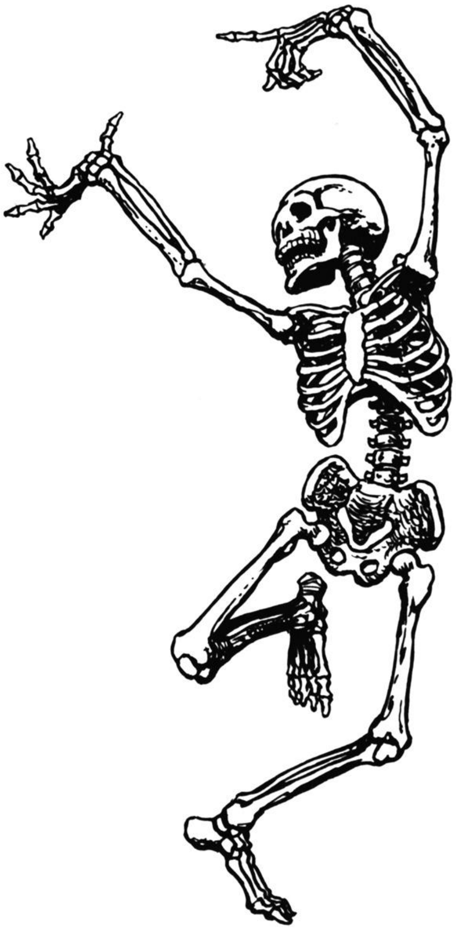
Sexual division of labour in rural 17th to 19th century Holland

A study of limb bone cross-sectional geometry



Jaap Saers

Image on the cover: http://languagemoments.wordpress.com/2012/01/11/phil-wades-course-skeleton/

Sexual division of labour in rural 17th to 19th century Holland

A study of limb bone cross-sectional geometry

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1. Introduction

The objective of this thesis is to assess if there were differences in the activities between men and women living in rural Holland from the 17th century until the 19th century. The Dutch site of Middenbeemster, excavated by a team of archaeologists from the University of Leiden, the Netherlands, will be used as a case study. By combining historical knowledge and the principles of bone functional adaptation, a reconstruction will be made of the sexual division of labour within this Dutch farming community through the examination of long bone cross-sectional geometry.

1.1 Bone biomechanics and archaeological applications

Biomechanics is the application of mechanical principles to biological systems, from the design of tree trunks to the movements of microorganisms (Ruff 2008). Biomechanics applies engineering principles to biological tissues. Anthropologists have long been interested in how mechanical principles can be used to explain skeletal variation within and between species. Wolff's Law (Wolff 1892, Ruff 2008, Ruff et al. 2006) is a concept popularized by the German anatomist/surgeon Julius Wolff (1836–1902) in the 19th century that states that bone in a healthy individual will adapt to the habitual loads that are placed upon it during life, either by a change in shape or bone volume. This allows anthropologists to reconstruct differences in the habitual activities of past populations by studying the shape of limb bones. However, Wolff's law only refers to the trabecular bone and adheres to strict mathematical rules to explain the mechanical response. The term 'bone functional adaptation' is applied to describe the general premise that bone tissue and structure adapts to mechanical forces and focuses on cortical bone properties (Ruff et al. 2006).

The process of bone functional adaptation is schematically presented in figure 1.1. Increased strain under mechanical loading that is put on a bone, for example through increased body mass or regular activity, results in the formation of new bone which strengthens the bone reducing the strain to its original level. Habitual inactivity on the other hand, causes bone to be resorbed which weakens the bone until it reaches the original strain levels (Ruff 2008). This general model is supported by a large body of studies. Many of these studies are on archaeological skeletal collections (Lieberman et al. 2004, Ruff 1987, Pomeroy and Zakrzewski 2009), however, studies are increasingly being performed on modern athletic samples as well (e.g. Frost 1997, Shaw and Stock 2009a,b). An extreme example of the plasticity of the human skeleton is given by Trinkaus and colleagues (Trinkaus et al. 1994). Trinkaus compared the bilateral asymmetry of the humeri of professional tennis players to the humeri of a non-athletic sample. In the non-athletic group bilateral asymmetry of the humeri was evident but not by a large amount. The humeri of the tennis players, on the other hand, displayed a large amount of asymmetry. The main arm they used for playing tennis being 28 to 57% more robust than the other arm.

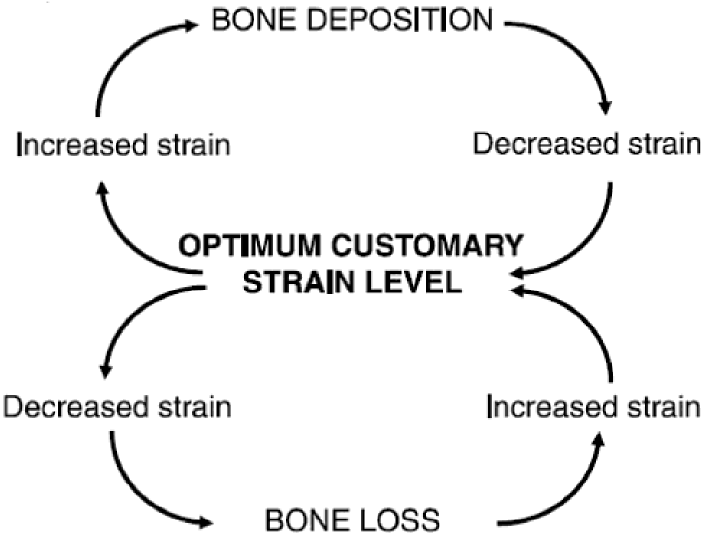

Figure 1.1. A schematic model of bone functional adaption. Figure from Ruff (2008), 184.

The optimum customary strain level indicated in figure 1.1 varies per bone and individual and is subject to many different variables such as anatomical location (weight bearing or not), diet, genetic background, disease, and age (Ruff 2008). It is very important to take this into consideration when interpreting the structural properties of bone. For example, due to bone loss at older ages, age differences have to be accounted for when comparing individuals within a population. Bones are most plastic when the individual is still growing (modelling). After the skeleton reaches maturity, modelling decreases to a trivial level. It persists in adults only when drastic mechanical loads are applied (Frost 1997).

The most common application of biomechanics by anthropologists and archaeologists is the cross-sectional analysis of long bone diaphyses. In this type of analysis a cross section is made at a specific site on the diaphysis of a long bone allowing the shape of the bone to be observed. To understand bone morphology, a bone biomechanical model is used. In the case of human limb bones, the diaphyses are modelled as hollow engineering beams that respond to mechanical loads. Rather than any other material property, it is the cross-sectional geometric shape that responds most to increased mechanical loads (Ruff 2008). Mechanical loads therefore determine the cross-sectional area, diameter and shape of a bone. When stresses in a beam reach a certain critical point the beam will fracture. The ability to resist breaking is referred to as strength. The resistance of a beam to deformation, prior to fracture is referred to as rigidity (Ruff 2008). These two characteristics are important in the biomechanical study of long bones. Different kinds of loadings exist that can result in failure (fracturing) of a beam. Compression and tension act around the long axis of a beam and respectively compress the beam or pull it apart. Bending is the result of both compression and tension on opposite sides of a cross section. Finally, torsion is a force where a beam is twisted around the long axis, producing diagonal, shearing stresses (Larsen 1997: 197-201, Ruff 2008). Rigidity and strength in pure compression and tension are proportional to the cross sectional area of the material inside a beam, which in the case of bone is the cortical bone area. However, bones are rarely subjected to pure tension or compression, the mechanically more important loadings being bending and torsion (Ruff 2008).

Resistance to pure compressive and tensile loadings are proportional to the amount of cortical bone in a cross section, known as cortical area (CA). Cortical area is calculated by taking the difference between the periosteal and the endosteal surfaces, represented by the medullary area (MA) and the total subperiosteal area (TA) (Ruff 2008, Larsen 1997). Bending and torsional rigidity are estimated using cross-sectional properties known as second moments of area (SMAs) or second moments of inertia. The bending second moment of area (I) is calculated by multiplying small areas of bone within a cross-section by the squared distances of these areas to the axis of bending (Ruff 2008). For bending rigidity (I) the second moments of area are calculated about an axis through the cross section, while for torsional rigidity (J) the second moments of area are calculated around the centroid (geometric center of an object) of the cross section (Ruff 2008). The bending second moments of area can be calculated about any axis through a cross section, however they are most commonly calculated about the anatomical axes (the medio-lateral (Iy) axis and the antero-posterior (Ix) axis) or as maximum (Imax) and minimum (Imin) SMAs. The polar second moment of area (J) is proportional to both torsional rigidity as well as twice the average bending rigidity, indicating that polar second moments of area provide a good indication of the average bending rigidity of a bone (Ruff 2008). To estimate bone strength (rather than rigidity) section moduli are used. Section moduli (Z) use second moments of area to estimate bone strength (Ruff 2008). Since the outermost surface of a cross-section is subjected to the highest amounts of stress under bending or torsion, second moments of area are divided by the distance from this surface to the bending axis or torsional centroid to determine the section moduli (Ruff 2008). Like second moments of area, bending section moduli are calculated in reference to the anatomical axes (Zmax, Zmin, Zx, Zy). Also, the torsional section modulus is referred to as the polar section modulus (Zp) and measures both torsional strength and twice the average bending strength just as (J).

Various methods exist to obtain cross-sections in order to calculate cross-sectional geometric properties. The cheapest and most straightforward way to obtain cross-sections is to saw through bones at specified diaphyseal sites. This practise is of course destructive and should therefore be avoided whenever possible. Images can be obtained noninvasively by external moulding, radiography, and computed tomography (CT) scanning. With CT scanning whole bones can be scanned, or a desired anatomical location. With the correct calibration of image display parameters the result is a detailed picture of the periosteal and endosteal contours of a bone. Several computer programmes have been developed to derive cross-sectional properties from two-dimensional CT images such as ImageJ for windows and NIH Image for macs[1].

There are limitations to the extent in which cross-sectional geometric properties of long bones can be used to reconstruct the habitual activities of

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[1] Available for free at www.hopkinsmedicine.org/fae/CBR.htm.

individuals in the past. Although the general process of bone functional adaptation has been proven by many experimental studies (Lanyon et al. 1975, Churches et al. 1979, Robling et al. 2002), the specific effects that habitual loadings have on the cross-sectional geometry of limb bones, as well as the contributions of factors other than regular stress, are contested (Lieberman et al. 2004, Ruff et al. 2006). There are many variables suspected to have an influence on the cross-sectional geometric shape of limb bones beside mechanical loadings. These variables include terrain, nutrition, hormonal status, genetic background, age, and climate amongst others. The magnitude of their influence on the ultimate shape of bones remains largely unclear. Further experimental studies on the effects of these variables are needed to increase knowledge of the specific effects these factors have on bone morphology (e.g. Lieberman et al. 2004, Shaw and Stock 2009a,b).

The biomechanics model has been in use in mainstream anthropology and archaeology since the 1970's (see Ruff 2008 for a brief historical overview). The application of the biomechanics model, specifically cross-sectional geometric analysis, has aided in the interpretation of activity patterns of past human populations. It has been used by anthropologists to investigate long-term evolutionary trends (Churchill 1994, Pearson et al. 2006, Trinkaus and Ruff 2012) as well as differences within and between populations. This type of research is used most often to distinguish between subsistence strategies (Ruff et al. 1984, Bridges 1989), division of labour (Pomeroy and Zakrzewski 2009), mobility (Ruff and Hayes 1983a,b), and ecological context (e.g. mobility across mountainous terrain or whether or not there was marine mobility) (Stock and Pfeiffer 2001, Nikita et al. 2011).

The majority of biomechanical publications deal with behavioural patterns associated with different subsistence strategies. Three types of subsistence economy are often distinguished: hunter-gatherers, agriculturalists, and industrial populations. In general (although there are exceptions), there is a continuous decline in sexual dimorphism in mobility from hunter-gatherers to industrial societies with agriculturalists in between (figure 1.2). Hunter-gatherers often display a large amount of sexual dimorphism (36 to 8%), agriculturalists generally display lower amounts of sexual dimorphism (9 to 2%), and industrial populations usually display a very weak sexual dimorphism (2 to 0%) (Ruff 1987).

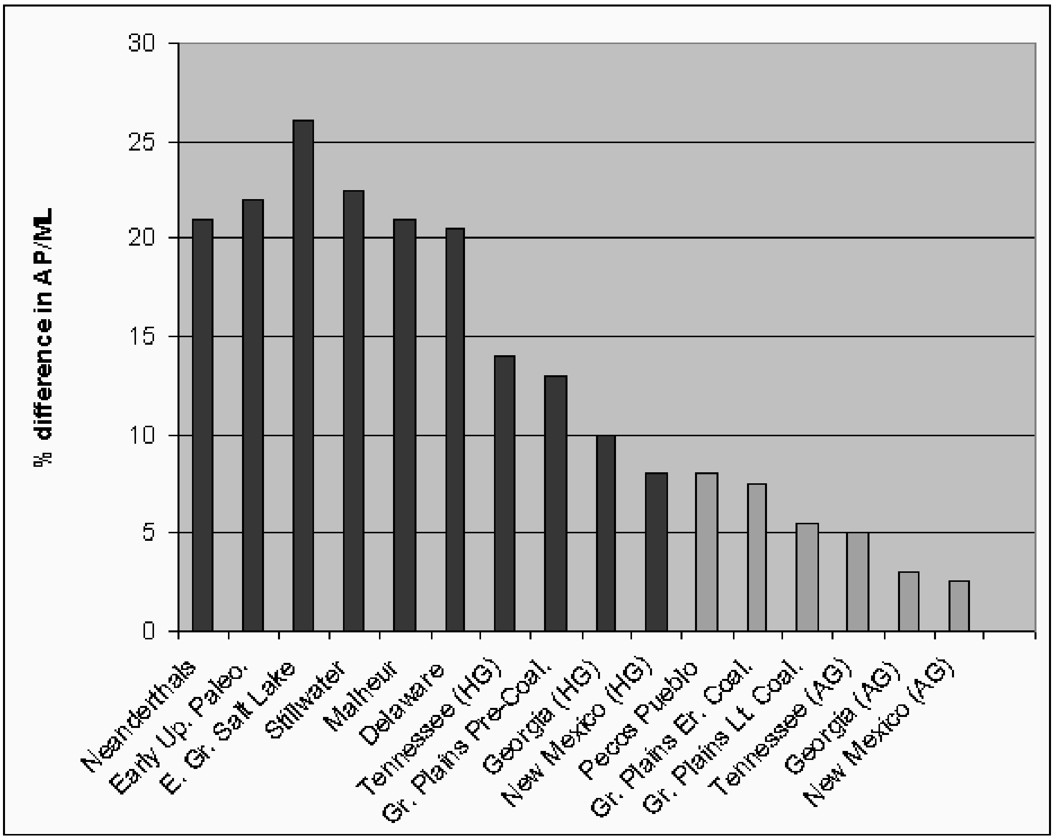

Figure 1.2. Sexual dimorphism in femoral midshaft AP/ML bending rigidity. Hunter-gatherers are in black, agriculturalists are in grey. Corrected for body size. Modified from Ruff (2000a), 85.

The effects of specific subsistence strategies on cross-sectional morphology is a popular type of research. It often focuses on transitions from one type of subsistence strategy to another within a population, such as the transition from a hunter-gatherer lifestyle to agriculture (Wescott 2008, Ruff et al. 1984). The transition from a hunter-gatherer subsistence strategy to an agricultural subsistence strategy was studied by Ruff and colleagues (1984) on the Georgia coast. They studied the long bone diaphyseal structure differences between the two samples. The agricultural group demonstrated a general decline in bending rigidity compared to the hunter-gatherers, in particular the subtrochantric antero-posterior bending rigidity (I_x) and torsional rigidity. This decrease resulted in more circular cross-sections for the agricultural group compared to the hunter-gatherer group resulting in a reduced antero-posterior bending rigidity. This observation has been interpreted as being the result of a more sedentary lifestyle with less mobility (Ruff et al. 1984). Bridges (1989) performed a similar study on the adoption of agriculture in the Southeastern United States. Contrary to Ruff et al. (1984), Bridges found no significant differences in the cross-sectional properties between the agricultural and pre-agricultural groups, and concluded that the transition to agriculture did not result in an increased workload. The adoption of maize agriculture was interpreted as more intensive than hunting and gathering and resulted in stronger femoral midshafts, tibiae, radii, humeri and ulnae. Differences between the sexes also led to the interpretation that a change in the sexual division of labour had occurred with the adoption of the agricultural subsistence strategy (Bridges 1989).

A large amount of biomechanical research in anthropology focuses on the differences between the activities of men and women (Ruff 1987, Ruff and Hayes 1983a,b, Saers 2011). Sexual dimorphism in this context is interpreted as being the result of sexual division of labour where males and females perform different tasks. In modern industrial societies sexual dimorphism (when corrected for differences in body mass) is very slight. Figure 1.2 shows a collection of archaeological populations where sexual dimorphism is much larger. It is clearly visible from figure 1.2 that, in general, sexual dimorphism in femoral midshaft AP/ML bending rigidity is largest in hunter-gatherers where differences in mobility are greatest, decreases with the adoption of agriculture, and diminishes even further in industrial societies. In the study performed by Bridges (1989) the Mississippian had an increase in lower limb bone strength compared to the archaic population. However, in both groups females were similar in upper- and lower limb strength. Bridges (1989) interprets the increased disparity between the sexes as the result of an increase in the variety of activities taken on by females with the shift in subsistence strategy. An interesting result of Bridges' (1989) study is the observed bilateral asymmetry of the agricultural females' distal humeri, possibly indicating the use of mortar and pestles in the processing of maize.

Terrain has a substantial effect on femoral robusticity (figure 1.3) (Ruff 1999). The greater relative femoral strength of individuals inhabiting mountainous areas is consistent with the expected mechanical consequences of travelling through rugged terrain. The humerus does not exhibit this pattern, although evidence is less abundant compared to femoral data (Ruff 2008). This would also be expected since the humerus serves no locomotor function and should therefore remain unaffected by the ruggedness of terrain. The humerus does however play a substantial role in discussions of land versus water transportation. Stock and Pfeiffer (2001) studied two populations with different modes of subsistence. Protohistoric Andamanese Islanders that practised a primarily marine mode of subsistence were compared to Later Stone Age South Africans who foraged over rough terrain on land. The Islanders showed substantially more humeral rigidity compared to the South Africans, and the South Africans displayed a substantially higher femoral rigidity (Stock and Pfeiffer 2001).

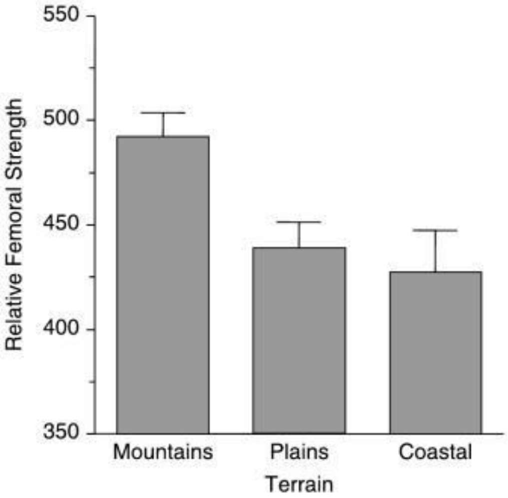

Figure 1.3. Effect of terrain on femoral midshaft polar second moment of area, controlled for subsistence strategy and sex, ±1SD. Figure from Ruff (2008), 191.

Research by Cowgill (2010) on subadult groups shows that humeral and femoral strength between groups is established as early as the first year of life and is maintained throughout the development of the individual. This suggests that genetic and systemic factors influence postcranial bone strength and morphology as well as mechanical factors. Modelling and remodelling are also affected by systemic factors such as health, nutrition and hormonal status. Cowgill’s (2010) research showed for example that the nutritionally stressed Kulubnarti sample, compared to other groups, displayed the lowest subadult postcranial robusticity. This suggested that, due to nutritional stress, the subadults showed a lower bone mass and lower levels of activity in addition to the impact of maternal malnourishment, which produced small infants. Ruff et al. (2006) emphasize that past research clearly shows the effects of habitual loadings on the morphology and strength of the postcranium and point out that it is likely that there is interaction between genetics and environment which should be considered when interpreting long bone morphology.

It has been observed frequently in the anthropological literature that females have more medio-laterally strengthened femora than males who generally possess more antero-posteriorly strengthened femora (Ruff and Hayes 1983a,b, Stock 2006). This observation has often been linked to the differences in body shape between males and females. Females generally have a wider bi-iliac breadth than males, resulting in a more acute angle between the femora and the pelvis, and thus a higher amount of medio-lateral stress on the femora. The effect is thought to be less on the portion of the femur that is closer to the knee. The tibia was thought to be unaffected by the increased pelvic breadth of females, however recent research contradicts this hypothesis (Shaw and Stock 2011).

It should be clear from this short overview that the application of biomechanics to skeletal populations is not without difficulties. Many variables that contribute to bone morphology and therefore cross-sectional properties are only vaguely understood with the magnitude of their contribution being uncertain. Careful consideration of all possible variables is required when interpreting cross-sectional geometric data. When this is done correctly, cross-sectional geometry has the potential to be a highly informative source of information on the activities of past populations.

1.2 Biocultural context of the seventeenth to the nineteenth century Beemster polder.

The village of Middenbeemster lies in the Beemster polder. This polder was reclaimed from a large body of water called the Beemstermeer in 1612 AD, and inhabited continuously since this time. Middenbeemster (Middle-Beemster) was founded almost immediately after the draining of the polder (Klooster 2009) (figure 1.4).

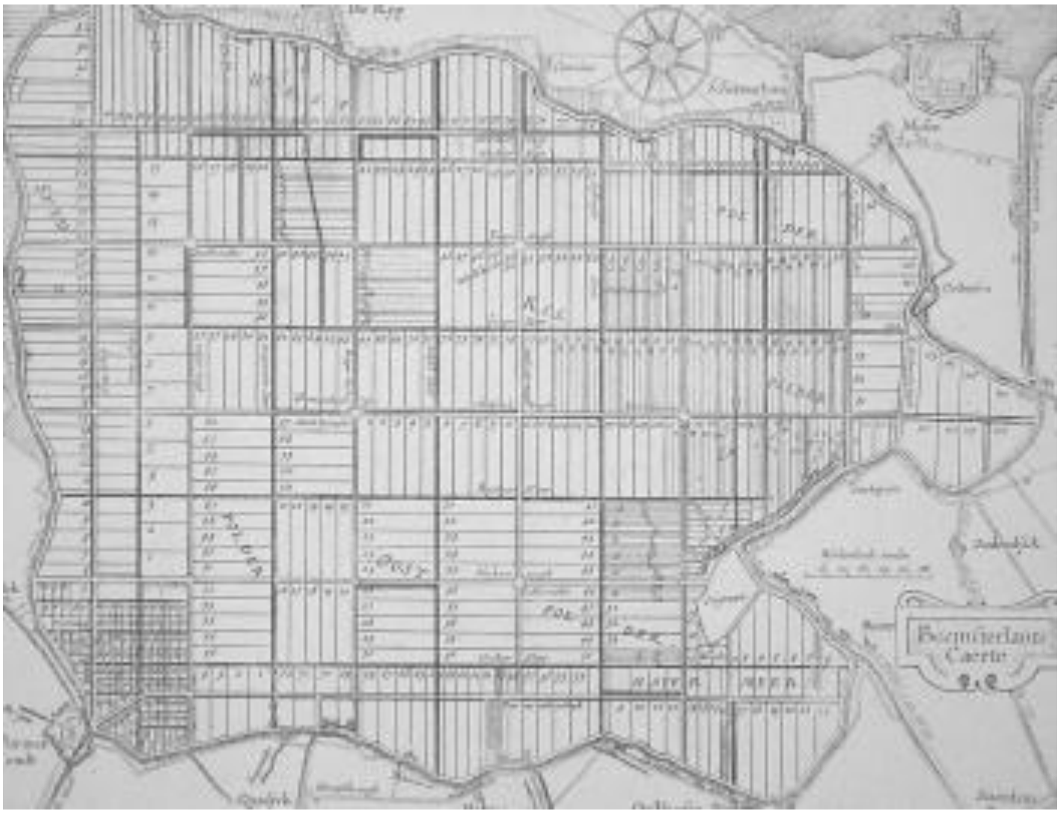

Figure 1.4. Map of the Beemster polder from 1658, with Middenbeemster in the centre, at the time still known as 'Middel Beemster'.

Initially five churches were designed to be built in the newly drained landscape, but eventually only one was constructed; the church in Middenbeemster. All inhabitants of the Beemster were buried at the Middenbeemster cemetery around the church as well as within the church. The cemetery was in use from the beginning of the 17th century until 1866 when a new cemetery was taken into use on the periphery of Middenbeemster, which is still in use today (Griffioen 2011). In 1999 the Beemster polder was placed on the UNESCO world heritage list because of its unique design in square plots, which had never been done on such a grand scale.

The bulk of economic activities performed in the Beemster polder from the seventeenth to the nineteenth century were a mix of stock farming and agriculture. A wide range of other occupations are known from historical records such as: shopkeepers, barkeepers, soldiers from neighbouring forts, clergymen, and wealthy landowners. Most of the individuals buried in the cemetery are expected to have been farmers. In the seventeenth century, large quantities of milk and other dairy products were produced in the Beemster polder compared to other rural Dutch areas (de Vries 1974). Production of hops (*Humulus lupulus*), flax (*Linum usitatissimum*) and rapeseed or coleseed (*Brassica napus*) increased in the seventeenth century. Rapeseed especially was in high demand. The growing demand in these crops played an important role in persuading urban capitalists to invest in land reclamation. The first reason given by investors in the Beemster polder project in their request to gain governmental permission to drain the Beemstermeer was coleseed production (de Vries 1974). Although the drained land was originally used for cereal production, it was gradually turned into pasture land for cattle because the high water table and soil conditions were not suitable for arable farming. From the late seventeenth century onwards most of the land in the Beemster was used for cattle-farming. The Beemster is still very well known today for its Beemster-cheese.

From the seventeenth century until the nineteenth century the place of the woman would ideally be around the house, tending to the home-area, buying and preparing food and taking care of the children, while the men worked farther away from the house, either in the fields or in specialized shops. However, it is not expected that all households conformed to this idealized scenario, and exceptions to this general patter are expected (Mook 1977).

The terrain of the Beemster is quite unique. It is a completely flat piece of land divided up into equal plots, separated by fences but mostly by ditches that are filled with water. The absence of relief in the terrain is something that does not occur in many places in the world. It is expected to have a negative effect on the robusticity of the lower limbs. This expectation is based on the observation that lower limb robusticity significantly increases when terrain becomes more rugged (Sparacello and Marchi 2008).

When the Beemster polder was drained in the seventeenth century, things were going very well with the Dutch economy. This period is also referred to as the Dutch “Golden Age” (Arblaster 2006). After the Golden Age there have been many periods of growth as well as periods of severe crisis. The Low Countries were constantly at war with much larger nations such as the England, France, Austria and Spain. Diseases amongst crops and animals such as the “potato blight” and “cattle plagues” (runderpest) resulted in frequent periods of famine and general malnutrition (Arblaster 2006, Bergman 1967, Lindeboom et al. 2010).

Dietary sufficiency is very important for bone growth and the effects of these periods of nutritional stress will be explored in the discussion section.

1.3 Research questions

The skeletal assemblage from Middenbeemster, excavated in the summer of 2011 by the University of Leiden, the Netherlands, is fascinating for a variety of reasons. The sample is large, consisting of about 450 individuals and contains individuals from all age groups, the majority being well preserved. The sample is yet to be described meaning that every piece of information is a welcome addition to the rapidly growing body of data available for this population. The historical data on the period from which the skeletal assemblage dates is abundant. Death records have been recovered for many individuals, alongside a map of the cemetery with the names and burial locations of individuals buried after 1829. This allows for a correlation between the excavation plan, the historical map, and the death records. This means that for individuals buried in the cemetery after 1829, the sex, age at death, and socioeconomic status can be retrieved after the correlation between the map, the excavation plan, and the death records is complete. This allows for the methods used in describing the skeletal sample to be tested; a unique opportunity.

This thesis will focus on the differences in the habitual activities performed by males and females in the Middenbeemster area. There are several ways in which these differences can be observed skeletally. The distribution of musculoskeletal stress markers can be mapped across the skeleton after which the differences in the distributions between males and females can be compared. Another way of assessing past behaviour is the analysis of distributions of trauma and activity-related pathologies such as osteoarthritis across the skeletons. A good example of this kind of analysis is a study performed by Berger and Trinkaus (1995). In their study they compared the trauma patterns of pooled Neanderthal males and females to modern clinical samples and a specialized group of athletes: North American rodeo performers. The distribution of trauma for the Neanderthals was comparable to that of the rodeo performers. This result supported the general idea of Neanderthal hunting tactics that required up close encounters with large and dangerous animals. This thesis however, will be employing cross-sectional geometry to reconstruct the habitual behavioural patterns of the inhabitants of the Beemster polder in the seventeenth to the nineteenth century. Computed tomography scanning will be employed to obtain cross-sections at specific sites of the humerus, femur, and tibia. From these cross-sections the relevant mechanical properties will be calculated and a comparison of the results will be made between the males and females. The results will be put into context through comparison with previously published skeletal assemblages including populations with an agricultural subsistence strategy, modern athletic groups, modern cadaveric groups, and out-groups with different subsistence strategies and/or environmental settings.

1.4 Hypotheses

The null-hypothesis states that there was no sexual division of labour in the Middenbeemster sample. In this case there should be very little sexual dimorphism in the lower- and upper limbs after correcting for body size. A difference of around two percent or less is expected in this case, which is comparable to sexual dimorphism in modern industrial societies (Pearson et al. 2006, Ruff 1987). If sexual dimorphism is higher than two percent the null-hypothesis will be rejected. Three scenarios have been developed to describe the pattern of variation in males and females. As formal hypotheses these are:

1. Males and females differed in mobility and performed different tasks. In this case significant sexual dimorphism should be observed in the lower limbs and in the upper limbs.
2. Males and females differed in mobility, but otherwise performed the same tasks. Significant sexual dimorphism should be observed in the lower limbs but not in the upper limbs.
3. There was no difference in mobility between males and females but different tasks were performed involving the upper limbs. Significant sexual dimorphism should be observed in the upper limbs but not in the lower limbs.

These hypotheses can be tested through the cross-sectional geometric analysis of CT scans of archaeological long bones. The results of the cross-sectional geometric analyses will be compared to historical evidence of the role of men and women in rural seventeenth to nineteenth century Holland. In the discussion section the nature of the performed tasks and their cross-sectional geometric signatures will be speculated upon. In the conclusion of this thesis the hypotheses will be either be rejected or ranked according to the likelihood that they are correct.

2. Materials and methods

In this chapter the skeletal sample from Middenbeemster and the comparative samples are introduced. The methods and procedures of the CT scanning of the bones will be explained in detail. The methods of data analysis will be provided. Finally, the statistical methods that are applied to the data will be explained.

2.1 The Middenbeemster skeletal assemblage

The skeletal assemblage from Middenbeemster consists of roughly 450 individuals. The site was excavated in the summer of 2011 by a team of archaeologists from Leiden University and Hollandia Archeologists, led by Dr. Menno Hoogland from Leiden University. The description of the entire sample is still in progress, however, a part of the sample has already been described. The cemetery was taken into use in the early seventeenth century, just after the Beemster polder was drained. The cemetery was in use until 1866 when a new cemetery was taken into use on the periphery of Middenbeemster (Griffioen 2011). The cemetery was cleaned out in 1829, leading to the removal and reburial of the individuals that were buried prior to this time. Skeletons that were buried on the periphery of the central area, and those buried deepest were not removed. Thus, the majority of the assemblage dates to the nineteenth century. Archival data will eventually allow for a determination of the proportion of individuals that were buried before and after the cleaning of the cemetery.

An inventory was made of the presence/absence of all skeletal elements and the preservation of the individual skeletons was recorded. Age and sex estimations were obtained using the *Standards for Data Collection from Human Skeletal Remains* (Buikstra and Ubelaker 1994) in combination with the method developed by *the workshop of European anthropologists* (WEA 1980). Stature was calculated using several different methods, of which the method with the lowest standard deviation was chosen. Metric and non-metric data were obtained through the use of a custom recording form, and a description was made of observable pathological conditions and abnormalities. Samples for DNA analysis were taken from each skeleton prior to description, preferably from the teeth.

From the described skeletal assemblage a subsample of 47 adult individuals was selected for this study (N♀ = 23 and N♂ = 24). These individuals were selected by the author according to the following criteria:

1. The individual must be over 18 years old.
2. The individual may not have movement impairing pathologies such as osteoarthritis.
3. The limb bones must be in good condition without damage to the diaphysis.
4. The femoral head must be intact for body mass estimation.

A list of the individuals used in this study is included in appendix C.

2.2 Comparative samples

The results of the Middenbeemster sample will be placed into a global context by comparing them to a wide range of groups. These groups include archaeological populations of hunter-gatherers and agriculturalists, as well as modern groups of athletes and cadaveric samples. Short descriptions of the origins, demography, subsistence activities, and methods of obtaining cross-sections are provided for each sample in appendix A.

2.3 Preparation of cross-sections

The left tibia, the left femur and both humeri were scanned with a Phillips Brilliance 64 CT scanner at the Amsterdam Medical Centre, Amsterdam. When the left femur or tibia was not available, the right side was used. While most humans are right handed, the left lower limbs are slightly stronger and larger than the right ones. This is probably related to leaning more heavily on the left limb while performing right handed activities (Wescott and Cunningham 2006). The bilateral asymmetry of the lower limbs is not significant however, especially after data has been corrected for differences in bone length. Scans were taken at 1mm increments with the machine set to 120Kv, with a 250mm wide field of view. A complete 3D digital reconstruction of the bone was generated after rendering. The cross-sections were taken from the 3D CT images at 50% and 35% (from the distal end) length on the femur and the humerus and at 50% on the tibia. These cross-sectional locations were chosen based on standard use in cross-sectional geometric research, and to avoid major muscle attachment sites such as the deltoid tuberosity on the humerus. The results have to be corrected for differences in body size. For this purpose the femoral head diameter is a reliable indicator. The femoral head diameter was measured along the supero-inferior plane (Auerbach and Ruff 2004).

Before scanning each bone was positioned in relation to the sagittal and coronal planes on a custom made board. The bones were then scanned as a package with the bones placed from left to right in the following order: the tibia, the femur, the left humerus, and the right humerus. The CT scanning of the packages resulted in a digital 3D image of the package which could then be manipulated at a 3D working station at the Amsterdam Medical Centre using IMPAX 6.4.0.4841 software. Many cross-sectional properties are influenced by the positioning of the bone (e.g. Ix, Iy). It is therefore of great importance that the bones are uniformly positioned before measurements are taken (Ruff and Hayes 1983a, Ruff 2002). The aligning was done according to three x,y,z, reference axes. The x,y,z, reference axes for the femur and the tibia conform to the ones used by Ruff (2002) and Ruff and Hayes (1983a) (figure 2.1). The x,y,z, reference axes used for the humeri conform to Ruff (2002) (figure 2.2). See appendix B for a more thorough description of methodology.

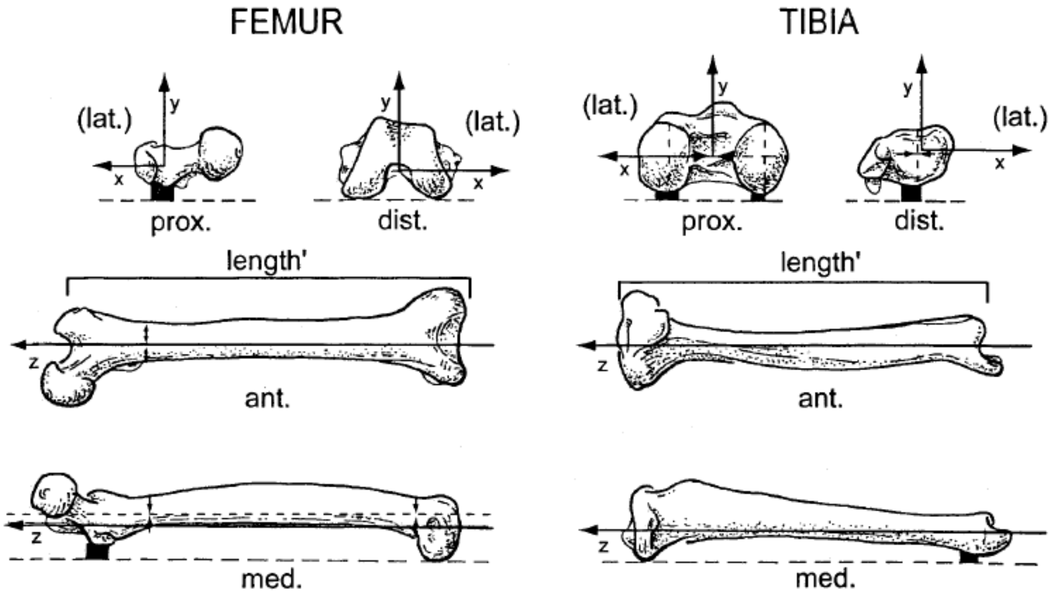

Figure 2.1. Reference axes and cross sectional locations of the tibia (a), and the femur (b). Figure from from Ruff 2002, 338.

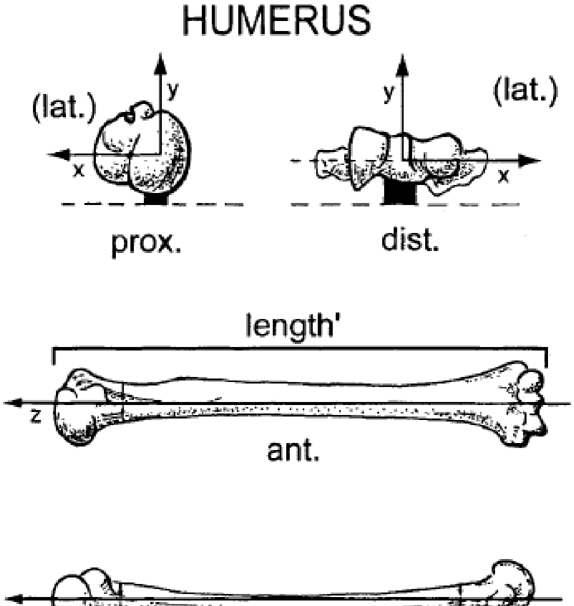

Figure 2.2. Reference axes and cross sectional locations of the Humerus. Figure from Ruff 2002, 338.

2.4 Determination of cross-sectional properties

A total of 47 CT scans were taken resulting in the analysis of 188 individual bone scans. Using a 3D working station, cross-sections were obtained from the digital

3D images created by the CT scanner. Seven cross-sections were obtained per CT scan resulting in a total of 329 cross-sectional images. The images were then saved and imported into Image J (a free image processing program available at: http://rsb.info.nih.gov/ij/) and the analysed using Moment Macro, provided for free by Dr. Christoffer Ruff at http://www.hopkinsmedicine.org/fae/mmacro.htm. Moment Macro works by calculating cross-sectional properties based on the density of pixels in a given area of an image under the assumption of an elliptical cross-sectional shape (Knobbe 2010).

The cross-sectional properties that were calculated with Moment Macro are; total subperiosteal area (TA), cortical area (CA), second moments of area (Ix, Iy) and minimum and maximum second moments of area (Imin and Imax respectively). The polar second moment of area (J) represents torsional rigidity or twice the average bending rigidity and could be calculated by taking the sum of the maximum and minimum second moment of area (Imax+Imin). The ratio of Ix/Iy was also calculated and is used to quantify diaphyseal shape and AP/ML bending rigidity (Ruff 2008). The Ix/Iy index will sometimes be referred to as the anatomical shape index. Iy/Ix (ML/AP) is also sometimes used in the literature as a shape index. Both indices are therefore calculated in this study to make comparisons easier. An Ix/Iy value that is larger than 1.0 and an Iy/Ix value lower than 1.0 indicate an elliptical shape in the antero-posterior plane. These “shape” indices provide information on how the bone is distributed in the cross-section. They allow for a simple assessment of the planes in which a bone is strengthened (Ix/Iy) and whether the bone is relatively circular or strengthened elliptically in an unspecified plane (Imax/Imin). A summary of the cross-sectional geometric properties, their abbreviations, units and definitions are presented in table 2.1.

Table 2.1. Definitions of cross-sectional geometric properties.

Property	**Abbreviation**	**Units**	**Definition**
Cortical area	CA	Mm^2	Tensile/compressive strength
Total subperiosteal area	TA	Mm^2	Total area of the cross-section
Percent cortical area	%CA	%	(CA/TA)*100
Second moment of area about the ML (x) axis	Ix	Mm^4	AP bending rigidity
Second moment of area about the AP (y) axis	Iy	Mm^4	ML bending rigidity
Maximum second moment of area	Imax	Mm^4	Maximum bending rigidity
Minimum second moment of area	Imin	Mm^4	Minimum bending rigidity
Polar second moment of area	J	Mm^4	Torsional (and twice the average) bending rigidity

The reader is asked to pay special attention to the fact that properties measured *about* an axis indicate strength in a plane of bending *perpendicular* to that axis. This is illustrated by figure 2.3.

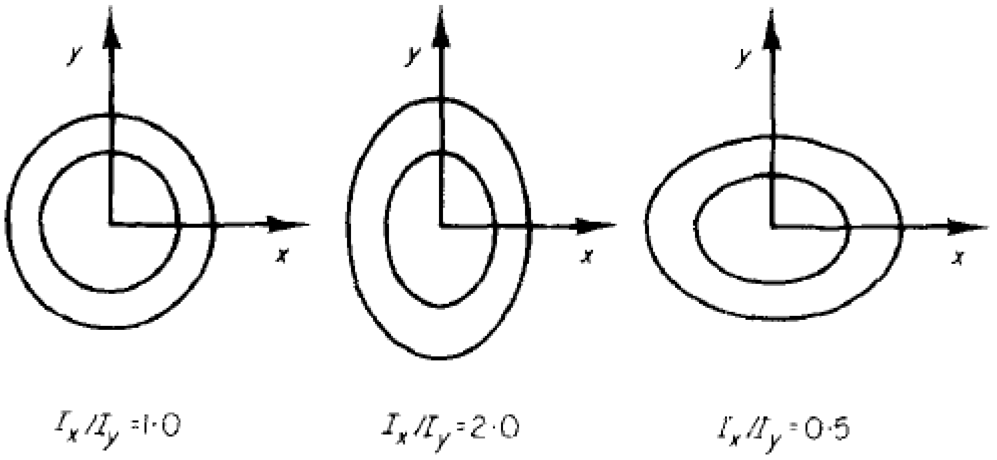

Figure 2.3. The effects of different cross-sectional shapes on the Ix/Iy ratio. Image from Ruff 1987, 393.

Humeral bilateral asymmetry was calculated using the dominant and the non-dominant arms, rather than left and right, to account for differences in handedness (Trinkaus 1994). Asymmetry (a) was calculated as:

$$a = 100 \times (X_{max} - X_{min})/X_{min}$$

where X stands for any biomechanical property. The percentage of sexual dimorphism (d) was determined by comparing differences in mean values for males and females as:

$$d = 100 \times (X_{male} - X_{female})/X_{female}$$

2.5 Size standardization

To control for the effects of differences in body size between the individuals in the sample the cross-sectional properties had to be size-standardized. This is required because body size inherently influences the loads that are placed upon the limb bones (Ruff 2008). Correcting for body size within and between populations assures that only activity related loadings are analysed. Femoral head diameter is used for body size standardization because it correlates very well with body size (Ruff et al. 1991). Body mass was calculated as the average of three equations as recommended by Pomeroy and Stock (2012):

$$BM = 2{,}2393 \times FHD - 39{,}9 \text{ (McHenry 1992)}$$
$$BM = 2{,}2683 \times FHD - 36{,}5 \text{ (Grine et al. 1995)}$$
$$BM♂ = 2{,}7413 \times FHD - 54{,}9;\ BM♀ = 2{,}426 \times FHD - 35{,}1 \text{ (Ruff et al. 1991)}$$

where BM is the body mass (in kg) and FHD is the maximum femoral head diameter (in mm). The equation by McHenry (1992) is designed to be applied to small “pygmy” populations. The equation by Grine et al. (1995) is designed to be applied to especially large populations. The equation by Ruff et al. (1991) is based on modern U.S. whites. Estimates from the equation were adjusted downwards by 10%, as recommended by the authors, to account for the increased adiposity of very recent U.S. adults (Ruff et al. 1991, Nikita et al. 2011). In a recent article Pomeroy and Stock (2012) argue that the most accurate way of assessing body mass is to take the average of these three equations, unless a population is especially large or small. As the current sample is not especially large or small, the method proposed by Pomeroy and Stock (2012) is applied.

The cross-sectional areas (CA) of the lower limbs were standardized by body mass, and second moments of area (I and J) were standardized by body mass multiplied by the square of bone length as recommended by Ruff (2008). The humeri were size standardized through the use of powers of bone length. The cross-sectional areas (CA) of the humeri were standardized for body size by dividing by bone length to the power three. The cross-sectional moments of area (I and J) of the humeri were size standardized by dividing by bone length to the power of 5.33 (Ruff et al. 1993, Stock and Pfeiffer 2001). The method of size standardization for the humeri was chosen because it did not require the availability of an intact femoral head. Intact pairs of humeri were difficult to obtain, and the additional requirement of an intact femoral head would decrease sample size even further.

2.6 Data analysis

Statistical significance is examined by parametric or non-parametric tests depending on the nature of the data. Independent samples t-tests were used to assess statistical significance between the sexes. When a sample fails to pass Levene’s test for Equality of Variances, a Mann-Whitney U non-parametric test is performed to assess significance. Significance was set at $p \leq 0.05$ for all comparisons. All statistical analyses were performed using SPSS 20 for Windows.

3. Results

In this chapter the cross-sectional properties of the males and females from the Middenbeemster skeletal assemblage will be presented. First the lower limbs will be discussed to assess differences in mobility, followed by a discussion of the variation in cross-sectional properties of the upper limbs. The cross-sectional properties will be subjected to statistical tests in order to assess the significance of the presented data. Statistical results presented in this chapter are the results independent samples t-tests unless specified otherwise.

The males (n=24) weighed an estimated 75,5±6,2 kilogrammes and the females (n=23) weighed an estimated 60,8±6,6 kilogrammes. All of the cross-sectional properties presented in this chapter therefore had to be size-standardized to compensate for inherent differences in body size within and between the sexes. Measurements of area (CA and TA) are in mm^2 and second moments of area (Ix, Iy, Imax, Imin, J) are in mm^4.

3.1 The distal femur

The cross-sectional properties of the distal femora of the males and females from the Middenbeemster sample, taken at 35% bone length, are presented in table 3.1. The sample consists of 22 males and 22 females.

Table 3.1. Cross-sectional properties of the femur at 35% bone length for males and females. All measurements are size standardized. Significant results are in bold.

Property Femur 35%	**Male Average (SD) N=22**	**Female Average (SD) N=22**	**Significance (p)**
TA	855.20 (82.63)	859.12 (98.14)	.885
CA	561.34 (56.29)	556.23 (69.14)	.788
%CA	65.82 (5.86)	64.88 (5.54)	.576
Iy	195.77 (39.33)	186.20 (42.38)	.436
Ix	179.20 (27.02)	161.58 (40.78)	.095
Imax	204.11 (38.72)	189.99 (42.62)	.250
Imin	170.85 (25.27)	157.80 (39.61)	.195
J	374.96 (61.75)	347.79 (81.38)	.214
Iy/Ix	1.09 (0.14)	1.16 (0.11)	.072
Ix/Iy	0.93 (0.12)	0.87 (0.09)	.057
Imax/Imin	1.19 (0.11)	1.21 (0.10)	.485

Some slight sexual dimorphism can be observed from the results of the distal femur presented in table 3.1. However, no differences reach statistical significance. Both males and females have roughly equal bone areas (t=-1.45 df=42 p=0.885). Mean cortical bone area is also roughly similar for both males and females (t=0.270 df=42 p=0.788). This results in about equal percentages of cortical area in the males compared to the females (t=.563 df=42 p=0.576).

The males and females have roughly equal values of medio-lateral bending rigidity (Iy) (t=0.787 df=42 p=0.436), but the males have a slightly larger mean antero-posterior bending rigidity (Ix) (t=1.707 df=42 p=0.095) compared to the females. The males are also slightly more robust in terms of maximum bending rigidity (t=1.167 df=42 p=0.250), and minimum bending rigidity (t=1.316 df=42 p=0.195). The males also have a slightly higher mean torsional bending rigidity (J) compared to the females (t=1.262 df=42 p=0.214).

In terms of diaphyseal shape the females have more medio-laterally strengthened femora than the males, statistical significance however is not reached at the 0.05 level (t=-1.843 df=42 p=0.073 for Iy/Ix, and t=1,958 df=42 p=0.057 for Ix/Iy). The Ix/Iy shape index of the femoral midshafts of both the males and females is smaller than 1.0 indicating a shape that is slightly more medio-laterally strengthened than antero-posteriorly. The females have slightly more elliptical shapes as indicated by their slightly higher Imax/Imin index. The difference however, does not reach statistical significance with (t=-0.704 df=42 p=0.485).

In most cross-sectional properties the females are more variable than the males, which is visible in their larger standard deviations. Exceptions here are the shape indices Ix/Iy and Iy/Ix, and %CA, where the males show higher variability.

3.2 The femoral midshaft

The cross-sectional properties of the femoral midshafts of the Middenbeemster males and females, taken at 50% bone length are presented in Table 3.2. The sample consists of 21 males and 21 females.

Table 3.2. Cross-sectional properties of the femur at 50% bone length. All measurements are standardized to correct for differences in body size. Significant results are in bold.

Property Femur 50%	**Male Average (SD) N=22**	**Female Average (SD) N=21**	**Significance (p)**
TA	791.92 (58.74)	795.32 (84.07)	.878
CA	617.89 (53.56)	625.08 (77.94)	.726
%CA	78.02 (3.70)	78.52 (4.07)	.679
Iy	186.86 (44.39)	176.67 (46.43)	.466
Ix	167.93 (21.83)	155.31 (35.27)	.163
Imax	200.72 (39.29)	187.34 (51.97)	.345
Imin	154.07 (20.33)	144.63 (28.34)	.215
J	354.80 (57.36)	264.36 (114.78)	**.012***
Iy/Ix	1.12 (0.23)	1.14 (0.16)	.709
Ix/Iy	0.96 (0.21)	0.90 (0.14)	.474
Imax/Imin	1.30 (0.14)	1.28 (0.16)	.763

**Result of Mann Whitney U non-parametric test.*

After a correction has been made for body size differences, only torsional bending rigidity (J) remains significantly different between males and females. The males and females have roughly equal total periosteal areas (t=-0.154 df=41 p=0.878), cortical areas (t=-0.353 df=41 p=0.726), and percentages of cortical area (t=-0.417 df=41 p=0.679).

On average, the males are slightly larger in terms of medio-lateral bending rigidity (Iy) (t=0.736 df=41 p=0.466), as well as antero-posterior bending rigidity (Ix) (t=1.419 df=41 p=0.163), but statistical significance is not reached. The males also display slightly larger values of maximum bending rigidity (t=0.995 df=41 p=0.345), as well as minimum bending rigidity (t=1.260 df=41 p=0.215), but neither reaches statistical significance. A significant difference is present in the polar second moment of area (J) where the male average was significantly larger than the female average (Z=-2.503 p=0.012). The sample failed Levene's test for equality of variances (F=13.482 p=0.01), most likely due to the high variability of the female sample, as expressed by their large standard deviation. Therefore, a Mann-Whitney U non-parametric test was performed.

The males and females are roughly equal in midshaft shape and no significant differences were found in Iy/Ix (t=-0.376 df=41 p=0.709) and Ix/Iy (t=0.723 df=41 p=0.474). The Ix/Iy shape index of the femoral midshafts of both the males and females is smaller than 1.0 indicating a shape that is more medio-laterally strengthened than antero-posteriorly. There is no difference in the Imax/Imin shape index with (t=0.303 df=41 p=0.763), indicating that the males and females possess equally elliptical cross-sectional shapes.

The females are more variable in their cross-sectional properties compared to the males, as evidenced by their higher standard deviations. The only exceptions are the three shape indices.

3.3 The tibial midshaft

The cross-sectional properties of the tibial midshafts of the Middenbeemster males and females, taken at 50% bone length, are presented in table 3.3. The sample consists of 21 males and 21 females.

Table 3.3. Cross-sectional properties of the tibia at 50% bone length for males and females. All measurements are size standardized. Significant results are in bold.

Property Tibia 50%	Male Average (SD) N=21	Female Average (SD) N=21	Significance (p)
TA	625.14 (49.13)	583.60 (71.55)	**.034**
CA	483.71 (55.77)	446.06 (65.79)	.052
%CA	77.24 (4.94)	76.40 (5.76)	.615
Iy	147.59 (33.26)	113.77 (22.18)	**.000**
Ix	199.51 (41.62)	156.87 (47.05)	**.003**
Imax	240.76 (51.31)	180.29 (44.67)	**.000**
Imin	106.34 (14.14)	90.35 (19.68)	**.004**
J	347.10 (61.92)	270.64 (61.13)	**.000**
Iy/Ix	0.76 (0.18)	0.76 (0.17)	.952
Ix/Iy	1.39 (0.32)	1.39 (0.33)	.959
Imax/Imin	2.26 (0.36)	2.01 (0.29)	**.015**

After correcting for differences in body size, sexual dimorphism is clearly visible in the cross-sectional properties of the tibiae of the Middenbeemster males and females. The males have significantly larger average total periosteal areas compared to the females (t=2.193 df=40 p=0.034). The males also have larger average cortical areas compared to the females but the p value falls just beyond the significance level of 0.05 (t=2.001 df=40 p=0.052). The males and females are roughly equal in their average percentage of cortical area and no statistical differences are observed (t=0.507 df=40 p=0.615).

The males display a significantly higher average medio-lateral strengthening (Iy) of the tibia than the females (t=3.877 df=40 p=<0.001). The males also have significantly more antero-posteriorly strengthened tibiae (Ix) compared to the females (t=3.111 df=40 p=0.003). The average maximum bending rigidity of the males is significantly larger than the females (t=4.073

df=40 p=<0.001). The average minimum bending rigidity is also significantly larger in the males compared to the females (t=3.024 df=40 p=0.004). The average polar second moment of area is also significantly larger in the males than in the females (t=4.027 df=40 p=<0.001). From these results it is clear that the males have significantly stronger tibiae than the females, even after a correction has been made for differences in body size.

The males and females are equal in their anatomical shape indices with t=0.061 df=40 p=0.952 for Iy/Ix and t=-0.051 df=40 p=0.959 for Ix/Iy. A significant difference is present for the Imax/Imin index (t=2.537 df=40 p=0.015), indicating that the males have a significantly more elliptical cross-sectional shape than the females.

3.4 The non-dominant distal humerus

The cross-sectional properties of the non-dominant distal humerus of the males and females are presented in table 3.4. The sample consists of 18 males and 17 females.

Table 3.4. Cross-sectional properties of the non-dominant distal humerus, taken at 35% bone length for males and females. Significant results are in bold.

Property Non-dominant humerus 35%	Male Average (SD) N=18	Female Average (SD) N=17	Significance (p)
TA	864.13 (113.99)	850.44 (166.00)	.777
CA	634.73 (83.59)	637.97 (136.08)	.932
%CA	737.14 (63.62)	753.05 (77.22)	.509
Iy	2.36 (0.58)	2.26 (0.76)	.657
Ix	3.26 (0.65)	2.93 (1.02)	.259
Imax	3.33 (0.68)	3.00 (1.02)	.265
Imin	2.29 (0.54)	2,19 (0.76)	.648
J	5.62 (1.19)	5.19 (1.76)	.399
Iy/Ix	722.17 (87.16)	777.77 (88.46)	.070
Ix/Iy	1.40 (0.17)	1.30 (0.14)	.055
Imax/Imin	1.47 (0.14)	1.38 (0.12)	**.041**

Second moments of area are multiplied by 10 to the power six.

Some slight differences can be observed between the non-dominant distal humeri of the males and females, however, the only significant differences that can be observed at the 0.05 level is in the Imax/Imin index. The total subperiosteal area is roughly equal for the males and females (t=0.286 df=33 p=0.777). Equal average values are also observed for cortical area (t=-0.085 df=33 p=0.932). The percentage of cortical area therefore is also roughly equal with the female average slightly larger than the male average (t=-0.667 df=33 p=0.509).

The male average second moment of area about the antero-posterior axis (Iy) is slightly larger than the female average (t=0.449 df=33 p=0.657). The average second moment of area about the medio-lateral axis (Ix) is also larger in the males than the females, but statistical significance is not reached (t=1.148 df=33 p=0.259). The males display slightly larger average maximum second moments of area than the females (t=1,134 df=33 p=0.265). The males also display slightly larger mean values of minimum second moment of area (t=0.460 df=33 p=0.648). The average polar second moment of area is also slightly larger in the male sample compared to the female sample (t=0.885 df=33 p=0.399).

Both male and female humeri are stronger in the antero-posterior plane than the medio-lateral plane. The male humeri are more antero-posteriorly strengthened than the female humeri with t=-1.873 df=33 p=0.070 for Iy/Ix and t=1.987 df=33 p=0.055 for Ix/Iy. There is a significant difference in the Imax/Imin shape index (t=2.126 df=33 p=0.041), indicating that the males have significantly more elliptical distal humeri compared to the females.

3.5 The dominant distal humerus

The cross-sectional properties of the dominant distal humerus of the males and females are presented in table 3.5. The sample consists of 18 males and 17 females.

Table 3.5. Cross-sectional properties of the dominant humeri at 35% bone length for males and females. Significant results are in bold.

Property Dominant humerus 35%	Male Average (SD) N=18	Female Average (SD) N=17	Significance (p)
TA	895.40 (120.35)	882.76 (161.74)	.794
CA	659.22 (78.97)	661.20 (136.98)	.488*
%CA	73.94 (5.46)	75.13 (7.78)	.604
Iy	2.61 (0.66)	2.44 (0.80)	.493
Ix	3.43 (0.70)	3.13 (1.06)	.335
Imax	3.51 (0.75)	3.18 (1.07)	.298
Imin	2.52 (0.61)	2.38 (0.79)	.564
J	6.04 (1.34)	5.57 (1.84)	.394
Iy/Ix	0.76 (0.08)	0.79 (0.08)	.275
Ix/Iy	1.34 (0.13)	1.29 (0.13)	.264
Imax/Imin	1.41 (0.13)	1.34 (0.13)	.120

**Mann Whitney U non-parametric test. Second moments of area are multiplied by 10 to the power six.*

No statistically significant differences were found between the male and female dominant distal humeri after a correction had been made for differences in body size. The average total subperiosteal area of the dominant distal humeri is roughly equal for males and females after correcting for differences in body size (t=0.263 df=33 p=0.794). The values of cortical area failed Levene's Test for Equality of Variances (F=4.252 and p=0.047). The sample was therefore analysed with a Mann-Whitney U non-parametric test resulting in a non-significant difference between males and females (Z=-0.693 p=0.488). The percentage of cortical area also does not differ significantly between the sexes (t=-0.524 df=33 p=0.604).

No difference was found in mean medio-lateral bending rigidity (Iy) between the males and females (t=0.693 df=33 p=0.493). The same is observed for the antero-posterior second moment of area (Ix) (t=0.978 df=33 p=0.335). The average maximum second moment of area is slightly larger in the male sample but it does not significantly differ from the female average (t=1.057 df=33 p=0.298). The average minimum second moment of area is also slightly larger in the male sample, but again a statistically significant difference is not observed (t=0.583 df=33 p=0.564). No statistically significant difference was found in the average polar second moment of area either (t=0.863 df=33 p=0.394).

The shape indices indicate a more antero-posteriorly strengthened shape for the dominant distal humeri of both the males and the females, with the males slightly more strengthened in the antero-posterior plane than the females. The differences do not meet statistical significance (t=-1.111 df=33 p=0.275 for Iy/Ix and t=1.136 df=33 p=0.264 for Ix/Iy). The males show a larger average Imax/Imin shape index compared to the females, however the difference did not reach statistical significance (t=1.597 df=33 p=0.120).

It is remarkable that not a single significant difference was found between the males and females in the distal dominant humerus. This may indicate the practice of similar activities for men and women, or the practice of different activities that put similar mechanical loads on the humeri. The females display a higher amount of variability in the cross-sectional properties of the dominant humeri as evidenced by their higher standard deviations compared to the males.

3.6 Bilateral asymmetry of the distal humeri

The differences between the dominant and non-dominant distal humeri are presented in table 3.6 and figure 3.1. Bilateral asymmetry was calculated as 100*(dominant – non-dominant)/non dominant. The arm with the highest polar second moment of area (J) was chosen as the dominant arm, as J is a good measure for the (twice) average bending rigidity of the bone (see materials and methods: determination of cross-sectional properties). The mean difference between the male and female percentages was calculated by subtracting the female mean from the male mean. A positive value indicates that males have a higher mean percentage of bilateral asymmetry and a negative value indicates that the females have a higher mean percentage of bilateral asymmetry. The sample consists of 18 males and 17 females.

Table 3.6. Percentage bilateral asymmetry of the humeri at 35% bone length for males and females. All measurements are size. Significant results are in bold.

Property Bilateral asymmetry humerus 35%	**Male Average (SD) N=18**	**Female Average (SD) N=17**	**Mean Difference**	**Significance (p)**
TA	4.08 (3.05)	4.42 (4.20)	-0.34	0.785
CA	4.78 (4.54)	3.93 (4.20)	0.85	0.569
%CA	3.78 (2.87)	1.75 (1.37)	2.03	**0.019***
Iy	10.78 (7.21)	10.25 (8.90)	0.53	0.847
Ix	7.19 (6.36)	9.45 (8.98)	-2.26	0.395
Imax	7.42 (6.86)	9.00 (9.49)	-1.58	0.575
Imin	10.68 (6.24)	10.70 (9.55)	-0.02	0.993
J	8.02 (6.25)	8.64 (8.78)	-0.62	0.811
Ix/Iy	7.46 (4.42)	7.89 (5.27)	-0.43	0.797
Imax/Imin	6.92 (5.11)	9.15 (6.24)	-2.23	0.255

**Mann Whitney U non-parametric test.*

Bilateral asymmetry between the distal humeri is presented in table 3.6. The males and females do not differ much from each other in bilateral asymmetry. Bilateral asymmetry in the total area is about 4.1% for the males and 4.4% for the females (t=-0.275, df=33 p=0.785). Bilateral asymmetry in cortical area is 4.8% in the males and 3.9% in the females (t=0.575 df=33 p=0.569). The differences in percentage of cortical area failed Levene's test for the equality of variance. A non-parametric Mann-Whitney U tests was therefore performed, resulting in a significant difference (Z=-2.343 and p=0.019).

The males and females were roughly equal in bilateral asymmetry in the medio-lateral second moment of area with males showing 10.8% asymmetry and females showing 10.3% (t=0.194 df=33 p=0.847). The females on the other hand display slightly larger values of asymmetry in antero-posterior bending rigidity with a difference of 9.5% while the males display a difference of 7.2% (t=-0.863

df=33 p=0.395). The females also display slightly more asymmetry in maximum second moment of area with a value of 9.0% compared to 7.4% for the males (t=-0.567 df=33 p=0.575). The mean minimum second moment of area is equal in both sexes with a value of 10.7% for both males and females. The bilateral asymmetry of the polar second moment of area is 8.0% for the males and 8.4% for the females (t=-0.009 df=33 p=0.993).

The males have a bilateral asymmetry of about 7.5% in their anatomical shape indices while the females show a difference of 7.9% (t=-0.260 df=33 p=0.797). The males have an average bilateral asymmetry in the Imax/Imin shape index of 6.9% while the have a higher value of 9.2% (t=-1.159 df=33 p=0.255). The sexes are quite equal in terms of bilateral asymmetry. The only statistically significant difference is in the percentage of cortical area where the males have significantly more bilateral asymmetry than the females. The mean percentages of bilateral asymmetry of the distal humeri are presented in figure 3.1.

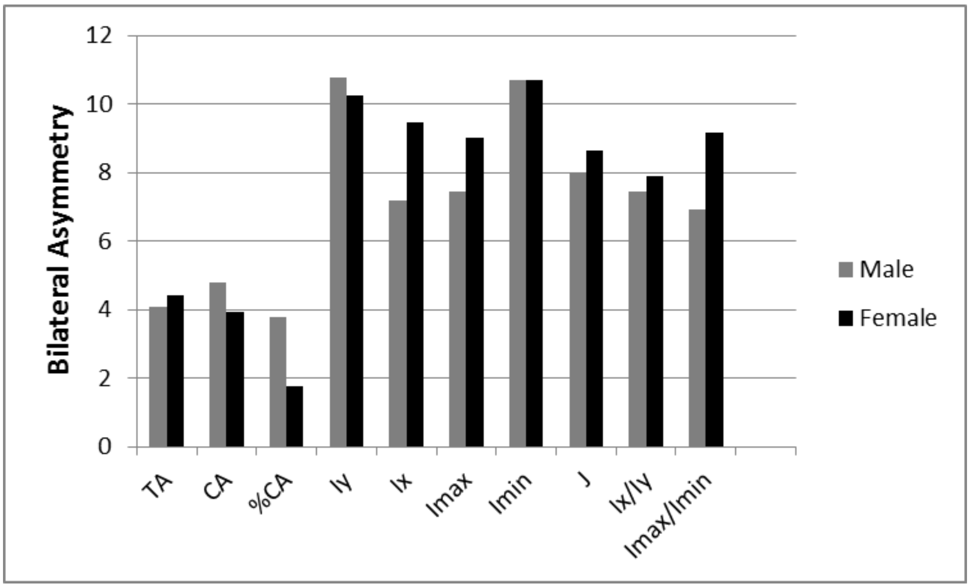

Figure 3.1. Average bilateral asymmetry of the distal humeri at 35% bone length. Males in grey, females in black.

3.7 The non-dominant humeral midshaft

The cross-sectional properties of the humeri of the Middenbeemster male and female samples are presented in table 3.7. The sample consists of 19 males and 17 females.

Table 3.7. Cross-sectional properties of the non-dominant humeri taken at 50% bone length for males and females. All measurements are size standardized. Significant results are in bold.

Property Non-dominant humerus 50%	Male Average (SD) N=19	Female Average (SD) N=17	Significance (p)
TA	944.58 (119.36)	890.12 (164.42)	.260
CA	660.99 (87.21)	650.17 (128.11)	.767
%CA	70.32 (7.56)	73.43 (7.81)	.234
Iy	3.10 (0.70)	2.84 (0.97)	.352
Ix	3.44 (6.90)	2.87 (0.95)	**.046**
Imax	3.89 (0.76)	3.39 (1.09)	.114
Imin	2.65 (0.60)	2.32 (0.78)	.160
J	6.54 (1.30)	5.71 (1.85)	.124
Iy/Ix	0.91 (0.13)	1.01 (0.19)	.261*
Ix/Iy	1.12 (0.16)	1.02 (0.18)	.083
Imax/Imin	1.49 (0.18)	1.48 (0.16)	.865

**Mann Whitney U non-parametric test. Second moments of area are multiplied by 10 to the power six.*

The males have slightly more robust non-dominant humeri than the females but the only significant difference is in antero-posterior bending rigidity (Ix). Males also show more antero-posteriorly strengthened humeri. The average total periosteal area is slightly larger in the males than in the females, statistical significance was not reached (t=1.146 df=34 p=0.260). The average cortical area was roughly equal in both the males and the females and no significant differences were observed (t=0.299 df=34 p=0.767). The females show a slightly higher average percentage of cortical area but the difference with the males is not significant (t=-1.213 df=34 p=0.234).

The average second moment of area about the antero-posterior axis (Iy) is higher in the male sample compared to the females, but the difference is not significant (t=0.944 df=34 p=0.352). The difference in the second moment of area about the medio-lateral axis (Ix) is significant (t=2.073 df=34 p=0.046). The males thus have significantly stronger non-dominant humeral midshafts in the antero-posterior plane. The males are stronger in their average maximum second moments of area but the difference does not reach significance (t=1.621 df=34 p=0.114). The males also display a higher average minimum bending rigidity but here statistical significance is not reached either (t=1.437 df=34 p=0.160). This results in a higher average polar second moment of area for the males compared to the females (t=1.578 df=34 p=0.124).

While the male average midshaft shape is more antero-posteriorly strengthened than the average female midshaft shape. The Iy/Ix shape index failed Levene's Test for Equality of Variances. Thus, a Mann-Whitney U non-parametric test was performed to assess significance. This resulted in a non-significant difference (Z=-1.125 and p= 0.261). The difference in Ix/Iy nears significance but fails to reach it (t=1.784 df=34 p=0.083). The male and female non-dominant humeral midshafts are equally elliptical and their Imax/Imin shape indices do not differ significantly (t=0.171 df=34 p=0.865).

The general trend appears to be that the males are slightly stronger than the females. This observation however is not supported by statistical analysis except for the antero-posterior second moment of area. The females show a larger variability in all of the cross-sectional properties, as evidenced by their higher standard deviations for all of the averages.

3.8 The dominant humeral midshaft

The cross-sectional properties of the humeri of the Middenbeemster male and female samples are presented in table 3.8. The sample consists of 19 males and 17 females.

Table 3.8. Cross-sectional properties of the dominant humeri taken at 50% bone length for males and females. All measurements are size standardized. Significant results are in bold.

Property Dominant humerus 50%	Male Average (SD) N=19	Female Average (SD) N=17	Significance (p)
TA	977.38 (119.54)	935.27 (178.82)	.407
CA	681.94 (79.02)	681.24 (140.92)	.985
%CA	70.19 (6.29)	73.08 (7.16)	.193
Iy	3.36 (0.72)	3.12 (1.11)	.451
Ix	3.66 (0.71)	3.19 (1.18)	.146
Imax	4.21 (0.78)	3.82 (1.41)	.301
Imin	2.80 (0.59)	2.48 (0.85)	.195
J	7.02 (1.34)	6.31 (2.21)	.245
Iy/Ix	0.92 (0.12)	1.00 (0.17)	.115
Ix/Iy	1.10 (0.16)	1.03 (0.17)	.174
Imax/Imin	1.52 (0.14)	1.54 (0.20)	.651

Second moments of area are multiplied by 10 to the power six.

The males display a slightly increased total periosteal area compared to the females, but the difference is not significant (t=0.839 df=34 p=0.407). Cortical areas are roughly equal between the male and female samples (t=0.019 df=34 p=0.985). The average percentage of cortical area is slightly higher in the females but the difference is not significant (t=-1.329 df=34 p=0.193).

The average second moment of area about the antero-posterior axis is slightly larger in the males but the difference is not significant (t=0.762 df=34 p=0.451). Average antero-posterior bending rigidity is also slightly larger in the males, but the difference is not significant either (t=1.488 df=34 p=0.146). The average maximum second moment of area is larger in the male sample compared to the female sample but the differences are not significant (t=1.050 df=34 p=0.301). The average minimum second moment of area is also larger in the male sample (t=1.322 df=34 p=0.195). The average polar second moment of area is larger in the males as well, but again the differences are not significant (t=1.183 df=34 p=0.245).

The male anatomical shape is slightly oval and more strengthened in the antero-posterior plane than the average female shape index. The differences in shape approach statistical significance but do not hold up at the 0.05 level (t=-1.617 df=34 p=0.115 for Iy/Ix and t=1.390 df=34 p=0.174 for Ix/Iy). The male and female samples are roughly equally elliptical with the females showing a slightly larger average. The Imax/Imin index did not differ significantly (t=0.456 df=34 p=0.651).

The females show a large amount of variation in their cross-sectional properties, as evidenced by their larger standard deviations compared to the males. This is exceptionally clear in the second moments of area where the standard deviation is roughly 36% of the average. The males appear to possess slightly stronger humeri than the females, however the differences are not statistically significant.

3.9 Bilateral asymmetry of the humeral midshaft

The differences between the cross-sectional properties of the dominant and the non-dominant humeral midshaft are presented in table 3.9 and figure 3.2.

Table 3.9. Bilateral asymmetry of the humeri at 50% bone length for males and females. All measurements are size standardized. Significant results are in bold.

Property Bilateral asymmetry humerus 50%	**Male Average (SD) N=18**	**Female Average (SD) N=17**	**Mean Difference**	**Significance (p)**
TA	3.70 (3.20)	5.23 (3.73)	-1.53	.196
CA	4.08 (4.94)	5.73 (5.29)	-1.65	.342
%CA	2.92 (2.36)	3.07 (2.73)	-0.15	.861
Iy	10.77 (7.78)	11.40 (10.73)	-0.63	.840
Ix	9.35 (9.00)	11.23 (10.62)	-1.88	.569
Imax	8.85 (8.47)	12.84 (11.50)	-3.99	.241
Imin	7.10 (7.30)	8.57 (7.97)	-1.47	.568
J	7.70 (7.63)	10.47 (9.28)	-2.77	.332
Ix/Iy	10.81 (10.22)	9.07 (9.20)	1.74	.595
Imax/Imin	5.91 (3.61)	8.71 (7.15)	-2.80	.141

The females show larger amounts of bilateral asymmetry in all of the cross-sectional properties except for the Ix/Iy index. No statistically significant differences were found between the dominant- and non-dominant humeral midshafts of the males and the females.

Bilateral asymmetry in total subperiosteal area is about 3.7% for the males and 5.2% for the females (t=-1.320 df=34 p=0.196). The bilateral differences in cortical area are 4.1% for the males and 5.7% for the females (t=-0.965 df=34 p=0.342). The percentage of cortical area does not differ much with values of 2.9% for the males and 3.1% for the females. Contrary to the distal humerus, the males and females do not differ significantly in the percentage of cortical area with (t=-0.177 df=34 p=0.861).

The average bilateral asymmetry for the medio-lateral second moment of area is 10.8% in the male sample and 11.4% in the female sample (t=-0.204 df=34 p=0.840). The average difference in the second moment of area about the medio-lateral axis is about 9.4% for the males and 11.2% for the females (t=-0.575 df=34 p=0.569). The bilateral asymmetry in maximum bending rigidity is 8.9% in the males and 12.8% in the female (t=-1.193 df=34 p=0.241). The bilateral asymmetry in minimum bending rigidity is 7.1% for the males and 8.6% in the females (t=-0.577 df=34 p=0.568).

The Ix/Iy index is the only cross-sectional property where the males possess higher bilateral asymmetry than the females in the humeral midshaft. The male humeri differ 10.8% while the female humeri differ 9.1% (t=0.536 df=34 p=0.595). The average bilateral asymmetry is 5.9% in the male sample and 8.7% in the female sample with (t=-1.506 df=34 p=0.141).

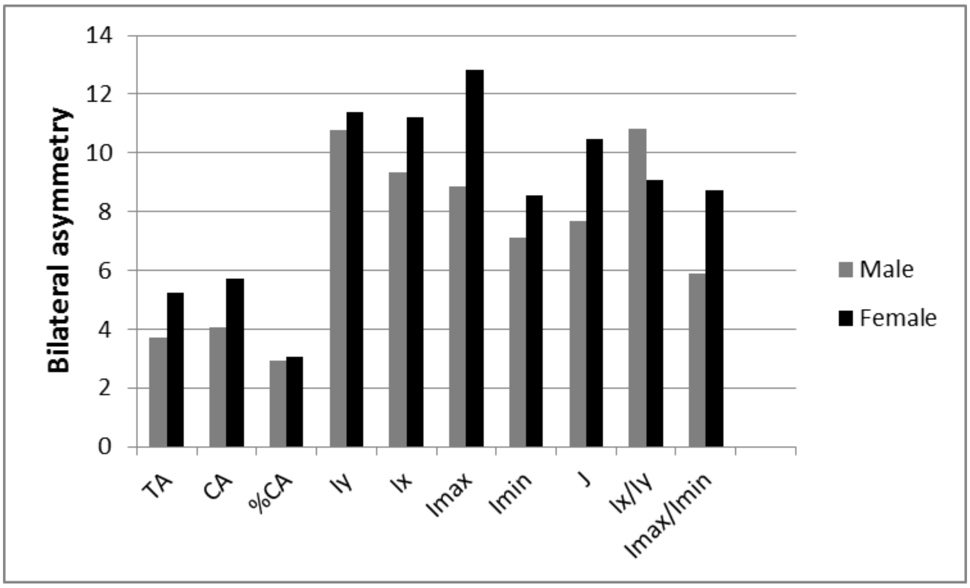

Figure 3.2. bilateral asymmetry of the humeri at 50%. Males are in grey, females are in black.

3.10 Effects of age

To assess whether or not age has an effect on the cross-sectional properties, a selection of cross-sectional properties of the femur are plotted against four age classes. These age classes consist of: Early Young Adults 18-25 (EYA), Late Young Adults 26-35 (LYA), Middle Adults 36-49 (MA), and Old Adults 50+ (OA). The effects of age on mean polar second moment of area is presented in figure 3.3.

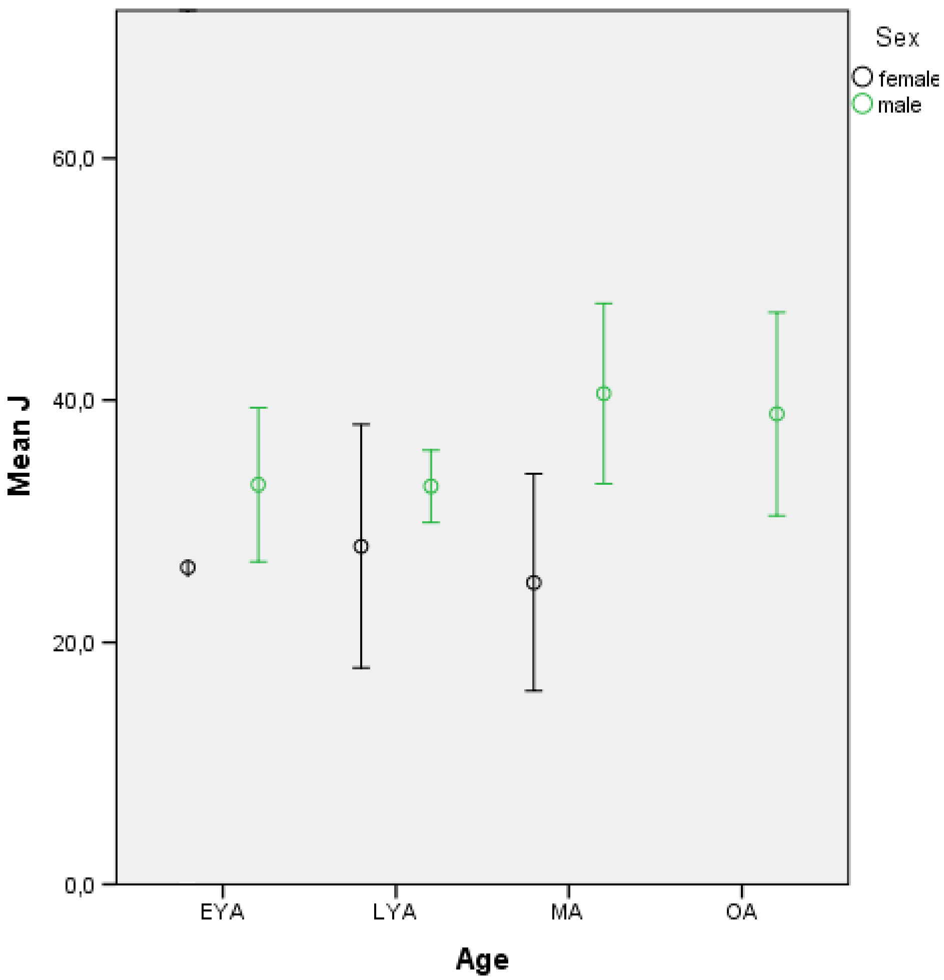

Figure 3.3. Mean±1SD polar second moment of area of the femoral midshaft per age class. Number of males per age class: 6 EYA, 8 LYA, 5 MA, 3 OA. Number of females per age class: 2 EYA, 8 LYA, 10 MA, 0 OA.

The polar second moment of area of the femoral midshaft appears to increase slightly with age in the males and reduce slightly in females. Taking into account the small amount of individuals within age classes it is assumed that mean polar second moment of area is roughly equal between the age classes. This indicates that the older Middenbeemster individuals possessed equally strong bones as the younger portion of the sample.

The effects of age on the percentage of cortical area of the femoral midshafts of the Middenbeemster males and females are presented in figure 3.4.

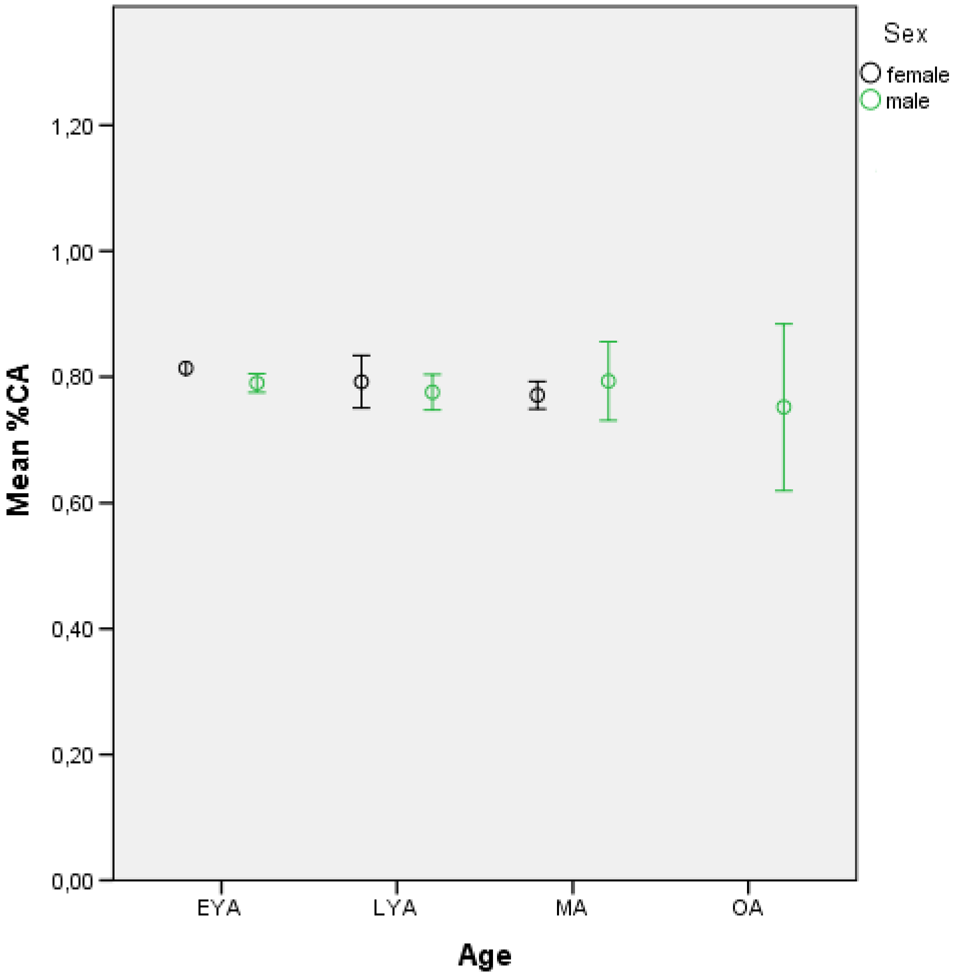

Figure 3.4. Mean±1SD percentages of cortical area of the femoral midshaft, plotted against age classes. Number of males per age class: 6 EYA, 8 LYA, 5 MA, 3 OA. Number of females per age class: 2 EYA, 8 LYA, 10 MA, 0 OA.

The mean percentage of cortical area appears to slightly decreases per age class. However, all results remain within one standard deviation from each other. It can therefore be concluded that the percentage of cortical area is roughly equal between the four age classes.

The effects of age on the femoral midshaft shape of both males and females from the Middenbeemster sample are presented in figure 3.5.

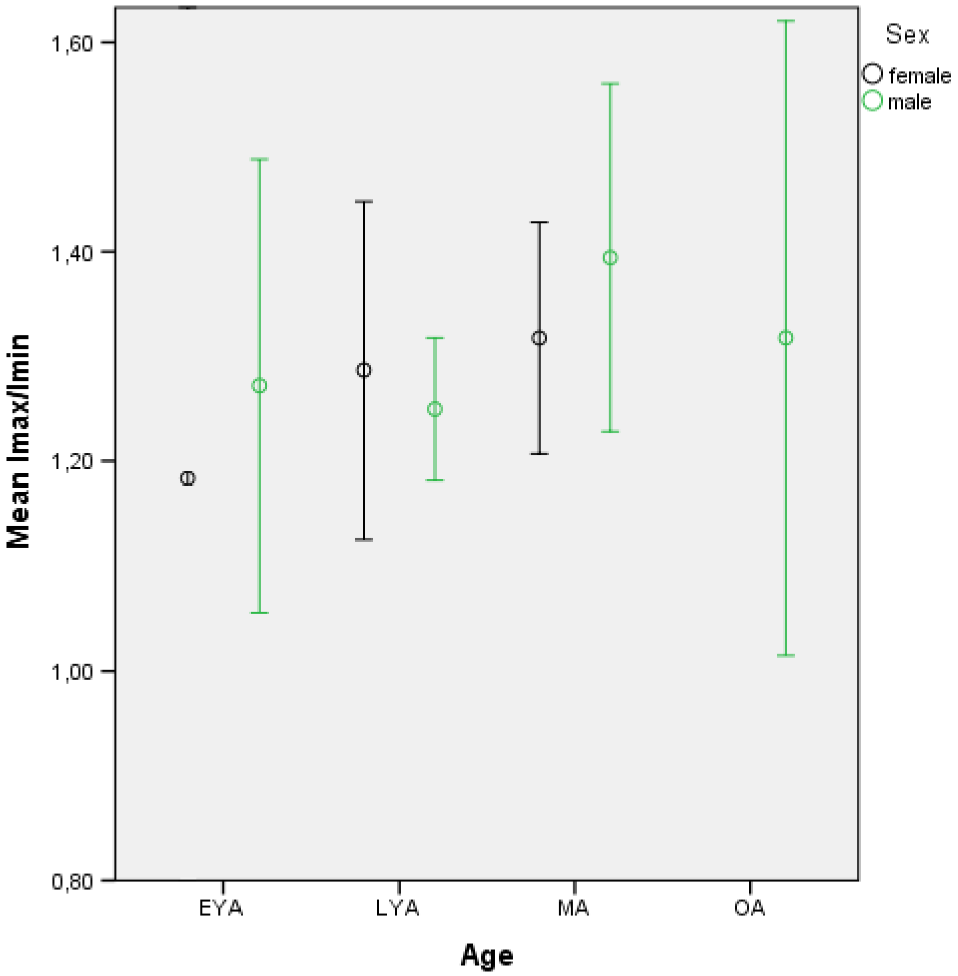

Figure 3.5. Mean±1SD Cross-sectional shape index of the femoral midshaft, plotted against age classes. Number of males per age class: 6 EYA, 8 LYA, 5 MA, 3 OA. Number of females per age class: 2 EYA, 8 LYA, 10 MA, 0 OA.

Figure 3.5 appears to show a slight increase in cross-sectional shape with age. All measurements do stay within one standard deviation from the rest. The small sample sizes most likely affect a large portion of the observed variation. It is concluded that age also has no substantial effect on the diaphyseal femoral midshaft shape.

3.11 Summary

The males displayed larger averages for most of the cross-sectional properties in the lower limbs as well as the upper limbs. Few of these differences however are statistically significant. In the femora only the polar second moment of area of the femoral midshaft differ significantly. This indicates that the male femora are indeed significantly more robust at midshaft than those of the females. The distal femora did not show any significant differences although some trends were visible. The females showed a more medio-laterally strengthened distal femoral shape than the males (p=0.057).

Unlike the femora, the tibiae showed a lot of sexual dimorphism as many of the cross-sectional properties of the tibiae displayed highly significant differences. The tibiae of the males were significantly stronger than those of the females, even when corrected for differences body size. The anatomical shape indices however, are quite similar and do not differ significantly. The males had significantly more elliptical tibiae compared to the females, as evidenced by their significantly larger Imax/Imin index. This indicates that the directions of the mechanical loads that were placed upon the tibiae during life were similar, but that the males were subjected to significantly heavier mechanical loads. This will be discussed in more detail in the discussion section.

The males and females displayed few differences in the non-dominant distal humeri. There appeared to be slight differences in the anatomical shape indices, but none reached the 0.05 level. The males did have significantly more elliptical distal humeri than the females. The dominant distal humeri were also very similar in terms of average strength as well as in shape. Bilateral asymmetry ranged between 5% and 10% for both males and females in the second moments of area. The only noticeable difference between the male and female samples in bilateral asymmetry is found in the shape indices where the males display more asymmetry than the females. The differences between the dominant and the non-dominant humeri did not reach statistical significance in the male and the female samples.

The only significant difference found at the humeral midshaft was the second moment of area about the medio-lateral axis of the non-dominant humerus. Here the males showed a significantly higher average value than the females. Differences in the average shape were also observed but they did not meet statistical significance at the 0.05 level. Similar differences were observed in the dominant humeri but again the results were not significant. The females showed higher bilateral asymmetry for all of the cross-sectional properties that were discussed. The bilateral asymmetry did not reach significance in either the males or the females.

The effects of age on the cross-sectional properties of the sample was assessed by plotting a selection of cross-sectional properties of the femur against four age categories. No significant effect of age was found on the cross-sectional properties of the Middenbeemster males and females.

4. Discussion

In this section the results for the lower and upper limbs will be put into cross-cultural context through comparisons with extant and past populations. The lower limbs will be discussed in the context of mobility. The humeri will be discussed as an indicator for differences in manual activities. Issues that exist with the sample used in this study will also be discussed. Finally, the sexual division of labour in nineteenth century Middenbeemster will be explored. For background information on the comparative samples the reader is referred to Appendix A.

4.1 Discussion of lower limbs in context: mobility

The act of moving across the landscape places mechanical loads on the lower limbs. When mobility increases, the amount of mechanical loading also increases. It is therefore expected that more mobile individuals possess stronger lower limbs than less active individuals. In this section the cross-sectional properties of the femur and the tibia are put into context by comparison to modern and archaeological populations.

The percentage of femoral diaphyseal cortical area has been reducing exponentially from the birth of the genus *Homo* in the Early Pleistocene, until the present (Ruff et al. 1993). Fossils attributed to the species *Homo erectus* have the largest percentage of cortical area. The increased diaphyseal robusticity in our hominid ancestors has been interpreted as being the result of both medullary contraction (stenosis) and periosteal expansion compared to modern humans (Ruff et al. 1993). Articular robusticity however, has not seen such a temporal decline. Articular to shaft proportions therefore have changed during human evolution. Ruff and colleagues (1993) argue that a mechanical explanation is the most likely for this phenomenon. This is in agreement with observations from studies on athletes compared to control groups such as the study performed by Shaw and Stock 2009a. In their study two athletic samples consisting of field hockey players and cross-country runners, showed a significant increase in the percentage of tibial cortical area compared to the non-athletic control group. The cross-country runners had a mean %CA of 79,9%, the hockey players had a mean %CA of 79,5%, while the non-athletic control sample has a mean %CA of 74,6%. The individuals from Middenbeemster have a relatively high percentage of femoral midshaft cortical area compared to modern populations. Both Middenbeemster males and females have average percentages of cortical area around 78% on the femoral midshaft. These percentages are comparable to Early Modern humans, as well as the athletic samples from Shaw and Stock (2009a). Medieval and Neolithic agricultural Italian male and female samples show similar average values of percentage cortical area in the femoral midshaft of around 76% (Sparacello and Marchi 2008). The Middenbeemster males and females display an average percentage of cortical area of 65% on the distal femur, comparable to Archaic *Homo sapiens* (Ruff et al. 1993).

The average percentages of cortical area of the distal femur and the femoral midshaft, through the course of human evolution are presented in figure 4.1. One should keep in mind that the recent *Homo sapiens* sample is a pooled sex sample consisting of a collection of 300 Amerindian foragers and horticulturalists from different sites as well as twenty modern U.S. white autopsy samples. The recent *Homo sapiens* sample therefore consists of a wide range of modern human populations and ranges from 47 to 88% cortical area at the midshaft (Ruff et al. 1993). Both the Middenbeemster males and females display percentages of cortical area that are most comparable to the Archaic *Homo sapiens* sample albeit around two percent lower.

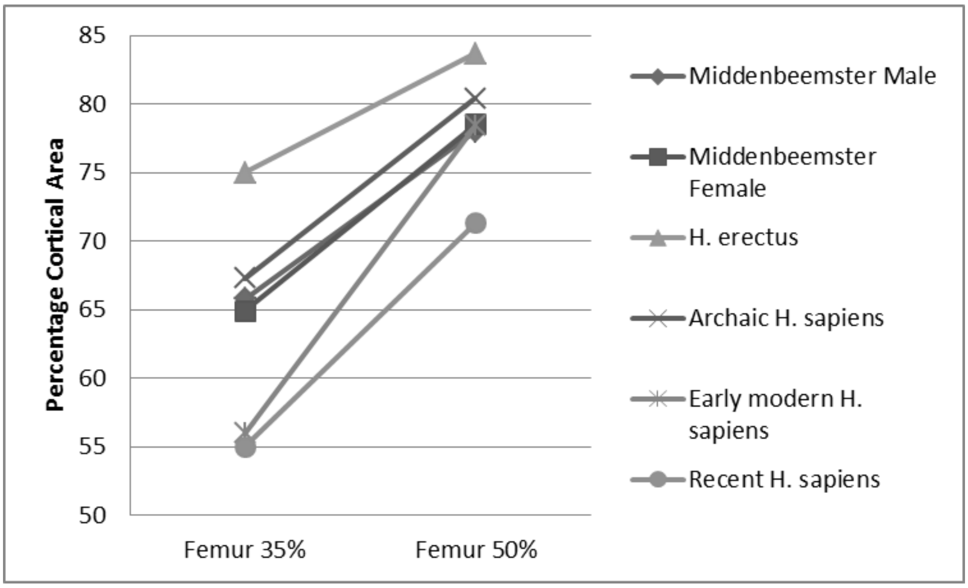

Figure 4.1. Percentages of cortical area of the Middenbeemster males and females compared to hominids and modern humans. Comparative data from Ruff et al. 1993.

These data suggest that the Middenbeemster sample consists of active individuals on the higher portion of the modern human range. However, the contribution of genetics to the observed percentages should be considered. A study on individuals of Chinese and Japanese descent by Garn and colleagues (1964) showed that they have less cortical thickness than white referent populations, and this tends to remain small in first generation immigrants to the United States. Individuals of Asian birth showed an average cortical mass that was 1.37 standard deviations below the comparative white sample. Although there was an increase in American-born Asians, the cortical mass still showed an average that was 1.19 standard deviations below the white control group (Garn et al. 1964). Garn and colleagues concluded that cortical bone mass must be at least partly genetically mediated due to its persistence in American-born Asians. One also has to keep in mind that structural rigidity is not only obtained by bone mass but also by bone shape.

The shape indices of the distal femora of the Middenbeemster males and females are presented in table 4.1 along with a modern and an archaeological reference sample. One should keep in mind that differences in bone positioning when taking cross-sections may have a noticeable effect on the results. This is a danger present in using samples taken by different researchers when comparing differences in shape. Maximum second moments of area and shape indices are regarded as more reliable than the anatomical shape indices as they are not influenced by errors in positioning.

Table 4.1. Diaphyseal cross-sectional shape indices of the distal femora of the Middenbeemster sample compared to other populations.

Femur 35%	**Ix/Iy Mean (SD)**		**P**	**Imax/Imin Mean (SD)**		**p**
Sample (n)	M	F		M	F	
Middenbeemster (m22, f22)	0.93 (0.14)	0.88 (0.09)	0.057	1.19 (0.11)	1.21 (0.10)	n.s.
Modern U.S. (m23, f24)	1.02 (0.02)	0.99 (0.04)	n.s.	1.18 (0.20)	1.27 (0.03)	<0.01
Pecos Pueblo (m59, f60)	1.21 (0.03)	1.07 (0.02)	<0.001	1.36 (0.03)	1.18 (0.02)	<0.001

n.s. = not significant. M = male, F = female.

Both the Middenbeemster males and females show predominantly medio-laterally strengthened distal femora. This is unusual compared to the other populations presented in table 4.1. The Middenbeemster females have more medio-laterally strengthened distal femora than the males, and even one standard deviation above the mean does not reach antero-posterior strengthening. The males that are one standard deviation above the mean do reach the point of antero-posterior strengthening. The modern U.S. samples display quite rounded femora with the males slightly more antero-posteriorly strengthened and the females slightly more medio-laterally, although this difference is not significant. The females show a significantly more elliptical shape in the U.S. white sample. The Pecos males have significantly more antero-posteriorly strengthened femora than the females. They also have significantly more elliptically shaped distal femora compared to the females. The Middenbeemster and U.S. white samples are similar in mean Imax/Imin shape. The females have comparable Imax/Imin shape indices while the Pecos males are larger than the males of the other populations. In terms of sexual dimorphism the Middenbeemster sample is not comparable to any of the above mentioned samples, due to the fact that there are no significant differences in shape of the distal femora in the Middenbeemster sample. The Middenbeemster males and females appear to differ in mean Ix/Iy index but statistical significance is not reached (p=0.057). A larger sample size may provide a clearer distinction between the Middenbeemster males and females.

Medio-laterally strengthened distal femora are quite uncommon. Active individuals generally have more antero-posteriorly strengthened diaphyses, while inactive (modern urban) individuals have relatively circular shapes (Ruff 1987, Ruff 2008, Pearson et al. 2006). Possible factors contributing to this unusual femoral diaphyseal shape will be explored below.

The mean second moments of are of the Middenbeemster males and females are presented in table 4.2.

Table 4.2. Mean second moments of area of the distal femur of the Middenbeemster males and females.

Femur 35%	**Ix Mean (SD)**		**Iy Mean (SD)**		**Imax Mean (SD)**		**Imin Mean (SD)**		**J Mean (SD)**	
Sample (n)	M	F	M	F	M	F	M	F	M	F
Midden-beemster (m22, f22)	179.19 (27.02)	161.58 (40.77)	195.76 (39.32)	186.20 (42.37)	204.11 (38.71)	189.98 (42.61)	170.85 (25.26)	157.79 (39.60)	374.96 (61.75)	347.78 (81.38)

The Middenbeemster males show larger means for all of the second moments of area presented in table 4.2. None of the observed differences reach statistical significance due to the large amount of variability in both sexes. The females display larger standard deviations in all of the second moments of area indicating that the females were more variable in mobility levels than the males. Unfortunately no suitable comparative samples could be found for the second moments of area of the distal femoral diaphysis.

The shape indices of the femoral midshaft of the Middenbeemster sample and comparative samples are presented in table 4.3.

Table 4.3. Diaphyseal cross-sectional shape indices of the femoral midshaft of the Middenbeemster sample compared to other populations.

Femur 50%	**Ix/Iy Mean (SD)**		**P**	**Imax/Imin Mean (SD)**		**p**
Sample (n)	M	F		M	F	
Middenbeemster (m22, f21)	0.94 (0.21)	0.90 (0.14)	n.s.	1.30 (0.14)	1.29 (0.16)	n.s.
Modern U.S. (m23, f24)	1.21 (0.04)	1.23 (0.05)	n.s.	1.24 (0.03)	1.28 (0.04)	n.s
Pecos Pueblo (m59, f60)	1.14 (0.03)	1.05 (0.02)	<0.01	1.48 (0.03)	1.29 (0.02)	<0.001
Georgia Coast Pre-Agri. (m8, f12)	1.28 (0.05)	1.16 (0.06)		1.34 (0.07)	1.22 (0.04)	
Georgia Coast Agri. (m11, f9)	1.08 (0.05)	1.03 (0.05)		1.28 (0.05)	1.23 (0.03)	
Ligurian Neolithic (m9, f8)	1.40 (0.17)	1.19 (0.20)	<0.05			
Ligurian Medieval (m12, f9)	1.17 (0.20)	1.04 (0.08)	n.s.			

n.s. = not significant.

It can be observed in table 4.3 that pre-agricultural populations show more sexual dimorphism in femoral midshaft shape than agricultural populations, and that industrial populations display less sexual dimorphism than agricultural populations (see also figure 1.2). The Pecos Pueblo sample is very dimorphic. The Geogia Coast agricultural sample is not very dimorphic, similar to Middenbeemster. The Middenbeemster sample displays much larger standard deviations compared to the rest of the samples. The Middenbeemster sample is the only sample in which the femoral midshaft is more strengthened in the medio-lateral plane than in the antero-posterior plane. The male modern U.S., Pecos Pueblo, pre-agricultural Georgia Coast and both Ligurian samples are heavily strengthened in the antero-posterior plane. The female Neolithic Ligurian, pre-agricultural Georgia Coast and modern U.S. samples are heavily strengthened in the antero-posterior plane as well. There is not much variation in the circularity index (Imax/Imin) between the females of all the samples. The males display more variation in the Imax/Imin index. The modern U.S. males have the most circular diaphyses, as evidenced by their lowest mean Imax/Imin relative to the other males. The Pecos Pueblo males have extremely elliptical femoral midshafts. The Middenbeemster males are in the middle, having slightly larger means than the Georgia Coast agriculturalists and slightly smaller means than the Georgia Coast pre-agriculturalists. The Middenbeemster sample shows the least sexual dimorphism in circularity of the femoral midshaft.

The midshaft second moments of area of the Middenbeemster males and females compared to two Ligurian samples are presented in table 4.4.

Table 4.4. Diaphyseal cross-sectional second moments of area of the femoral midshaft of the Middenbeemster and Ligurian samples.

Femur 50%	**Ix Mean (SD)**		**Iy Mean (SD)**		**Imax Mean (SD)**		**Imin Mean (SD)**		**J Mean (SD)**	
Sample (n)	M	F	M	F	M	F	M	F	M	F
Midden-beemster (m22, f21)	167.93 (21.83)	155.30 (35.26)	186.86 (44.38)	176.66 (46.42)	200.72 (39.28)	187.34 (51.97)	154.07 (20.32)	144.63 (28.33)	354.80 (57.35)	264.36 (114.78)
Ligurian Neolithic (m9, f8)	273.66 (77.43)	221.19 (45.67)	194.57 (46.56)	188.84 (18.71)					468.22 (121.51)	410.03 (58.20)
Ligurian Medieval (m12, f9)	256.64 (29.12)	180.74 (26.48)	221.41 (41.32)	173.45 (23.81)					478.06 (62.39)	354.20 (48.41)

Unfortunately no suitable modern samples were available for comparison of the femoral midshaft second moments of area. The Ligurian samples originate from the same geographic area, within a few miles of each other and they lived during similar climatic conditions. The Neolithic sample consists of highly mobile pastoralists, while the Medieval sample consists of a sedentary fishing community. In all of the second moments of area presented in table 4.4, the males show larger mean values than the females. In the Middenbeemster sample the only significant difference between the males and females is found in the polar second moment of area (J). The Ligurian Medieval sample shows much more sexual dimorphism than the Ligurian Neolithic sample, indicating a decrease in female mobility in the Medieval Ligurians. This matches historical data of the females performing more sedentary tasks. The mean sexual dimorphism in polar second moment of area is 34.2% in Middenbeemster which is comparable to the sexual dimorphism of the Ligurian Medieval sample which has a mean sexual dimorphism of 35.0%. The Neolithic sample displays less sexual dimorphism with a mean of 14.2%. In the Middenbeemster sample the females show more variability in second moments of area, indicating more variation in mobility among females. In the Ligurian samples on the other hand, the males show much more variability. A striking difference between the Middenbeemster sample and the Italian samples is that the Middenbeemster males and females are much more gracile.

A large difference between the populations presented in table 4.4 is the terrain across which they travel during their daily activities. Liguria is a coastal region in Northwestern Italy, located between the mountains and the sea, and consists of rugged, hilly terrain (Sparacello and Marchi 2008). In contrast, the Beemster polder is a completely flat piece of land. Several studies have shown that the type of terrain has a substantial effect on lower limb robusticity (Pearson et al. 2006, Ruff 1999). As the ruggedness of terrain decreases, the femoral midshaft robusticity decreases as well (see figure 1.3). It is expected that the observed differences in second moments of area are at least partly influenced by the large contrast in the ruggedness of the terrain between the Italian and Dutch samples.

Sparacello and Marchi (2008) argue that terrain plays a large role in the strength of the lower limbs but not in shape, a conclusion that was also reached by Ruff (1999) who did not find any correlation between femoral midshaft shape and terrain type. Sparacello and Marchi argue that diaphyseal strength correlates with terrain while diaphyseal shape correlates with levels of mobility. However, the shape of the femoral midshafts of the populations presented in table 4.3 do not agree with this observation. The modern U.S. have highly antero-posteriorly strengthened femoral midshafts even though they are the least mobile group. They do, however, have the most circular midshafts. These observations indicate that the relationship between diaphyseal midshaft shape and mobility is not as straightforward as Sparacello and Marchi suggest. It appears that the relationship between mobility and diaphyseal shape holds up between genetically close-related and/or geographically similar groups such as The Ligurian and Georgia Coast populations. However, interpreting this relationship between less similar populations is much more problematic. A large influence on the diaphyseal shape of the lower limbs, apart from mobility, are body proportions (Ruff 2008, Shaw and Stock 2011). The effects of body proportions on the cross-sectional shape of the lower limbs will be discussed below.

The cross-sectional shape of the tibial midshafts of the Middenbeemster males and females are presented in table 4.5 along with comparative samples.

Table 4.5. Diaphyseal cross-sectional shape indices of the tibial midshaft of the Middenbeemster sample compared to modern and archaeological samples.

Tibia 50%	**Ix/Iy Mean (SD)**		**P**	**Imax/Imin Mean (SD)**		**p**
Sample (n)	M	F		M	F	
Middenbeemster (m21, f21)	1.39 (0.32)	1.39 (0.33)	n.s.	2.26 (0.36)	2.01 (0.29)	0.015
Modern U.S. (m23, f24)	1.54 (0.06)	1.46 (0.06)	n.s.	2.15 (0.11)	2.04 (0.08)	n.s.
Pecos Pueblo (m59, f60)	1.94 (0.06)	1.81 (0.05)	n.s.	3.15 (0.08)	2.70 (0.07)	<.001
Runner (m15)				2.60 (0.50)		
Hockey (m15)				2.22 (0.27)		
Modern U.K. (m20)				2.28 (0.28)		

n.s. = not significant.

As in the femur, the Middenbeemster tibial midshafts are less strengthened in the antero-posterior plane than the comparative populations. One should keep in mind that the cross-sections of the comparative populations were obtained by different authors, and that differences in the anatomical positioning of the bones may have occurred. The maximum/minimum bending rigidity indices are not affected by differences in placement and should be considered as more reliable. The males and females of the agricultural populations consisting of Middenbeemster and Pecos Pueblo differ significantly in maximum/minimum bending rigidity while the modern industrial U.S. whites do not. This may be indicative of a difference in mobility between the agricultural males and females.

The effects of mobility patterns on the cross-sectional shape of the tibia is demonstrated clearly by the modern British athletic samples (Shaw and Stock 2009a). The runner's display significantly more elliptical tibiae than the hockey players and the non-athletic control sample. Shaw and Stock (2009a) explain this observation as the result of adaptation to different types of mechanical loadings between the three samples. Cross-country running consists of running in a generally straight line, subjecting the lower limbs to predominantly antero-posterior loadings. As a result the tibiae of the runners are strengthened in the antero-posterior plane. The hockey players on the other hand often have to change direction rapidly, subjecting the lower limbs to mechanical loadings from many different directions. As a result the tibiae of the hockey players are adapted to mechanical loads from multiple directions by distributing bone more equally within the cross-section, resulting in a more "rounded" shape. The non-athletic control group has a significantly more circular cross-sectional shape than the cross-country runners. The hockey players have an even less elliptical mean tibial midshaft shape, but the difference is not significant (Shaw and Stock 2009a). Differences in mobility are therefore expected to be visible in the circularity index (Imax/Imin), similar to the differences between the cross-country runners and the non-athletic control group.

The Middenbeemster male Imax/Imin shape index is roughly similar to the modern U.K. control sample. The Middenbeemster females display a less elliptical cross-sectional shape than the Middenbeemster male, and the U.K male control sample. The males and the females are equally strengthened in the antero-posterior plane, evidenced by their equal Ix/Iy indices. The males however, have more elliptically shaped tibial midshafts, as indicated by their significantly larger mean Imax/Imin index. This difference is comparable to the difference between the cross-country runners and the non-athletic controls. The significant difference between the male and female Imax/Imin can therefore be interpreted as a consequence of a difference in levels of mobility.

Shaw and Stock (2011) have demonstrated a significant relationship between relative pelvic breadth (bi-iliac breadth/length measurements) and the diaphyseal shape of the tibia and the femur, where a wider relative pelvic breadth is correlated to higher medio-lateral strengthening of the lower limbs. Medio-laterally strengthened lower limbs are more often found in females due to their relatively wider pelvic breadths compared to males (Ruff 2008). In males these cross-sectional shapes are found in cold-adapted populations such as the Inuit or Neanderthals (Ruff 1995, Shaw and Stock 2011, Trinkaus 1997, Trinkaus and Ruff 2012), as well as many other species of early *Homo* (Trinkaus and Ruff 2012). This can be attributed to Bergmann's rule and Allen's rule stating that individuals adapted to colder environments possess shorter limbs and broader bodies compared to individuals that inhabit the lower latitudes. This increases relative pelvic breadth (bi-iliac breadth/bone length) and results in higher medio-lateral loads on the lower limbs due to the more acute angle of the lower limbs to the pelvis.

The observation that relative body breadth influences the diaphyseal shape of both the femur and the tibia may help to explain the unusual medio-lateral strengthening of the Middenbeemster femora described above, as well as the lack of antero-posterior strengthening of the Middenbeemster tibiae relative to comparative samples. The modern Dutch are currently the tallest population in the world, standing about two inches taller than the number two (Maat 1995, de Swaan 1989). They are also amongst the broadest populations in the world (C. Shaw, personal communication). It is somewhat unclear what is the cause behind this phenomenon. Improved nutrition from the 1850's onward undoubtedly contributed to an increase in height (Maat 1995). An often cited explanation for the large size of the modern Dutch is a relatively large consumption of dairy products, as well as good healthcare (Frederiks et al. 2000). If the large size of the Dutch is indeed (partly) caused by a large proportion of dairy products in the diet, this may also explain the relatively large mean body sizes of the Middenbeemster population, as the majority of the Beemster's inhabitants were dairy farmers.

To investigate whether or not the unusual shapes of the femoral and tibial diaphyses are caused by body breadth, the bi-iliac breadths of the

Middenbeemster males and females will have to be measured. Relative body breadth can then be assessed by dividing the bi-iliac breadth by the relevant bone lengths (Shaw and Stock 2011). Unfortunately, the assessment of the effects of body shape on the lower limbs of the Middenbeemster sample exceeds the scope of the current study. It should be a priority in future biomechanical research concerning the Middenbeemster population.

There are multiple additional factors that may have had an effect on the final limb bone morphology observed in the Middenbeemster population. One theoretical explanation relates to the flatness of the terrain as a possible contributor. One can imagine that walking up or down a hill places significantly more antero-posterior stress on the lower limbs than walking across flattened terrain. While this may not be the cause of the medio-lateral strengthening of the lower limbs, it is possible that less antero-posterior strengthening is required when traversing only flat terrain. While this may work in theory, no correlation has been found so far between differences in terrain and differences in lower limb geometry (Ruff 1999, Sparacello and Marchi 2008).

Other explanations include a genetic pre-disposition towards medio-laterally strengthened lower limbs, or a lifetime of medio-lateral loading while performing specific activities. The latter seems unlikely, especially when taking into account the flatness of the Beemster terrain. In summary, with the currently available data a number of factors may account for the unusual cross-sectional shapes observed in the lower limbs of the Middenbeemster sample.

The second moments of area of the male and female tibial midshafts of the Middenbeemster sample and modern U.K. samples are presented in table 4.6.

Table 4.6. Diaphyseal second moments of area of the tibial midshaft of the Middenbeemster sample compared to modern athletes.

Tibia 50%	**Ix Mean (SD)**		**Iy Mean (SD)**		**Imax Mean (SD)**		**Imin Mean (SD)**		**J Mean (SD)**	
Sample (n)	M	F	M	F	M	F	M	F	M	F
Midden-beemster (m21, f21)	199.51 (41.61)	156.87 (47.04)	147.58 (33.25)	113.77 (22.17)	240.76 (51.31)	180.29 (44.67)	106.34 (14.13)	90.35 (19.68)	347.10 (61.91)	270.64 (61.13)
Hockey (m15)					319.60 (37.68)		145.80 (21.91)		465.40 (51.06)	
Runner (m15)					359.31 (42.26)		142.03 (28.62)		501.34 (78.11)	
U.K. Control (m20)					264.60 (42.26)		116.44 (12.04)		381.04 (79.14)	

Unfortunately, no suitable modern industrial or archaeological comparative data was available for the female tibiae. The Middenbeemster males have significantly higher means compared to the females for all of the cross-sectional properties displayed in table 4.6. Both the hockey players and cross-country runners display significantly higher cross-sectional moments of area than the non-athletic control group. This is a clear indication that increased mobility levels correlate with increased tibial robusticity (Ruff 1983a,b, Shaw and Stock 2009a, Stock 2006). The fact that the males and females differ significantly in tibial midshaft shape and strength points towards the conclusion that there were differences in mobility between the Middenbeemster males and females.

The Middenbeemster male tibiae are more gracile than the modern U.K. athletes. This is not a surprising result as the modern British athletes are well nourished and lead very active lives. However, the Middenbeemster males are also more gracile than the British non-athletic control group. This is unexpected as the Middenbeemster individuals are thought to have been a highly active population. A study on musculoskeletal stress-markers in combination with osteoarthritis in the upper limbs of the Middenbeemster population indicated regular heavy labour, with osteoarthritis showing up as early as 25 years of age (J. Palmer, in prep., personal communication). There are many factors besides activity that determine a bone's cross-sectional rigidity. An important factor in bone growth is adequate nutrition. Historical data suggests that there were many periods of nutritional stress in the Beemster region from the seventeenth to the nineteenth century. Cattle plagues and potato blights caused periods of severe famine in the region (Arblaster 2006). Knibbe (2007) writes that the Dutch population was generally well fed in the beginning of the nineteenth century. The amount of food deteriorated up to the 1870's. Harvests failed in 1830, 1838, and 1841. The effects of these harvest failures was slightly mitigated by grain imports (Knibbe 2007). The potato blights of 1846-1847 had more severe consequences on nutrition, especially in the lower classes but also affecting the middle classes that were usually able to feed themselves properly (Bergman 1969). In the fifties harvest failures coincided with the Crimean War, making the imports of food very expensive. During the fifties the availability of food was at the lowest level of the entire period (Knibbe 2007). The decrease in the availability of food, the increase in food prices, and a decrease in wages resulting in severe hunger amongst the lower classes (Bergman 1969). Finally, Bergman (1969) writes that in the nineteenth century foreigners noted that:

> *"the Dutch labourer was physically weak and that he took great quantities of liquor. Dutch authors blamed the potato for this."* (Bergman 1969, 392)

A study of dental hypoplasia in the Middenbeemster population is currently being undertaken, with preliminary results showing frequent periods of growth impingement, most likely as a consequence of nutritional stress or disease (A. Meurrens, in prep., personal communication). Cowgill (2010) researched the effects of nutritional stress on subadult postcranial robusticity by comparing a nutritionally stressed population to adequately fed populations. The nutritionally stressed population showed much lower subadult postcranial robusticity. Nutritional stress affects modelling and remodelling of bone, and provides less energy for activity that stimulates bone growth. Nutritional deficiency additionally affects the mothers, resulting in small children (Cowgill 2010). It is therefore plausible that inadequate nutrition may be partly responsible for the low level of lower limb robusticity compared to modern industrial populations.

A striking difference is evident between the results of the tibial- and femoral midshafts. Sexual dimorphism in the femoral midshaft only reaches statistical significance in the polar second moment of area. Sexual dimorphism in the tibial midshaft reaches statistical significance in all of the cross-sectional geometric properties except for Ix/Iy and %CA. The opposite was expected due to the inherent differences in pelvic breadth between males females. It was expected that this inherent difference in body width would affect the proximal lower limbs to a greater extent than the distal elements. Stock (2006) provides an answer to this apparent discrepancy. Stock argues that patterns of correlation between mobility and robusticity generally increase from the proximal to the distal lower limbs. He suggests that there is a stronger relationship between patterns of diaphyseal hypertrophy and differences in habitual behaviour between groups in the distal elements. Despite this trend, femoral midshaft shape indices show the strongest correspondence with terrestrial mobility, particularly among males from different populations (Stock 2006). The lower limb results partly agree with Stock’s (2006) findings in that the male tibial midshafts are significantly stronger than the females. The males also possess significantly stronger femoral midshafts, however, Stock argues that femoral midshaft shape correlates best with differences in mobility. Femoral midshaft shape does not differ significantly between the Middenbeemster males and females. Besides differences in mobility levels, there are many different factors that influence diaphyseal shape. The effects of body breadth, as well as the additional possible factors discussed above, on the cross-sectional geometry of the Middenbeemster sample are not known at this time. Without proper knowledge about these variables, differences in lower limb strength, evidenced by cortical bone area and second moments of area are regarded in this study as more reliable. Due to the significant differences in strength observed in the lower limbs, it is concluded that there was a difference in the general mobility patterns of males and females in Middenbeemster, where the average male was more mobile than the average female.

4.2 Discussion of upper limbs in context: manual activities

In this section the dominant- and non-dominant humeri are put into a global context through comparison with other archaeological and athletic groups. Temporal trends do not exist for the lower limbs besides the fact that bilateral asymmetry in males has generally been reducing since the Middle Palaeolithic (Trinkaus et al. 1994). Trends are difficult to spot due to the large amount of manual activities that are performed by an individual during life and the multitude of directions in which mechanical forces can be applied. Past populations are generally more robust than modern industrial societies (Ruff 1987). This decrease in robusticity has been interpreted as the result of a decline in activity in more modern populations (Ruff 2008). Hunter-gatherers generally possess more robust upper limbs than agricultural populations, and agricultural populations are generally more robust than industrial populations. Although exceptions are sometimes found, for example by Bridges (1989) where workloads increased significantly for females with the adoption of maize agriculture in the Southeastern United States.

The majority of the Beemster population consisted of dairy farmers. Other known professions are, but are not limited to: shopkeepers, soldiers stationed in neighbouring forts, clerks, gentlemen farmers, carpenters, and priests (Falger et al. 2012). For the majority of the population the milking of cows would have been an activity that was regularly performed, as well as carrying containers of milk. As the Beemster is a drained landscape, constant management of water was necessary. This most likely included the digging of ditches. When digging the dominant arm is often used for steering while the non-dominant and is used for the heavy lifting. If a lot of digging was performed by the inhabitants of the Beemster, this is expected to increase the strength of the non-dominant arm reducing bilateral asymmetry.

In this part of the discussion the results for the distal humeri will be put into context through comparison with athletic and non-athletic modern samples as well as archaeological assemblages. Variation in Ix/Iy and Imax/Imin will be explored to assess variation in the directions of humeral strengthening. The polar second moment of area will be used to assess the general rigidity of the distal humeri of the Middenbeemster males and females compared to other samples. Bilateral asymmetry in polar second moment of area and shape indices will be used to assess the extent of bilateral versus unilateral activities. Due to the presence of the deltoid muscle insertion in a large portion of the humeral midshaft cross-sections, true cross-sectional properties could not be assessed. The deltoid muscle insertion distorts the shape of the cross-section as well as the amount and distribution of bone across the section. The humeral midshaft will therefore not be discussed further in this study.

The shape indices of the non-dominant distal humeri are presented in table 4.7 along with comparative archaeological and athletic samples.

Table 4.7. Diaphyseal cross-sectional shape indices of the non-dominant distal humeri of the Middenbeemster sample and comparative samples.

Non-Dominant Humerus 35%	**Ix/Iy Mean (SD)**		**P**	**Imax/Imin Mean (SD)**		**p**
Sample (n)	M	F		M	F	
Middenbeemster (m18, f17)	1.40 (0.17)	1.30 (0.14)	.055	1.47 (0.14)	1.38 (0.12)	.041
Ligurian Neolithic* (m9, f8)	1.10 (0.09)	1.12 (0.15)	n.s.			
`Ligurian Medieval* (m12, f9)	1.25 (0.18)	1.28 (0.15)	n.s.			
Swimmers (m15)				1.48 (0.28)		
Cricket (m16)				1.57 (0.15)		
U.K. non-athletic (m20)				1.60 (0.29)		

**Dominant is right and non-dominant is left.*

n.s. = not significant.

The non-dominant distal humeri of the Middenbeemster females are significantly less elliptical than those of the males. The males show more antero-posteriorly strengthened distal humeri compared to the females, however this difference just fails to reach statistical significance at the 0.05 level. The Ligurian samples differ significantly from eachother, with the Neolithic sample displaying much less antero-posterior strengthening of the non-dominant humerus. The Middenbeemster females show a similar diaphyseal Ix/Iy shape index to the Ligurian Medieval females. The Middenbeemster males are not similar in Ix/Iy to any of the comparative samples used in table 4.7. The Modern British non-athletic control group has the most elliptical non-dominant distal humeri. The Middenbeemster females have the least elliptical non-dominant distal humeri of the samples presented in table 4.7. Due to anatomical differences between male and female humans, some slight inherent variation is expected in humeral shape. These differences in upper body shape are not expected to be as pronounced as the differences in the lower limbs, and are not expected to lead to significantly different diaphyseal shapes for males and females.

The significant differences in diaphyseal shape of the non-dominant distal humeri amongst the Middenbeemster males and females may indicate different habitual loading histories. The Middenbeemster males have more antero-posteriorly strengthened humeri, as well as more elliptical humeri than the females. This indicates that the male humeri are more adapted to mechanical loads from a single direction. The females were more adapted to loads from multiple directions and torsional mechanical stress. A possible explanation for these observations is that males tended to engage more in activities that included the lifting of heavy objects which produced antero-posterior mechanical stress. The females are more adapted to loads from different directions, such as in circular motions. This may be an indication that females were more often engaged in domestic activities such as washing, cleaning, and food processing where more circular motions are common.

The cross-sectional diaphyseal shape of the dominant distal humeri are presented in table 4.8.

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Table 4.8. Diaphyseal cross-sectional shape indices of the dominant distal humeri of the Middenbeemster- and comparative samples.

Dominant Humerus 35%	**Ix/Iy Mean (SD)**		**P**	**Imax/Imin Mean (SD)**		**p**
Sample (n)	M	F		M	F	
Middenbeemster (m18, f17)	1.34 (0.13)	1.29 (0.13)	.264	1.41 (0.13)	1.34 (0.13)	.120
Ligurian Neolithic* (m9, f8)	1.12 (0.09)	1.12 (0.17)	n.s.			
Ligurian Medieval* (m12, f9)	1.19 (0.16)	1.25 (0.12)	n.s.			
Swimmers (m15)				1.54 (0.21)		
Cricket (m16)				1.45 (0.20)		
U.K. non-athletic (m20)				1.66 (0.21)		

**Dominant is right and non-dominant is left.*

n.s. = not significant.

In contrast to the non-dominant humeri, no significant differences were found between the dominant distal humeri of the Middenbeemster males and females. The males tend to have more elliptical humeri than the females but the difference does not reach significance at the 0.05 level.

It is worth mentioning that in both the dominant- and the non-dominant distal humeri the non-athletic males show the most elliptical diaphyses. This is not unexpected as swimming places mechanical stress on the humeri in varying directions, while cricket players are subjected to severe torsional loadings while bowling. The cricket players differ significantly from the non-athletic control group. The throwing motion places severe torsional stress on the humerus. A more rounded humeral diaphysis is better adapted to cope with torsional stress (Shaw and Stock 2009b). The differences in shape between the dominant and the non-dominant arms of the cricket players are very marked, and as expected the dominant humerus is significantly more rounded than the non-dominant humerus. The Middenbeemster females have the most circular mean diaphyses, followed by the Middenbeemster males and the cricket players. The Middenbeemster males and females possess more medio-laterally strengthened distal humeri than the Ligurian samples. As with the non-dominant humeri the Middenbeemster females are quite comparable to the Medieval Ligurian females. None of the agricultural samples show a significant difference in antero-posterior strengthening between males and females.

The dominant male humeri are slightly less strengthened in the antero-posterior plane than the non-dominant humeri. This is not unexpected as the dominant arms is often used in more varied activities than the non-dominant humerus which is mainly used for lifting. The female average Ix/Iy shape index is roughly equal between the dominant and the non-dominant humeri. No significant differences were found at the 0.05 level in any of the populations presented in table 4.8. This does not mean that there was an absence of sexual differences in behaviour. Marked sexual differences in behaviour have been noted historically for the Ligurian Medieval sample (Sparacello and Marchi 2008), yet no significant differences in shape were observed. Thus, while the absence of sexual differences in upper limb shape is not indicative an absence of a sexual division labour, the presence of sexual differences in shape most likely does indicate differences in habitual activities.

The interpretation of humeral cross-sectional shape is not without difficulties, as a specific diaphyseal shape may be caused by a number of different factors. For example, a high Ix/Iy shape index can be related to bending generated by flexion and extension of the elbow joint (Rhodes and Knüsel 2005). Intense use of the finger and wrist flexors and the elbow flexors can lead to a large development of the superior extensions of the supraepicondylar ridges, resulting in an increase of Iy (Ruff and Larsen 2001). Reduction in the use of these muscles leads to a reduction in Iy, and thus an increase in Ix/Iy. This index then appears to show antero-posterior strengthening of the humeri while in reality it is showing a lack of medio-lateral strengthening. This example illustrates that the interpretation of behaviour from humeral cross-sectional shape is difficult. The interpretation can be strengthened by also adding values of robusticity to the assessment. This will be done below.

Bilateral asymmetry in the shape of the distal humeri of the Middenbeemster sample is presented in table 4.9 along with comparative samples.

Table 4.9. Bilateral asymmetry in shape of the distal humeri of the Middenbeemster sample and comparative samples.

Bilateral Humerus 35%	**Ix/Iy Mean (SD)**		**P**	**Imax/Imin Mean (SD)**		**p**
Sample (n)	M	F		M	F	
Middenbeemster (m18, f17)	7.46 (4.46)	7.89 (5.27)	0.797	6.92 (5.11)	9.15 (6.24)	0.255
Towton Swordsmen (m13)	28.07					
Fishersgate (m9)	6.25					
Swimmers (m15)				10.58		
Cricket (m16)				12.07		
U.K. non-athletic (m20)				10.24		
Ligurian Neolithic (m9, f8)	5.59	7.15				
Ligurian Medieval (m12, f9)	6.51	7.90				

The Middenbeemster population shows less mean bilateral asymmetry in distal humerus shape than the modern British athletic and non-athletic samples. Both Middenbeemster males and females show very little bilateral asymmetry compared to the modern British samples. This could be an indication that both males and females were involved in more bimanual activities than modern British urban individuals. The highest amount of bilateral asymmetry in humeral shape is found in the Towton swordsmen sample (Rhodes and Knüsel 2005). Unilateral use of the dominant limb during weapons training resulted in significantly different shapes between the dominant and non-dominant humeri in the Towton sample. This is contrasted by the contemporary non-military Fishersgate sample that was used by Rhodes and Knüsel as a comparison (Rhodes and Knüsel 2005). The Ligurian Medieval males appear to be quite comparable in bilateral asymmetry with the Middenbeemster males showing the highest level of asymmetry. The Ligurian Medieval females and the Middenbeemster females are identical in bilateral asymmetry as was also the case in the dominant and non-dominant humeri. The Middenbeemster females are more asymmetrical in the circularity index than the males, although statistical significance is not reached. The Middenbeemster males and females both show less bilateral asymmetry than the modern samples in the circularity index. A lower amount of bilateral asymmetry indicates more frequent loading of both arms in similar directions, rather than just one arm. This explains the high levels of asymmetry in the shape of the Towton swordsmen and cricket samples, that are reached due to their habitual unilateral loadings.

The polar second moments of area, as well as the bilateral asymmetry in the polar second moments of area of the Middenbeemster sample and comparative samples are presented in table 4.10.

Table 4.10. Mean torsional rigidity and bilateral asymmetry of the dominant and non-dominant humeri of the Middenbeemster sample and comparative samples. Measures of J are size standardized.

Humerus 35%	**J Dominant Mean (SD)**		**J Non-Dominant Mean (SD)**		**J Bilateral asymmetry Mean (SD)**	
Sample (n)	M	F	M	F	M	F
Middenbeemster (m18, f19)	6.04 (1.34)	5.57 (1.84)	5.62 (1.19)	5.19 (1.76)	8.02 (6.25)	8.64 (8.78)
Euroamerican* (m25, f13)					8.73	10.76
Georgia Coast* (m19, f18)					9.90	4.94
Jomon* (m10, f13)					6.44	9.83
Tennis players (m34, f11)					74.56	39.14
Swimmers (m15)	252.26 (58.31)		235.97 (44.00)		7.94 (5.75)	
Cricketers (m16)	287.63 (72.09)		215.79 (60.49)		35.00 (13.78)	
U.K. Controls (m20)	200.53 (69.17)		178.58 (52.01)		11.81 (8.19)	
Ligurian Neolithic* (m6, f8)	268.31 (66.28)	162.69 (22.66)	236.92 (43.96)	162.88 (19.11)	16.57	3.93
Ligurian Medieval* (m10, f8)	211.13 (46.86)	150.92 (20.77)	204.52 (42.77)	148.96 (26.59)	9.44	5.60
Middenbeemster Alternate (m18, f16)**	201.64 (16.44)	166.46 (36.11)	188.95 (18.16)	154.50 (36.06)	6.94 (6.99)	8.44 (6.92)

Middenbeemster second moments of area are multiplied by 10 to the power six.

**Dominant is right and non-dominant is left.*

*** See forthcoming explanation.*

In this study the humeri were size standardized by dividing the raw second moments of area by bone length to the power 5.33. The modern British athleteand control samples, as well as the Ligurian samples were size standardized using a different method from the one used in this thesis, therefore values of polar second moment of area are not comparable with Middenbeemster. Body size was therefore also standardized using the alternate method to make Middenbeemster comparable to these samples. This alternate method standardizes body size in the same way as the lower limbs; by dividing the raw second moment of area by the product of body mass and the square of bone length. The Middenbeemster sample that was standardized through the use of this method is presented in table 4.10 as “Middenbeemster alternate”.

Within the Middenbeemster alternate sample the differences in polar second moment of area between the dominant distal humeri of the males and females are statistically significant (as assessed with a Mann-Whitney U non-parametric test, Z=-3.105 and p=0.002). A Mann-Whitney U non parametric test showed that the difference in polar second moment of area between the non-dominant distal humeri of the males and females is also statistically significant (Z=-2.933 and p=0.003). In both the dominant and the non-dominant humeri the males are therefore significantly more robust than the females. In the alternately standardized sample the males show significant bilateral asymmetry in several cross-sectional properties including the polar second moment of area (t=-2.209, p=0.034). The females did not display any significant differences in cross-sectional properties between the dominant and the non-dominant arms in the alternatively standardized sample. The cross-sectional properties of the Middenbeemster males and females that were size standardized according to the alternate method are presented in appendix D.

It is striking that there are no significant differences between the Middenbeemster males and females, while both the dominant- and non-dominant humeri in the Middenbeemster alternate sample do display significant differences in second moments of area. It was not expected that the two methods of body size standardization would yield such disparate results. Fortunately, the lower limbs were all standardized using the same method, therefore this problem will not affect the lower limb interpretation. Shape indices do not need to be size standardized, therefore they are not affected by this issue either. A plausible explanation for the large difference that is observed between the two samples is that the female sample is reduced by three individuals in the Middenbeemster alternate sample. The differences in bilateral asymmetry that are observed between the two body size standardizations were less surprising. The more robust (dominant) arms are usually slightly larger than the less robust (non-dominant) arms. As the Middenbeemster humeri were size-standardized by dividing by bone length to the power 5.33, the larger and often more robust bone will therefore be divided by a higher number, reducing the bilateral asymmetry. This occurs to a much lesser extent in the Middenbeemster alternate sample which is size standardized by the product of body mass and the square of bone length. In the following section the differences in polar second moment of area of the Middenbeemster alternate sample will be compared to the Ligurian and modern U.K. samples. When second moments of area are being discussed the Middenbeemster alternate sample will simply be referred to as Middenbeemster.

The Middenbeemster males are equal to the modern U.K. control group in the polar second moment of area of the dominant humerus, albeit with a much lower standard deviation. The non-dominant humeri of the Middenbeemster males are more robust than the modern British males. The Middenbeemster males possess slightly lower mean values of torsional rigidity than the Ligurian Medieval males in both the dominant and the non-dominant distal humeri. The Middenbeemster females have more robust dominant humeri than both the Neolithic and the Medieval Ligurian females. However, the values of polar second moment of area of the Ligurian samples presented in table 4.10 are of the right and the left humerus, rather than the dominant- and the non-dominant humeri. This means that the dominant value is underestimated while the non-dominant value is over-estimated. It is therefore likely that the Medieval females are again similar to the Middenbeemster females in humeral robusticity. The U.K. controls have the lowest values of polar second moment of area of all the males presented in table 4.10. The cricket players have the highest values of torsional bending rigidity of the dominant humeri of all the males, while their non-dominant humeri are much less robust. This was expected due to the high amount of unilateral loadings placed on the humeri in cricket. The swimmers have high values of polar second moment of area in both arms. This also matches expectations due to the high level of bilateral loading that is experienced when swimming (Shaw and Stock 2009b). The Middenbeemster males have the lowest standard deviations of all the populations presented in table 4.10, indicating very little variability in polar second moment of area. As with all of the previously discussed limbs the females have much higher standard deviations, indicating much more variability in humeral rigidity, and possibly more variation in regularly performed tasks.

Large values of bilateral asymmetry are observed in the tennis players, cricketers, and the male Ligurian Neolithic sample. In the athletic samples this large percentage of bilateral asymmetry can be explained by the great amounts of unilateral loadings experienced when hitting the ball with the racquet for tennis players and throwing the ball in the cricket players. The Ligurian Neolithic economy was based on pastoralism and consisted of highly combative warrior-sheperds. The relatively large value of bilateral asymmetry observed in the males is thought to be the result of extensive weapons training and manual deforestation performed with one-handed stone axes (Sparacello and Marchi 2008).

The Middenbeemster males have a lower average bilateral asymmetry than the females, although the difference is not very pronounced. From the results presented in table 4.10 it appears that bilateral asymmetry in polar second moment of area between 9 and 11 % is common for modern industrial populations when observing the results of the male U.K. control sample and male and female Euroamericans. A closer look at table 4.10 however, reveals the difficulties in interpreting values of bilateral asymmetry. No clear distinctions can be made based on subsistence strategy due to the lack of general trends in bilateral asymmetry. This is evidenced by the observation that the pattern of sexual dimorphism in bilateral asymmetry is roughly similar between the Jomon and the Euroamerican samples. The Jomon were marine and terrestrial hunter-gatherers with a clear sexual division of labour (Knobbe 2010, Trinkaus et al. 1994), while the Euroamericans come from a sedentary industrial population where sexual division of labour is less pronounced (Trinkaus et al. 1994).

Some general observations can be made from the upper limb data that was presented in this section. The Middenbeemster females are almost identical to the Ligurian Medieval females in shape, bilateral asymmetry, and strength of the dominant and the non-dominant humeri. While this observation does not mean that the exact same activities were performed. It is indicative of equal levels of mechanical stress that were experienced in similar directions. The males do not show any exact similarities to any of the samples discussed in this study. This is not unexpected as none of the comparative male samples shared similar economic activities with the Middenbeemster males.

The Middenbeemster males are more gracile than the Ligurian and athletic male samples. The males are equal to the modern British non-athletic sample in the average rigidity of the dominant humerus, and possess slightly stronger non-dominant humeri. This indicates that the Middenbeemster males used their non-dominant arms relatively more often and/or in more strenuous activities than the modern U.K. industrial males. This may be an indication for the lifting of heavy objects that require the use of both arms. Another possibility is the frequent use of a shovel or pitchfork, in which the non-dominant arm is often used for lifting while the dominant arms is used for steering. The females show a higher average bilateral asymmetry than the males, indicating that the females performed more unilateral tasks.

The Middenbeemster males have significantly stronger dominant and non-dominant humeri compared to the females after body size standardization. This is indicative differences in habitual upper limb loading where the males were experiencing significantly higher mechanical loads than the females. The males have the lowest standard deviations of all the samples presented in table 4.10 indicating little variability in humeral strength between the males. As was the case in the lower limbs the females display a much higher standard deviation than the males. This indicates more variability in humeral strength in the Middenbeemster females and possibly the performance of more variable activities between females.

4.3 Causality and general sample issues

A prominent issue with the current study is that there are no genetically and geographically similar populations with which to compare the Middenbeemster sample. When comparing cross-sectional geometric properties it is preferable to have comparative material with the same genetic background. Terrain and climate also exert a substantial influence on diaphyseal lower limb morphology and rigidity (Pearson 2000, Stock 2006). An ideal comparative sample would be from a contemporary Dutch population, so that the effects of genetics and terrain are controlled for. While the comparison of the Middenbeemster population to modern and archaeological populations from all over the world has its issues, the variation in the sexual dimorphism within these populations provide a good interpretive framework from which conclusions on the extent of sexual division of labour within the Middenbeemster sample can be drawn. Sexual differences in activity patterns are known for these populations and the resulting dimorphism can safely be used to place the results from Middenbeemster into a wider context.

The comparative samples used in this study were taken by various authors. All authors followed the same procedures for aligning bones as this study. However, slight differences in positioning are undoubtedly present between the Middenbeemster sample and the comparative samples, resulting in slightly different values of cross-sectional properties such as the anatomical shape index (Ix/Iy). Ideally all measurements would have been taken by the same author.

Another problem with the comparative samples used in this study is that most of the cross-sectional properties of these samples were not obtained from CT scans or direct sectioning but from a combination of periosteal moulding and radiography. O’Neill and Ruff (2004) and Stock (2002) have noted that cross-sectional properties obtained with radiometric methods overestimate second moments of area. This suggests that second moments of area of samples that were obtained with radiometric methods may be inflated compared to the actual values. The cross-sectional properties of the following groups were obtained through a combination of periosteal moulding and radiography: Modern U.S., Georgia Coast, Pecos Pueblo, Euroamerican, Jomon, and the Ligurian Neolithic. The remaining samples used in this study were obtained through direct sectioning or CT scanning and should therefore be more accurate.

All cross-sectional properties were corrected for differences in body size, however, body shape was not. Body shape (bi-iliac breadth/length) is a large factor contributing to the cross-sectional shape of the lower limbs (Ruff 2000b, Shaw and Stock 2011). The contribution of differences in body shape is unknown for the Middenbeemster sample used in this study. Unfortunately, correcting for variation in body breadth is beyond the scope of the current study. Correcting for differences in body shape will allow a more accurate estimation of the factors that contributed to the medio-lateral strengthening of the Middenbeemster femoral midshafts. It is currently hypothesized that a wide body shape is responsible for a large portion of the unusual medio-lateral strengthening of the femoral midshafts. This hypothesis will need to be tested in future efforts.

The Middenbeemster sample consists males and females ranging in age from young adulthood to old adulthood. It is well known from modern clinical research that elderly individuals often lose large quantities of bone resulting in osteopenia or osteoporosis, especially post-menopausal women (Ruff 2008). It has been noted that active populations do not suffer from osteoporosis as much as modern industrialized populations (Ruff 2008, 198, Ruff and Hayes 1988). An assessment was made of the effects of age on the cross-sectional properties of the Middenbeemster males and females. The mean polar second moment of area, mean percentage of cortical area, and the mean circularity index of the Middenbeemster males and females were plotted against four age classes (figures 3.3, 3.4, and 3.5). This resulted in no clear decrease with age for any of the cross-sectional properties. The observation that the percentage of cortical area does not decrease much with age may be an indication that the Middenbeemster populations was more active than modern industrial populations.

The Dutch are currently the tallest population in the world. The average height of the Dutch population started increasing rapidly between AD 1850 and 1900 (Maat 1995). However, most of the Middenbeemster collection predates this occurrence. Body size was estimated by taking the average of three different equations, as recommended by Pomeroy and Stock (2012) for populations of average height. The equation by McHenry (1992) was designed to be applied to small "pygmy" populations. The equation by Grine et al. (1995) is designed to be applied to especially large populations. The equation by Ruff et al. (1991) is based on modern U.S. whites and was scaled downwards by 10% to account for the increased adiposity of recent U.S. adults (Ruff et al. 1991). By using the average of the three methods, body size may have been over-or underestimated. This is not known as the equations have not been tested on Dutch populations.

A biased sample was created by excluding individuals with movement impairing pathologies from the sample used in this study. There is a good chance that some of the individuals from the sample had movement impairing illnesses that did not show up skeletally. The exclusion of individuals with osteoarthritis was done to conform to most published cross-sectional geometric studies. The idea behind this choice is that osteoarthritis limits the movement of limbs and hinders normal activity. However, the exclusion of individuals with osteoarthritis may have led to the exclusion of the most active portion of the population (see: Wood et al. 1992).

Finally, the Middenbeemster sample consists of individuals that have been buried over a period of 200 years. The majority of the sample is from the nineteenth century as the cemetery was cleaned out in 1829. However, it is likely that a portion of the sample predates the nineteenth century, as the individuals that were buried the deepest and the ones buried on the periphery of the centre of the cemetery were not removed. The individuals that make up the sample may have grown up in different economic settings. Certain periods in the history of the Beemster were marked by severe famine, war and disease, while other periods saw wealth and economic growth (Arblaster 2006). Whether a person grew up in a period of famine or wealth will have had a large effect on the development of the skeletal system and therefore on the cross-sectional geometric properties of that individual. Until more data is recovered from the historical records, the effects of growing up in different historical periods can only be speculated upon.

4.4 Discussion of sexual division of labour

The null-hypothesis states that there was no sexual division of labour in the Beemster polder between the seventeenth and the late nineteenth century. If the null hypothesis is correct very little sexual dimorphism should be present in the lower- and upper limbs after correcting for body size. In modern industrial societies where no marked sexual division of labour is present, sexual dimorphism ranges between zero and two percent (Pearson et al. 2006, Ruff 1987). If sexual dimorphism is higher than two percent the null-hypothesis will be rejected. Three broad scenarios were established in the event that the null hypothesis was rejected. As formal hypotheses these are:

1. Males and females differed in mobility and performed different tasks. In this case significant sexual dimorphism should be observed in the lower limbs and in the upper limbs.
2. Males and females differed in mobility, but otherwise performed the same tasks. Significant sexual dimorphism should be observed in the lower limbs but not in the upper limbs.

3. There was no difference in mobility between males and females but different tasks were performed involving the upper limbs. Significant sexual dimorphism should be observed in the upper limbs but not in the lower limbs.

In this section the extent of sexual dimorphism within the Middenbeemster sample will be discussed, followed by a conclusion on which hypothesis correlates best with the gathered data.

According to Stock (2006) femoral midshaft shape correlates best with levels of mobility. Ruff (1987) found that sexual dimorphism in femoral midshaft antero-posterior relative to medio-lateral bending rigidity is greatest in hunter-gatherers (8-36%), intermediate in agricultural groups (2-9%), and the least dimorphic in industrial societies (0-2%). The Middenbeemster sample shows a sexual dimorphism of 4.1% in femoral antero-posterior/medio-lateral bending rigidity (Ix/Iy). Thus, sexual dimorphism in Ix/Iy bending rigidity is twice as high as would be expected from a modern industrial urban population. This places Middenbeemster at the lower end of the agricultural range of femoral midhaft sexual dimorphism. This is expected for a sedentary nineteenth century Western-European agricultural population. The place of the Middenbeemster sample between populations with a range of different subsistence strategies is presented in figure 4.2.

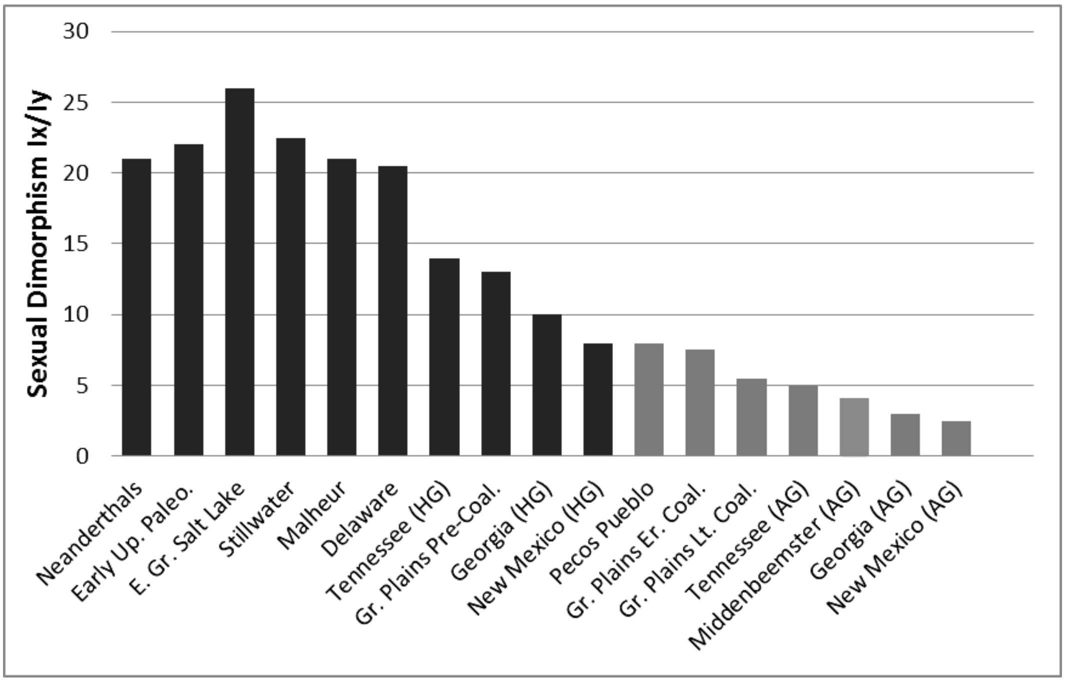

Figure 4.2. Sexual dimorphism in femoral midshaft AP/ML bending rigidity (Ix/Iy). Hunter-gatherers are in black, agriculturalists are in grey. Corrected for body size. Modified from Ruff 2000a, 85.

The Middenbeemster males and females both have a percentage of femoral midshaft cortical area of around 78%. This percentage is relatively high compared to modern industrial populations, U.S. whites for example have an average of around 70% (Ruff 1987). The Ligurian Neolithic pastoralists and Medieval fisherman described in Sparacello and Marchi (2008) show equally high percentages of midshaft cortical area of around 76%. A high amount of sexual dimorphism was found in the Ligurian samples, and a marked sexual division of labour was likely present in both groups. Sexual division of labour is documented historically for the Medieval sample (Sparacello and Marchi 2008). However, there are no significant differences in the percentages of cortical area of the femoral midshaft in the Ligurian populations. In the study by Shaw and Stock (2009a), the non-athletic control group showed a significant difference to the athletic samples in the percentage of cortical area of the tibia. In the Middenbeemster sample the percentage of cortical area in the tibial midshaft and the femoral midshaft are roughly equal. It has been suggested (Sparacello and Marchi 2008) that a hypothetical threshold must be crossed to start bone strengthening. It is possible that the Middenbeemster females, just like the Ligurian females crossed this hypothetical threshold, leading to new cortical bone formation that is comparable to the males. This threshold was also crossed by the athletic sample from Shaw and Stock (2009a), but not by the non-athletic control sample, leading to significant differences in percentages of cortical area. This is an indication that both the Middenbeemster males and females were highly active. However, genetic contributions to the high percentages of cortical area in the Ligurian and Middenbeemster samples cannot be excluded. A comparison to other Dutch populations is required to assess the effects of genetics, activity, and diet on the percentages of cortical area on the Middenbeemster population.

Stock (2006) argues that the midshafts of the femur and the tibia provide the best correlations with mobility. It is exactly in these locations that the significant differences in lower limb strength between males and females occur in the Middenbeemster sample. A significant difference was found in the mean polar second moments of area of the Middenbeemster male and female femora. In the tibiae the sexual differences were much more pronounced. The males displayed significantly larger values of TA, CA, Ix, Iy, Imax, Imin, and J, indicating that after correcting for body size the males still had significantly larger and stronger tibiae than the females. As these are the locations that correlate best with mobility it can be concluded that the Middenbeemster males were more mobile than the females.

The sexual differences in the femoral midshaft shape indices do not differ significantly (p=0.474 for Ix/Iy and p= 0.763 for Imax/Imin). In the distal femur the sexual differences in shape index become larger although differences still do not reach significance at the 0.05 level (p=0.057 for Ix/Iy and p=0.485 for Imax/Imin). In the tibiae the shape differences reach significance (p=0.959 for Ix/Iy, and p=0.015 for Imax/Imin). It appears that from proximal to distal the shape indices become more significant. This means that differences between males and females increase from the proximal to distal end of the limb. It has been demonstrated in the femur that the correlation between activity and cross-sectional shape increases from proximal to distal, this relationship between activity and cross-sectional shape was not found in the tibia (Stock 2006). The differences between males and females that have been found in the lower limbs of the Middenbeemster sample are in agreement with predictions following Stock

(2006). Differences in lower limb shape therefore support the conclusion that the Middenbeemster males were more mobile than the females.

The sexual dimorphism that has been observed in the lower limbs of the Middenbeemster sample is not as pronounced as it is in hunter-gatherers, but it is more pronounced than in modern industrial populations. Although the males possessed significantly higher mean polar second moments of area in the lower limbs compared to the females, there was a very large amount of variation within the female sample, as evidenced by their extraordinarily large standard deviations. The extensive variability in the female sample indicates that economic roles may not have been the same for all women and that there was a large amount of variability in the level of mobility. The males display less variability in the cross-sectional properties of the lower limbs indicating more uniform levels of activity between males. Besides levels of activity the small sample size is likely an additional contributor to the observed variation.

The differences between the Middenbeemster males and females are not limited to the lower limbs. The distal humeri display significant differences in shape and strength between the sexes. Two different ways of correcting for body size were applied to the Middenbeemster humeri. In both the males were stronger on average than the females, but only the Middenbeemster alternate sample showed highly significant differences. As the comparative samples have been standardized using this methodology, the Middenbeemster alternate results will be discussed here.

The Middenbeemster males possess significantly stronger humeri than the females. The males show less bilateral asymmetry compared to the females. These results indicate that the Middenbeemster males experienced heavier mechanical loads than the females. The males also used their non-dominant arm more often than females. The females show more rounded humeral shapes, indicating that they experienced more loads from multiple directions, or torsional loads. The differences in strength and shape of the dominant and non-dominant humeri of the Middenbeemster males and females suggest that different habitual activities were performed. The males showed less bilateral asymmetry in strength and shape of the distal humeri compared to the females. In combination with stronger and more elliptical humeral shapes, this points towards activities that required lifting of heavy objects with both arms. The females showed slightly more bilateral asymmetry, less robust humeri, and more rounded diaphyses. This shows that the females experienced less heavy loads than the males, that they did not perform as many bilateral manual activities, and that the females experienced either torsional loads or more equal loads from multiple directions. These kinds of loadings are hypothesized to be more related to domestic activities, rather than strenuous manual labour.

The Middenbeemster females show very high standard deviations in humeral polar second moment of area. Female standard deviations are much higher than those of the Middenbeemster males. This observation was also made for the lower limbs. Again this is interpreted as indicative of more behavioural variability in the females compared to the males. It appears that while a portion of the females was relatively inactive, other females engaged in strenuous upper limb activities.

The Beemster polder was inhabited by individuals from varying social standings. One of the main purposes of the Beemster polder besides agriculture was to provide countryside estates for the wealthy inhabitants of neighbouring cities (de Vries 1974). It is therefore expected that the Middenbeemster sample consists of individuals from various social standings. The higher social classes had access to better quality nutrition and were most likely less active than the lower classes. It is hypothesized that the high variability in female cross-sectional properties may be related to socioeconomic status. The ideal picture of a nineteenth century family was that the man worked away from home while the woman performed more domestic activities such as tending to the house and the children (Mook 1977). Possibly when the man did not make enough money, the woman was required to work outside of the house as well. Another possibility is that the lower class females only worked the fields occasionally during harvest seasons. It is speculated that young children died most often during harvest seasons. It is considered plausible that during harvest seasons women were required to work the fields and leave their children home alone if no one was available to tend to them. However, this has not yet been tested against the historical records (M. Hoogland, personal communication). These hypotheses explain the high variability in strength and shape of the lower and upper limbs of the Middenbeemster females. The historical records will allow for the assessment of the socioeconomic status of a portion of the sample used in this study.

Currently the correlation between a historical map of the cemetery and the excavation map is still underway. An assessment of the effects of differences in socioeconomic status and patterns of activity will be possible in the future.

In conclusion, the null hypothesis is rejected as significant differences occur between the males and females in the lower and upper limbs. A combination of the three hypotheses mentioned earlier was most likely true for the Middenbeemster sample. The average male was significantly more mobile than the average female, as evidenced by their significantly stronger lower limbs. Differences in distal diaphyseal humeral shape and strength also indicate that different manual activities were performed by males and females in the Beemster polder. The significant difference in strength was obtained after subjecting the sample to a different method of size-standardization that required the deletion of three out of nineteen females. The fact that the deletion of three random females leads to a significant difference in sexual dimorphism may be another indication of the high variability of the female sample. It is concluded that hypothesis 1 fits best with the general pattern of sexual dimorphism that is observed. The data suggests that there was a general sexual division of labour in the seventeenth to nineteenth century Beemster polder. The high variability of the female sample suggests that the role of females in society was not straightforward. While a portion of the female sample was not physically very active, other females were highly mobile and engaged in strenuous activities that required the use of the upper limbs.

5. Conclusions

The aim of this study was to assess whether there were differences in levels of mobility and manual activities of the male and female inhabitants of the Beemster polder in the seventeenth to the nineteenth centuries. By applying the principles of bone functional adaptation (Wolff's Law), cross-sectional geometric analysis was utilized to infer differences in the rigidity and shape of the lower and upper limb bones of the Middenbeemster males and females. This is the first time that a cross-sectional geometric analysis has been performed on a Dutch archaeological sample.

A large problem in the current study was the absence of suitable comparative samples. None of the comparative samples were Dutch, resulting in a genetic and geographical distance between the Middenbeemster sample and the comparative samples. This made comparisons of bone shape and rigidity difficult between populations.

The extent of sexual dimorphism in lower limb shape in the Middenbeemster sample places it on the lower end of the agricultural spectrum. Sexual dimorphism in lower limb strength and shape is lower than is observed in hunter-gatherers and higher than observed in modern industrial societies. When compared to archaeological and modern populations the Middenbeemster sample displayed unusual femoral shape. It is unclear what the underlying cause is behind this observation but it is hypothesized that a relatively wide body breadth may be a large contributing factor. Correcting for body breadth exceeded the scope of this study, however it is recommended for future efforts. The results of the analysis of the lower limbs suggest that there was a significant difference in strength between males and females where the males were stronger than the females. This significant increase in strength was interpreted as indicative of differences in mobility levels between the Middenbeemster males and females where the average male was significantly more mobile than the average female.

Differences in humeral robusticity and shape between males and females indicate sexual differences in upper limb loading patterns. Significant differences were found in the shape of the non-dominant humeri where the males had more antero-posteriorly strengthened humeri as well as more elliptical humeral shapes.

The dominant distal humeri were not significantly different in shape. The application of a different method of body size standardization that required the deletion of three females resulted in highly significant differences of humeral robusticity where the males possessed much stronger humeri than the females. The males displayed more elliptical distal humeral cross-sections, less bilateral asymmetry, and stronger humeri compared to the females. The females had more rounded humeral diaphyses, a larger amount of bilateral asymmetry, and significantly weaker humeri compared to the males, as evidenced by their significantly lower values of polar second moment of area. It is concluded from these results that the Middenbeemster males generally were involved in more strenuous manual activities involving both arms. The gracility of the females compared to the males is interpreted as indicative of less intensive upper limb use, most likely due to a higher involvement in domestic activities.

The Middenbeemster females displayed very high standard deviations compared to the males in the cross-sectional properties of both the upper and the lower limbs. This is interpreted as an indication that gender roles were not fixed for women in the Beemster polder and that some of the females were highly mobile and performed strenuous manual labour.

The results obtained in this study suggest that there was a sexual division of labour in the seventeenth to nineteenth centuries in the Beemster polder that generally conforms to hypothesis one. Hypothesis one states that a sexual division of labour was present in which the males were more mobile and performed different manual tasks than the females. The males generally performed more strenuous activities, as evidenced by their larger robusticity even after differences in body size have been corrected for. However, the high variability of the female cross-sectional properties suggests that the true picture is more complex and that many women were not confined to the performance of domestic tasks, but instead joined the males in more intensive labour activities. As more information about the people that inhabited the Beemster polder is being uncovered through osteological and historical research, the data obtained in this study will become increasingly valuable by allowing it to be interpreted within an increasingly detailed framework.

5.1 Future research directions

The current research opens up several possible avenues for future study. Analysis of the lower limbs resulted in some interesting findings: the male femora were much more medio-laterally strengthened than would be expected for males. A study on the body shape of males and females and the effects this may have on femoral shape is recommended for future endeavours. To make the results from this thesis more valuable, not just body size needs to be corrected for, but also body shape.

There are several reasons why the Dutch are an interesting population for the study of cross-sectional geometry. One reason is that they are amongst the tallest and broadest people in the world. It would be interesting to see if this has any effects on diaphyseal cross-sectional morphology. Another reason is the Dutch terrain. Few places exist in the world where the terrain is as flat as in the Netherlands, and particularly the Beemster polder. The influences of the ruggedness of terrain on lower limb bone strength have been documented in the literature. If one such a study would be undertaken in the future, the Middenbeemster skeletal collection would be a very valuable addition.

The abundance of historical data provide almost limitless possibilities for future analyses. The recovery of a map of the cemetery with the names and locations of individuals that were buried after 1829, as well as death records that list the exact age, sex, and socioeconomic status provide a wealth of historical data on the Beemster population. After the correlation of the historical map to the excavation plan is completed, the death records can be linked to the actual skeletons.

The availability of historical data such as date of birth and exact age allow some of the individuals to be connected to specific historical events. Periods of severe malnutrition have been discussed in this study such as the infamous potato blight of the mid-nineteenth century. This allows for a comparison between the cross-sectional properties of individuals who grew up in these stressful periods and individuals who grew up in more favourable times. This allows for a well-controlled study of the effects of nutritional stress on bone growth.

Another interesting possible avenue of research that can be explored using the historical records is an assessment of the effects of socioeconomic status on cross-sectional geometry. It is expected that physical workload is higher in the lower classes than in the more wealthy upper classes. It is therefore expected that cross-sectional strength is increased in the lower classes. However, although the more wealthy inhabitants of the Beemster polder are expected to be less active, they did have access to better quality nutrition, perhaps mitigating the differences in activity. It was hypothesized in the discussion that especially females in the lower classes may have been forced to work the fields because their husbands alone did not make enough money to provide for the entire family. This hypothesis may be tested by comparing the cross-sectional properties of the wealthier females to the lower class females.

Finally, the historical data allows for the testing of the methods used for the estimation of age and sex. If for example the age estimation of the historically documented sample (buried between 1829 and 1866) is over- or underestimated by the methods that are used, this can be taken into consideration when analysing the individuals that were buried before 1829, resulting in more accurate age and sex estimations.

A large problem in the current study was the absence of suitable comparative samples. To provide a proper comparative context for the results of the current analysis, additional Dutch Medieval to modern populations need to be studied. Several skeletal collections exist in the Netherlands that would be very suitable for this purpose. The “Paardenmarkt” collection consists of a Medieval urban population from the city of Alkmaar, located a few kilometres from the Beemster polder (R. Schats, in prep.). The site dates from AD 1448 to 1572 and consists of individuals from all ages and sexes, including a mass grave from the siege of Alkmaar in 1573. It is currently housed at the University of Leiden in the Laboratory for Human Osteoarchaeology. Another excellent comparative Dutch population is currently being excavated in Oldenzaal. The Oldenzaal assemblage consists of an estimated 2000 individuals dating from the Merovingian (Early Medieval) period until the late Medieval period. This population also provides a great opportunity to study possible temporal differences in mechanical loadings between the Early and Late Middle Ages.

Schooling was not mandatory for Dutch children until the early twentieth century. It is likely that subadults engaged in strenuous activities typical of adults in most pre-industrial societies. Bones are most plastic when an individual is still growing. Thus, if strenuous physical activity takes place during the adolescent growth spurt it is likely to be reflected by cross-sectional geometry. A cross-sectional geometric analysis of subadults may indicate at which age children began working heavily in domestic or agricultural activities.

Humeral cross-sectional shapes can be the result of a myriad of different activities. In order to get a better idea of which types of activities were performed the cross-sectional geometric data has to be combined with other types of evidence. A study of the distribution of musculoskeletal stress markers across the upper limbs may prove to be very useful. This allows cross-sectional shapes to be linked to the frequent use of specific muscles, providing a more detailed picture from which habitual behaviour may be reconstructed. Activity related pathologies such as osteoarthritis may also prove to be a valuable addition to the cross-sectional geometric data gathered in this study.

The vast majority of cross-sectional geometric studies are performed in the Unites States and publications of European populations are sparse. The current study represents the first time that cross-sectional geometric analysis has been applied to a Dutch archaeological population. The results obtained from the current study are therefore a valuable contribution to the international fields of bioarchaeology and biological anthropology.

Abstract

In the summer of 2011, archaeologists from Leiden University excavated the post-Medieval cemetery site of Middenbeemster, the Netherlands. The Middenbeemster skeletal collection provides unique research possibilities due to the availability of detailed historical information on a portion of the excavated individuals. The discovery of a historical map of the cemetery allows for the identification of all individuals buried after 1829, providing age at death, sex, and socioeconomic status. This study applies biomechanical models to cross-sections of human limb bones in order to assess the variability in the habitual activities that were practised by the male and female inhabitants of the Beemster polder from the seventeenth to the nineteenth centuries. Cross-sections were obtained by Computed Tomography Scanning of lower and upper limb bones followed by digital sectioning. By combining historical data and the principles of bone functional adaptation, a reconstruction of life on one of the first polders is attempted. Results show that the presence of a sexual division of labour where the males were generally more mobile than females, and performed more strenuous manual activities. The males were very similar in limb bone strength and shape, but the female sample showed a high amount of variability. While a portion of the females were relatively gracile, other females showed very robust lower and upper limb bones indicating high mobility and strenuous manual labour. This indicates that economic roles were not the same for all females in the seventeenth to nineteenth century Beemster polder. The current study represents the first time that cross-sectional geometric analysis has been applied to a Dutch archaeological population. The results obtained from the current study are therefore a valuable contribution to the international fields of bioarchaeology and biological anthropology.

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Appendix A

Modern U.S.

(Ruff 1987)

The modern U.S. sample consists of adult white urban males and females obtained from cadavers used in anatomy classes plus a few specimens from a bone bank (Ruff 1987). The femoral sample consists of 23 males and 24 females, and the tibial sample consists of 19 males and 23 females. The males and females of the sample were equally mobile (Ruff 1987). Cross-sectional properties were obtained by sectioning the bone using a saw. After sectioning the cross-sections were digitized using a digitizer. Finally the digital images were analysed using the computer program SLICE (Nagurka and Hayes 1980).

Pecos Pueblo

(Ruff 1987)

The Pecos Pueblo sample consists of 59 males and 60 females. Pecos Pueblo was a late prehistoric and early historic (AD 1300-1600) agricultural community living in north-central New Mexico (Ruff 1987). No evidence of food shortages or severe malnutrition was found by osteological and archaeological investigations (Ruff and Hayes 1983a). Significant differences in mobility were observed in this population, with males being significantly more mobile than the females (Ruff and Hayes 1983b). Cross-sectional properties were obtained by sectioning the bone using a saw. After sectioning the cross-sections were digitized using a digitizer and analysed using the computer program SLICE (Ruff and Hayes 1983a). Only the lower limbs of the Pecos Pueblo sample were used in this study.

Georgia Coast pre-agricultural

(Ruff et al. 1984)

The Georgia Coast pre-agricultural group represents a biologically and culturally homogenous group dating between 2000 BC and 1150 AD. The sample consists of eight males and twelve females (Ruff et al. 1984). Their subsistence economy relied on hunting, gathering and fishing (Larsen 1982). In addition to terrestrial mobility the group also relied on marine travel (Weiss 2003). Males were predominantly hunters while the females gathered plants and shellfish (Larsen 1982). Cross-sections were obtained by direct sectioning, digitized using a digitizer and analysed using the computer program SLICE (Ruff et al. 1984).

Georgia Coast Agricultural

(Ruff et al. 1984)

The Georgia Coast Agricultural group consists of adult individuals dating from AD 1150 to 1550, before European contact (Larsen 1982). The sample consists of eleven males and nine females (Ruff et al. 1984). The subsistence economy relied primarily on maize agriculture in combination with coastal resources (Larsen 1982). Cross-sections were obtained by direct sectioning, digitized using a digitizer and analysed using the computer program SLICE (Ruff et al. 1984).

Towton Swordsmen

(Rhodes and Knüsel 2005)

The Towton swordsmen group were casualties of the historic Battle of Towton during the Wars of the Roses (1455-1487). The sample consists of 13 blade-injured males dating to AD 1461 (Rhodes and Knüsel 2005). The Towton swordsmen often trained with weapons resulting in several unilateral loading of the upper limbs. The Towton humeri were scanned using CT-scanning (Rhodes and Knüsel 2005).

Fishersgate

(Rhodes and Knüsel 2005)

The Fishersgate sample comes from the cemetery of St. Andrew, Fishergate, U.K., and dates between AD 1195 and the fifteenth century (Rhodes and Knüsel 2005). The sample consists of nine male individuals. It should be noted that, although these individuals do not display peri-mortem blade injuries like the Towton sample, it cannot be firmly established that they did not train with weapons. The Fishersgate humeri were scanned using a CT-scanner (Rhodes and Knüsel 2005).

Modern U.K. Athletic samples

(Shaw and Stock 2009a,b)

The modern U.K. athletic samples derive from two publications by Shaw and Stock (2009a,b). The groups consisted of male varsity level athletes between the ages of 19 and 29 who started practising their respective sports at an early age, as well as a non-athletic control group. Habitual mechanical loading, diet, and health histories were assessed through questionnaires. The tibiae of fifteen field hockey players, fifteen cross-country runners, and twenty non-athletic controls were studied. The humeri of fifteen swimmers, sixteen cricketers, and twenty non-athletic controls were studied. Cross-sectional images were obtained using Peripheral quantitative computed tomography (pQCT) scanning (Shaw and Stock 2009a,b).

Ligurian Neolithic

(Sparacello and Marchi 2008)

The Ligurian Neolithic sample was radiometrically dated between 6000 and 5500BC (Sparacello and Marchi 2008). The sample belongs to the homogenous Squared Mouth Pottery Culture and consists of nine males and eight females. Archaeological finds indicate that the group practised a largely pastoralist subsistence strategy. The group is also thought to be highly combative. Marchi et al. (2006) argued that the high degree of sexual dimorphism found in both lower and upper limbs was the result of sexual division of labour, with more mobile males and more sedentary females. Marchi et al. (2006) stress that the greater male femoral robusticity might have been augmented by travelling across the rugged terrain. Cross-sections were obtained using polysiloxane moulds and measurements of biplanar radiographs (Sparacello and Marchi 2008).

Ligurian Medieval

(Sparacello and Marchi 2008)

The Ligurian Medieval sample derived from the necropolis of San Paragorio in Noli, Italy, and dates between the tenth and the fifteenth centuries (Sparacello and Marchi 2008). The necropolis lies within five kilometres of the sites where the Neolithic burials were found. The sample consists of seventeen males and nine females (Sparacello and Marchi 2008). Noli has been well known for its reliance on marine activities since the Roman age. It is deduced from historical records that almost everybody was directly or indirectly involved in fishing or curing (Sparacello and Marchi 2008). During the Medieval period *sciabica* fishing was performed: nets were placed in the water with boats and then pulled ashore by groups of people on land. Although the casting of the nets was the fishermen's duty, every component of the family (including women, elderly, and children) was involved to some degree in pulling nets ashore. This particular type of fishing is quite stressful and involves both upper and lower limbs (Sparacello and Marchi 2008). Fishing was mostly a nocturnal activity, during the day other subsistence activities were performed such as curing and cultivating small family-held plots in the hills (Sparacello and Marchi 2008). Cross-sections were obtained by direct sectioning.

Euroamerican

(Trinkaus et al. 1994)

The Euroamerican sample comprises of the remains of 25 males and 13 females from the Rio Grande region of New Mexico, U.S., that were donated to science. The sample consists of individuals that were born in the early to middle twentieth century. Most of the sample consists of urban or semi-urban individuals. The complete sample was forensically identified as "Caucasian" and should therefore have a primarily European Ancestry. The cross-sections were obtained through a combination of the use of external moulds and radiography (Trinkaus et al. 1994).

Jomon

(Trinkaus et al. 1994)

The Jomon sample consists of prehistoric populations of sedentary hunter-gatherers. The Jomon exploited both terrestrial and marine resources and lived in settlements between these two ecozones. The sample consists of ten males and thirteen females. The Jomon had a sexual division of labour where the males hunted terrestrial animals, the females gathered plants and raw materials, and both sexes cooperated in fishing activities (Knobbe 2010). The cross-sections were obtained through a combination of the use of external moulds and radiography (Trinkaus et al. 1994).

Tennis players

(Trinkaus et al. 1994)

The sample consists of professional tennis players, studied in the 1970's (Priest et al. 1974). The sample consists of 34 males and 11 females. Due to the high level of unilateral activity patterns the tennis players provide an extreme example of non-pathological bilateral asymmetry. The cross-sections obtained using x-rays (Trinkaus et al. 1994).

Georgia Coast

(Trinkaus et al. 1994)

The Georgia Coast sample that was used for humeral comparisons is not the same population that was used for lower limb comparisons. The sample consists of an early historic Georgia Coast Amerindian sample from the island site of Santa Catalina de Guale de Santa Maria (Larsen et al. 1991**)**. The sample consists of a Spanish missionized horticultural population. The population subsisted on a combination of maize agriculture and coastal resources (Trinkaus 1994). The sample consisted of the paired humeri of nineteen males and eighteen females. Cross-sections were obtained by direct sectioning. Endosteal and subperiosteal contours were digitized and the cross-sectional geometric properties were calculated using the computer program SLICE (Nagurka and Hayes, 1980).

Appendix B

Procedure of obtaining cross-sectional properties from limb bones

Out of the approximately 200 Middenbeemster individuals that have been described so far 47 adults were deemed suitable for use in the current study. The limb bones of these 47 individuals were scanned using a CT scanner housed at the Amsterdam Medical Centre. The CT machine could process a maximum of fifteen scans per night, therefore four sessions were required to obtain the scans of the 47 individuals. The bones were placed upon a custom made board from in the following order from left to right: the tibia, the femur, the left humerus, and the right humerus (figure B.1).

Figure B.1. Limb bones placed in the CT scanner on a custom made board.

The CT scanning of the packages resulted in a digital 3D image of the package which could then be manipulated at a 3D working station at the Amsterdam Medical Centre using IMPAX 6.4.0.4841 software.

A total of 188 bones were scanned. All bones were manually placed into anatomical position according to the x,y,z axes described by Ruff (2002) using

IMPAX. The editing of the CT scans with IMPAX again resulted in a substantial amount of data traffic within the hospitals computer system. A maximum of 20 bones could therefore be placed into anatomical position per day without hindering the regular activities of the hospital. After all bones were placed into anatomical position the cross-sectional images could be taken at 35% and 50% bone length for the femur and the humerus, and at 50% bone length for the tibia. This resulted in 329 cross-sectional images. Examples of cross-sections of the tibia, femur, and humeri at all cross-sectional locations used in this study are presented in figures B.2 to B.8.

The Images were edited to remove unwanted trabecular bone when necessary. These images were then loaded into the program imageJ with which the following cross-sectional properties were manually calculated: TA, CA, Ix, Iy, Imax, Imin. The raw cross-sectional properties were saved in excel files in which the remaining cross-sectional properties were calculated (%CA, J, shape indices) and body size standardizations were applied.

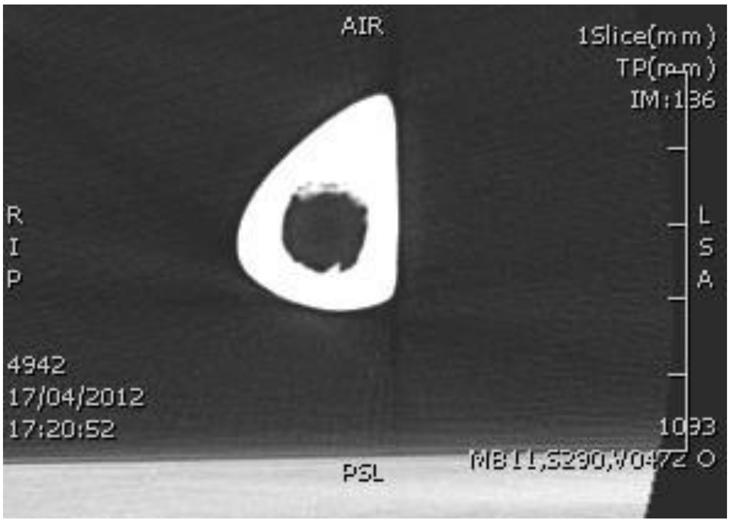

Figure B.2. Cross-section of the tibia of individual mb11s290v0472.

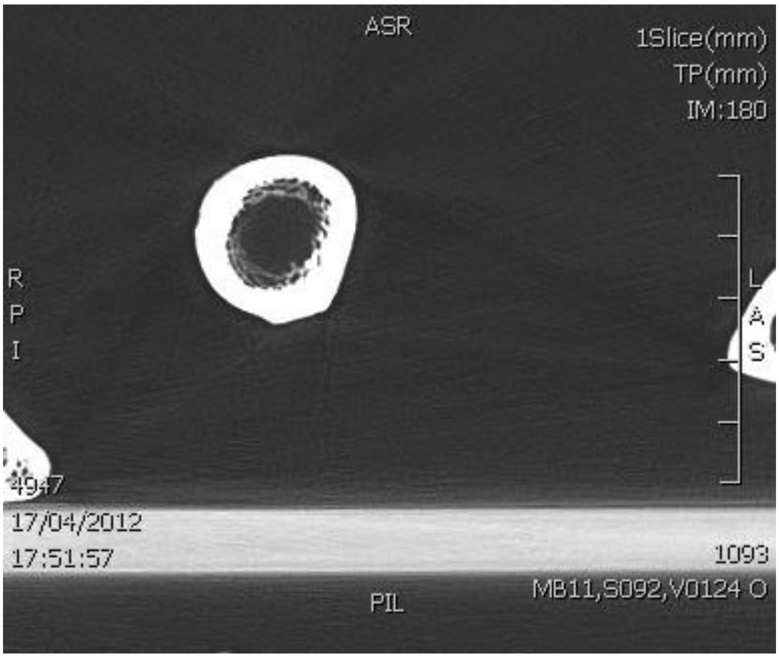

Figure B.3. Distal femoral cross-section of individual mb11s092v0124.

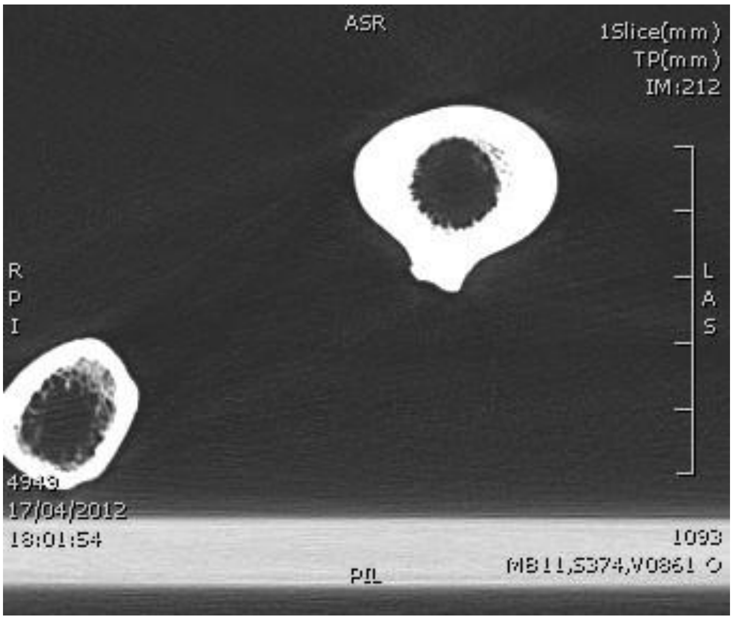

Figure B.4. Femoral midshaft cross-section of individual mb11s374v0861. Left humerus is partly visible.

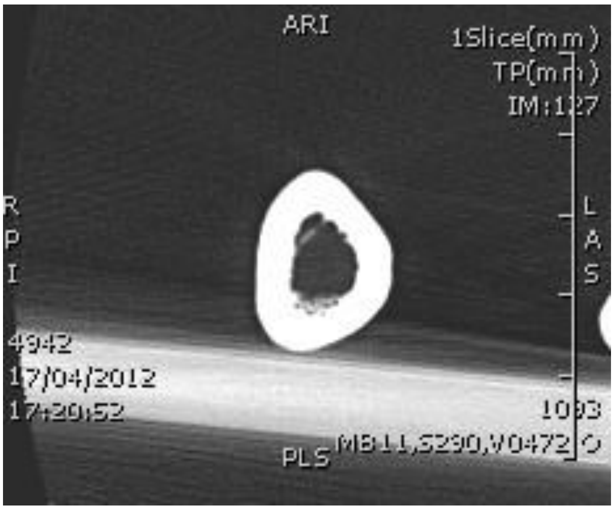

Figure B.5. Right distal humeral cross-section of individual mb11s290v0472

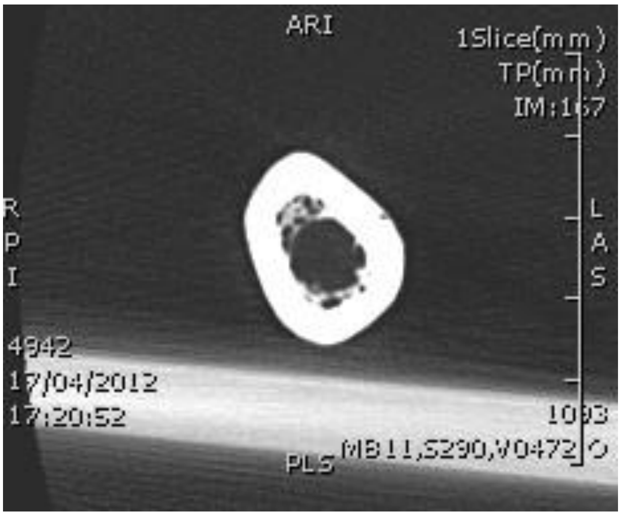

Figure B.6. Right humeral midshaft cross-section of individual mb11s290v0472

Appendix C

Table C.1. Find and feature numbers of the individuals used in this study.

Males (n=24)	**Females (n=23)**
mb11s059	mb11s045v0055
mb11s064v0050	mb11s053v0290
mb11s092v0124	mb11s149v0280
mb11s226v0282	mb11s198v0601
mb11s233v0304	mb11s243v0381
mb11s236v0335	mb11s369v0886
mb11s239v0369	mb11s370v0806
mb11s261v0422	mb11s388v0952
mb11s290v0472	mb11s401v0876
mb11s306v0561	mb11s413v0896
mb11s310v0550	mb11s428v0945
mb11s313v0926	mb11s430v0965
mb11s337v0714	mb11s453
mb11s368v0794	mb11s461v0990
mb11s374v0861	mb11s466v1010
mb11s379v0851	mb11s468v1009
mb11s402v0907	mb11s476v1054
mb11s432v0981	mb11s481v1046
mb11s435v0929	mb11s487v1096
mb11s467v1022	mb11s501v1097
mb11s473v1003	mb11s512v1005
mb11s482v1048	mb11s521v1150
mb11s502	mb11s527v1053
mb11s505v1095	

Appendix D

The cross-sectional properties of the dominant and non-dominant humeri that have been size standardized using the alternate method are presented in tables D.1 and D.2.

Table D.1. Cross-sectional properties of the Middenbeemster dominant distal humeri. Size standardized using the alternate method. Significance assessed using Mann-Whitney U non-parametric tests. Significant results are in bold.

Property dominant humerus 35%	**Male Average (SD) N=18**	**Female Average (SD) N=16**	**Statistics P (Z)**
TA	444.89 (21.68)	412.69 (41.01)	**.017** **(-2.381)**
CA	330.07 (21.79)	308.67 (46.83)	0.157 (-1.415)
%CA	74.31 (5.43)	74,68 (7.61)	.581 (-0.552)
Iy	8.59 (0.99)	7.29 (1.49)	.**010** **(-2.588)**
Ix	11.58 (0.89)	9.36 (2.22)	**.001** **(-3.278)**
Imax	11.82 (0.94)	9.57 (2.23)	**.001** **(-3.312)**
Imin	8.34 (0.94)	7.07 (1.48)	**.012** **(-2.519)**
J	20.16 (1.64)	16.64 (3.61)	**.002** **(-3.105)**
Ix/Iy	1.36 (0.14)	1.28 (0.13)	.168 (-1.380)
Imax/Imin	1.43 (0.14)	1.36 (0.14)	.241 (-1.173)

Table D.2. Cross-sectional properties of the Middenbeemster non-dominant distal humeri. Size standardized using the alternate method. Significance assessed using Mann-Whitney U non-parametric tests. Significant results are in bold.

Property Non-dominant humerus 35%	**Male Average (SD) N=18**	**Female Average (SD) N=16**	**Statistics P (Z)**
TA	431.51 (22.32)	394.90 (43.55)	**.006** **(-2.726)**
CA	318.58 (26.85)	296.38 (46.99)	.062 (-1.863)
%CA	73.96 (6.61)	75.00 (0.08)	.448 (-0.759)
Iy	7.94 (1.00)	6.72 (1.64)	**.021** **(-2.312)**
Ix	10.96 (1.08)	8.74 (2.06)	**.001** **(-3.381)**
Imax	11.17 (1.10)	8.91 (2.07)	**.001** **(-3.416)**
Imin	7.72 (0.89)	6.54 (1.60)	**.014** **(-2.450)**
J	18.90 (1.80)	15.45 (3.62)	**.003** **(-2.933)**
Ix/Iy	1.39 (0.16)	1.31 (0.14)	.190 (-1.311)
Imax/Imin	1.46 (0.14)	1.37 (0.11)	.112 (-1.587)