An Assessment of Socioeconomic Impact on Childhood Skeletal Growth and Maturation in Medieval and Early Modern Denmark

by

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Abstract

A multifactorial approach is taken to observe for changes in childhood health in Medieval and Early Modern Denmark. Samples originate from three cemeteries located in the urban cities of Horsens and Odense. The dates of theses samples are of particular interest due to historic records documenting the Middle Ages as a time of hardship with extreme fluctuations in climate impacting agriculture and food availability as well several repeated waves of deadly plague. Variations in health are observed in the form of longitudinal growth, body size, epiphyseal growth and cortical thickness; encompassing various facets of the growth and development processes. Cortical thickness has not been thoroughly applied to studies of health and physiological stress despite evidence of its value. Unlike previous work that has relied on 2D measurements from X-rays, 3D imaging is used to visualize the bone structure and measure appositional growth. There is no evidence of stunted growth or development delay between temporal periods. This could suggest that the documented hardships of the Middle Ages were mitigated by Denmark's unique environment and marine access, or could be evidence of cultural value and protection of children. There is however, a temporal change in age-related mortality patterns with an increase in individuals aged 14 to 18 in 1250-1450 but low infant mortality. By contrast, in the post-Reformation sample, there is an increase in infant mortality and decrease in older child and adolescent deaths. CT imaging of cortical thickness provided an effective means of studying appositional growth in a past population and observations show potential for greater sensitivity in identifying physiological stress than the traditional use of longitudinal growth.

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Pour Paul-Egide Brunet

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1. Introduction

Skeletal remains offer a unique perspective into the human experience; past and present. The skeleton exhibits characteristics of a person that may have been visible to their peers such as their biological sex, age, stature, and facial features. Osseous tissues also maintain records of life events such as healed or non-healed trauma, signs of disease, and evidence of stress. By looking at each of these clues bioarchaeologists can reconstruct pieces of a persons' life. When this exercise is extended to a larger sample such as a cemetery, this provides valuable information about the collective population; mortality rates, life expectancy, diseases and trauma experienced, etc.

Children are among the most vulnerable in any population; their bodies have high energy demands as they go through substantial changes in body size and physiological development. A stressor in the form of disease, insufficient or inadequate nutrition, or psychological trauma, can impede on the natural growth process causing stunting and developmental delays. This is typically studied based on longitudinal growth, particularly the length of long bones. These studies operate under the assumption that a shorter stature represents stunted growth (Steckel, Rose, Larsen, & Walker, 2002). Stature is a continuous genetic trait with an estimated genetic contribution towards adult stature ranging from 60 to 80% (Palmer & Hirshhorn, 2003). The level of genetic contribution varies depending on population and sex (Hirshhorn et al., 2001). While the environment and its stressors do have an impact on final stature, genetics will have a greater contribution. Thus, there are important differences in stature depending on the genetic population. When a single genetic population experiences a change in stature that cannot be explained by genetic drift or the introduction of new genetic material, this suggests an environmental change. Bioarchaeologists will also look for signs of lesions or non-specific stress markers to indicate a period of hardship. The appearance of these markers depends on the severity and duration of the stress episode. The absence of such markers does not indicate the absence of physiological stress. In addition to innate variations in the stress response, the evidence of such events can become obscured by bone remodeling and catch-up growth; accelerated growth periods when environmental conditions become favourable again.

In healthy growing children, as the long bones increase in length, they also gain width and bone thickness at a consistent rate until adolescence (Hummert, 1983). Longitudinal growth, the increase in length and consequently stature, occurs concurrently with appositional growth, the addition of bone thickness and strength. Changes in either of these can reflect a disruption in the expected growth process. Few researchers have included measurements of appositional growth to assess childhood stress, likely due to challenges in assessing the inner structures of the bones. To do so would require either destructive cutting of the bones or access to medical imaging tools such as X-ray or computed tomography (CT). Appositional growth could offer valuable information about childhood health and stress. Changes in appositional growth have been observed to be more sensitive indicators of physiological stress (Hatch, Willey, & Hunt, 1983; Mays, 1995; Mays, Ives, & Brickley, 2009). Changes in the cortical thickness are also less susceptible to the effects of catch-up growth than in longitudinal measurements (Hummert, 1983). Furthermore, levels of appositional bone accrued during childhood and adolescence are an important predictor for bone loss later in life, risk of fracture, and long-term health (Garn, 1971; Gosman, Hubbell, Shaw, & Ryan, 2013).

1.1 Purpose and Significance

It is largely accepted that in studies of bioarchaeology and human osteology, the best practice is to include and consider all possible lines of evidence (Ribot & Roberts, 1996). This study will be taking that approach in assessing childhood growth and development. Research will focus on indicators of growth and development that can be observed from archaeological samples and provide evidence of stunting or maturational delay resulting from physiological stress. The observed indicators will encompass both longitudinal and appositional growth, skeletal maturation, and body size; reflecting multiple aspects of the growth and development process. Longitudinal growth will be assessed in the form of long bone length. The timing and progression of epiphyseal fusion will represent maturation. Body size will be estimated using regression equations developed by Ruff (2007). Finally, appositional growth will be observed using measurements of cortical thickness. Few studies (Garn, 1971; Hatch et al., 1983; S Mays, 1995; S Mays et al., 2009) have assessed appositional growth on a population scale and most of these are limited in scope due to their use of X-rays. This study will use CT scanning for a non-destructive three-dimensional assessment of cortical thickness. CT scans will provide complete visualisation of the cortical bone and the medullary cavity, allowing for distinction between resorption and deposition of bone at the endosteal and periosteal surfaces and an accurate assessment of the actual tissues as opposed to an estimation based on an X-ray image and an assumption of cylindrical areas.

The research sample will consist of subadult skeletal remains from three cemetery sites from two important urban centers in Denmark. The dates of these burials span from the tail end of the Early Middle Ages to the Early Modern period. This time period is one known for climactic fluctuations that drastically impacted agriculture and the economy. In addition to climate change, Denmark also experienced multiple waves of devastating plague during this time. It would be expected that the health of Danish citizens would suffer because of the events they faced, but to date there is no bioarchaeological evidence of this (Yoder, 2006, 2010, 2012).

The sample is limited to subadults as these clearly represent the non-survivors of the population. While Saunders & Hoppa (1993) observed minimal differences in long bone length between the survivors and non-survivors in their sample, there is still potential that observable and unobservable differences do exist between the two groups. In addition, there is a decreased likelihood of sexual dimorphism in cortical thickness and bone length when observing skeletally immature individuals.

This work will allow researchers to gain a perspective of the life and health of children; a perspective that may not otherwise be preserved or accurately represented in mediums such as historical documents. Evidence of stunted growth and childhood exposure to physiological stress provides insight into a larger part of the past than can be obtained from historical records. These skeletal markers provide information about health, access to nutrition, and exposure to disease. Greater knowledge concerning the growth and development for this population will be beneficial to bioarchaeological research. Most of the standards and references used are based on modern Western populations, predominantly of European ancestry. There are clear variations between these reference groups and archaeological samples (Boldsen, 1984; Boldsen & Søgaard, 1998) and as a consequence, the standards used simply perpetuate erroneous information about the archaeological populations on which they are applied.

A multifactorial approach is taken towards the study of growth and development incorporating multiple facets of these physiological processes. These are complex processes and the research methods should adequately reflect this. Some of the methods used such as longitudinal growth have a long history of application in bioarchaeology. Appositional growth is a known aspect of growth recorded in some longitudinal clinical studies (Garn, 1971) and applied in some archaeological contexts (Hatch et al., 1983; Mays, 1995; Mays et al., 2009).

Despite the availability and access to better imaging methods, to date visualization of cortical thickness using CT has not been applied to studies of growth and development in past populations. This study aims to rectify that and test its usefulness as a research tool.

1.2 Research Objectives

The primary objective of this research project is to assess childhood growth and development in Denmark during the Medieval and postmedieval periods. Samples dating to differing time ranges will be used to determine if any variations in growth and development can be observed in the skeletons of subadults during a period of known socioeconomic change and challenges to population health.

This larger objective was broken down into four more specific research questions:

1- Is there evidence of growth stunting when comparing longitudinal growth with dental age, and is stunting more pronounced during a particular time period covered by the sampled remains?

2- Can the regression equations developed by Ruff (2007) provide useful results in assessing body size? If so, do the results indicate a time of physical wasting?

3- Are there variations in the growth process in terms of the sequence and timing of epiphyseal fusion between temporal periods and compared to other populations?

4- Is the growth-related remodeling of cortical bone more susceptible to stunting as a result of environmental stress than is longitudinal growth? Does the use of cortical thickness, particularly when visualised with CT offer a promising option for the study of growth and development in past populations?

Chapters 2, 3, and 4 provide a summary of the pertinent literature that has informed and guided this research project. Chapter 2 deals with the historical and research background necessary for the cemetery sites studied. This chapter will discuss the historical and climactic events experienced in Medieval and post-Medieval Denmark and how these impacted human health. It will also provide an overview of some of the bioarchaeological work that has been done involving this time period and part of the world. Chapter 3 addresses the study of childhood health in archaeological contexts and what can be gained from such studies. There will be a summary of important studies that have been done to understand growth and development in archaeological contexts. These include studies of long bone length and stature, maturational changes, growth tempo and velocity, and stress markers. This chapter will also cover the challenges and limitations faced by archaeologists in understanding childhood health in the past. Finally, chapter 4 will provide information about cortical thickness; how this can be a useful tool for growth studies, the factors that impact it, and some practices and findings derived from clinical and bioarchaeological research. The materials and methods for this project can be found in chapter 5. There is background information for the cemetery sites and the criteria for burial dating. The methods describe some summary statistics about the sample used for analysis, as well as the bones, measurements, and tools that will be used to study growth and development and the rationale behind these. Chapter 6 presents the results and statistical analyses of this research dividing information based on longitudinal growth, body size, maturation, and appositional growth. A discussion of the results is presented in Chapter 6 along with an in-depth summary for each aspect of growth and development relating findings back to the research objectives previously outlined. These data will also be discussed in relation to additional factors such as age, sex, site, temporal period, and evidence of trauma or illness. Particular attention will be placed on the application of cortical thickness as a potential indicator of stress during childhood. Chapter 7 outlines the conclusions made based on this research project concerning childhood health in Medieval and postmedieval Denmark and the various aspects of growth and development that were studied. Finally, this chapter considers the limitations of this study and the future directions for further research in childhood growth and development, stressing the validity of incorporating cortical thickness as an indicator of stunted growth.

2. Life and Death in Medieval Denmark

2.1 Introduction

In studying population health, especially in past populations, the greatest concerns lie in understanding how people lived; what events impacted health, how the human organism physically responded to those health challenges, and which if any of those physiological changes can be observed in archaeological samples. The three archaeological samples used in this study come from urban centers in Denmark; one from Odense, two from Horsens. The dates for these burials range from the 12th century to the 18th century; starting from the tail end of the Early Middle Ages and ending in the Early Modern period. The dates and locations of these burials and consequently the deaths of the individuals being studied are important to give a larger context to the environment and living conditions in which these people lived and died.

Discussions of plague, climate change, and variations in agricultural success typically deal with large-scale trends that are generalized for most of Europe, although usually with a focus on the Western countries such and England and Italy (Benedictow, 1992). In Scandinavian countries, such as Denmark, with climates, terrain, and use of marine resources that differed largely from the rest of Europe, the general patterns of events experienced throughout most of Europe will not be consistently representative (Andrén, 1989a). This section will provide a review of the larger factors influencing health and life in Medieval Denmark including temporal changes in climate, subsistence practices, economic organization, and sources of disease. A description of mortality and burial practices during the Medieval period illustrates what bioarchaeologists can expect within this particular context. Finally, a summary of some of the bioarchaeological work that has been done using Medieval Danish material is presented to understand the physical impact these various stress factors actually had on the population and how they can be recognized in human remains.

2.2 Denmark in the Middle Ages

Historical records denote that the Medieval period was a tumultuous time in European history. Most records focus on events outside of Scandinavia. Benedictow (1993) argues that historical accounts and records from England, the best source of material, are closely related to events witnessed in Scandinavia. The geography, climate, and background in the Scandinavian countries are somewhat different from England and Europe in general, but large sweeping trends can possibly be inferred. Climactic patterns in Europe are typically classified in three main categories; Mediterranean, Atlantic, and continental (Hoffmann, 2014). Under these broad divisions, both England and Denmark would fall into the Atlantic pattern which is largely impacted by the warming of oceanic air by the Gulf stream (Hoffmann, 2014). Benedictow (1992) and Hybel & Paulsen (2007) attempt to corroborate these larger trends with reports from Denmark and Scandinavia whenever possible however, there are areas that are lacking in details and supporting evidence. Archaeological findings provide an additional line of evidence that may assist in revealing details not otherwise recorded.

The Middle Ages in Denmark start much later than in the rest of Europe; in the 10^{th} century, with the most pivotal changes occurring after the baptism of King Harald Bluetooth and the eventual integration of Denmark as a Christian state (Andrén, 1989a). The Middle Ages persisted until the mid-16^{th} century and are separated into the Early Middle Ages, from the 10^{th} to 13^{th} century, and the Late Middle Ages from the 13^{th} until the mid-16^{th} century. This period of time in Scandinavia is therefore half the length it is in other parts of Europe (Boldsen, 1996).

There were many variables at play that influenced the daily lives of Danish citizens including climate, nutritional sources, population size, and geography among others.

Climate plays a significant role in the quality of life, especially when the majority of the population relies on subsistence-based agriculture (Aberth, 2013). In Denmark, approximately 90% of the population lived in rural areas (Boldsen, 1996). Minute changes in weather could have a significant impact on the growth season and crop yields. When communities rely on local food sources, a bad season can have devastating effects on health and nutrition. In the absence of the expected crops, other food sources need to be exploited. This would cause an increased strain on resources and would likely result in reduced quantity and diversity of foods consumed by a household.

The dates and actual degree fluctuations in temperature relevant to the Middle Ages are frequently debated and remain unconfirmed. The current body of knowledge is built upon a variety of sources. Documentary evidence written at the time provides a written testament to the reality witnessed by the people. These documents include records of grain prices, harvest records, and weather journals (Aberth, 2013). While these records lack the scientific rigor that would be desirable, they reflect closely how the population was impacted by the weather; especially data concerning crops and the price of grains. There are scientific sources of evidence that can generally corroborate most of the documentary data. Lines of evidence such as oxygen isotopes, radiocarbon readings taken from ice cores, dendrochronology, lichenometry, analyses of pollen and peat bogs, as well as insect and faunal remains in archaeological contexts inform researchers on climactic trends (Aberth, 2013; Grove, 1988). Both the historic and scientific lines of evidence agree that Europe experienced a warm period sometime from 800 until 1300 and a subsequent series of cooler weather fluctuations that lasted until the mid-19^{th} century (Aberth, 2013).

During the Early Middle Ages, Europe in general experienced uncharacteristically mild weather. This period is often referred to as the Medieval Warm Period or the Little Optimum (Aberth, 2013). Hoffmann (2014) cautions that these descriptions are generalizations largely based on British data and suggests an alternative description of a 'global climate anomaly', recognizing the worldwide impact of these fluctuating weather patterns. While the overall trend was of warmer weather, this was not constant and fluctuated in a wave-like pattern until the shift experienced in the 14^{th} century (Hoffmann, 2014). There is debate over the precise date-range for this period, but it lasted possibly from 800 until 1300 CE, conclusively from 1100 until 1300 (Aberth, 2013). Ice core temperatures from Greenland support peak temperatures occurring between 800 and 1000 (Hoffmann, 2014). Fagan (2000) states that these four centuries were the warmest among the past 800 years. This warm period opened some previously frozen sea passageways, allowing for greater exploration and settlement by seafaring peoples such as the Vikings. For the groups residing in Scandinavian countries, this also allowed for plentiful and profitable exploitation of marine resources (Aberth, 2013; Fagan, 2000). The sale and trade of marine resources would become increasingly important during the Middle Ages with church-mandated dietary restrictions and precautionary measures to minimize the spread of plague (Christensen, 2003). The warmer and longer summers also allowed for extended and prosperous agricultural seasons (Hybel & Poulsen, 2007; Yoder, 2010). This period of economic prosperity permitted the eventual growth in population size and encouraged greater urbanization. It is estimated that the Danish population numbered around one million during this time of prosperity (Benedictow, 1993). In rural settings, people started exploiting what were previously marginal lands (Fagan, 2000). These lands would be those most vulnerable to future climactic fluctuations. Increased consumption of cereals and bread was encouraged for religious, medical, and socioeconomic reasons, creating a rise in demand for grains (Hoffmann, 2014). While the elites enjoyed processed white bread, peasants subsisted largely on porridge and ale made from coarser cereals such as barley (Hoffmann, 2014). The greater demand for food, particularly cereals, caused by a growing population encouraged widespread clearing of land, more intensive agriculture, and a reduction in the diversity of crops (Hoffmann, 2014). These practices not only reduced the variety of the diet, it also left the crops far more vulnerable to failure when faced with the climactic instability that was experienced during this time (Hoffmann, 2014).

Towards the end of the 12th century, the trend of warm summers was coming to an end and weather systems were leading into the Little Ice Age (Hybel & Poulsen, 2007). The 'Little Ice Age' was not a period of consistently cold weather as the name might imply. It was a series of frequent weather fluctuations (Grove, 1988). These instabilities in weather conditions were particularly challenging to those who relied on subsistence-based agriculture for survival. Multiple seasons of low or failing crop yields due to extreme rainfall and extended winters led to socioeconomic hardship for farmers and nutritional stress for their families. This period is sometimes referred to as the 'Late Medieval Agrarian Crisis' (Andrén, 1989a). The theory of the 'Late Medieval Agrarian Crisis' was originally developed by Abel in 1976 based on mass farm desertion observed in Germany (Jäger, 1981). This theory was founded on one specific country and is not based on regional or local evidence from other parts of Europe (Jäger, 1981). Further scholarship (e.g. Epstein, 2005; Hoffmann, 2014; Jäger, 1981) disagrees that the term 'crisis' is appropriate to describe the ecological, demographic, political, religious, and socioeconomic challenges of this time. In most cases the reason for most farm desertions cannot be discerned

(Jäger, 1981). While hardships were certainly experienced, populations adapted to the changing ecological situation, adopting more sustainable agricultural and economic practices. In some regions, crop yields were observed to continuously increase up until the impact of the Black Death (Epstein, 2005). It is suggested that the increased mortality rate was a response to the continuously growing populations reaching the limits of the local carrying capacity (Hoffmann, 2014). Epstein (2005) refutes this suggestion, doubting that family size remained completely unchecked.

Repeated loss of crop yields did lead to widespread famine, which had an important impact on mortality (Hybel & Poulsen, 2007). Areas with access to marine resources were able to supplement their diets during times of crop shortage, but growing local and foreign demand would periodically put stress on this resource as well, causing documented herring shortages in the late 14th and early 15th centuries. The socioeconomic changes and growing divisions between rural and urban lives emphasized the pre-existing divisions in social classes. The elites who lived comfortably in urban centers remained largely unaffected by variations in climate and economic situations (Yoder, 2012). From 1315 until 1322 the 'Great Famine' affected most of Europe including Scandinavia (Hybel & Poulsen, 2007). The first waves of the Black Death followed closely, entering Denmark in 1349 and continuing to have an impact for the following three centuries (Christensen, 2003; Ziegler, 1988). Due to its position as a political and economic trade hub, Copenhagen tended to be the first and most severely affected area in Denmark (Christensen, 2003). Once the Black Death would strike an area, people who were already in a weakened health state were more likely to succumb to disease (DeWitte & Wood, 2008). The Black Death had an extremely elevated mortality rate, but the disease was not completely indiscriminate. DeWitte & Wood (2008) observed some selectivity in Black Death victims excavated from East Smithfield in London, however the degree of selectivity was much lower than that represented from a standard attritional cemetery. A much larger proportion of the entire population will be represented in a sample of Black Death victims, however these samples do not provide an ideal catastrophic representation of the living population from that time period (DeWitte & Wood, 2008). Demographic groups that were more vulnerable, particularly children, were most likely to succumb to the plague during its first waves (Grainger, Hawkins, Cowal, & Mikulski, 2008). Earlier burials have high concentrations of juveniles, but later graves see them occupying a smaller percentage of the burial population (Grainger *et al.*, 2008). The Black Death killed approximately 30 to 50% of the European population (DeWitte & Wood, 2008). The exact death toll is difficult to piece together particularly in rural areas (Christensen, 2003).

With such a large decline in the overall population, restructuring was necessary at nearly every social level. Throughout Europe, the agricultural crisis was intensified due to the lack of people available to tend the fields (Bowsky, 1964; Grove, 1988). Intensive cereal growth, as was being practiced, required substantial time and hard labour to maintain (Hoffmann, 2014). The population deficit starting from the famines and continuing with the Black Death would persist well into the 16th century (Hybel & Poulsen, 2007). Farm lands and villages were abandoned en masse, and after experiencing firsthand the dangerous vulnerability of agricultural based subsistence, residents of rural areas reformed their focus in favour of further exploitation of cattle. While cereal crops were more susceptible to fluctuations in weather, they had allowed for greater production and consumption of calories than was available in the later, cattle-focused period. Although sources suggest that the Danish people had a healthy diet and were generally of good health for the time, their downfall was caused by uncontrollable factors of weather and plague (Hybel & Poulsen, 2007). Throughout the Medieval period, Northern Europe tended towards higher meat consumption than populations in Southern, dryer climates (Hoffmann, 2014). In the Late Middle Ages, the average European was consuming more meat, therefore there was a growing demand for raising and slaughtering livestock (Aberth, 2013). This shift rewarded the agricultural shift and led to increased productivity and a rapid recovery of economic footholds (Hybel & Poulsen, 2007). Despite the many agricultural changes, the number of farms remained relatively consistent between the years 1200 and 1600 (Hybel & Poulsen, 2007). In the aftermath of the Black Death, households established greater separation between living spaces and livestock, reducing but not completely eliminating the spread of zoonoses (Aberth, 2013). By the end of the Middle Ages, arable lands had been reclaimed and agriculture was as strong as it had been prior to the devastation of the 14th century. Growing demand for cod and herring from Christianized Europe maintained a strong market for marine exports from Denmark (Aberth, 2013; Christensen, 2003). The economic changes had little effect on the wealthy, but allowed for increased wealth and stability among the peasant class as land and food were more widely available and accessible. After remaining at a standstill since the 1300s, urbanization picked up again by the late 15th century seeing renewed and more complex division of labour (Hybel & Poulsen, 2007). Moderate, but irregular cooling persisted until the last half of the 19th century (Hybel & Poulsen, 2007). The population is seen to increase in the 16th century following these economic changes (Boldsen, 1997). The population fully recovered from the extreme mortality rates of the 14th century caused by plague and famine around the last century of the Little Ice Age as a result of the more prosperous economic situation Hybel & Poulsen, 2007; Paine, 2000).

2.3 Death and Burial in the Middle Ages

Under the epidemiological transition model (Omran, 1971), the European Middle Ages would be situated in Stage One: the Age of Pestilence and Famine. It is characteristic in this stage for the majority of deaths to be caused by disease or nutritional instability. The bulk of these deaths consisted of infants and young children. As infant mortality is likely greatly underreported during this time, the estimate of births surviving to adolescence ranges from 40 to 70% (Hoffmann, 2014). Leprosy and tuberculosis had important health impacts, but The Black Death had a tremendous impact on demography due to its high mortality rate, and frequent waves.

With the adoption of Christianity came uniform and consistent funerary practices, most notably with an emphasis on piety and burial. This was a marked departure from the pagan funerary rituals which varied with cultural groups, but often incorporated cremation and offerings of valuable or symbolic items. In most cases, people were aware of their imminent deaths and would take the necessary measures to ensure a 'good Christian death' with confidence that they were safe in the hands of God and would be at peace in the afterlife (Ariès, 1976). Once a person was determined to be deceased, the body was laid out, washed, contained within a shroud or winding sheet and placed either directly into the ground or enclosed in a wooden coffin (Daniell, 1997; Kacki, Rahalison, Rajerison, Ferroglio, & Bianucci, 2011). Typically, each grave contained one single body, although multiple interments did occur, usually indicating a filial relationship such as husband and wife or child and parent (Daniell, 1997; Kacki et al., 2011). A clear exception is the occurrence of mass graves to bury a large amount of dead as was used in some cities during the height of the Black Death, for example East Smithfield in London.

In excavating Medieval cemeteries, some commingling of remains may also occur due to superposition of burials or later burials cutting into inadequately marked older graves.

Despite the high infant and child mortality, there is little mention or portrayal of the funerary treatment of these age groups until the 15^{th} century (Daniell, 1997). There were slight differences in the subadult burial clothes based on age, particularly in the incorporation of the chrisom, a cloth worn during baptism (Daniell, 1997). Most Europeans could expect a proper Christian burial. There were few exceptions that would bar a baptized individual from burial in consecrated ground. Certain allowances were made, such as permitting midwives to perform baptisms on infants, to permit the burial of infants during a time when they had a high risk of death (Daniell, 1997). This practice likely minimized the likelihood that infants or young children received differential burial treatment that excluded them from cemetery grounds. In some cemeteries, specific areas are reserved for infants and children while in others they are buried among adults (Parker Pearson, 2003). In Christian Medieval cemeteries, child burials tend to be found close to the church (Craig-Atkins, 2014).

Archaeological excavations of Medieval cemeteries became more commonplace in the 1960s (Daniell, 1997). A wide array of cemeteries throughout Europe have been excavated and allow researchers to get a more complete image of the lived experience of the average person as well any regional differences. Some of these in Denmark have been thoroughly excavated and studied, providing information about Scandinavian life that often was not preserved in historical documents.

2.4 Bioarchaeology of Denmark

The vast majority of bioarchaeological research pertaining to past Danish populations concerns skeletal remains dating to the Middle Ages. There are several reasons for this. The dominant custom for funerary treatment was inhumation, typically in consecrated areas such as churches or monasteries (Rudbeck et al., 2005). These existing buildings, remains of buildings, or the documented locations of them, allow archaeologists to more easily locate human remains from this period. Widespread written records were absent from Scandinavia until Christianization in the 11th century, much later than in other European countries (Boldsen, 1996). Written records from Northern Europe can also provide some insight into how Denmark fit into the economic and trade systems, and general trends. These records offer an additional source of information, however, any existing documents may be incomplete, inaccurate, or biased. These documents record information that was considered important, most of which centered around ecclesiastic events (Johansen, 2002). Written records are also incomplete as over several centuries many have gone missing or have been destroyed (Johansen, 2002). Nevertheless, they can provide greater insight into aspects of life that did not survive into the archaeological record and they can help verify conclusions drawn from archaeological analysis.

Studies of Danish material have contributed largely to the body of bioarchaeological knowledge of paleopathology, most notable in the epidemiology and diagnosis of leprosy. Møller-Christensen played an essential role to the entire field of palaeopathology in his palaeopathological study and understanding of leprosy. His work provided the first extensive descriptions of skeletons exhibiting symptoms of leprosy from various sites throughout Denmark. Johannes G. Andersen expanded on Møller-Christensen's work, studying alternative symptoms of leprosy, further refining the diagnostic criteria for the disease and reassessing skeletons previously studied by Møller-Christensen (e.g. (Andersen & Manchester, 1988; Andersen, Manchester, & Shahzady Ali, 1992). This focus on disease-related lesions, as manifested in osteological remains, is partly related to the collections available for analysis. Many of the excavated cemeteries contained notable examples of pathological disease of the skeleton. Cemeteries catering to a more select portion of the population, such as cemeteries associated with hospitals, monasteries, and leprosariums have the potential of yielding a greater concentration, and perhaps more advanced examples, of pathological lesions than would a more representative village cemetery (Bennike, 1991).

In a field such as palaeopathology, or any study of disease, a certain amount of qualitative analysis is necessary given the wide variation in the ways that a disease can manifest itself. The descriptive observations can be further analyzed statistically through the use of progressive scores and nominal statistics. A wide variety of demographic and environmental variables need to be considered to truly understand the aetiology and the physical response between a human body and a disease (Boldsen, 1997).

Pathological conditions, such as leprosy, did not affect everyone during the Middle Ages. Observations, such as those made by Boldsen (2001), illustrate how significant the impact of the disease was on an average rural community such as Tirup where 23 to 46% of individuals may have suffered from leprosy. Individuals exhibiting the most obvious symptoms of leprosy were systematically removed from the larger population and isolated in leprosaria (Boldsen, 2001). The spread of leprosy reached its peak in Denmark during the Early Middle Ages (Boldsen & Mollerup, 2006). By 1400, partially as a result of systematic isolation and due to acquired immunity from increased contact with cattle and *M. bovis*, leprosy was in decline in Denmark, with earlier eradication in urban centers (Boldsen & Mollerup, 2006).

These abnormal pathological conditions had an important impact on the lives of the average person and were an unfortunate reality of life in the Middle Ages as was the Black Death. Paine (2000) suggests that the death toll from the Black Death impacted the demographic distribution of certain parts of Europe for up to 150 years. While the Black Death is an extreme example of the impact of an epidemic, such projections demonstrate the lasting impact that any large-scale cause of death can have many generations into the future.

The excavation and analysis of rural Tirup has provided a wealth of palaeodemographic information that has allowed for a solid base to palaeoepidemiological analyses (Milner & Boldsen, 2017). This is due in large part to the total excavation of the cemetery, even beyond the cemetery limits to ensure the inclusion of all potential burials (Boldsen, 1996; Boldsen, pers. comm.). As a parish cemetery, there is limited risk of selection bias as may be observed in some ecclesiastic cemeteries or those linked with hospitals or almshouses (Boldsen, 1996; Sullivan, 2004). Tirup has allowed for crucial research into various nonspecific stress indicators and their long-term impacts on health and mortality risk (e.g. Boldsen, 1998a, 1998b, 2007).

Boldsen (1996) looked at childhood mortality in three rural Danish cemeteries; Löddeköpinge, Tirup, and Westerhus, and the suburban St. Mikkel cemetery. This study looked at mortality patterns in those aged between 1 and 20, intentionally leaving out infants to avoid any potential representation bias. An overall pattern of increased mortality, particularly in those over the age of 5 was observed from 1100 to 1300 (Boldsen, 1996). This is counter to the standard expected pattern of high infant and young child mortality in early rural communities and has more far-reaching impacts on the overall demographic and economic situation (Boldsen, 1996). Urban communities such as Sct. Mikkel fared much worse, likely due to increased contact and spread of disease. Given the high childhood mortality observed, these centers would have depended on immigration to maintain a viable population (Boldsen, 1996).

Despite contemporary accounts of multiple nutritional, climactic, epidemiological, and economic hardships experienced by the average person during the Middle Ages, the bioarchaeological record does not seem to provide evidence of extreme physiological stress. Average stature is greater in the Middle Ages than that of individuals from the Viking period and would not exhibit a significant decrease until the 19th century (Boldsen & Søgaard, 1998). Within the Middle Ages, differences in stature were observed between rural, suburban and urban centers. Rural occupants, on average were shorter than urban and suburban contemporaries (Boldsen & Søgaard, 1998).

To further explore the impact of status on health and everyday life, Yoder (2006, 2010, 2012) used stable isotope analysis to determine if dietary differences existed between social classes and if diets changed through time during the Middle Ages. Given the degree of social stratification and the drastic economic, climactic, and physiological stress variation throughout the Middle Ages, there is certainly potential for dietary disparity. The sites studied include the Øm Kloster, a rural monastery with burials of monks, elites and some peasants dating through almost the entire span of the Middle Ages, St. Mikkel, a suburban site dating from the early 12th century to the early 16th century, and Ribe, an urban site used between 1,250 and the early 15th century (Yoder, 2010). Yoder (2010) looked at nitrogen and carbon isotope levels to determine proportions of food sources for each site and through time within the individual sites. The changes in diet through time and between sites were not as evident as was expected. There were no significant regional differences between Øm Kloster and St. Mikkel; however the residents of Ribe exhibited statistically significant higher levels of ^{15}N (Yoder, 2010). Around the midpoint of the Middle Ages, Ribe's levels of ^{13}C decreased significantly, indicating reduced consumption of marine resources. The monks and elites buried at Øm Kloster had a much more diverse diet, rich in terrestrial animals and plants in comparison with the other two sites (Yoder, 2006). The variation between sites was concluded to be more closely related to proximity with food sources or access through trade rather than status (Yoder, 2006, 2010). While Scandinavians may have had greater access to marine resources in comparison to other European countries, access was still variable within the country based on physical proximity to bodies of water

A more in-depth look at the temporal and status-related difference of diet is taken in Yoder (2012). This study focuses on burials at only the Øm Kloster site. The status of individuals is determined based on the location of burial. During this period, quantity and quality of nutrition was not purely dictated by status and food availability. The Christian church imposed certain dietary restrictions and obliged fasting on pre-determined days of the week and around holy periods (Yoder, 2006). The monks at Øm Kloster, Cistercian monks, had more rigid restrictions concerning their own diets. They were supposed to be self-sustained; growing the plants, raising the livestock, and preparing all foods that they would eat (Yoder, 2006). In addition to self-reliability, the monks followed stringent diets. With time, these restrictions were gradually lifted. During the early period of the Middle Ages, the monks' diet was very similar to that of the peasants; predominantly composed of C_3 plants and terrestrial animals. The monks consumed more terrestrial and marine proteins largely due to due ease of access (Yoder, 2012). By the midpoint of the Middle Ages, the monks had increased amounts of protein from all sources in their diet. During the later Middle Ages the elites and the monks had similar diets. While the monks seemed to experience a rise in social status in terms of the quality and quantity of their food, very little temporal difference was observed in the elites or the peasants (Yoder, 2012).

2.5 Summary

Multiple historical sources present this image of the Middle Ages as a period of socioeconomic instability with widespread impact of famine and disease. These sources suggest that the population experienced extreme physiological stress. To date there is very little bioarchaeological evidence in Denmark to support those suggestions. There are multiple possible explanations for the lack of consistency between the historical representation and the physical evidence. It is most likely that the explanation lies within the variability in the physiological response to stress experiences. Most accounts of Black Death (Benedictow, 1992; Ziegler, 1988) describe it a fast-killer. Even in cases where the disease was prolonged or an individual survived, there are no known skeletal indicators for the presence of Black Death. Famine may be observed in the form of nutritional deficiencies such as scurvy or rickets, particularly in children, but again this requires survival during a period of stress for an unpredictable amount of time sufficient for the stress to etch itself onto the skeletal structures. Mass death, as described during the Great Famine and the initial waves of Black Death may be discerned by the evidence of mass graves, such as East Smithfield in London, but in smaller centers or areas that were adamant to follow traditional burial practices, large-scale death did not necessarily require mass graves. To further explore and understand this time period and the lives of those who lived during it, the only option is to explore additional and more sensitive lines of evidence. This study seeks to do so in focusing on growth and development patterns in Medieval Danish subadults living in urban centers.

3. Childhood Health in Past Populations

3.1 Introduction

A human skeleton can reveal a great deal about who that person was in life: their age, their sex, disease or injuries they may have suffered, repetitive muscle use indicating types of work or hobbies, the foods they ate, and general quality of their health in life. But an osteobiography of a single individual provides only a tiny sliver of perspective into the lives of people who lived in the past. A more complete and complex picture can be gained by looking at skeletal samples. From a population, we can divulge information about life expectancy, patterns in quality of life, sexual disparity, social stratification, changes in activity levels and subsistence strategies, and much more. Taking the population approach also allows researchers to gain perspective of the lives of women and children; segments of the population that were seldom discussed and rarely contributed towards surviving historical records. Childhood health from past populations gives insight into the availability and access to food as well as the disease load impacting children and wider demographic groups. The health status of children can also provide information about the cultural roles and value of children in society. During periods of recorded history, these multiple lines of evidence can provide more accurate and reliable pictures of life in the past when the right tools and methods are applied to analysis. There are many hurdles to overcome in working with archaeological samples of children. In addition to the challenges imposed by genetic variation, there are challenges due to the nature of any archaeological sample; the multitude of variables that are unknown and cannot be verified conclusively. Despite the unanswered questions, there is still great value to these investigations and much knowledge to be gained.

3.2 What can be Learned?

3.2.1 Childhood growth and development

The study of childhood health is particularly intriguing given the implications of the presence of child remains within the archaeological record. Children and adolescents undergo substantial physical changes as their bodies grow and mature, reaching adult size and morphology. Their presence in the archaeological record clearly indicates a failure to accomplish the evolutionary goal of reaching adulthood and perpetuating genetic material. An additional missing piece to this complex puzzle is the fact that in most cases, the cause of death is unknown, therefore it is not known if a particular individual has died due to poor health, as a result of accident, or from intentional neglect or violence.

While the presence of pathological lesions may indicate a possible contributor towards the cause of death, there is no confirmation that this is the case. In conjunction with or in the absence of pathological lesions, non-specific stress markers are used to assess possible interruptions and disturbances experienced during childhood growth and development. Buikstra (1977) suggests that these nonspecific stress markers indicate acute stress events while delayed maturation would be a sign of chronic stress. These signs of acute stress can be observed in the form of dental enamel hypoplasias (DEH), pits or furrows resulting from insufficient material for tooth formation (Hillson & Bond, 1997). The tooth continues to grow, but the enamel is thinner and more porous due to shortened cellular matrix secretion (Hillson and Bond, 1997). Growth arrest lines such as Harris lines show an increased bone density at the location of the growth plate during a period of growth arrest. In adults, these indicators can be remodeled, obliterating any evidence of childhood stress (Lewis, 2007). More specific indicators of nutrient deficiency point to malnutrition or undernutrition; this may also have an impact on growth. Vitamin D deficiency is characterized by rickets, the bowing of long bones. Iron-deficiency anaemia can leave tell-tale signs in the form of cribra orbitalia, pitting of the orbital bone, and porotic hyperostosis, lesions on the parietal and occipital bones (Roberts & Manchester, 2010). The presence of pathological lesions on bone can indicate the presence of chronic infection, but not all afflictions that could have an impact on skeletal growth can be detected through lesions on bone. The skeleton does not provide a complete medical record.

In addition to stress markers, evidence of stunted growth or delayed maturation has been used as an indicator of nutritional stress independent of or concurrent to periods of extreme illness. Bioarchaeologists have frequently employed growth and development data as a means to assess childhood health (Steckel, et al., 2002). These studies often operate under the assumption that evidence of stunted growth or delayed maturation indicates nutritional stress and/or periods of disease. This assumption is highly reductionist as the relationships between growth, maturation, and health are much more complex; these processes are heavily dependent on genetic variation. While growth and development may experience cessation or delay in the face of stress, once conditions return to a favourable state, and growth resumes, there is potential for catch-up growth to occur, which can make up for any potential loss. In the event of continued stress for prolonged periods, the delays and deficits in growth can be irreparable. Skeletal maturation tends to only be delayed in very extreme cases, or as a means to allow for catch-up growth (Acheson, 1960). The physical changes in the human skeleton provide at least some information about health and susceptibility to physiological stress. The frequency, age of occurrence, and time period associated with stress episodes give indications of the nutritional quality, food availability, disease load, and general exposure to stress in the particular population. General patterns can be compared to observe larger cultural and biological patterns.

Skeletal growth is considered to be an effective indicator of overall health since it is the product of a synergistic relationship between nutrition and disease (Steckel, Sciulli, & Rose, 2002). It is important to remember that short stature or the presence of any nonspecific stress marker in itself is not necessarily a risk for early death; it is merely a potential indicator for an underlying condition that may put the individual at greater risk of illness, physiological stress, or death. When studying an archaeological sample, the stature measured does not represent stature among the living population (Wood, Milner, Harpending, & Weiss, 1992). During periods of high mortality, a greater and more representative distribution of stature would be available within the dead. In contrast, during typical attritional conditions there are more selective pressures at work in determining which individuals live or die (Byers, 1994).

3.2.2 Cultural and societal change

The physical growth and development of children is a reflection of the quality of the social, economy and political environment in which they were born (Lewis, 2007). Children have been described as the canaries in the coalmine of population health (Halcrow & Tayles, 2008). They are the most vulnerable members of a population and are the first to bear witness to biocultural changes in a society (Bennike, Lewis, Schutkowski, & Valentin, 2005). DeWitte & Wood (2008) observed higher concentrations of juveniles in the earliest Black Death mass graves at East Smithfied. As the more vulnerable demographic group, children were more likely to succumb early and quickly to the initial waves of the epidemic. The presence of disproportionally high child deaths in a cemetery, especially beyond early childhood, could suggest a particularly trying time experienced by the population, whether as a result of food scarcity or disease. Goodman & Armelagos (1989) note that infants and children are at greatest risk when past populations have experienced a change in subsistence strategies. Differences in mortality within the same population and time period can also indicate social inequality and wide disparities in resource access. Within a genetically similar population, socioeconomic status has generally been found to be the most significant health determinant, with those of low socioeconomic status typically being smaller and experiencing slower maturation than the elites (Bogin, 1999; Cardoso, 2007). While this is frequently a trend, it is not always the case such as in the example of Denmark from the Middle Ages to the present where an increase in mean stature was concurrent with increases in GDP but also an increased variance in adult stature (Boldsen & Søgaard, 1998). In this setting, GDP and stature were not correlated. Rather the observed differences in Denmark are likely the result of a change in the breeding populations and migration from rural to urban centers (Boldsen & Søgaard, 1998)

It is a common misconception, largely based on artistic depictions, that in past societies childhood was not a distinct period in a person's life and rather that children were treated as miniature adults. Extensive research has demonstrated that this was not the case in Medieval Europe (Orme, 2001). Children did enjoy a certain amount of careful and privileged treatment. For lower and middle class families, it was necessary for children to contribute and assist with daily tasks from an early age, but not to the same level as adults (Hybel & Poulsen, 2007). Organized schooling became available by 1278, demonstrating the value placed on the education of children. In many countries there was a specified age of majority which could be as high as 21 (Orme, 2001). There is some ambiguity in the precise definitions of terms such as 'infant' or 'child' and the age at which a certain term is given to someone in the Middle Ages (Orme, 2001). It is likely that definitions are based on changing societal roles and development of personal and physical strength rather than chronological age (Perry, 2005). Patterns of illness or injury can provide information about the importance and treatment of children at any particular time period, and can give indications as to when the cultural transition from child to adult occurs (Perry, 2005). Further, patterns in sex distribution can indicate more complex social patterns concerning sex preference.

3.3 The Study of Growth and Development in Archaeological Contexts

An archaeological sample is cross-sectional in nature. Skeletal growth and development are continuous processes that vary in velocity based on season, age, and various other external and internal factors (Garcin, Bruzek, Alduc-Le Bagousse, Sellier, & Veleminsky, 2010). As a consequence, any study of growth and the construction of growth curves must be a composite of many individuals rather than a longitudinal observation based on one or several children. This has an averaging effect and causes the observation of a short period of accelerated change, a growth spurt for example, to be more difficult to detect. By observing variations in size and changes in skeletal maturity throughout the skeleton and pinpointing patterns of differential growth, these crucial periods of accelerated growth and skeletal maturity are more likely to be detected. Using growth curves, growth tempo, or growth velocity may allow for better representation of the actual growth process experienced by the population (Humphrey, 2003). Two populations could have the same mean stature but arrive to this stature through different growth patterns. Graphical representation can illustrate periods of stunted or accelerated growth, therefore providing evidence of potential stress if stunting is occurring at periods where it would not be expected.

Traditionally, in both clinical and anthropological research, the study of growth and development has focused on stature or lengths of long bones. Stunting of size or height either in comparison to some developed standard for age or between adult measurements of varying temporal or geographic groups is used as a proxy to indicate childhood stress. Since there is limited information available about the individuals recovered from archaeological contexts, data and research derived from clinical research, especially longitudinal growth studies are used to inform and guide work based on archaeological samples. In most cases the measurements used are not directly comparable. While stature can easily be measured for a living person, a certain amount of approximation is necessary to obtain the same measurement from a skeleton.

During excavation, undisturbed remains that are in anatomical position can be measured in situ (e.g. Boldsen, 1984; Boldsen & Søgaard, 1998). While this is standard procedure in Western Denmark, it is not widely done at sites elsewhere. Typically, stature is determined using regression equations that use one or several long bone lengths. The stature estimation equations using long bone lengths developed by Trotter & Gleser (1952) were derived from a modern American population but have been widely applied to archaeological samples. These equations have been found to be problematic when applied to populations varying from those from which they were developed, particularly European archaeological samples (Boldsen, 1984; Ruff, Garofalo, & Holmes, 2013). Ruff (2007) developed regression equations for the estimation of stature using long bone lengths and other body size indicating measurements based on data from the Denver Growth Study. This Denver data has been described by Maresh (1970), and has frequently been applied in studies of growth in archaeological populations (Humphrey, 2003). The Denver Growth Study consists of a longitudinal study where radiographs were taken at six-month intervals. Ruff (2007) noted that Maresh (1970) failed to account for distortion of measurements due to radiography. Another limitation to the use of data from the Denver Growth Study in comparison to archaeological samples is the impact of temporal variation. The children included in the Denver Growth Study were observed between 1927 and 1967. A secular trend of increased growth and accelerating maturity had been noted during this period (Eveleth & Tanner, 1990). These children came from middle to upper class homes. They likely lived in environments of reduced physiological stress in comparison to past and preindustrial populations. Saunders & Hoppa (1993) note that the children used in this particular growth study exhibited high growth velocities and reached adult stature greater than the mean height for the United States during the period. Ruff (2007) includes the means to calibrate for the differences between the reference collection and any sample, allowing for the use of these equations on diverse genetic and temporal populations (Ruff et al., 2013).

Boldsen (1984) suggests that the most accurate measurements and comparisons, in terms of stature, are based on crude long bone length rather than stature estimates. Using the raw long bone lengths instead of estimated stature avoids the possibility of applying misrepresentative stature calculations. The use of long bone lengths still provides the opportunity to use and test any other equations using the actual long bone lengths, and allows for the possibility to determine new methods for measurement or comparison, such as ratios. By looking at long bones individually rather than stature estimations, differential growth and variations in proportionality can also be observed. When there are differences in growth velocity, or catch-up growth has occurred, this impacts the proportionality of long bones (Boldsen & Søgaard, 1998). This would therefore impact any stature estimation that does not take this into consideration. Jantz & Owsley (1984) observed differential growth in the long bones of pre and post-contact Arikara subadults. In this sample, the post-contact group experienced greater stress and stunting, but exhibited longer bone length in the upper limb. This suggests that stress either did not affect the entire body equally or that the effects where mitigated at a later time and compensated for with catch-up growth.

Vertebral measurements are used as an indicator of stunted growth during early childhood and risk predictor of health complications in later life. Due to the early development of the vertebral neural canal, it preserves any potential stunting that may have occurred prior to the fourth year of age without allowing for recovery and catch-up growth after the stress episode (Clark et al., 1986). Stress at this age and decreased size of the neural canal can have long-term implications on individual health and quality of life. Reduction in the size of the vertebral neural canals are related to vertebral wedging, greater cortical bone loss, and an increased risk for osteoporosis and back pain (Clark et al., 1986; Larsen, 1999). Stress and stunted growth during the development of the vertebral neural canal could indicate improper development of the immunological system; this is a result of the concurrent development of the skeletal structures of the vertebrae and that of the thymolymphatic tissues (Clark et al., 1986). The vertebral neural canal can be observed in conjunction with vertebral body height for a more complete measurement of lifetime stress experience. The vertebral body continues to grow into adulthood. Therefore, if both measurements appear to be reduced, this would indicate chronic experience of stress throughout the growth period. If only the vertebral neural canal is affected, stress was experienced earlier in life but catch up growth allowed for other skeletal elements to reach expected dimensions (Clark, 1988).

In addition to the increase in size experienced by the human body with age, there is also development, where the parts of the body progressively change into the mature adult state (Bogin, 1999). In the skeleton this can be observed in the appearance of ossification centers, fusion of epiphyses, and changes in the morphology and size of bones (Chapeskie, 2006). These developmental changes are less susceptible to delay than is longitudinal growth, but they can be delayed in extreme or prolonged cases of stress or alternatively to allow for catch-up growth following the end of a stress experience (Acheson, 1960). The presence of particular ossification centers can provide an estimate of minimum age, but cannot reliably indicate maturation level when found in an archaeological context, given how difficult these are to recover (Scheuer & Black, 2000). To assess epiphyseal fusion for evidence of maturational delay, the timing of fusion events is compared to other indicators of age such as dental development. Again, these standards are typically derived from clinical data founded on observations of modern samples. Humphrey (1998) developed a standard to assess maturation by comparing the subadult growth velocity of various measurements in proportion to the adult dimensions. These measurements included long bone lengths, articular diameters and other size indicators such as maximum scapular breadth. This method avoids introducing bias by using standards from genetically distinct populations, but would require a large sample to have sufficiently representative adult values.

Stress indicators have questionable reliability. In clinical cases Harris lines have been observed in 25% of cases when a known stress event occurred, but were also observed in 10% of cases with no known stress event (Lewis & Roberts, 1997). Since dental development is a fairly reliable indicator of chronological age, the location of dental enamel hypoplasias (DEH) on different teeth can provide a good record of stress episodes and the age when these were experiences. These nonspecific stress indicators have often been studied along with other indicators of growth faltering. Bennike et al. (2005) compared two medieval Danish cemeteries; Aebelholt and Naestved. At Naestved, subadults were shorter, and also experienced more DEH and maxillary sinusitis with more important differences exhibited in those over 10 years of age. Naestved was the site of a leprosarium, it would therefore be expected for the town cemetery to contain individuals who experienced augmented levels of physiological stress. The differences between these two samples could be influenced by socioeconomic differences as Aebelholt would tend towards wealthier residents and Naestved would tend towards lower status. Neither sample is representative of a typical population during this time period. These results cannot be extended to make conclusions about mortality risk without incorporating an adult or survivor sample for comparison (Boldsen, 2007).

Skeletal tissues undergo remodeling throughout life. As long bones accrue in length, they also increase in diameter and width, both at a fairly similar rate until adolescence (Hummert, 1983). Mays (1995) noted that appositional growth was a more sensitive indicator of physiological stress. Changes in cortical thickness appear to be less susceptible to the effects of catch-up growth than are longitudinal measurements (Hummert, 1983) and therefore could act as a valuable indicator of childhood health and stress. Changes in cross-sectional skeletal tissues as part of the growth process and the alteration of these tissues by physiological stress to the system are promising avenues for research. Furthermore, levels of appositional bone accrued during childhood and adolescence are an important predictor for bone loss later in life, risk of fracture, and long-term bone health (Gosman et al., 2013). Appositional growth has not received the same level of attention as longitudinal growth despite evidence suggesting that changes in appositional growth may be a more sensitive indicator of stress (Mays, 1995; Mays et al., 2009).

3.3 Challenges

3.3.1 Definition of health and physiological stress

While it is a desirable goal in archaeology to gain information about past population health, this is an extremely challenging task. Health is an ambiguous concept, even when applied to living populations. The World Health Organization (1948) defines health as "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity". In a skeletal sample, it is only the physical well-being that can be observed. Health cannot be directly determined from a human skeleton, but rather lesions or other symptoms are used in interpretations of poor health. The absence of pathological lesions, infirmity, physical genetic disorders, or stunted size becomes the osteological concept of health; a definition that cannot completely assess the well-being of the living person. A person`s quality of life can be greatly impacted by various neurological conditions and illnesses affecting the soft tissues that will leave no trace on the skeletal remains. The skeletal manifestations of pathological lesions have been argued to either over or under represent the actual prevalence of disease in a population (Wood et al., 1992). In most cases, what researchers in past population health are actually measuring are periods of poor health manifested in the form of nonspecific stress indicators or pathological lesions. Once those who exhibit evidence of poor health have been identified, the remaining individuals are essentially considered to be healthy by default, due to the absence of evidence indicating otherwise.

The remodelling of bone as a result of illness or nutritional deficiencies is limited to proliferative addition of bone to the periosteum or resorption, leading to the loss of bone tissue. The patterns in distribution and manifestation of these two types of bone alterations are used to attempt to diagnose the ailments suffered by individuals in life. The ability to recognize the signs of disease or deficiency is limited to those that leave their mark on skeletal tissues. Most of these require a certain period of infection for the pathological lesions to manifest themselves. As a result, there are alternate interpretations when observing the skeletal remains of deceased individuals and determining the absence or presence of disease. Individuals who do not display pathological lesions or stress markers may have been healthy and not affected by any ailment, or they may have succumbed to their illness in such a short time that the telltale signs of the illness did not manifest themselves on the bone. When lesions and stress markers are observable, these can be interpreted in two ways; the individual suffered for some time and eventually succumbed, or the individual was healthy and resilient enough to survive a sufficient duration of time for lesions to manifest themselves (Wood et al., 1992). The mixed representation of 'robust' and 'frail' individuals creates an added caveat to studying archaeological populations in the possibility of bias based on survivorship. The individuals composing the archaeological sample under study are non-survivors; they may not be representative of the healthy individuals who survived childhood. If the goal of study is to determine the ideal or optimal growth and development pattern, then this might be a concern.

3.3.2 Genetic influences on growth and development

Patterns in growth and development are determined by various genetic and environmental factors. The end phenotype is therefore constructed by multiple influencing factors. The genetic contributions towards the processes of growth and development are complex traits, controlled by multiple genes and then further modified by external factors. As with all complex traits, there is a certain amount of natural variation within any population.

There are some differences in the growth and development processes, the timing of growth spurts, size and shape of elements, and stature that are explained by sexual dimorphism. Through most of their physical development, girls are at more advanced stages than are boys of the same age (Bogin, 1999). The differences are not consistent and vary throughout the body. Garn et al (1967) note developmental differences between boys and girls even before birth. In infancy the discrepancy is minimal, amounting to a difference in days or weeks (Garn et al., 1967). By early childhood differences can be significant and may be observed in dental maturity and long bone dimensions, beginning with the femur (Garn et al., 1967; Hewitt & Acheson, 1961). Meanwhile, it is only after the age of ten that growth related dissimilarities become evident in the pelvis (Hewitt & Acheson, 1961). Although females reach skeletal maturity prior to males, the male pubertal growth spurt has a longer duration than it does in females. This growth spurt is what produces the sexual dimorphism, including greater male adult stature (Humphrey, 1998). Sex determination methods in adults are highly accurate and reliable, although inter-population variation must be accounted for to ensure best results. In subadults, adolescents, and young adults, these methods, largely based on secondary sex traits, are not as efficient. Most archaeological reports simply do not attempt to determine sex for juveniles due to the challenges in accuracy. As a strategy to avoid the complicated influence of sex on growth and due to greater availability of data from military records, studies generally focus on data concerning male growth patterns (e.g. Boldsen & Søgaard, 1998; Maat, 2005; McKern & Stewart, 1957). In addition to sex-related differences in growth and development, there is also evidence suggesting that males are more susceptible to the influence of environmental stress and are therefore more likely to exhibit growth stunting and developmental delay than are girls (Belcastro & Mariott, 2008; Chan, Chang, & Hsu, 1961).

As mentioned, there is a large genetic component influencing growth trajectories and maturation patterns. It would therefore be expected to observe variation between different geographic and genetic populations. There are variations within the same genetic populations that occur through time, largely due to changing lifestyles, medical access, and nutritional security. One noted change is the secular trend of observed stature increase beginning in the late 19th century (Eveleth & Tanner, 1990). In Denmark, males experienced an increase in height of 14 centimetres in the span of only four generations, between the 1830s and the 1960s to 1970s

(Boldsen & Søgaard, 1998). In their long-term study of stature change in Portugal between the Mesolithic and the 20th century, Cardoso & Gomes (2009) note a total stature variation of 10 centimetres for the entire temporal period. The contemporary Danish population is descendant of a fairly isolated and closed genetic population, retaining similar genetic profiles as those found in the Late Roman Iron Age (Melchior, Gilbert, Kivisild, Lynnerup, & Dissing, 2008). The Danish results (Boldsen & Søgaard, 1998) most closely resemble those obtained by Maat (2005) for the Netherlands. The Netherlands are geographically closer to Denmark and may have greater genetic similarities between their populations than in Portugal. Boldsen & Søgaard (1998) suggest that the change in stature observed in the recent Danish population may be the result of fluctuations in allele frequency and changes to the gene pool within the population. This consideration of a change in allele distribution within a genetic population is a reasonable explanation that is not frequently considered as a reason for stature increase. A person's height is a visible trait and may be subject to sexual selection, especially in societies where a person's height has a significant impact on a person's life opportunities.

Linear growth has been found to be more sensitive to disruption by external factors than other indicators of growth and development such as skeletal maturation (Ferro-Luzzi & Susanne, 1984; Johnston & Zimmer, 1994), appositional growth (Mays, 1995; Mays, et al., 2009), and dental calcification (Cardoso, 2007). The best approach to observe changes in health and stress response would be to combine observations of various lines of evidence.

3.3.3 Archeological samples

There are several intermediary steps that occur between a living population and the population available for osteological analysis. At each step there are additional risks of bias. As mentioned, from the living population, only those who died will be preserved archaeologically and these individuals may not fairly represent the demographics and physiological measurements of the living population from which they came. Once death has occurred, preservation is dependent on the type of funerary treatment. Burial is one of the most common practices to deal with the dead. However, not everyone is given equal funerary treatment. This is common with infants who might be buried in areas separate from others, leading to greater difficulty in locating these burials and a low representation in archaeological findings. During the Middle Ages there are varying patterns in the burial of children and infants. These may be clustered together in a specific area of the cemetery or scattered among the adult burials (Daniell, 1997; Orme, 2001). Preservation of the skeletal remains is dependent on the soil conditions of the area, weather, temperature, access by and presence of scavengers, as well as the size and type of bone. Smaller, more fragile bones are less resistant to taphonomic factors and less likely to be preserved; this is a further source of the underrepresentation of infants in the archaeological record. The preserved skeletons must be found by someone, hopefully an archaeologist, or someone who can recognize and identify the presence of human remains. Excavator experience with the human skeleton will influence their capability to recognize and retain all skeletal material. Finally, once the skeletal remains are excavated, they must be kept and curated to enable osteological study. From that point the sample is whittled down by the completeness and availability of elements needed for analysis. Even in an ideal situation of preservation and excavation methods, the sample that osteologists are working with are far-removed from the original living population for which inferences are being made. This problem is of greater concern when research is focused on sub-adults since they tend to be the most susceptible to underrepresentation (Saunders, 2008). In excavated medieval cemeteries, infants occupy anywhere from 0 to 25% of the assemblage despite the fact that at times this demographic should represent about 33% of the cemetery population (Guy, Masset, & Baud, 1997).

An additional caveat is the fact that these children represent the non-survivors and therefore may not represent the same growth and development profiles as those experienced by their peers who survived into adulthood. In the absence of data and observations of contemporary, healthy childhood growth there are extremely limited means to get to this valuable information. Inferences can be made based on stress-markers occurring during childhood and preserved in adults of a population. Markers such as dental enamel hypoplasias, growth arrest lines, final adult stature, or constrained vertebral neural canals can demonstrate manifestations of stress during childhood. These markers provide brief snapshots into a person's past, but give an incomplete representation of their lived experience. The stresses experienced in childhood can also be obscured in older individuals by the process of bone remodelling or incidences of catch-up growth (Boldsen & Søgaard, 1998).

An archaeological sample will seldom be an adequate representation of the living population due to the very nature that this sample is created by dying and therefore no longer being a part of the living population (Milner & Boldsen, 2017). It is inaccurate to equate these as representative samples. Such an assumption has negatively impacted research and the validity of conclusions. These practices have been called out and with renewed awareness steps can now be taken to remedy past mistakes.

3.3.4 The Osteological Paradox

There are important limitations to consider in any bioarchaeological research, but these are particularly crucial for studies of health, growth and development, demography, and palaeoepidemiology. The Osteological Paradox by Wood *et al.* (1992) provided an important shift in the practice of bioarchaeology, highlighting integral problems in research, largely due to assumptions being made about the samples. The authors note three of the most important issues impacting research as being; demographic non-stationary, selective mortality, and hidden heterogeneity (Wood et al., 1992).

The first concern arises out of the application of traditional demography models. These models usually assume that the population in question is stationary, that they are a closed population with a genetic populace that remains constant. Such a population would not experience migration or immigration; none of the genetic population leaves and there are no new additions to the gene pool. In addition, these models presume stationary fertility and mortality rates, zero population growth, and a static age structure. No actual human populations exist in a vacuum as such models would presume. Fertility and mortality rates are closely tied together and have an important contribution in the formation of the samples that will become the source of archaeological research. This also ties into Wood et al. (1992)'s second concern.

Selective mortality refers to the fact that not everyone in a given population has an equal chance of death at a particular moment. At any given time, certain age groups, a particular sex, people with innate frailties and genetic or physical predispositions to disease, are more likely to die than others who do not share those characteristics. The sample of a population that is recovered from a cemetery is just that; a sample. It is not a direct reflection of the living population from which they came. Two standard mortality models are considered in archaeological contexts; attritional and catastrophic. The attritional model is represented by a typical cemetery in which the majority of the surrounding population is represented. Due to typical mortality risks, these contain higher numbers of children and older adults than other age groups. A catastrophic model is assumed to be more representative of the entire population. This would be created as a result of a natural disaster, epidemic, or other sources of widespread non-selective mortality. However, it would appear that there are very few truly catastrophic samples. As previously discussed, DeWitte & Wood (2008) studied the East Smithfield Black Death burials in London and concluded that there was still a certain amount of selectivity in the demographic composition of the site and that the Black Death did not simply kill indiscriminately. While sample size is a frequent restriction in archaeological research, the largest sample will still not be fully representative of the living.

Finally, hidden heterogeneity refers to the unknown distribution of frailty within those represented in an archaeological sample (Wood et al., 1992). As discussed, not everyone has an equal chance to die. Some are more vulnerable, whether due to disease, nutritional deficiency, or genetic risk. There will also be some who die of accidental causes. It is challenging to identify the 'healthier' dead within the larger sample. The stress markers previously mentioned give an indication that individuals endured difficult periods during their lives, but this concern is far more complex than a binary division of frail people indicated by lesions or stunting and 'healthy' people who do not exhibit these. Wood et al. (1992) argue that those who have lesions or stunted growth may in fact be less frail that others who succumbed to a stressor before being able to develop these indicators. While there is some truth to this argument, individuals with stressors clearly indicate some greater vulnerability, in addition to the fact that they have died, than their contemporaries who survived.

Saunders & Hoppa (1993) explored the question of survivor bias and observed that non-survivors experience higher morbidity for age and exhibit greater stunting in stature in comparison to their surviving cohort. While these differences were statistically significant, the actual difference in femoral length amounts to, at most, several millimetres; a minimal difference for the purposes of gross measurement (Saunder & Hoppa, 1993). Boldsen & Søgaard (1998) did not observe a significant difference in stature of survivors compared to non-survivors at Tirup, however they did note differences in long bone proportions resulting from catch-up growth. The potential differences between survivors and non-survivors do raise important concerns in the application of age estimation techniques that were developed using living (survivor) reference populations. Primeau, Friis, Sejrsen, & Lynnerup, (2012) argue that the concern for survivor bias is irrelevant as long as comparisons are limited to other archaeological samples. Since these samples would all represent non-survivors, it would eliminate this particular risk of bias. While this is a sound argument, all archaeological populations are not equal in their representations of frailty. A higher mortality rate would lead to a sample that is more representative of the living population, and therefore exhibiting less distinction between survivors and non-survivors (Wood et al., 1992).

The primary message to take away from Wood et al. (1992) is that researchers must be aware of the assumptions being made about their samples, data and methodology, and cautious about the conclusions that can be made. The Osteological Paradox has not doomed bioarchaeological research, but rather helps ensure that good science practices are adopted and maintained. Several suggestions have been made to give more strength to research and conclusions. Cohen (1994) suggests looking at patterns in history and other populations that have experienced a similar event such as a transition from foraging to agriculture in his example. There are certain limited ways that the human body and populations react to a stimulus and by observing multiple occurrences, patterns will likely emerge. Wood et al. (1992) stress the importance of developing techniques to better detect the varying degrees of frailty as well as the mechanics of disease. Important steps have been taken towards addressing these concerns, many of which are described in Milner & Boldsen (2017). Several authors have encouraged the use of multiple indicators of health to enable researchers to gain a more complete picture of health states and individual frailty. By looking at various signs of stress within the body, including markers that form at different ages and stages of development, researchers can form a more confident conclusion and can assess the duration of stress episodes; whether it was an isolated incident or a chronic experience (Steckel et al., 2002). Bioarchaeology in general has become increasingly multidisciplinary. Clinical data about disease and physiological stress as well as medical imaging of living people can better inform what can manifest itself in the skeleton as well as the severity and length of illness that would be required to do so. This information can then be applied to bioarchaeological work.

3.4 Summary

Any research based on human skeletal remains from past populations must face a particular set of challenges due to the nature of the samples used. In very few cases are informative records available. There are very few known variables. All other information must be determined based on the evidence at hand and whatever context is available. Genetic factors influence growth and contribute diversity within and between populations. Fortunately, clinical research on contemporary samples can give indication of general patterns and particularities such as the effects of sexual dimorphism and sex-related differences in the growth process. Good research methods recognize the challenges imposed upon the researcher by the nature of their samples and allow for ways to overcome or work with these limitations. A key method to do so is to explore various lines of evidence. In growth and development, this would include measurements of longitudinal and appositional growth, and measurements of maturation. It is worthwhile to undertake these methods and to work to overcome the aforementioned challenges due to the wealth of information that can be obtained. The lives of children and adolescents are seldom recorded or represented and yet the social treatment and the health of this demographic group reveals the values of a cultural group and act as early signs of biocultural phenomena that may be experienced by the entire community.

4. Cortical Thickness

4.1 Introduction

Studies of growth and development have traditionally focused on the use of long bone lengths as a means to gauge possible growth stunting. These measurements can only describe changes in longitudinal growth. By contrast, measurement of cortical thickness allows for assessment of appositional growth. Both are essential parts of the growth process. While appositional and longitudinal growth are typically concurrent, it is during periods of abnormal growth that the balance between the increase in bone length and the increase in bone width can deviate from each other. Broadly speaking, growth and bone size are closely tied to an individuals' age; however, the relationship is not a simple one (Scheuer & Black, 2000). Stunted growth as a result of any form of physiological stress can result in dimensions that are low for the chronological age. These can lead to underestimation of age in the absence of other, more reliable sources of age estimation such as dental age (Cardoso, 2007).

Cortical thickness has not received a great deal of attention as an indicator of growth stunting or a reflection of health in past populations. Archaeological applications of cortical thickness have largely been used in the context of ancient hominids, usually in comparing bone morphology and locomotion patterns (Mays, 2001) or to assess loss of bone density and osteoporosis in adults (Agarwal, Glencross, & Beauchesne, 2011). Clinical studies have a longer history of using measurements of cortical thickness as approximations for bone density and to track childhood growth, usually employing radiographic images to do so. This section will present information about the process of appositional growth, the factors that influence it, and the ways in which cortical thickness has been studied in the past.

4.2 Growth and Development

Long bones develop under the process of endochondral ossification. During this process, the midshaft region of the bone experiences a thickening of the perichondrium. Mineralization occurs along blood vessels, forming a constricted band at the external midshaft that will develop into the periosteum (Scheuer & Black, 2000). Meanwhile at the center of the cartilage, chondrocytes increase in size while the cytoplasm becomes vacuolated. Together, these assist in degenerating the denser tissues in the middle of the bone, allowing space for blood vessels by way of the nutrient artery. The cartilaginous tissue within the bone is converted into a trabecular network of spongy bone. Osteoclasts then break down these tissues and maintain the medullary cavity in the middle of the diaphysis (Scheuer & Black, 2000).

In appositional bone growth, the cortical area is first expanded from beneath the periosteum and then calcification occurs, followed by increasing bone density (Fujita, Fujii, & Goto, 1999). Throughout life, bones endure a continuous process of deposition and resorption. The shape and size of long bones will vary between individuals to some degree as a result of natural variation, mechanical pressures, nutritional quantity and quality, hormone exposure, and genetic influence (Gosman et al., 2013). Appositional growth tends to be proportional to longitudinal growth (Meachen-Samuels, 2010). The general tendency that persists throughout childhood and into male adolescence is for greater addition of periosteal bone and increased loss of endosteal bone. The end result is a bone with a steadily increasing total diameter and a proportionally increasing medullary cavity. In adolescent females the endosteal surface has been found to remain relatively stable while there is continued remodelling of the medullary cavity (Hatch et al., 1983). It is in adolescence that sex-related variations in the structure of long bones begin to be observable.

4.3 Health and Physiological Stress

Childhood appositional growth is an important predictor for later bone loss and fracture risk (Gosman et al., 2013). Bone loss has been observed to be a common reason for disability in later life and an important factor contributing towards osteoporosis (Garn, 1971). Reduced bone thickness has also been correlated with congenital heart disease (Garn, 1971). These risk factors that have been linked with cortical thickness have important implications about long-term health status and injury risks throughout the human lifespan.

It would be erroneous to assume that healthier individuals would necessarily have bones with greater diameters. The overall result of appositional growth is the product of combined periosteal and endosteal remodelling. Therefore, the size of the medullary cavity must also be taken into account (Gosman et al, 2013). In healthy growth, bone thickness is maintained through a balance of periosteal and endosteal activity. During times of physiological stress, the deposition of new bone may be slowed or halted and resorption of calcified tissues may accelerate to supplement for mineral deficiencies elsewhere in the body. This period of stress would therefore be exhibited in the form of a thinner cortical layer compared with healthier individuals. Hummert (1983) suggests that an organism may leach minerals from the cortical bone to allow for catch-up growth when longitudinal growth has been delayed. If this is a common occurrence, it would indicate that the body strives to attain maximal stature and will sacrifice bone thickness to do so. Catch-up growth in the diameters of long bones is a less likely occurrence (Hummert, 1983). Simply measuring bone diameter would also ignore the effect of cortical drift; an uneven distribution of bone between the medio-lateral or the antero-posterior sides (Garn, 1971). These inconsistencies of bone distribution could indicate the influence of repeated use or a bone condition such as osteogenesis imperfecta (Roberts & Manchester, 2010).

While the medullary cavity tends to maintain a fairly consistent width despite age, Garn, Guzmán, & Wagner (1969) observe that cortical thickness can be affected at the periosteal and/or the endosteal surfaces. In children experiencing protein-calorie malnutrition, a cross-section of the second metacarpal revealed a 30% reduction of cortical thickness despite a surprisingly large subperiosteal layer (Garn et al., 1969). This emphasizes the need to visualize the internal structures to assess appositional growth rather than relying on diameter or circumference of the bones.

Stature and long bone length are predominantly determined by genetics and are highly variable within and between genetic populations. This is one of the greatest challenges in using stature to assess health in past populations; standards need to be developed on a relevant and related population. Cortical thickness certainly has a genetic component. The extent of genetic influence on cortical thickness is not completely understood, however there appears to be less genetic variation in cortical thickness than what is observed in stature and long bone length (Hummert, 1983). The use of indices or ratios helps to minimize the influence of size and facilitates comparison between individuals and populations.

Evidence suggests that appositional growth may be a more sensitive indicator of physiological stress than the more widely-used longitudinal growth values (Hatch et al., 1983; Mays, 1995; McEwan, Mays, & Blake, 2005). Cortical thickness is markedly affected by nutrition (Garn, 1971; Hatch et al., 1983). Garn (1971) notes up to 40% endosteal bone loss in the metacarpals of children experiencing protein-energy malnutrition. Even in cases of moderate malnourishment, the cortical bone can be affected (Hummert, 1983). Once in a rehabilitation setting with sufficient and supplemental nutrition, the recovery and catch-up in lost bone thickness is prolonged, maintaining evidence of the period of stress in the bone for a long time.

Isolated archaeological examples of fractures concurrent with low cortical values corroborate the clinical observations. Agarwal et al. (2011) noted two adult individuals at Çatalhöyük with low second metacarpal cortical thickness values for their age category who also demonstrated evidence of fractures. One young adult male had multiple rib fractures and was affected by a chronic systemic disorder that was predominantly manifest in the thoracic region. The second individual was also a young adult with healed fractures to the lower limb and the neural arch (Agarwal et al., 2011). It is suggested that these individuals with weakened, less robust bones were at greater risk than others to injury and damage to their bones. Unfortunately, it is not known what is the cause or the effect; is trauma due to weakened bones, or were bones underdeveloped as a result of reduced activity load in the aftermath of injury and disease?

Archaeological evidence has linked low cortical values with traditional nonspecific stress indicators. Hatch et al. (1983) looked at cortical thickness and the presence of Harris lines in two Mississippian sites. Low femoral cortical thickness was found to be related to burial location and sex. Those with the lowest bone thickness were found in the mounds, areas reserved for more high-status individuals (Hatch et al., 1983). Adolescent males recovered from the mounds also displayed higher frequency of transverse lines. It was suggested that some of the elites may have achieved their position in society and undergone strenuous preparation for future roles before adulthood. Once in an elite position, they were not required to partake in strenuous physical labour, contributing towards the lower cortical thickness values (Hatch et al., 1983). These results are not entirely surprising given evidence suggesting that boys nearing puberty are particularly susceptible to physiological stress (Lewis, 2007). Mays (2005) compared linear and appositional growth between a Medieval English site, Wharram Percy, and a modern North American sample. As expected based on previous evidence of widespread physiological stress, the Wharram Percy sample had much shorter long bone lengths and estimated statures compared to the modern sample. The comparison of cortical index provided a much more pronounced difference between the two groups (Mays, 2005). Mays (1995; 2005) also notes that subadults displaying transverse lines showed a slight, but not significant tendency towards lower than average stature, but had a significantly lower cortical index than those without transverse lines.

4.4 Cortical Thickness, Age and Sex

Measurements based on subadults are ideal for the study of stress-related cortical thickness variation where there are no baseline standards for age and sex, which is often the case when studying past populations. Cortical thickness increases fairly consistently with age over the course of growth and skeletal development despite slight differences in the tempo of bone deposition and resorption (Agarwal et al., 2011). Bone diameter and cortical thickness continue to increase until approximately the age of 30, up to five years after most epiphyses have fused and an individual is considered to be skeletally mature (Duren, Seselj, Froehle, Nahhas, & Sherwood, 2013). By taking into account and controlling for age, departures from the expected growth pattern and potential evidence of physiological stress can be detected.

There is some sexual variation in the rate of appositional growth; Duren et al. (2013) found significant sex-related differences in the diameter of second metacarpals and long bones: a five percent difference can be measured by the age of two. However, actual bone thickness does not exhibit significant sexual dimorphism until adolescence. A similar pattern was observed in the radius and ulna by Fujita et al. (1999). This is another reason why measuring and visualizing the internal structures of long bones is beneficial. Himes et al. (1975) report consistently higher cortical area index values for girls from the ages of one to seven. This data comes from a moderately malnourished Guatamalan sample. The differences observed between the sexes could potentially be a result of higher female resistance to physiological stress. In adults, there is a significant difference in cortical thickness between sexes due to sexual dimorphism and sex-related variation in bone loss (Agarwal et al., 2011). These sex-related differences become evident in late adolescence or, most likely, in late young adulthood (Gosman et al., 2013). Duren et al. (2013) observe a significant difference in cortical thickness between boys and girls in a group aged fourteen and over. Unfortunately, due the pooled sample, the precise age at which sex-related differences become significant cannot be determined. Fujita et al. (1999) noted significant difference between sexes by the age of fifteen in their study of forearm bones. The samples used by Fujita et al. (1999) and Duren et al. (2013) came from modern clinical samples, therefore maturation may occur earlier in these samples than in an archaeological sample due to the effects of the secular trend. The general trend in adulthood is for the total width and the medullary width to increase with age (Garn, 1971; Mays, 2001). After the age of 40, the rate of deposition is slower than the rate of resorption, which results in a steadily decreasing net cortical thickness (Garn, 1971; Mays, 2001). This pattern is consistent in both archaeological and modern samples of European descent (Mays, 2001). Sex-related differences in bone thickness may become more pronounced due to female reproductive function. During pregnancy and lactation women suffer increased bone loss compared to men of the same age (Agarwal et al., 2011). This would have a greater impact in societies where women are having many children and are breastfeeding for long periods. Bone loss in women accelerates and becomes more pronounced after menopause, leading to significant differences between mature adult males and females (Agarwal, et al., 2011; Duren et al., 2013).

The directionality and extent of bone remodelling may be influenced by repetitive activity. In the Spitalfields collection, Mays (2001) observed a significant increase in medio-lateral bone width in the second metacarpal of master weavers. Lazenby (2002) notes that the palmar surface of the second metacarpal is thicker for all ages and both sexes in a 19th century Southwestern Ontario sample. This is explained by the greater use of the palmar surface when grasping or manipulating objects. Consequently, the balance of bone thickness will vary between elements due to variation in biomechanical use. For example, Wescott & Cunningham (2006) observed increased lower limb strength in Arikara women during a period of intensified horticultural practices. Meanwhile men, who devoted more time engaged in hunting, fishing, and combat displayed increased right humeral strength, the bilateral discrepancy presumably the result of preferred hand use (Wescott & Cunningham, 2006). The bones of children and adolescents would not be as susceptible to occupation-related remodelling and variation in handedness as would those of adults, however, the impact of biomechanical load should be considered particularly when comparing populations with widely differing activity patterns.

4.5 Bones Measured for Cortical Thickness

Studies have used a variety of long bones to assess cortical thickness including the femur, tibia, radius, humerus, second metacarpal, ulna, metatarsals, mandible (Garn, 1971; Hardant et al., 2011) and rib (Agarwal et al., 2011). The most frequently used bones tend to be the femur and the second metacarpal. Both have mostly spherical cross-sections throughout childhood. During adolescence, the shape of the femur changes due to the development of the linea aspera. Despite the similarities in their shapes, these bones vary significantly in their physiological roles in weight-bearing and repeated use which may dictate variations in individual bone deposition. The choice will likely be dictated by the sample population and the visualization method employed. When possible, it is ideal to sample more than one skeletal element to address variation in biomechanical impact between weight-bearing and non-weight bearing bones and to control for possible differences related to handedness.

Clinical research tends to use the second metacarpal for cortical thickness measurements (Garn, 1971; Garn et al., 1969; Santiago et al., 1977). The second metacarpal is the largest bone in the hand and can easily be viewed in hand-wrist X-rays which were commonly used in growth studies. Garn (1971) expresses preference for the second metacarpal due to its tubular shape and centered medullary canal; facilitating estimations of area and circumference from traditional X-rays. This bone has also been found to be a good gauge for axial bone mass, an accurate indicator of appositional growth, which aids in predicting risk of future wrist or forearm fractures (Hediger et al., 2008). Duren et al., (2013) suggest that the second metacarpal demonstrates the strongest genetic influence for cortical thickness. There is very little soft tissue covering the second metacarpal in the living, reducing the impact of distortion and therefore minimizing the potential imaging variation between living and archaeological samples (Ives & Brickley, 2004). In excavated remains, the metacarpals are less likely to be fully preserved or recovered and may not be an ideal choice for measurement. The third, fourth, and fifth metacarpals are most likely to be affected by genetic abnormalities and as such are unreliable for measurement (Garn, 1971).

The femur is a good choice for measurement. It is a large, fairly robust bone that tends to preserve well and in subadults has a fairly round cross-section. Gosman et al. (2013) measured cortical thickness in the tibiae and femora of children aged 0 to 18 to observe changes in bone geometry. The midshaft was observed to have the most stable shape (Gosman et al., 2013). Meachen-Samuels (2010) argues in favour of the femur as an indicator of general body mass. It is the element most likely to experience remodeling as a result of strain and mechanical loading.

The femur was found to be a more sensitive indicator of physiological stress than the second metacarpal by Robb et al. (2012) who explained the difference based on the speed of the bone's growth and development.

4.6 Visualizing Cortical Thickness

X-ray has been the traditional method of visualising the inner structures of bones. Both clinical and archaeological studies of cortical thickness have largely been conducted using X-rays. The limitation in the reliance on this technology is that it assumes that the antero-posterior and medial-lateral dimensions are the same. This is not the case, especially with the tibia which is triangular in cross-section. Measurements of the cortical bone are consequently diameters of the total bone width and of the medullary width. These measurements can be challenging to do, particularly for the medullary diameter since the margins can be irregular (Ives & Brickley, 2004). Area can be calculated if it is assumed that the bone is a cylindrical tube (Garn, 1971). In addition, visualization on one plane risks missing irregularities in cortical drift. Another option is to physically cut the bone samples in half to expose the true cross section. Such a destructive approach is not ideal from a preservation perspective and would be difficult to have approved by collection curators for large-scale population samples.

Computed tomography (CT) scanning should be considered as a promising alternative to traditional radiography. This technology allows for the visualization of the inner bone structures with high reliability. A three-dimensional image is advantageous when looking at cross-sectional structures and the multiple panes of view allow for visualization of subtle changes in bone density that may only be seen in a particular orientation. The disadvantages associated with the use of CT scans are possible blurring of images due to patients' breathing, image distortion as a result of changing tissue density, and long-term radiation exposure to the patient (Garvey & Hanlon, 2006). These concerns are not relevant when studying skeletal samples.

To date the use of CT imaging on archaeological material has largely been isolated to case studies, particularly to image mummified remains without disturbing wrappings or to examine physiology of palaeanthropological specimens (e.g. Semut, 1985). This technology does not require a specialist. In the author's experience, a quick training session and a few practice scans were sufficient to allow for independent work.

4.7 Methodology

Measurements of cortical thickness are fairly standard and largely based off of work by Garn et al. (1967), developed while working with data from the Fels Longitudinal Study. Most measurements are made using X-rays, therefore they only represent data on one anatomical plane, typically antero-posterior. Using calipers, the image is measured at the midshaft for total bone width and medullary width. Studies tend to use measurements of the midshaft with good reason. Gosman et al. (2013) note that the distal femur and proximal tibia exhibit significant shape change, likely as a result of locomotion. The midshaft area is easily identified even when epiphyses are not fused in subadults, also there is a higher error rate when assessing cross-sectional geometry at the diaphyseal ends (Macintosh, Davies, Ryan, Shaw, & Stock, 2013).

The cortical thickness width is determined by subtracting the medullary width from the total bone width. This measurement takes into consideration the net change between the ongoing bone deposition and resorption which measures the overall growth pattern (Garn, 1971; Gosman et al., 2013). Cortical thickness will be highly correlated with age and size since bone thickness will increase as growth progresses. To diminish the influencing factor of size, cortical thickness is often represented as an index or percentage of the total bone thickness. Measurements of cortical thickness area or cortical index are also useful in representing actual bone density (Garn, 1971). Cortical index is preferred over bone mineral density and bone mineral content since it is less heavily influenced by age and is more susceptible to stress (McEwan et al., 2005). While these measurements are related, density and thickness are not the same thing. Measurements of bone density are more relevant to studies looking at the strength and inner structure of bone, such as research concerning osteoporosis or vertebral body fractures.

Lateralization is a concern, particularly in the upper limb which may exhibit changes due to handedness. Ives & Brickley (2004) and Agarwal et al. (2011) both found the right second metacarpal to be bigger than the left side, but the differences were not significant. Both of these observations were made on adults. While each sample should be tested for lateralization, data suggests that left and right elements do not vary significantly and can be pooled together.

More research is necessary to determine the impact of population variation and the influence of the secular trend on cortical thickness. Mays (2001) observed that the pattern of change in adult total bone and medullary width is consistent between a modern sample and the Spitalfields collection dating to the 19th and 20th centuries. After middle age, the rate of bone resorption at the endosteal surface is greater than the level of bone deposition at the periosteal surface, leading to a net decrease that continues with age (Mays, 2001). The archaeological sample does exhibit thinner net cortical bone throughout adulthood. The difference between these populations is partially attributed to the secular trend, but largely caused by drastic changes in childhood health and access to nutrition. As with other aspects of growth and maturation, the overall trend between populations remains the same.

4.7 Summary

Bone strength and health is determined by both quality and quantity of bone deposition. While remodeling of bone tissue continues throughout life, the majority of bone density is established by the end of puberty (Duren et al., 2013). Disruptions in the growth process by means of health, diet, illness, physical activity levels, or injury during this crucial period can leave an individual with reduced cortical thickness. Lower cortical thickness would expose individuals to an increased risk for future fractures and have long-term impacts on adult health. Analysis of both clinical and archaeological data suggests that stunting of appositional growth is a promising indicator of physiological stress. Cortical thickness may be more sensitive to stress than long bone length and is less likely to experience catch-up growth; therefore, the stunted growth is preserved in the skeletal record for much longer. Measurements have largely focused on the femur and the second metacarpal due to their cylindrical shape which allows for extrapolations based on X-ray measurements. Current medical technology such as CT scanners allow for a three-dimensional image of bones, permitting researchers to obtain more accurate information about appositional bone growth, and how it is affected by physiological stress.

5. Materials and Methods

5.1 Materials

Research was conducted on three collections of skeletal remains housed at the Department of Anthropology, University of Southern Denmark (ADBOU) laboratory, located in the city of Odense. The Ole Wormsgade cemetery located in Horsens, dates from the 12th to 16th centuries. The Odense Black Friars cemetery was in use from the 14th to 17th centuries, with most burials occurring between 1530 and 1600. Horsens Klosterkirke was used during the 13th to early 19th centuries. All three cemeteries were located in two important urban centers in Medieval Denmark and span from the tail end of the Early Middle Ages to the Early Modern period. Horsens is located on the eastern edge of Jutland. Odense is north central on the island of Fyn. Both cities are located within close access to the Kattegat Sea, allowing for access to marine resources (see Figure 5.1).

The Ole Wormsgade site (HOM 1649) was excavated from January 2007 until April 2009 (Pedersen, 2010). The cemetery dates from the 13th until early 19th centuries and consists of 650 in situ graves, 578 of which included preserved skeletal remains (Pedersen, 2010). Among the preserved skeletons, 132 children were identified. Stray finds from grave fills and other contexts contributed an additional 216 children. Those from the latter group were typically incomplete. Many burials had been truncated as a result of roadwork, limiting completeness for a large proportion of the sample. Pedersen (2010) states that more children were expected, but either were not sufficiently preserved for recovery or were located elsewhere. Due to preceding urban development, some material from the cemetery was likely lost. There were fewer young children than anticipated, and few youths around 20 years of age. Ole Wormsgade has a bimodal distribution in ages of death with peaks around 8-10 years and again between 30 and 40

(Pedersen, 2010). A total of 82 subadults were recovered, representing 16% of the cemetery population.

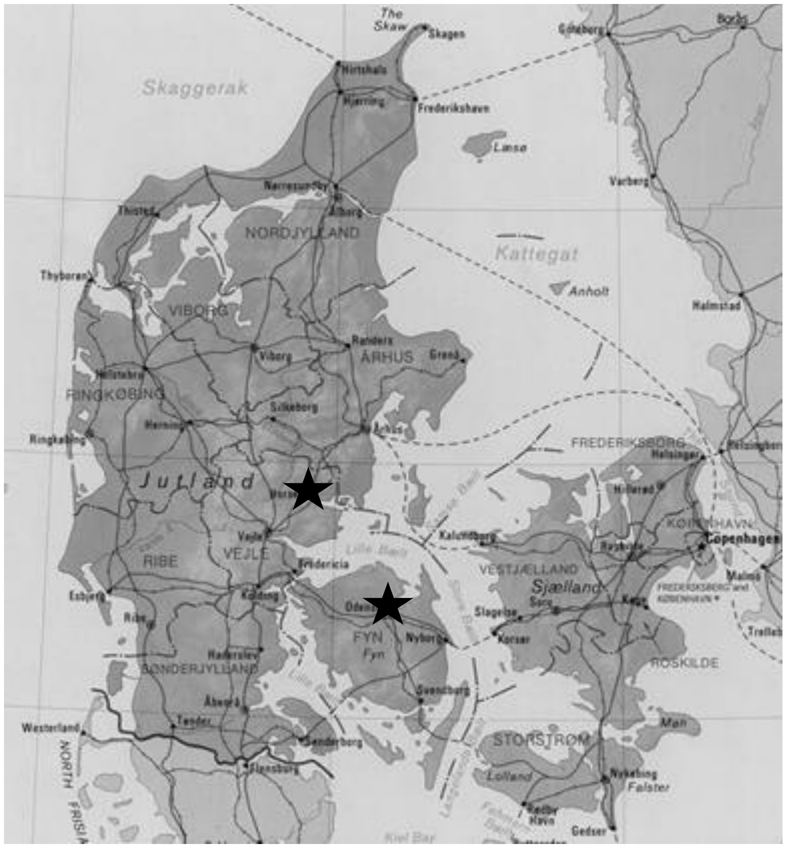

Figure 5.1: Map of Denmark with stars marking the locations of Horsens (leftmost) and Odense (rightmost).

Courtesy of the University of Texas Libraries, The University of Texas at Austin
http://www.lib.utexas.edu/maps/europe/denmark_rel99.jpg

The Black Friars site (SBT 79, SBT 81) had early excavations, from 1978 until 1981. The cemetery was initially associated with a monastery with the burials occurring around 1300. Even after the monastery was demolished, the cemetery was maintained for public burial into the early 17th century, with most burials occurring after Reformation (Boldsen & Mollerup, 2006). A total of 624 individuals were excavated, most with fairly good preservation. 40.4% of the individuals were under the age of 15 (Boldsen & Mollerup, 2006). This demographic distribution is as expected for an attritional cemetery dating to the late Middle Ages.

Horsens Klosterkirke (HOM 1271) was also excavated in the past decade from November 2006 until March 2008. While the cemetery was used from 1536 until 1856, it is believed that the majority of the excavated burials are post-medieval (Tarp, 2010). Most of the burials had low completeness and medium preservation, which greatly limited the sample size for the current study. There was a total of 221 in situ burials, plus a minimum of 281 additional individuals recovered from other contexts (Tarp, 2010). Children represent 16% of the cemetery sample, most of which were infants. Like at Ole Wormsgade, this is a very low proportion of children in the cemetery. This would suggest lack of preservation, or further unexcavated burials. Tarp (2010) notes that individuals at Horsens Klosterkirke were on average, shorter than individuals from Danish sites dating to the Medieval period.

Table 5.1: A breakdown of the cemetery site, city, and date range sampled for study

Cemetery	City	Date range (AD)	Sample size
Ole Wormsgade	Horsens	1351-1539	100
Black Friars	Odense	1300-early 1600s	50
Klosterkirke	Horsens	1536-1856	18

All sufficiently preserved subadults from each collection were examined in this study, see Table 5.1. For the purpose of this study, subadults are defined as individuals who have not yet reached skeletal maturity and retain unfused epiphyses. These individuals are typically under the age of 20 years. The presence of pathological lesions was noted, but individuals were not excluded from analysis on this basis. A total of 168 individuals were studied: 100 from Ole Wormsgade, 50 from Black Friars, and 18 from Klosterkirke.

5.1.1 Chronological dating of individuals

While there are dates of use associated with each of the cemeteries sampled, these dates span over wide ranges; from three to four-hundred years. Further refinement of these dates is possible for some individuals at Ole Wormsgade and Black Friars using patterns in arm positioning within the grave, a technique that had been widely used on Medieval burials in Denmark (e.g. Boldsen, 1984; DeWitte & Hughes-Morey, 2012; Yoder, 2006, 2010). Horsens Klosterkirke dates largely to the post-medieval period, at which point there is no longer a distinguishable pattern in arm positions. This method is based on fairly consistent trends in the positioning of arms that changed throughout the period and has had a long history of use by Danish researchers (Kieffer-Olsen, 1993). Kieffer-Olsen (1993)'s thesis provided an in-depth examination of this method; applying it to eight Medieval Danish burial sites of varying ages and corroborating the patterns with stratigraphy as well as absolute dates from dendrochronology and radiocarbon dating. There are four discrete positions that have been identified and applied to burials: A- arms at sides, B- hands over the pelvis, C- hands over the abdomen, and D- hands crossed over the chest. The patterning of arm position is not always clearly distinguishable, and changes in pattern are not a clear-cut method of dating, nevertheless, they do provide guidance, help to refine a date estimation, and have proven to be a viable relative dating method. The A arm position was the dominant pattern for the early medieval period and used from 1050 until approximately 1300. Arm position B is widespread from 1250 until 1350 at which point the C position becomes dominant until 1450. Arm position D remains the dominant pattern until the end of the 16th century (Jantzen, Kieffer-Olsen, & Madsen, 1994; Kieffer-Olsen, 1993). The division in time periods based on arm positions is particularly helpful in observing groups from pre-, peri-, and post-Black Death (DeWitte & Hughes-Morey, 2012). This pattern was not limited to adults. In the current study, arm position was noted for many subadults, including infants. This funerary custom was clearly a widespread practice during the Medieval period, including young and old individuals.

All four of Kieffer-Olsen (1993)'s arm positions are observed among the two Medieval sites. At Black Friar's only three arm positions were used; 1-arms at sides, 2-arms over pelvis, and 3-arms over chest. The distinction was not made between Kieffer-Olsen (1993) B and C categories. As there are only 4 individuals sampled from Ole Wormsgade that were described with the C arm position, the categories of B and C were joined and considered along with the second arm position at Black Friars. Data on arm positioning was available for 81 of 147 individuals. Of the 40 individuals at Black Friars with recorded arm positions, 23 were located in the post-medieval part of the cemetery. The distribution of arm positions recorded among medieval and post-medieval individuals at Black Friars is noted in Table 5.2. In the sample of 50 subadults from Black Friars used for study, 28 of these belong to the post-medieval part of the cemetery. The 'arms over pelvis' arm position is most common. Only one example of the A position was noted.

Table 5.2: Arm positions for Medieval and post-medieval sections of Black Friars cemetery

Time Period	**Arm Position**			
	Arms at Sides (1050-1300)	**Arms over Lower Trunk (1250-1450)**	**Arms over Chest (1450-1500)**	**No record**
Medieval	1	10	6	5
Post-Medieval	0	15	8	5
Total	1	25	14	10

There is representation for each of the four time periods within this sample; 1050-1300 characterized by burials with arms at sides, 1250-1450 characterized by arms over the abdomen or pelvis, 1450-1500 characterized by arms over the chest, and post-1536 represented by the Klosterkirke burials and the Southern burials at Black Friars. Figure 5.2 illustrates the distribution of individuals from each cemetery dating to the four time periods. Changing temporal trends in arm positioning within the grave allows for the identification of a shorter possible interval for the date of burial and consequently death as the sometimes-wide ranges of cemetery use. Ole Wormsgade was used from the early period of 1050 to 1300 with most burials occurring from 1250 to 1450 with only a few burials dating to the 1450 to 1500 period. These results are consistent with cemetery records (Pedersen, 2010). The Black Friars site has burials dating to each of the four time periods, but the majority (56%) date to the postmedieval period.

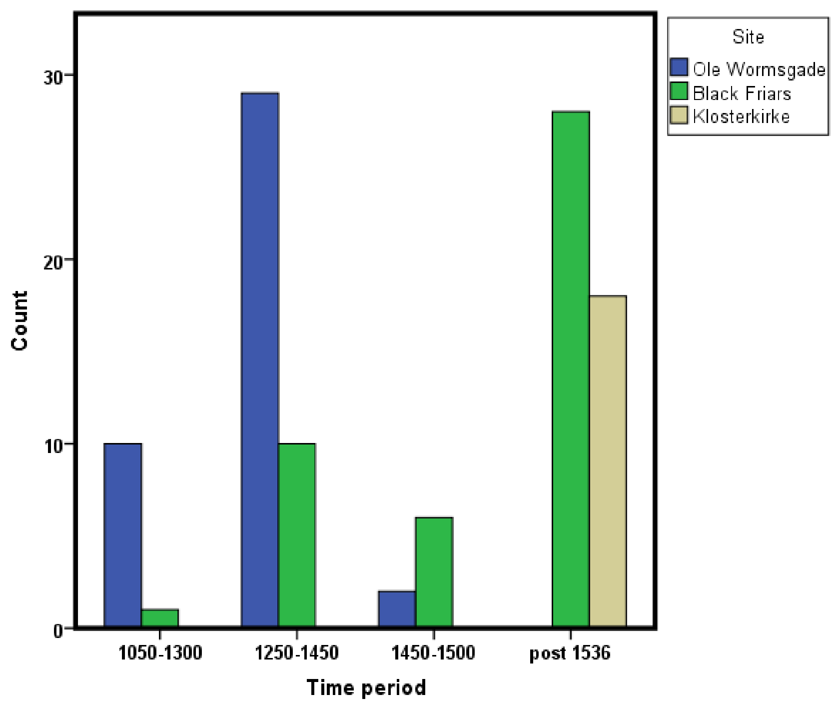

Figure 5.2: Time period of burials for each site based on arm position and burial records.

Horsens Klosterkirke burials all occurred after Reformation in 1536 and would all fall into the postmedieval category (Tarp, 2010). The majority of all burials sampled occurred from 1250 to1450 or after 1536 with Ole Wormsgade representing the bulk of the earlier period.

Table 5.3: Age category distribution for each time period

	Time Period				
Age category	**1050-1300**	**1250-1450**	**1450-1500**	**post-1536**	**Total**
0-1	1	1	3	12	17
2-4	0	4	2	3	9
5-7	4	6	1	9	20
8-13	3	13	3	14	33
14-18	3	13	1	6	23
19+	0	2	1	2	5
Total	11	39	11	46	107

Temporal differences in age are represented in Table 5.3. Data for age at death and time of burial are available for 107 of the available burials. Once subdivided between age categories, the temporal periods of 1050-1300 and 1450-1500 have too few individuals to reliably discern any demographic patterns. However, looking at the 1250-1450 and post-1536 time periods, there is a large increase in infants; from 2.6% in the early period to 26% in the later one. In contrast, the 14-18 years age category decreases from 33.3% to 13%. All other age categories stay fairly consistent. The post-1536 pattern is what would be expected for a pre-industrial population, but the 1250-1450 age distribution is indicative of a high mortality rate. This period coincides with multiple famines and the spread of Black Death, although (Boldsen, 1996) observed a similar pattern in Tirup, a sample dating prior to the Black Death.

5.2 Methods

5.2.1 Data collection

Age was determined using dental eruption (Ubelaker, 1989) and dental calcification (Moorrees, Fanning, & Hunt, 1963) when teeth were sufficiently preserved. Dental age was assessed macroscopically, and from CT images whenever possible in the subsample used for cortical thickness assessment. CT allowed for better visualization of developing unerupted teeth. The basiocciput (Tocheri & Molto, 2002) was used in infants when it was preserved and unfused. In individuals with fully erupted second molars, the sequence of epiphyseal fusion was used to assist in age estimation. Skeletal age based on long bones was calculated using regression equations from Primeau et al. (2012). These equations were developed from a Medieval Danish sample and should be more representative of the genetic population during the period of study than other stature estimation equations such as the more widely used Trotter & Gleser (1952).

Sex was estimated using the sex determination method outlined by Schutkowski (1993) using the sciatic notch, the sciatic depth, the iliac arch, the iliac curvature, the mental protuberance, shape of dental arc, and the angle of gonion. While this collection is not of known age or sex, attempts were nevertheless made to estimate sex in part to test the applicability of sex estimation methods in subadults. Sex estimation is not typically done for subadults. The methods used to determine sex from skeletal remains rely primarily on secondary sex traits. The distinction between males and females for morphological mandibular or pelvic traits are not as evident in subadults, but can purportedly still be discerned before puberty with reported success rates typically ranging from 69.4 to 90% (Mittler & Sheridan, 1992; Schutkowski, 1993; Sutter, 2003; Weaver, 1980). Sex-related differences in the ilium, particularly the greater sciatic notch, have been observed during fetal development (Reynolds, 1945). In general, subadult sex estimation methods have greater accuracy on individuals over the age of 10 and have a tendency to be better at identifying males than female (Mittler & Sheridan, 1992). This would therefore have a tendency to erroneously identify more females as males than vice versa. While the sex estimates made on these subadults cannot be confirmed or refuted they can be used to test possible sources of variation in growth data.

Part of population health is the capability of children to thrive in their living conditions and survive into adulthood. Any archaeological sample cannot be considered to be completely representative of the original living population; there are multiple selection factors to determine which individuals remain present in the samples that become available for study. When studying subadults, it can be expected that certain age groups, especially neonates, and infants, will be underrepresented due to differential burial practices and the small fragile bones being more susceptible to taphonomic factors affecting preservation. Figure 5.3 shows the frequencies of individuals belonging to maturational-based age intervals with distinction between the three cemetery sites used. Age category occupation is normally distributed for Ole Wormsgade according to a Shapiro-Wilk test of normality, with peak values in the 8-13 age range and few over 19. Black Friars shows an almost normal distribution, with slightly higher numbers of infants. The 8 to 13 category is the most populated age category in all sites, but most individuals sampled are aged between 5 and 18. While a normal distribution is anticipated in.

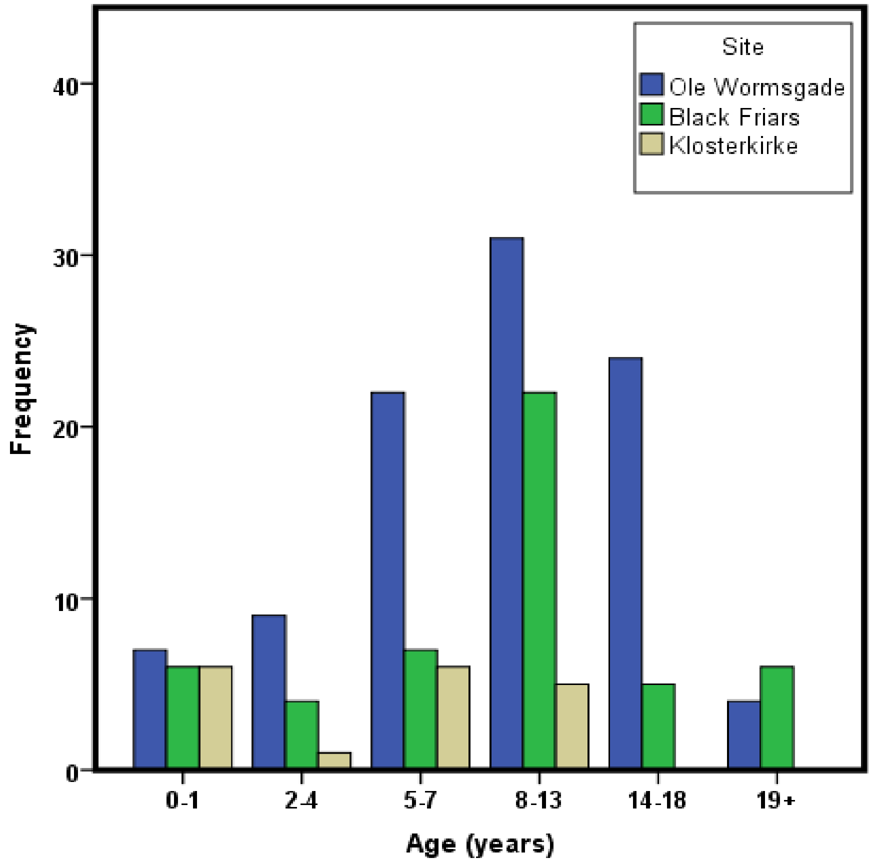

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Figure 5.3: Age distribution for the three cemetery samples

some biological measurements, this is not the case with human mortality curves. The expected mortality distribution of a preindustrial population would feature high infant mortality. However, this is not what is typically observed in archaeological populations, instead there tends to be a high representation of older children as in these samples (Paine & Boldsen, 2008). This underrepresentation of children in the archaeological record, particularly during the Middle Ages is commonly noted (Guy et al., 1997). Ole Wormsgade and Horsens Klosterkirke both had low representation of children in general, around 16% of the total population (Pederson, 2010; Tarp, 2010). Black Friars is closer to the expected levels of 50% (Chapeskie, 2006) with 40.5% of the entire population under the age of 15 (Boldsen & Mollerup, 2006). Some of the site-related variations in age distributions may be explained by the temporal variations previously discussed.

Out of 165 individuals, 17 lacked sufficiently preserved material to estimate sex. Counts for each category for sex estimation can be found in Table 5.4. Overall, there is a fairly even distribution between sexes with 50% male/probable male, 47% female/probable female, and 3% indeterminate. The greatest sex difference was at Black Friars with 62.5% male/probable male, 33.3% female/probable female, and 4.2% indeterminate.

Table 5.4: Sex estimation results for all sites

Site	Male	Probable Male	Indeterminate	Probable Female	Female	Unknown
Ole Wormsgade	29	7	2	9	39	11
Black Friars	28	2	2	1	15	2
Klosterkirke	4	4	0	2	4	4
Total	61	13	4	12	58	17

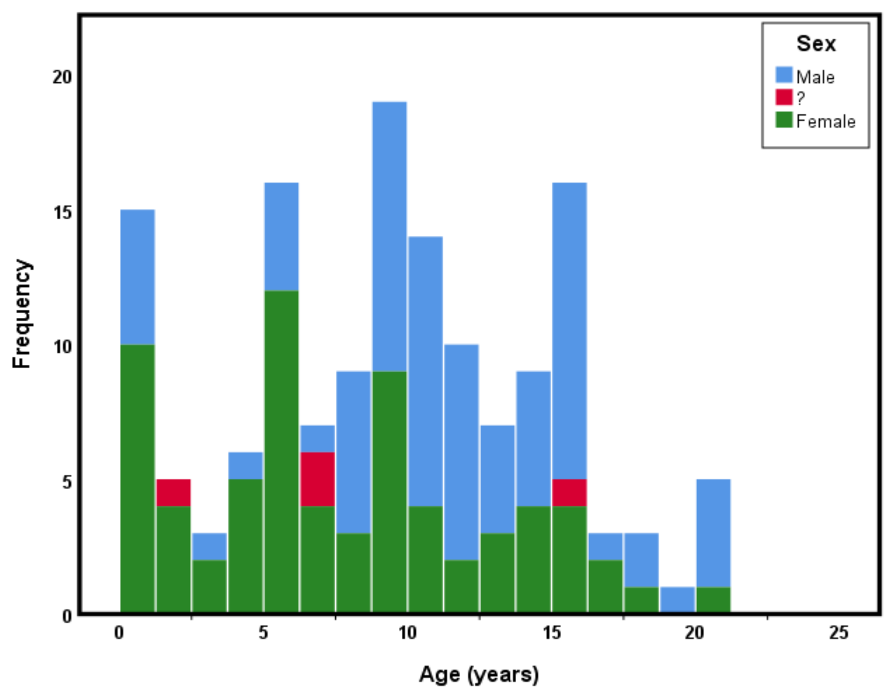

Figure 5.4: Histogram displaying the ages of individuals of male (blue), female (green), and indeterminate (red) sex

There is an unequal age distribution for sexes as shown in Figure 5.4. The indeterminate category has the lowest average and consists of younger individuals with none over the age of 15. Individuals estimated as female have an average age of 7.54 years. There is a positively skewed distribution with most individuals falling in the 5-10 year range. Males have an average age of 11.13 and show a bimodal distribution with peaks around 10 and 15 years of age. The females in this sample trend towards a lower age of death, clustering in early childhood versus males who tend to be in late childhood to early adolescence.

Measurements and data collected were primarily of metric and macroscopic nature. Raw long bone lengths of the left and right clavicle, humerus, ulna, radius, femur, tibia, and fibula were collected using maximum diaphyseal length. Whenever possible, measurements were taken with and without epiphyses. Other measurements taken when sufficiently preserved were femoral metaphyseal breadth, maximum supero-inferior femoral head breadth, and bi-iliac breadth. The latter three measurements were used to validate the use of regression equations for estimation of body size developed by Ruff (2007). The inclusion of body size can provide information on wasting in addition to the assessment of potential skeletal stunting. Measurements under 15 cm were taken using sliding calipers. All other measurements were made using an osteometric board. The regression equations use different measurements dependant on age. This method therefore can only be applied to individuals with good age estimates. Equations using the femoral metaphyseal breadth are available up until the age of 12. The femoral head breadth can be used for ages 7 to 17. The standard error rates associated with the femoral metaphyseal breadth for ages 7 to 12 are higher than those associated with the femoral head breadth, therefore when possible, measurements with the lowest standard error was taken when multiple options are available.

Epiphyseal fusion was scored using a five-phase scale for the thirty-three epiphyses listed in Table 5.5. Phase 0 describes epiphyses which have not yet begun to unite to the diaphyses. Before fusion occurs, the surfaces of both the diaphysis and epiphysis have a billowed appearance. In phase 1, fusion has begun but less than 50% of the surfaces are united. In cases where the united epiphysis has been broken off of the diaphysis, a phase 1 epiphysis can be distinguished from a phase 0 epiphysis by examining the adjoining surfaces of bone. Fusion

Table 5.5: List of epiphyses observed for each skeletal element

Skeletal Element	Epiphysis
Cranium	Spheno-occipital synchondrosis
Clavicle	Medial epiphysis
Scapula	Acromion
	Inferior angle
Vertebrae	Superior body
	Inferior body
	Spinous process
Humerus	Proximal epiphysis
	Distal epiphysis
	Medial epicondyle
Radius	Proximal epiphysis
	Distal epiphysis
Ulna	Proximal epiphysis
	Distal epiphysis
Os coxa	Iliac crest
	Ischial tuberosity
	Acetabulum
Sacrum	Superior epiphyseal ring
	Auricular epiphysis
	Ventral spaces between sacral segments (S_{1-2}, S_{2-3}, S_{3-4}, S_{4-5})
Femur	Femoral head
	Greater trochanter
	Lesser trochanter
	Distal epiphysis
Tibia	Proximal epiphysis
	Distal epiphysis
Fibula	Proximal epiphysis
	Distal epiphysis
Calcaneus	Calcaneal tuberosity
Talus	Lateral tubercle

typically begins at the centre of the surface; spongy bone will be exposed if an epiphysis which has begun to unite is broken. Phase 2 will be given to epiphyses that have over 50% but less than 100% of the surface fused. Again, if the epiphysis were to break off of the diaphysis, spongy bone would be evident on the connecting surface. In phase 3, the development of spongy bone uniting the epiphysis to the diaphysis is complete but infilling of the epiphyseal line with periosteal bone is incomplete. Phase 4 is the final phase; the periosteum is complete and has filled the remaining cavity left by the epiphyseal line. At some locations, such as the femoral head, a scar persists demarcating the epiphyseal line. Care must be taken not to interpret the presence of an epiphyseal scar as incomplete fusion. Due to the variability of definitions and scoring methods in past studies on epiphyseal fusion, comparison of data can be challenging. This five-phase scoring method was developed to objectively examine the process of fusion in as many distinct stages as possible; this is a continuous process that can take over two years from start to finish at some epiphyses (Ubelaker, 1989).

5.2.2 CT scanning

A sub-sample of 49 individuals were selected for CT scanning. This sample consisted of individuals from all three cemeteries having at least two nearly intact and well-preserved femora, humeri or 2nd metacarpals. These skeletal elements were chosen since they are most frequently studied in relevant clinical and archaeological literature. The femur and humerus lend themselves well to measures of cortical thickness due to their relatively circular shape. Robb et al. (2012) found the femur to be more sensitive to stress-related change than the second metacarpal. As a load-bearing bone, the femur is subject to greater mechanical pressures and may reflect changes in cortical thickness as a result of activity patterns and body weight (Ruff, 2003). The effect of load-bearing mechanical changes is of increasing concern as children age and develop their locomotor skills, but should not display significant individual variation until they are old enough to experience profession-related variations in activity patterns. In contrast, the humerus and metacarpals are not load bearing, but bilateral asymmetry may be observed as a result of handedness.

Agarwal et al. (2011) did not observe significant differences in cortical thickness between left or right elements in their assessment of cortical thickness and cortical index of the second metacarpal. Whenever possible, both left and right were measured to independently determine if any significant differences in bilateral asymmetry can be observed. Prior to CT scanning the bones were measured for antero-posterior and medio-lateral diameter using sliding calipers and circumference using a measuring tape at the midshaft. Midshaft location was determined by measuring the entire diaphyseal length with an osteometric board and using the mid-point of maximum diaphyseal bone length.

CT scans were all done by the author over the course of four days at the Institute of Forensic Medicine at the University of Southern Denmark using a Siemens Somaton Spirit scanner. The bones belonging to one single individual were placed in standard sagittal orientation. When possible all elements were scanned in one image. All scans were done using a pre-programmed setting tailored for human bone of 130 kV/89 mA at 1 mm slices and taken at a perpendicular plane. Images were saved in DICOM format on DVDs for later analysis.

Analysis and measurement of digitized CT scans was done using Materialise Mimics 16.0 medical imaging software. The Mimics software has predetermined settings recognizing various types of biological tissues based on their densities. The Bone (CT) setting was used for most of the scans. In some younger individuals, it was necessary to manually increase the threshold to accurately reflect the actual bone tissue. This is likely because the bones of infants and young children are more cartilaginous and therefore not the same level of density detected by the software (Bogin, 1999).

Individual masks were made for each bone (Figure 5.5). Using Mimics, the maximum diaphyseal lengths measured and the midshaft point was determined in antero-posterior view. The slice number of this midpoint was noted to ensure consistency through all midpoint measurements. From this midpoint, the view was changed to the axial orientation. New masks were created by manually highlighting the medullary cavity (Figure 5.6). Antero-posterior and medio-lateral diameters were measured of the midshaft as a whole and of the medullary cavity. The medullary and cortical area for each 1mm axial slice was then exported from Mimics as a Notepad file listing the area for each corresponding numbered slice.

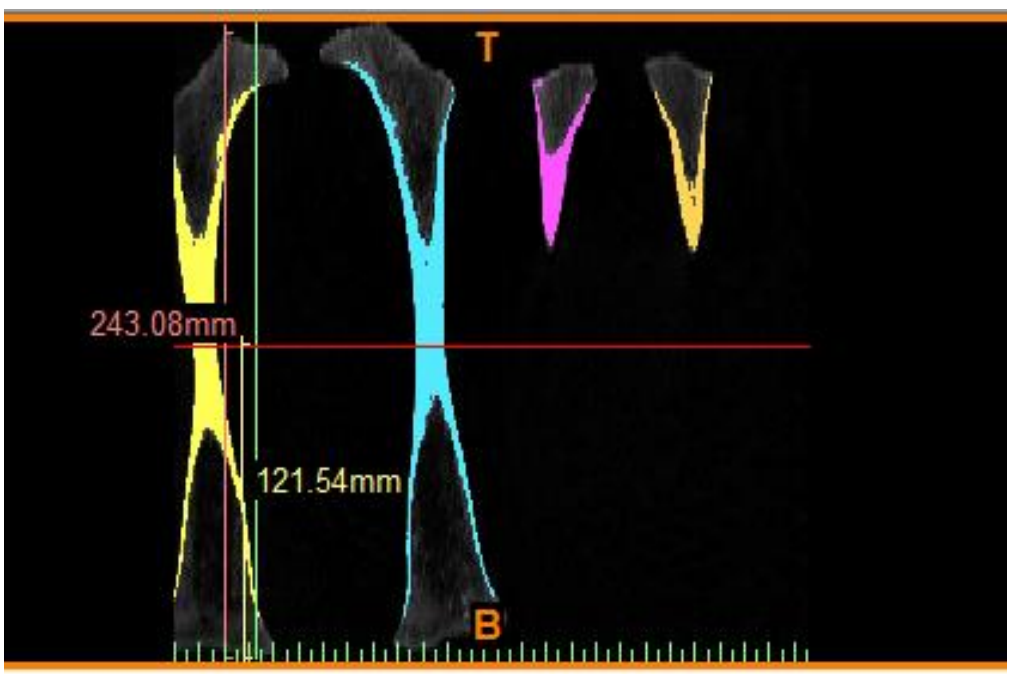

Figure 5.5: Antero-posterior view of CT scan in Mimics with both femora on the left, and proximal humeri on the right.

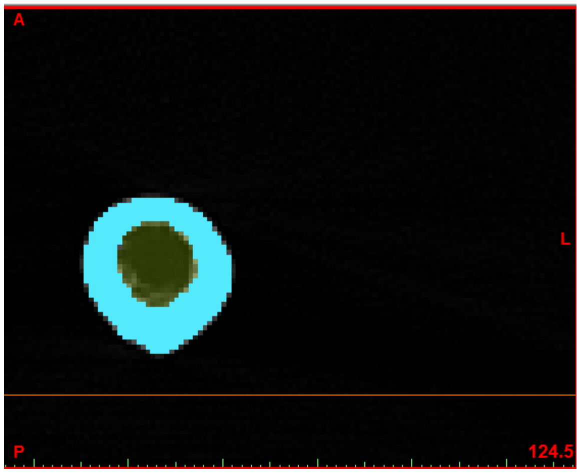

Figure 5.6: Cross-section of a femur in axial view. The cortical bone mask (blue) was automatically generated by Mimics using the Bone (CT) setting. The medullary cavity (yellow) was manually masked by selecting the non-bone area.

5.2.3 Analysis

Statistical analyses were performed using IBM SPSS 20 statistical analysis software. Growth and development were assessed based on multiple measurements including dental eruption and calcification, epiphyseal fusion, cortical thickness, long bone lengths, and other metric indicators including; femoral metaphyseal breadth, maximum supero-inferior femoral head breadth, and bi-iliac breadth.

Comparing the various markers of maturation and growth throughout the body provides a more thorough assessment of any potential delays and stunting during childhood and adolescence. As dental age is considered to better reflect chronological age, this was used as a baseline to contrast with skeletal age as determined by long bone length. Maturation rate as described by Buikstra (1977); femur length/dental age was determined to reflect the changing tempo of growth at varying points during childhood. The range of ages for each phase of epiphyseal fusion was assessed with latest age of non-fusion noted for Phase 0, the total range of ages observed for Phases 1, 2, and 3, and the earliest age of completed fusion was noted for Phase 4. These observations were then compared to known-age data from the Bosnian war dead (Schaefer & Black, 2007).

As cortical thickness is not a widely-used measurement in studies of growth and development, these values were closely scrutinized to ensure that they adequately reflected growth related changes. Patterns for the three elements studied were observed for individual variation and relationship to age. Maturation rate for cortical area and medullary area were also assessed as done with long bone length to study variations in tempo. Finally, the percentage of total bone cross-section occupied by bone (CT%) was used to look at variation in values independent of size-related differences. This allowed for the identification of individuals with potentially anomalous values and therefore potential stunting.

To explore the influence of temporal period on growth, time periods as determined by arm position and grave location, were compared graphically and using analysis of variance to long bone length, maturation, and body size. The study samples were also compared to modern Western populations using body size data from 2006 WHO standards, and cortical thickness percentage data from the Fels longitudinal study (Garn, 1971). Sex was considered as a potential source of variation in long bone length, body size, maturation rates, and cortical thickness.

6. Results

6.1 Longitudinal Growth

One of the research goals was to investigate temporal variation in health in Denmark as the population is documented to have undergone significant changes in lifestyle, disease exposure, and nutritional access. Figure 6.1 shows trends in femoral diaphyseal length for each time period. As can be observed, there is very little difference that can be detected between the respective time periods. The data from all three sites follow similar trajectories with a continuous increase in size until approximately 20 years of age when growth tapers off. A secondary group does seem to exist within this data but is present in all sites and time periods. The majority of values cluster along a strong linear trend, however, there is a small sample that exhibits lower values for age. These individuals with lower values would represent those who had experienced growth stunting prior to or around the time of their death leaving them shorter for their age, but not below the normal range of variation.

Dental age is considered to be more reliable and less subject to delay under the influence of physiological stress (Cardoso, 2007). Dental age was therefore compared to skeletal age, determined using the size of long bones, to assess the degree of delay in skeletal stunting versus dental age. A paired samples t-test shows a statistically significant difference between dental and skeletal age ($p=0.01$), however the mean values; 11.45 for dental age and 11.04 for skeletal age do not vary drastically and both values maintain a high correlation. Figure 6.2 further illustrates the interaction between these two variables. Deviation between dental age and skeletal age becomes more pronounced after the age of 10, at which point a deviation of 0.5 years

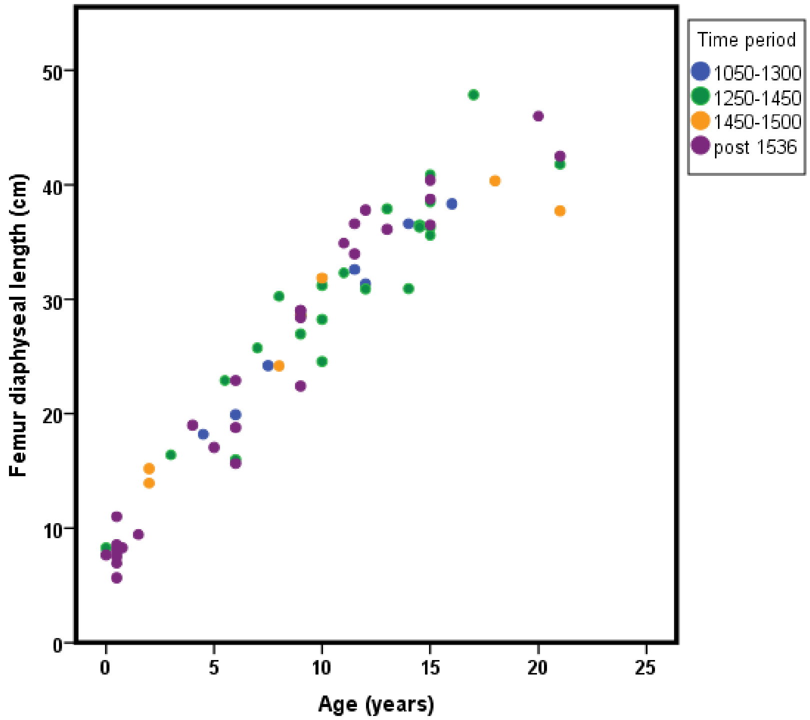

Figure 6.1: Mean diaphyseal length of the femur by age for each time period based on arm positioning and burial location

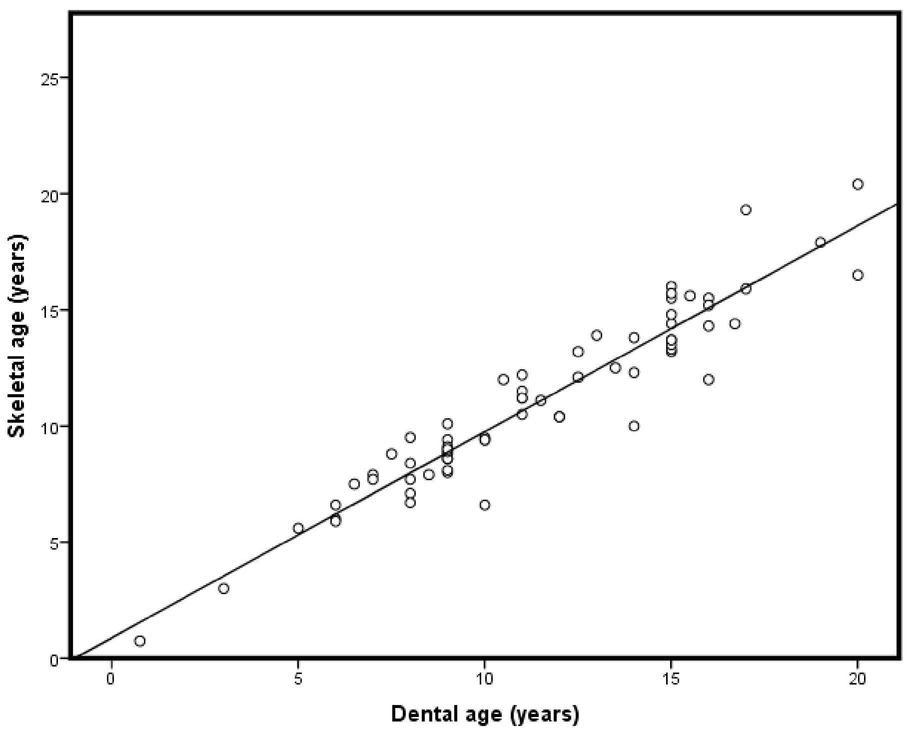

Figure 6.2: Skeletal age determined using long bone lengths compared dental age estimates:

does not have quite as much of an impact on an age estimation. This could be due to age estimation methods or could be evidence of growth stunting. To further explore these variables a generalized linear model test using a gamma distribution was run on the squared difference between dental and skeletal age with dental age as a predictor model. The dental age model has a greater impact than the intercept (p=0.003) and has an important impact on the variation (p=0.001).

An additional measure of growth and potential delay is the maturation rate, represented by the femur length divided by age (Buikstra, 1977). When graphed against age as in Figure 6.6, this represents the amount and changes in growth or maturation rate throughout life. The maturation rate has high values during infancy, tapering off until the 5th year. A slight peak occurs in adolescence around 17 years of age and growth likely ceases during the third decade of life, after the sample limit of 21 years. Figure 6.3 shows very close adherence to the general trend for all three of the sites surveyed. An ANOVA test indicates that there is no

Table 6.1: The results of an ANOVA test assessing variation in maturation rate between time periods and cemetery sites

		Sum of Squares	df	Mean Square	F	Sig.
	Between Groups	36.293	3	12.098	3.105	0.033
Time	Within Groups	249.320	64	3.896		
	Total	285.613	67			
	Between Groups	20.550	2	10.275	2.763	0.068
Site	Within Groups	334.668	90	3.719		
	Total	355.218	92			

significant difference in the growth rates for the different cemetery sites, however, there is a statistically significant different between time periods (Table 6.1). The temporal difference is likely due to the age distribution variations observed between time periods. The 1250-1450 time period has very low infant representation and consists primarily of individuals aged 8 to 18. This period has a mean maturation rate of 3.18 cm/year. The post-1536 period has a much higher mean maturation rate at 4.66 cm/year, largely due to the high representation of infants and low count of adolescents.

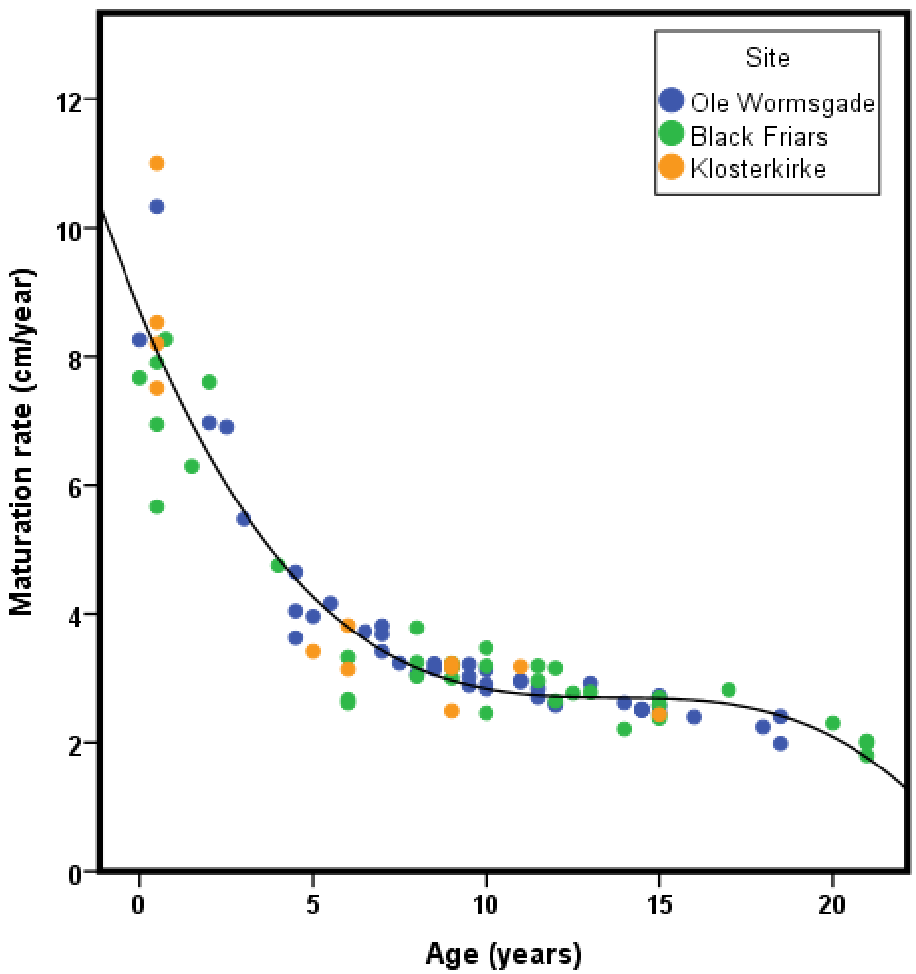

Figure 6.3: Maturation rate (cm/year) using diaphyseal femur growth by age with markers indicating site of burial.

When looking at possible differences in maturation rate due to sex (Figure 6.4) the adolescent growth spurt can no longer be detected in males, but the growth spurt in females is shown around 14 to 15 years of age.

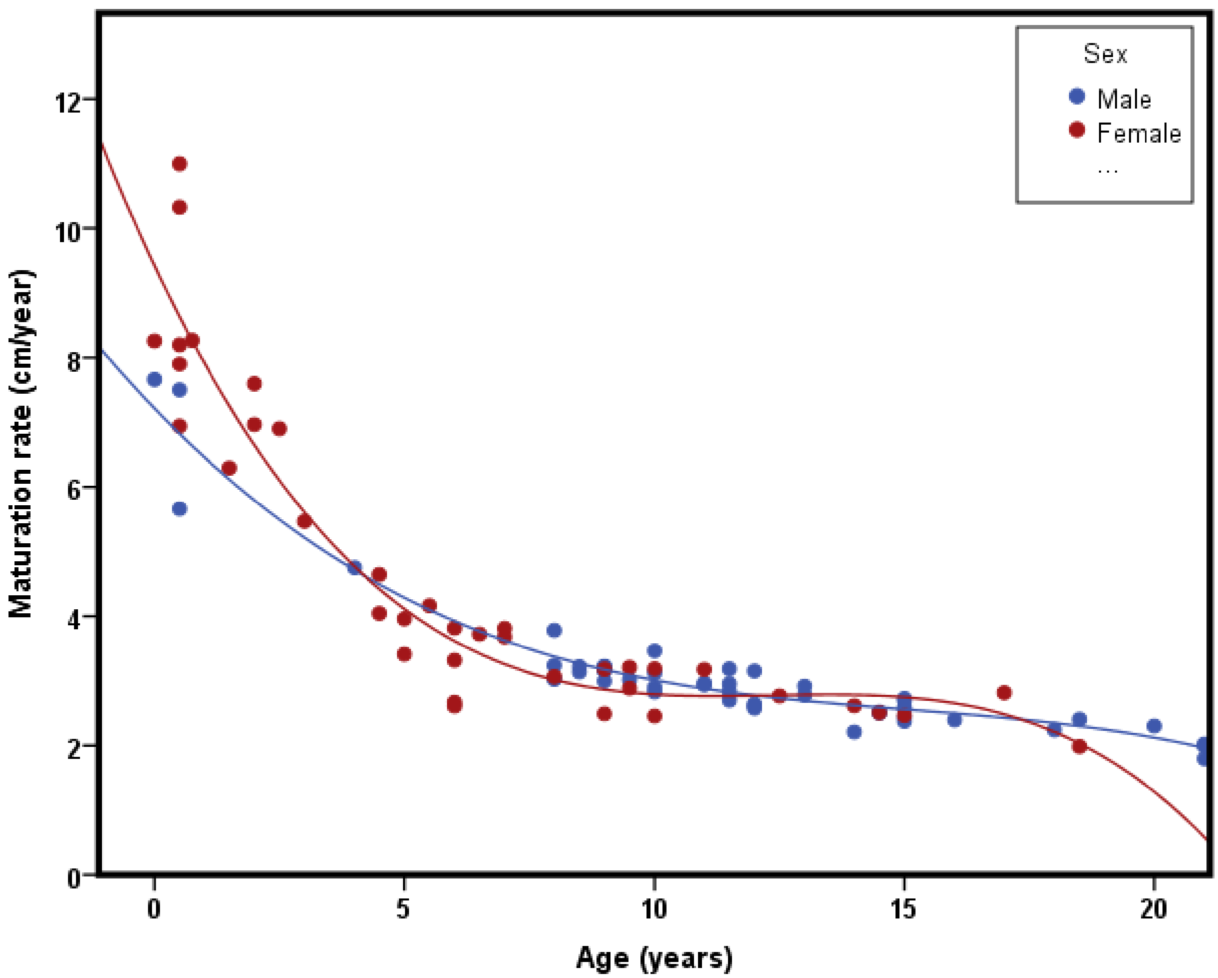

Figure 6.4: Maturation rate (cm/year) using diaphyseal femur growth by age with markers indicating sex

6.2 Body Size

Body size estimation equations as described by Ruff (2007) were used to assess another dimension of health. Low body size and body weight can indicate wasting, in contrast to stunting, which can be observed in the form of reduced stature or long bone length. Body size could be determined for 88 individuals from the total sample of 168. In Figure 6.5, estimations for body size in kilograms are plotted against age. For comparison, median and 5th percentile data from WHO (2006) are included up until the age of 10 years. Most of the Danish values fall in between the 5th percentile and the median for modern living children. The lowest body size estimate was 3.87 kg for a neonate and the highest value was 67.15 kg for a 17-year-old. Only one estimate could be made based on bi-iliac breadth. While other measurements were taken, they were clearly inaccurate as they produced unreasonable body mass estimates.

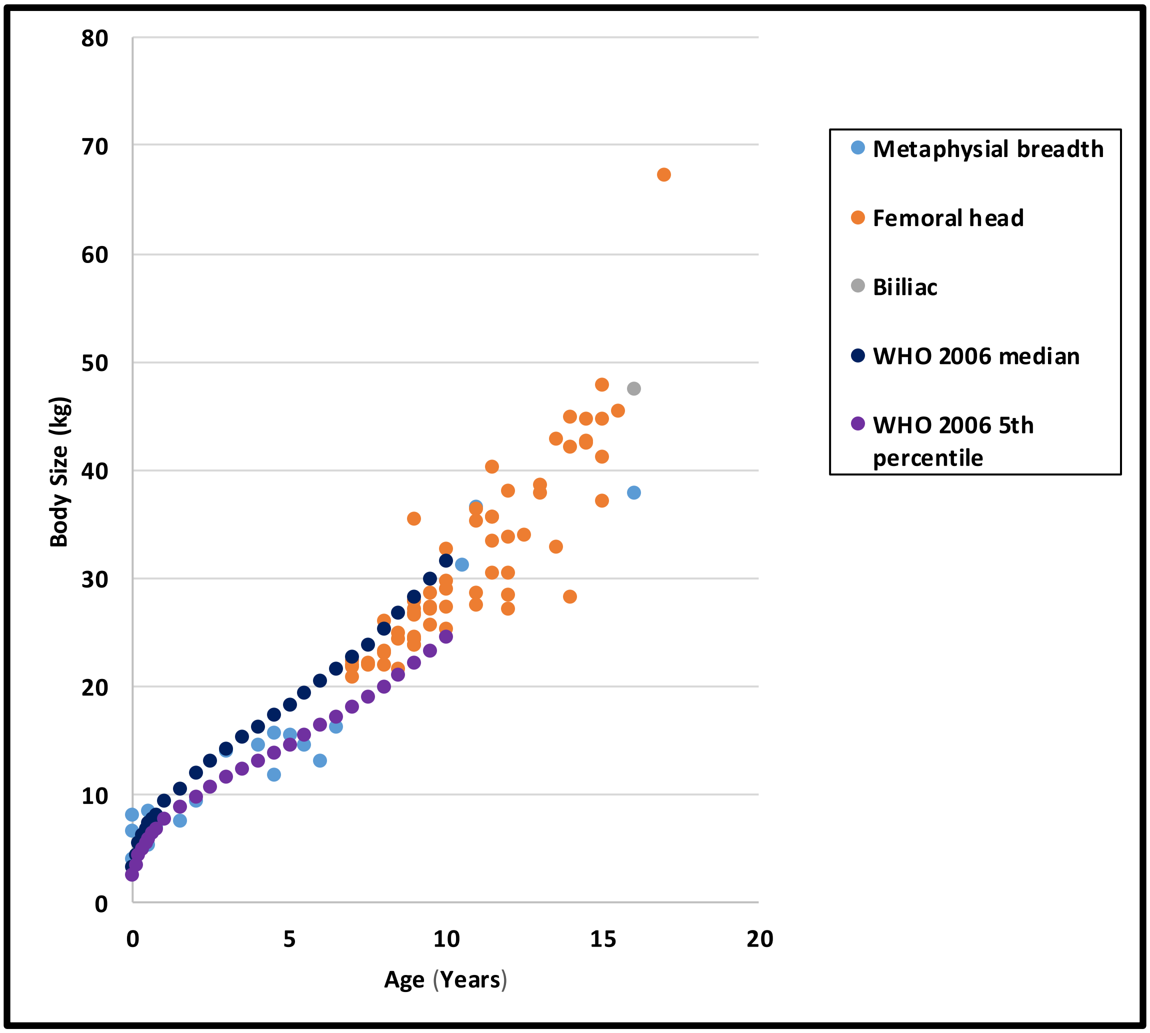

Figure 6.5: Body size (kg) as per Ruff (2007) by age compared two modern WHO standards

6.3 Epiphyseal Fusion

The fusion of epiphyses occurs gradually as skeletal elements near adult proportions. These maturational events are better indicators of age for older children and adolescents. Maturation is less subject to delay or stunting than is skeletal growth and therefore more likely to accurately reflect true chronological age than long bone length. Tables 6.2 and 6.3 summarize the observed ages for the five phases of epiphyseal fusion in the sample. The age provided for Phase 0 represents the latest age observed with no fusion activity. For Phase 4, the age indicates

Table 6.2: Ages observed for all phases in the epiphyses of the axial skeleton

	Phase 0	Phase 1	Phase 2	Phase 3	Phase 4	Sample size
Spheno-occipital synchondrosis	<16	14-18	21	17-21	>9	64
Csuperior	<18	7.5-21	-	-	>15	99
Tsuperior	<21	6-21	19-20	15	-	111
Lsuperior	<21	6-21	20	15	-	126
Cinferior	<17	7-21	15.5	15	>20	97
Tinferior	<21	6-19	20-21	15	-	112
Linferior	<17	4-21	20-21	15-18.5	-	125
Cspine	<6	-	-	-	>5	51
Tspine	<16	14	-	-	>10	36
Lspine	<16	14	-	18.5	>11	38
Superior epiphyseal ring	<16	9-21	16-21	18-21	-	85
Auricular epiphysis	<21	13-18	6-11	-	-	91
S_{1-2}	<18	4-21	12-18	14-20	-	87
S_{2-3}	<18	7-20	11-21	17-20	>18	69
S_{3-4}	<15	7-20	9-21	15-21	>18	59
S_{4-5}	<17	7-18	10-16	11-21	>18	25

the earliest age of complete fusion. There is a wide variation in the phases that can be observed at one location even within a single year. Some epiphyses, such as the distal humerus, begin and end fusion very quickly, with most activity occurring between the age of 14 and 15. The patterns in fusion for the three cemeteries and four time periods were consistent with each other.

Table 6.3: Ages observed for all phases in the epiphyses of the appendicular skeleton

	Phase 0	Phase 1	Phase 2	Phase 3	Phase 4	Sample size
Medial clavicle	<21	9	-	17	-	95
Acromion	<21	14	-	-	>20	77
Inferior angle	<21	-	-	-	>9	39
Proximal humerus	<18	14	-	15-20	>20	111
Distal humerus	<14	14	15	14-15	>14	110
Proximal radius	<21	-	-	16	>14	105
Distal radius	<18	14	-	16-19	>20	100
Proximal ulna	<15	11-15	14-15	14-18	>15	110
Distal ulna	<21	13	-	18-19	>16	94
Iliac crest	<21	-	-	18	>17	119
Ischial tuberosity	<18	-	20-21	16-19	-	104
Acetabulum	<15	14-16	-	15	>15	125
Femoral head	<18	-	10-13	17-21	>16	124
Greater trochanter	<16	-	-	16-21	>16	115
Lesser trochanter	<17	-	-	16-21	>16	104
Distal femur	<21	-	20-21	17	>16	109
Proximal tibia	<17	-	20	17-21	>16	107
Distal tibia	<18	-	-	17-20	>16	96
Proximal fibula	<21	-	-	18.5	-	57
Distal fibula	<17	-	-	17-21	>19	74
Calcaneal tuberosity	<15	6.5	15	16-21	>17	67
Talar lateral tubercle	<14	7-15	-	-	>11	71

6.4 Cortical Thickness

A total of 49 individuals were initially CT-scanned for cortical thickness study. One could not be further analyzed due to an image processing error, reducing the total sample to 48. The total elements surveyed consisted of 89 femora (42 pairs), 88 humeri (40 pairs) and 38 2nd metacarpals (13 pairs). For the majority of individuals both the left and right elements were sufficiently complete and preserved for scanning.

Table 6.4: Results of paired samples t-test for lateralization in cortical area values

Right-left pairs	Mean	Standard deviation	Std. error mean	t	Df	Sig. (2-tailed)
Cortical area - femur	0.013	12.729	1.964	0.007	41	0.995
Cortical area humerus	3.393	6.496	1.027	3.303	39	0.002
Cortical area 2nd metacarpal	0.571	1.625	0.434	1.315	13	0.211

Paired samples t-tests were performed to assess for lateralization. There is no significant difference between left and right values for the femur or the 2nd metacarpal, but there is a statistically significant difference in the humerus ($p=0.002$) as shown in Table 6.4. Based on the measurements of 40 pairs, the right humerus is on average 3.39 mm^2 larger than the left, a difference of 3.48%. This suggests the evidence of lateralization as a result of preferred handedness and use of the upper limb. Figure 6.6 illustrates the directionality of this difference and the general trend of increased lateralization with age, particularly between the ages of 5 and 10.

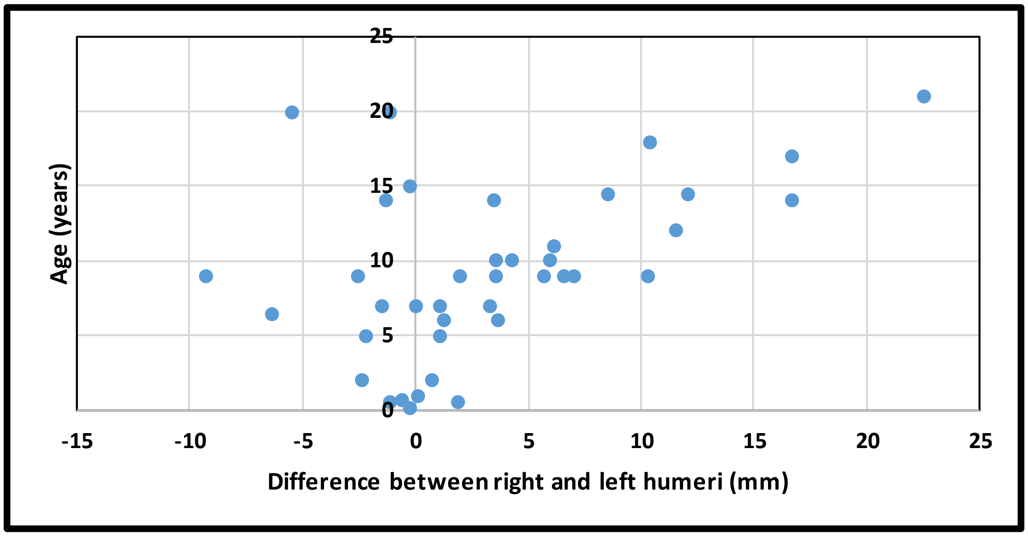

Figure 6.6: The directionality and difference in cortical area between right and left humeri as observed by age

The distribution of cortical area at the midshaft to diaphyseal length is illustrated for the femur (Figure 6.7), humerus (Figure 6.8), and 2nd metacarpal (Figure 6.9). As was expected, cortical area increases steadily with diaphyseal length. There is a linear relationship between diaphyseal length and cortical thickness in the humerus and the 2nd metacarpal. In the femur

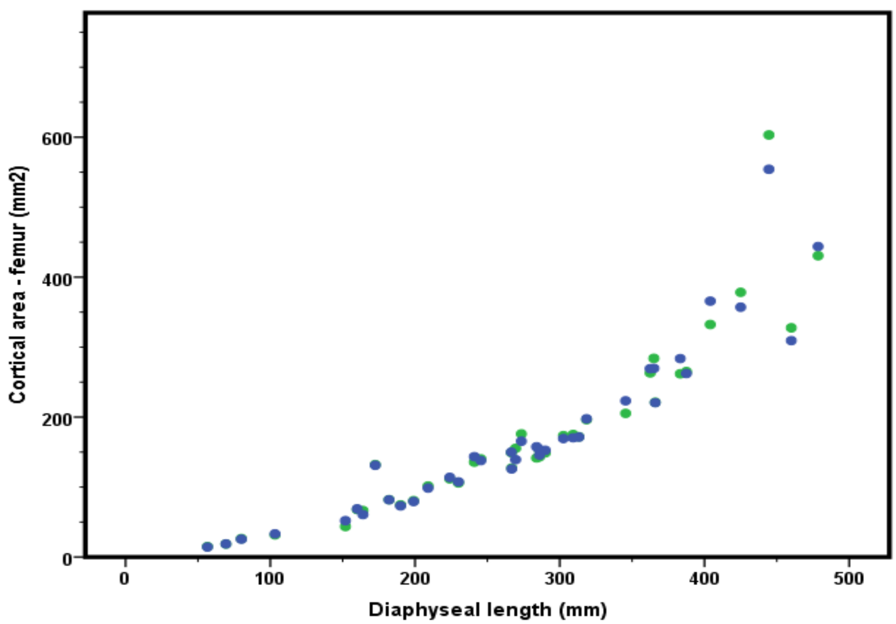

Figure 6.7: The cortical area (mm2) in relation to diaphyseal length (mm) for the femur. Right side elements are represented in blue while left side elements are in green.

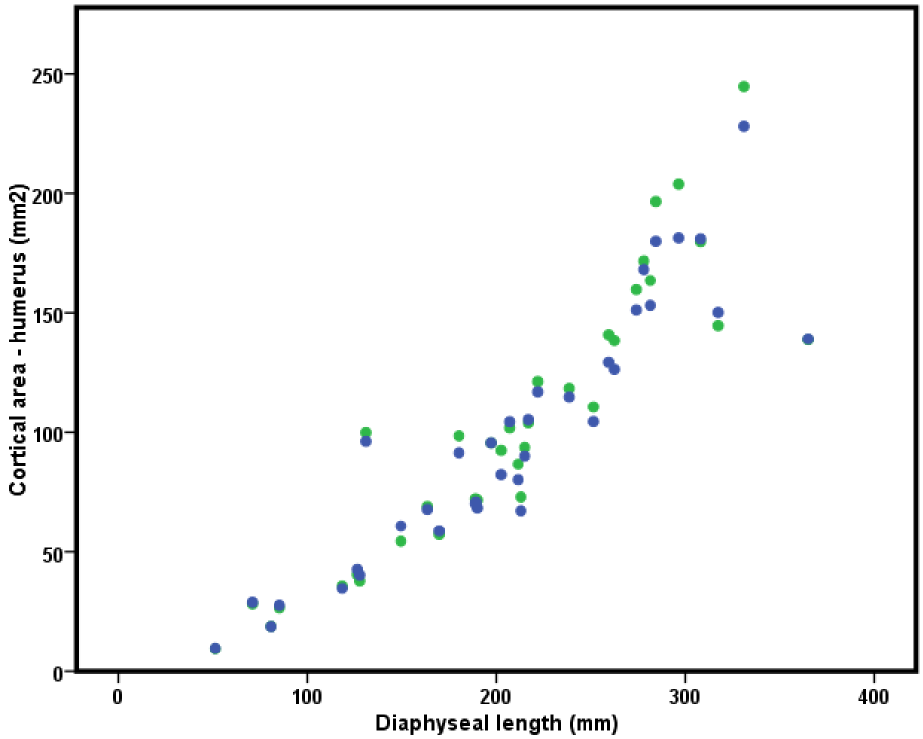

Figure 6.8: The cortical area (mm2) in relation to diaphyseal length (mm) for the humerus. Right side elements are represented in blue while left side elements are in green.

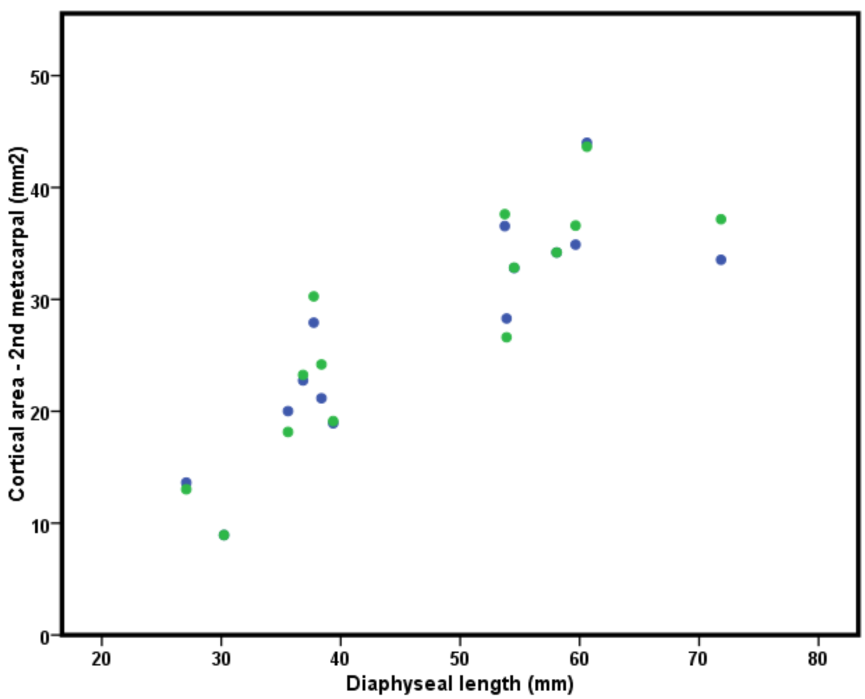

Figure 6.9:The cortical area (mm2) in relation to diaphyseal length (mm) for the second metacarpal. Right side elements are represented in blue while left side elements are in green.

there is an accelerated increase in cortical thickness in comparison to diaphyseal length when diaphyseal length reaches around 400 mm. Both left and right elements are represented on Figures 6.7, 6.8, and 6.9.

In Figure 6.10 cortical area (mm^2) for the femur, humerus, and 2nd metacarpal are plotted against estimated age. Cortical area indicates the actual area of a cross-sectional slice that is occupied by bone. As anticipated, cortical area increases steadily with age for each element. Larger bones such as the femur have larger cortical areas. With age, there is an increasing range

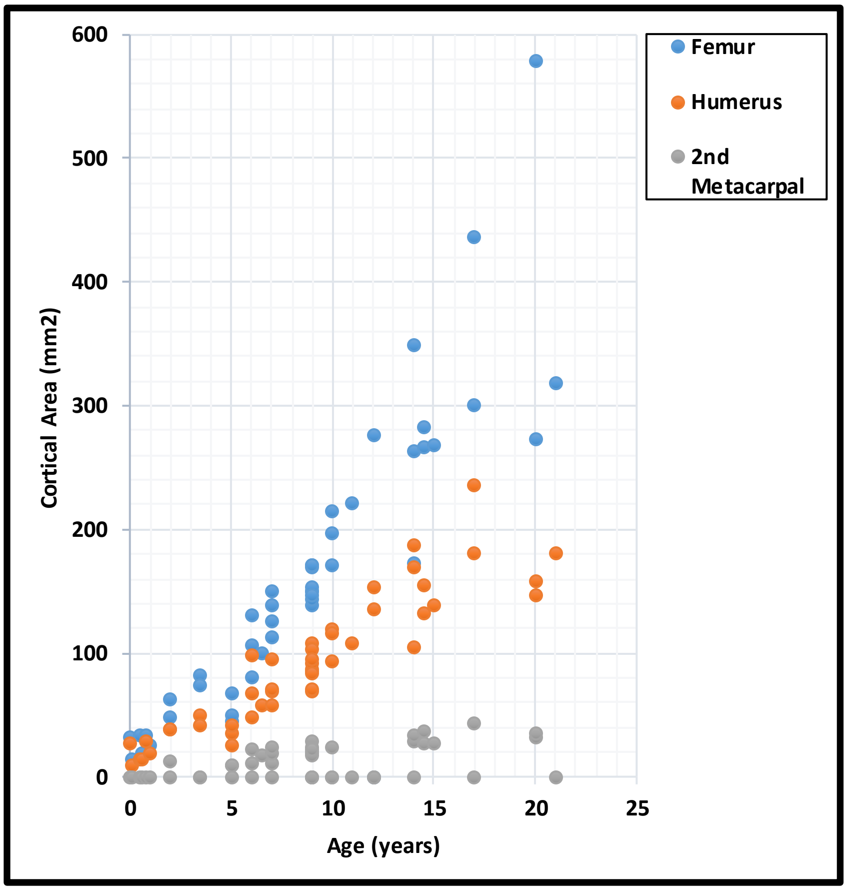

Figure 6.10: Values for cortical area (mm2) in the femur, humerus and 2nd metacarpal as distributed by estimated age

in cortical area values for all three elements observed. Figure 6.11 shows logarithmically transformed cortical area values by age to better visualize the differences between the femur, humerus and second metacarpal. The transformed values still show the steady increase in size with age, but again with a much more pronounced increase in the femur.

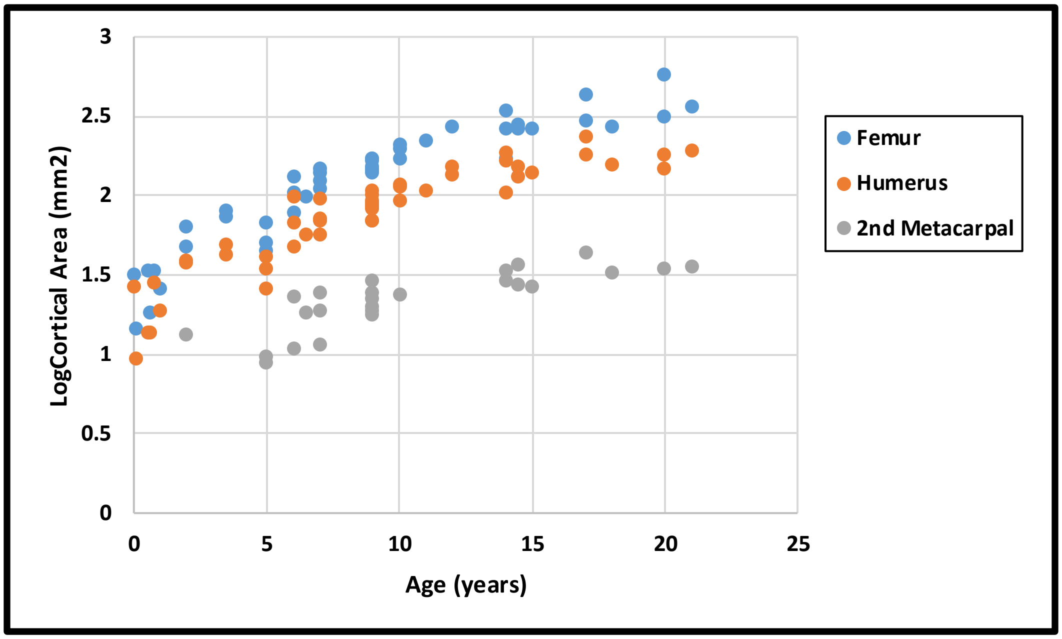

Figure 6.11: Log transformed cortical area (mm^2) for the femur, humerus, and second metacarpal compared to age

Both cortical area and medullary area were measured as it is the combined areas of these two measurements that have an impact on bone strength and therefore represent potential stunting and future health risk factors. The relationship between cortical area and medullary area is nearly linear, with a slight exponential trend (Figure 6.12). In the femur there is a gradual increase in the values for cortical area in contrast to medullary area occurring around adolescence. This is not the case with the humerus or 2nd metacarpal where cortical area begins to level off while the medullary area continues to increase. Both medullary area and cortical area increase with age during childhood and adolescence but the association between the two values is not consistent throughout life (Figure 6.13). The cortical area shows an accelerated increase beginning around adolescence. Medullary area also shows some acceleration in size increase, but this occurs in late adolescence and is not as pronounced as the increase in cortical area deposition. Figure 6.13 shows this pattern in the femur, but the same pattern is observed in the humerus and 2nd metacarpal.

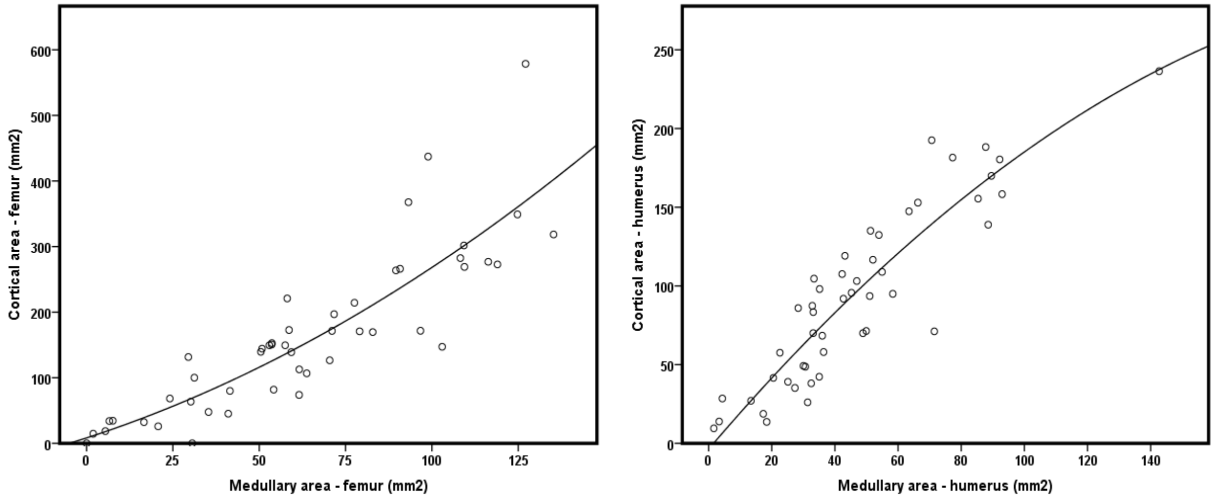

Figure 6.12: Cortical area versus medullary area for the femur (left) and the humerus (right)

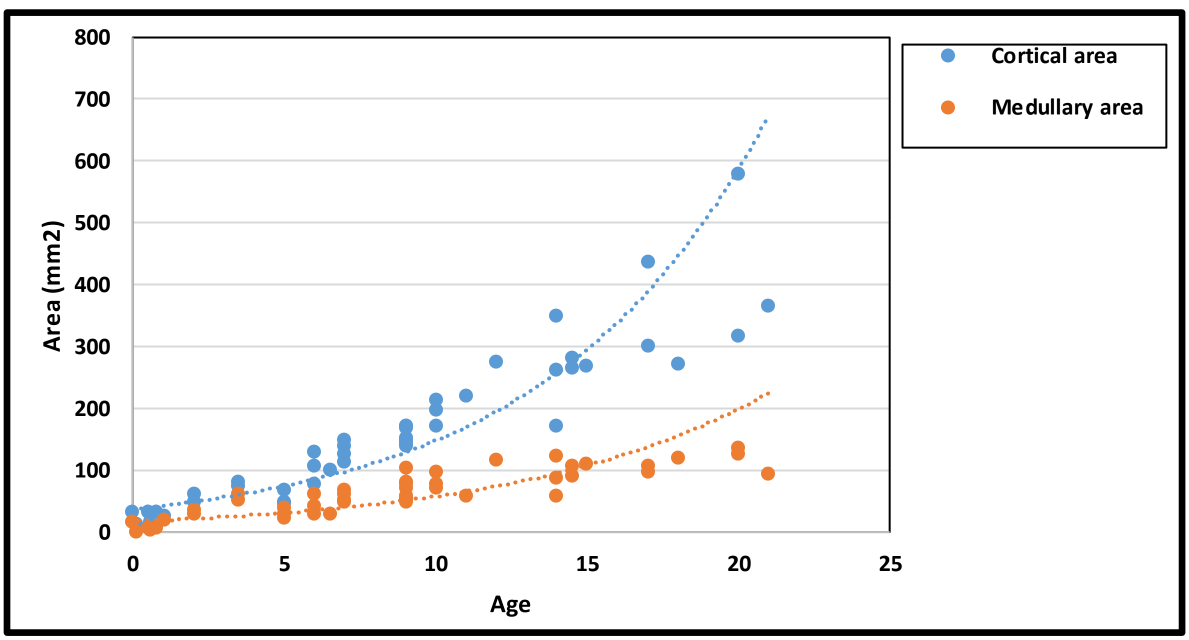

Figure 6.13: Cortical and medullary area values by age for the femur

To assess tempo of growth for the cortical and medullary areas, a maturation rate for both of these were determined by dividing measured areas by age. These were plotted against age in Figure 6.14 and Figure 6.15 to illustrate the changing growth rate for cortical and medullary area throughout the growth period. As with diaphyseal maturation rate (Figures 6.3 and 6.4), there is a high growth rate around the time of birth that drops off until adolescence. In the cortical area, there is an increased rate of growth that is evident beginning around the age of 10, reaching peak levels around 16 years and tapering off by the early twenties. The medullary area shows less drastic changes in growth rate although the same general pattern is observed. There is a high increase in medullary size around birth with growth rate decreasing afterwards until a slight adolescent increase that reaches its peak around the age of 17 before dropping off.

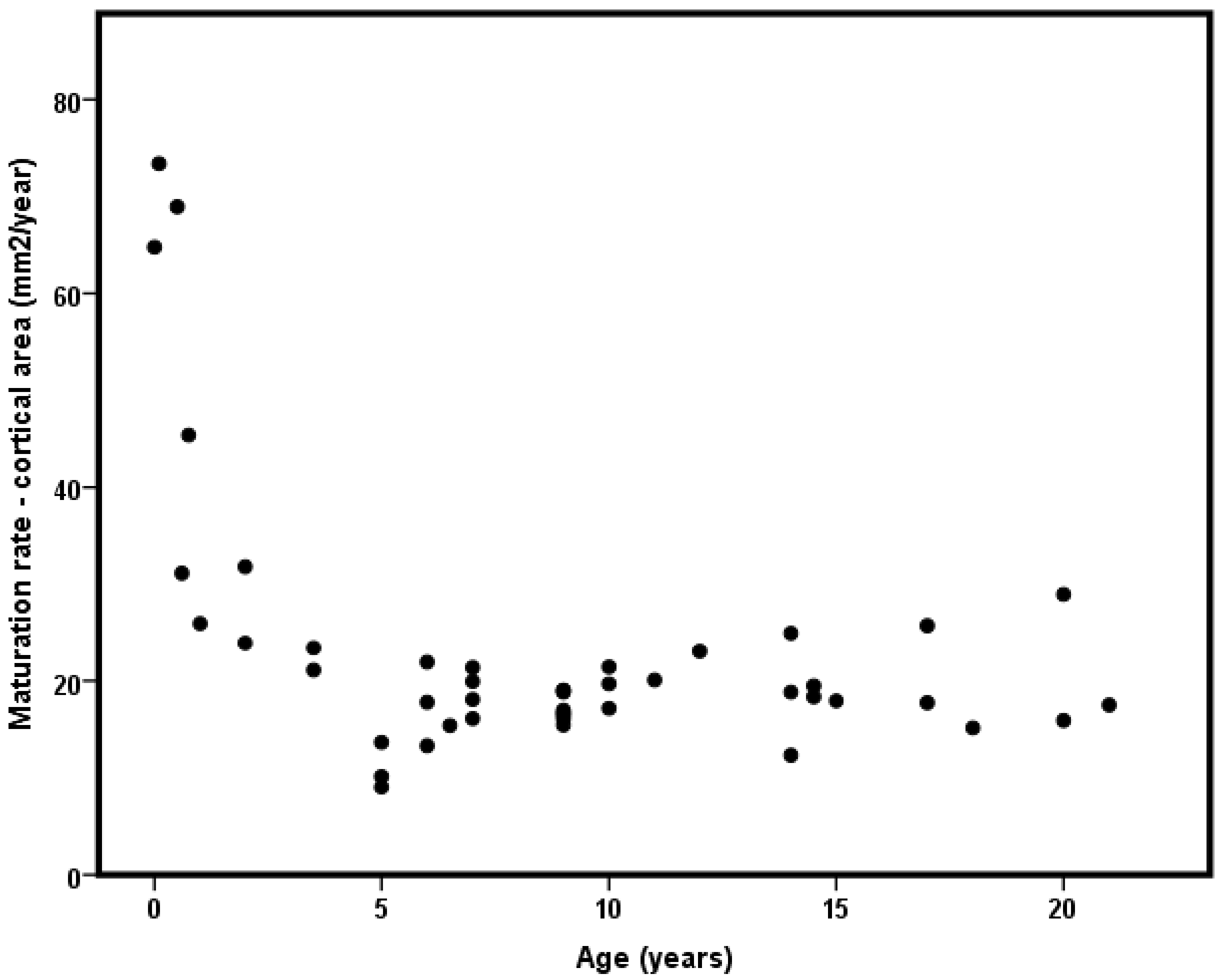

Figure 6.14: Maturation rate for cortical area (left) by age

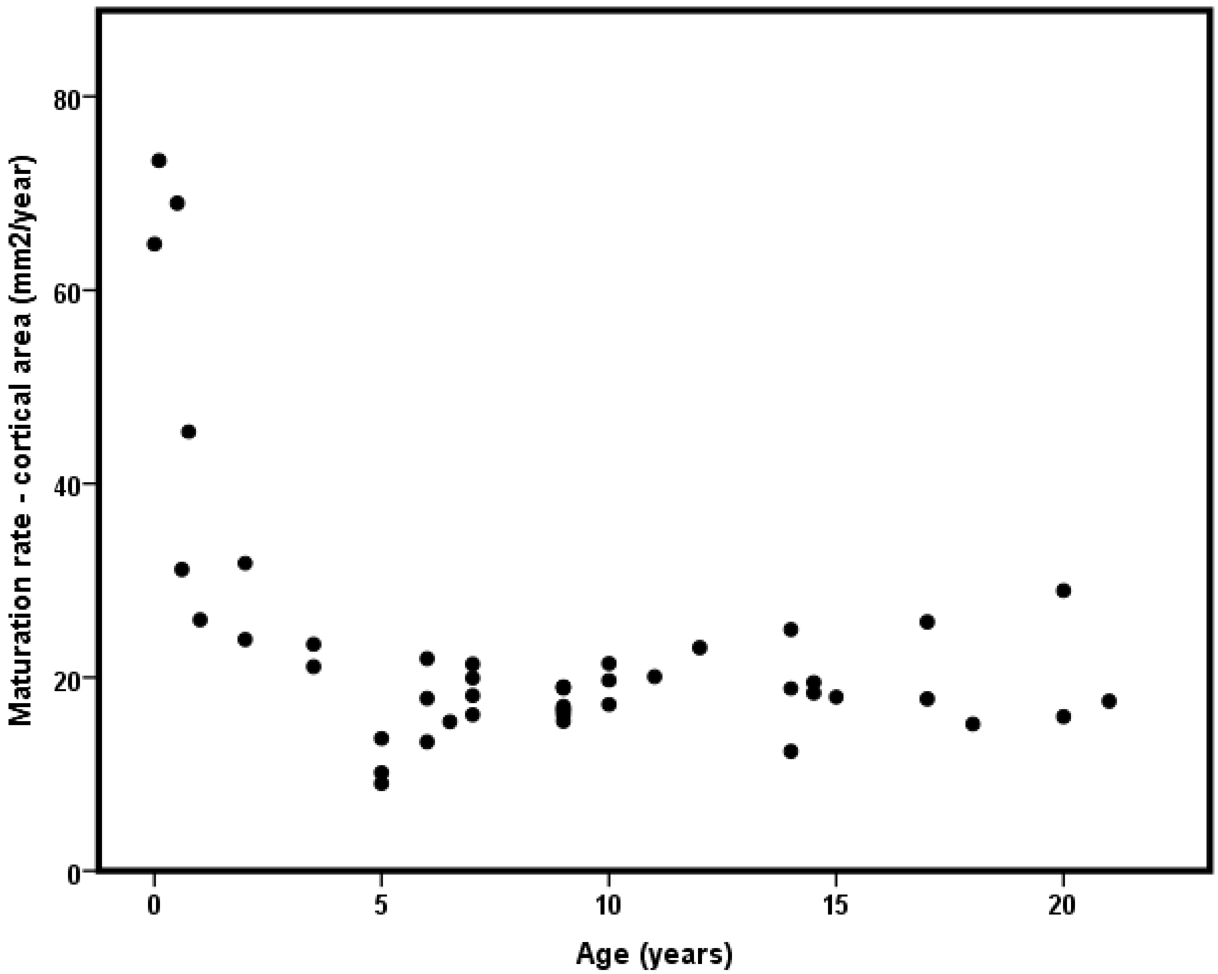

Figure 6.15: Maturation rate for medullary area (right) by age

To control for the influence of size and therefore age, the percentage of total cross-section occupied by cortical area (CT%) was calculated by dividing the cortical thickness area by the total area of the cross-sectional slice. Paired samples t-tests show no significant difference between left and right values for the femur (p=0.153) and the humerus (p=0.172). There was a significant difference observed in the 2nd metacarpal (p=0.024) with the left side, on average, 2.11% larger than the right. This difference could be skewed due to the very small sample (13 pairs). Figure 6.16 shows a slight increase in values in relation to age, particularly in the femur, but this relationship is not statistically significant as shown in Table 6.5. There is no clearly discernable pattern between values.

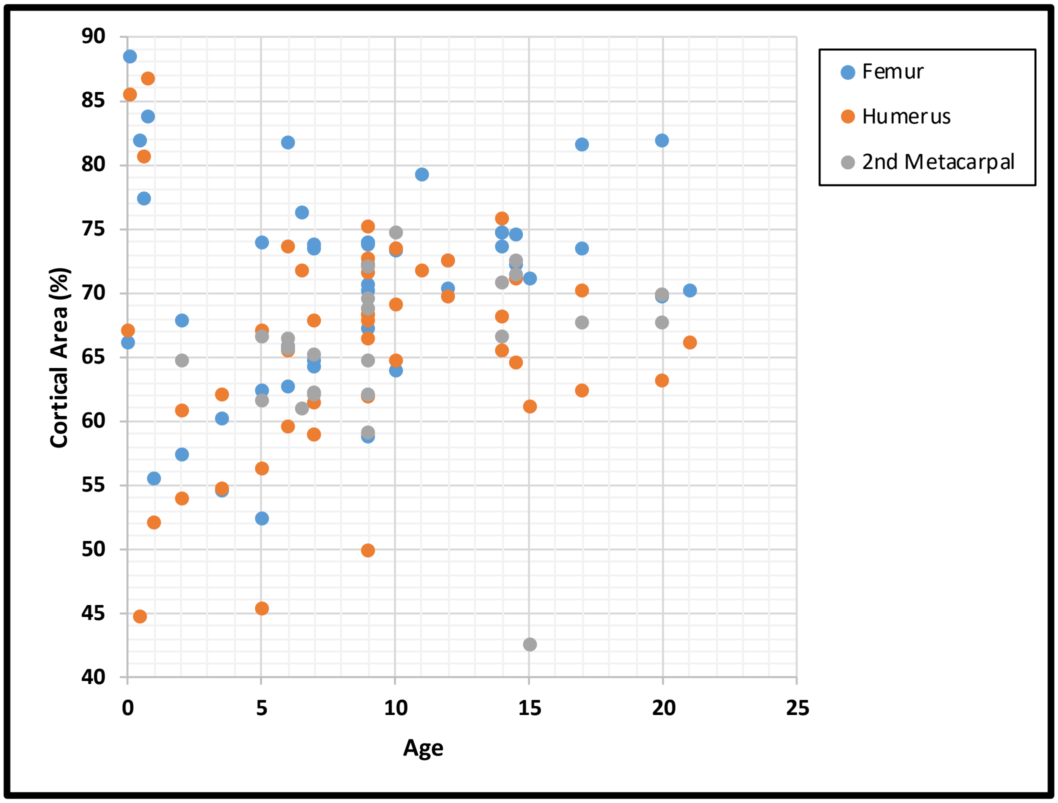

Figure 6.16: Distribution of cortical area (%) for the femur, humerus, and 2nd metacarpal based on estimated age (years)

There is a cluster of very widely ranging CT% values between the age of neonate until 5 years. This age group also displays the greatest range in values. There is no significant difference in CT% between sexes (p-values range from 0.94 to 0.686 when equal variances are not assumed). As with diaphyseal length, One-Way ANOVA tests indicate no significant relationship between cortical area or CT% for the femur, humerus, and 2nd metacarpal and time period (Table 6.6).

Table 6.5: Correlations between cortical thickness percentage (CT%) and age. For the femur, humerus, and age variables N=48. For the second metacarpal N=28.

		CT% - femur	CT% - humerus	CT% - 2nd metacarpal
CT% - femur	**Pearson correlation**			
	Sig. (2-tailed)			
CT% - humerus	**Pearson correlation**	0.685**		
	Sig. (2-tailed)	<0.001		
CT% - 2nd metacarpal	**Pearson correlation**	0.317	0.421*	
	Sig. (2-tailed)	0.123	0.036	
Age	**Pearson correlation**	0.258	0.157	0.233
	Sig. (2-tailed)	0.077	0.288	0.263

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

Table 6.6: Analysis of variance for cortical thickness percentages between different time periods

		Sun of squares	Df	Mean square	F	Sig.
CT% - femur	Between groups	85.798	3	28.599	0.400	0.754
	Within groups	5514.69	31	71.442		
CT% - humerus	Between groups	87.748	3	29.249	0.328	0.805
	Within groups	2767.88	31	89.287		
CT% - 2nd metacarpal	Between groups	30.375	3	10.125	0.747	0.546
	Within groups	149.11	11	13.556		

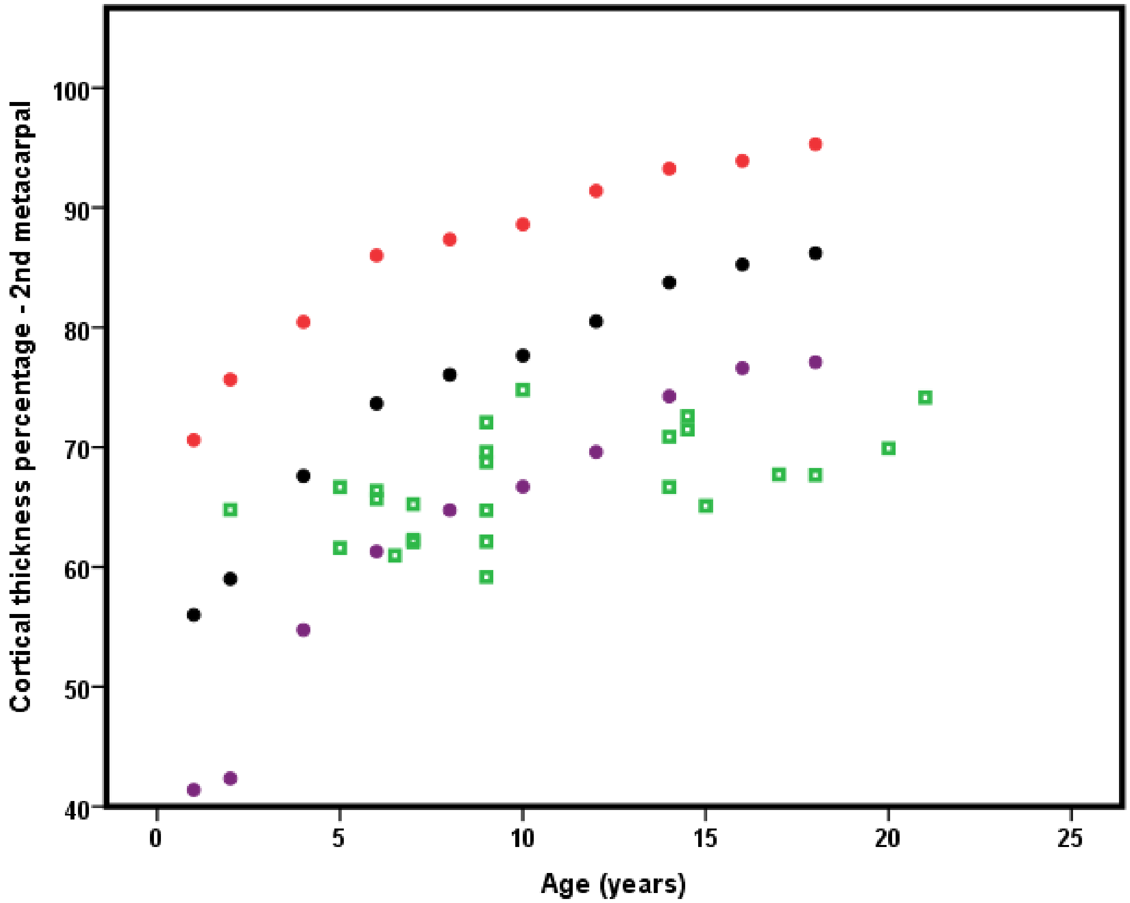

Figure 6.17: Average cortical thickness area percentage for the 2nd metacarpal for the combined Danish sample (green) compared to 5th (purple), 50th (black) and 95th(red) percentiles from the Fels longitudinal study

With the goal of comparing these Danish sites to genetically and temporally separated populations, the CT% was compared to values for the 5th, 50th, and 95th percentiles (averaged between sexes) from the Fels Longitudinal study (Garn, 1971) in Figure 6.17. Most of this archaeological sample falls in between the 5th and 50th percentiles values from Fels with others falling below the 5th percentile, showing far lower cortical thickness in this past population than in modern populations, particularly after the age of 10.

6.5 Pathological Lesion and Trauma

Individual SBT 403 demonstrated bowing of the tibia, fibulae, and a slight antero-posterior curvature to the femora; bone deformations consistent with rickets (see Figure 6.18). Rickets is the result of chronic vitamin D deficiency during the growing period (Roberts & Manchester, 2010). The absence of vitamin D limits the absorption of calcium and phosphorus and therefore impairs mineralization leading to softening of the bone tissue (Roberts & Manchester, 2010). The classic symptom of rickets is the bowing of the lower limb bones due to the impact of weight-bearing on the softened bone tissue. Only in severe cases are the bones of the upper limb impacted (Aufderheide & Rodriguez-Martin, 2011). The irregularities in bone deposition can impact the epiphyseal plate, leading to long-term deformities, often in the form of flared metaphyseal ends, and stunted linear growth (Aufderheide & Rodriquez-Martin, 2011).

Figure 6.18: Lower limb bones from Black Friars individual 403 showing bowing particularly in the tibiae and fibulae

As the cortical thickness data was based on a small sample, there were few examples of pathology or trauma that were observed within this sub-group. In addition to the potential rickets case, 1496 from Ole Wormsgade showed clear dental enamel hypoplasia, Black Friars 18 shows possible early signs of leprosy, and 551 from Black Friars experienced a crushing injury to a foot resulting in permanent deformity. Individual 403 already demonstrates signs of nutritional stress in the form of vitamin D deficiency and is a likely candidate for other manifestations of physiological stress. Looking at the diaphyseal length of the femur for age (Figure 6.19), this individual does not show evidence of long bone stunting. The same pattern is also observed in

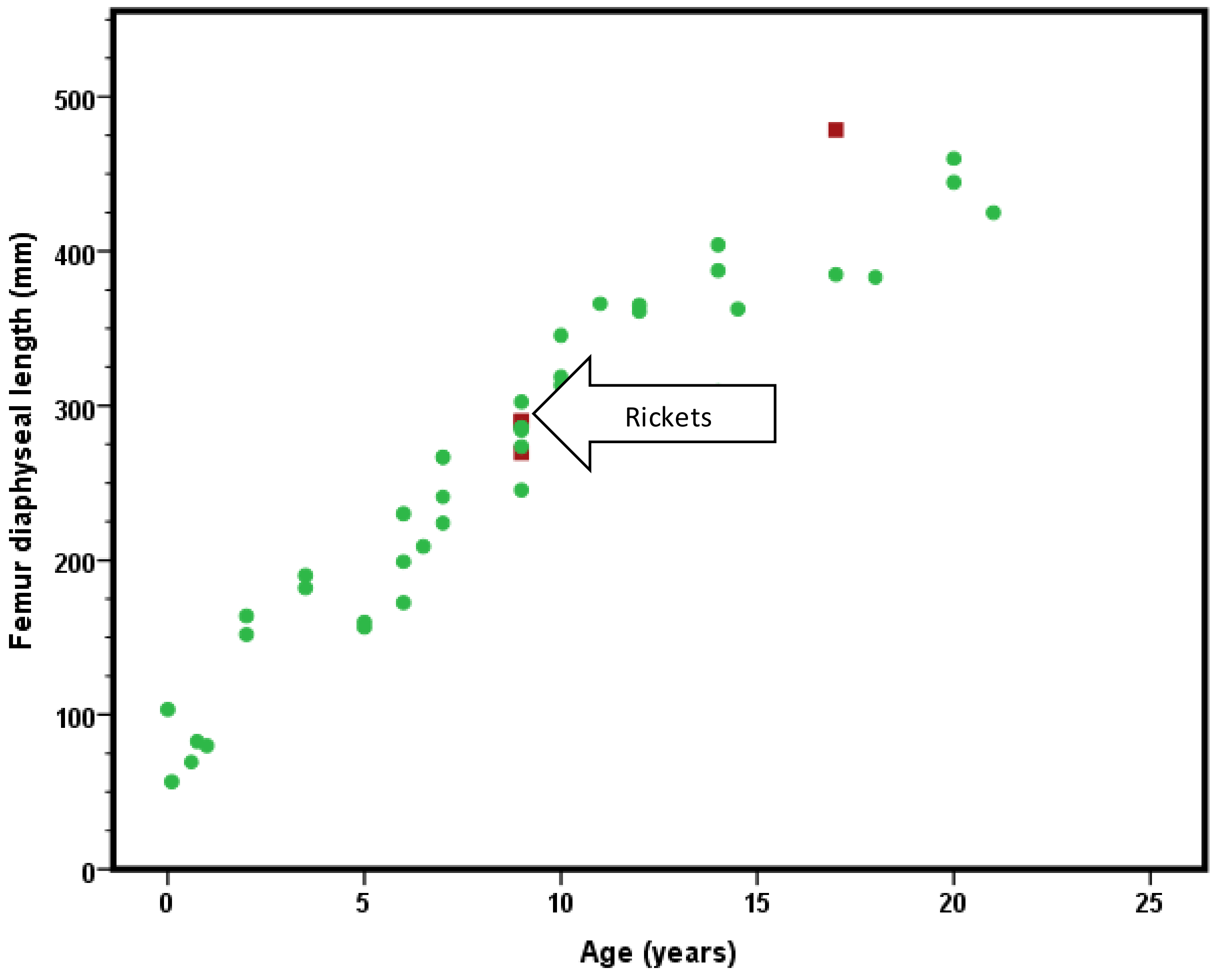

Figure 6.19: Femoral diaphyseal length (mm) by median age with SBT 403 individual, possible rickets case identified

the humerus. In cross-section the medullary cavity is centered and there is no obvious anomaly in the configuration of the medullary cavity or the cortical thickness that would suggest cortical drift. When observing the CT%, this individual displays very low values for both the humerus and the femur (see Figure 6.20). 2nd metacarpals were not preserved for this individual. Individual 551 has very high cortical thickness values but average diaphyseal length. The other examples of pathological cases show average values for age for both diaphyseal length and CT%.

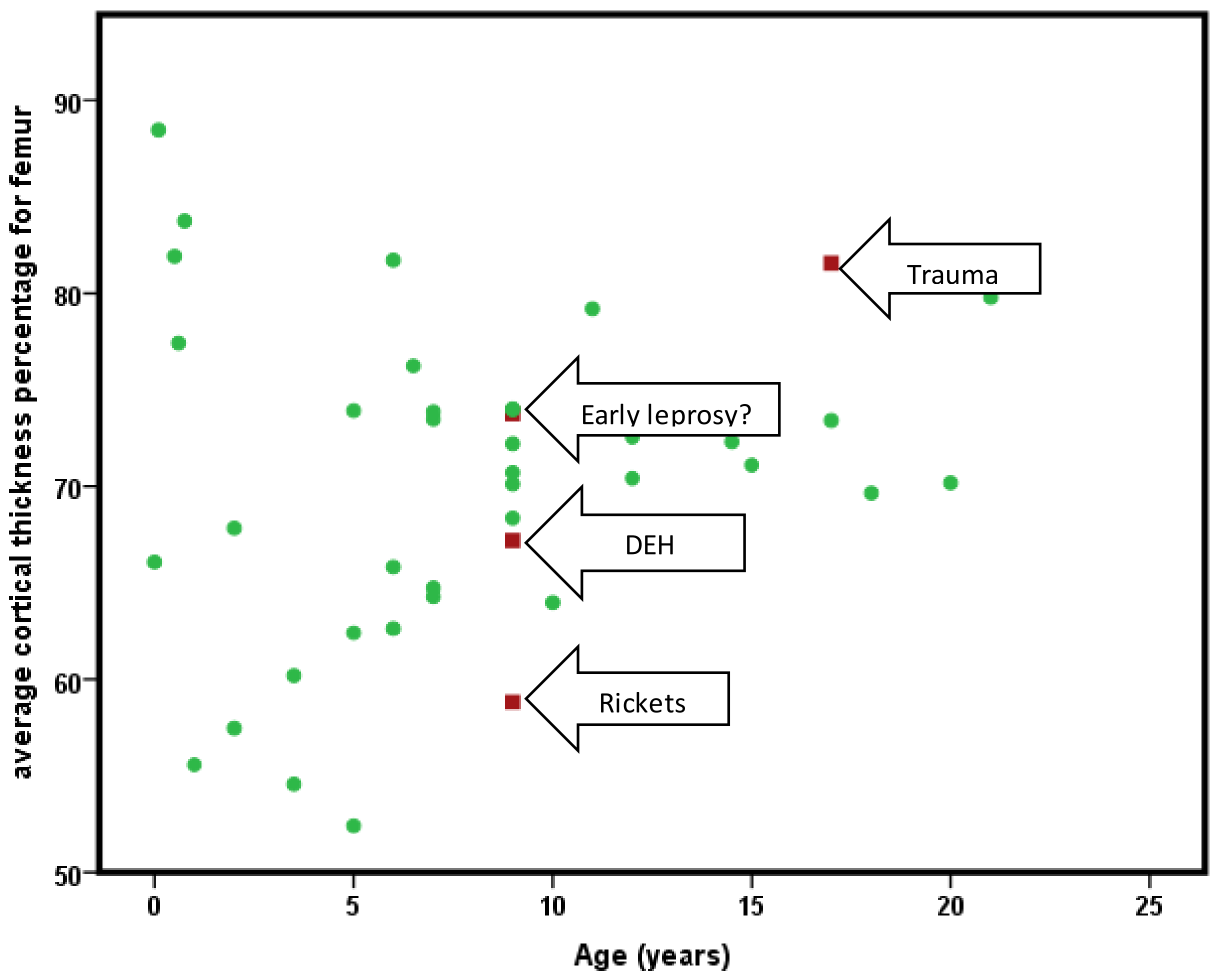

Figure 6.20: Average cortical thickness area percentage for the femur by age with pathological specimens highlighted

7. Discussion

7.1 Introduction

This study focused on childhood health. Children, particularly infants are notoriously underrepresented in the archaeological record. Guy et al. (1997) suggest that children under 1 year should represent 23-32% of the cemetery population during the Middle Ages although archaeological excavations typically report 0 to 24% for this demographic group. The presence of some well-preserved infants at all three cemetery sites suggests that infants were not completely excluded from burial in the cemetery area. The theoretically 'missing' infants may be absent from the records for various reasons including variations in burial treatment, differential preservation, or recovery bias. Unbaptized infants may not have permitted to be buried within consecrated burial grounds, and may have been buried outside the cemetery limits or received a different type of funerary treatment (Daniell, 1997). Black Friars and Klosterkirke show slight peaks in the infant age category, but these numbers are nowhere near the expected values. While Ole Wormsgade shows a normal distribution, this is not an expected pattern. Typical mortality distributions in an archaeological or undeveloped population should show high infant mortality. Paine & Boldsen (2008) observed that in an epidemic scenario, such as with the Black Death, there is high incidence deaths in older children and young adults as was observed in this sample. Black Friars shows a normal distribution for ages 2 to 19+ with a slight peak for infants. The majority of the total sample represents individuals aged from 8 to 13 years. Ole Wormsgade and Horsens Klosterkirke had low representation of children in general, both around 16% (Pederson, 2010; Tarp, 2010). Black Friars is closer to the expected levels of 50% (Chapeskie, 2006) with 40.5% under the age of 15 (Boldsen & Mollerup, 2006). These levels can be difficult to compare due to varying cut-off ages to identify subadults. There is no way to verify if the recovered remains characterize a representative sample of the populations they came from, however, based on Guy et al. (1997)'s finding, the number of children in these three cemeteries are very close to the anticipated levels and within range of typical archaeological reporting for the Middle Ages.

The temporal pattern in age distribution provides an interesting perspective. In the 1250-1450 time period there is very low infant mortality, with only 2.6% mortality represented by individuals under the age of 1. This rises to 26%, a number that would be expected in a pre-industrial society, in the post-1536 sample. The bulk of the deaths in 1250-1450 fall into the 8-13 and 14-18 age categories, each at 33.3% as described in Paine & Boldsen (2008). After 1536, the proportion older children remains similar, but the number of adolescents falls to 13%. The 1250 to 1450 time period spans over documented periods of famine, notably the 'Great Famine' from 1315 to 1322 (Hybel & Poulsen, 2007) as well as the Black Death epidemic which entered Denmark in 1349 (Christensen, 2003; Ziegler, 1988). The high level of mortality would explain the observed pattern of mortality age distribution. The low number of infants can also be tied to the previous finding of high adult female mortality in rural Danish communities (Boldsen & Paine, 1995).

The estimation of sex for juveniles is rarely undertaken, despite the important impact that sex has on growth and development patterns. Estimation of sex from skeletal remains is largely based on the development of secondary sex traits, especially those in the os coxa. In adults, sex determination is very reliable. Prior to adolescence, the features used are not clearly developed, however several studies have reported successful application of sex estimation methods on subadults albeit with less reliable results (e.g. Mittler & Sheridan, 1992; Schutkowski, 1993; Sutter, 2003; Weaver, 1980). Sex determination was attempted whenever the ilia and mandible were sufficiently preserved, which was the case for 148 individuals. There is a fairly equal distribution between sexes in the overall sample with 50% classified as male or probable male, 47% classified as female or probable female, and 3% that remained indeterminate. The Black Friars site showed the greatest imbalance in sex ratio with nearly double the amount of males as females with 62.5% males or probable males and 33.3% females or probable females. Bardsley (2014) discusses evidence of a pattern of gender imbalance in Medieval England. Multiple lines of evidence including poll taxes and archaeological remains, suggest that after the mid-13th century, there is a decline in the number of women (Bardsley, 2014). Bardsley (2014) proposes that fewer girls survived to adulthood, and if they did manage to survive childhood, they tended to die younger than males of the same cohort. The difference in mortality could be based on biological and cultural conditions. There may have been a cultural preference for boys, leading to infanticide of girls, or preferential treatment of boys such as prolonged lactation or greater access to food (Bardsley, 2014). The two individuals observed with evidence of nutritional deficiencies; the aforementioned case of rickets and one individual with pronounced dental enamel hypoplasias, were both determined to be males. At the time it was generally believed that women required less food than men (Bardsley, 2014). Since adult males do tend to be slightly larger and have greater muscle mass than women do, there is some truth to the suggestion that men would have greater caloric needs. However, for growing children any nutritional deficiencies could cause significant physical and developmental consequences. While this assumption was erroneous, that in itself is not an indication of parental neglect or preferential treatment towards boys. It has been suggested that women could also be more susceptible to disease and deficiencies due to the nature of their daily tasks; remaining indoors and getting insufficient sunlight exposure, treating and caring for family members who may be ill, etc (Bardsley, 2014). However, the growing body of research into the lives of women in Medieval Europe suggests that women did far more work outside the home than had previously thought (Jones, 2013). The division of labour was not a clear division between genders and rather was far more dependent on socioeconomic status with peasant women performing far more physical tasks outdoors (Jones, 2013). Boldsen and Paine (1995) observe increased adult female mortality in rural Medieval Danish cemeteries, almost double that of urban centers. To be able to observe this, clearly, adult women are well represented and numerous in the archaeological sample, a fact suggesting that female-specific infanticide would be unlikely. This high female mortality will in turn have an important impact on the community's fertility rate and therefore infant and child mortality. With less children being born, there would be less child deaths in general leading to a pattern like that observed in this study for the 1250-1450 period. Unfortunately, the cause of death is not known for this sample and it cannot be determined if the sex difference in mortality pattern is due to intentional actions or biologically founded susceptibility and mortality risk.

The imbalance in sex ratios could also be a result of error. Sex estimation in subadults is not nearly as reliable as it is in adults. These methods are based on secondary sex traits which become more evident and observable after adolescence. The sex estimation method used, Schutkowski (1993), has been found to perform better on males than females (Schutkowski, 1993; Sutter, 2003). It is therefore far more likely to misidentify females as males as opposed to vice versa. This might explain the slight imbalance with a greater number of males than females. While the difference in representation of sexes in the overall sample is not large, the slightly higher representation of male subadults over female subadults is a pattern that becomes more imbalanced as the stress burden increases (Saunders & Barrans, 1999). Females have been proposed to possess greater buffering abilities against physiological stress (Belcastro & Mariott, 2008; Chan et al., 1961).

Unfortunately, the sex estimates have limited use in studying growth patterns due to an unequal distribution of ages for each sex. The indeterminate category had the lowest average age at 7.25 years and had the smallest age range from neonate to 15 years. This is not surprising as the younger individuals are likely to be more challenging to classify as one sex or the other. For females there is a positively skewed age distribution with most individuals falling between the ages of 5 and 10 with average of 7.54 years and a range from neonate to 20 years. Males have a slightly higher range; from neonate to 21 years, but an average of 11.13 years. This sex-related difference in age could suggest variation in mortality risk, with the majority of female subadult deaths occurring in early to mid-childhood, while male subadults succumb later in mid-childhood nearing adolescence, a time when males have been found to be more vulnerable to illness (Lewis, 2007). The pattern observed in this sample does suggest some culturally-based preferential treatment towards maintaining male child health over that of female children, however this could be impacted by error in sex estimation, or sampling error.

7.2 Longitudinal Growth

The Medieval period was a time of considerable economic and demographic change throughout Europe. It has been expected that evidence of physiological stress and poor health should be particularly apparent during the 1250 to 1450 period due to widespread famine, the impact of disease, and the general shift in economic and subsistence practices. Growth evidence from Danish samples do not seem to reflect this anticipated pattern. There is no significant difference in femoral diaphyseal length between time periods. The growth trends all follow similar trajectories with the exception of the 1450 to 1500 period which show an earlier dip in diaphyseal length after the age of 20. This is likely simply an artifact of the small sample group for this time period. There is evidence of individuals who had experienced growth delays in all sites and all time periods.

Diaphyseal length reflects longitudinal growth and is used in skeletal assessment of age. Longitudinal growth is considered to be more vulnerable to stunting as a result of physiological stress than are other indicators of age and maturation. Dental age in particular, based on dental calcification and eruption patterns, is considered to be more representative of actual chronological age than is skeletal age. Both values were closely related, but a statistically significant difference was observed between dental and skeletal age. As would be expected given its resistance to physiological delay, dental age is more advanced than skeletal age by 0.41 years on average. The pattern of skeletal versus dental age variation is minimal during early childhood but becomes more evident around the age of 10. Some of this may simply due to incongruences in age estimation techniques, an average discrepancy of 0.41 years, especially after the first decade falls within the ranges of most age estimation methods for this age group. Nevertheless, it would be expected that at least some individuals are exhibiting the signs of physiological stress in the form of stunted growth. These results indicate the presence of growth stunting, but not a widespread or extreme experience of it.

The tempo of growth and maturation is as an additional measurement of childhood health that could indicate periods of stress and developmental delay (Buikstra, 1977). When represented against age, the maturation rate fluctuates throughout life. The pattern observed for this Danish sample reflects the anticipated pattern of high rates of maturation and growth in infancy which gradually decreases until early childhood, around the age of 5 here. A slight increase in the maturation rate in observed in adolescence, in this sample, between the ages of 15 and 17.5 which is consistent with the adolescent growth spurt. As this sample includes individuals of both sexes, the growth spurt is averaged between males and females. When looking at the sexes separately, females have a higher maturation rate than males in infancy and early childhood. Growth velocity for females slows around the age of 7, an age that typically does see a decrease in growth activity in healthy children, and then accelerates around the age of 13 as would be expected in the adolescent growth spurt. In contrast, the males do not demonstrate the expected typical pattern in growth velocity; it gradually decreases from birth until adulthood, with no noticeable peak indicating the adolescent growth spurt. These patterns in growth combines with the imbalance in age distribution between sexes suggests a cultural difference in the treatment of male and female children. Despite a slower growth velocity, the males tend to live longer than the seemingly healthier girls. This would be possible if parents are intentionally investing more resources into maintaining and preserving the health of males as has been suggested by Bardsley (2014) in Medieval England. A large disadvantage faced by archaeological studies of growth and development is that these constructed growth curves are composite of multiple individuals each represented at one static moment within their growth trajectory. Errors in age estimation or a lack of individuals within a particular age category will confound data and frequently obscure these short periods of time when spurts occur. The adolescent growth spurt, an important change in the growth process and in cultural identity was discernable from this sample and became more visible in females when sex estimations were applied. While sex estimation is not frequently undertaken in bioarchaeology, this is a very useful piece of information for growth studies. Larger samples including multiple individuals of diverse ages would better represent the growth trajectory and possibly allow to distinguish between the growth trajectories for males and females.

7.3 Body Size

Body size was estimated based on metaphyseal breadth of the distal femur, maximum breadth of the femoral head, and biiliac breadth in combination with long bone lengths using equations by Ruff (2007). The equations could be successfully applied to 52.4% of the total sample. There were challenges in obtaining good measurements of the biiliac breadth, which resulted in only including one body size estimate using this metric. The equations appear to perform appropriately in providing plausible results. In comparison to modern data from the WHO (2006), the Danish sample falls in between the 5^{th} percentile and the median. If the body size estimations are accurate, this would mean that this past population is largely below modern averages in terms of body size. Given the effects of the secular trend that has lead to an increase in body size and stature since the 1850s, as well as widespread increase in overweight and obesity in modern populations, this result is not surprising and would not necessarily suggest that individuals in medieval Denmark were experiencing drastic wasting. The Ruff (2007) equations themselves are derived from a modern reference sample which could introduce bias when applied to archaeological samples. There were no differences between time periods, therefore there is no evidence of particular hardships or chronic wasting during a specific time frame. These values would need to be compared to standards from their own time period for better context. In the absence of such records, perhaps future comparison with other contemporaneous samples would provide added perspective.

7.4 Epiphyseal Fusion

The timing and progression of epiphyseal fusion is an aspect of maturation that can indicate developmental delay whether due to physiological stress, trauma, or other external factors. Epiphyseal fusion is much less susceptible to developmental delay than is longitudinal growth and appears to be more consistent between populations. Among the locations observed, epiphyseal fusion is noted as early as the age of 4 on the vertebral bodies and on the sacrum. In many locations fusion can begin as late as the third decade such as on the clavicle and iliac crest. These age markers perform their best during late childhood and adolescence as most changes occur during those years, however there is a great deal of variation in ages and progressive fusion at certain locations. This sample included individuals aged from birth up until 21 years.

Table 7.1: Comparison of epiphyseal results from Schaefer and Black (2007) and the current Danish sample in the appendicular skeleton

	Schaefer and Black (2007)		Danish sites	
	Last non-fusion	First fusion	Last non-fusion	First fusion
Med clav	23	21	21	-
Acromion	18	17	21	9
Prox hum	20	18	18	20
Dist hum	14	15	14	14
Prox rad	18	16	21	14
Dist rad	19	17	18	20
Prox ulna	18	15	15	15
Dist ulna	20	17	21	16
Iliac crest	20	18	21	17
Ischial tub	18	17	18	-
Fem head	18	15	18	16
G trochan	18	15	16	16
L trochan	18	15	17	16
Dist femur	19	17	21	16
Prox tibia	18	17	17	16
Dist tibia	18	16	18	16
Prox fib	18	17	21	-
Dist fib	18	17	17	19

None of the individuals observed had all epiphyses fully fused. Based on other research (McKern & Stewart, 1957; Schaefer & Black, 2007) 21 would be the earliest age at which most epiphyses would be fully fused. The patterns of epiphyseal fusion for all time periods and cemetery sites were consistent with each other. The results were also compared to observations made by Schaefer and Black (2007) on a sample of 258 Bosnian males of known age from a modern context. The patterns of epiphyseal fusion observed in this Medieval Danish sample is highly consistent with the patterns Schaeffer and Black (2007) observed in the Bosnian males (Table 7.1). Paired t-tests found no significant differences in age of last non-fusion (p=1.00) or age of first full fusion (p=0.621) for the Bosnian sample compared to this Danish sample. The differences noted are largely due to this Danish sample covering a younger group of individuals than the Bosnian one. Additional sources of variation include the presence of both males and females in this sample and the use of estimated age. The similarities between this past population and a genetically distinct modern population show how the patterns of epiphyseal fusion remain quite constant despite changes that have occurred in growth and body size patterns especially in recent years.

7.5 Cortical Thickness

Diaphyseal length of long bones is a standard measurement in studies of growth and development. Stunting of stature, observed by proxy in the stunting of long bones, is interpreted as a sign of non-specific physiological stress. A comparison of cortical area versus diaphyseal length illustrates that both values are highly correlated and increase together as both longitudinal and appositional growth occur concurrently. The rate of size increase in cortical thickness occurs quite steadily in the humerus and 2nd metacarpal. The femur displays a slightly more accelerated pattern after the age of 7. Some consideration must be made for the increasing contribution of the linea aspera to total area and cortical thickness of the femur which becomes more prominent in late childhood (Scheuer & Black, 2000). The increasing size of the linea aspera would therefore contribute a growing proportion of the total area of the femur while no equivalent landmark would do so on the humerus or the 2nd metacarpal.

Garn (1971) noted that cortical thickness increases steadily with age until the 5th decade. This pattern is observed in this sample of individuals for the entire age range from neonate to young adult. As age increases, the range in values observed increase as well. With age, there is greater potential for natural variation as increasing environmental factors can impact the resulting phenotype. Growth patterns do vary between sexes; however, no significant difference was found between sexes in this sample. Duren et al. (2013) did not observe significant sexual dimorphism in bone thickness until the adolescent growth spurt had occurred,

O'Neill and Ruff (2004) note minimal error rates when using a casting method or measuring cortical thickness from radiographs for the tibia and femur. Casting yielded average standard errors of 4-9% while measurements from X-rays had average standard errors from 7-16%. The impact of these deviations from true cross-section are largely dismissed since most of the error resulted from estimations of the medullary cavity and this structure is not significant in studies of biomechanical strength (O'Neill & Ruff, 2004). There is value in having more precise measurements of cortical area and general dimensions of the medullary cavity in assessing growth, development, and the impact of stressors on these biological processes. Reduction of bone strength and physical integrity can be caused by a reduction in the deposition of periosteal bone or by increased loss of endosteal bone. By simply observing the external circumference and total area of the bone ignores the changes than may be happening within the medullary cavity. There is also possibility of cortical drift which can indicate imbalances in the system and can suggest the presence of certain pathological disorders such as osteogenesis imperfecta. While the methods of measurement discussed by O'Neill and Ruff (2004) are accurate, images obtained using CT are better approximations of true cross-sections if such imaging tools are available and accessible. Both cortical and medullary areas were assessed for this sample. Medullary and cortical area are highly correlated and follow a close to linear relationship. In the femur, the cortical area increases in size quicker than the medullary cavity due to the added impact of the linea aspera. In the humerus and the 2nd metacarpal, medullary area continues to increase, while the cortical area eventually slows its size increase. These changes in size are predominantly based on age-related changes. Both cortical and medullary area show an accelerated level of size increase as adolescence approaches, although cortical area increases much quicker than does medullary area. As with longitudinal growth, there is a changing tempo in the levels of growth for both the cortical and medullary areas. As observed in Garn (1971) both cortical and medullary area see high rates of size increase around the time of birth which then gradually decrease. A secondary increase in the growth rate occur in adolescence. This adolescent growth spurt seems to occur slightly later in appositional growth than in longitudinal growth. In the medullary cavity, this growth spurt occurs between the ages of 10 and 21, but peaks around the age of 16. For medullary area, this growth spurt is subtler, remaining fairly constant from about late childhood, peaking around and tapering off in the early twenties.

Asymmetry in cortical area was observed in the humerus, but not in the femur or 2nd metacarpal. There was an average increase in cortical area on the right side by 3.48%. Lateralization becomes more pronounced after early childhood. The increase in asymmetry in humeral cortical thickness occurs around the same age that children would be attending school and writing or regularly performing some sort of work (Orme, 2001). During the Medeival period, schooling was largely limited to the upper classes, however by the age of 7, most middle and lower-class children were regularly assisting with household chores and may even have been working outside the home or undertaking apprenticeships (Orme, 2001). Regular repeated work, weather it manual labour, tapestry work, or writing would influence muscle development and eventually alter bone morphology. The observed patterns are consistent with previous findings of bone circumference and length (Čuk, Lebon-Seljak, & Štefančič, 2001), although the difference seen in bone area is more pronounced than either bone circumference (2.1%) or bone length (1.4%) in 42 adults (Čuk et al., 2001). While an unanticipated finding, these results suggest that humeral cortical thickness may be useful in identifying handedness. Cortical thickness will be influenced by biomechanical loading, as evidenced by the differences observed in the left and right humerus, however, the ability of the body to deposit bone in response to greater mechanical load and stimulation will still be related to health.

A ratio or percentage of cortical thickness versus total bone cross-section allows to control for the influence of size and age. When these values are compared to age, other patterns that are not dependant on age become more discernable. There is a slight increase in CT% values with age, but this relationship is not statistically significant. One interesting observation is the great range in values of CT% for neonates including a cluster of very high values. A possible explanation for this is that these individuals thrived, reaching optimal growth while in utero. Since they did not survive long after birth, they were not subject to physical wasting experienced by children that survived for longer periods of time. No significant difference was found between left and right elements for %CT in the femur or humerus. A significant difference was observed in the 2nd metacarpal with the right bones averaging at 66.01% and the left at 68.12%. The 2nd metacarpal is the most widely used skeletal element for investigations of cortical thickness. Previous work (Agarwal et al., 2011; Ives & Brickley, 2004) has not identified significant asymmetry. This could be due to a very small sample size of 13 pairs or could suggest morphological changes due to preferential use of one hand over the other.

CT% of the 2^{nd} metacarpal for this Medieval Danish sample was compared to the 5^{th}, 50^{th}, and 95^{th} percentiles from the Fels Longitudinal study for the same measurement as reported by Garn (1971). The Fels Longitudinal study was and remains a large-scale longitudinal study sampling various health-related measurements in an American population. The archaeological data falls largely below the 50^{th} percentile of the modern sample. A large proportion even falls below the 5^{th} percentile. The Fels data is based on 25,000 individuals and represent a modern sample, which has been described as well-fed and robust, even within a modern context (Garn, 1971). There are many potential confounding factors impacting cortical thickness data from Fels, including the fact that researchers only measured the 2^{nd} metacarpal and that this was done based off of X-rays. There could easily be variation in the measurements due to different data collection techniques. The 2^{nd} metacarpal data for the Danish sample consists of only 38 bones (13 pairs) and therefore represents just 25 individuals. Comparing the Danish data to a contemporaneous sample would provide better contextual insight into the health status of this sample.

Among the sub-sample of individuals used for CT scanning there were few examples of trauma or pathological lesions. Individual 403 from Black Friars displays deformity of the lower limbs consistent with rickets, a nutritional deficiency caused by inadequate vitamin D. From Ole Wormsgade there was one individual with pronounced dental enamel hypoplasias. Black Friars had two other individuals of interest; one with possible early signs of leprosy, and a second with crushing trauma to a foot which would have caused permanent deformity at the time. The dental enamel hypoplasia and rickets are both nonspecific indicators of stress. When observing the femoral and humeral diaphyseal lengths by age for these individuals, none deviated from the average trend, showing no evidence of longitudinal growth stunting. When these same individuals were observed for CT% of the femur and humerus, the individual with rickets demonstrates extremely low values for age. While this is only based on one case, this individual appeared to have average values and no evidence of growth stunting when looking at long bone length and yet appositional growth measurements highlighted this individual due to below-average values. Pinhasi et al. (2006) also observed no significant difference in long bone length when comparing subadults with or without evidence of rickets. This finding is consistent with the suggestion that cortical thickness could be a more sensitive indicator of stress than longitudinal growth (Hatch et al., 1983; Mays, 1995; McEwan et al., 2005).

Cortical thickness as assessed using cortical area and CT% provided an additional perspective of the growth and development process. Observations followed the patterns of age-related change noted in clinical (Garn, 1971; Duren et al., 2013) and archaeological (Mays, 2001) studies. Cortical area asymmetry is observed in the humerus, likely due to handedness, but this does not have an important impact on CT% of the same bone. The 2nd metacarpal had more variable values and was more difficult to measure in this archaeological sample. The femur provided clearer trends and relationships with age, sex, and maturation. This element is also more likely to be preserved in an archaeological context and is easier to measure. This research suggests that cortical thickness provides added insight into growth and development in past populations, the femur is likely the best bone the measure, and CT scanning provides greater perspective into the actual mechanisms of appositional growth and stress.

8. Conclusions

8.1 Summary of Findings

The main research objective of this study was to assess childhood growth and development in Denmark over the Medieval and postmedieval periods. This was done using a multifactorial approach, examining growth and development using multiple facets of these complex physiological processes. By incorporating measurements of longitudinal growth, body size, maturation, and appositional growth, a more complete picture of the physiological childhood experience is obtained, providing a more nuanced view of the impact and severity of stress during this time in history.

In addition to an overall perspective of childhood health, this research also contributes a test of the potential use of 3D imaged cortical thickness as an indicator of physiological stress on a population level. To date the use of cortical thickness has largely been limited to X-rays, usually in clinical settings. When CT scanning is used in archaeological studies, this is typically in application to evaluate biomechanical structures or for comparative anatomy between humans and other hominids.

Specific research questions were developed and presented in Chapter 1 based on the individual aspects of growth and development that were used for study. The first objective looked at longitudinal growth in diaphyseal length, evidence of stunting, and temporal variation. Skeletal age based on diaphyseal length was delayed in comparison to dental age. The difference between the two is statistically significant with an average delay of less than half a year. While these findings suggest a degree of delay in longitudinal growth, the difference between values is not drastic, and does not indicate widespread physiological hardship. While it was not included within the scope of this study, it would be interesting to look at adults in the population to assess the potential impact of catch-up growth on survivors. When comparing growth trends for all temporal periods, a significant difference was observed, but this is likely an artifact of the disparity in age distribution. There was no difference in maturation rate between the three archaeological sites. All sites and time periods show a close adherence to a linear relationship between diaphyseal length and age with a few individuals falling slightly below that trend. This illustrates same occurrences of delay, but not a widespread pattern of devastation. This would suggest that the growth patterns of the population as a whole were not greatly impacted by the documented socioeconomic changes or that perhaps children were provided with added protection due to sacrifices by their families, indicating their cultural value in society. The cultural value and protection afforded towards children was not uniform. Sex-related differences were observed in the age of death as well as the maturation rate in long bones. The pattern emerging from these lines of evidence suggest that males were given a degree of preference to help ensure and prolong survival.

Body size was estimated using regression equations developed by Ruff (2007). The equations could be used on more than half of the sample and provided plausible measurement of body size. The values for these Danish samples fell between the 5th percentile and the median of modern data collected by the WHO (2006). This suggests that body size during the Medieval and postmedieval periods was below modern averages. With growing rates of overweight and obesity in modern society, these discrepancies are not surprising. Comparing the Danish samples based on time period, there was no significant difference. No time period provides evidence for increased wasting in comparison to the others, illustrating a consistent level of food, specifically calorie access throughout the assessed time frame.

The timing and sequence of epiphyseal fusion reflects skeletal maturation. While longitudinal and appositional growth demonstrate an increase in size, maturation represents the progressive achievement of adult form. Maturation is far more resistant to developmental delay that longitudinal and appositional growth and shows less heritability. No difference related to time period was observed. In fact, the sequence and values for epiphyseal fusion observed in these Danish collections are consistent with those observed in a postmedieval English population (Beauchamp, 2008), a modern North American population (McKern,and Stewart, 1957), and a modern Bosnian population (Schaeffer and Black, 2007). These findings emphasize how consistent the developmental skeletal changes are, despite genetic and large temporal differences.

The existing body of literature suggests that appositional growth as represented by measures of cortical thickness are more effective indicators of growth stunting that the long-used standard of diaphyseal length and longitudinal growth (Hatch, et al., 1983; Mays, 1995; McEwan et al., 2005). The observation of one individual with evidence of rickets that had normal diaphyseal length for age, but abnormally low values for cortical thickness percentage is consistent with previous findings. Cortical thickness has been found to be a viable indicator of physiological stress. Given the complex nature of health, growth and development, and physiological stress, a multifactorial approach to these is beneficial. The incorporation of cortical thickness as a regular measurement would add an extra tool to learn more about past populations. The use of 3D images obtained using CT are beneficial in that they avoid potential error due to estimation and approximation of the medullary cavity as is required in the use of X-rays. While the size of the medullary cavity tends to increase consistently with cortical thickness, variation can occur as a result of genetic conditions such as osteogenesis imperfecta or due to stress-induced asymmetry (Albert & Greene, 1999). The humerus is not an ideal bone to use to measure stress-based variation in cortical thickness since it demonstrates asymmetry, likely as a result of preferred hand use. The femur and 2nd metacarpal performed very well. The 2nd metacarpal is the bone most frequently used in clinical settings and therefore has a wealth of literature and standards developed based on it. For the purpose of an archaeological sample, the femur has greater representation and preservation rates and would be the preferred element for measurement of cortical thickness.

Based on current findings, the picture we obtain of health and life during the Medieval and Early Modern periods in Denmark varies somewhat from what has been expected based on the general trends observed in Europe. Temporal changes in age at death distribution indicate that there was increased mortality in the 1250-1450 time period during which famine and the Black Death were known to have impacted Scandinavia. However, looking at growth and maturation, there is no time-specific pattern influencing physiological stress responses. This deviation in Denmark and Scandinavia in general is not entirely surprising. Since human occupation in Europe, Scandinavia has found itself in the margins, partly due to its geographic isolation. This pattern would persist well into the Medieval period (Andrén, 1989b). Not only was contact and cultural dissemination constrained, the environment in which Scandinavian people lived was very different from the rest of Europe; they inhabited a different ecological zone and had access to different resources. The most important of these resources was fish and other marine sources of nutrition, which likely helped supplement any shortages experienced during times of agricultural struggle. While the emphasis is typically placed on agriculture and the impact of cereals (Fagan, 2000; Grove, 1988), not even peasants were fully reliant on cereals as sources of food and income (Hoffmann, 2014). These observations concur with more recent opinions that the ‘Late Medieval Agrarian Crisis’ and the many hardships described from the Middle Ages may not have been quite as severe or widespread as had been previously believed (Hoffmann, 2014). These patterns also tie into larger questions within bioarchaeology concerning hidden heterogeneity. There were clear time-related changes in mortality, but no evidence of growth delay or stunting, suggesting that death occurred quickly before a stress response could occur.

8.2 Future Research

This current study is limited in that it focused on childhood health in two urban Danish centers. The observations made may not accurately reflect those of people living in more rural areas who were likely more dependant on agriculture for food and therefore more susceptible to the ecological and economic changes documented during this time period. The focus on subadults also limits the measurements to those of non-survivors who may not be representative of those who survived into adulthood. Wider sampling to include adults from the same population as well and adults and subadults from rural populations would provide a more complete view of the situation in Denmark during the Middle Ages and the postmedieval period.

Cortical thickness is a valuable source of information about both the growth process and the impact of physiological stress. To date, there has been limited use of appositional growth to study health in past populations and none using 3D imaging. As a result, most standards for comparison come from clinical data, and therefore represent very different population groups. To date, no large-scale studies have conducted inter-population comparisons of cortical thickness and appositional growth. This would be a necessary task to undertake before the widespread application of cortical thickness as a proxy for health variation can be applied to studies of past populations. While stunting in longitudinal growth is an important reflection of health during the growth period, it is one part of an extremely complex picture. The more elements are measured and incorporated together, the closer researchers can get to an accurate representation of life in the past.

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