Title: Bone Strength in Medieval Denmark: robusticity analyses from a rural and urban sample

Authors:

Parker, Kaela – University of Manitoba

Larcombe, Linda – University of Manitoba

Stock, Jay T – Western University

Boldsen, Jesper L – University of Southern Denmark

Marx, Heidi – University of Manitoba

Hoppa, Robert D – University of Manitoba

Abstract

Objectives: The aim of the current study was to understand the transition in lower limb loading and terrestrial mobility during the urbanization revolution in medieval Denmark. This was accomplished by comparing the cross sectional geometric properties of the femora from two populations, the rural cemetery of Tirup and the urban Black Friars cemetery.

Materials and Methods: Using two skeletal samples, the rural cemetery of Tirup, Jutland (1150-1350 A.D.), and the urban Black Friars cemetery, Funen (1240-1607 A.D.), cross sectional geometric properties of the right femora were examined. The cross sectional geometric properties of adult long bones are reflections of *in-vivo* loading. General patterns of relative mechanical loading during life can be interpreted by calculating the cross sectional geometric properties of a long bone's diaphysis. Compressive and tensile rigidity and strength (CA), maximum and minimum bending rigidity (I_{min}, I_{max}), torsional rigidity (J), bending rigidity along the anteroposterior and mediolateral axes (I_x, I_y), and diaphyseal shape (I_{max}/I_{min}; I_x/I_y) at the femoral midshaft were calculated from 104 CT scans, 48 from Tirup (32 males, 16 females) and 56 from Black Friars (38 males, 18 females).

Results: The results indicate significantly greater robusticity among the Black Friars sample for both males and females.

Discussion: In opposition to the prevalent understanding of physicality in medieval communities, the results suggest that lower limb loading (and inferred terrestrial mobility) was greater in the urban setting. Cemetery make-up and population variation between the samples cannot, however, be discounted.

Key Words: Bone functional adaptation, biomechanics, medieval, Denmark, rural vs. urban

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The medieval period in Denmark was a time of population urbanization, climatic cooling, and changing socio-economic and religious conditions. The medieval period began with the transition to Christianity around 1000 A.D. (Hybel and Poulsen 2007). This transition led to an overall improvement in health and life expectancy (Benedictow 2003) but also curtailed much of the freedom previously enjoyed by Viking women (Sawyer and Sawyer 1993). The medieval period can be broadly separated into two sub-periods, the early medieval period (ca. 1050-1350 A.D.) and the late medieval period (ca. 1350-1536 A.D.). The early medieval period was characterized by agricultural development, population expansion, stable weather patterns, and dramatic urbanization (Hybel and Poulsen 2007). As the early medieval period closed, the climatic downturn of the Little Ice Age (1300-1850 A.D.) led to a decline in health (Steckel, 2004), a decrease in food security (Jordan 1996), and an increased susceptibility to disease (DeWitte and Wood 2008). The early medieval period culminated with the demographically catastrophic Black Death epidemic (1349-1350 A.D.) (Hybel and Poulsen 2007). The late medieval period continued until the Protestant Reformation (1536 A.D.) and was characterized by urban expansion, dissatisfaction with the power of the Catholic Church, and increased social stratification (Benedictow 2003; Hybel and Poulsen 2007).

Skeletal morphology is affected by many factors (Ruff et al. 2006). While the principles behind bone functional adaptation are complex (Pearson and Lieberman 2004), there is significant evidence linking mechanical loading during life to the cross sectional distribution of cortical bone (Roblin et al. 2000; Ruff et al. 2006; Shaw and Stock 2009a, 2009b; Stock et al. 2013). *In vivo* loading applied to bone can, therefore, be estimated by examining a bone's cross sectional geometric properties (Ruff 2008). Robusticity, or the overall strengthening of a skeletal element through the addition of bone tissue (Stock and Pfeiffer 2004), is largely linked to habitual physical activity during life (Ruff 2008). In general terms, mechanical loading puts strain on long bones which activates bone deposition, while decreased strain leads to bone resorption (Ruff et al. 2006).

To analyze loading in long bones in past populations, bioarchaeologists commonly employ mechanical beam theory, modelling the long bones as cylindrical beams. While mechanical loading situations experienced in life are much more complex that those modeled in beam theory, this type of analysis allows for the interpretation of relative loading during life (Liebermann et al. 2001; Ruff et al. 2006; Ruff 2008). The analysis of cross sectional geometry to evaluate physical activity has been applied to understanding subsistence strategies (e.g. Ruff 1987a; Stock and Pfeiffer 2004; Wescott 2006), mobility patterns (e.g. Macintosh et al. 2015; Stock 2006; Weiss 2003; Wescott 2006), activity patterns (e.g. Bridges 1989; Rhodes and Knüsel 2005), behavioural patterns (e.g. Ruff 1999; Ruff and Larsen 2001), and the sexual division of labour (e.g. Ogilvie and Hilton 2011; Ruff 1987a; Saers et al. 2017; Wescott 2006).

Lower limb robusticity has primarily been used to examine variations in terrestrial mobility (Davies and Stock 2014; Holt 2003; Larsen 2015; Macintosh et al. 2014; Ruff 1987a, 1994a; Shaw and Stock 2013; Sládek et al. 2006; Stock 2006; Stock and Pfeiffer 2004; Stock et al. 2011; Wescott 2006) with specific emphasis on the variations noted between hunter-gatherers and agriculturalists. Previous research has noted significant decreases in torsional rigidity (Larsen 2015) and anteroposterior bending strength and rigidity of the femoral shaft (Ruff 1987a; Ruff and Larsen 1990; Ruff et al. 1984) suggesting that terrestrial mobility decreased with the onset of agriculture. Additionally, the circularity of the shaft has been used to analyze mobility. A less circular lower limb diaphysis has been linked to increased mobility among past populations and long-distance runners as ground reaction forces are predominantly in the anteroposterior plane, leading to more anteroposteriorly elongated femoral (Ruff 2010) and tibial shafts (Shaw and Stock 2009, 2013).

Using the cross sectional geometric properties of the right femoral midshaft, the current research will examine robusticity differences between individuals living in rural and urban medieval Denmark. Very little research has investigated the differences between agriculturalists and early urban environments. The aim of this research is to position lifestyle in medieval Denmark within this transition from rural to urban living. The research will address the question of whether the rural Danish sample was more robust than the urban sample. Williams et al. (2018) found a significantly a higher prevalence of degenerative joint disease among European medieval farmers when compared to craftsmen which they attributed to the intensive, repetitive loading experienced by farmers, a finding that was paralleled by Croft et al. (1992) in contemporary farmers and urban controls. In an analysis of upper limb robusticity from medieval England, Mays (1999) found that rural males and females presented significantly more robust upper limbs than their urban contemporaries. According to Mays (1999) this indicated that medieval rural living was significantly more physically demanding than urban living. While Holt et al. (2018) noted greater tibial robusticity among urban females than among rural burials in Europe from the Iron Age to Modern period, the broad time periods used obscure any strictly rural versus urban patterns. According to Holt et al. (2018), urbanization did not significantly affect bone morphology in historic Europe. However, the authors caution that samples with a clearer rural/urban distinction are required to clarify whether the patterns seen in their study are accurate. When comparing pre-industrial Dutch skeletal samples, Saers et al. (2017) found that differences in femoral and tibial robusticity tended to be site specific rather than illustrating a clear rural-urban dichotomy. The authors note, however, that the variation in cross sectional geometric properties was greater in the urban sample, suggesting a wider range of tasks undertaken in towns. Meizner et al. (2019), when comparing robusticity in medieval and early modern rural sample, noted that agriculturalists who undertook cereal crop cultivation were more robust than those who farmed cattle. Danish medieval farming would have been highly physically demanding with males sowing, plowing, and harrowing fields as well as tending to cattle and horses (and sometimes pigs) (Hybel and Poulsen 2007; Poulsen 1997). Women, on the other hand, would have been in charge of tending to the gardens and milking the cattle (Hybel and Poulsen 2007). Cattle raising became increasingly important throughout the medieval period as a major export industry and economic activity (Hybel 2000; Poulsen 2004). Historical evidence also suggest that females helped out in the fields during harvest time (Sawyer and Sawyer 1993). On top of the actual physical labour undertaken on medieval farms, Hybel and Poulsen (2007) estimate that medieval farms would have averaged approximately fifteen hectares. From this we can intuit that medieval agriculturalist would have been highly mobile, regularly loading their lower limbs as they traversed and worked the fields. Given the intensity of farming, it was hypothesized that the rural sample would be more robust that the urban sample.

Materials and Methods

Adult lower limb robusticity was examined in two archaeological populations from medieval Denmark: the rural cemetery of Tirup (ca. 1150-1350 A.D.) and the urban Black Friars cemetery (ca. 1240-1607 A.D.). The Cemetery Collections are currently housed at the ADBOU Laboratory Facilities, curated by the University of Southern Denmark with permission to study the skeletal material granted by ADBOU and the University of Southern Denmark. The cemetery of Tirup was unearthed in Eastern Jutland, immediately west of the medieval town of Horsens (Boldsen 1984a; Keiffer-Olsen 1993). Usage of the rural cemetery spanned ca. 1150 until 1350 A.D. when the cemetery was abandoned (Milner et al. 2015), a common practice during this time period (Hybel and Poulsen 2007). Individuals interred in Tirup would have been exclusively peasants who engaged in agricultural labour. Work on a medieval Danish farm followed the seasons and was a year round commitment (Hybel and Poulsen 2007). Hybel and Poulsen (2007) overview a year on a medieval Danish farm. The year began with plowing the field in May. By ca. 1000 A.D., Medieval Danish farms employed the heavy moldboard plough to cultivate fields (Hybel and Poulsen 2007; Poulsen 1997). While horses and oxen were used to pull the plow through the soil (Hybel and Poulsen 2007), individuals working the farms were required to walk behind and guide the plough (likely walking several kilometers per day) (Graessle 2018). Oats were sown in late May. Dung was then spread over the fields in late June. Haymaking took place between June and August. Barley and oat fields were harvested in late August. Harvesting was undertaken with a sickle, hay was gathered using hayforks and rakes, sheaved, and transported to barns. Finally, threshing lasted from late November into January of the following year (Hybel and Poulsen 2007). On top of the physical labour associated with farming grain, many farmsteads also raised animals (Hybel and Poulsen 2007). Strenuous physical labour would have been central to rural medieval living in Denmark (Hybel and Poulsen 2007). Both males and females would have undertaken habitually strenuous physical activity on Danish medieval farms (Milner et al. 2015).

The urban cemetery, Black Friars, was located on the periphery of the medieval town of Odense on the island of Funen (Becher 1999). During the medieval period (ca. 1050- 1536 A.D.), the Dominican Friars themselves would have made up a proportion of the burials. The remainder of the cemetery would have housed secular burials (Jakobsen 2008). The Black Friars or Dominicans arrived in Scandinavia in 1223 A.D., remaining for the next 300 years (Jakobsen 2008; Orrman 2003). The Dominicans actively recruited well-educated young men from the social elite (Bennett 1937). As a mendicant, or begging order, vows were taken to abstain from property ownership, leaving the friars dependent on the goodwill of lay people (Jakobsen 2008). The friars spent their days in pursuit of knowledge and conversion (Bennett 1937). In order not to detract from their theological duties, the friars themselves were exempt from manual labour (Singman 1999). Lay brothers were pious labourers who performed manual tasks for the monasteries (Singman 1999; Toke 1913). Lay brothers would also have been interred in the Black Friars cemetery.

The inclusion of women and children among the burials demonstrates that secular burials also existed within the Black Friars cemetery. In Denmark during the medieval period, it was customary to be buried within one's local parish cemetery. As such, the Black Friars cemetery would have housed members of all social strata from peasant to the social elite; however, there was a notion that interment in a "beggar" cemetery meant greater divine attention in the afterlife (Jakobsen 2008). As such, it is possible that a higher proportion of the secular burials would have been those of the middle and upper class who could afford to pay for the closeness to God (the Church) (Jakobsen 2008, 2019). That being said, archaeological evidence seems to suggest that the in Odense, the Franciscan monastery, Greyfriars, was the chosen burial ground for the social elite (Johannsen et al. 2001).

The Black Friars cemetery was in use well into Denmark's early modern period. In order to compare results with the rural cemetery, only individuals interred during the medieval period were included in this analysis. Burial date was estimated using arm position (Kieffer-Olsen

1993), burial location within the cemetery (Mollerup and Boldsen 2010), and relative dating carried out at excavation (Nielsen 1982a, 1982b; Urth 1978). A more in-depth description of the archaeological dating procedure is provided in Parker (2019).

Sex was determined using standard osteological techniques (Buikstra and Ubelaker 1994; Phenice 1969). Age-at-death was estimated using transition analysis as described by Milner and Boldsen (2012) and Boldsen et al. (2002). Transition analysis relies on the premise that skeletal changes associated with aging are unidirectional and that by employing statistical methods (logistic regression and Bayes' Theorem), age-at-death can be more precisely estimated than when using conventional age-at-death estimation techniques (Milner and Boldsen 2012).

Diaphyseal robusticity analyses were undertaken on all complete, well-preserved right adult femora. Adults over the age of 50 years-at-death were excluded from the analysis to limit bias associated with age-related changes in cortical bone (See Frost 2003 for an overview). Given the symmetry between the right and left femora (Auerbach and Ruff 2006), if the left femora exhibited better preservation and completeness than the right, it would be used instead. However, no individual met this criteria and only right femora were included. Individuals exhibiting macroscopic indications of pathology that would affect the size and shape of the femora were excluded. In total, 104 CT scans, 48 from Tirup (32 males, 16 females) and 56 from Black Friars (38 males, 18 females) were included in the analysis. Of the total sample, 199 individuals were excluded, 91 from Tirup (55 males, 36 females) and 108 from Black Friars (62 males, 46 females). The majority of exclusions were due to preservation and completeness issues.

Femora were scanned with a Siemens SOMOTOM Spirit® Computed Tomography scanner, housed at the Institute of Forensic Medicine in Odense, Denmark. Bones were placed on the scanner bed in an anteroposterior position as they appear in standard anatomical position and scanned from proximal to distal end. Scans were taken at 3mm increments, with a pitch of 2.0, and an effective mAs of 30. Scans were processed and reoriented around repeatable axes (see Ruff 1981) using MIMICS medical imaging software version 19.0. The midshaft slice was then selected and exported into the open-source image analysis software ImageJ, using the BoneJ plugin (Doube et al. 2010), for geometric analysis. The midshaft slice calculated as the 50% point between the most proximal point of the greater trochanter (selected for ease of slice placement in the MIMICS program) and the midpoint between the distal epiphyses. Several studies use the femoral midshaft to calculate femoral robusticity (See Holt 2003; Holt et al. 2018; Larsen et al. 1995; Macintosh et al. 2014; Maggiano et al. 2008; Ruff 1987b, 1994b, 1999; Stock 2006; Stock and Pfeiffer 2004). Misplacement of the midshaft point can significantly affect cross sectional geometric calculations (Ruff 2000; Sládek et al. 2010). Sládek et al. (2010) caution against including elements into a cross sectional analysis if the midshaft point cannot be estimated within 14 to 20 mm. In order to limit error locating the 50% point, only femora where slice location could be accurately calculated, those with intact greater trochanters and distal epiphyses, were included. Bones exhibiting minor damage that did not affect measurements of the midshaft slice were included.

Cross sectional geometric properties examined for this project include cortical area (CA), medullary area (MA), percent cortical area (%CA), second moments of area (I_{min}, I_{max}, I_x, and I_y), and polar second moments of area (J) (Table 1). A bone's ability to resist failure (fracturing) is referred to as strength; its ability to resist bending prior to failure is known as rigidity. Cortical area, or the cross sectional area of a long bone's diaphysis, is a measure of rigidity and strength in axial compression and tension. As bone is rarely subjected to compression and tension alone, second moments of area measure bending rigidity, while torsional rigidity, a bone's ability to resist bending while torsional or twisting forces are applied, is measured as a polar second moment of area (Ruff, 2008). The distribution of the bone about the maximum and minimum axes can be understood through a shape ratio (I_{max}/I_{min}). The shape of the bone around the x and y axes (I_x/I_y) was also calculated. Percent cortical area is a measure of the total cross sectional area compared to medullary area of bone (Ruff 2008).

Physical activity and muscle loading are not the sole determinants of skeletal robusticity. Long bone length and body mass will also affect bone's cross sectional geometry. Stress is increased in longer bones as bending moments, measured as the force at a particular point multiplied by the distance between the point and the origin of the force, are increased, while body mass (also a mechanical load) increases load magnitude (Ruff et al. 1991). In order to control for these effects, size must be accounted for. Following Ruff (2008), size was standardized for cross sectional areas using body mass and for second moments of area using body mass by limb length squared. Physiological femoral length was measured using an osteometric board. Physiological femoral length is measured by placing both femoral condyles on the base of an osteometric board and measuring to the most proximal point of the femoral head (Raxter et al. 2006). Body mass was estimated using an average from femoral head diameter equations devised by Ruff et al. (1991), McHenry (1992), and Grine et al. (1995). It is generally agreed that in the absence of a complete skeleton averaging body mass estimates from these three equations provides the most accurate body mass approximation (Auerbach and Ruff 2004; Elliot et al. 2016; Pomeroy and Stock 2012). As the shape of bone (I_{max}/I_{min}; I_x/I_y) is represented as a ratio, standardization is not required.

Cross sectional geometric properties were compared by sex for the Tirup (rural) and Black Friars (urban) cemetery samples. Only maximum second moments of area (I_{max}) were normally distributed and, as such, independent sample t-tests were used to compare them. Other measures of bone geometry (CA, MA, %CA, I_{min}, I_x, I_y, J, I_{max}/I_{min} and $1_x/1_y$) had skewed distributions and, thus, were compared using non-parametric Mann-Whitney U tests. Table 2 presents the results for the Shapiro-Wilk Test of Normality. Statistical analyses were conducted in IBM SPSS version 25.

Results

Rural versus urban body proportion differences:

Mean femoral length and body mass estimates are presented in Table 3. The rural sample was significantly taller (based on femoral length) than the urban sample for both males and females. Interestingly, body mass was significantly greater among the urban sample. This suggests that the urban sample was shorter and stockier than the rural sample.

Rural versus urban differences in strength:

Summary statistics for the femoral midshaft rigidity are presented in Table 4. Figures 1 through 4 illustrate the variation in femoral rigidity (size-standardized I_x, I_y, I_{max}, I_{min}, and J) and femoral shape (I_{max}/I_{min}) between Tirup and Black Friars. When compared to rural males, urban males presented significantly greater bending rigidity along the anteroposterior and mediolateral axes (size-standardized I_x and I_y; Fig. 1). The same pattern was seen between urban and rural females. Additionally, both urban males and females (Black Friars) presented significantly greater minimum and maximum bending rigidities (size-standardized I_{max} and I_{min}) when compared to the rural sample from Tirup (Fig. 2). Females displayed a much greater change in rigidity along the maximum axis (size-standardized I_{max}). This likely lead to the significant difference in cross sectional shape (I_{max}/I_{min}) noted in females but not in males (Fig.3). Females from Tirup exhibited significantly more circular shafts than those interred at Black Friars. Males and females from the Black Friars sample also presented significantly higher torsional rigidity (size-standardized J) at the femoral midshaft than their rural contemporaries from Tirup (Fig.4). Again, the difference was greater among females than among males. A similar pattern, with the urban sample presenting greater size-standardized cortical areas than the rural sample, was noted in males and females, however the results were not statistically significant at $p<0.05$. Taken together the data indicate that the rural sample was more gracile than the urban sample.

Rural versus urban differences in cortical bone and medullary area:

When percent cortical area was compared between the samples, the rural sample exhibited a greater amount of cortical bone than the urban sample. However, the differences between mean percent cortical area were not significant for either males or females. While size-standardized cortical area was greater among both males and females from Black Friars (not significant), an even greater increase in size-standardized medullary area (not significant) led to the decrease in percent cortical areas between the rural and urban sample.

Discussion

Given the high intensity of labour and incredible physical demands associated with medieval farming, it was hypothesized that robusticity would be greater among the rural sample when compared to the urban sample. In the current analysis, lower limb loading among the urbanites was markedly higher than among their rural contemporaries. Although the difference in cortical area (size-standardized) was not statistically significant at $p<0.05$, the higher measures of bending and torsional rigidity (size-standardized I_x, I_y, I_{max}, I_{min}, and J) observed among the urban group, considered more relevant indicators of mechanical loading in life (Ruff 2010; Stock and Pfeiffer 2004), were statistically significant. The higher rigidity along the anteroposterior and mediolateral axes (size-standardized I_x and I_y), as well as torsional rigidity (size-standardized J) and greater minimum and maximum bending rigidities (size-standardized I_{min} and I_{max}), suggest that lower limb loading, inferred to represent terrestrial mobility, was greater among the urban sample. The data does not support the hypothesis that the skeletal samples from the rural cemetery would be more robust than those interred in urban cemetery.

There are several possible explanations as to why the Tirup and Black Friars cemetery populations do not conform to the hypothesis: 1) the rural-urban dichotomy, as it refers to individuals living in Denmark during the medieval period, is perhaps overstated, with individuals from urban setting also living highly physical and strenuous lifestyles; 2) the Dominican Friars were outliers within their wider population, having unique levels of mobility; 3) better urban lifestyles lead to stronger bones; 4) genetic variation between the populations affected limb proportionality.

Interpreting rural versus urban differences in medieval Denmark in terms of a strict is dichotomy may be slightly problematic. First, the possibility that individuals living in rural areas were relocating into urban spaces (and thus interred in urban cemeteries) cannot be discounted. The medieval period in Denmark was a time of population influx from rural to urban centers with population size increasing dramatically throughout the early medieval period (Hybel and Poulsen 2007). In fact, ongoing analyses by one of the authors (JB) suggest that as many as 75% of all people buried in urban cemeteries in Viborg, Jutland, were immigrants from surrounding areas. Second, at least among the labourers, urban living may have had similarities to rural living, with both urban and rural families working land plots. Holt et al. (2018) cautiously suggest that the lack of difference in rural and urban limb robusticity in their European sample may reflect similar levels of physical activity between rural and urban communities. However, the current study seems to suggest that individuals buried in the urban Black Friars cemetery were more terrestrially mobile, or, at the very least, loaded their lower limbs more significantly than those interred in Tirup. In part, the difference in robusticity may be a result of different types of loading among urbanites and farmers. A proportion of the males interred in the Black Friars cemetery would have been lay brothers, who were charged with the monastery's manual labour (Singman 1999; Toke 1913). Secular males interred in the cemetery could have found work in physically demanding trades such as potters, smiths, ship builders, carpenters, shoemakers, skinners, bakers, and butchers (Hybel and Poulsen 2007). Urban females may also have found work outside of the home, some in very physically demanding positions, such as laundresses, builders, and ferry workers (Jacobsen 1983).

The cross sectional shape about the x and y axis is significantly more circular in the males interred in Black Friars, possibly suggesting a decrease in terrestrial mobility among the urban males (I_x/I_y) when compared to the males interred at Tirup (Table 4). However, given that the other indicators of robusticity suggest that the rural sample was less robust, decreased terrestrial mobility among the Black Friars males seems unlikely. It is possible that the shape ratio of the shaft along the x and y axes is a result of greater mediolateral bending during horse riding and not a decrease in terrestrial mobility. The significant increase in mediolateral bending rigidity (size-standardized I_y) supports this conclusion. Throughout the twelfth century, the Danish aristocracy adopted the European courtly and chivalric culture, meaning that males actively pursued skills in horsemanship and knighthood (Corsi 2014). The lower limb muscles, specifically the adductors and extensor muscles of the hip, are actively engaged during horse riding which would have affected femoral robusticity. Historical documentation suggests that secular burials in Dominican cemeteries may have been skewed towards the middle class and social elite (Jakobsen 2008, 2019). As such, it is possible that horsemanship was more prominent among those interred in the Black Friars cemetery. This may also explain why the same change in shape (I_x/I_y) is not seen among the females interred in Black Friars when compared to rural females. That being said, based on archaeological evidence from cemeteries around Odense, the Greyfriars cemetery, and not the Black Friars, seems to have been the preferred burial location for the social elite (Johannsen et al. 2001).

As a portion of the urban males would have been Dominican Friars, their inclusion in the sample may have biased the analysis away from the "urban reality". Holck (2007) found that the Dominican Friars interred at St. Olav's monastery in Oslo, Norway, exhibited significantly higher bone mineral density than the comparative rural population. According to Holck (2007), the bone density maintenance among the friars was an indication of physicality, suggesting that the friars led more physically demanding lifestyles than farmers. This is at odds with the historical literature on the lifestyle of the Dominican Friars (Hinnebusch 1960, 1975). That being said, for much of their adult lives, the friars were required to walk long distances in pursuit of conversion (Singman 1999). Hinnebusch's (1960: 449) assertion that the friars went out into the world “two by two, on foot, penniless, begging for bread” seems to indicate a high level of terrestrial mobility in the order. This, however, does not fully explain the differences in robusticity as strength and rigidity were significantly higher in both urban males and females. Unfortunately, very little information has been published on the day-to-day lives of Danish females in the medieval period.

Another factor that may have played a role in the urban and rural variation in robusticity was the socioeconomic status of the cemetery populations. The expansion of urban centers during the medieval period in Denmark was paralleled by an increase in social stratification, a relatively unheard-of entity in rural medieval communities (Andersson 2003). In their analysis of height discrepancies in Scandinavia, Werdelin et al. (2002) found that urbanites had significantly longer lower limbs (which they interpret to indicate taller stature) than their rural contemporaries. Werdelin et al. (2002) argued that the differences in stature reflected the importance of urban areas as administrative centres. Urban centres, especially smaller ones, would have housed a higher proportion of individuals of high social standing (Werdelin et al. 2002). It should be noted that in their study, where differences in limb length versus total stature were controlled for, Boldsen and Søgaard (1998) found no evidence of greater stature in urban communities when compared to rural settings. Sparacello et al. (2011) interpreted increased robusticity in Iron Age Samnite males from Italy as an indication of status as weapon use was mediated by status. However, in medieval Europe, from a strictly biomechanical perspective, higher status individuals would likely be less robust as strenuous physical labour was generally undertaken by the poor. That being said, the differential availability of resources between the peasants and the middle class cannot be fully discounted.

How different access to resources affects bone strength is debated. According to recent research (Chevalley et al. 2009; Pando et al. 2014; Yingling and Khaneja 2006), in cases of under nutrition, bone cannot reach optimal strength. Even when malnutrition is rectified and catch-up growth ensues, evidence indicates that full bone strength recovery is unachievable (Chevalley et al. 2009; Pando et al. 2014; Yingling and Khaneja 2006). If this were the case, it may explain the discrepancies seen among the rural and urban samples. The Black Friars sample may have been of higher socioeconomic status than the rural cemetery. The Black Friars themselves were often recruited as young men from elite families (Bennett 1937) and thus may have had greater access to resources during skeletal development, leading to higher bone deposition. Additionally, a higher percentage of lay burials in the Black Friars cemetery may have been those of the middle class or elite (Jakobsen 2019). Populations experiencing nutritional stress lose cortical bone mainly from the endosteal surface (thus increasing the medullary cavity; Garn et al. 1969). An analysis of mean percent cortical area can be cautiously interpreted as indicative of similar nutritional stress in the two samples. If nutritional stress were affecting the populations differently, differences in the ratio of medullary area to cortical area would be expected. This was not the case between Black Friars and Tirup. No significant differences existed in medullary area ($p_{\text{males}} = 0.498$, $p_{\text{females}} = 0.075$) or the ratio of medullary area to cortical area ($p_{\text{males}} = 0.183$, $p_{\text{females}} = 0.202$). However, without correcting for fertility patterns and age distribution, which is outside the scope of this analysis, a simple comparison of percent cortical area to assess nutritional deficiency between the rural and urban sample is overly simplistic. Historical literature also suggests that the early medieval period was a time of flourishing harvests, abundant resources, and general good health in Denmark; even the poorest peasant could subsist off of the land (Anderson 2011; Fagan 2000). Furthermore, the link between malnutrition and bone strength has been disputed (Galusca et al. 2008; Lambert et al. 2005; Temple et al. 2013).

Another explanation for the robusticity differences between the samples is the effect of population variation. Boldsen (1990a) has suggested that rural communities in medieval Denmark would have been quite insular leading to relative genetic isolation. Throughout the medieval period trade routes expanded, enticing merchants from around Europe to move to Denmark to capitalize on the thriving trade economy. The influx of genetic material, specifically Dutch and German, would have influenced the gene pool in urban centers (Boldsen 1990a; Lockhart 2007). This phenomenon has been noted as it pertains to height disparities around Denmark and Sweden (Boldsen 1990a; Boldsen and Kronborg 1984; Werdelin et al. 2002). It is possible that the genetic variation leading to differences in physique between the two populations is, at least in part, responsible for the variation in robusticity between the two samples. Genetic factors have an influence on bone shape, both directly and indirectly (Ruff et al., 2006). While the extent to which genetics affects skeletal plasticity is still poorly understood (Pearson, 2000), research on mice has shown that genetics play a role in base level bone robusticity and bone's sensitivity to mechanical loading (Akhter et al. 1998; Kodama et al. 2000; Robling and Turner 2002; Wallace et al. 2010). While standardizing for size mitigates the effect of genetic differences and differences in physique, research indicates that differences in robusticity may not be completely accounted for by standardizing for body size (Akhter et al. 1998; Kodama et al. 2000; Robling and Turner 2002; Wallace et al. 2010).

Furthermore, it has been observed that Danish skeletal material deviates from other populations in limb proportions, making estimates of stature from long bone length inaccurate (Boldsen 1984b, 1990b; Boldsen and Søgaard 1998). In particular, body proportions vary considerably both within and between populations both contemporarily and in medieval Denmark. The possibility that the same is true with the body mass estimation calculations cannot be discounted. While the body mass estimation equations used in the current analysis have been shown to perform relatively well, at least among males (Auerbach and Ruff 2004; Eliot et al. 2016; Pomeroy and Stock 2012), their accuracy has not been systematically tested on Danish material. It is well known that there are significant differences in body proportions between areas in Denmark (i.e. long bone lengths against body height measured in the grave varies dramatically from site to site; Boldsen 1990b). Ruff et al. (2012) discussed how the mismatching of body proportions between reference and target samples, whether by region or time period, can introduce significant bias into an analysis. It is possible that the variation in robusticity between the urban and rural sample is a reflection of an overestimation of body mass in the rural sample or an underestimation of body mass in the urban sample. Given the likelihood that the urban sample is comprised of greater population variation, the possibility that the body mass estimation equations do not perform equally well for both samples is not outside of the range of possibility. This would lead to discrepancies in the size standardized data. Add to this that there is a relationship between lean mass and robusticity. Given that there is a significant difference in body proportions (both body mass and femoral length) between the two samples, the surprisingly high size-standardized robusticity among the urban sample may have been influenced by factors such as variation in body composition and musculature. The influence of these factors is currently untestable.

Conclusion

This study suggests that lower limb loading was greater in the urban medieval sample (Black Friars) when compared to its rural contemporary (Tirup). The significantly higher bending and torsional rigidity may be indicative of increased terrestrial mobility in both urban males and females when compared to their rural contemporaries. Without an analysis of upper limb loading, it is difficult to ascertain whether this indicates a true variation in loading intensity or simply differences in loading type. The greater robusticity among the urban sample can be understood through greater population variation within the urban community, as well as through socioeconomic, occupational and body proportion differences among the rural and urban samples. The inclusion of the Dominican Friars within the urban cemetery sample may also have skewed the data for urban males, as the friars likely pursued high levels of terrestrial mobility.

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Table 1

Description of cross-sectional geometric properties and shape ratios.

Variable	**Abbreviations**	**Biomechanical relevance**
Cortical area	CA^a	Compressive/tensile strength
Medullary area	MA^a	Area of the medullary cavity
Percent cortical area	%CA	Percentage of cortical area relative to total area
Second moments of area about:		
Maximum axis	I_{max}^a	Maximum bending rigidity
Minimum axis	I_{min}^a	Minimum bending rigidity
Anteroposterior axis	I_x^a	Anteroposterior bending rigidity
Mediolateral axis	I_y^a	Mediolateral bending rigidity
Polar second moment of area	J^a	Torsional and twice average bending rigidity ($I_{max}+I_{min}$)
Shape ratio	I_{max}/I_{min}	Distribution of bone along the minimum and maximum axes
	I_x/I_y	Distribution of bone along the x and y axes

CA = mm^2; all second moments of area and polar second moments of area = mm^4; descriptions from Ruff and Hayes (1983), Ruff (2008), Stock and Macintosh (2015). a: indicates all values that have been standardized for body size

Table 2

Results from the Shapiro-Wilk Test of Normality

Test	**W**	**df**	**p-value**
CA^a	0.960	100	**0.004**
MA^a	0.934	100	**<0.001**
%CA	0.920	100	**<0.001**
I_{min}^a	0.925	100	**<0.001**
I_{max}^a	0.982	100	0.195
I_x^a	0.964	100	**0.008**
I_y^a	0.950	100	**0.001**
J^a	0.963	100	**0.007**
I_{max}/I_{min}	0.905	100	**<0.001**
I_x/I_y	0.974	100	**0.0047**

a: indicates all values that have been standardized for body size; bold indicates significance at $p<0.05$.

Table 3

Femoral length and body mass estimates for the Tirup and Black Friars samples.

Variable		Tirup			Black Friars			t	df	p-value
	Sex	N	Mean	SD	N	Mean	SD			
Fem length (mm)	♂	32	463.19	25.84	38	447.07	18.15	3.054	68	**0.003**
	♀	16	427.13	16.70	14	411.75	20.38	2.271	28	**0.031**
	Total	48	451.17	28.71	52	437.56	24.40	2.560	98	**0.012**
Body mass (kg)	♂	58	66.11	6.39	66	68.43	5.47	-2.184	122	**0.031**
	♀	35	53.94	4.50	35	56.42	5.59	-2.041	68	**0.045**
	Total	93	61.53	8.24	101	64.29	7.94	-2.358	192	**0.019**

N: number of bones included; SD: standard deviation; bold indicates significance at $p<0.05$; Fem. length is measured using physiological femoral length as describe in Raxter et al. 2006.

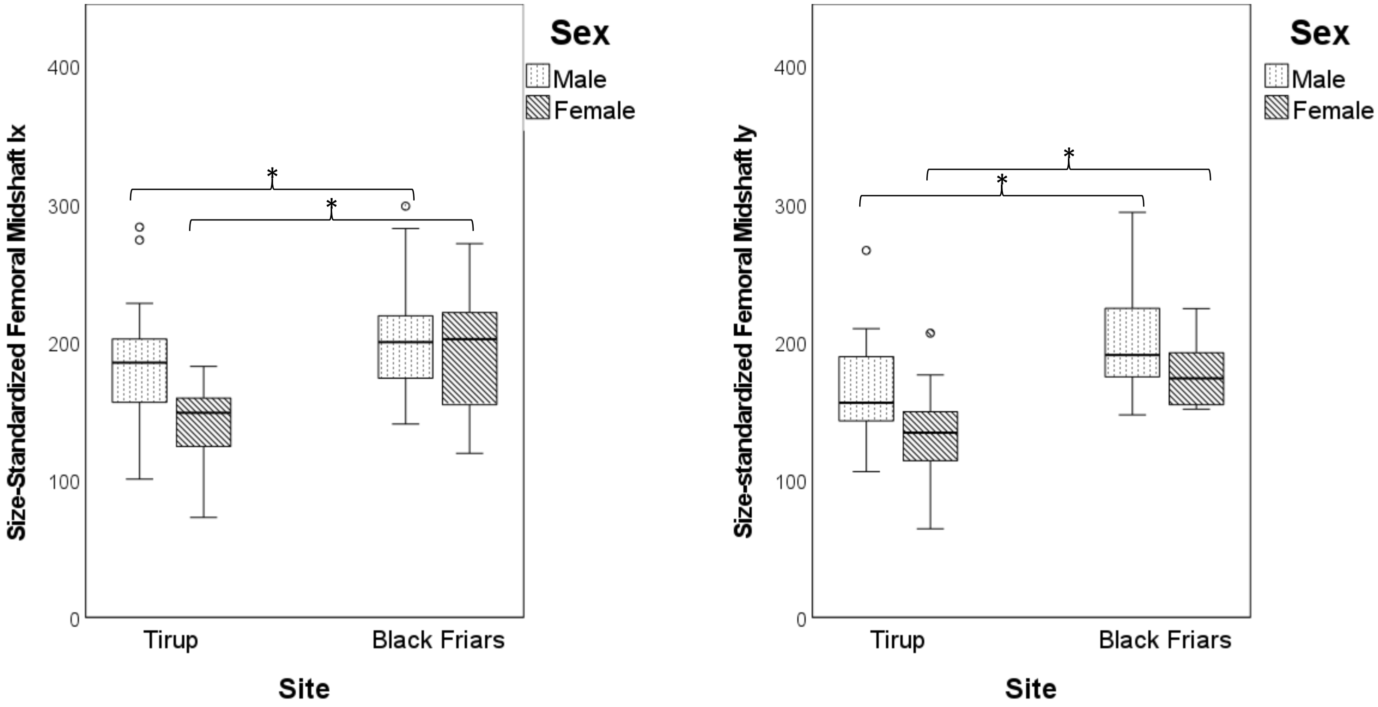
Table 4

Summary statistics for the femoral geometric properties by sample and sex.

Cross-sectional property	Tirup			Black Friars			
	N	Mean	SD	N	Mean	SD	p-value
♂	32			38			
$CA^{a\dagger}$		634.83	67.20		659.57	75.62	0.156
$MA^{a\dagger}$		197.12	48.71		214.62	58.52	0.498
$\%CA^{\dagger}$		77.05	4.66		76.16	5.98	0.183
I_{max}^{a}		192.12	42.04		228.20	43.80	**0.001**
$I_{min}^{a\dagger}$		152.75	30.66		181.80	39.01	**0.001**
$I_x^{a\dagger}$		175.43	47.86		205.72	44.82	**0.024**
$I_y^{a\dagger}$		163.80	34.12		204.46	43.70	**<0.001**
$J^{a\dagger}$		344.60	68.21		410.00	78.13	**0.001**
$I_x/I_y^{\dagger}$		1.12	0.193		1.03	0.198	**0.014**
$I_{max}/I_{min}^{\dagger}$		1.27	0.196		1.27	0.170	0.953
♀	16			18			
$CA^{a\dagger}$		596.08	82.92		616.81	88.99	0.515
$MA^{a\dagger}$		185.51	60.87		234.84	84.83	0.075
$\%CA^{\dagger}$		76.94	7.06		73.18	8.70	0.202
I_{max}^{a}		148.89	33.29		207.62	31.37	**<0.001**
$I_{min}^{a\dagger}$		127.76	26.84		159.75	28.15	**0.006**
$I_x^{a\dagger}$		142.52	29.09		191.57	43.32	**0.004**
$I_y^{a\dagger}$		133.95	32.54		166.59	48.89	**0.001**
$J^{a\dagger}$		276.64	58.91		367.37	56.93	**<0.001**
$I_x/I_y^{\dagger}$		1.07	0.133		1.09	0.231	0.667
$I_{max}/I_{min}^{\dagger}$		1.17	0.103		1.31	0.129	**0.002**

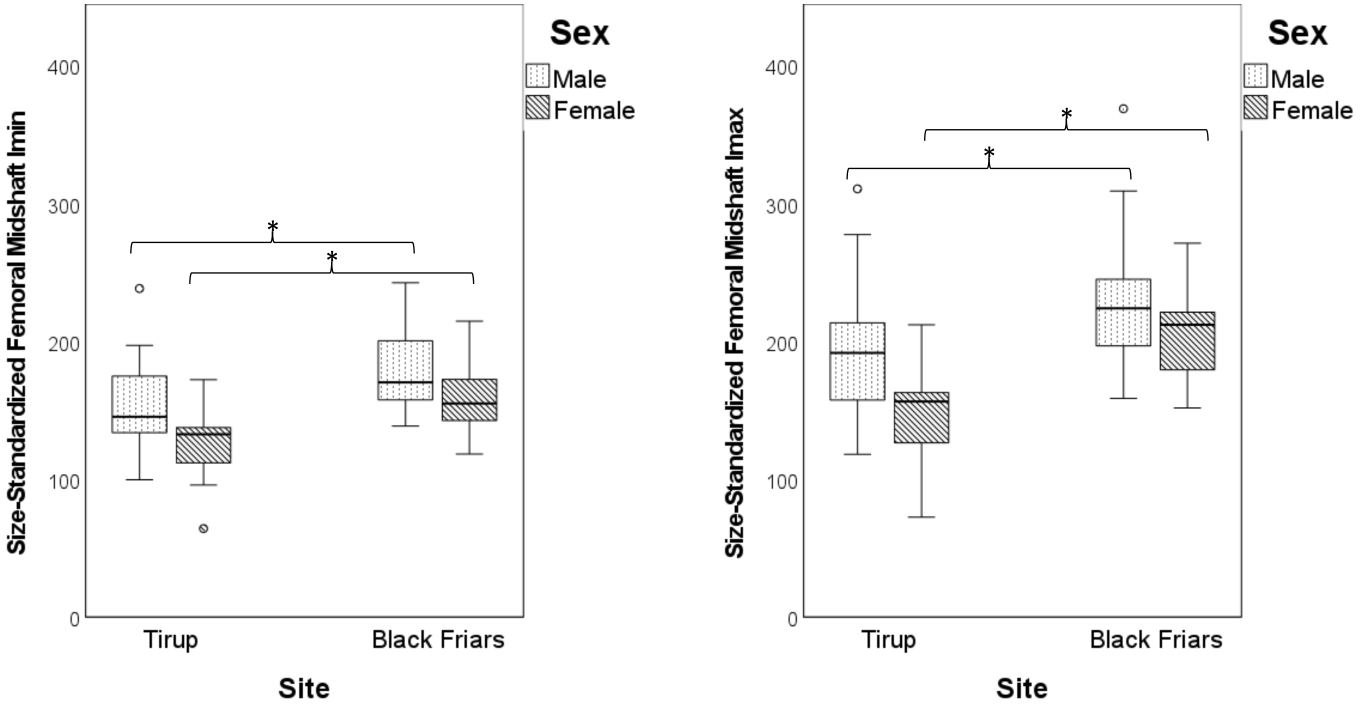
[†]Mann-Whitney non-parametric test results, all other results represent *t*-test values; N: number of bones included; SD: standard deviation; CA: cortical area (mm^2); I_{max}: bending rigidity along the maximum axis (mm^4); I_{min}: bending rigidity along the minimum axis (mm^4); I_x: bending rigidity along the anteroposterior axis (mm^4); I_y: bending rigidity along the mediolateral axis (mm^4); J: torsional rigidity (mm^4); a: indicates all values that have been standardized for body size following Ruff 2008; bold indicates significance at $p<0.05$.

Figure 1. Box plots for variation in anteroposterior and mediolateral femoral midshaft bending rigidities (I_x, I_y).



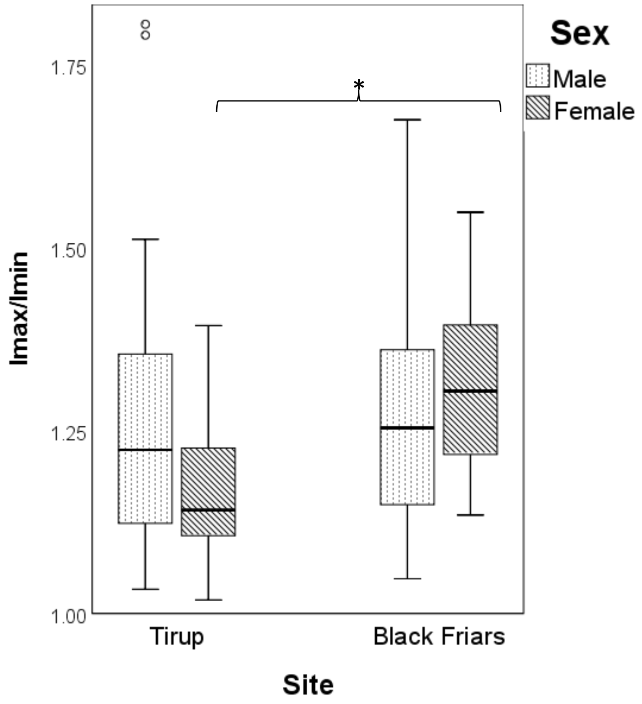
The midline denotes the median with the box denoting the 25th and 75th centiles, while the whiskers denote the distribution of data excluding outliers. * denotes significance at $p<0.005$.

Figure 2. Box plots for variation in minimum and maximum femoral midshaft bending rigidities (I_{min}, I_{max}).



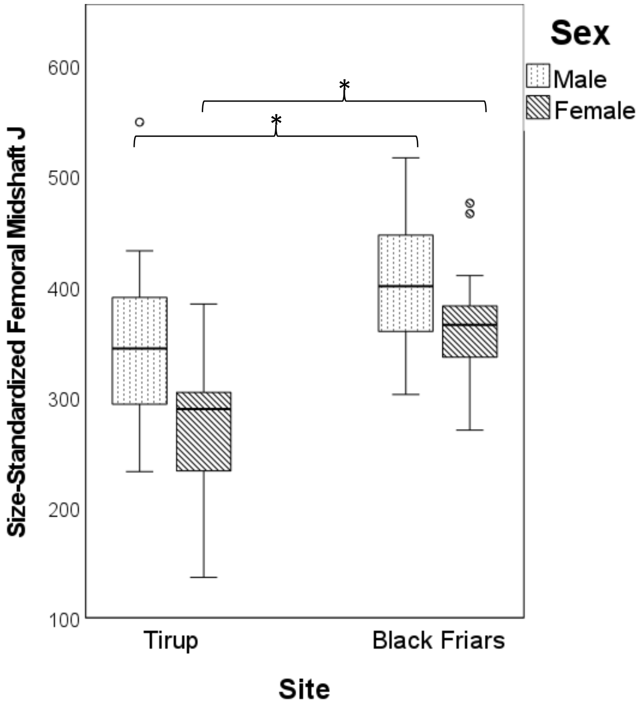
The midline denotes the median with the box denoting the 25th and 75th centiles, while the whiskers denote the distribution of data excluding outliers. * denotes significance at p<0.005.

Figure 3. Box plots for variation in femoral midshaft shape (I_{max}/I_{min}).



The midline denotes the median with the box denoting the 25th and 75th centiles, while the whiskers denote the distribution of data excluding outliers. * denotes significance at p<0.005.

Figure 4. Box plots for variation in femoral midshaft torsional bending rigidities (J).



The midline denotes the median with the box denoting the 25th and 75th centiles, while the whiskers denote the distribution of data excluding outliers. * denotes significance at $p<0.005$.