. The frequency of trabecular bone loss and osteoporosis in the femoral neck and fourth lumbar vertebrae was compared by time period using chi-square tests (χ^2). The results were not significantly different for any comparison.

Fracture frequency rates remain relatively constant between the medieval and post-medieval periods for all fractures in males and females. Figures 5.49 through 5.54 illustrate the frequency of osteoporotic fractures by time period.

Figure 5.47 Trabecular bone classification in the femoral neck by time period

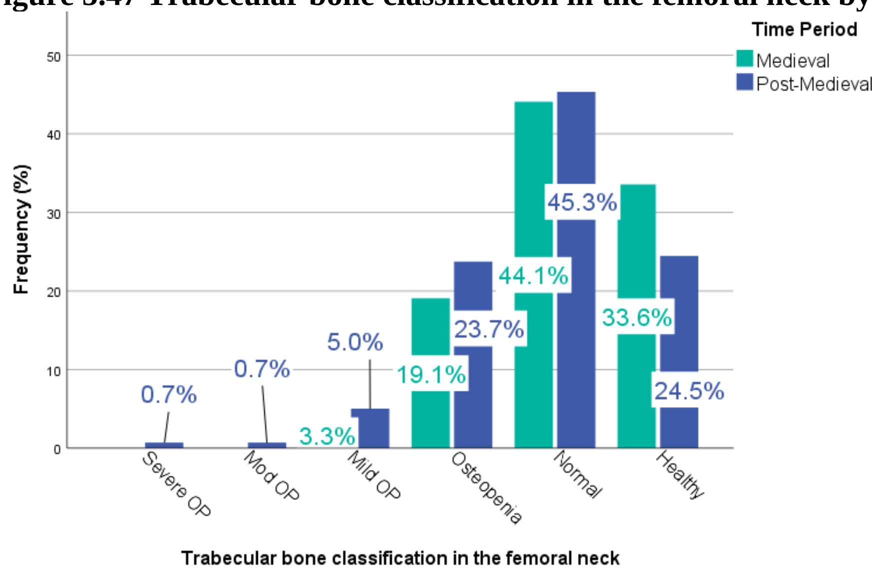


Figure 5.48 Trabecular bone in the fourth lumbar vertebra classification by time period

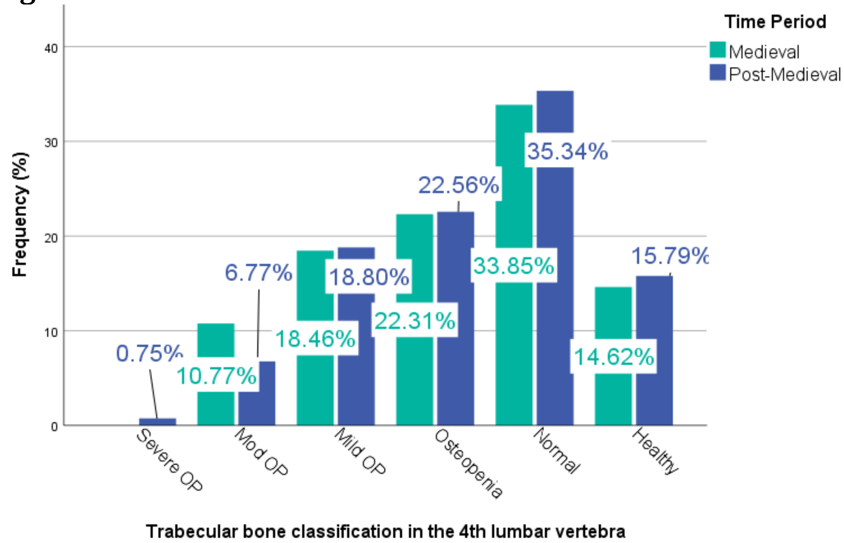


Figure 5.49 Femoral neck fracture frequency by time period

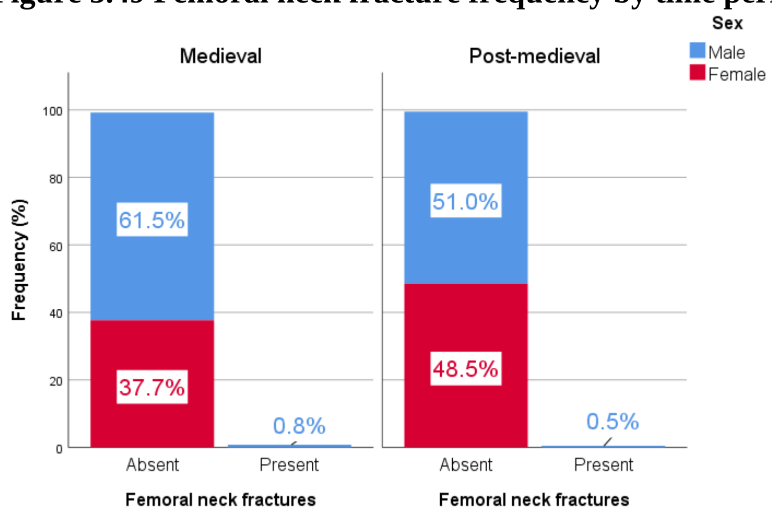


Figure 5.50 Colles' fracture frequency by time period

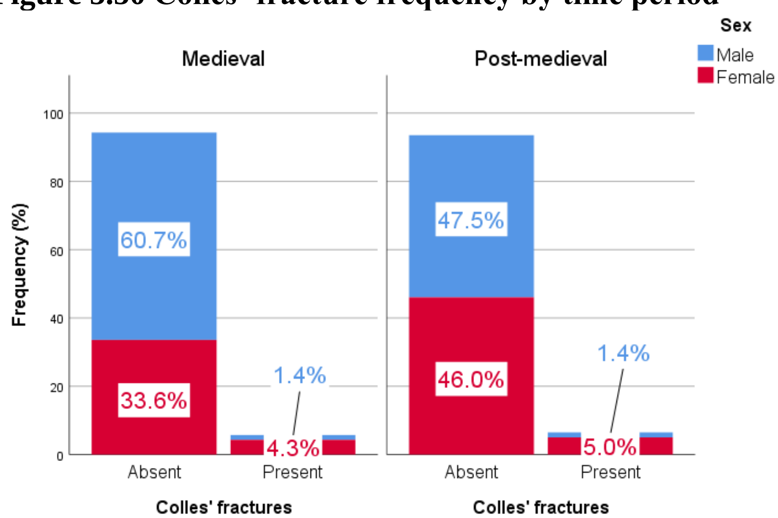
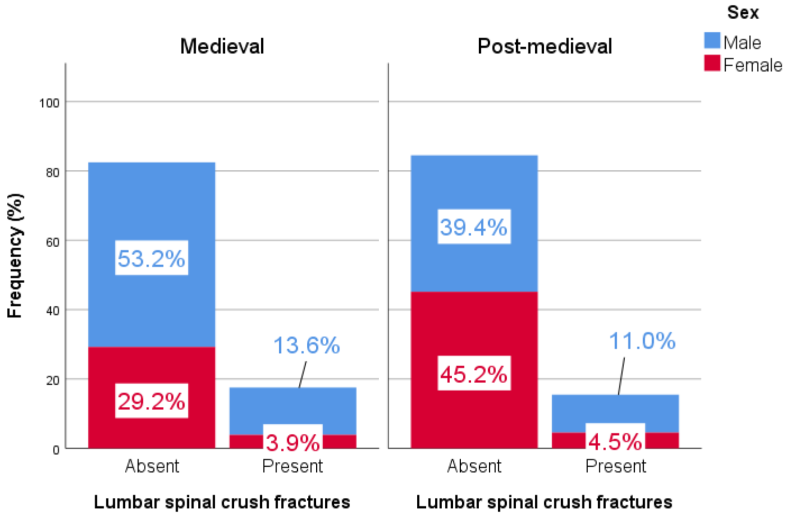


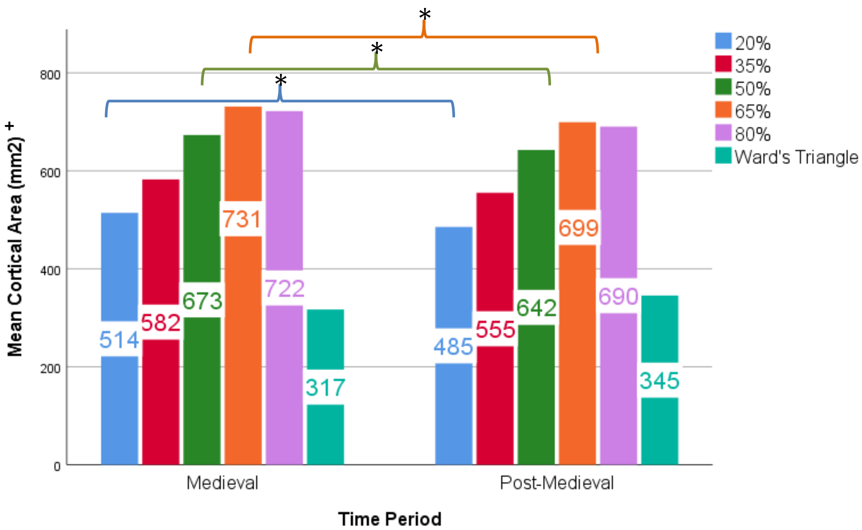
Figure 5.51 Lumbar crush fracture frequency by time period



5.4.5 Biomechanics

In general, a maintenance in strength and rigidity with decreases for certain variables is noted for males between the medieval and post-medieval periods. In females an increase in femoral robusticity is noted between time periods. At Ward's triangle, however, a marked increase in strength and rigidity is noted in the post-medieval period in both sexes. Independent samples t-tests were used to compare temporal differences in means for biomechanical properties (CA, TA, %CA, I_{min}, I_{max}, J, Z_{max}, Z_{min}, Z_p, average cortical thickness, and I_{max}/I_{min}) at designated slices along the femoral shaft and neck (20%, 35%, 50%, 65%, 80%, and Ward's triangle). The following results were significant at the 95% confidence interval for males ($n_{medieval}$= 78; $n_{post-medieval}$= 53): cortical area at 20% (t=2.087; df=129; p=0.039), percent cortical area at 20% (t=2.395; df =129; p=0.018), cortical area at 50% (t=2.171; df =129; p=0.032), total area at 50% (t=2.150; df =129; p=0.033), cortical area at 65% (t=2.284; df =129; p=0.024), total area at 65% (t=1.957; df =127.945; p=0.041), I_{max}/I_{min} at 80% (t=2.411; df = 129; p=0.017); total area at Ward's triangle (t=-2.070; df =92.352; p=0.032), minimum second moment of area at Ward's triangle (t=-2.737; df =71.068; p=0.008), maximum second moment of area at Ward's triangle (t=-2.329; df =69.867; p=0.021), polar second moment of area at Ward's triangle (t=-2.528; df=124; p=0.013), maximum section modulus at Ward's triangle (t=-2.362; df =124; p=0.020), minimum section modulus at Ward's triangle (t=-3.019; df =124; p=0.003), polar section modulus at Ward's triangle (t=-2.431; df =72.182; p=0.018) and I_{max}/I_{min} at Ward's triangle (t=2.048; df = 124; p=0.043). Female femoral size and strength tend to increase from the medieval (n=34) to post-medieval period (n=47), with percent cortical area at 20% (t=2.067; df =79; p=0.042), minimum second moment of area at 20% (t=-2.632; df=79; p=0.010), maximum second moment of area at 20% (t=-2.098; df=79; p=0.039), polar second moment of area at 20% (t=-2.411; df=79; p=0.018), polar section modulus at 20% (t=-2.034; df=79; p=0.045), minimum second moment of area at 35% (t=-2.040; df=79; p=0.045), minimum second moment of area at 50% (t=-1.993; df=79; p=0.050), minimum second moment of area at 65% (t=-2.130; df =79; p=0.036), total area at 80% (t=-2.827; df =63.685; p=0.006), minimum second moment of area at 80% (t=-3.218; df =71.816; p=0.002), maximum second moment of area at 80% (t=-3.482; df =61.383; p=0.001), polar second moment of area at 80% (t=-3.582; df=64.595; p=0.001), maximum section modulus at 80% (t=-3.134; df =68.765; p=0.003), minimum section modulus at 80% (t=-2.0.94; df =79; p=0.039), polar section modulus at 80% (t=-2.977; df =74.434; p=0.004), and minimum second moment of area at Ward's triangle (t=-2.022; df =56.242; p=0.048) meeting significance standards at a 95% confidence interval. Figures 5.52 through 5.67 illustrate the relevant size-standardized biomechanical results by time period.

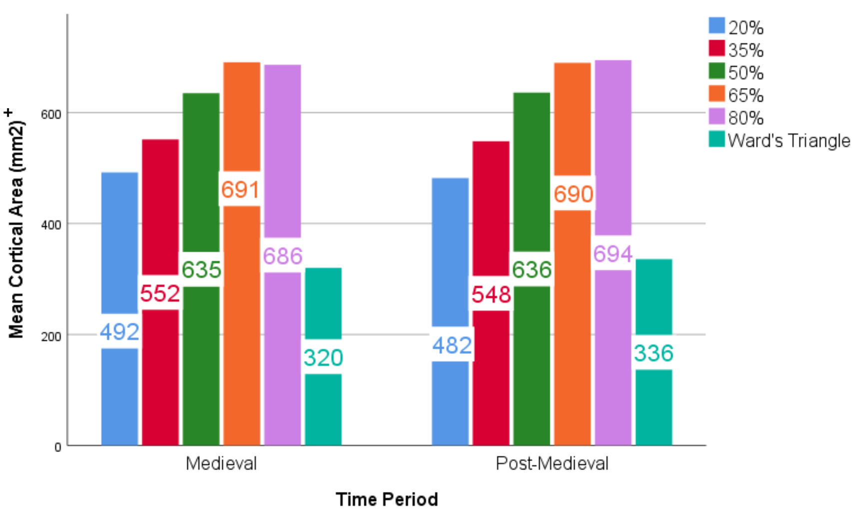
Figure 5.52 Mean cortical area by time period for males



*significant at p<0.05

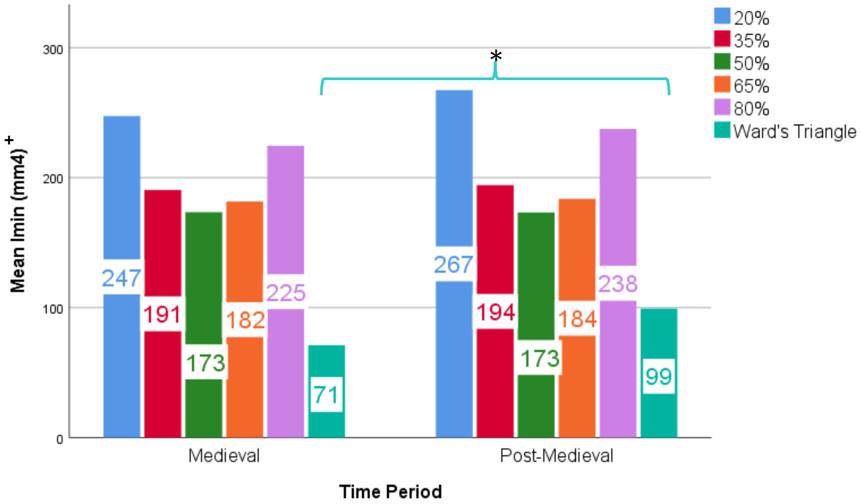
+CA values except are size- standardized; $CA_{STD} = CA/BM$

Figure 5.53 Mean cortical area by time period for females



+CA values except are size- standardized; $CA_{STD} = CA/BM$

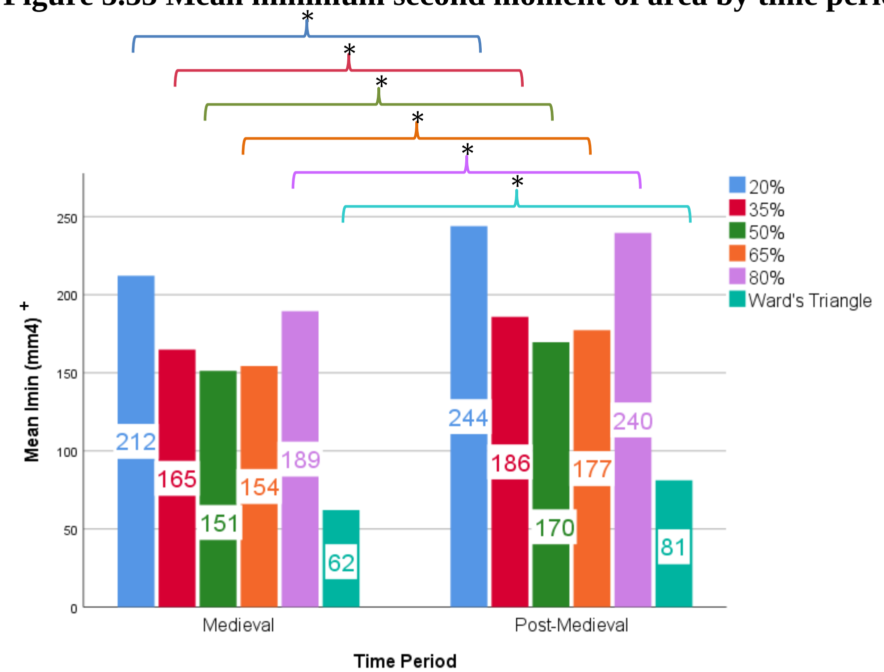
Figure 5.54 Mean minimum second moment of area by time period for males



*significant at $p<0.05$

+ I_{min} values are size-standardized: $I_{minSTD} = I_{min}/(BM*Fem\ Length^2)$

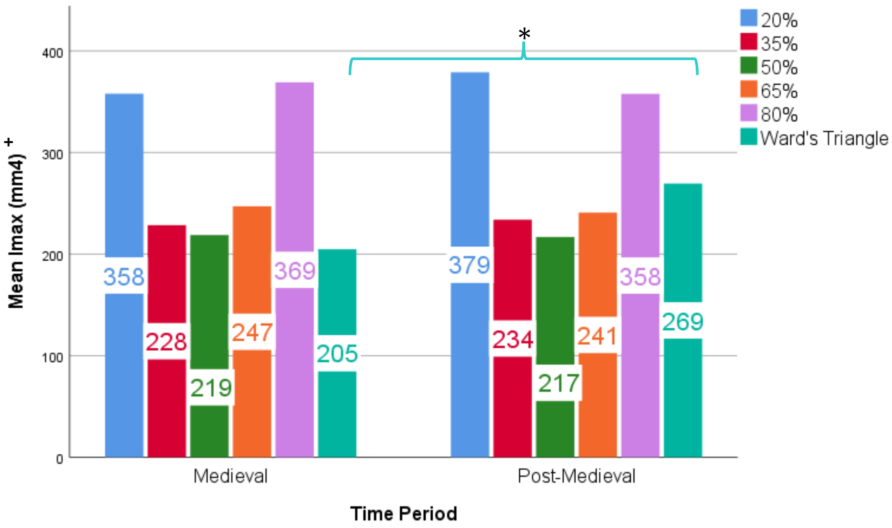
Figure 5.55 Mean minimum second moment of area by time period for females



*significant at $p<0.05$

+ I_{min} values are size-standardized: $I_{minSTD} = I_{min}/(BM*Fem\ Length^2)$

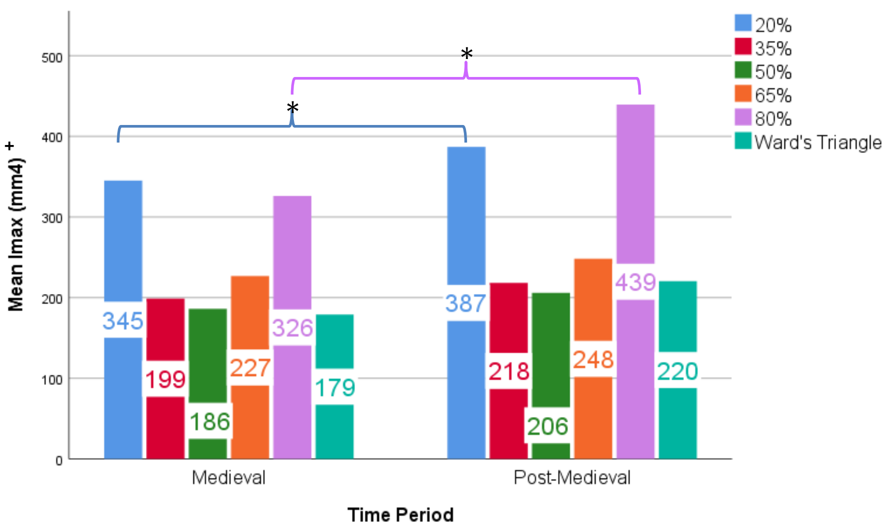
Figure 5.56 Mean maximum second moment of area by time period for males



*significant at $p<0.05$

+ I_{max} values are size-standardized: $I_{maxSTD} = I_{max}/(BM*Fem\ Length^2)$

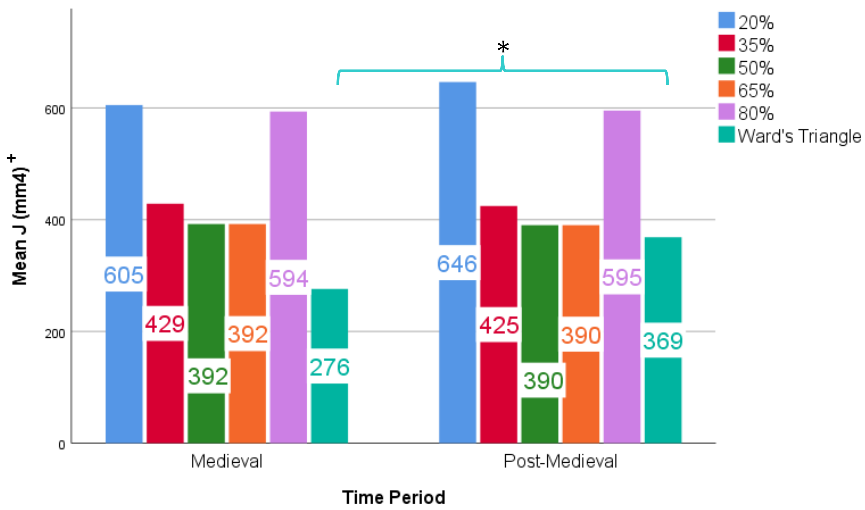
Figure 5.57 Mean maximum second moment of area by time period for females



*significant at $p<0.05$

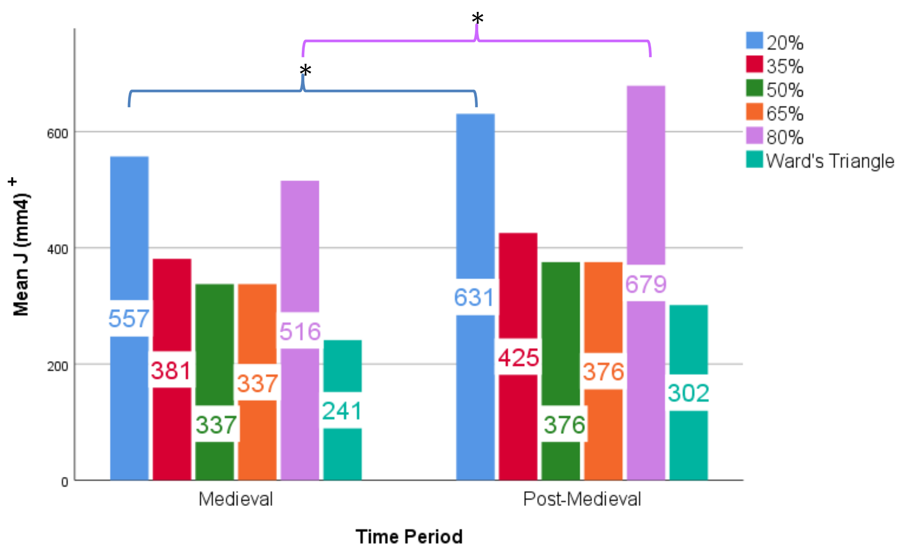
+ I_{max} values are size-standardized: $I_{maxSTD} = I_{max}/(BM*Fem\ Length^2)$

Figure 5.58 Mean polar second moment of area by time period for males



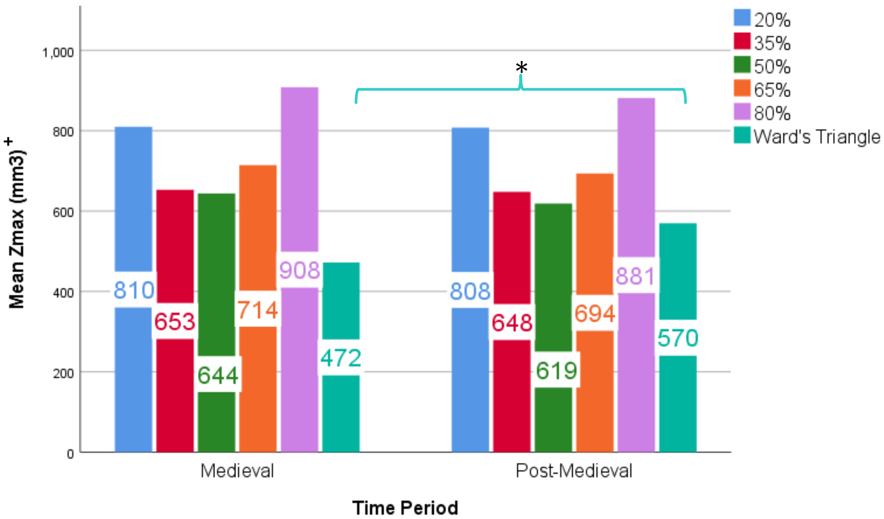
*significant at $p<0.05$
+ J values are size-standardized: $J_{STD} = J/(BM*Fem\ Length^2)$

Figure 5.59 Mean maximum second moment of area by time period for females



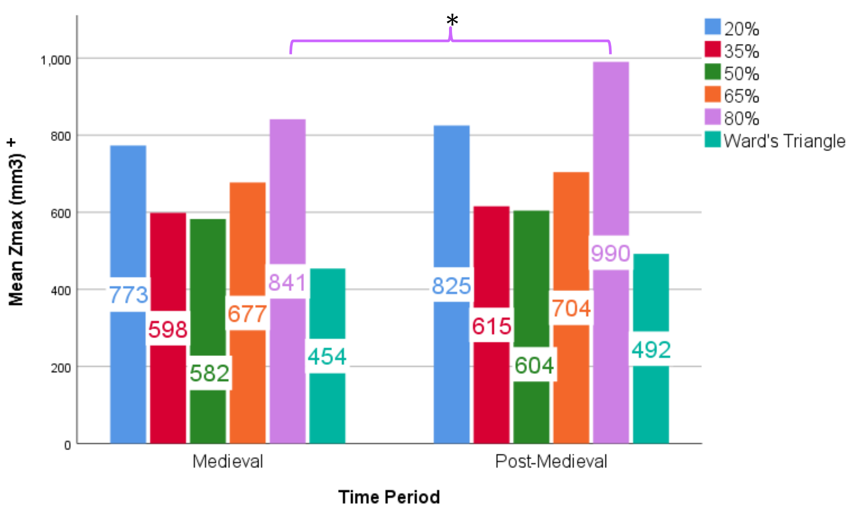
*significant at $p<0.05$
+ J values are size-standardized: $J_{STD} = J/(BM*Fem\ Length^2)$

Figure 5.60 Mean maximum section modulus by time period for males



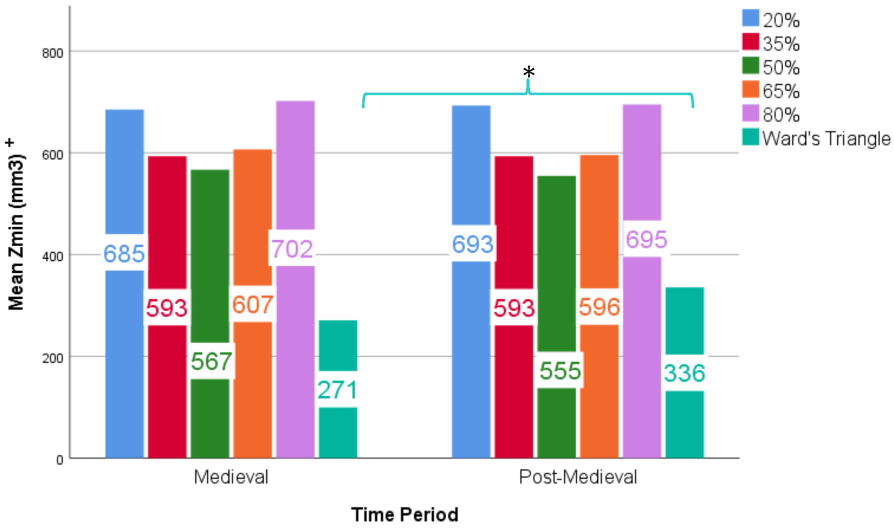
*significant at p<0.05
+ Z_{max} values are size-standardized: $Z_{maxSTD} = Z_{max}/(BM*Fem\ Length)$

Figure 5.61 Mean maximum section modulus by time period for females



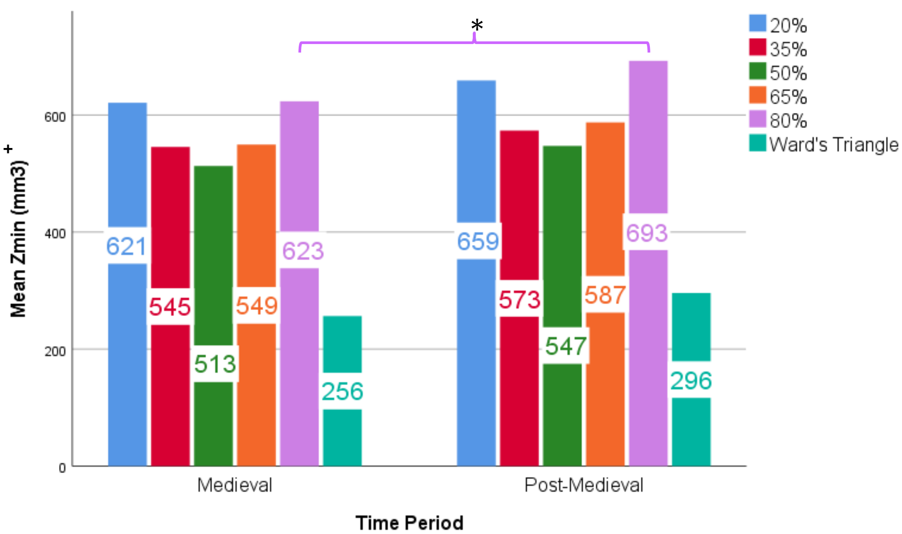
*significant at p<0.05
+ Z_{max} values are size-standardized: $Z_{maxSTD} = Z_{max}/(BM*Fem\ Length)$

Figure 5.62 Mean minimum section modulus by time period for males



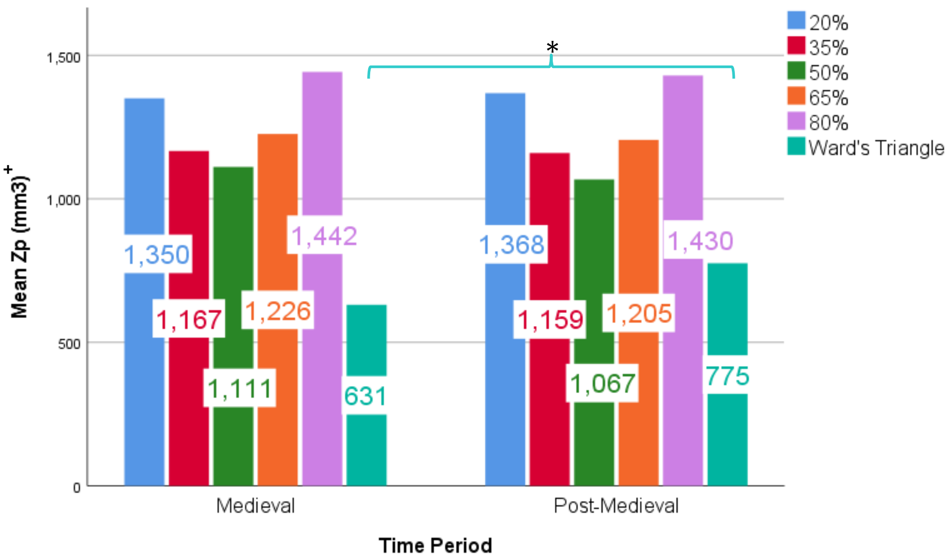
*significant at $p<0.05$
+ Z_{min} values are size-standardized: $Z_{minSTD} = Z_{min}/(BM*Fem\ Length)$

Figure 5.63 Mean minimum section modulus by time period for females



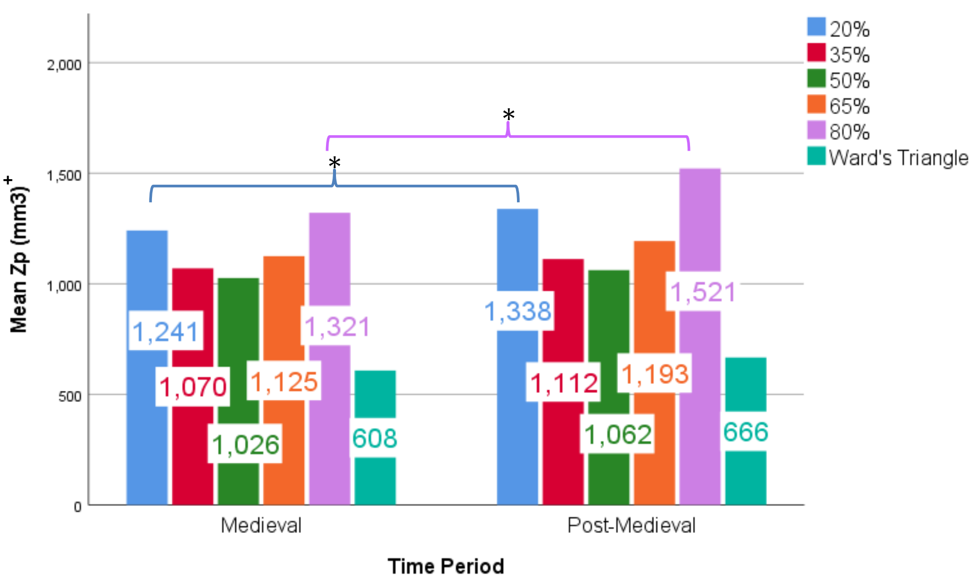
*significant at $p<0.05$
+ Z_{min} values are size-standardized: $Z_{minSTD} = Z_{min}/(BM*Fem\ Length)$

Figure 5.64 Mean polar section modulus by time period for males



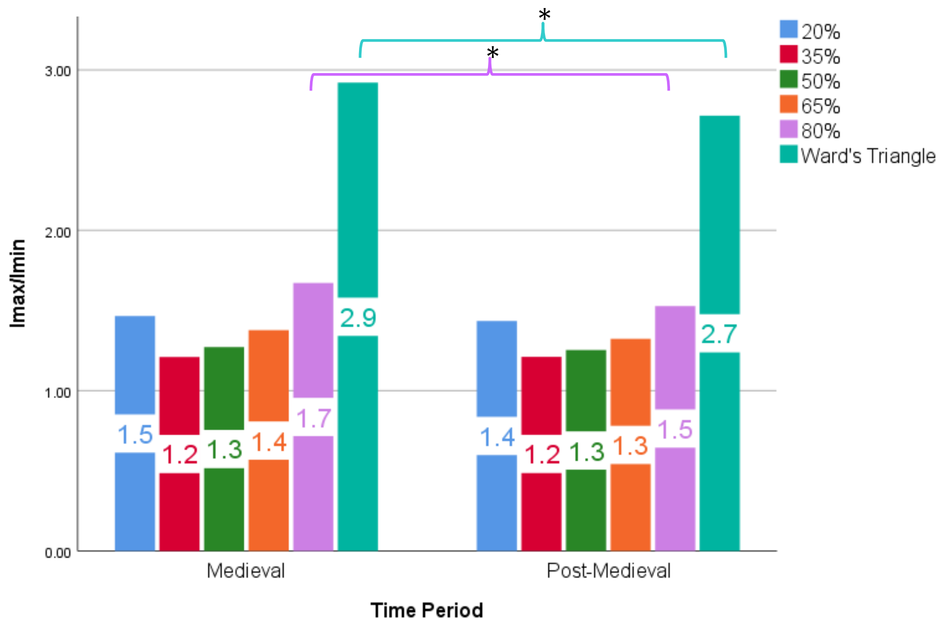
*significant at p<0.05
+ Z_p values are size-standardized: $Z_{pSTD} = Z_p/(BM*Fem\ Length)$

Figure 5.65 Mean polar section modulus by time period for females



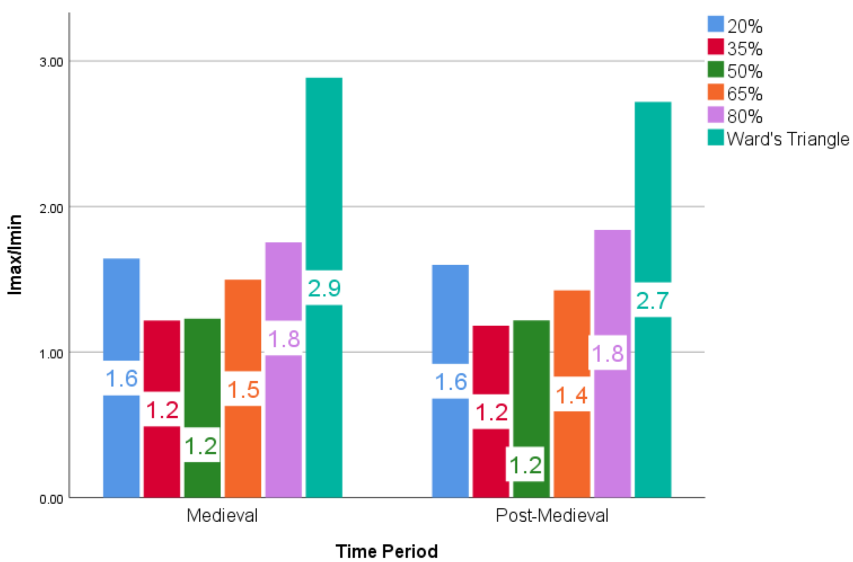
*significant at p<0.05
+ Z_p values are size-standardized: $Z_{pSTD} = Z_p/(BM*Fem\ Length)$

Figure 5.66 Mean shape ratio (I_{max}/I_{min}) by time period for males



*significant at $p<0.05$

Figure 5.67 Mean shape ratio (I_{max}/I_{min}) by time period for females



5.5 Age-related Changes

Older individuals were expected be healthier than younger individuals but present more non-life-threatening degeneration (Hypothesis 3). Individuals that died in older age categories were expected to be taller and lighter than those who died young. However, older individuals would present more instances of indulgence-related disorders and degeneration in the weight bearing joints as well as more osteoporosis. Individuals who died in older age categories will present smaller, weaker bones but fewer osteoporotic fractures than those who died in younger age-categories. The following results pertain to hypothesis 3.

5.5.1 Stature

Significant differences were found in mean stature (F=2.758; df = 3; p=0.043) by age category among males ($n_{<30}$ = 109; $n_{30\text{-}50}$= 101; $n_{50\text{-}70}$= 10; $n_{>70}$= 20) (Table 5.10). No significant age-related differences in femoral length or stature existed among females. Mean stature and mean femoral length were compared by age category (<30, 30-50, 50-70, and >70 years-at-death) using one-way ANOVAs.

Table 5.10 Comparison of mean stature (cm) by age category for males

Age Category	Age Category	Mean Δ	p-value
<30	30-50	1.242	0.184
	50-70	-4.133	0.065
	>70	2.462	0.127
30-50	50-70	-5.374	0.017*
	>70	1.220	0.452
50-70	>70	6.594	0.012*

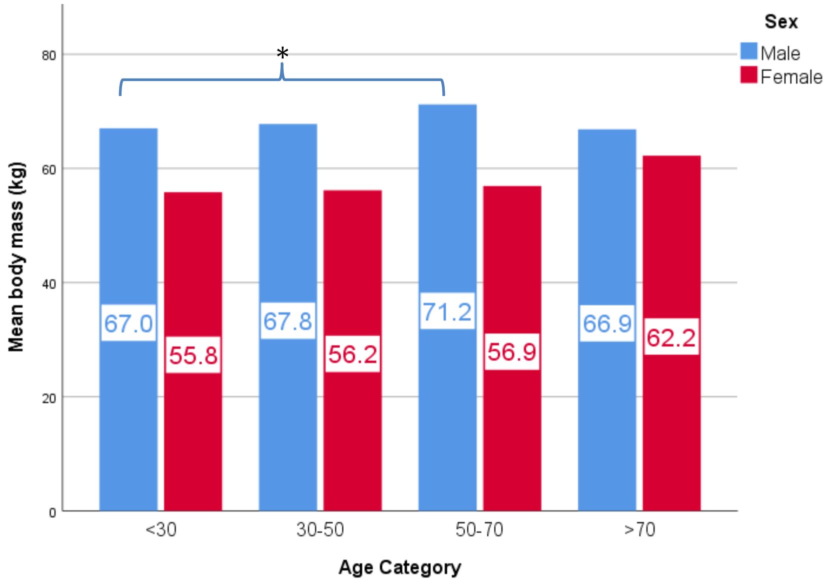
*significant at a 95% confidence interval

5.5.2 Body Mass

No significant differences in mean body mass were noted between the age categories for either sex when using the bi-iliac breadth body mass estimation method (Fig. 5.68). A significant increase in body mass was noted for males between the <30 (n= 103) and 50-70 (n= 9) years-at-death age categories (p=0.045) when body mass was calculated using femoral head diameter.

Neither sex presented age-related differences in BMI using either bi-iliac breadth or femoral head diameter to estimate body mass.

Figure 5.68 Mean body mass (FHD) by age category



*significant at p<0.05

5.5.3 Indulgence-Related Disorders and Degeneration

No significant differences were seen for any indulgence-related disorder with the exception of DISH in males (χ^2=8.859; df=3; p=0.020) and when the sexes were combined (χ^2=17.651; df=3; p=0.003), as well as combined indulgence-related disorders in males (χ^2=11.825; df=3; p=0.005) and when sexes were combined (χ^2=44.125; df=3; p<0.001). Significant differences in dorsal calcaneal spurs with age were also noted in males (χ^2=25.617; df=3; p<0.001) and when sexes were combined (χ^2=18.931; df= 3; p<0.001). The frequency of DISH and combined indulgence-related disorders are presented in Tables 5.11 through 5.16.

Table 5.11 Frequency of DISH between age categories in males

Age category		DISH		Total
		Absent	Present/eDISH	
<30	Count – N (%)	78 (97.5)	2 (2.5)	80
	Standardized residuals	0.5	-1.7	
30-50	Count – N (%)	73 (90.1)	8 (9.9)	81
	Standardized residuals	-0.2	0.7	
50-70	Count – N (%)	7 (87.5)	1 (12.5)	8
	Standardized residuals	-0.1	0.5	
>70	Count – N (%)	9 (75.0)	3 (25.0)	12
	Standardized residuals	-0.6	2.2	
Total	Count	167	14	181

Table 5.12 Frequency of DISH between age categories when sexes are combined

Age category		DISH		Total
		Absent	Present/eDISH	
<30	Count – N (%)	149 (98.7)	2 (1.3)	151
	Standardized residuals	0.5	-2.0	
30-50	Count – N (%)	128 (92.8)	10 (7.2)	138
	Standardized residuals	-0.3	1.2	
50-70	Count – N (%)	18 (94.7)	1 (5.3)	19
	Standardized residuals	0.0	0.1	
>70	Count – N (%)	10 (76.9)	3 (23.1)	13
	Standardized residuals	-0.7	2.9	
Total	Count	305	16	321

Table 5.13 Frequency of combined indulgence-related disorders between age categories in males

Age category		Indulgence-related disorders		Total
		Absent	Present	
<30	Count – N (%)	43 (78.2)	12 (21.8)	55
	Standardized residuals	1.5	-1.9	
30-50	Count – N (%)	29 (52.7)	26	55
	Standardized residuals	-0.9	1.1	
50-70	Count – N (%)	3 (50.0)	3 (50.0)	6
	Standardized residuals	-0.4	0.5	
>70	Count – N (%)	4 (36.4)	7 (63.6)	11
	Standardized residuals	-1.1	1.4	
Total	Count	79	48	127

Table 5.14 Frequency of combined indulgence-related disorders between age categories when sexes are combined

Age category		Indulgence-related disorders		Total
		Absent	Present	
<30	Count – N (%)	75 (81.5)	17 (18.5)	92
	Standardized residuals	1.3	-2.0	
30-50	Count – N (%)	59 (62.1)	36 (37.9)	95
	Standardized residuals	-0.9	1.4	
50-70	Count – N (%)	8 (72.7)	3 (27.3)	11
	Standardized residuals	0.1	-0.2	
>70	Count – N (%)	4 (36.4)	7 (63.6)	11
	Standardized residuals	-1.3	2.0	
Total	Count	146	63	209

Table 5.15 Frequency of dorsal calcaneal spurs between age categories in males

Age category		Dorsal Calcaneal Spurs		Total
		Absent	Present	
<30	Count – N (%)	42 (60.9)	27 (39.1)	69
	Standardized residuals	3.0	-2.4	
30-50	Count – N (%)	15 (20.8)	57 (79.2)	72
	Standardized residuals	-2.4	1.9	
50-70	Count – N (%)	2 (28.6)	5 (71.4)	7
	Standardized residuals	-0.4	0.3	
>70	Count – N (%)	4 (25.0)	12 (75.0)	16
	Standardized residuals	-0.9	0.7	
Total	Count	63	101	164

Table 5.16 Frequency of dorsal calcaneal spurs between age categories when sexes are combined

Age category		Dorsal Calcaneal Spurs		Total
		Absent	Present	
<30	Count – N (%)	68 (56.7)	52 (43.3)	120
	Standardized residuals	2.4	-2.1	
30-50	Count – N (%)	38 (31.7)	82 (68.3)	120
	Standardized residuals	-1.8	1.5	
50-70	Count – N (%)	5 (35.7)	9 (64.3)	14
	Standardized residuals	-0.4	0.3	
>70	Count – N (%)	4 (22.2)	14 (77.8)	18
	Standardized residuals	-1.3	1.1	
Total	Count	115	157	272

In general, an increase in degenerative joint disease frequency and severity exists with age, however a decrease is noted in the oldest old (>70 years-at-death) age category. When the sexes were combined, significant differences with age existed for degenerative joint disease of the hips (χ^2=13.513; df=3; p=0.003), the knees (χ^2=9.093; df=3; p=0.027), and the lumbar spine (χ^2=44.125; df=3; p<0.001). Age also significantly affected the frequency of any degenerative joint disease in the weight bearing joints (χ^2=42.753; df=3; p<0.001). When the sexes were analyzed separately degenerative joint disease in the hips (χ^2=11.346; df=3; p=0.017), the knees (χ^2=8.535; df=3; p=0.014), the lumbar spine (χ^2=22.1275; df=3; p<0.001), and when combined (χ^2=27.203; df=3; p<0.001) are significant in males; only combined degenerative joint disease (χ^2=18.327; df=3; p<0.001) and degenerative joint disease in the lumbar spine remain significant for females (χ^2=21.578; df=3; p<0.001). Frequencies for degenerative joint diseases are provided below in Tables 5.17 through 5.26.

Table 5.17 Frequency of degenerative joint disease in the hips between age categories when sexes are combined

Age category		**Hip OA**		**Total**
		Absent	**Present**	
<30	Count – N (%)	201 (99.0)	2 (1.0)	203
	Standardized residuals	0.5	-2.2	
30-50	Count – N (%)	167 (91.8)	15 (8.2)	182
	Standardized residuals	-0.6	2.7	
50-70	Count – N (%)	21 (95.5)	1 (4.5)	22
	Standardized residuals	0.0	0.1	
>70	Count – N (%)	21 (100)	0 (0)	21
	Standardized residuals	0.2	-0.9	
Total	Count	410	18	428

Table 5.18 Frequency of degenerative joint disease in the knees between age categories when sexes are combined

Age category		Knee OA		Total
		Absent	Present	
<30	Count – N (%)	189 (99.5)	1 (0.5)	190
	Standardized residuals	0.3	-1.7	
30-50	Count – N (%)	168 (96.0)	7 (4.0)	175
	Standardized residuals	-0.2	1.3	
50-70	Count – N (%)	21 (91.3)	2 (8.7)	23
	Standardized residuals	-0.3	1.9	
>70	Count – N (%)	23 (100)	0 (0)	23
	Standardized residuals	0.1	-0.7	
Total	Count	401	10	411

Table 5.19 Frequency of degenerative joint disease in the lumbar spine between age categories when sexes are combined

Age category		Lumbar VO		Total
		Absent	Present	
<30	Count – N (%)	78 (62.4)	47 (37.6)	125
	Standardized residuals	3.6	-3.1	
30-50	Count – N (%)	36 (26.9)	98 (73.1)	134
	Standardized residuals	-2.6	2.2	
50-70	Count – N (%)	1 (6.7)	14 (93.3)	15
	Standardized residuals	-2.1	1.8	
>70	Count – N (%)	3 (27.3)	8 (72.7)	11
	Standardized residuals	-0.7	0.6	
Total	Count	118	167	285

Table 5.20 Frequency of degenerative joint disease in the weight-bearing joints between age categories when sexes are combined

Age category		DJD combined		Total
		Absent	Present	
<30	Count – N (%)	67 (57.8)	49 (42.2)	116
	Standardized residuals	3.9	-2.9	
30-50	Count – N (%)	30 (22.1)	106 (77.9)	136
	Standardized residuals	-2.7	2.0	
50-70	Count – N (%)	0 (0)	15 (100)	15
	Standardized residuals	-2.3	1.7	
>70	Count – N (%)	3 (27.3)	8 (72.7)	11
	Standardized residuals	-0.5	0.4	
Total	Count	100	178	278

Table 5.21 Frequency of degenerative joint disease in the hips between age categories for males

Age category		Hip OA		Total
		Absent	Present	
<30	Count – N (%)	114 (98.3)	2 (1.7)	116
	Standardized residuals	0.4	-1.7	
30-50	Count – N (%)	96 (88.9)	12 (11.1)	108
	Standardized residuals	-0.6	2.5	
50-70	Count – N (%)	9 (100)	0 (0)	9
	Standardized residuals	0.2	-0.7	
>70	Count – N (%)	20 (100)	0 (0)	20
	Standardized residuals	0.3	-1.1	
Total	Count	239	14	253

Table 5.22 Frequency of degenerative joint disease in the knee between age categories for males

Age category		Knee OA		Total
		Absent	Present	
<30	Count – N (%)	105 (100)	0 (0)	105
	Standardized residuals	0.3	-1.8	
30-50	Count – N (%)	97 (93.2)	6 (5.8)	103
	Standardized residuals	-0.3	1.7	
50-70	Count – N (%)	9 (90.0)	1 (10.0)	10
	Standardized residuals	-0.2	1.3	
>70	Count – N (%)	20 (100)	0 (0)	20
	Standardized residuals	0.1	-0.8	
Total	Count	231	7	238

Table 5.23 Frequency of degenerative joint disease in the lumbar spine between age categories for males

Age category		Lumbar VO		Total
		Absent	Present	
<30	Count – N (%)	41 (61.2)	26 (38.8)	67
	Standardized residuals	2.8	-2.3	
30-50	Count – N (%)	20 (24.4)	62 (75.6)	82
	Standardized residuals	-2.2	1.8	
50-70	Count – N (%)	1 (20.0)	4 (80.0)	5
	Standardized residuals	-0.7	0.6	
>70	Count – N (%)	3 (30.0)	7 (70.0)	10
	Standardized residuals	-0.5	0.4	
Total	Count	65	99	164

Table 5.24 Frequency of degenerative joint disease in the lumbar spine between age categories for females

Age category		Lumbar VO		Total
		Absent	Present	
<30	Count – N (%)	37 (63.8)	21 (36.2)	58
	Standardized residuals	2.3	-2.0	
30-50	Count – N (%)	16 (30.8)	36 (69.2)	52
	Standardized residuals	-1.4	1.3	
50-70	Count – N (%)	0 (0)	10 (100)	10
	Standardized residuals	-2.1	1.8	
>70	Count – N (%)	0 (0)	1 (100)	1
	Standardized residuals	-0.7	0.6	
Total	Count	53	68	121

Table 5.25 Frequency of degenerative joint disease in the weight-bearing joints between age categories for males

Age category		DJD combined		Total
		Absent	Present	
<30	Count – N (%)	37 (56.9)	28 (43.1)	65
	Standardized residuals	3.2	-2.3	
30-50	Count – N (%)	15 (17.9)	69 (82.1)	84
	Standardized residuals	-2.5	1.8	
50-70	Count – N (%)	0 (0)	4 (100)	4
	Standardized residuals	-1.2	0.8	
>70	Count – N (%)	3 (30.0)	7 (70.0)	10
	Standardized residuals	-0.2	0.1	
Total	Count	55	108	163

Table 5.26 Frequency of degenerative joint disease in the weight-bearing joints between age categories for females

Age category		DJD combined		Total
		Absent	Present	
<30	Count – N (%)	30 (58.8)	21 (41.2)	51
	Standardized residuals	2.2	-1.8	
30-50	Count – N (%)	15 (28.8)	37 (71.2)	52
	Standardized residuals	-1.2	1.0	
50-70	Count – N (%)	0 (0)	11 (100)	11
	Standardized residuals	-2.1	1.7	
>70	Count – N (%)	0 (0)	1 (100)	1
	Standardized residuals	-0.6	0.5	
Total	Count	45	70	115

5.5.4 Degenerative Disorders - Osteoporosis

In general, an increase in the loss of trabecular bone is seen with age. Statistically significant differences were observed in the frequency of osteoporosis in the fourth lumbar vertebrae for females (χ^2=12.995; df=3; p=0.002) and when sexes were combined (χ^2=12.841; df=3; p=0.004), as presented in Tables 5.27 and 5.28. There is also a significant increase in the severity of trabecular bone loss in the fourth lumbar vertebrae in females (χ^2=30.795; df=15; p=0.003) and the femoral neck in males (χ^2=32.744.841; df=12; p<0.001), as presented in Tables 5.29 and 5.30. Figures 5.69 and 5.70 illustrate the age-related changes in the severity of trabecular bone loss in the femoral neck and fourth lumbar vertebrae respectively. Age-related changes in the frequency of osteoporotic fracturing were not statistically significant.

Table 5.27 Frequency of osteoporosis in the fourth lumbar vertebra by age category in females

Age category		OP in the 4th Lumbar Vertebra		Total
		Absent	Present	
<30	Count – N (%)	43 (81.1)	10 (18.9)	53
	Standardized residuals	1.1	-1.6	
30-50	Count – N (%)	31 (63.3)	18 (36.7)	49
	Standardized residuals	-0.4	0.6	
50-70	Count – N (%)	2 (25.0)	6 (75.0)	8
	Standardized residuals	-1.5	2.2	
>70	Count – N (%)	0 (0)	1 (100)	1
	Standardized residuals	-0.8	1.2	
Total	Count	76	35	111

Table 5.28 Frequency of osteoporosis in the fourth lumbar vertebra when sexes are combined

Age category		OP in the 4th Lumbar Vertebra		Total
		Absent	Present	
<30	Count – N (%)	92 (80.0)	23 (20.0)	115
	Standardized residuals	1.0	-1.6	
30-50	Count – N (%)	86 (69.4)	38 (30.6)	124
	Standardized residuals	-0.4	0.6	
50-70	Count – N (%)	5 (35.7)	9 (64.3)	14
	Standardized residuals	-1.6	2.6	
>70	Count – N (%)	5 (62.5)	3 (37.5)	8
	Standardized residuals	-0.3	0.5	
Total	Count	188	73	261

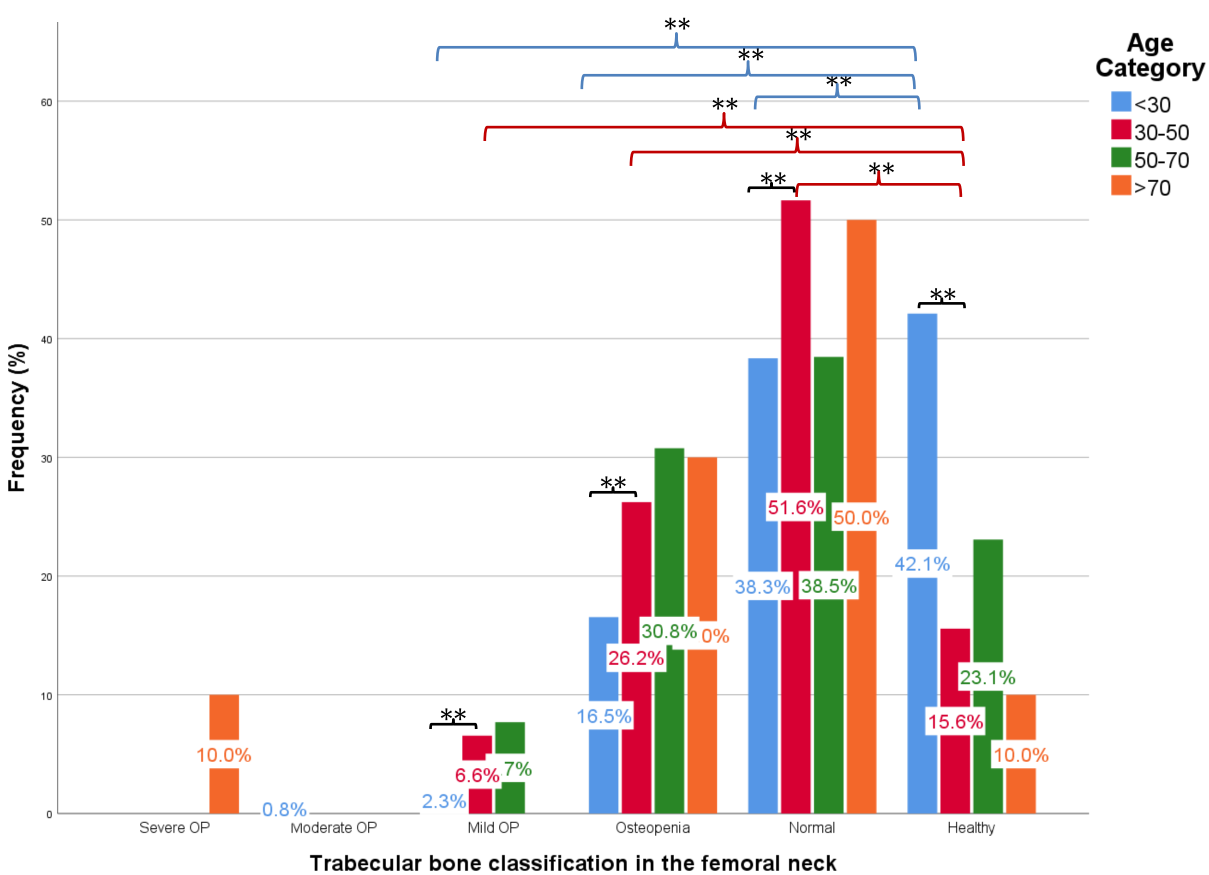
Table 5.29 Frequency of trabecular bone loss severity in the fourth lumbar vertebra by age category for females

Age cat.		Trabecular bone loss in the 4th Lumbar Vertebrae						Tot
		Severe OP	Mod. OP	Mild OP	Osteo-penia	Normal	Healthy	
<30	Count – N (%)	0 (0)	3 (5.7)	7 (13.2)	12(22.6)	20(34.2)	11 (48.1)	53
	Std. Res.	-0.7	-0.8	-1.3	-0.4	0.9	1.7	
30-50	Count – N (%)	0 (0)	6 (12.2)	12(24.5)	14(28.6)	14(28.6)	3 (6.1)	49
	Std. Res.	-0.7	0.8	0.4	0.5	-0.3	-1.3	
50-70	Count – N (%)	0 (0)	1 (12.5)	5 (62.5)	2 (25.0)	0 (0)	0 (0)	8
	Std. Res.	-0.3	0.3	2.5	0.0	-1.6	-1.0	
>70	Count – N (%)	1(100)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1
	Std. Res.	10.4	-0.3	-0.5	-0.5	-0.6	-0.4	
Total	Count	1	10	24	28	34	14	111

Table 5.30 Frequency of trabecular bone loss severity in the femoral neck by age category in males

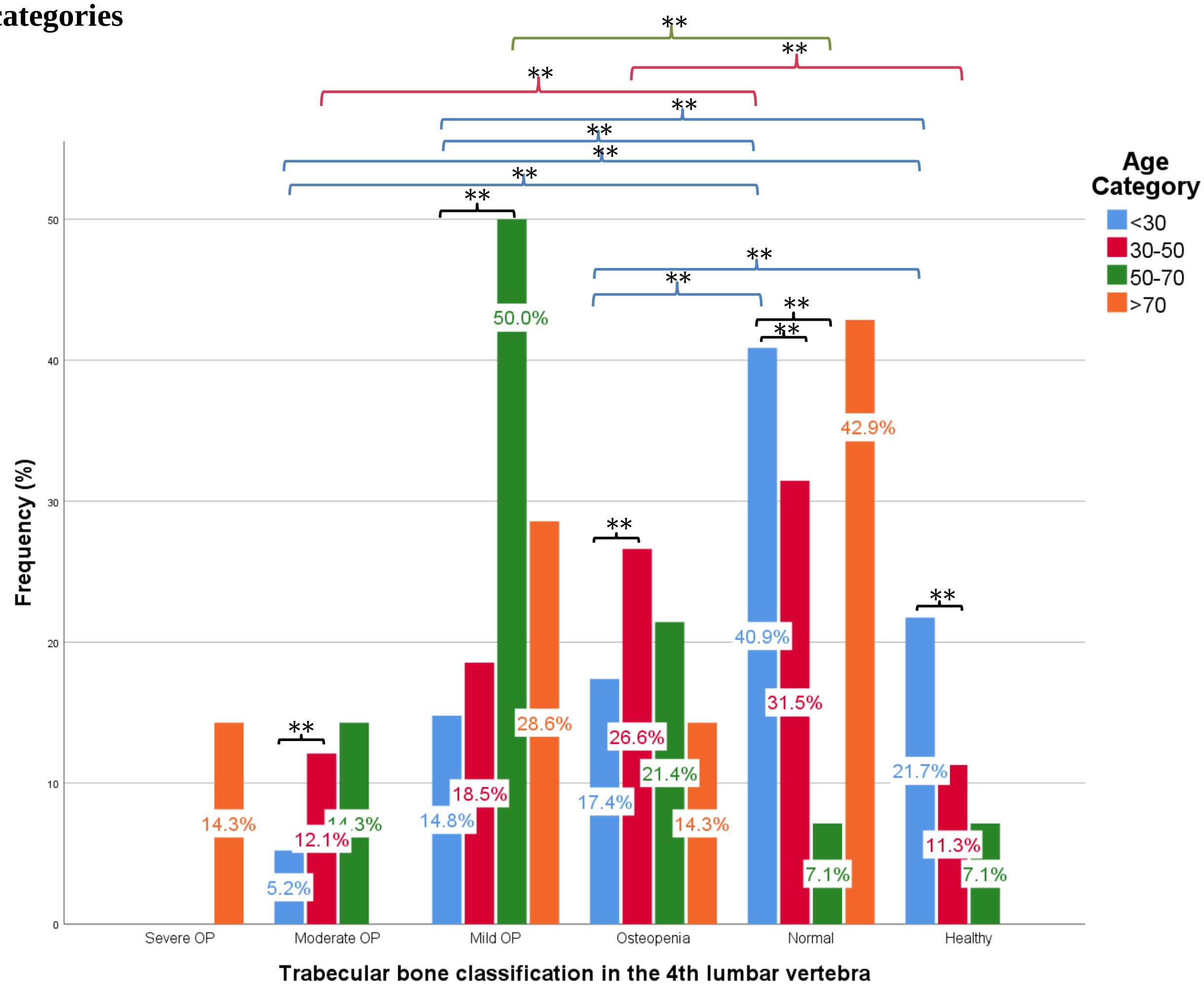
Age cat.		Trabecular bone loss in the femoral neck					Total
		Severe OP	Mild OP	Osteo-penia	Normal	Healthy	
<30	Count – N (%)	0 (0)	1 (1.3)	13 (16.5)	27 (34.2)	38 (48.1)	97
	Std. Res.	-0.7	0.1	-1.2	-1.5	2.9	
30-50	Count – N (%)	0 (0)	1 (1.4)	21 (28.4)	40 (54.1)	12 (16.2)	74
	Std. Res.	-0.7	0.1	1.0	1.1	-2.2	
50-70	Count – N (%)	0 (0)	0 (0)	1 (20.0)	4 (80.0)	0 (0)	5
	Std. Res.	-0.2	-0.2	-0.1	1.2	-1.2	
>70	Count – N (%)	1 (10.0)	0 (0)	3 (30.0)	5 (50.0)	1 (10.0)	10
	Std. Res.	3.9	-0.3	0.5	0.2	-1.2	
Tot.	Count	1	2	38	76	51	168

Figure 5.69 Distribution of trabecular bone loss in the femoral neck between age categories



**significant at p<0.001

Figure 5.70 Distribution of trabecular bone loss in the fourth lumbar vertebra between age categories



**significant at p<0.001

5.5.5 Biomechanics

Mean CA, TA, %CA, I_{min}, I_{max}, *J*, Z_{max}, Z_{min}, Z_p, average cortical thickness and I_{max}/I_{min} were compared for different age categories (males: $n_{<30}$=56, n_{30-50}=59, n_{50-70}=2, $n_{>70}$=10; females: : $n_{<30}$=40, n_{30-50}=34, n_{50-70}=5, $n_{>70}$=0). For the majority of biomechanical comparisons no age-related differences were observed for either males or females. For females, decreases in minimum section modulus at 20% between the <30 and 30-50 years-at-death age categories (p=0.030), percent cortical area at Ward's triangle between the <30 and 50-70 years-at-death age categories (p=0.005), percent cortical area at Ward's triangle between the 30-50 and 50-70 years-at-death age categories (p=0.041), average cortical thickness at 80% between the <30 and 30-50 years-at-death age categories (p=0.031), and average cortical thickness at Ward's triangle between the <30 and 50-70 years-at-death age categories (p=0.033) were significant at the 95% confidence interval. For males, the comparisons presented in Table 5.31 were significant. Age-related differences in the femoral shaft's biomechanical properties were analyzed using one-way ANOVAs. Figures 5.71 through 5.86 present size-standardized results for age-related changes in biomechanical properties.

Table 5.31 Significant comparisons for age-related biomechanical changes in males

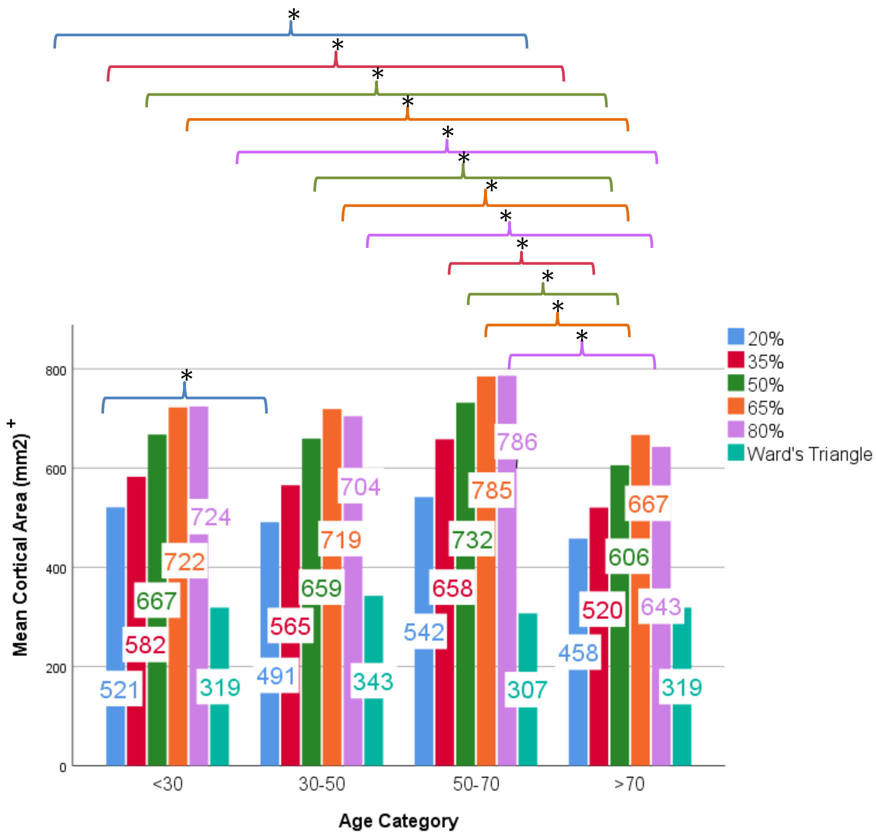
Slice	Biomechanical property	Age category 1	Mean 1	Age category 2	Mean 2	p-value
20%	CA	<30	519 mm^2	30-50	490 mm^2	0.031*
	CA	<30	519 mm^2	>70	458 mm^2	0.014*
	%CA	<30	37.87%	>70	32.46%	0.028*
	Avg. cort. thick	<30	4.07 mm	>70	3.58 mm	0.036*
35%	CA	<30	580 mm^2	>70	520 mm^2	0.027*
	CA	50-70	658 mm^2	>70	520 mm^2	0.025*
	%CA	<30	60.63%	>70	54.70%	0.019*
	J	<30	410 mm^4	30-50	450 mm^4	0.007*
	J	30-50	450 mm^4	>70	390 mm^4	0.016*
	J	50-70	500 mm^4	>70	390 mm^4	0.043*
	Z_{max}	50-70	776 mm^3	>70	600 mm^3	0.039*
	Z_p	50-70	1382 mm^3	>70	1078 mm^3	0.048*
	Avg. cort. thick	<30	599 mm	>70	535 mm	0.043*
50%	CA	<30	665 mm^2	>70	606 mm^2	0.021*
	CA	30-50	660 mm^2	>70	606 mm^2	0.035*
	CA	50-70	732 mm^2	>70	606 mm^2	0.030*
	TA	50-70	962 mm^2	>70	826 mm^2	0.031*
	%CA	<30	77.67%	30-50	75.36%	0.023*
	%CA	<30	77.67%	>70	43.59%	0.029*
	I_{min}	<30	168 mm^4	30-50	180 mm^4	0.042*
	I_{min}	30-50	180 mm^4	>70	156 mm^4	0.035*
	I_{max}	<30	210 mm^4	30-50	227 mm^4	0.047*
	I_{max}	30-50	227 mm^4	>70	192 mm^4	0.024*
	I_{max}	50-70	265 mm^4	>70	192 mm^4	0.034*
	J	<30	380 mm^4	30-50	410 mm^4	0.034*
	J	30-50	410 mm^4	>70	350 mm^4	0.021*
	J	50-70	470 mm^4	>70	350 mm^4	0.039*

	Z_{max}	<30	626 mm^3	>70	556 mm^3	0.039*
	Z_{max}	30-50	646 mm^3	>70	556 mm^3	0.008*
	Z_{max}	50-70	753 mm^3	>70	556 mm^3	0.011*
	Z_{min}	30-50	574 mm^3	>70	511 mm^3	0.023*
	Z_p	50-70	1294 mm^3	>70	1004 mm^3	0.019*
65%	CA	<30	719 mm^2	>70	667 mm^2	0.0.39*
	CA	30-50	720 mm^2	>70	667 mm^2	0.037*
	CA	50-70	785 mm^2	>70	667 mm^2	0.040*
	TA	<30	881 mm^2	30-50	920 mm^2	0.021*
	%CA	<30	81.01%	30-50	78.25%	0.021*
	%CA	<30	81.01%	>70	76.64%	0.047*
	I_{min}	<30	174 mm^4	30-50	194 mm^4	0.001*
	I_{min}	30-50	194 mm^4	>70	159 mm^4	0.003*
	I_{max}	<30	236 mm^4	30-50	253 mm^4	0.049*
	I_{max}	50-70	298 mm^4	>70	226 mm^4	0.047*
	J	<30	380 mm^4	30-50	410 mm^4	0.034*
	J	30-50	410 mm^4	>70	350 mm^4	0.021*
	J	50-70	470 mm^4	>70	350 mm^4	0.039*
	Z_{max}	50-70	805 mm^3	>70	661 mm^3	0.047*
	Z_{min}	<30	584 mm^3	30-50	625 mm^3	0.006*
	Z_{min}	30-50	625 mm^3	>70	550 mm^3	0.006*
	Z_p	<30	1188 mm^3	30-50	1255 mm^3	0.020*
	Z_p	30-50	1255 mm^3	>70	1120 mm^3	0.001*
	Z_p	50-70	1359 mm^3	>70	1120 mm^3	0.047*
80%	CA	<30	717 mm^2	>70	643 mm^2	0.008*
	CA	30-50	705 mm^2	>70	643 mm^2	0.026*
	CA	50-70	786 mm^2	>70	643 mm^2	0.023
	%CA	<30	66.19%	30-50	63.24%	0.040*
	%CA	<30	66.19%	>70	58.46%	0.004*
	I_{min}	<30	220 mm^4	30-50	242 mm^4	0.042*
Ward's	TA	<30	870 mm^2	30-50	972 mm^2	0.021*
	%CA	<30	36.67%	>70	32.54%	0.022*
	I_{min}	<30	72 mm^4	30-50	93 mm^4	0.032*
	I_{max}	<30	196 mm^4	30-50	268 mm^4	0.016*
	J	<30	270 mm^4	30-50	360 mm^4	0.018*
	Z_{max}	<30	466 mm^3	30-50	562 mm^3	0.032*
	Z_p	<30	633 mm^3	30-50	752 mm^3	0.042*

*significant at a 95% confidence interval

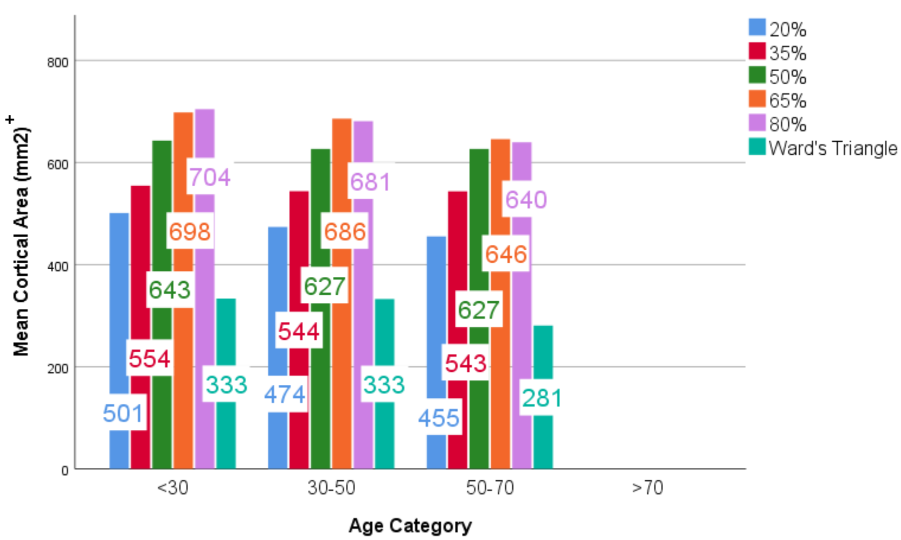
All values except % cortical area, avg. cortical thickness, and I_{max}/I_{min} are size- standardized; CA_{STD} = CA/BM; TA_{STD} = TA/BM; I_{STD} = I/(BM*Fem Length^2); J_{STD} = J/(BM*Fem Length^2); Z_{STD} = Z/(BM*Fem Length)

Figure 5.71 Mean cortical area by age for males



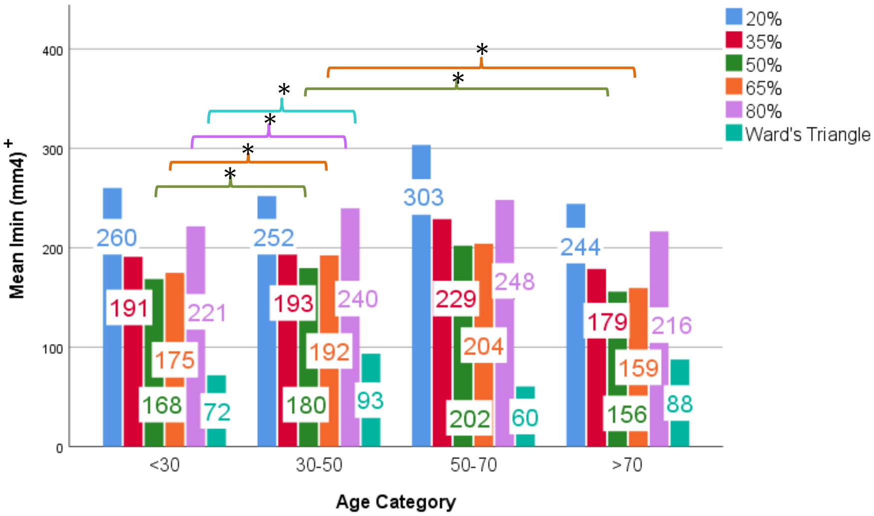
*significant at $p<0.05$
+CA values except are size- standardized; CA_{STD} = CA/BM

Figure 5.72 Mean cortical area by age for females



+CA values except are size- standardized; CA_{STD} = CA/BM

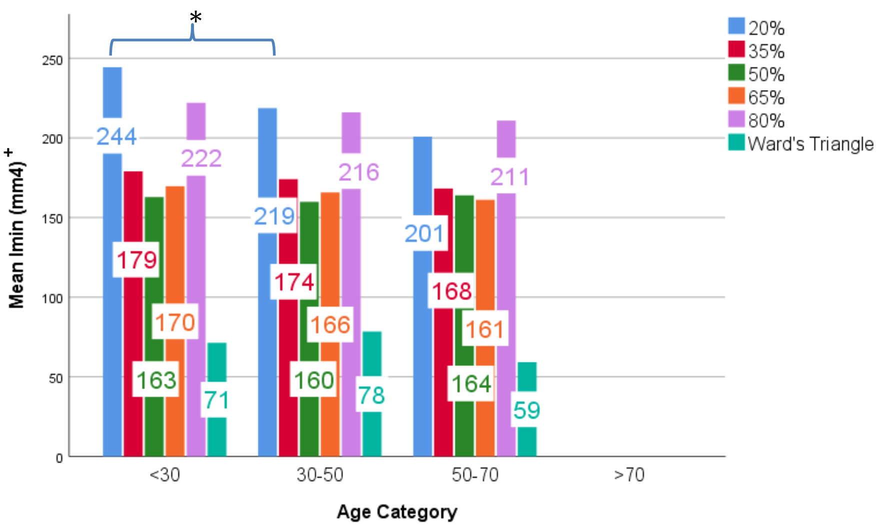
Figure 5.73 Mean minimum second moment of area by age for males



*significant at $p<0.05$

+ I_{min} values are size-standardized: $I_{minSTD} = I_{min}/(BM*Fem\ Length^2)$

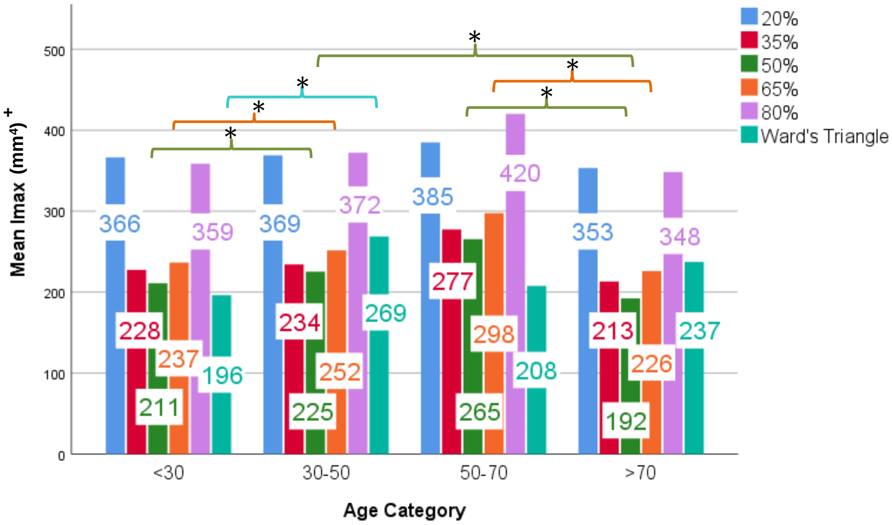
Figure 5.74 Mean minimum second moment of area by age for females



*significant at $p<0.05$

+ I_{min} values are size-standardized: $I_{minSTD} = I_{min}/(BM*Fem\ Length^2)$

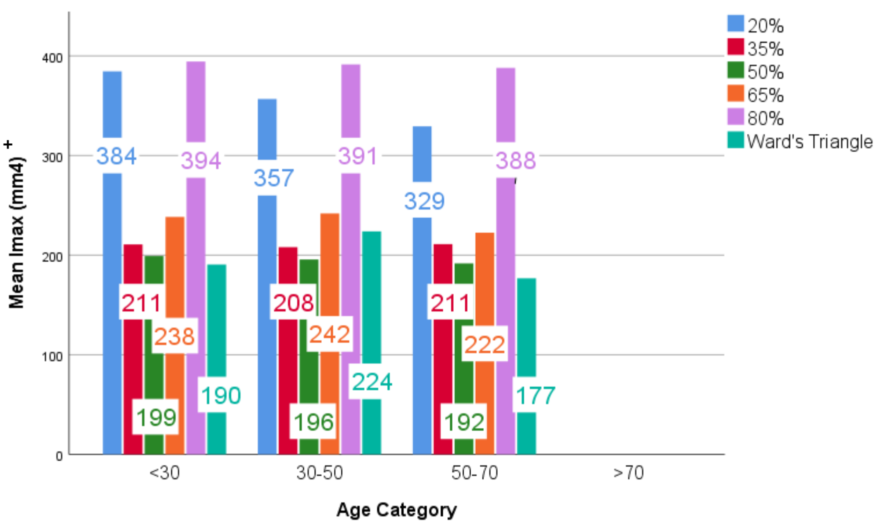
Figure 5.75 Mean maximum second moment of area by age for males



*significant at $p<0.05$

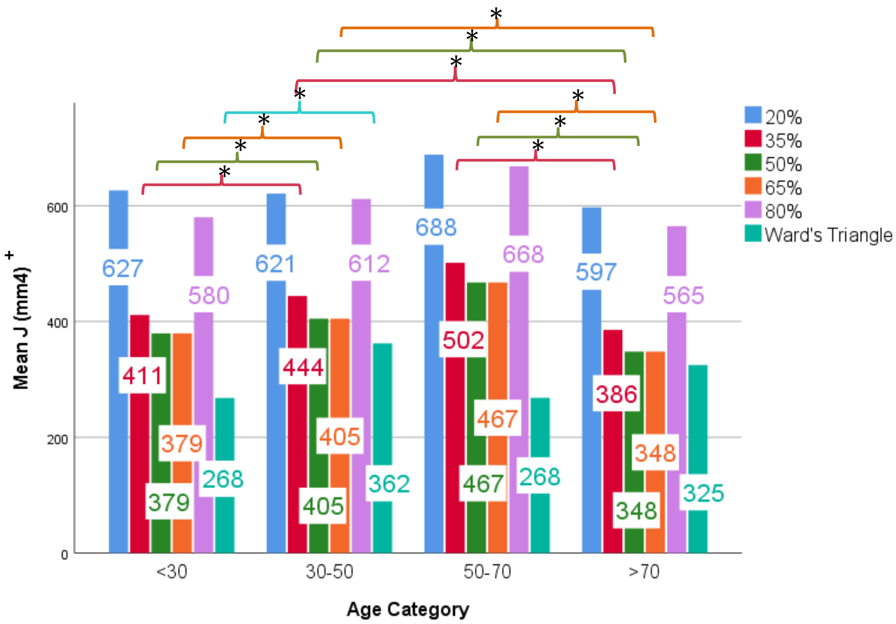
+ I_{max} values are size-standardized: $I_{maxSTD} = I_{max}/(BM*Fem\ Length^2)$

Figure 5.76 Mean maximum second moment of area by age for females



+ I_{max} values are size-standardized: $I_{maxSTD} = I_{max}/(BM*Fem\ Length^2)$

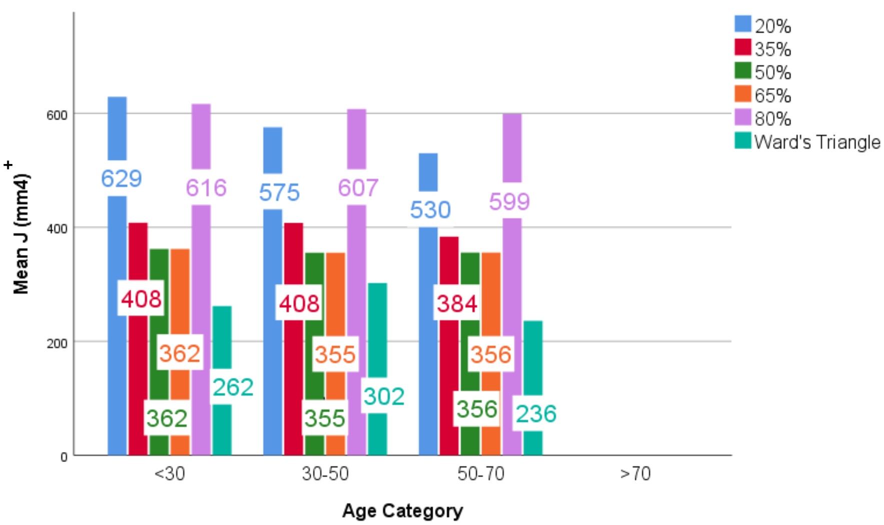
Figure 5.77 Mean polar second moment of area by age for males



*significant at $p<0.05$

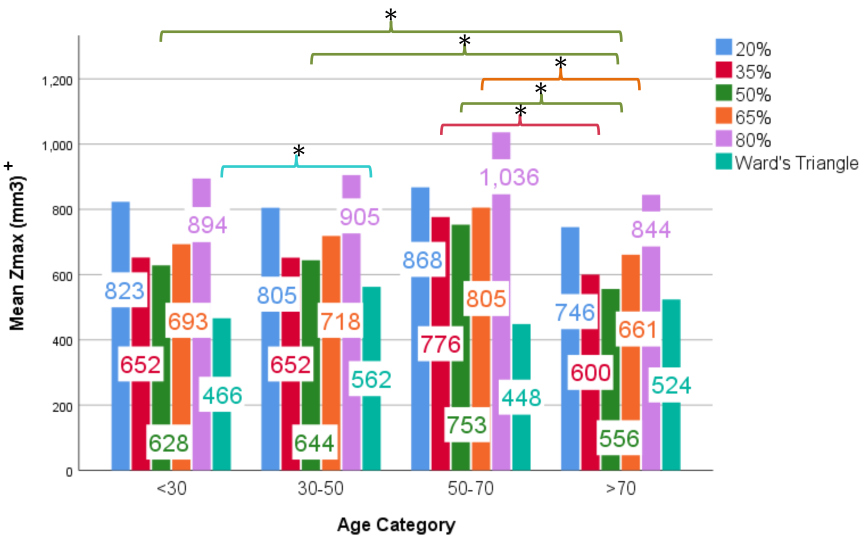
+ J values are size-standardized: $J_{STD} = J/(BM*Fem\ Length^2)$

Figure 5.78 Mean polar second moment of area by age for females



+ J values are size-standardized: $J_{STD} = J/(BM*Fem\ Length^2)$

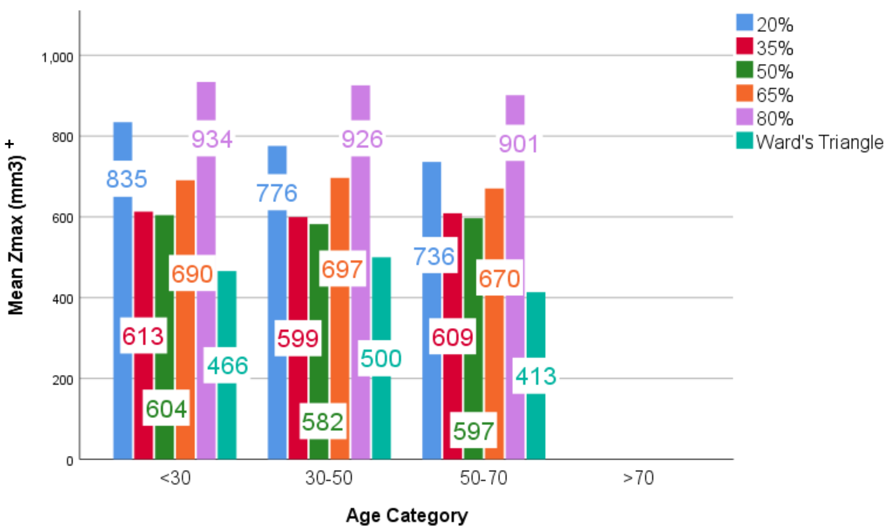
Figure 5.79 Mean maximum section modulus by age for males



*significant at $p<0.05$

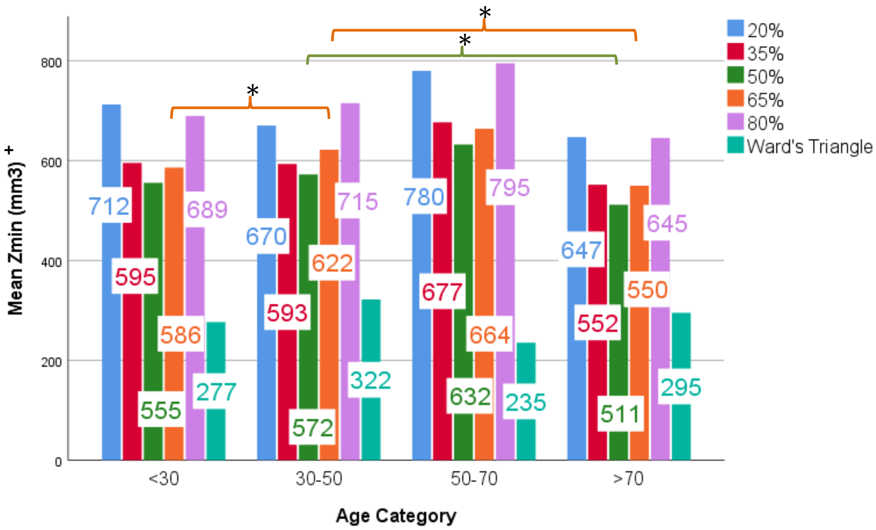
+ Z_{max} values are size-standardized: $Z_{maxSTD} = Z_{max}/(BM*Fem\ Length)$

Figure 5.80 Mean maximum section modulus by age for females



+ Z_{max} values are size-standardized: $Z_{maxSTD} = Z_{max}/(BM*Fem\ Length)$

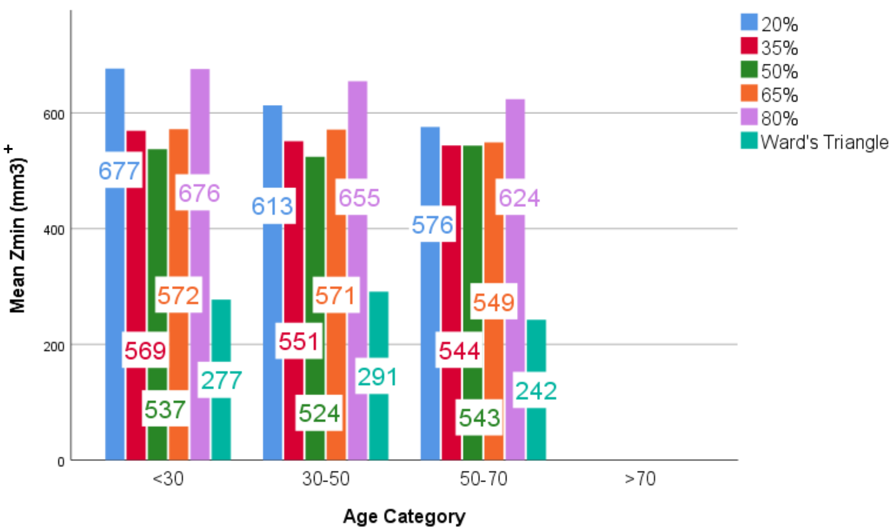
Figure 5.81 Mean minimum section modulus by age for males



*significant at $p<0.05$

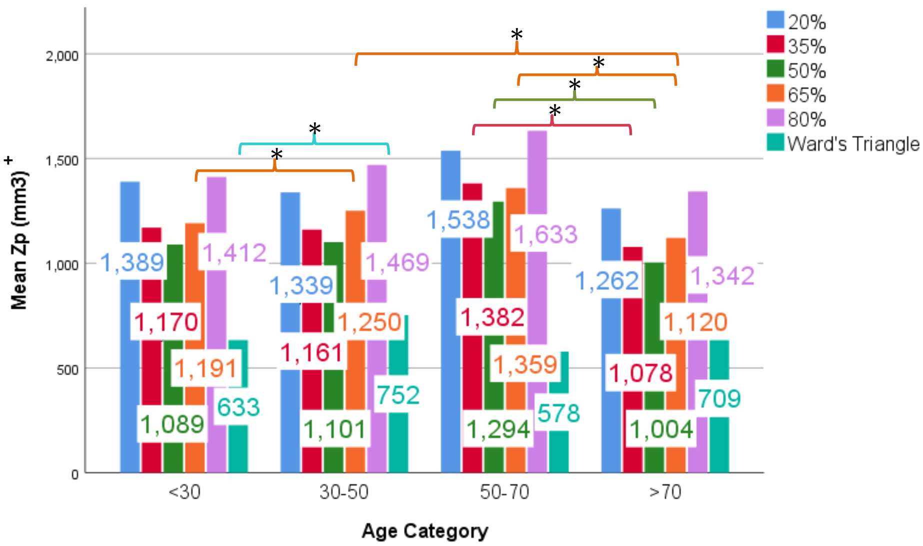
$^{+}$ Z_{min} values are size-standardized: $Z_{minSTD} = Z_{min}/(BM*Fem\ Length)$

Figure 5.82 Mean minimum section modulus by age for females



$^{+}$ Z_{min} values are size-standardized: $Z_{minSTD} = Z_{min}/(BM*Fem\ Length)$

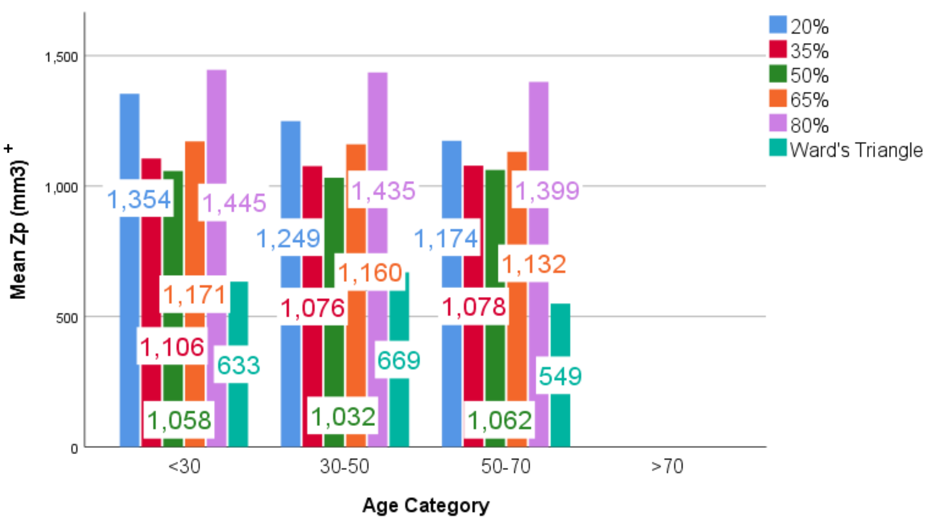
Figure 5.83 Mean polar section modulus by age for males



*significant at $p<0.05$

+ Z_p values are size-standardized: $Z_{pSTD} = Z_p/(BM*Fem\ Length)$

Figure 5.84 Mean polar section modulus by age for females



+ Z_p values are size-standardized: $Z_{pSTD} = Z_p/(BM*Fem\ Length)$

Figure 5.85 Mean shape ratio (I_{max}/I_{min}) by age category for males

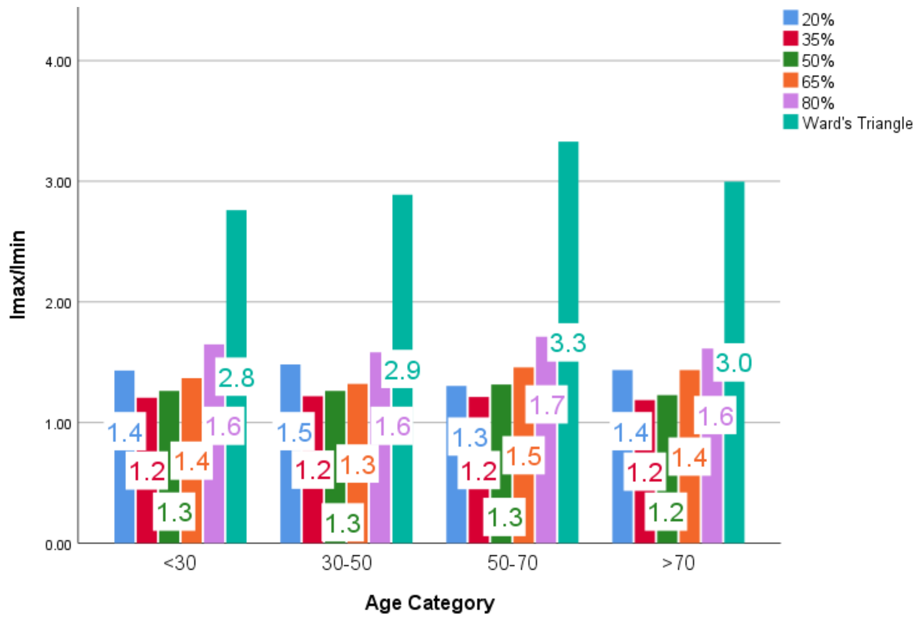
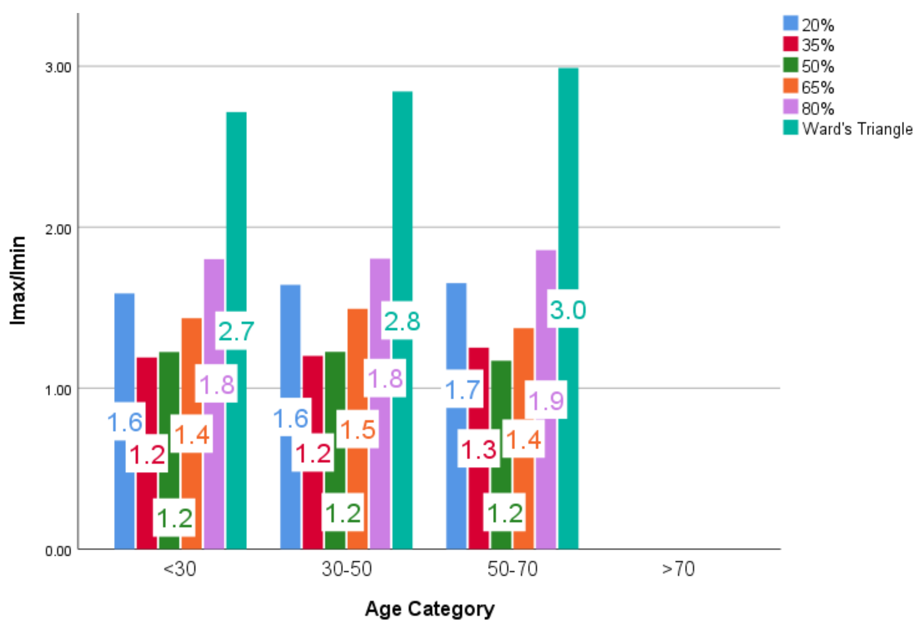


Figure 5.86 Mean shape ratio (I_{max}/I_{min}) by age category for females



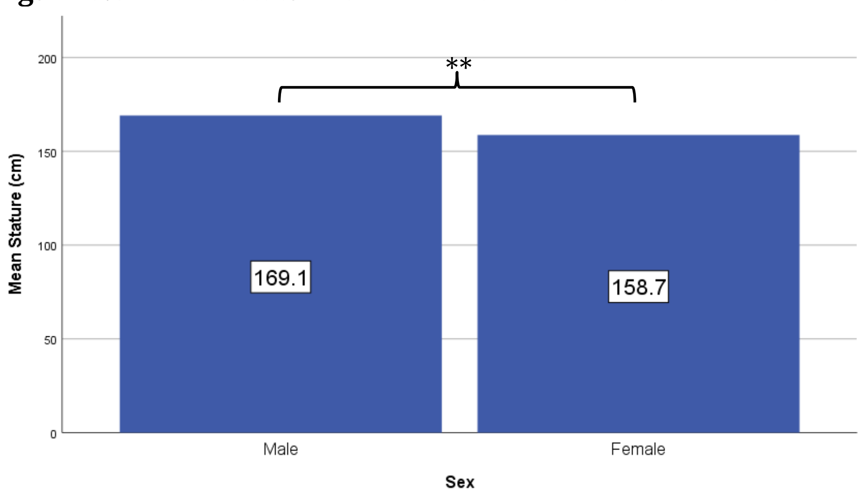
5.6 Sex Comparison

Sex was expected to affect health outcomes and lived experience. Hypothesis 4 perdicted that males would be taller and heavier and exhibit less osteoporosis and osteoporotic fracturing than their female contemporaries. However, males would present more indulgence-related disorders and degeneration in the weight bearing joints. Finally, males were expected to exhibit more robust, stronger femora than females. The following results relate to Hypothesis 4.

5.6.1 Stature

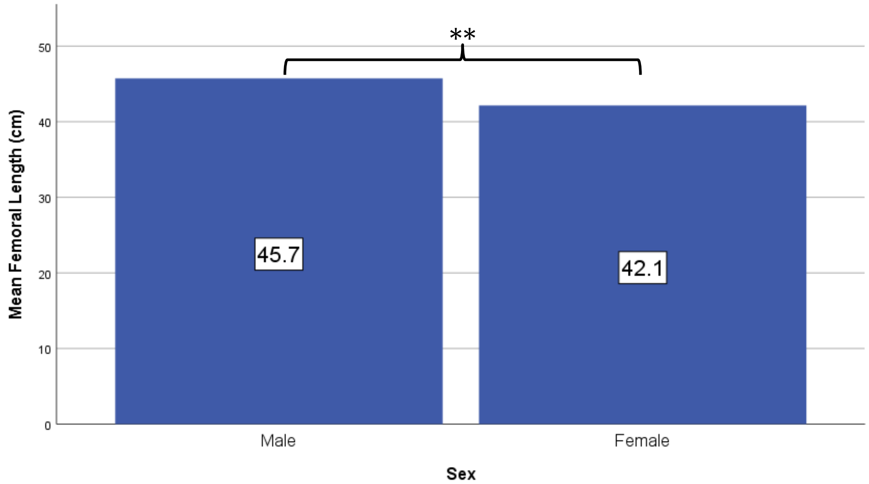
Differences in stature and femoral length were compared between males and females using independent samples t-tests. Significant differences in stature (n_{males}= 257; $n_{females}$= 189; t=16.071, df=444, p<0.001) and femoral length (n_{males}= 131; $n_{females}$= 81; t=13.534, df=397, p<0.001), where males were taller than females, were noted. Stature and femoral length by sex are illustrated in Figures 5.87 and 5.88.

Figure 5.87 Mean stature differences in males and females



*significant at p<0.01

Figure 5.88 Mean femoral length differences in males and females

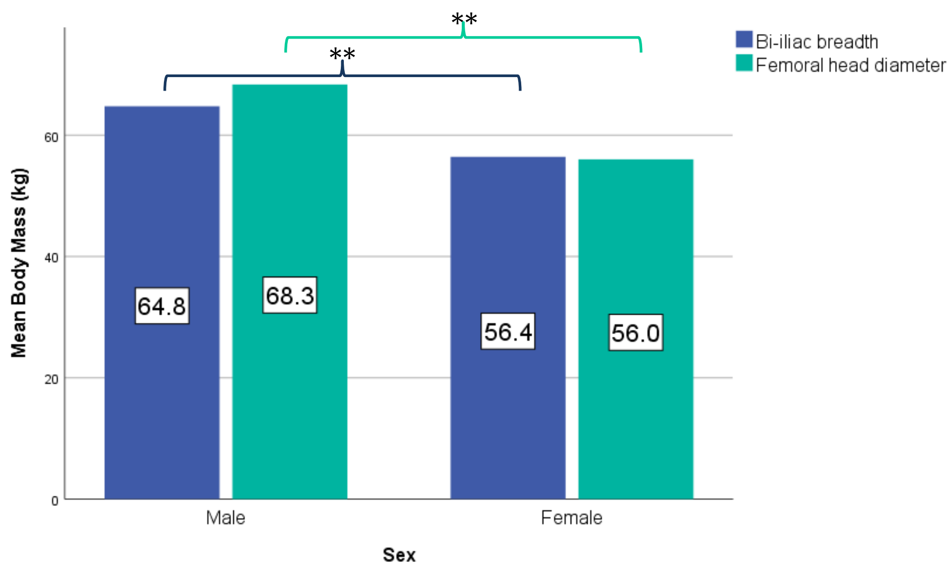


*significant at p<0.01

5.6.2 Body Mass

Significant differences in body mass existed when body mass was calculated using both bi-iliac breadth (n_{males}= 81; $n_{females}$= 57; t=6.934; df=135.9; p<0.001) and femoral head diameter (n_{males}= 245; $n_{females}$= 184; t=20.736; df=427; p<0.001). Figure 5.89 illustrates the changes in body mass by sex using the two body mass estimation methods.

Figure 5.89 Mean body mass difference by sex



*significant p<0.01

5.6.3 Indulgence-Related Disorders and Degeneration

Males presented a higher frequency for all indulgence-related disorders (Tables 5.32 through 5.34). Significant differences existed in the frequency of DISH (χ^2=6.510; df=1; p=0.008), plantar calcaneal spurs (χ^2=3.793; df=1; p=0.037), and in the presence of any indulgence-related disorder (χ^2=9.126; df=1; p=0.002).

Table 5.32 Frequency of DISH between the sexes

Sex		DISH		Total
		Absent	Present/eDISH	
Females	Count	141	2	143
	% within site	98.6%	1.4%	100%
	Standardized residuals	0.4	-1.9	
Males	Count	173	14	187
	% within site	92.5%	7.5%	100%
	Standardized residuals	-0.4	1.6	
Total	Count	314	16	330

Table 5.33 Frequency of plantar calcaneal spurs between the sexes

Sex		Plantar Spurs		Total
		Absent	Present	
Females	Count	106	10	116
	% within site	91.4%	8.6%	100%
	Standardized residuals	0.5	-1.4	
Males	Count	135	27	162
	% within site	83.3%	16.7%	100%
	Standardized residuals	-0.5	1.2	
Total	Count	241	37	278

Table 5.34 Frequency of indulgence-related disorders between the sexes

Sex		Indulgence-related disorder		Total
		Absent	Present	
Females	Count	67	16	83
	% within site	80.7%	19.3%	100%
	Standardized residuals	1.3	-2.0	
Males	Count	80	51	131
	% within site	61.1%	38.9%	100%
	Standardized residuals	-1.1	1.6	
Total	Count	147	67	214

In general, males presented more cases of degenerative joint disease in all weight bearing joints. No significant differences in the frequency of degenerative joint disease in the hips, knees, or lumbar spine or in any degeneration of the weight-bearing joints was noted. Sex differences in degenerative joint disease were also compared using chi-square tests (χ^2).

5.6.4 Degenerative Disorders - Osteoporosis

Females exhibited significantly more osteoporosis in the femoral neck than males (χ^2=9.385; df=1; p=0.003). Although not statistically significant, females also presented a higher frequency of osteoporotic fourth lumbar vertebrae. Table 5.35 presents the distribution for osteoporosis in the femoral neck between the sexes. Figures 5.90 and 5.91 illustrate the distribution of trabecular bone loss in the femoral neck and fourth lumbar vertebra respectively.

When fracture frequency differences between males and females were compared, males presented a higher frequency of femoral and lumbar crush fractures, while females presented a higher frequency of Colles' fractures. The differences were significant for Colles' fractures (χ^2=7.520; df=1; p=0.010) (Table 5.56) and lumbar spinal crush fractures (χ^2=6.391; df=1; p=0.013) (Table 5.37).

Table 5.35 Frequency of femoral neck osteoporosis between the sexes

Sex		**OP in the femoral neck**		**Total**
		Absent	**Present**	
Females	Count	104	11	115
	% within site	90.4%	9.6%	100%
	Standardized residuals	-0.5	2.3	
Males	Count	173	3	176
	% within site	98.3%	1.7%	100%
	Standardized residuals	0.4	-1.9	
Total	Count	277	14	291

Table 5.36 Frequency of Colles' fractures between the sexes

Sex		Colles' fractures		Total
		Absent	Present	
Females	Count	111	13	124
	% within site	89.5%	10.5%	100%
	Standardized residuals	-0.5	2.0	
Males	Count	151	5	155
	% within site	97.4%	2.6%	100%
	Standardized residuals	0.5	-1.8	
Total	Count	262	17	279

Table 5.37 Frequency of lumbar crush fractures between the sexes

Sex		Spinal crush fractures		Total
		Absent	Present	
Females	Count	115	13	128
	% within site	89.8%	10.2%	100%
	Standardized residuals	0.8	-1.8	
Males	Count	143	38	181
	% within site	79.0%	21.0%	100%
	Standardized residuals	-0.7	1.5	
Total	Count	258	51	309

Figure 5.90 Distribution of trabecular bone loss in the femoral neck by sex

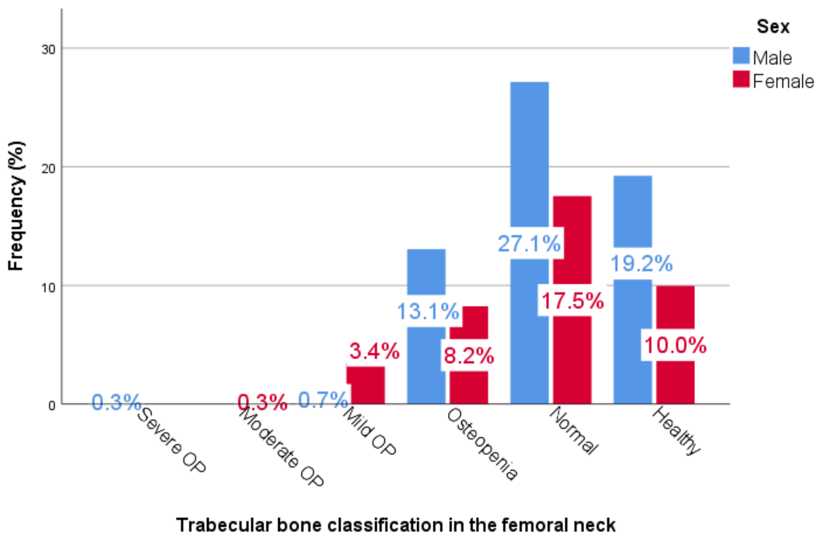
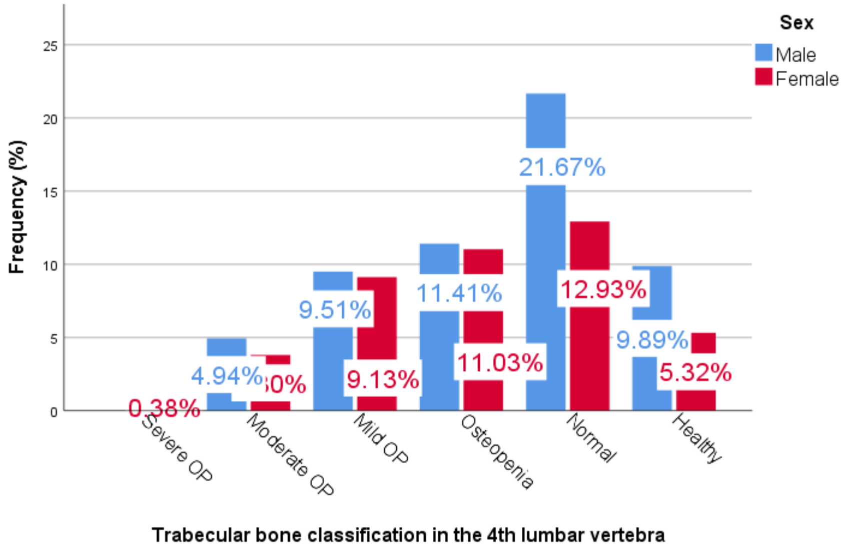


Figure 5.91 Distribution of trabecular bone loss in the fourth lumbar vertebra by sex



5.6.5 Biomechanics

In general males exhibited larger, stronger bones than females. Interestingly, for %CA at Ward's triangle, male femora were significantly smaller than their female counterparts. Sex differences in biomechanical properties (CA, TA, %CA, I_{min}, I_{max}, Z_{max}, Z_{min}, Z_p, average cortical thickness, I_{max}/I_{min}) were evaluated along the femoral shaft at 20%, 35%, 50%, 65%, and 80% and at Ward's triangle using independent samples t-tests. The results of the independent sample t-tests are presented in Table 5.38. Figures 5.92 through 5.99 illustrate size-standardized sex differences in biomechanical properties.

Table 5.38 Comparison of sex differences in biomechanical properties along the femoral shaft

Biomechanical property	Slice	t	df	p-value
CA (mm^2)	20%	1.603	210	0.110
	35%	1.981	210	0.049*
	50%	2.294	210	0.023*
	65%	2.547	210	0.012
	80%	1.444	210	0.150
	Ward's	-0.015	203	0.988
	20%	0.359	210	0.530

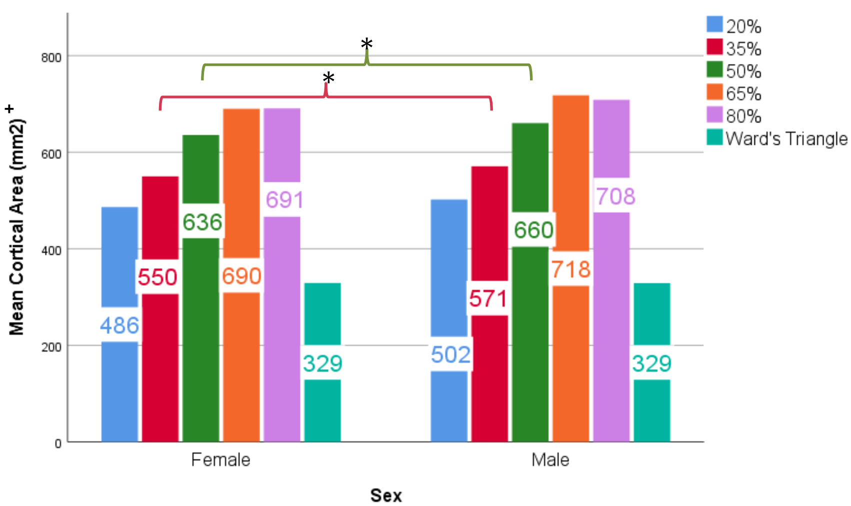
TA (mm^2)	35%	2.002	210	0.047*
	50%	2.001	210	0.047*
	65%	-0.054	210	0.957
	80%	-1.154	117.049	0.251
	Ward's	1.960	203	0.051
%CA	20%	1.10	198.1	0.273
	35%	0.42	210	0.675
	50%	0.90	210	0.368
	65%	2.63	209	0.009*
	80%	1.93	137.5	0.055
	Ward's	-3.62	203	<0.001*
I_{min} (mm^4)	20%	3.123	210	0.002*
	35%	2.492	210	0.013
	50%	2.345	210	0.020*
	65%	2.786	210	0.006*
	80%	1.464	210	0.145
	Ward's	1.322	203	0.188
I_{max} (mm^4)	20%	-0.002	210	0.998
	35%	2.958	210	0.003*
	50%	3.160	210	0.002*
	65%	0.966	210	0.335
	80%	-1.232	111.282	0.221
	Ward's	1.328	203	0.186
***J* (mm^4)**	20%	1.314	210	0.190
	35%	1.862	210	0.064
	50%	2.913	210	0.004*
	65%	2.913	210	0.004*
	80%	-0.386	114.629	0.700
	Ward's	1.339	203	0.174
Z_{max} (mm^3)	20%	0.462	210	0.645
	35%	2.922	210	0.004*
	50%	2.756	210	0.006*
	65%	1.072	210	0.285
	80%	-0.867	115.601	0.388
	Ward's	1.139	203	0.256
Z_{min} (mm^3)	20%	2.765	210	0.006*
	35%	2.310	210	0.004*
	50%	2.515	210	0.013*
	65%	2.489	210	0.014*
	80%	2.154	210	0.032*
	Ward's	1.088	203	0.278
Z_p (mm^3)	20%	2.019	210	0.045*
	35%	2.665	210	0.008*
	50%	2.029	210	0.044*
	65%	2.265	210	0.025*

	80%	0.226	125.051	0.822
	Ward's	1.166	203	0.245
Avg. cortical thickness (mm)	20%	6.06	210	<0.001*
	35%	5.31	210	<0.001*
	50%	6.77	210	<0.001*
	65%	5.64	210	<0.001*
	80%	4.41	210	<0.001*
	Ward's	1.50	203	0.136
I_{max}/I_{min}	20%	-4.721	210	<0.001*
	35%	0.578	210	0.564
	50%	1.957	210	0.052
	65%	-3.156	210	0.002*
	80%	-4.131	210	<0.001*
	Ward's	0.670	195.489	0.504

*significant at a 95% confidence interval

All values except % cortical area, avg. cortical thickness, and I_{max}/I_{min} are size- standardized; CA_{STD} = CA/BM; TA_{STD} = TA/BM; I_{STD} = I/(BM*Fem Length^2); J_{STD} = J/(BM*Fem Length^2); Z_{STD} = Z/(BM*Fem Length)

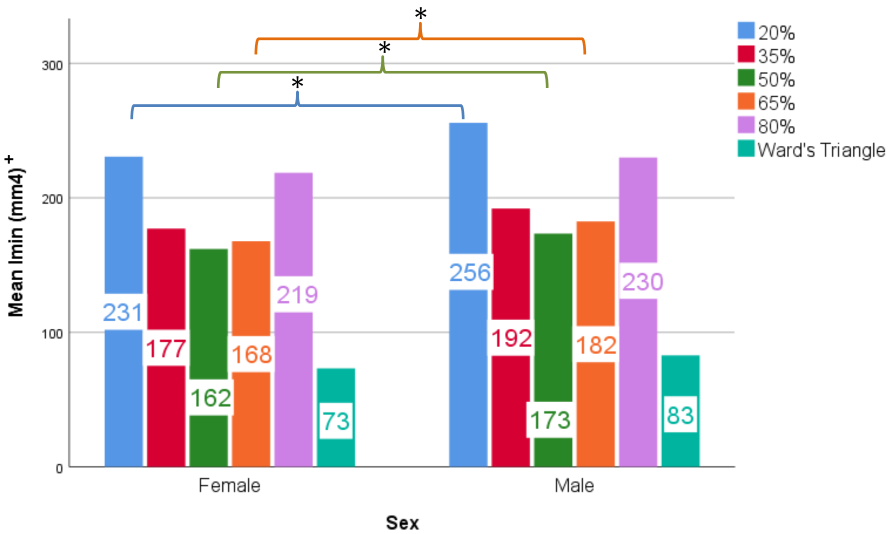
Figure 5.92 Mean cortical area by sex



*significant at $p<0.05$

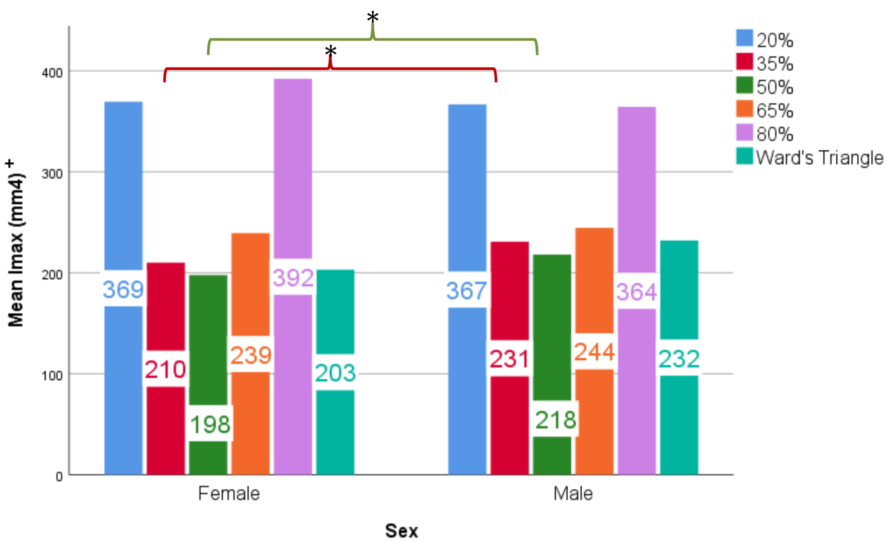
$^+$CA values except are size- standardized; CA_{STD} = CA/BM

Figure 5.93 Mean minimum second moment of area by sex



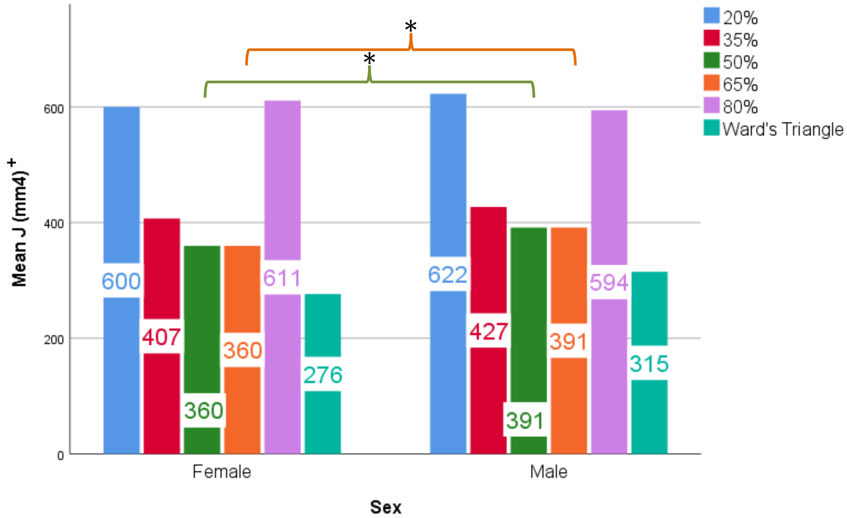
*significant at $p<0.05$
+ I_{min} values are size-standardized: $I_{minSTD} = I_{min}/(BM*Fem\ Length^2)$

Figure 5.94 Mean maximum second moment of area by sex



*significant at $p<0.05$
+ I_{max} values are size-standardized: $I_{maxSTD} = I_{max}/(BM*Fem\ Length^2)$

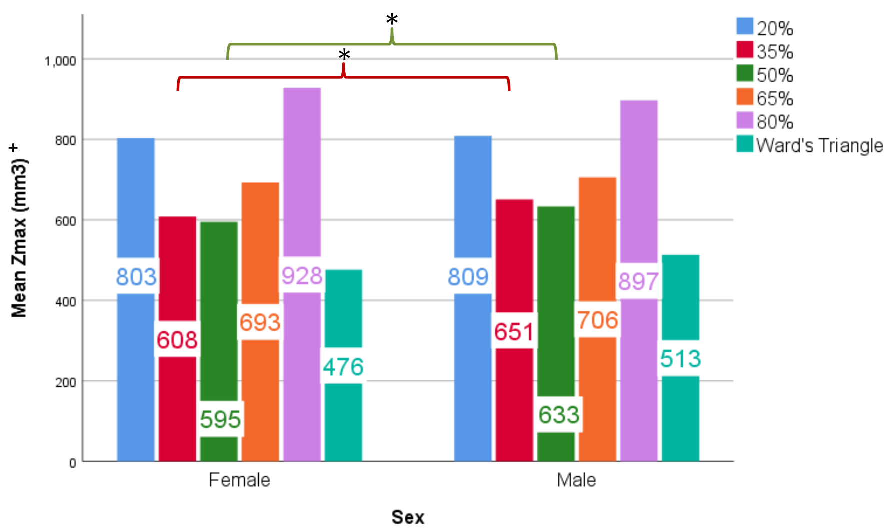
Figure 5.95 Mean polar second moment of area by sex



*significant at $p<0.05$

$^{+}$ J values are size-standardized: $J_{STD} = J/(BM*Fem\ Length^2)$

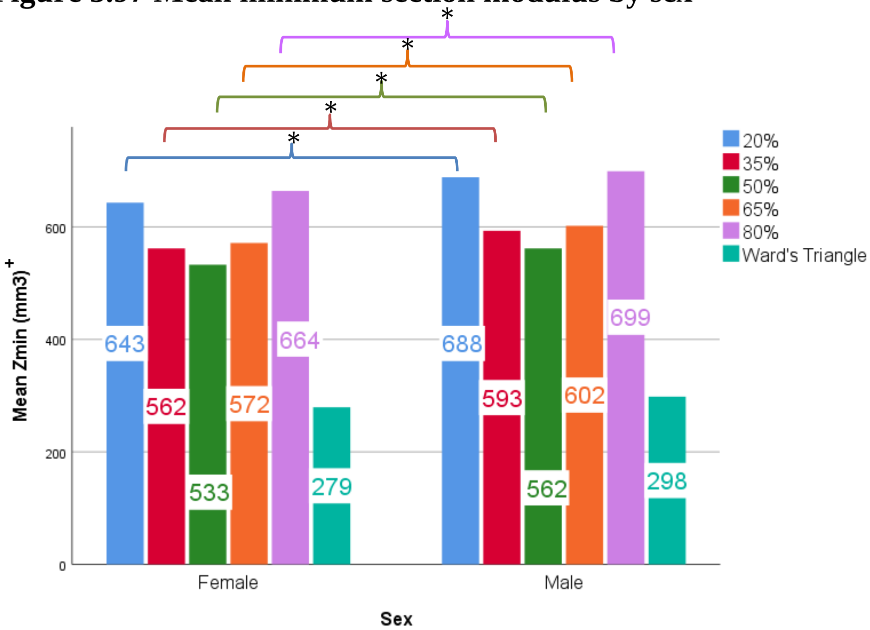
Figure 5.96 Mean maximum section modulus by sex



*significant at $p<0.05$

$^{+}$ Z_{max} values are size-standardized: $Z_{maxSTD} = Z_{max}/(BM*Fem\ Length)$

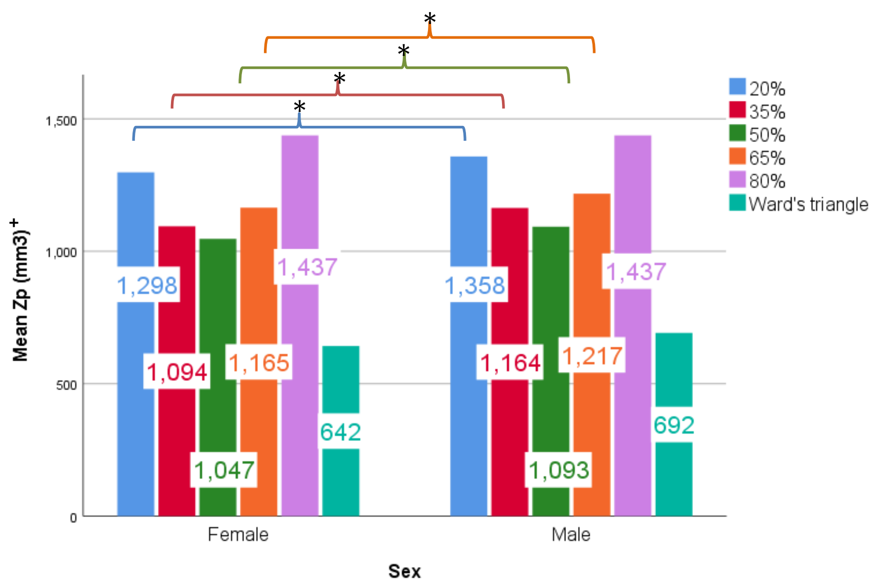
Figure 5.97 Mean minimum section modulus by sex



*significant at $p<0.05$

$^{+}$ Z_{min} values are size-standardized: $Z_{minSTD} = Z_{min}/(BM*Fem\ Length)$

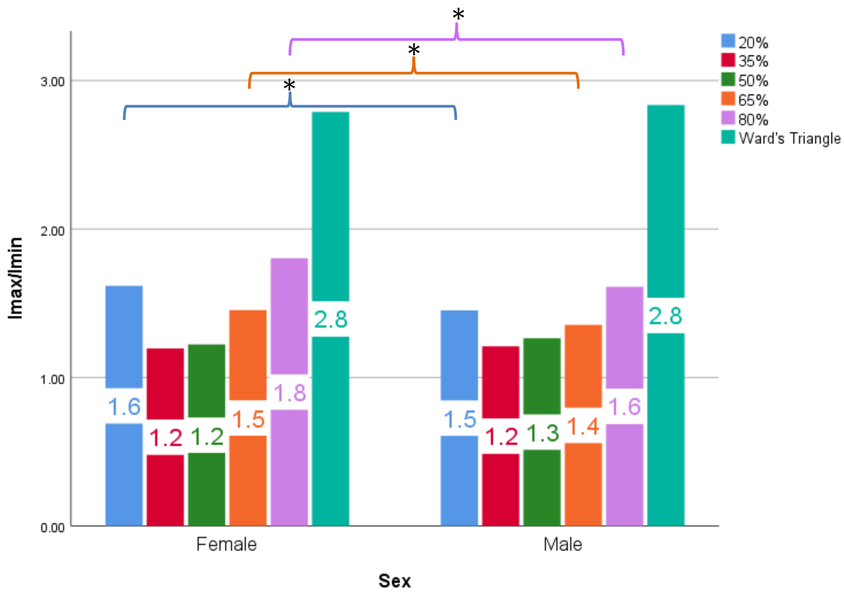
Figure 5.98 Mean polar section modulus by sex



*significant at $p<0.05$

$^{+}$ Z_p values are size-standardized: $Z_{pSTD} = Z_p/(BM*Fem\ Length)$

Figure 5.99 Mean shape ratio (I_{max}/I_{min}) by sex



*significant at p<0.05

5.7 Size-related Differences

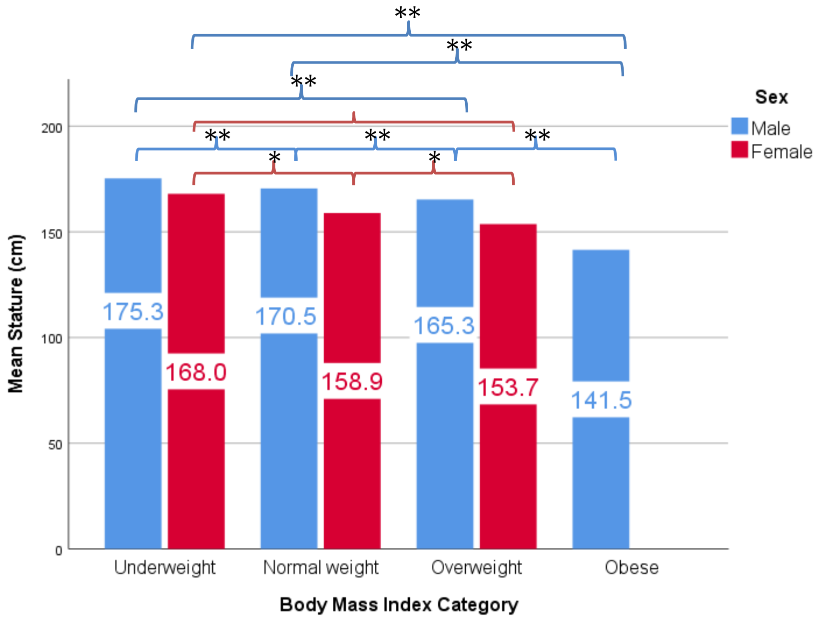
It was hypothesized that underweight and overweight individuals would be less healthy than "normal" weight individuals in that "normal" weight individuals would be taller, present fewer indulgence-related disorders and degeneration in the weight bearing joints, exhibit less osteoporosis and fewer osteoporotic fractures than lighter individuals (but more than heavier individuals), and, as body mass increased, individuals would present larger, stronger femora.

5.7.1 Stature

Differences in stature and femoral length were compared between BMI categories (underweight, "normal" weight, overweight, and obese). No significant differences in stature or femoral length were noted for either males or females when body mass was estimated using bi-iliac breadth. When BMI was calculated from body mass estimated using femoral head diameter, significant decreases in stature in males ($n_{underweight}$=1; $n_{\text{“normal”weight}}$=176; $n_{overweight}$=58; n_{obese}= 1; F=17.848; df=3; p<0.001) and females ($n_{underweight}$=5; $n_{\text{“normal”weight}}$=155; $n_{overweight}$=15; F=9.871;

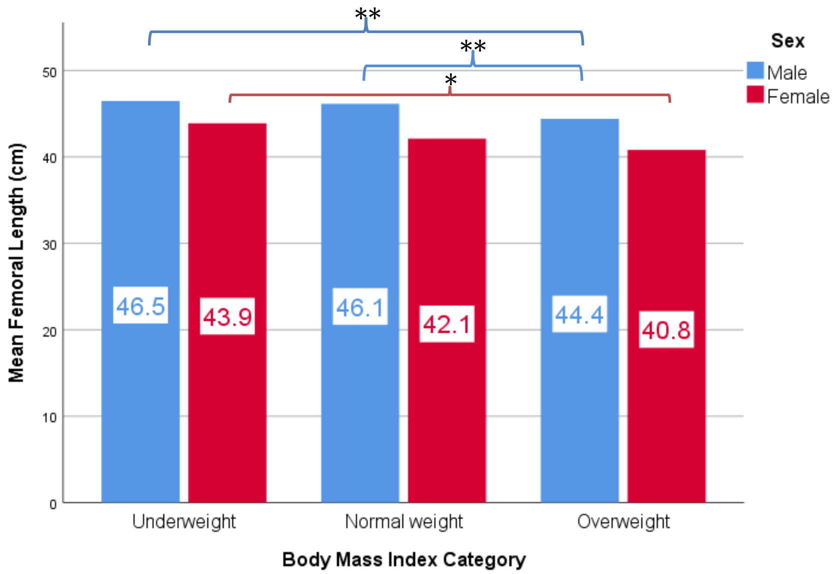
df=2; p<0.001) existed as body mass increased. A significant decrease in femoral length with increasing body mass was also noted in males ($n_{underweight}$= 1; $n_{“normal”weight}$=168; $n_{overweight}$=56; F=10.164; df=2; p<0.001); in females a significant decrease between the underweight (n=65) and overweight (n=12) categories (p= 0.022) existed. Figures 5.100 and 5.101 illustrate the differences in stature and femoral length between the BMI categories.

Figure 5.100 Mean stature differences by BMI category



*significant at p<0.05; **significant at p<0.01

Figure 5.101 Mean femoral length differences by BMI category



*significant at p<0.05; **significant at p<0.01

5.7.2 Indulgence-Related Disorders and Degeneration

No statistically significant differences were observed for any test. Chi-square (χ^2) tests were undertaken to analyze differences in indulgence-related disorders in distinct body mass categories which were estimated using both bi-iliac breadth and femoral head diameter. BMI categories were compared to the frequency of each indulgence-related disorder.

The frequency of degenerative joint diseases was also compared to the BMI categories. The results were not statistically significant for either sex or when the sexes were combined using either method for estimating body mass.

5.7.3 Degenerative Disorders - Osteoporosis

An increase in the frequency of osteoporosis is noted as body mass increases, when body mass is calculated using the femoral head diameter. No pattern is seen when body mass is calculated using bi-iliac breadth. No significant differences in frequency or severity of trabecular bone loss were noted in either sex or when sexes were combined with the exception of osteoporosis in females in the fourth lumbar vertebrae, which was significantly less frequent in the "normal" weight category than in individuals that were under- or overweight (χ^2=1.945; df=1; p=0.021) when body mass was estimated using the femoral head diameter. Table 5.39 presents the frequency of osteoporosis in the fourth lumbar vertebrae. Differences in trabecular bone loss by size, calculated using both bi-iliac breadth and the femoral head diameter, were analyzed using chi-square tests (χ^2).

A slight increase in the frequency of femoral neck and Colles' fractures is seen with increased body mass. Lumbar crush fractures are more common in the "normal" weight category than the overweight and underweight categories, when body mass is estimated using femoral head diameter. No pattern is seen when body mass is estimated using bi-iliac breadth. None of the results were significant for either sex or when the sexes were combined.

Table 5.39 Frequency of osteoporosis in the fourth lumbar vertebrae for females

BMI category		**OP in the 4th lumbar vertebrae**		**Total**
		Absent	**Present**	
Underweight	Count	0	1	1
	% within site	0%	100%	100%
	Standardized residuals	1.3	-0.8	
"Normal" weight	Count	66	24	90
	% within site	73.3%	26.7%	100%
	Standardized residuals	0.4	-0.6	
Overweight	Count	3	5	8
	% within site	37.5%	62.5%	100%
	Standardized residuals	-1.1	1.7	
Total	Count	69	30	99

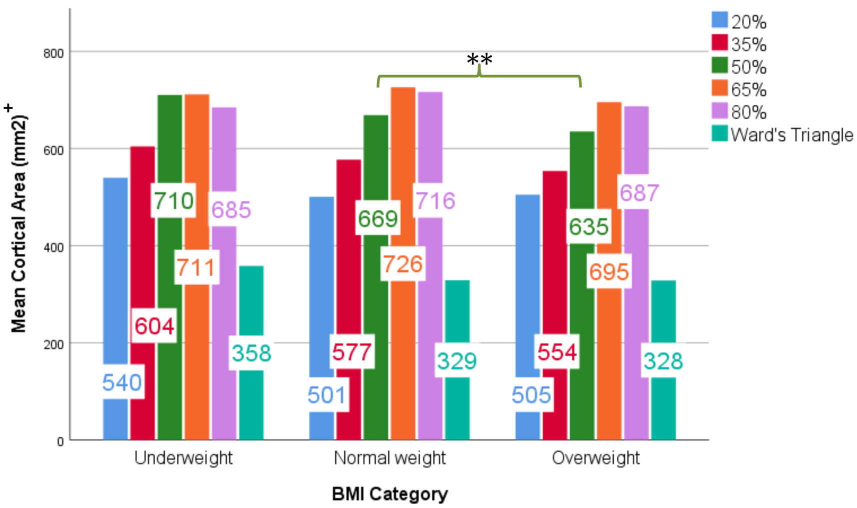
5.7.4 Biomechanics

For females, the strongest and largest category is generally the "normal" weight category. Increasing size and femoral strength is noted as body mass increases in males. When body mass is estimated using bi-iliac breadth, I_{max} (p=0.021), J (p= 0.026), Z_{max} (p=0.032), Z_p (p=0.035) and average cortical thickness ($p=0.029$) at 20%, I_{max} ($p=0.031$) and average cortical thickness ($p=0.014$) at 35%, I_{max} ($p=0.031$) and Z_{max} ($p=0.025$) at 65%, and average cortical thickness at Ward's triangle ($p=0.029$) were significantly different at the 95% confidence interval in males ($n_{underweight}=0$; $n_{\text{“normal”weight}}=52$; $n_{overweight}=3$; $n_{obese}=1$), with the overweight category being larger than the "normal" weight category for every comparison except average cortical thickness at 20% and 35%, which were larger in the "normal" weight category (not size-standardized). Too few individuals fell outside the "normal" weight category in females to compare differences. One-way ANOVAs were run to compare means for biomechanical properties (CA, TA, %CA, I_{min}, I_{max}, Z_{max}, Z_{min}, Z_p, average cortical thickness, I_{max}/I_{min}) along the femoral shaft according to BMI category.

When body mass is estimated using the femoral head diameter, the following results showed significant differences. For females ($n_{underweight}=2$; $n_{\text{“normal”weight}}=75$; $n_{overweight}=4$), percent cortical area ($p=0.027$) and average cortical thickness ($p=0.013$) decrease significantly at 35% between the "normal" weight category and the overweight category; polar second moment of area increases significantly between the underweight and "normal" weight categories at 35% ($p=0.036$), 50% ($p=0.039$), and 65% ($p=0.039$), and I_{max}/I_{min} increase significantly (become less circular) between the normal and overweight categories at 20% ($p=0.022$) and the "normal" weight and underweight categories at 50% ($p=0.034$). For males ($n_{underweight}=1$; $n_{\text{“normal”weight}}=95$; $n_{overweight}=35$), total area ($p=0.043$) and average cortical thickness ($p=0.036$) at 20% decrease significantly between normal and overweight individuals as do total area ($p=0.001$) and average cortical thickness at 35% ($p=0.049$), cortical area ($p=0.046$), total area ($p<0.001$), and minimum second moment of area ($p=0.006$) at 50%, and total area at 65% ($p=0.008$). Figures 5.102

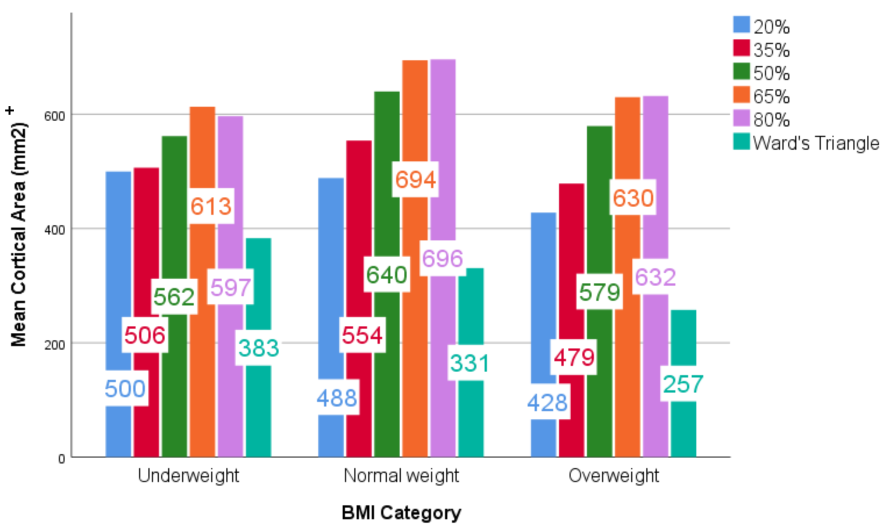
through 5.117 present size-standardized results for the biomechanical properties by BMI category, when body mass is estimated using the femoral head diameter.

Figure 5.102 Mean cortical area by BMI category (FHD) in males



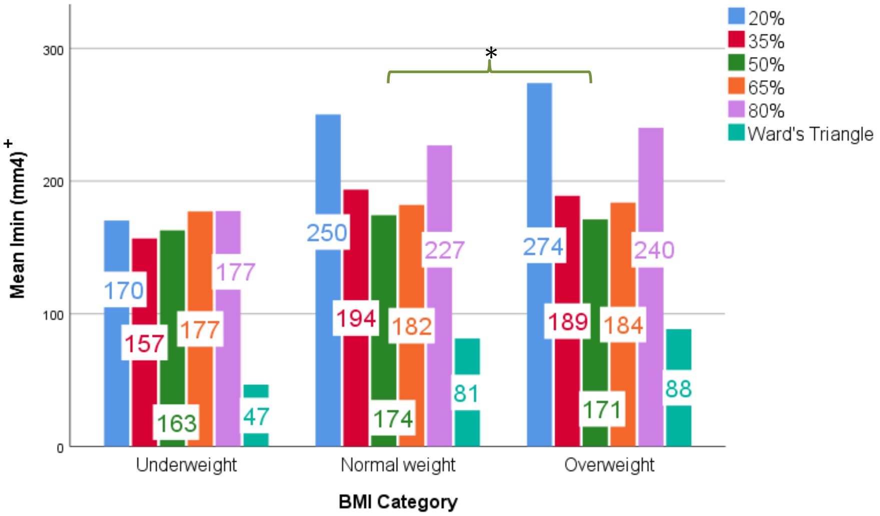
**significant at $p<0.01$
+CA values except are size- standardized; CA_{STD} = CA/BM

Figure 5.103 Mean cortical area by BMI category (FHD) in females



+CA values except are size- standardized; CA_{STD} = CA/BM

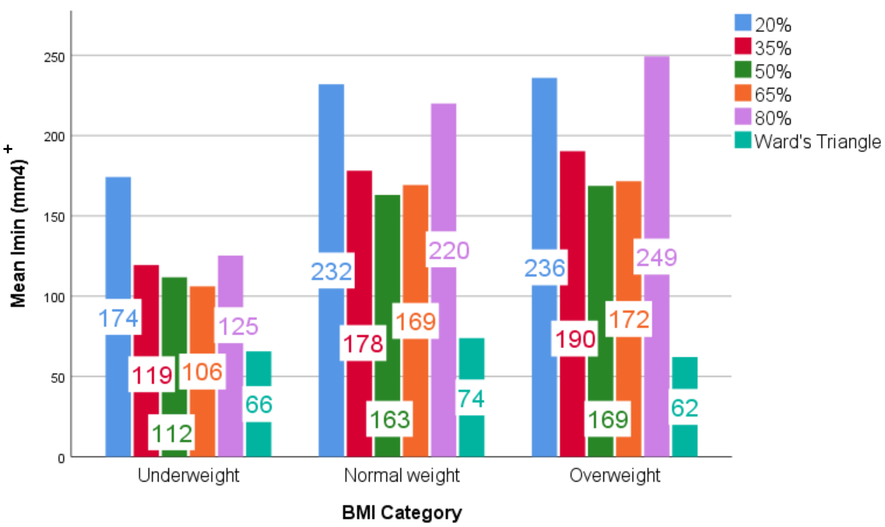
Figure 5.104 Mean minimum second moment of area by BMI category (FHD) for males



*significant at $p<0.05$

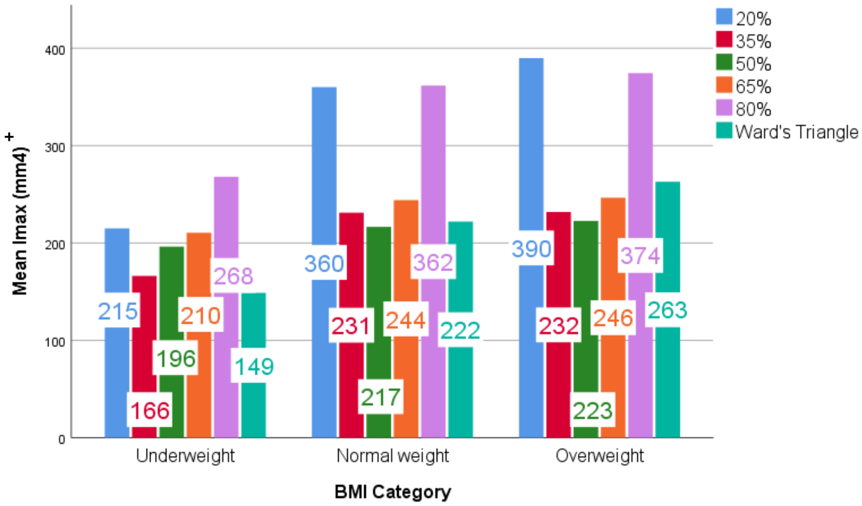
+ I_{min} values are size-standardized: $I_{minSTD} = I_{min}/(BM*Fem\ Length^2)$

Figure 5.105 Mean minimum second moment of area by BMI category (FHD) for females



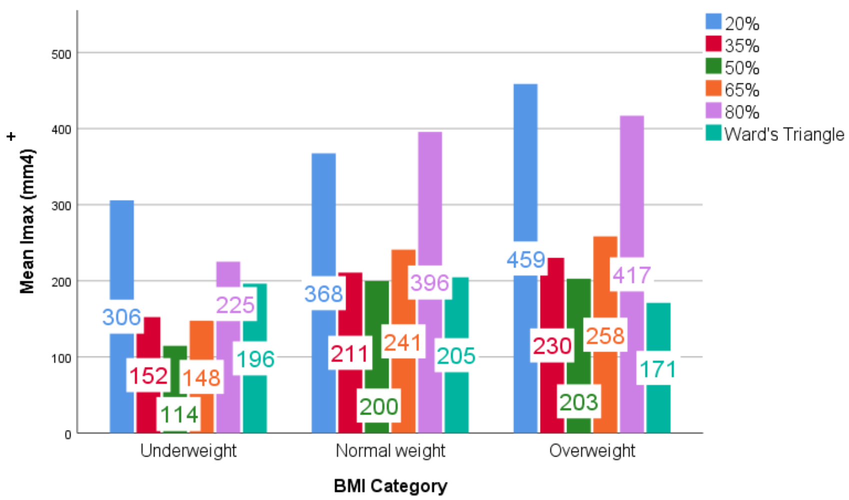
+ I_{min} values are size-standardized: $I_{minSTD} = I_{min}/(BM*Fem\ Length^2)$

Figure 5.106 Mean maximum second moment of area by BMI category (FHD) for males



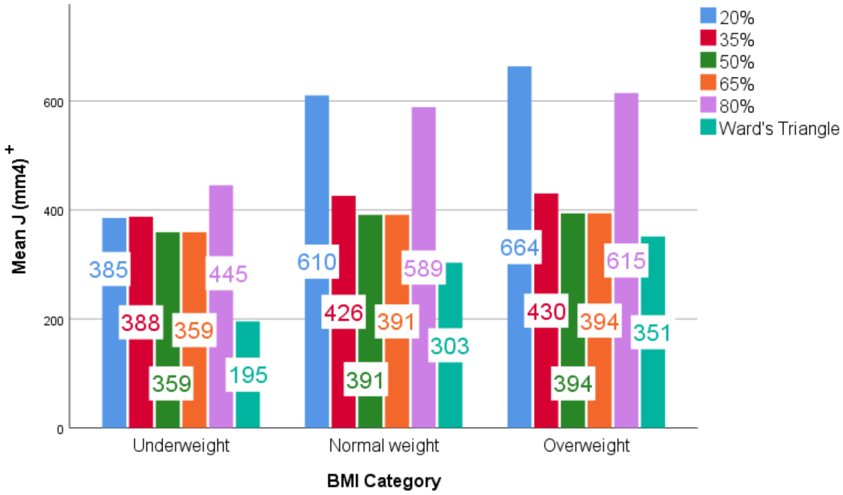
+ I_{max} values are size-standardized: $I_{maxSTD} = I_{min}/(BM*Fem\ Length^2)$

Figure 5.107 Mean maximum second moment of area by BMI category (FHD) for females



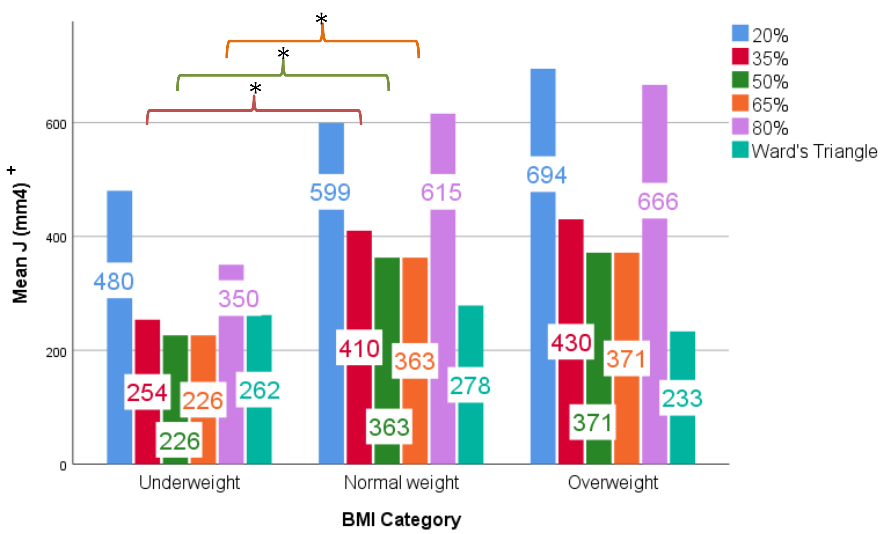
+ I_{max} values are size-standardized: $I_{maxSTD} = I_{min}/(BM*Fem\ Length^2)$

Figure 5.108 Mean polar second moment of area by BMI category (FHD) for males



+ *J* values are size-standardized: $J_{STD} = J/(BM*Fem\ Length^2)$

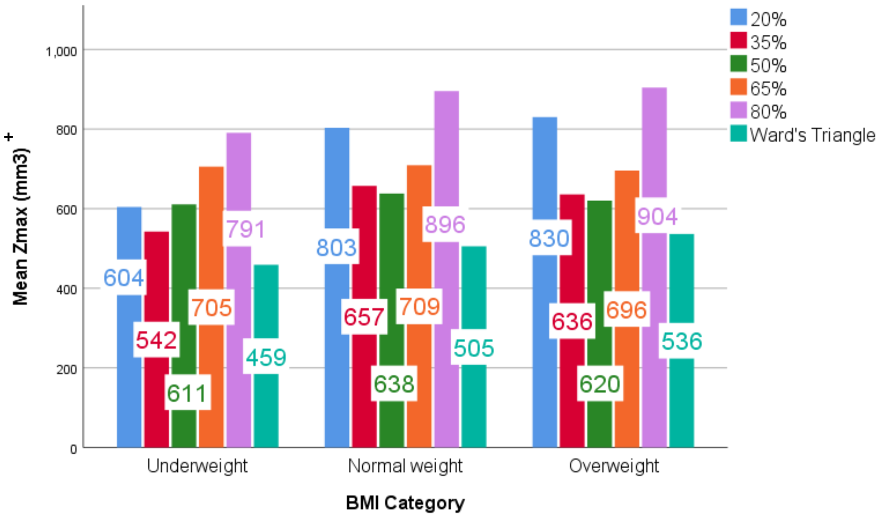
Figure 5.109 Mean polar second moment of area by BMI category (FHD) for females



*significant at p<0.05

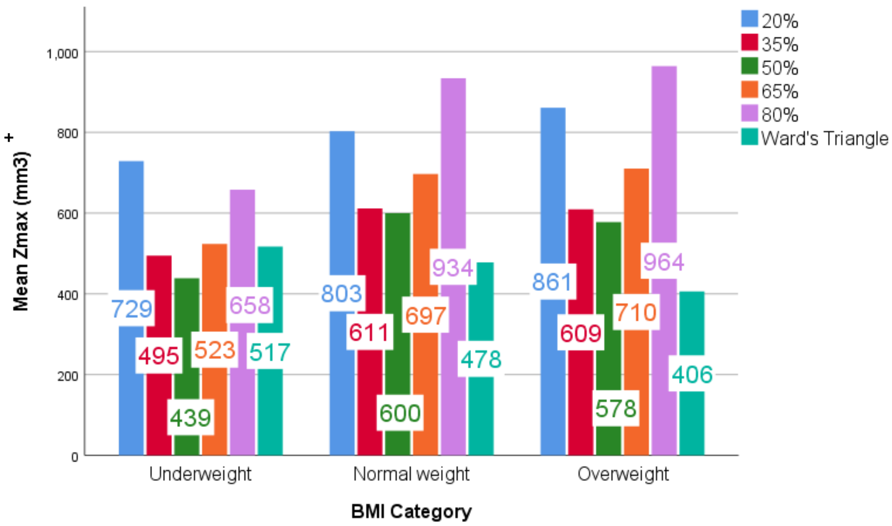
+ *J* values are size-standardized: $J_{STD} = J/(BM*Fem\ Length^2)$

Figure 5.110 Mean maximum section modulus by BMI category (FHD) for males



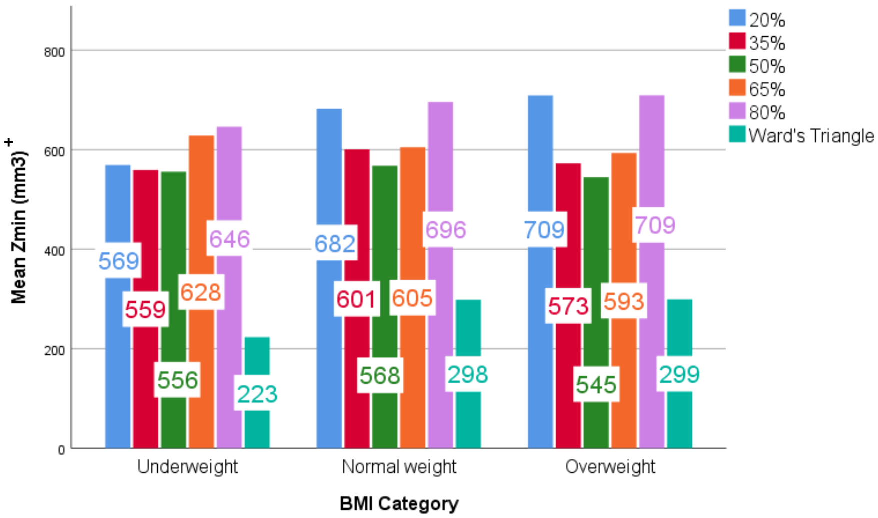
[+] Z_{max} values are size-standardized: $Z_{maxSTD} = Z_{max}/(BM*Fem\ Length)$

Figure 5.111 Mean maximum section modulus by BMI category (FHD) for females



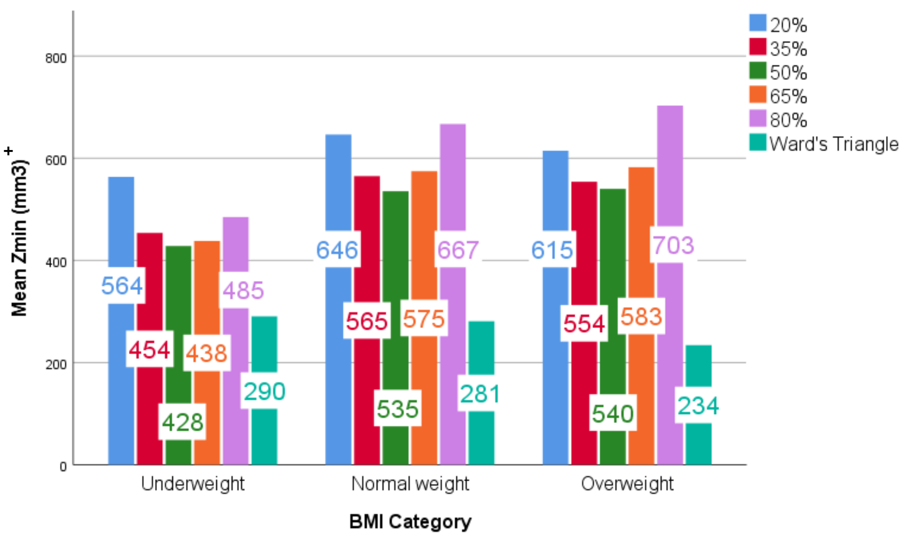
[+] Z_{max} values are size-standardized: $Z_{maxSTD} = Z_{max}/(BM*Fem\ Length)$

Figure 5.112 Mean minimum section modulus by BMI category (FHD) for males



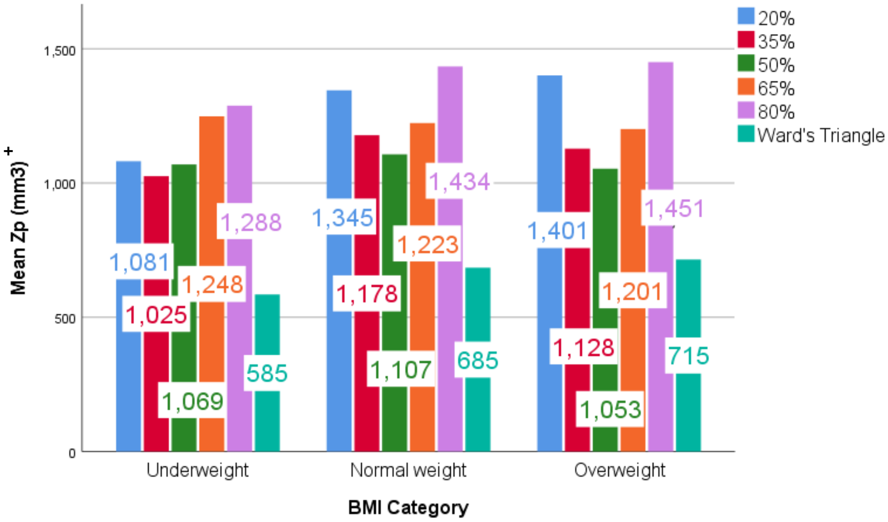
$^{+}$ Z_{min} values are size-standardized: $Z_{minSTD} = Z_{min}/(BM*Fem\ Length)$

Figure 5.113 Mean minimum section modulus by BMI category (FHD) for females



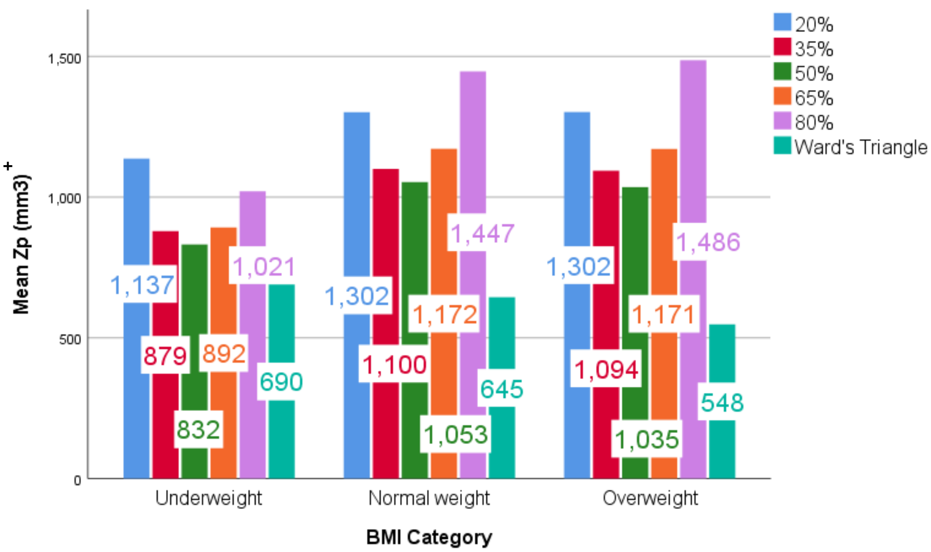
$^{+}$ Z_{min} values are size-standardized: $Z_{minSTD} = Z_{min}/(BM*Fem\ Length)$

Figure 5.114 Mean polar section modulus by BMI category (FHD) for males



$^{+}$ Z_p values are size-standardized: $Z_{pSTD} = Z_p/(BM*\text{Fem Length})$

Figure 5.115 Mean polar section modulus by BMI category (FHD) for females



$^{+}$ Z_p values are size-standardized: $Z_{pSTD} = Z_p/(BM*\text{Fem Length})$

Figure 5.116 Mean shape ratio (I_{max}/I_{min}) by BMI category (FHD) for males

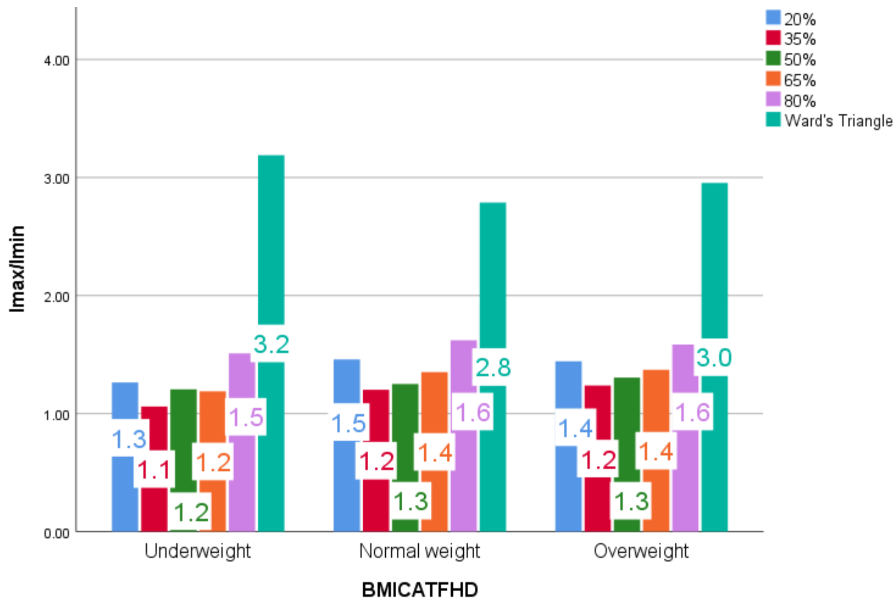
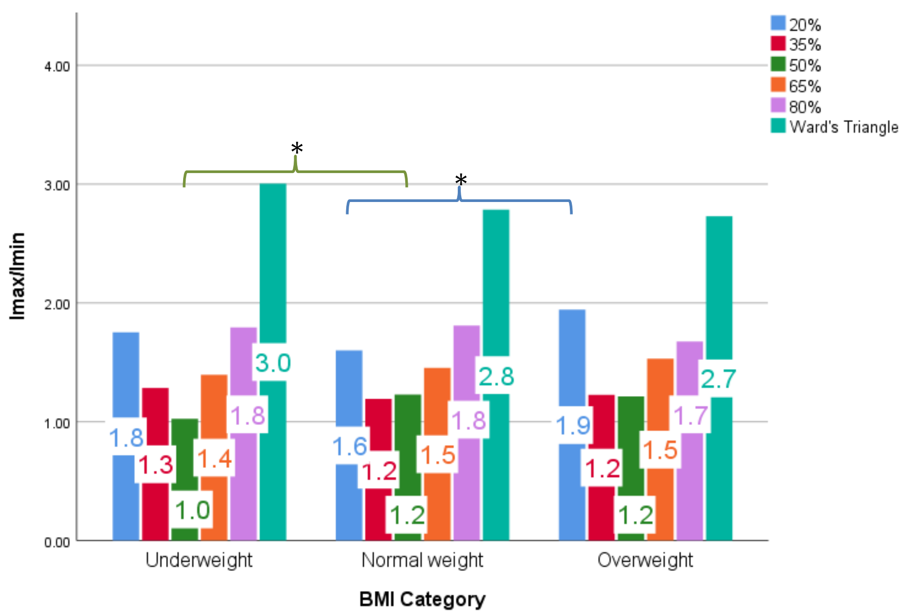


Figure 5.117 Mean shape ratio (I_{max}/I_{min}) by BMI category (FHD) for females



*significant at $p<0.05$

5.8 Summary

The previous chapter presented the results for the comparison of stature, body mass, indulgence-related disorders and degeneration, trabecular degeneration, and biomechanical properties between rural and urban sites, medieval and post-medieval periods, age categories, sexes, and BMI categories. The following chapter will discuss these results in terms of the broader literature and historical context.

Chapter 6: Discussion

6.1 Introduction

Trends in stature, body mass, indulgence-related disorders, and the cross-sectional geometric properties of the femoral shaft as they pertain to location of residence (rural to urban), time period (medieval to post-medieval), age, sex, and body size are discussed. The results are discussed in terms of the osteological literature and the documented history of Denmark and within a broader bioarchaeological context.

6.2 Rural to Urban Trends

6.2.1 Stature

Human development is a dynamic and multifaceted process which can be affected by genetics, nutrition, and environment (Mummert et al. 2011). Research has shown that growth and development are particularly sensitive to environmental upsets (Bogin 1999; Komlos 1994; Schell 1986). For instance, Komlos (1998) illustrated how a decrease in standard of living during the Industrial Revolution led to decreases in overall stature at the population level. While it is a somewhat tenuous relationship, stature has been used in archaeological research as an indicator of overall health in a population. The results of the stature comparison between the rural and urban sample, while not statistically significant, when paired with the significant decrease in mean femoral length suggest that the transition to urban living may have paralleled a decrease in overall health in Denmark. Several publications have illustrated the negative effect of urbanization on health. Petersen and colleagues' (2006) investigation of rural and urban mortality patterns in medieval Denmark established that individuals living in rural communities lived longer than their urban counterparts. The authors associated this trend with a higher quality of life among rural medieval Danes. An analogous trend is seen in the British data (Lewis and

Gowland 2007). According to Palubeckaite et al. (2002) the rural cemetery at Tirup (12th – 14th century CE) presented relatively few examples of developmental stress (linear enamel hypoplastic lesions). The authors argued that this indicated that stress associated with rural living in Denmark was likely acute and that ill health occurred periodically. Rasmussen et al. (2015) discussed the increased levels of lead poisoning among urban medieval Danes, where eating and drinking from lead-glazed pottery was in fashion. Sundman and Kjellstrom (2013) and Dyer (2002) emphasized the negative health outcomes of employment in urban workshops in medieval Sweden and England respectively. Kelmelis and Dangvard Pedersen (2019) caution against the direct interpretation of health based on the rural-urban dichotomy, arguing that this interpretation is often too simplistic and other underlying factors should also be considered. In their analysis of tuberculosis and leprosy prevalence in medieval Denmark, they found no evidence that the movement into urban areas lead to an increase in disease frequency. In Denmark, urbanization was a much slower process than in other European countries, most notably Britain (Hybel and Poulsen 2007). The lack of significance in the stature decrease may reflect this gradual transition. Therefore, temporal trends in health may be more telling than those based on residence location.

It is also possible that the decline in stature related to the migration of merchants into urban areas. The introduction of Germans and Dutch genetic material into the Danish gene pool (Lockhart 2007), may have diluted the tall stature of rural Danes. However, Boldsen (1990) argued that the increased genetic variation among the Danish urban sample would have led to an increase in height. Boldsen (1990) found that the rural medieval sample from Byholm was significantly shorter that the urban sample from Lille Sct. Mikkelsgade. The increase in height among the urban sample was estimated to be up to 8cm. According to Boldsen (1990), this was likely a reflection of population structure. In medieval Denmark the rural communities lived in relative isolation resulting in inbreeding and limiting genetic variation which manifested as decreased stature. The constant flow of migration from rural to urban areas would have made inbreeding unlikely in the urban communities (Boldsen 1990). Boldsen (1990) also suggested that differences in medieval height were correlated with social inequality. Werdelin et al. (2002) noted a similar pattern in their examination of height disparity among medieval and post-medieval Swedes. They argued that the increased height seen in the urban centres, when compared to other areas in Sweden and Denmark, reflected their importance as administrative centres. Urban centres, especially smaller ones, would have housed a higher proportion of individuals of high social standing. In Lund, immigration of Western Danes with relatively high social status, which is strongly correlated with health (DeWitte 2010; DeWitte and Wood 2008; DeWitte et al. 2013; Sullivan 2004; Sutherland 2005), was common. Yoder (2006) found no stature differences between the Danish rural sample of Øm Kloster and the urban samples of Sct. Mikkel and Ribe; however overall health at Øm Kloster was worse, which she posited was due to the sites use as a hospital and not due to rural health in medieval Denmark. Kaupová et al. (2013) noted a non-significant decrease in stature between a rural and urban sample from medieval Bohemia, suggesting that living conditions in the two areas were similar. Similarly, Niskanen et al. (2018) found no differences in stature between rural and urban medieval Swedes. In the post-medieval period the authors found that the urban population from Finland was significantly shorter than the rural population, although the authors caution that this may be more illustrative of a temporal trend as the rural sample is dated later than the urban sample (Niskanen et al. 2018). The trends seen in the current research may also illustrate a temporal rather than residential pattern as the Tirup sample is comprised of skeletal material from the early medieval period, while the use of the urban cemetery, Black Friars, spans the medieval period and into the post-medieval period.

The possibility of bias based on the method of stature reconstruction cannot be discounted. According to Boldsen (1984a) pre-industrial Danes exhibited a significant amount of catch-up growth, leading to limb to torso proportions that did not fit the available stature reconstruction estimation equations. In the current analysis, stature estimated using the Ruff et al. (2012) regression equations was found to be analogous to that measured in grave, which Boldsen (1984a) argued were highly accurate, and the gold standard for stature reconstruction – the anatomical method (Raxter et al. 2006). As such, any bias in stature is expected to be minor. However, due to the possibility of stature bias, femoral length was also used as a proxy for stature, as suggested by Boldsen (1984a).

As Boldsen (1990) and Boldsen and Kronborg (1984) note, stature differs significantly based on area of Denmark. It is possible that the differences in stature and femoral lengths seen between the current samples is reflective of the difference in location. Both historically and contemporarily, Western Jutland exhibits significantly higher average stature than the rest of the country (Boldsen 1990; Boldsen and Kronborg 1984). While location may have influenced the stature disparity between the rural and urban sample, Boldsen and Kronborg (1984) stated that stature in Denmark can be analyzed in two geographic regions, eastern Denmark and western Jutland. Both sites analyzed in this study fall within the parameters of eastern Denmark.

6.2.2 Body Mass

Body mass was analyzed separately using bi-iliac breadth and femoral head diameter, as the two methods garnered significantly different body mass results. The body mass estimates calculated using bi-iliac breadth may be more accurate than those estimated using the femoral head diameter (Auerbach and Ruff 2004); however, it must be noted that the bi-iliac breadth body mass estimation method includes an estimated stature component which introduces bias (Auerbach and Ruff 2004; Ruff et al. 2012). A Pearson's correlation coefficient was computed to assess the relationship between cortical area at the femoral midshaft and body mass estimated using bi-iliac breadth. Moore et al. (2007) found cortical area at the midshaft of the femur to be highly correlated to body mass. A significant positive correlation between the two variables in both males ($r = 0.301$; $p=0.024$) and females ($r=0.386$; $p=0.014$) was found. Due to the fragmentary nature of much of the sample, the femoral head diameter estimates are more useful for discussing patterns on a larger scale. Ruff et al. (1991) found that the femoral head diameter was strongly correlated to body mass at 18 years of age. Historically, weight likely did not fluctuate as significantly as it does in today's more sedentary society. When compared to cortical area at the femoral midshaft, a significant positive correlation was also calculated in both males ($r= 0.524$; $p <0.001$) and females ($r=0.472$; $p<0.001$). Additionally, while weight outputs using the two methods were different, body mass index (BMI) patterns for each method were similar, with the majority of individuals falling within the "normal" weight category. The larger proportion of individuals falling outside of the "normal" weight category when body mass is estimated using femoral head diameter may be due to the larger sample size. Additionally, if, as suggested by Price et al. (1989), the BMI cut-off for males were raised to 27.2 as opposed to 25, the number of males in the overweight category decreases significantly (more so when body mass is estimated using femoral head diameter).

A statistically significant increase in both male and female body mass was noted between the rural ($n_{male}=69$; $n_{female}=39$; avg. $BM_{male} = 66.1$ kg; $BM_{female} = 53.7$ kg) and urban ($n_{male}=176$; $n_{female}=145$; avg. $BM_{male} = 68.0$ kg; $BM_{female} = 56.7$ kg) samples when body mass was estimated using the femoral head diameter, suggesting that body mass increased with movement into urban space. The increase is paralleled by a statistically significant increase in body mass index (BMI) in females but not in males. While not statistically significant, a similar pattern is seen when body mass is estimated using the bi-iliac breadth body mass estimation method. Understanding this change in body mass in the context of medieval and post-medieval Denmark is difficult due to the paucity of literature on rural and urban lifestyle and body mass at the time. Additionally, even when body mass estimates are taken as accurate, BMI can only serve as an indication of body mass not as a measure of body fat itself. Using BMI classifications it is impossible to say whether the individuals classified as overweight/obese were truly overweight or whether the higher BMI is an indication of increased muscularity (Department of Health and Human Services and Centers for Disease Control and Prevention 2018). Strenuous activity and mechanical loading patterns in the past would have led to a much higher muscle to fat ratio than that seen today, which in turn would greatly increase body mass values (Siegmund and Papageorgopoulou 2011). According to Holt et al. (2018) life in rural and urban medieval European settings was likely similarly strenuous. Siegmund and Papageorgopoulou (2011) found that the average body mass in medieval Switzerland was high, especially in males (avg. BM= 71.7 kg, BMI = 26), which the authors allotted to significant physical activity leading greater than average muscularity as well as the short stature of the population. Niskanen et al. (2018) found that medieval Scandinavians had greater body masses than their medieval contemporaries in Europe.

The higher body mass estimates among the urban Danish sample analyzed in the current research may reflect both increased muscularity due to physical labour and decreased stature among the lower classes who flocked to urban settings, as well as increased indulgence and body fat in elite burials. The urban sample likely included more individuals of higher socioeconomic status than the rural sample; during the medieval period the wealthy could petition for burial in the church cemetery (Jakobsen 2008). After the Protestant Reformation, the Black Friars cemetery was one of few cemeteries that remained open and would have, by default, housed a greater number of wealthy individuals. While Yoder (2010) found that diet differed between rural and urban Danish medieval samples, diet was also strongly correlated with social status (Yoder 2012). Vercellotti et al. (2011) and Weiss et al. (2019) found that status significantly affected body mass among their medieval Italian samples from Trino Vercellese and Alba, Cuneo. High status males were significantly heavier than those interred in low status burials. Additionally, in order to combat food insecurity in urban centers, the Danish Kings, as early as Eric of Pomerania in 1422 CE, legislated the policing of food and food trade. Strict regulation was put in place to avoid merchants driving up food prices. The Copenhagen Recess (1540 CE) designated the prices of bread and beer based directly on the price of grain and hops (Mührmann-Lund 2016).

6.2.3 Indulgence-Related Disorders and Degeneration

The frequency of DISH and gout remains relatively low in both the rural and urban samples, which may be a sign of the relatively low affluence in Denmark at the time. However, a significant increase in the prevalence of plantar calcaneal spurs was noted between the rural and urban samples suggesting that vertical compression increased with the shift to an urbanized setting. It has been posited that plantar calcaneal spurs are much more prevalent today due to society’s increasing body mass (Menz et al. 2008; Weiss 2012). As body mass increased with movement into urban towns, it is not surprising that an increase in plantar calcaneal spurs was also noted. Again, this does not intuit that the urban population had more body fat than those living in a rural setting. In fact, an increase in dorsal calcaneal spurs was also noted between the samples, although the difference was not significant. This suggests that a maintenance in physical activities that stimulated the calcaneal tendon (i.e., walking, running, and jumping) existed. However, when paired with the fact that all cases of true DISH (n=2) and the majority of early DISH and gout present in the urban sample, an increase in indulgence was possible. As both DISH and gout are often described (archaeologically) as disorders of the wealthy (Giuffra et al. 2010; Harvey 1993; Jankauskas 2003; Rogers 2000; Rogers and Waldron 2001; Swinson et al. 2010; Waldron 1985; Wells 1973), this could relate to a higher number of elite burials in the urban sample (Jakobsen 2008).

An increase in the frequency of degenerative joint disease in the weight bearing joints was noted between the rural and urban samples when the sexes were combined. The increase is significant for degenerative joint disease in the knees, which was higher and more severe in the urban sample. Again, the link between degeneration of the weight bearing joints and body mass is not straight forward. While there is a link between increased body mass and incidence of degenerative joint disease in the knees, hips, and vertebrae (Abbate et al. 2006; Bridges 1992; Coggon et al. 2001; Felson et al. 1988; Jordan et al. 2007; Melanson 2007; Moore 2008; Sowers and Karvonen-Gutierrez 2010), the prevalence of degenerative joint disease in the weight bearing joints is also high among manual labourers, farmers, and athletes (Coggon et al. 1998; Cooper et al. 1994; Croft et al. 1992a,b; Larsen 2015). Rural agriculturalists often present significantly higher frequencies of weight bearing degenerative joint disease than their urban contemporaries, as exemplified by Kang et al. (2010) in rural China and Jordan et al. (1995) in rural North Carolina. Interestingly, when tested against body mass in prehistoric Californians, Weiss (2006) found no correlation between body mass and knee osteoarthritis and a negative correlation with degenerative joint disease in the hip. Knüsel et al. (1997) caution against directly associating degenerative joint disease with occupation. In their analysis of the medieval monastic cemetery of the Gilbertine Priory of St. Andrews in York, the authors found no difference in the frequency of spinal degeneration between lay people, canons, or the aristocracy. According to the authors, this questions the notion that vertebral degeneration is correlated to occupation.

The increase in osteoarthritis noted in the current research likely stems from the increased load placed on the weight bearing joints as body mass increased but may also indicate a change in occupation. However, life in urban centres in the medieval period would have been similar to that in rural communities (Hybel and Poulsen 2007). Many urban households maintained a plot of land to work in much the same way as rural farms (Dyer 1989). Again, as the urban sample spans a longer time period than the rural sample, this trend may in fact illustrate a temporal trend rather than one based on location of residence.

6.2.4 Degenerative Disorders – Osteoporosis

When comparing trabecular bone between the rural and urban samples, no statistically significant differences in frequency of osteoporosis or osteoporotic fracturing was noted. The frequency of osteoporosis was slightly higher among the rural sample, however the severity of bone loss was greater in the urban sample as was the frequency of osteoporotic fractures. The lack of significance is likely associated with the similar physicality of life in rural and urban Denmark. It should also be noted that due to its effect on bone density, osteoporosis is less likely to be present in the archaeological record, at least in severe forms, as it will be preferentially degraded. Thus, archaeological analyses of osteoporosis likely underestimate its prevalence. Paralleling the current findings, Holck et al. (2007) found no significant difference in osteoporosis between a medieval rural sample from Bjølset and urban samples from St. Clemens and St. Mary’s Churches in Oslo, Norway. Agarwal (2012) found that bone loss began at a much younger age in the medieval rural sample of Wharram Percy in Britain than the urban samples from St. Nicholas Shambles and the Royal Mint. The author posited that this was due in part to seasonal nutritional deficiency leading to suboptimal bone growth patterns in the rural sample. McEwan et al. (2004) noted that while the physicality of life in the rural population of Wharram Percy did not prevent bone loss, it was protective against osteoporotic fracturing. Agnew et al. (2010) found that vertebral fractures were more common in the rural medieval sample from Giecz than the urban sample from Poznań, Poland. However, the authors attributed this more to the rigorous lifestyle of medieval agriculturalists, not to the prevalence of spinal osteoporosis.

It is also interesting to note the general similarity in strength and rigidity at Ward's triangle between the rural and urban samples. In females, the shape ratio (I_{max}/I_{min}) was significantly higher (less circular) in the rural sample suggesting that the femoral neck among females was more strengthened to loading in one direction (Macintosh et al. 2015); no significant difference was noted, however, in either minimum or maximum second moments of area at Ward's triangle. The shape ratio (I_{max}/I_{min}) reflects the circularity of the bone. Decreased circularity has been linked to mobility whereby a less circular shaft denotes higher mobility due to the antero-posterior bending of the shaft during long distance walking or running (Ruff 2010). In males, a significant decrease in bending strength and rigidity along the minimum axis as well as a decrease in circularity was seen among the urban sample. This suggests that male femoral necks were weaker and less rigid along the minimum axis, and thus possibly more prone to fracturing. Additionally, a loss of bone area (identified by the decrease in %CA) is noted in males and females throughout the femoral shaft, significant around the knee, when the urban sample is compared to the rural sample. The decrease in bone in the femoral shaft corresponding with the decrease in bending strength and rigidity in the femoral neck in males may explain why all femoral neck fractures found in this study were among urban males.

In the current analysis, discordance exists between the frequency of spinal and hip osteoporosis (Table 6.1). According to Leslie et al. (2007), when discordance between spinal and femoral bone density exists bone density of the femur is a better predictor of osteoporotic fracture risk than lumbar bone density. Alternatively, spinal bone density is a good predictor of spinal fracture risk. This could explain the low frequency of femoral neck and Colles' fractures when compared to lumbar fractures in both the rural and urban samples.

Table 6.1 Frequency of osteoporosis in rural and urban medieval and post-medieval Denmark

Sex	Location	Method	Frequency
Female	Rural	Femoral neck	16.0%
	Urban	Femoral neck	7.8%
	Rural	4^{th} Lumbar Vertebrae	38.9%
	Urban	4^{th} Lumbar Vertebrae	29.8%
Male	Rural	Femoral neck	2.0%
	Urban	Femoral neck	1.6%
	Rural	4^{th} Lumbar Vertebrae	31.0%
	Urban	4^{th} Lumbar Vertebrae	22.9%

6.2.5 Biomechanics

Bone robusticity, as analyzed by the geometric properties of the right femora, increased between rural and urban Danes. No significant difference in cortical area was seen in either males or females suggesting a maintenance in compressive femoral strength. Total area at the distal femur (20% and 35% in males and 20% in females) increased significantly between the rural and urban sample signifying an increase in the outer dimensions of the distal femur, which was paralleled by a decrease in percent cortical area at 20% in both sexes. This suggests that around the knee there was a significant change in the distribution and amount of bone in the femoral shaft in both males and females. This, in itself, would have had no bearing on bone strength or rigidity. However, a lower percent cortical area when paired with a higher torsional rigidity signifies less bone is present but bone is distributed away from the neural axis of shaft leading to maintenance of torsional rigidity (Larsen 2015).

Measures of bending and torsional strength and rigidity are more applicable to real life forces acting on bone and thus are considered the most relevant indicators of mechanical loading in life (Ruff 2010; Stock and Pfeiffer 2004). A significant increase in bending rigidity and strength along the minimum axis (I_{min} and Z_{min}) throughout the femoral shaft and the maximum axis (I_{max} and Z_{max}) in the distal femur is noted in males. This increase is more prominent in females with a marked decrease in both bending strength and rigidity throughout the femoral shaft along the minimum and maximum axes. A significant increase in torsional rigidity (J) and strength (Z_p) is also noted in both males and females (although Z_p is not significantly different in males at 50% and 65%). Macintosh et al. (2015) found that the tibia presented a higher biomechanical response to stress around the knee. If this is paralleled in the femur it could explain the greater robusticity change noted in the distal femur. Stock (2006) found that strength in the distal femur correlated strongly with activity patterns. Mechanical loading at the mid-femur has been linked to subsistence strategies, with hunter-gatherers presenting high torsional rigidity which decreased with the transition to agriculture. This decrease has been associated with the different levels of mobility in each subsistence strategy (Larsen 2015). The significant increase in femoral robusticity in the current sample may suggest that the urban sample was more mobile than the rural sample; however, Ruff (2018) cautioned that mechanical interpretations along maximum and minimum axes are difficult to interpret without calculating the orientation of the axes (which was outside the purview of this analysis). The decrease in the I_{max}/I_{min} shape ratio (more circular) (significant at 65% and 80% in males and 65% in females) between the rural and urban samples, however, indicates a decrease in mobility. A less circular shaft has been tied to mobility; long distance walking and running increase antero-posterior bending of the femur, leading to a more antero-posteriorly elongated femoral shaft (Ruff 2010). The data suggests an increase in lower limb loading paralleled with a decrease in mobility. However, without an analysis of robusticity change in the upper limb, it is difficult to discern if the mechanical loading undertaken in the rural and urban communities simply changed from activities requiring greater mobility, as one would expect in a rural setting, to physical labour requiring more upper body strength. If this were the case, however, a significant increase in degenerative joint disease in the spine would be expected.

6.2.5 Rural to Urban Trend Summary

It was hypothesized (Hypothesis 1) that the rural sample would be healthier than the urban sample. The results seem to validate this hypothesis. The decrease in stature (significant for femoral length) noted between the two samples could demonstrate a decrease in overall health. The increase in body mass may signify an increase in indulgence among the urban population; however, based on historical documentation, it may be more illustrative of the cemetery make-up. The rural cemetery, Tirup, likely housed mostly agricultural workers (Milner et al. 2015), while the urban cemetery, Black Friars, would have housed a greater portion of elite burials along with the less affluent graves (Mollerup and Boldsen 2010). The poor buried in the Black Friars cemetery may have been buffered somewhat against famine by the strict policing of food distribution in Danish towns (Mührmann-Lund 2016). It is also possible that the increase in body mass in the urban sample is connected to an increase in muscularity, however when paired with the decrease in femoral robusticity this explanation loses some credibility. The significant increase in bending and torsional strength and rigidity of the femoral shaft between the two samples seems to suggest that the urban sample preformed more strenuous activities but were less mobile than the rural sample.

6.3 Temporal Trends

6.3.1 Stature

The temporal stature comparison illustrated a significant decrease in stature and femoral length between the medieval and post-medieval periods in both males and females. A stature decline in the post-medieval period has been noted among several European populations. Steckel (2004) referenced the extremely tall stature of medieval Northern European males (avg. 173 cm) but described a decrease in height as the medieval period closed, paralleling the beginning of the Little Ice Age. The average male height dropped to 167 cm. According to Steckel (2004), an increase of two to three degrees during the medieval warming period (900 – 1300 CE) was responsible for the elevated stature. By the 14th century temperatures dropped, leading to lower food production, economic isolation, and decline in health, which continued until the retreat of the Little Ice Age in the 18th century. Niskanen and colleagues' (2018) results for medieval and post-medieval Scandinavians and Finns paralleled those of Steckel (2004). Again, the authors concluded that the decreasing stature was a product of worsening health with the onset of the Little Ice Age. A temporal trend, which was significant in males, towards decreasing stature was also seen among medieval to post-medieval Swedes (Werdelin et al. 2002). According to Werdelin et al. (2002) standard of living fell in post-medieval Sweden, leading to an overall poorer health outcome. Although Gustaffson et al. (2007) found no significant stature decrease among Swedes between the 10th and 17th centuries. In the Netherlands, Maat (2005) noted a trend towards decreasing stature in the late medieval period which continued into the post-medieval period. Maat (2005) blamed this negative trend on increased urbanization and overcrowding.

Interestingly, the lowest calculated stature coincided with Netherlands ‘Golden Age’, when the Dutch experienced unprecedented economic prosperity. Maat (2005) argued that the decreased stature reflected the concentration of wealth in the upper echelons of society.

In accordance with the studies described above, the temporal decrease in stature noted in the current sample was likely associated with worsening health in the post-medieval period paralleling the Little Ice Age and its resultant crop failures (Fagan 2000). Across Europe the Little Ice Age led to widespread starvation. Denmark experienced a series of consecutive harvest failures and the Great Famine (1315-1322 CE) (Jordan 1996). A direct result of the poor harvest yields was that the rural poor flocked to urban centres where food security was strictly regulated. While food security may have been better in urban centers in the post-medieval period (Mührmann-Lund 2016), increased population density and close living spaces may have led to a decline in health. The post-medieval period also saw a concentration of wealth among the elite (Lockhart 2007) and likely a health disparity between the nobility and peasantry in the post-medieval period. The decrease in post-medieval health has previously been documented in the Black Friars cemetery. Scott (2015) illustrated a temporal increase in the level of skeletal stress.

6.3.2 Body Mass

Body mass did not exhibit a significant change temporally, however when height was accounted for which, as previously discussed decreased significantly in the post-medieval period, a significant increase in BMI was noted by time period for both males and females. Food scarcity along with the increasing cost of food was an issue around Europe in the post-medieval period (Anderson 2011). There are several possible explanations for this increase in BMI. It is possible that the increased BMI is illustrative of cemetery make-up with more elite burials existing in the post-medieval sample (Mollerup and Boldsen 2010), however considering the temporal decrease in stature, this seems unlikely. It is also possible that legislation, put in place in the late medieval period, which strictly regulated the distribution and sale of food in urban post-medieval Denmark (Mührmann-Lund 2016) gave post-medieval Danes better access to food even as food insecurity increased. However, given that historical sources suggest that peasants in the post-medieval period were unable to feed themselves, turning to begging for food in urban centres (Anderson 2011), the legislation of food distribution may not have been as affective as intended. The most likely explanation is that the poor in urban centres were required to undertake employment in increasingly physically demanding jobs leading to an overall increase in muscularity and body mass. In contrast to the data presented here, Niskanen et al. (2018) note a significant decrease in body mass, with little temporal variation in BMI, among Scandinavians and Finns in the post-medieval period following relative stability throughout and prior to the medieval period.

6.3.3 Indulgence-Related Disorders and Degeneration

A small (and not statistically significant) increase in the frequency of indulgence-related disorders was noted between the medieval and post-medieval periods. The temporal consistency suggests that the lived experience and diet were likely similar throughout these periods. Yoder (2010) found no temporal shift in diet between early and late medieval periods in Denmark. Food choices remained relatively consistent into the post-medieval period as well (Anderson 2011) and while the Protestant Reformation (1536 CE) allegedly loosened fasting proscriptions, fasting rituals were maintained in private by many post-reformation Danes (Albala 2011). The small increase in indulgence-related disorders could be accounted for by the increase in elite burials (Mollerup and Boldsen 2010) and availability of specialty food items in the post-medieval period (Anderson 2011).

Presenting rough frequencies of disease is problematic as the lived experience of a population is not necessarily reflected in the skeletal assemblage (Wood et al. 1992), however this is still common practice. If taken as indicative of the archaeological population's true frequency, the frequency of DISH among both medieval and post-medieval Danes is low compared to other archaeological populations from contemporaneous time periods (Table 6.2).

Without chemical analysis, the frequency of gout is even more difficult to estimate. Gout often involves only the first metatarsal and adjacent proximal pedal phalange, skeletal elements which are often preferentially degraded or missed during excavation. Buckley (2011) argued that gout presence, as opposed to prevalence, should be discussed. While frequency analysis was avoided, the medieval and post-medieval Danish samples do seem to present a significant amount of gout when compared to other medieval samples. Table 6.3 depicts the cases of gout in the current study as well as those from analogous time periods; single case studies were excluded.

Table 6.2 Prevalence of medieval and post-medieval DISH

Site	Time Period	Reported Frequency	Male	Female	Reference
Tirup and Black Friars, Denmark	Medieval	0.5 %	0.1%	0%	Current
Black Friars, Denmark	Post-medieval	0.6%	1%	0%	Current
Lithuania	Iron Age to Early modern		18.0%	2.6%	Jankausas 2003
Saint Servaas Basilica, Netherlands (Canons)	Late Medieval	100%			Janssen and Maat 1999
Ipswich Blackfriars, UK (Dominican monks)	Late Medieval	13.4%			Mays 1991
Ipswich Blackfriars, UK (Lay people)	Late Medieval	3.4%			Mays 2000b
Wharram Percy, UK	Late Medieval	15.9%			
Wells Cathedral, UK	Late Medieval	9.1%*			

The Royal Mint, UK	Late Medieval	4.0%*			Rogers and Waldron 2001
Onze Lieve Vrouwe Church, Netherlands	Late Medieval	40.4%			Verlaan et al. 2007
Merton Priory, UK	Late Medieval	8.6%			Waldron 1985

* Significantly higher in the monastic burials than lay burials

Table 6.3 Reported cases of medieval and post-medieval gout

Site	Time Period	Cases Reported	Sex	Reference
Tirup and Black Friars, Denmark	Medieval	11	2F; 9M	Current
Black Friars, Denmark	Post-medieval	10	3F; 7M	Current
Wairau Bar, New Zealand	AD 1288-1300	5	5M	Buckley et al. 2010
Apurguan, Guam	AD1000-1521	4	1F; 3M	Douglas et al. 1997
St. Peters' Barton-on-Humbers, UK	AD 950-1855	12	Not specified	Rogers 2000
Gogna-Gun Beach, Guam	AD 950-1450	14	7F; 7M	Rothchild and Heathcoate 1995
St. Peters' Barton-on-Humbers, UK	AD 950-1855	10	3F; 4M; 3?	Waldron 2007

An increase in the frequency of degenerative joint disease in the weight bearing joints was noted between the medieval and post-medieval periods. The increase was significant for osteoarthritis of the knees in males. As BMI increased in the post-medieval period, this increase in osteoarthritis was not surprising. It is more difficult to say whether the increase is associated with increased indulgence or muscularity. When understood in conjunction with other results, increased muscularity is more likely, possibly associated with an occupational transition. In contradiction to the current findings, Waldron (1995) found that degenerative joint disease in the knees and spine were more common in medieval than in post-medieval Britain. According to Waldron (1995) a change in activity is likely the cause, however he does cite the possible involvement of diet and body mass changes. Analyzing European samples from the Czech Republic and Slovakia (ca. 5700 BC), Crubézy et al. (2002) illustrated that, when corrected for age, the prevalence of degenerative diseases in the lower limb have remained constant over time, indicating that genetics play a significant part in the degeneration of joints.

6.3.4 Degenerative Disorders – Osteoporosis

In the current analysis, osteoporosis (when analyzed in the femoral neck) and osteoporotic fractures remained low in both the medieval and post-medieval periods. No significant temporal change in frequency between periods was noted. There is, however, a significant temporal increase in cortical bone size at Ward's triangle in both sexes. In males, total area as well as minimum and maximum bending and torsional strength and rigidity at Ward's triangle increased significantly with time. The shape ratio (I_{max}/I_{min}) decreased significantly between time period in both sexes, leading to a more circular neck in the post-medieval period. In females, bending strength along the minimum axis at Ward's triangle increased significantly between periods. Taken together, this indicates that post-medieval femora were stronger in the femoral neck than medieval femora, possibly suggesting that post-medieval femoral necks were less likely to fracture. A slight (and not statistically significant) decrease in osteoporotic fractures in the post-medieval period was seen. Interestingly, the amount of cortical bone (%CA) along the femoral shaft (significant at 20%) in males and females decreased while the total area of bone increased between the medieval and post-medieval periods. This indicates that individuals in the post-medieval period presented lower cortical bone mass, however the bone that was present was laid down away from the neural axis of the femur creating a larger medullary cavity and, thus, maintaining strength and rigidity in the femur.

The current data is well placed within previous investigations of medieval and post-medieval osteoporosis, most which suggest that bone mass was maintained more readily in archaeological populations than modern ones (Agarwal et al. 2004; Brickley 2002; Poulsen et al. 2001; Ruff and Hayes 1983). Agarwal et al. (2004) and Agarwal and Grynpas (2009) posited that the physically demanding lifestyle in medieval Wharram Percy, Yorkshire, would have protected the population from bone loss. Further, the authors speculated that reproductive factors, such as multi-parity and later weaning times, may have played a role in female bone maintenance. (These results are at odds with Mays (1996) and Mays et al. (1998) analyses of osteoporosis at Wharram Percy). Some research, while finding low bone mineral density in archaeological populations, does not find high levels of osteoporotic fracturing. This has been linked to the physicality of life in medieval settings (McEwan et al. 2004). When analyzing bone density in medieval Norway, Mays et al. (2006) note a significant amount of bone loss and osteoporotic fracturing which they posited was due to falls on harder ground in Norway resulting in a higher fracture prevalence. Curate et al. (2010) found that nuns interred in the Santa Clara-a-Vehla Convent cemetery (14^{th}-17^{th} Century) presented a higher than expected number of osteoporotic hip fractures, which they associated with a lack of sun exposure (Vitamin D) in the convent leading to lower peak bone mass development.

When compared to modern samples, medieval and post-medieval bone loss is often much lower. Vestergaard et al. (2005) estimated that the prevalence of osteoporosis in Denmark today is approximately 40.8% in women and 17.7% in men greater than 50 years of age. Poulsen et al. (2001) found that bone mineral density (BMD) was lower among medieval females but higher among medieval males from Norby than from modern Danish samples. This decrease was paralleled in both males and females in results from Bennicke and Bohr (1990). Ekenman et al.

(1995) found no difference between modern and medieval Swedish woman in terms of BMD; males were shown to have higher BMD than the comparative modern sample. Lees et al. (1993) stated that females from the Christ Church, Spitalfields cemetery (18th and 19th Century) did not exhibit the marked post-menopausal bone loss seen in modern women which they argued was due to physical activity and multi-parity's protective effect on age-related bone loss. Alternatively, when analyzed by Mays (1996) and Mays et al. (1998), similar patterns of bone loss were noted between modern women and medieval women interred in the medieval cemetery of Wharram Percy, which Mays (1996) argued questions the importance of lifestyle on osteoporosis severity. In the current analysis, the frequency of femoral neck osteoporosis in the historical population of Denmark, both rural and urban, is markedly lower than that of modern Danes (Table 6.3). However, due to differing technologies and inherent bias in the archaeological sample, this comparison must be made cautiously.

Table 6.4 Frequency of osteoporosis in Denmark

Sex	Time Period	Location	Method	Frequency
Female	Contemporary*	Combined	Clinical	40.8%
	Medieval	Rural	Femoral neck	16.0%
	Medieval	Urban	Femoral neck	0%
	Post-medieval	Urban	Femoral neck	10.8%
	Medieval	Rural	4th Lumbar	38.9%
	Medieval	Urban	4th Lumbar	32.0%
	Post-medieval	Urban	4th Lumbar	29.0%
Male	Contemporary*	Combined	Clinical	17.7%
	Medieval	Rural	Femoral neck	2.0%
	Medieval	Urban	Femoral neck	0%
	Post-medieval	Urban	Femoral neck	2.7%
	Medieval	Rural	4th Lumbar	31.0%
	Medieval	Urban	4th Lumbar	22.2%
	Post-medieval	Urban	4th Lumbar	23.4%

***** data from Vestergaard et al. 2005

6.3.5 Biomechanics

In general a maintenance of bone's biomechanical properties in the femoral shaft in males was seen between the medieval and post medieval periods, with significant decreases in cortical area at the distal, mid-, and mid-proximal femur. This points to a decrease in compressive strength between the medieval and post-medieval samples. The decrease in strength may simply reflect the loss of the Dominican friars in the post-medieval Black Friars sample. Holck (2007) found that the Dominican Friars interred at St. Olav's monastery in Oslo, Norway, exhibited significantly higher bone mineral density than the comparative rural population. According to Holck (2007), the bone density maintenance among the friars is an indication of physicality, suggesting that the friars led more physically demanding lifestyle than farmers, which is at odds with our current understanding of the lifestyle of the Dominican friars (Holck 2007). Bone strength among the Black Friars may also represent their upbringing, usually as members of the nobility (Bennett 1937). Increased access to food as young men may have led to higher peak bone mass among males recruited into Dominican order.

The decrease in strength may also indicate a change in physical loading in males in the post-medieval period. Occupations common in medieval and post-medieval Denmark included (but were not limited to) smiths, bakers, butchers, shoemakers, carpenters, and skinners. Occupations undertaken by urban post-medieval males may have put less compressive force on the femora. At the very least, these occupations likely required lower mobility than farming. The change in the shape ratio at the proximal femur to a more circular shaft may illustrate a decrease in mobility between the samples. Interestingly, Stock (2006) found that strength in the subtrochanteric region in the femur was more highly correlated to temperature than mobility with individuals from colder climates exhibiting stronger proximal femora than those from warmer climates. The increase in circularity between the medieval and post-medieval periods parallels the onset of the Little Ice Age. However, if changing temperatures were the cause of the shape change seen in the current analysis an increase in antero-posterior elongation of the proximal femur would be more likely than the decrease noted in the current analysis. It is more likely that the change in shape ratio is a result of different types of loading among urban craftsmen and farmers, where the latter are more mobile than the former. Without an analysis of upper body, specifically humeral robusticity, it is difficult to discern whether mechanical loading differed in intensity or merely in type. This interpretation cannot be verified as no rural sample from post-medieval Denmark was included in this analysis.

Interestingly, the temporal transition seems to have affected females more significantly than males. A significant increase in robusticity in the femoral shaft in females was noted between the medieval and post-medieval periods. Minimum bending rigidity and strength increased significantly along the femoral shaft, as does maximum bending strength and rigidity at the proximal and distal femur. Torsional strength and rigidity also increased significantly at the proximal and distal femur in females. In Scandinavia, many women moved to urban centers to gain independence and economic freedom (Jacobsen 1983; Sawyer and Sawyer 1993). However, lucrative positions in craft and trade were often closed to women and few positions in domestic service were available meaning that some women were forced to turned to more physical positions such as laundering clothes or working on ferries all while upholding traditional roles in the household (Jacobsen 1983). Females were also tasked with maintaining and working land plots in their own homes or for those under which they were employed (Dyer 1989). Contradictory to the current findings, Niskanen et al. (2018) found an increase in strength and robusticity in both males and females in the medieval period as compared to the Iron Age in

Scandinavia followed by a slight, and not significant, decrease in robusticity in the post-medieval period.

6.3.6 Temporal Trend Summary

The data presented in this analysis is in accordance with Hypothesis 2, that a temporal trend towards decreasing health would be seen between the medieval and post-medieval periods. The significant decrease in stature paralleled with the increase in BMI likely indicated an increase in muscularity between the periods. An increase in indulgence in the post-medieval sample is also possible. However, this is unlikely as no increase in indulgence-related disorders is seen, apart from knee osteoarthritis which could be linked to occupation or muscularity. The biomechanical analysis of the femur suggests that mobility and mechanical loading remained relatively constant for males. Interestingly, female femora are stronger and more robust in the post-medieval period suggesting that, for females, mechanical loading and mobility increased after the Reformation, possibly associated with the difficultly women had trying to find work in traditional roles (Jacobsen 1983).

6.4 Aging Trends

6.4.1 Stature

When compared by age category, stature among males was significantly taller in the 50 to 70 years-at-death age category than the 30 to 50 years-at-death age categories followed by decreased stature in the oldest age category (> 70 years-at-death). The higher stature in individuals who died between ages 50 to 70 is interesting as it may reflect increased survivorship in healthier (taller) males. It is possible that the healthier individuals were able to overcome instances of ill-health and thus exhibited better survival rates into older age, as posited by the osteological paradox (Wood et al. 1992). Kemkes-Grottenthaler (2005) determined that skeletal height, based on long bone length data archived in the Database for Prehistorical and Historical Anthropology, was significantly correlated to increased life expectancy, with taller individuals living to older ages. These findings are supported archaeologically (Gunnell et al. 2001; Saunders and Hoppa 1993; Steckel 2003) and contemporarily (Davey Smith et al. 2000; Waaler 1984), although some modern studies find an inverse relationship between height and longevity (Lemez et al 2017; Samaras and Storms 1992; Samaras and Elrick 2002). In fact, in the current analysis, as the oldest age category was also the shortest, it is possible that height parallels survivorship until age 70 years, after which height is detrimental to survivorship as posited by some more current research (Lemez et al 2017; Samaras and Storms 1992; Samaras and Elrick 2002).

The differences in stature by age groups may be confounded by the temporal differences noted between the medieval and post-medieval periods. When separated by time period, the differences remain significant in the post-medieval period, with the 50 to 70 years-at-death age category being significantly taller than all other age categories (<30, 30-50, >70 years) ($p_{<30}$ = 0.029; $p_{30\text{-}50}$ = 0.022; $p_{>70}$ = 0.007), indicating that taller males exhibit better survivorship in the post-medieval period (at least until age 70) but not the medieval period. DeWitte and Wood (2008) and DeWitte (2010) illustrated how the Black Death epidemic preferentially killed frail, unhealthy males. The post-Black Death population were more likely to live into older age (DeWitte 2014). No skeletons from Tirup or Black Friars could be accurately dated to the late medieval period. As such, the post-medieval sample represents the post-Black Death era in the current analysis.

The stature estimates by age category may be further biased by the use of the anatomical stature reconstruction method without an age correction term (Raxter et al. 2006). The regression equation without an age correction was selected for this analysis as it provided more consistent results with the skeletal length measured in grave (Boldsen 1984b). According to Raxter et al. (2007), using the formula without an age term will consistently underestimate stature if the age-at-death of the individual being assessed is below 50 years and may overestimate stature in individuals older than 50 years (although rarely). In the current analysis, this would mean that the true living stature of the <30 and 30 to 50 years-at-death age categories were taller than currently estimated. When stature estimates calculated with the age correction were compared by age category, the 50 to 70 years-at-death age category remains notably taller than all other age-categories, however no significant difference between heights remain. It is possible that this results from the increasingly small sample sizes in the older age categories.

6.4.2 Body Mass

In general, no significant differences were noted between age categories in terms of body mass. When compared to other categories of males, the <30 years-at-death age category was significantly lighter than the 50-70 years-at-death age category when body mass was estimated using femoral head diameter. However, when height was accounted for no significant differences in BMI remained. The lack of significant difference in BMI with age may suggest a similar level of indulgence and physicality in life among the age categories. However, results garnered using the femoral head diameter are expected to be more associated with age at approximately 18 years than body mass at time of death and, thus, cannot help in identifying aging patterns for body mass. As stature was calculated in part using the anatomical method without an age correction, BMI results (calculated using both the femoral head and bi-iliac breadth) would also be biased (as discussed in the stature section).

6.4.3 Indulgence-Related Disorders and Degeneration

Indulgence-related disorders, while significantly correlated to indulgence and obesity (see Menz et al. 2008; Rogers and Waldron 2001, Weiss 2012), are also significantly correlated to age (Jankauskas 2003; Maat et al. 1995; Ortner 2003; Rogers and Waldron 2001; Weiss 2012). Both DISH and gout are rarely seen in individuals below the age of 40 (Ortner 2003; van der Merwe et al. 2012). Weiss (2012) and Cermak and Kirchengast (2015) found that both plantar and dorsal calcaneal spurs increased with age. As expected, an increase in all disorders was seen with age in the current sample. However, only in the presence of DISH and eDISH was the difference significant. It is possible that small sample sizes in the older age categories are the cause of the lack of significance seen in plantar calcaneal spurs and gout.

Degenerative joint disease is also an affliction of older individuals (Anderson and Loeser 2010). Increased body mass may exacerbate the degeneration of the weight bearing joints, however age-related degeneration would also be present due to long term loading at the hips, knees, and lumbar spine. As expected, a significant increase in osteoarthritis in the knees and hips and vertebral osteophytosis in the lumbar spine was noted with age. Interestingly, the oldest age category (>70 years-at-death) often illustrated a decrease in the frequency of degenerative joint disease. It is possible that the decrease in frequency is illustrative of health among the individuals that survived into old age; however, it is equally likely that the small number of individuals that fell into the oldest age category (>70 years-at-death) is creating bias in the sample.

6.4.4 Degenerative Disorders – Osteoporosis

Clinically, osteoporosis is a disease of the elderly, especially post-menopausal women (Curate 2014). Age-related degeneration in bone has been seen both clinically (Khosla and Riggs

2005; Pietschmann et al. 2009; Riggs and Merton III) and archaeologically (Cho and Stout 2011; Drusini et al. 2000; Frigo and Lang 1995; Glencross and Agarwal 2011; Kneissel et al. 1994; Lees et al. 1993; Mafart et al. 2008; Mays 1996; Mays et al. 1998; McEwan et al. 2004). Interestingly, many researchers have not found a steady decline in bone density into old age in archaeological populations (Agarwal et al. 2004; Agarwal and Grynpas 2009; Ekenman et al. 1995; Poulsen et al. 2001). In a medieval Danish cemetery from Norby (1000-1250 CE), Poulsen et al. (2001) found that medieval women lost significant bone density at a younger age than that seen in modern Danish women. In the Danish medieval sample a significant increase in bone density among older women was also noted. The authors posited that the decrease in bone density was associated with multi-parity and the high mortality of women during their childbearing years. The increase in bone density among the older women was linked to the cessation of childbearing as well as the preferential survivorship of healthier, stronger females (Poulsen et al. 2001). Agarwal et al. (2004) note a significant age-related decrease in bone density in males at the Wharram Percy site in Yorkshire. No significant bone changes are seen among females, which the authors speculated was, again, associated with parity and later weaning times (Agarwal et al. 2004).

In the current study, a significant increase in osteoporosis is noted in the fourth lumbar vertebrae in females with age. Interestingly, when analyzed in the femoral neck, a significant increase in the frequency of osteoporosis into middle age is seen (30-50 years-at-death) with a decrease (not significant) into the older age categories. Paralleling the research discussed above, this could illustrate the effect of childbearing and breastfeeding on bone density as well as the high mortality of females of reproductive age. Other studies have identified parity and breastfeeding to be significant contributors to bone loss among reproductive aged women

(Agarwal 2008; Agarwal and Grynpas 2009; Agarwal et al. 2004; Beauchesne and Agarwal 2014; Martin and Armelagos 1979). Multiparity has been linked to higher bone density in older women as healthier, stronger women are expected to preferentially survive their reproductive years (Poulsen et al. 2001; Streeten et al. 2005). It was common for medieval Danish women to be married by sixteen years of age (Benedictow 2003), there is no evidence to suggest that this trend did not continue into the post-medieval period.

In males, an increase in osteoporosis in the oldest age category (>70 years-at-death) was seen in the femoral neck and an age-related increase was noted in the fourth lumbar vertebrae, although a decrease in the frequency of osteoporosis in the fourth lumbar vertebrae was noted in the oldest age category (>70 years-at-death). Osteoporotic fracturing was relatively low in the current study (although the frequency of vertebral crush fractures was elevated compared to femoral neck and Colles' fractures). Other researchers have noted this phenomenon previously even in the presence of bone loss (see Mays et al. 1998; McEwan et al. 2004). Osteoporotic fracturing, while not significantly different between age categories, was seen to increase into middle age then decrease into the older age categories. This pattern was noted for femoral neck fractures in males and spinal crush fractures in both males and females. Colles' fractures increased with age in females. It is possible that these frequencies indicate that the oldest individuals in the skeletal samples were indeed the healthiest, strongest members. In support of this assumption is the significant increase in bending and torsional strength and rigidity at Ward's triangle in the femoral neck between the young adult males (<30 years-at-death) and the middle-aged males (30-50 years-at-death). This increase continued into old age, although the increase was not significant. In males percent cortical area decreased significantly with age (with an increase in the 50 to 70 years-at-death age category). Paired with an increase in total area until the 50 to 70 years-at-death age category suggests that males, while losing bone mass, are maintaining bending and torsional strength and rigidity into older age. This was not true for females who displayed a significant decrease in the amount of bone (%CA) at Ward's Triangle with age paralleled with the decrease in percent cortical area and average cortical thickness along the femoral shaft (significant at 80%).

6.4.5 Biomechanics

Cortical bone geometry has previously been used to identify or verify age-related bone loss and osteoporosis in archaeological bone (Dequeker et al. 1997; Dewey et al. 1969; Drusini et al. 2000; Ericksen 1976, 1980; Martin and Armelagos 1979; Mays 1996, 2000; Richman et al. 1979; Ruff and Hayes 1982, 1983). Most of the more recent publications center around the loss of trabecular bone and only reference the loss of cortical bone with age (Farquharson and Speller 1997; Mays et al. 1998). In the current study, age-related cortical bone loss was noted in females resulting in a loss of compressive, bending, and torsional strength with age; however only the decrease in bending strength between the <30 and 30-50 years-at-death age categories met significance standards (α=0.05). In males, an interesting pattern was noted. The results indicated an initial decrease/maintenance in robusticity into middle age (30 to 50 years-at-death) followed by a significant increase in the older adult age category (50 to 70 years-at-death) with a final decrease in the oldest adults (>70 years-at-death). Again, this trend is possibly reflective of the increased survivorship of stronger males but may also indicate sample size bias in the older age categories.

6.4.5 Age Trend Summary

Age-trends are problematic to analyze given the difficulty accurately aging older individuals. Transition analysis, used in this study, allows for more precise age-at-death estimates in the older age categories (Milner and Boldsen 2012a). Based on the concepts discussed in the osteological paradox (Wood et al. 1992), it was hypothesized that older individuals would be healthier than younger individuals but would present more evidence of non-life-threatening degeneration (Hypothesis 3). In the current sample male stature increased significantly in the older adult age category (50-70 years-at-death), specifically in the post-medieval period, then decreased into senility. The frequency of osteoporosis increased with age among males, however the prevalence of osteoporotic fractures decreased among the older age. The decrease in osteoporotic fracturing is likely associated with a maintenance of robusticity. While the amount of bone in Ward's triangle decreased with age, an increase in bending and torsional robusticity was noted in the older age categories. A significant increase in robusticity existed along the femoral shaft among older adult males (50-70 years-at-death). An increase in indulgence-related disorders was also noted with age in males, with a decrease in the oldest age category (>70 years-at-death). This is not surprising as all "indulgence-related disorders" are also significantly correlated with age. Understood together, the results may illustrate that the preferential survivorship of the healthiest, strongest males. A bias based on sample size in the older age categories cannot, however, be discounted.

In females, stature and BMI remained consistent in all age categories. Osteoporosis increased with age, followed by a decrease (not significant) in the oldest age category, possibly illustrating the effect of multiparity and breastfeeding on bone loss in younger women. Healthier, stronger women who survived their reproductive years presented fewer cases of osteoporosis. Osteoporotic fracturing in the wrist and spine increased with age; however spinal crush fractures decreased in the oldest age category. The increase in fractures is likely associated with the age-related decrease in bone and bone robusticity. A decrease in cortical bone (%CA), paralleled by a decrease in compressive, bending, and torsional strength and rigidity, was noted in the femoral neck and shaft in females with age. Patterns of female aging seem to follow more consistently those seen among modern women.

6.5 Sex Comparison

6.5.1 Stature

As expected, males were significantly taller with significantly longer femora than females. This result is not particularly noteworthy, however the general lack of change in sexual dimorphism (ratio calculated as male/female) between the rural and urban samples (Table 6.5) and the medieval and post-medieval periods (Table 6.6) is of interest. Yoder (2006) found that the level of sexual dimorphism in the urban cemetery of Sct. Mikkel was greater than that seen in the rural cemetery of Øm Kloster. According to Yoder (2006) the greater height disparity suggested that females were treated more poorly in urban centres. However, Sawyer and Sawyer (1993) found no evidence that Danish women were mistreated in the medieval period. The lack of change in sexual dimorphism between the samples analyzed here may indicate that female health and the treatment of women did not change drastically with the movement to an urban environment or by time period.

During the Viking period, Scandinavian women were given a significant amount of autonomy over their lives. Women, especially older women, were treated with respect, often exhibiting the most lavish burials (even when compared to males) (Sawyer and Sawyer 1993). With the conversion to Christianity much of the freedom Viking women experienced was curtailed (Sawyer and Sawyer 1993). In medieval Denmark a woman's legal status depended upon marriage. Married women were subordinate to their husbands but enjoyed a significant amount of freedom, often conducting business on their husband's behalf. Widows were legally allowed to maintain property and continue business after the death of their husbands, at least theoretically, however severe taxation and guild restrictions against females employing skilled labour made it difficult for widows to conduct business. Additionally, widows had to remain single and exhibit a high moral character (as defined by the Church) in order to continue in their deceased husband's stead (Jacobsen 1983). During the post-medieval period the government granted single women the same privileges as widows; however, in reality it was still difficult, and became increasingly difficult, for women to find legal avenues for employment (Jacobsen 1983).

When comparing rural and urban living, urban females were granted more freedom and opportunity for economic advancement. In rural areas, women were tasked with brewing, baking, spinning, and weaving, however evidence suggests that women often helped in the fields as well (Sawyer and Sawyer 1993). While economic advancement was more available to women in towns, the avenues for social advancement were the same as in rural communities – marriage or inheritance (Sawyer and Sawyer 1993). For males social and economic advancement was more readily available. Merchants formed a ruling elite in Danish cities, possessing most of the economic and political power, and while females were often members of merchant associations, they generally served a social or religious function (Jacobsen 1983). In urban towns, women were able to gain a degree of economic independence if they had a craft skill, although were paid significantly less than males in the same vocation (Sawyer and Sawyer 1993). Women could get work in traditional roles such as cleaning, brewing, baking, making clothes, caring for the sick, as midwives, or as alewives and Brewster. Fortunate women could work as builders, mercers (who sold foodstuffs and items not associated with other guilds), drapers, or artisans. "Craft and trades that were lucrative, prestigious, and organized were often closed to women or restricted to those who were married or were born into the craft or trade, regardless of the fact that the craft in question might be women's work at home" (Jacobsen 1983: 19). Less fortunate women were relegated to lower level retail positions, heavy manual labour, or prostitution (Jacobsen 1983; Sawyer and Sawyer 1993).

Table 6.5 Male/female stature dimorphism between rural and urban sites

Measure	Site	Male Mean (cm)	Female Mean (cm)	Ratio
Stature	Tirup (rural)	169.3	158.9	1.07
	Black Friars (urban)	169.0	158.6	1.07
Femoral length	Tirup (rural)	46.4	42.7	1.09
	Black Friars (urban)	44.3	41.0	1.08

Table 6.6 Male/female stature dimorphism between medieval and post-medieval periods

Measure	Site	Male Mean (cm)	Female Mean (cm)	Ratio
Stature	Medieval	170.1	159.9	1.06
	Post-medieval	167.5	157.7	1.06
Femoral length	Medieval	45.5	41.9	1.09
	Post-medieval	44.0	40.9	1.08

6.5.2 Body Mass

Body mass decreased significantly between males and females. Again, given the larger stature and general robusticity in males, this was not surprising. When height was accounted for, BMI (when calculated using the femoral head diameter) was significantly smaller for females. Again, this is not particularly noteworthy as studies have shown that males tend to have higher BMI values than females (Kuczmarski et al. 1997; Must el at.1991). When sexual dimorphism in body mass was analyzed, results based on body mass calculated using the two body mass estimation methods conflict for the rural and urban sites (Table 6.7) but suggest a maintenance in size dimorphism by time period (Table 6.8). Again, this may signify a similar health and lived experience between sites and by time period.

Table 6.7 Male/female body mass dimorphism between rural and urban sites

Measure	Site	Male Mean (kg)	Female Mean (kg)	Ratio
Bi-iliac breath	Tirup (rural)	63.4	56.5	1.12
	Black Friars (urban)	65.3	56.4	1.16
Femoral head diameter	Tirup (rural)	66.1	53.7	1.23
	Black Friars (urban)	68.0	56.7	1.20

Table 6.8 Male/female body mass dimorphism between medieval and post-medieval periods

Measure	Site	Male Mean (kg)	Female Mean (kg)	Ratio
Bi-iliac breath	Medieval	65.1	56.7	1.15
	Post-medieval	64.4	56.3	1.14
Femoral head diameter	Medieval	67.1	55.5	1.21
	Post-medieval	68.0	56.7	1.20

6.5.3 Indulgence-Related Disorders and Degeneration

In the current analysis, males exhibited a significantly higher frequency of DISH/eDISH and plantar calcaneal spurs than females. Males also presented a higher frequency of gout although the difference was not significant. Research has illustrated that DISH and gout are much more common among males (Ortner 2003; Rogers and Waldron 2001). Prior to menopause, women are protected against gout as estrogen inhibits the production of uric acid. With age, the disparity in uric acid (and gout prevalence) between the sexes decreases, however males still exhibit significantly more gout than females in old age (Singh 2013). The aetiology of DISH is poorly understood, however hyperuricemia, as in gout, has been identified in patients with DISH (Miyazawa and Akiyama 2006). As such, it is possible that increased estrogen levels again protect females from the development of DISH. When separated by site and time period, neither DISH nor gout are significantly different in males or females, likely due to the low frequency of the disorders when categories are separated.

The current results for plantar calcaneal spurs are at odds with those found in the literature. While Benjamin et al. (2006) found that entheses in general, including those on the calcaneus, were more common in males, Fakharian and Kalhor (2014) and Toumi et al. (2014) found significantly more calcaneal spurs in females than males. Weiss (2012) found a similar result (although the difference was not statistically significant) in the archaeological sample from Ryan Mound, California (2180 – 250 BP). When separated by site and time period the difference between female and male plantar calcaneal spurs remains significant in the urban sample, Black Friars (n_{male}=107; n_{female}=85; χ^2 =4.057; df=1; p=0.033), but not in the rural, Tirup (n_{male}=55; n_{female}=31; χ^2 =0.593; df=1; p=0.403), medieval (n_{male}=93; n_{female}=56; χ^2 =1.616; df=1; p=0.157), or post-medieval (n_{male}=69; n_{female}=60; χ^2 =2.594; df=1; p=0.085) samples. It is possible that this illustrates a change in mechanical loading as Danes moved into urban spaces; however as time passed and many females were required to find employment outside of traditional female roles (Jacobsen 1983), mechanical loading patterns synchronized.

Males also presented more degenerative joint disease in the hips, knees, and lumbar spine, although the differences were not significant. This remained true when the sex comparisons were separated by site and time period, suggesting a similar joint degeneration pattern between urban and rural males and females through time. While Danish women were occupied in traditional female roles (cleaning, baking, sewing, etc.), in rural areas women often joined the males in the fields and in urban areas women were often employed in less conventional undertakings (building trades, ship work, manual labour) (Jacobsen 1983; Sawyer and Sawyer 1993). Additionally, many urban households had large land plots that females worked (Dyer 1989). Comparative data from Britain suggests that male and female roles were more strictly separated. Waldron (1997b) found that males presented more osteoarthritis in the hips than females in medieval and post-medieval Britain. The difference was higher in the medieval period than the post-medieval period. When comparing two sites in the UK, Wharram

Percy and Ensay, Sofaer-Derevenski (2000) found that significantly more females than males exhibited vertebral osteophytosis in the lumbar spine at Ensay. This was not the case at Wharram Percy. Sofaer-Derevenski (2000) argued that this illustrated differences in the sexual division of labour between the sites.

6.5.4 Degenerative Disorders – Osteoporosis

Osteoporosis is often discussed in terms of a female aging, as clinically, osteoporosis tends to occur more frequently among women (Alswat 2017). In this study, females presented significantly more osteoporosis in the femoral neck, a pattern that was replicated in the lumbar spine but failed to meet significance standards ($\alpha=0.05$). Interestingly, while females presented a higher frequency of osteoporotic bone and Colles' fractures, the overall frequency of osteoporotic fracturing was higher in males than females (significantly so for lumbar crush fractures). Male bones presented significantly less cortical bone at the femoral neck (%CA at Ward's triangle) than females. However no significant difference in bending or torsional strength was noted, possibly suggesting a sexual division of labour leading to increased fracture risk in males. A previous analysis of fracture frequency from the Black Friars, Tirup, and Sct. Mikkel cemeteries suggested that Danish males were more prone to fracturing in general (Milner et al. 2015).

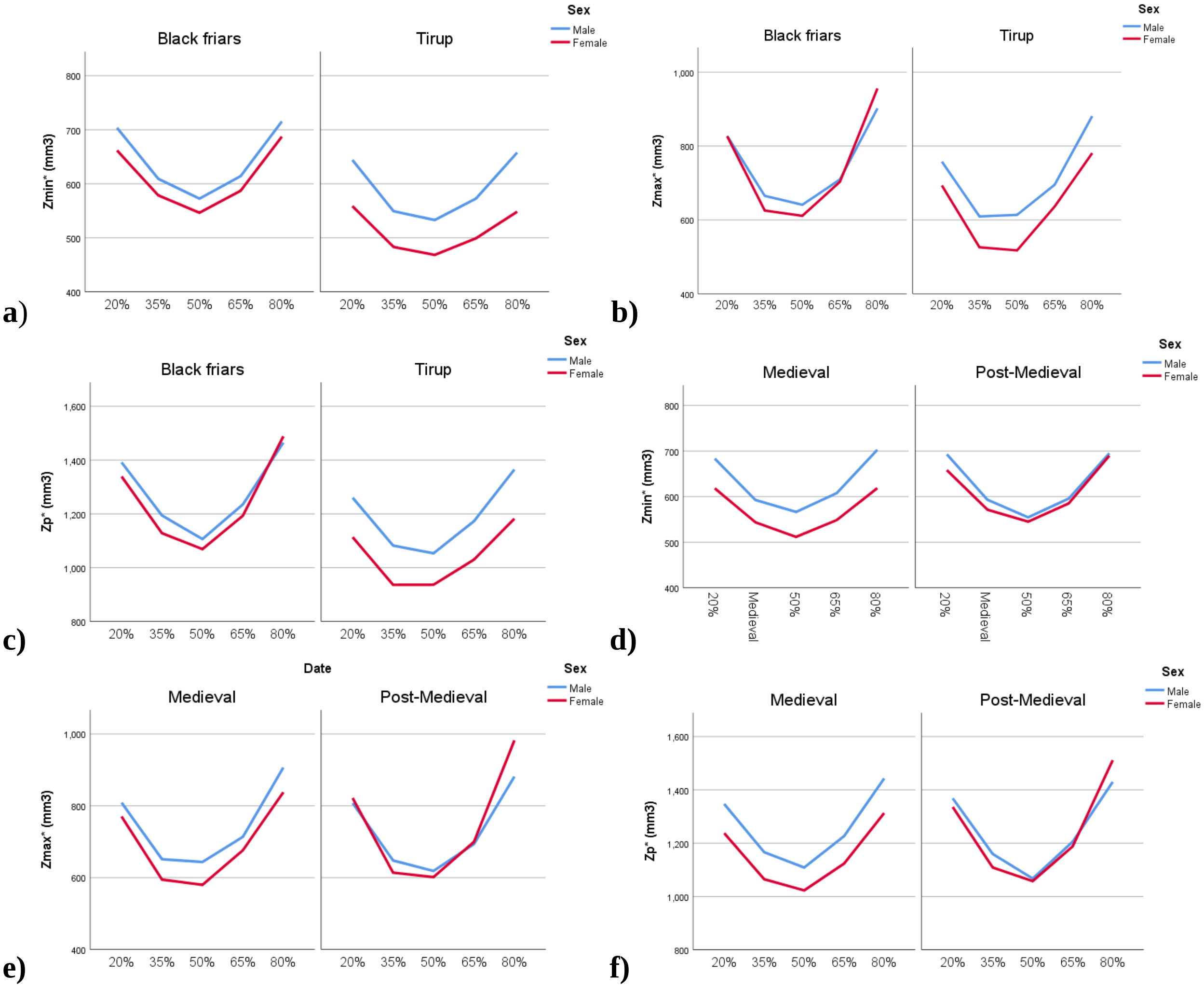
When separated by site and time period, the difference in the frequency of Colles' fractures between the sexes remained significant for the Tirup ($n_{male}=42$; $n_{female}=27$; $\chi^2=8.385$; df=1; p=0.007) and medieval ($n_{male}=87$; $n_{female}=53$; $\chi^2=4.976$; df=1; p=0.034) samples while lumbar crush fractures remain significant for the Black Friars ($n_{male}=133$; $n_{female}=107$; $\chi^2=5.283$; df=1; p=0.016) and post-medieval ($n_{male}=78$; $n_{female}=77$; $\chi^2=4.779$; df=1; p=0.024) samples. As men also presented more cortical bone and bone area in the shaft in all comparisons (significant for TA at 35% and 50%, %CA at 65% and average cortical thickness from 20-80%), it is likely that a difference in occupational loading leading to different types of fracturing in rural, medieval and urban, post-medieval males existed.

6.5.5 Biomechanics

Even when standardized by size, male femora are significantly larger and stronger than female femora. Male femora were stronger in compression (significant at 35% and 50%) and in bending strength and rigidity around the minimum (significant for Z_{min} at 20%-80% and I_{min} at 20%, 50% and 65%) and maximum (significant for Z_{max} at 35% and 50% and I_{max} at 35% and 50%) axes. Torsional strength (Z_p was significant from 20-65%) and rigidity (J was significant at 50% and 65%) was also greater among males. Males presented significantly more circular shafts than females at 20%, 65% and 80%. This is interesting as a more circular shaft in females was expected. Ruff (2010) argued that greater mediolateral bending in the female femur as a result of different mechanical loading caused by wider pelves leads to a more circular shaft, especially around the proximal femur. A less circular shaft has been tied to mobility. Long distance runners, for example, exhibit antero-posteriorly elongated femoral shafts resulting from significant antero-posterior bending of the femoral shaft while running (Ruff 2010).

Interestingly, when separated by site and time period, a slightly different pattern in sexual dimorphism arose (Figure 6.1). A distinction in bending and torsional strength and rigidity was seen between males and females in the rural and medieval samples, likely indicating a stricter sexual division of labour (Figure 6.1 a, b, c). In the urban and post-medieval samples the distinction between the sexes is obscured (Figure 6.1 d, e, f). Ruff (2010) explained increased sexual dimorphism in bone strength between hunter-gatherers and agriculturalists as differences in the sexual division of labour. In the current sample, the decreased sexual dimorphism in the urban, post-medieval period could reflect the urban woman's need to seek employment outside of convention. As previously discussed, women in urban centers were often required to work in heavy manual labour as laundresses, builders, or on ferry boats (Jacobsen 1983; Sawyer and Sawyer 1993). Traditional employment become increasingly scarce in the post-medieval period and women were forced to look for employment through increasingly unconventional and often illegal avenues (Jacobsen 1983). Women employed in domestic services were also likely expected to undertake a significant amount of physical labour. Many households possessed land plots and working these plots would have fallen under the purview of female domestic servants (Dyer 1989). Shapland et al. (2015) noted a greater frequency of spondylolysis in poor medieval females from Britain which they argued indicated that young medieval females of low socioeconomic status were subjected to increased stress when put in service at a very young age. It is possible that the current data is illustrating a similar trend in Denmark with post-medieval females being employed in heavy manual labour at a younger age than their male counterparts, at least in urban centres. Saers (2012) found that, in the medieval Netherlands, males were significantly stronger and more robust than females. Little variation existed in male robusticity but females presented a significant amount of variation suggesting females did a variety of roles (Saers 2012).

Figure 6.1 Sex differences in femoral strength by site and time period



*Size-standardized Z_{STD} = Z/(BM*femoral length)

a) Comparison of Z_{min} between Black Friars and Tirup; b) Comparison of Z_{max} between Black Friars and Tirup; c) Comparison of Z_p between Black Friars and Tirup; d) Comparison of Z_{min} between medieval and post-medieval samples; e) Comparison of Z_{max} between medieval and post-medieval samples; f) Comparison of Z_p between medieval and post-medieval samples.

6.5.6 Sex Comparison Summary

At first, the differences perceived between the sexes were much as expected (hypothesis 4). Males were significantly taller and heavier and presented more indulgence-related disorders than females, while females exhibited more osteoporotic bone (although, unexpectedly, males presented more osteoporotic fracturing). And, for the most part, male femora were more robust than female femora. However, when reanalyzed by site and time period an interesting shift in the pattern occurred. The significant difference in indulgence related disorders disappeared, with the exception of plantar calcaneal spurs in the urban sample possibly indicating a shift in mechanical loading practices with the move to an urban environment. Osteoporotic bone remains more common in females while osteoporotic fracturing remains more common in males. The type of fracturing may indicate differences in occupation with Colles' fracturing being significantly more common in rural and medieval males and lumbar crush fracturing being more common in urban and post-medieval males. No change in sexual dimorphism in stature or body mass existed with the transition to urban living or by time period, suggesting that the treatment of females remained constant.

Possibly the most interesting change in pattern is the transition in robusticity between samples. Male femora were expected to remain significantly stronger and more robust than female femora; however, this was not the case for the urban and post-medieval samples. Female femoral strength and rigidity is near equivalent to that of males in the later urban sample. Jacobsen (1983) documented occupations available to women in medieval and post-medieval Denmark. While some women were able to gain employment in domestic service, these positions were rare, and became increasingly rare with the passing of time and females found employment elsewhere. Domestic service positions likely comprised a significant amount of physical labour. Women unable to access these positions looked for employment as laundresses, builders, ferry(wo)men, etc. (Jacobsen 1983). This data also questions the notion of a larger elite portion of the urban, post-medieval cemetery as females of higher socioeconomic status would not have been seeking employment.

6.6 Body Size Trends

6.6.1 Stature

Significant decreases in stature and femoral length exist as BMI, calculated from femoral head diameter, increases in both males and females. This trend could suggest that the heavier individuals were less healthy overall than the lighter individuals. When separated by site and time period, the decrease in stature remains significant in both males and females for all comparisons ($p<0.05$) except in females during the post-medieval period ($p=0.075$). The lack of significant difference in stature by BMI in post-medieval females may relate to the limited resources available in the post-medieval period (Anderson 2011). In communities where females are considered subordinate to males access to limited resources is often preferentially allocated to males (Hyder et al. 2005). Extremely limited resources in the post-medieval period paired with an occupational transition for many females may have led to an increase in BMI (i.e., muscularity) without a change in overall health (i.e., stature). The fact that the difference in stature by BMI category remains significant for males, may indicate that certain males were preferentially given resources over others. However, as no difference was noted in stature between BMI categories when body mass was calculated using bi-iliac breadth, this association must be made cautiously.

6.6.2 Indulgence-Related Disorders and Degeneration

Interestingly, no significant differences in indulgence-related disorders or degenerative joint disease in the weight bearing joints existed by BMI category (using both body mass estimation methods). In fact, indulgence-related disorders and degeneration of the weight bearing joints were more common in the “normal” and overweight categories than other categories (although very few males fell into the underweight and obese categories). There are several possible explanations for this. First, it is possible that the lack of indulgence-related disorders in the obese weight category indicates an issue with the body mass estimation methods. However, on other samples both methods have been shown to estimate body mass reliably, at least in males (Auerbach and Ruff 2004; Elliot et al. 2016; Pomeroy and Stock 2012). The second possibility is that of an epigenetic and age-related origin for the disorders. As previously discussed, DISH, gout, plantar calcaneal spurs, and degenerative joint disease are strongly correlated to increased age (Anderson and Loeser 2010; Cermak and Kirchengast 2015; Ortner 2003; van der Merwe et al. 2012; Weiss 2012). Tsukahara et al. (2005) identified a genetic marker, collagen 6A1, as associated with susceptibility to DISH in Japanese patients. Soto-Hermida et al. (2014) and Iliopoulos et al. (2008) have found gene signatures associated with osteoarthritis. Research has also identified gene variants associated with gout (Reginato et al. 2012) and likely genetic predispositions to calcaneal spurring (Rogers et al. 1997). Genetic analyses were outside the purview of the current analysis, however a hereditary component to the disorders discussed here seems likely and an association with age was noted above. In the Danish sample, body mass does not seem to affect an individual's susceptibility to DISH, gout, plantar calcaneal spurs, or degeneration of the weight bearing joint. Occupation may also have increased the risk for certain disorders. The small sample sizes outside of the normal and overweight categories may be creating bias in the samples.

6.6.4 Degenerative Disorders – Osteoporosis

An increase in osteoporosis was noted as body mass, calculated using the femoral head diameter, rises (not significant). Traditionally, increased body mass has been seen as protective against osteoporosis, as individuals with increased body mass also generally present higher bone mass than lighter individuals (Cho and Stout 2011). However, more recent clinical literature has linked increased body mass to lower bone mineral density values and increased osteoporosis, especially in post-menopausal women (Cao 2011; Cobayashi et al. 2005; Goulding et al. 2000; Kim et al. 2010; Zhao et al. 2007). When assessed in the fourth lumbar vertebrae, osteoporosis was significantly more common in the under- and overweight categories than in the "normal" weight category in females. According to a study on female rats, late onset menarche leads to suboptimal bone density in later life, resulting in weaker, less robust bones (Yingling and Khaneja 2006). A similar result was found in humans however the authors concluded that genetics was more likely the cause of both low bone mineral density and late onset menarche (Chevalley et al. 2009). Low body fat mass has long been understood to delay menarche (Frisch and McArthur 1974; Frisch and Revelle 1970; Maclure et al. 1991). Underweight females likely presented lower body fat values than normal and overweight individuals.

When separated by site and time period, the frequency of osteoporosis in the fourth lumbar vertebrae remains significantly higher in the overweight category than in the "normal" weight category for urban ($n_{\text{"normal" weight}}=77$; $n_{\text{overweight}}=6$; $F=4.213$; $df=1$; $p=0.043$) and post-medieval ($n_{\text{"normal" weight}}=58$; $n_{\text{overweight}}=6$; $F=5.101$; $df=1$; $p=0.027$) females. Small sample sizes in the underweight and overweight categories from the medieval and rural sample may account for the lack of significant results. The results may also suggest a different health experience for women in the post-medieval period. If the BMI increase in the post-medieval period in females was associated with muscularity, it is possible that overwork and increased mechanical loading in younger females (Shapland et al. 2015) limited the accumulation of bone mass in young women. The amount of bone (%CA and average cortical thickness) in the femoral shaft decreases significantly between the normal and overweight categories. The decrease in circularity of the femoral shaft, an indication of increased mobility (Ruff 2010), between the “normal” and overweight categories lends credence to this assessment. As menarche occurs later with high rates of physical activity (Malina 1983), the increased BMI, if associated with muscularity and an increasingly physically demanding lifestyle in the post-medieval period, could have delayed menarche in females again resulting in suboptimal bone growth.

As for osteoporotic fracturing, Colles’ and femoral neck fractures were more common as body mass increased (not significant). Lumbar crush fractures were more common in the “normal” weight category (not significant). The relatively low frequency of fracturing may account for the lack of significance and, if the decreased bone mass seen among the heavier females is a result of suboptimal bone formation in young working women, the former result is not surprising. The increased frequency of lumbar crush fractures in the “normal” weight category may allude to differences in occupation; however, as none of the results were significant, it may also be immaterial. When separated by site and time period the results were not significant.

6.6.5 Biomechanics

As body mass affects overall skeletal robusticity, body mass was adjusted for in the biomechanical comparisons. This was done in an attempt to go past the actual effect of body mass on skeletal robusticity and compare aspects of robusticity produced by activity and lifestyle between the BMI categories. There are limitations with this approach as there is a risk of complicating the data by removing the effect of body mass. Therefore, it must be noted that interpretations of the data are likely more complex then presented here. In females, when adjusted for size, the strongest, most robust category was generally the “normal” weight category, although the overweight females present more robust bones for many comparisons (not significant). A significant increase in torsional and bending strength along the shaft was noted in females between the underweight and “normal” weight categories. When separated by site and time period this remained true for the medieval period ($p<0.05$); all the underweight females ($n=5$) were from the medieval period. The low BMI of the underweight category may suggest emaciation or ill-health which would lead to suboptimal bone growth. The significantly taller stature of the underweight category seems to oppose this notion. However, it is possible that the individuals identified as “underweight” experienced catch-up growth after periods of ill-health. Catch-up growth occurs in cases were ill-health or under-nutrition is rectified. In their analysis using a rat model, Pando et al. (2014) found that rats that underwent catch-up growth exhibited more fragile, less robust bones. Long term feeding at optimal feeding levels allowed for a level of strength correction, however full bone strength recovery was unachievable. Periods of ill health or under nutrition resulting in delayed menarche, followed by catch-up growth, is also correlated to weaker, less robust bones in females (Chevalley et al. 2009; Yingling and Khaneja 2006). Catch-up growth is often not complete unless the underlying disorder causing a cessation in growth is rectified quickly (Cutler et al. 2016). If this were the case, bone strength would also likely reach normal or near normal levels. As the underweight individuals were the tallest in the sample, it is more likely that the individuals identified as underweight were ill at the time of death. Tuberculosis was a significant issue in medieval and post-medieval Denmark (Dangvard Pedersen 2016). While all individuals with skeletal evidence of tuberculosis, as well as other infectious diseases (as described in ADBOU 2015 and Ortner 2003), were excluded from the sample, only approximately 5 – 10% of pre-antibiotic tuberculosis cases manifested in a skeletal response (Roberts 2012). The significant increase in circularity between the “normal” weight and underweight categories at the femoral midshaft indicate an increase in physical activity in the heavier category. As a disease affecting the respiratory system, tuberculosis significantly hampers ability to do physical activity which would, in turn, affect skeletal robusticity. The shape ratio increase between the underweight and "normal" weight categories remains significant for medieval females (p=0.022). As all underweight skeletons were found in the medieval sample, this is not surprising. It is also possible that the underweight individuals fell into the elite social class and thus were not expected to do the demanding physical labour required of the less wealthy.

A significant decrease in circularity also exists between the overweight and "normal" weight females at the distal shaft (20%). This could illustrate a difference in activity between weight categories, whereby the overweight category was more mobile. As previously discussed, the shape of the distal femur has been correlated to activity patterns (Ruff 2010; Stock 2006). When separated by site and time period, the differences in I_{max}/I_{min} shape ratio remain significant for the post-medieval ($n_{\text{“normal” weight}}$=45; $n_{overweight}$=2; p=0.027) and urban ($n_{\text{“normal” weight}}$=62; $n_{overweight}$=3; p=0.007) samples. Occupational change for females in the post-medieval period has been heavily referenced in this chapter. Again, if the increased BMI of the overweight females is reflective of muscularity, a transition in occupation in the post-medieval, urban sample may explain this result.

When the data was compared without standardizing for size, the normal weight females remain more robust for many of the comparisons (data not presented). This contradicts what is expected. Biomechanically speaking, because of the effects of additional weight on bone robusticity, it is expected that robusticity will increase as body mass increases. There are several explanations why the data is incongruous with expectation. Firstly, the data might be signaling a change in body mass in life for the heavier females because femoral head diameter is more consistent with body mass at skeletal maturity (Ruff et al. 1991) and femoral robusticity responds to strain throughout adulthood. It is also possible that we are seeing evidence of ill health in the heavier individuals prior to death leading to compromised mobility and bone atrophy. Additionally, as only four individuals fall into the overweight category for females (whereas there are 75 individuals in the "normal" weight category), the effects of sample size bias cannot be overlooked. While each of these explanations hold credence and they all likely influenced the results in varying degrees, it is most likely that inaccuracies with body mass estimation calculations are leading to issues with the results. For body mass estimated with both femoral head diameter and bi-iliac breadth, Elliot and colleagues (2016) found that the equations worked well for males but accuracy and reliability were problematic in female calculations. In males in the current sample, as expected, robusticity increases as body mass index increases when comparisons were done on the raw (unstandardized) data.

In males (when standardized for size), strength and rigidity tended to increase as body mass increased. When body mass was estimated using bi-iliac breadth, bending strength and rigidity along the maximum axis (Z_{max} and I_{max}) were significantly larger in the overweight category than the "normal" weight category along the femoral shaft (20%, 35%, and 50%) as was torsional strength (Z_p) at the distal and mid-proximal femur. A similar pattern is seen when body mass was estimated using femoral head diameter, however only cortical area and minimum bending rigidity (I_{min}) at the midshaft are significantly different by BMI category.

When separated by site and time period, extremely small sample sizes outside of the "normal" weight category ($n_{underweight} = 0$; $n_{overweight} \leq 1$; $n_{obese} \leq 1$) make statistical analysis using BMI estimated with the bi-iliac breadth method problematic. When reanalyzed using femoral head diameter, the following results were significant by site in males: I_{min} (p=0.007); *J* (p=0.22) Z_{max} (p=0.044), Z_{min} (p=0.040), Z_p (p=0.027) at 20% were significantly larger in the overweight category in the rural sample of Tirup ($n_{underweight} = 0$; $n_{\text{“normal” weight}} = 28$; $n_{overweight} = 8$), cortical area at 50% (p=0.025), 65% (p=0. 045) and 80% (p=0.017) were significantly larger in the "normal" weight category while total area at 20% (p=0.007), 35% (p=0.001), 50% (p<0.001), 65% (p=0.001) was significantly larger in the overweight category in the Black Friars sample ($n_{underweight} = 1$; $n_{\text{“normal” weight}} = 67$; $n_{overweight} = 27$) as was Z_{min} (p=0.037) and %CA (p=0.019) at Ward's Triangle. Additionally, the femoral neck was also significantly less circular (p=0.014) in the overweight category in the urban sample, Black Friars. The increased cortical area in the "normal" weight category at Black Friars suggests that the femora of urban males of "normal" weight were more strengthened to compression than in overweight males. This was not paralleled by a change in the amount of cortical bone (%CA). This is interesting as overweight males are more robust in all other categories. This may indicate differences in mechanical loading in life. However, as bending and torsional strength are more illustrative of lifetime mechanical loading, the current data indicates that larger bodied individuals were more robust than lighter individuals as their femora were more strengthened to bending and torsion. By proxy, heavier body mass in males is more likely associated with muscularity than body fat levels. No significant differences were seen by BMI category when separated by time period.

6.4.5 Body Size Trend Summary

Trends associated with size are difficult to discern from the skeletal record as an accurate, universal body mass estimation method has yet to be identified. Additionally, using BMI categories, originally created to ascertain body fat, can be confusing as increased BMI, termed overweight or obese, may reflect increased mass due to bone density or muscularity. Hypothesis 5 stated that underweight and overweight individuals would be less healthy than "normal" weight individuals. The results of the current analysis, especially those associated with females, seem to be consistent with this hypothesis, although body mass did not seem to affect indulgence or degeneration in the weight bearing joints in medieval Denmark. A decrease in stature was noted as body mass increased in both males and females. Heavier categories, likely resulting from muscularity not body fat, were likely overworked and undernourished. In females, as the underweight category was also the tallest, these individuals were likely healthy (possibly of elevated social standing) during growth, then fell ill with a disease that limited mobility later in life leading to decreased muscularity and femoral robusticity. The lack of stature differences by BMI category in post-medieval females is likely associated with the limited resources available in the post-medieval period leading to an overall poorer health experience (Anderson 2011) paired with the fact that many urban women were forced to seek employment in more physically demanding occupations (Jacobsen 1983). As muscularity increased among these women, it did not lead to a change in stature as food was scarce. In males, "normal" weight individuals were significantly taller than overweight individuals who were significantly taller than obese individuals, suggesting that health decreased as BMI increased. No difference in indulgence-related disorders or degenerative joint disease was seen by BMI category. No change in the frequency of osteoporosis was noted either, with the exception of osteoporosis identified in the fourth lumbar vertebrae which was significantly less frequent among "normal" weight than over- or under-weight females. It was expected (Hypothesis 5), that robusticity would increase with body mass, this was not the case among females with "normal" weight females presenting the strongest most robust femora. The decrease in bone density and strength could be a result of late onset menarche associated increased physical activity in the overweight category. This difference only remained significant in the urban and post-medieval samples when separated by site and time period, suggesting that urban, post-medieval women had a significantly different health and mechanical loading experience in life than medieval, rural women. In males, robusticity increased with BMI, which suggests that, in the current sample, increased BMI was more likely associated with muscularity not body fat. If interpreted from an evolutionary perspective, it is possible that females present a more significant response to stress, whereby bone strength and robusticity are compromised in order to maintain reproductive health.

6.7 Summary

This chapter has discussed the results in the context of the broader biological and historical literature. Stature, body mass, indulgence-related disorders and degeneration, bone loss and femoral robusticity were discussed in order to identify trends based on the location, time period, age, sex, and body size results presented in Chapter 5. Chapter 7 will summarize the results, present conclusions, and identify areas for future research.

Chapter 7: Conclusion

7.1 Summary of results

The main objective of the research was to assess health and aging in medieval and post-medieval Denmark. Using the data collected on the Danish medieval rural sample from Tirup and the medieval and post-medieval urban sample of Black Friars, trends in stature, body mass, femoral robusticity, and indulgence-related disorders and degeneration were analyzed. The medieval and post-medieval periods provide excellent samples for analyzing biocultural transitions as at this time Denmark underwent extensive social, environmental, and residential change. During the medieval period Christianity replaced the old Viking religions, the urbanization revolution took place, the climate changed leading to several consecutive crop failures, and the Danish population was decimated by the Black Death epidemic. The post-medieval period began with the Protestant Reformation (1536 CE) and the abolishment of strict fasting rituals. Life expectancy is believed to have improved after the reformation but lived experience may not have (Benedictow 2003; Dangvard Pedersen 2016; Scott 2015). In the current research, differences based on site location (rural versus urban), time period, age, sex, and body size were evaluated. This research explored five hypotheses. Table 7.1 provides an overview of the hypotheses and indicates whether the data presented in the current analysis support the hypotheses.

Table 7.1 Revisiting the hypotheses

Hypothesis	Sub-hypotheses	Supported	Notes
Hypothesis 1: The rural sample will be healthier than the urban sample	The rural sample will be taller.	Yes	Significant for femoral length.
	The rural sample will be lighter.	Yes	When calculated using femoral head diameter.
	The rural sample will exhibit fewer indulgence-related	Yes	The rural sample exhibited a significantly higher frequency of plantar calcaneal spurs and

	disorders and degeneration.		degenerative joint disease (significant in the knees).
	The rural sample will present a less osteoporosis.	No	No significant difference in osteoporosis.
	The rural sample will exhibit greater femoral size and strength.	No	
Hypothesis 2: The medieval sample will be healthier than the post-medieval sample	The medieval sample will be taller.	Yes	
	The medieval sample will be lighter.	Yes	
	The medieval sample will exhibit fewer indulgence-related disorders and degeneration.	Yes	Non-significant increase in indulgence-related disorders and degenerative joint disease (significant in the knees).
	The medieval sample will present less osteoporosis.	No	No significant difference in the frequency of osteoporosis was noted.
	The medieval sample will exhibit greater femoral size and strength .	No	Males maintain femoral robusticity temporally (although a decrease in compressive strength is noted); a significant increase in female femoral robusticity was seen temporally.
Hypothesis 3: Older individuals will be healthier than younger individuals but will present more non-life-threatening degeneration	Individuals who died in older age will be taller.	In males up to 70 years-at-death	Individuals who died at older ages were taller; although a decrease in oldest category (>70 years-at-death) was noted.
	Individuals who died in older age will be lighter	No	No significant differences.
	Individuals who died in older age will present more indulgence-related disorders and degeneration.	Yes	
	Individuals who died in older age will present more osteoporosis but fewer osteoporotic fractures.	Yes, partially	In females a significant increase in femoral neck osteoporosis was noted in middle age; in males a decrease in osteoporosis in the fourth lumbar vertebrae was seen in the > 70 years-at-death age category.

	Individuals who died in older age will exhibit weaker femora.	In females	In males, a significant increase in femoral robusticity was noted in the 50-70 years-at-death age category.
Hypothesis 4: Sex will affect perceived health.	Males will be taller.	Yes	See discussion below.
	Males will be heavier.	Yes	See discussion below.
	Males will present more indulgence-related disorders and degeneration.	Yes	
	Males will exhibit less osteoporosis.	Yes	
	Males will exhibit greater femoral size and strength.	Yes	See discussion below.
Hypothesis 5: "Normal" weight individuals will be healthier than overweight individuals.	"Normal" weight individuals will be taller	Yes	Except in females in the post-medieval period.
	"Normal' weight individuals exhibit fewer indulgence-related disorders and degeneration than overweight and obese individuals.	No	No significant difference in indulgence-related disorders or degenerative joint disease.
	"Normal" weight individuals will present less osteoporosis than underweight but more than overweight and obese individuals.	Partially	Significantly less lumbar osteoporosis was found in the "normal" weight category than others. A non-significant increase in femoral neck osteoporosis was noted as body mass increases.
	Femoral size and strength will increase as body mass increases.	In males	In females the "normal' weight females exhibited the most robust femora (size-adjusted).

Given the plethora of research concluding that living in rural areas meant better survivorship and a higher quality of life during the medieval period (Dyer 2002; Lewis and Gowland 2007; Palubeckaite et al.2002; Petersen et al. 2006; Sundman and Kjellstrom 2013), it was hypothesized (Hypothesis 1) that the rural sample would be healthier than the urban sample. The results support this hypothesis. The urban sample was shorter than the rural sample, possibly suggesting decreased overall health. The urban sample also presented significantly higher BMI and indulgence-related disorders and degeneration (significant for plantar calcaneal spurs and degenerative joint disease in the knees). The significant increase in bending and torsional strength and rigidity of the femoral shaft between the two samples seems to suggest that the urban sample preformed more strenuous activities but the change in circularity of the femoral shaft may indicate lower mobility than the rural sample. It is also possible that the increase in femoral robusticity is reflective of changes in physical loading among the poor, whereby the intensity of physical activity remained increased while mobility decreased. These results corroborate the historical data suggesting that individuals living in rural settings in medieval and post-medieval Europe were healthier than urbanites. Previous research has illustrated that survivorship was higher for those interred in the Tirup cemetery when compared to their urban contemporaries interred in Sct. Mikkel (Petersen et al. 2006). Urban medieval Europeans also demonstrated higher frequencies of lead poisoning (Rasmussen et al. 2015), chronic maxillary sinusitis (Sundman and Kjellstrom 2013), and infant mortality (Lewis and Gowland 2007). As suggested by Kelmelis and Dangvard Pedersen (2019), understanding the data based purely on rural and urban life is too simplistic. In the current analysis, the decrease in health is likely more indicative of cemetery composition, not differences in urban and rural health in medieval Denmark. As one of few cemeteries that remained open after the Protestant Reformation in Odense, Denmark, more elite burials would have been present in the Black Friars cemetery (Mollerup and Boldsen 2010). It is also possible that the policing of food and food distribution would have buffered individuals of lower socioeconomic status buried in the Black Friars cemetery against starvation (Mührmann-Lund 2016). Additionally, the urban sample spans the medieval and post-medieval period while the rural sample only covers the early medieval period.

As such, it is likely that, at least in part, the differences seen between the sites are reflective of temporal trends.

It was hypothesized (Hypothesis 2) that a temporal transition towards decreasing health would be seen among the medieval and post-medieval Danish sample. In the current analysis a significant decrease in stature, paralleled by a significant increase in BMI, was noted between the time periods. The results are well placed within the historical context as the onset of the Little Ice Age prompted a decrease in health across the European continent in the 14th century (Fagan 2000). The shift in climate led to poverty, starvation, and increased disease susceptibility in both rural and urban settings (Jordan 1996). Considering the lack of food, the temporal increase in BMI is slightly confounding. No significant temporal changes were noted in indulgence-related disorders or degeneration of the weight bearing joints with the exception of osteoarthritis of the knees. It is likely that the increased BMI was caused by greater muscularity among the poor as they tried to combat the growing food insecurity brought on by the Little Ice Age. Additionally, bias associated with different cemetery make-up in the medieval and post-medieval samples (whereby the post-medieval sample presents a greater number of elite burials) cannot be discounted. In males, a maintenance in femoral robusticity was noted. This seems at odds with the previous interpretation however, considering the greater amount of mobility required in farming when compared to the occupations undertaken by urban males, it can be assumed that physical loading changed in type without changing in intensity. This is consistent with our understanding of the history of Denmark during the post-medieval period. While farming still predominated in many areas of Denmark, urban males found work as potters, smiths, ship builders, carpenters, shoemakers, skinners, bakers, and butchers, etc. (Hybel and Poulsen 2007). An unexpected pattern arose for female femora, which were stronger and more robust in the post-medieval period. Initially, this seems to contradict our current understanding of gender roles in Denmark during the post-medieval period. However, Jacobsen (1983) documents the difficultly women had trying to find employment in traditional roles. A possible explanation for the trend could be that as time passed, females were forced to seek jobs in increasingly unconventional and physically demanding positions.

In all the skeletal samples, rural, urban, medieval, and post-medieval, the oldest individuals in a skeletal population can be understood as the healthiest, least frail of a skeletal sample (Wood et al. 1992). They were the individuals who were able to overcome instances of ill health during life. As such, it was hypothesized (Hypothesis 3) that individuals who died at an older age would be healthier but exhibit a higher frequency of non-life threatening disorders than those who died younger. The data collected on the Tirup and Black Friars samples partially supports this hypothesis suggesting that health patterns are complex and multi-faceted. In males, the tallest category was the 50 to 70 years-at-death category. All other categories were smaller (significant for the <30 and 30-50 years-at-death age categories). Research has supported the notion that taller individuals live longer (Davey Smith et al. 2000; Gunnell et al. 2001; Steckel 2003; Waaler 1984). Using conventional age-at-death estimation techniques the oldest age category is generally >50. As such, previous archaeological research on stature may be confounded by the use of broad age-at-death categories for older adults. The more precise age-at-death estimates from transition analysis (Milner and Boldsen 2012a) add to our understanding of aging during the medieval and post-medieval period in that they indicate that stature increased into older age (70 years-at-death), but tall stature was detrimental to extended longevity (as suggested by Lemez et al 2017; Samaras and Storms 1992; Samaras and Elrick 2002) and indicate that additional research using more precise age-at-death estimates is required. Bias introduced by the inclusion of the anatomical stature estimation method without an age correction cannot be discounted. No significant differences in height were seen in females. No significant differences in BMI were noted for either sex suggesting a maintenance of physicality and indulgence throughout life. Only BMI estimated using the femoral head diameter provided large enough sample sizes for analysis. As femoral head diameter body mass estimates are expected to correlate more strongly with body mass at around 18 years of age (instead of body mass at time of death), they are not particularly helpful in identifying aging patterns for body mass. As expected, indulgence-related disorders and degeneration of the weight bearing joints increased with age. DISH, gout, plantar calcaneal spurs, and degenerative joint disease are all significantly correlated with increased age (Jankauskas 2003; Maat et al. 1995; Ortner 2003; Rogers and Waldron 2001; Weiss 2012).

As a disorder associated with aging, it was expected that osteoporosis would increase with age. In females, osteoporosis analyzed in the fourth lumbar vertebrae increased with age, while femoral neck osteoporosis increased significantly in middle age (30 to 50 years-at-death) but decreased into old age (not significant). This pattern has been noted in previous research and, thus, is well situated in the bioarchaeological literature. Parity and breastfeeding are significant contributors to bone loss among reproductive-aged women (Agarwal 2008; Agarwal and Grynpas 2009; Agarwal et al. 2004; Beauchesne and Agarwal 2014; Martin and Armelagos 1979) and stronger, healthier women are expected to preferentially survive their reproductive years (Poulsen et al. 2001; Streeten et al. 2005). A decrease in female femoral robusticity was also noted in old age. In males, osteoporosis increased with age, although a decrease in individuals who died in the oldest age category (> 70 years-at-death) was noted. This decrease was paralleled by femoral robusticity. Individuals who died between 50 to 70 years presented the strongest most robust femora. This increase was followed by a decrease in the oldest adults (>70 years-at-death). Again, this trend is possibly reflective of the increased survivorship of stronger males but may also indicate sample size bias in the older age categories.

At first, the differences perceived between the sexes were consistent with our understanding of gender roles in medieval and post-medieval Denmark (Hypothesis 4). Males were significantly taller and heavier and presented more indulgence-related disorders than females, while females exhibited more osteoporotic bone (although, unexpectedly, males presented more osteoporotic fracturing). For the most part, male femora were more robust than female femora. However, when separated by time period an interesting shift in pattern occurred. Male femora were expected to remain significantly stronger and more robust than female femora, however this was not the case for the urban and post-medieval samples. Female femoral strength and rigidity (size standardized) was nearly equivalent to that of males in the later urban sample. Jacobsen (1983) documented occupations available to women in medieval and post-medieval Denmark. While some women were able to gain employment in domestic service, these positions were rare, and became increasingly rare with the passing of time. Many females sought employment in unconventional and physically demanding positions. Domestic service positions likely comprised a significant amount of physical labour as well. Women unable to access these positions looked for employment as laundresses, builders, ferry(wo)men, etc. (Jacobsen 1983).

The final hypothesis tested (Hypothesis 5) was that individuals whose BMI fell into the “normal” weight category would be healthier than those whose BMI was classified as underweight, overweight, or obese. The results support this hypothesis. A decrease in stature was noted as body mass increased. The individuals classified as overweight/obese likely presented higher BMIs associated with muscularity, not body fat. These individuals were likely overworked and undernourished. Underweight females, as the tallest in the sample, were likely healthy during growth, then fell ill with a disease that limited mobility later in life leading to decreased muscularity and femoral robusticity. “Normal” weight females presented the strongest most robust femora. Additionally, osteoporosis identified in the fourth lumbar vertebrae was significantly less frequent among “normal” weight than over- or under-weight females. In males, “normal” weight individuals were significantly taller than overweight individuals who, in turn, were significantly taller than obese individuals, suggesting that health decreased as BMI increased. Robusticity increased with BMI. This suggests that a decrease in resources may have affected female bone growth more significantly than males. Alternatively, it could suggest that male children were preferentially fed over female children and thus were able to maintain bone strength more readily in adulthood.

Overall, the results suggest individuals living in the rural area of Tirup were healthier than those interred in the Black Friars Cemetery in Odense, Denmark. Whether this trend is indicative of differences in rural and urban life in medieval and post-medieval Denmark or a site-specific difference in health is difficult to ascertain. The increase in indulgence seen between the rural and urban samples is likely more revealing of cemetery composition than health disparity between the samples. Additionally, given the significant disparity in time, whereby the Black Friars cemetery spans a much greater time period than the Tirup cemetery, the patterns seen in the samples are likely more indicative of temporal trends than site specific patterns.

A decrease in overall health is noted between medieval and post-medieval samples, as indicated by the decrease in stature between the time periods, although the lack of sexual dimorphism change in stature and body mass between samples suggest that females were treated similarly in both periods. It seems that life in post-medieval Denmark became more strenuous than in the medieval period, although requiring less mobility in males. The temporal transition was found to be much more significant in females than males. In post-medieval females, femoral robusticity increased significantly and became almost equivalent to that seen among the post-medieval males when standardized for size. This transition is possibly associated with the lack of conventional employment opportunities available to females in the post-medieval period (Jacobsen 1983).

Age-at-death significantly affected perceived health, specifically in males, in the medieval and post-medieval period. The healthiest, most robust individuals died between the age of 50 to 70 years. These males were the tallest and presented the most robust femora. Interestingly, stature seems to have been detrimental to longevity after the age of 70. Without the use of an age estimation technique that could precisely age older individuals, this decrease in height in the oldest age category would have been obscured. Interestingly, individuals who lived to old age did exhibit a lower frequency of osteoporosis and certain indulgence-related disorders.

BMI also significantly affected health outcome in medieval and post-medieval Danes. Increased BMI seems to have been detrimental to overall health. The increased BMI was likely not associated with body fat. It is more likely that for many, higher BMI denoted an increase in muscularity, not body fat. In light of the hardships faced during the medieval and post-medieval period, specifically the increasing food scarcity, it stands to reason that individuals were forced to work harder (leading to more robust femora) as time progressed. From an evolutionary perspective, it seems logical that females present a more significant response to stress, whereby bone strength and robusticity are compromised in order to maintain reproductive health.

7.2 Future research

The analysis of the Danish medieval and post-medieval skeletal material from the rural cemetery of Tirup and the urban cemetery of Black Friars led to several interesting and unexpected conclusions. However, it also indicated several areas where future investigation is required. According to Kelmelis and Dangvard Pedersen (2019), understanding Danish health based on the rural–urban dichotomy may be too simplistic for Danish samples. As only one urban and one rural sample were included in the current analysis, it is impossible to corroborate or contradict this statement. Running the analysis on a greater number of rural and urban samples would aid in a more in-depth understanding of rural and urban health in historical Denmark. Additionally, analyzing a greater number of sites, both rural and urban, that spanned the entire medieval and post-medieval periods would allow for the differentiation of trends associated with location and time period.

In the current analysis, femoral robusticity was evaluated and inferences were made about the physicality of life and differences in the amount of mobility required by the different samples. The results suggest a temporal maintenance of femoral robusticity in males and an increase in females. Historical documentation indicates that life may have been more difficult for the poorer sector of society in late medieval and post-medieval Europe (Fagan 2000; Jordan 1996; Steckel 2004). It is possible that the types of mechanical loading change as occupations changed. As such, an investigation of upper limb robusticity, specifically humeral robusticity, would allow for more precise conclusions to be approached. Additionally, investigating osteoarthritis and degeneration associated with the different types of occupations could aid in understanding the mechanical loading pattern changes in medieval and post-medieval Denmark. While bone size was analyzed, bone quality was not. Bone strength is a product of both the amount of bone laid down and the makeup of bone itself. Undertaking an analysis of bone quality would aid in broadening our understanding of archaeological bone health.

Broadening the scope of the biomechanical investigation to include more samples, specifically samples where socioeconomic status and occupation are known or could be ascertained, would aid in disentangling some of the conclusions approached in the current analysis. If similar patterns in robusticity are noted, whereby differences in bone maintenance are perceived between females and males, it may be possible to unravel sexual differences in bone plasticity and bone's response to mechanical loading. It would also be beneficial to undertake biomechanical research including juvenile skeletal material. Historical records suggest that British females began physically demanding domestic service work at very young ages (Shapland et al. 2015). Understanding the effect of physical labour and poor nutrition in childhood and how it differentially affected males and females would aid in understanding the response of bone to different types of stress. Collaborative research using aDNA and sex hormone mapping could also aid in understanding this mechanism.

Studying skeletal patterns associated with aging can help understand factors of selective mortality and hidden heterogeneity of risk, as the oldest individuals in a skeletal sample were the healthiest, least frail of the population. Until recently patterns of skeletal aging could not be meaningfully analyzed in the oldest old of a sample given the inability of conventional age-at-death estimation techniques to accurately and precisely age older individuals. Newer techniques, such as Transition Analysis, are allowing for meaningful research to be undertaken on older individuals. The accuracy of Transitional Analysis has been questioned as it still relies on degeneration of the skeleton as well as using aspects of the pelvis that are often preferentially degraded in skeletal material. As such, newer and more accurate age-at-death estimation techniques, such as the CEI method, could aid in untangling age-related degeneration and diseases in skeletal material.

There is still a great deal that is not known about the skeleton and archaeological remains. Yet, new technologies and improving methodology are allowing for unprecedented levels of analysis on archaeological samples. Researching skeletal health in the past is an important avenue for understanding life and health experience in historic and prehistoric populations.

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