THE RELATIONSHIP OF PELVIC SCARS AND PELVIC INSTABILITY

THROUGH AN ANALYSIS OF THE GROSS MORPHOLOGY

AND MICROARCHITECTURE OF THE PUBIC SYMPHYSIS

by

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LIST OF ABBREVIATIONS

Abbreviation	Description
BMI	Body mass index
BV/TV	Bone volume/total volume
Conn.D	Connectivity density
cm	Centimeters
DA	Degree of anisotropy
DPP	Dorsal pubic pitting
HRCT	High-resolution computed tomography
mm	Millimeters
PAS	Preauricular sulcus
PTL	Pubic tubercle length
Tb.Sp	Trabecular spacing
Tb.Th	Trabecular thickness
TXSTDSC	Texas State University Donated Skeletal Collection
µm	Micrometers

1. INTRODUCTION

Research Problem

Dorsal pubic pitting and the preauricular sulcus have long been considered indicators of parity status (Angel, 1969; Houghton, 1974; Cox, 2000), which has important implications for studies of paleodemography, biomechanics, and forensics. Dorsal pubic pitting appears as indentations in the dorsal surface of the pubic bone. The preauricular sulcus is a groove running parallel to and beneath the auricular surface of the ilium. Both of these features – often referred to as scars in the literature – appear with varying levels of depth. However, as early as the 1970s, researchers questioned the relationship between pelvic scars and child bearing (Holt, 1978). More recent studies have also discovered a correlation between pelvic scars and factors other than pregnancy suggesting that these scars may be an indicator of pelvic instability rather than biological parity (Andersen, 1986; Snodgrass and Galloway, 2003; Ubelaker and De La Paz, 2012; Maass and Friedling, 2014).

Pelvic instability, defined as hypermobility of the pelvic joints, is commonly associated with pregnancy, obesity, physical activity, age, and other risk factors (Walheim et al., 1984; Greve et al., 2007; Garras et al., 2008; Branco et al., 2014; McCrory et al., 2014; Ubelaker et al., 2012). Though pelvic instability cannot be directly observed in skeletal remains, the findings that the pubic symphysis is over-aged in parous females (Bongiovanni, 2016) and the auricular surface is over-aged in obese males and females (Wescott and Drew, 2015) suggest that these joints are wearing more rapidly than in the general population. As age indicators in adults are based on the rate of joint degeneration due to regular movement, these studies show that obesity and parity may place greater stress on the pelvic joints and wear them more quickly than the typical aging process. Therefore, individuals who have high risk factors for pelvic instability may be more likely to be over-aged using standard pelvic indicators of age, and may also have higher rates of pelvic scars.

Previous studies suggest that there may be different patterns of stress in groups with pelvic instability. For example, Bongiovanni (2016) found that females who had given birth transition through the stages of pubic symphysis morphology at an earlier age than nulliparous females but there is no significant difference in the aging of the auricular surface. This suggests that mechanical stress due to pelvic instability affects the anterior pelvic joint (pubic symphysis) more than the posterior joints (sacroiliac joint). On the other hand, Wescott and Drew (2015) discovered greater changes in the auricular surface than the pubic symphysis in obese individuals, suggesting that the burden of weight places greater stress on the posterior joints than the pubic symphysis.

The microarchitecture of trabecular bone, measured through high-resolution computed tomography (HRCT), is a popular medium for investigating biomechanical responses (Kivell, 2016). Research shows that trabeculae become less organized (more anisotropic) and trabecular density increases under novel stimuli, such as a change of gait (Huiskes et al., 2000). This suggests that when gait, and therefore loading, changes in circumstances such as pregnancy and obesity, similar trabecular changes should appear in bones associated with gait, such as the pubic bone. Furthermore, if the preauricular sulcus is indeed related to risk factors for pelvic instability and other than parity, individuals with this scar should present with higher anisotropy and bone density due to novel loads in the pelvic girdle.

Purpose of study

Multiple studies have examined the relationship between pelvic scars and parity status, but none has included other possible risk factors for pelvic instability such as obesity and age. This thesis seeks to test if pelvic instability is a possible causal factor in the presence of pelvic scars. Specifically, this study will examine if the prevalence of pelvic scars is higher in all groups with high risk factors associated with pelvic instability. This study will also for the first time use HRCT to examine if there is an association between pelvic scarring and pubic bone trabecular structure, especially trabecular anisotropy, bone volume ratio, connectivity, thickness, and spacing. Establishing common factors among individuals with pelvic scars will aid in understanding the possible etiology of the scars and improve interpretations of skeletal remains in forensic and bioarchaeological investigations. Determining the frequency of pelvic scaring in a diverse group of modern humans will also be informative for establishing baseline presence.

Research Questions

If pelvic scars are "parity scars," then pelvic scars will only be found in females with a history of childbirth. Since previous studies have found pelvic scars in nulliparous females and males, parity as the sole cause can be ruled out (Holt, 1978; Andersen, 1986; Cox and Scott, 1992; Snodgrass and Galloway, 2003; Maass and Friedling, 2014). To examine the relationship between pelvic scars and pelvic instability, several research questions must be tested. The primary research question for this study is: "Are pelvic scars caused by pelvic instability?" A related secondary question is "Does the cause of pelvic instability create different patterns of stress?" Since pelvic instability should result in greater wear on pelvic joints, it is first necessary to determine if individuals with higher risk of pelvic instability have greater wear on the pelvic joints. This will be done by determining if individuals in high risk groups are systematically over-aged using the pubic symphysis. If individuals in high-risk groups for pelvic instability are consistently over-aged, it will be assumed that pelvic instability can be detected using these criteria. It is important to note, however, that not all individuals in high-risk groups for pelvic instability exhibit pelvic instability in the general population. Therefore, a lack of indicators suggesting pelvic instability in this study does not necessarily indicate that those individuals did not experience the condition in life.

If pelvic instability is a causal factor for pelvic scars, the following findings are expected:

1) Pelvic scars (dorsal pubic pitting and preauricular sulcus) will be found more frequently in individuals with known risk factors for pelvic instability (parous females, obese nulliparous females, non-obese females of both groups, and obese males) than in individuals in low risk groups (normal weight nulliparous females and normal weight males). Pubic tubercle length is also expected to be larger in these risk groups. The null hypothesis is there is no difference in prevalence between high and low risk groups.
2) Individuals with scars and a larger pubic tubercle will exhibit greater age-related wear of the pubic symphysis than individuals without scars. In other words, individuals with pelvic scars will exhibit greater positive bias (transition earlier) in age estimation phases. The null hypothesis is that there will be no significant differences between sex and age-matched individuals with and without pubic scars in pubic symphysis joint wear.

3) Among individuals with risk factors for pelvic instability, those who have greater joint wear will have greater prevalence of pelvic scars. The null hypothesis is that there is no significant difference in the frequency of pelvic scars or the size of the pubic tubercle in parous females or obese individuals that over-aged or not overaged.

Previous research has shown that parous females are more likely to be over-aged using the pubic symphysis (Bongiovonni, 2016), and that obese individuals tend to be over-aged in the auricular surface (Wescott and Drew, 2015). To investigate whether there are different patterns of joint stress associated with different causes of pelvic instability, I will test if the frequency of anterior pelvic scars (pubic tubercle length and dorsal pubic pitting) are greater in females who have given birth compared to obese individuals and if posterior scars (preauricular sulcus) are more prevalent in obese individuals. Specifically, the following questions will be addressed:

1) Do dorsal pubic pitting frequency and pubic tubercle size increase more among women who have given birth than between obese individuals?
2) Do preauricular sulci occur in higher frequencies among obese individuals compared to non-obese, and in females who have given birth compared to females who have not?

In addition to these questions, measurements of the trabecular microstructure of the pubic bone will be compared to pelvic instability risk factors and scar presence.

3) Trabecular structure parameters commonly associated with load adaptation, particularly trabecular thickness, will be highest in individuals with scars, parous females, and obese individuals, and will be positively associated with

increasing body mass index, known age-at-death, pubic tubercle length, and positive age estimation error.

Broader impact

If associations are made between risk groups for pelvic instability, scar appearance, and trabecular microarchitecture, this study would be the first to provide evidence for detecting pelvic instability in dry bone. This would inform our understanding of how load and gait changes impact gross and microscopic morphology. In addition, if pelvic scars are found to be associated more broadly with pelvic instability than with parity alone (as with obesity), then this would be further evidence against the preauricular sulcus and dorsal pubic pitting as "scars of parturition." If pelvic scars are related to pelvic instability and there are different patterns between scars caused by pregnancy and obesity, this study could provide evidence for the possibility of separating the causal factors for pelvic instability.

Furthermore, if pelvic instability and positive age estimation bias are found to be related, this would have strong implications for how anthropologists estimate age using the pubic symphysis. Age estimation is a critical component of the biological profile for both the archaeological and forensic interpretation of skeletal remains, and an inaccurate age estimation could result in misidentification of a skeleton or the misinterpretation of past communities' demographics. Therefore, it is important to identify factors that may confound adult age estimations. If pelvic instability due to obesity or parity accelerate aging signs in the pubic symphysis, age estimation techniques should be adjusted to take these factors into account. The analysis of the pubic symphysis microarchitecture via HRCT may help illuminate how trabecular bone changes to accommodate pelvic instability.

Literature Review

Anatomy of the human pelvis

The innominate, or os coxae, is comprised of three bones that fuse with age: the ischium, pubis, and ilium (Figure 1.1). This thesis is concerned with phenomena involving the pubis and ilium.

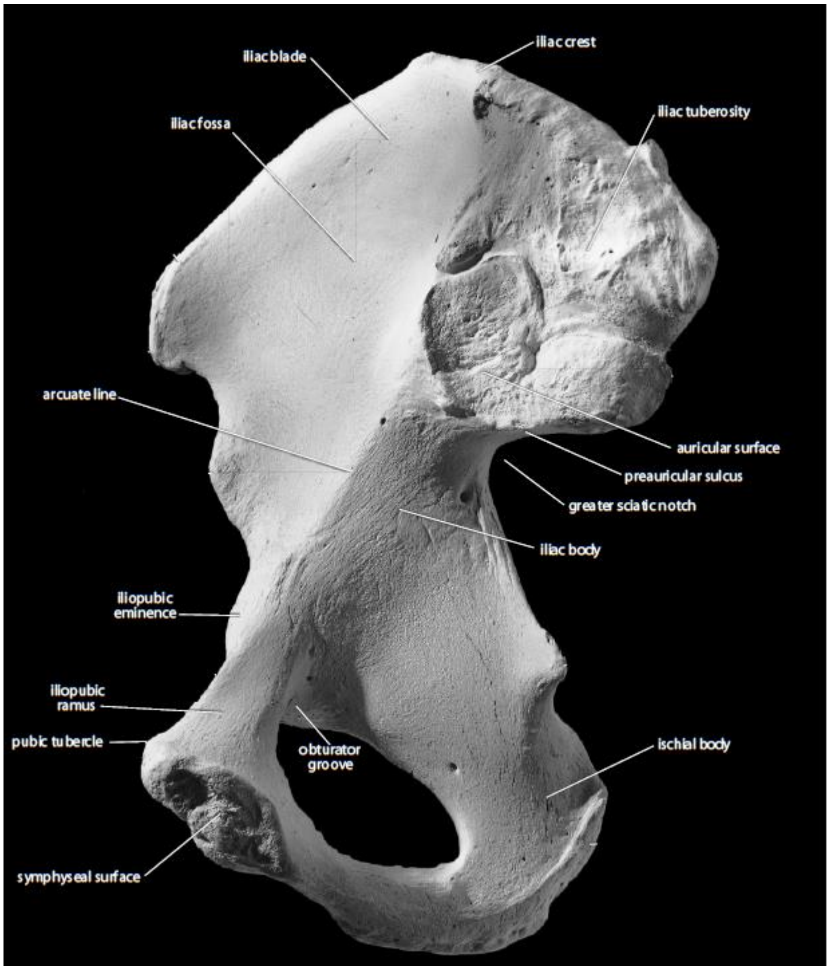

Figure 0.1 - Right os coxae, medial view. Superior is up, anterior to the left (White et al., 2012:229).

The connective tissues discussed below are illustrated in Figure 1.2. The pubic symphysis is the most anterior joint of the pelvic girdle and joins the two pubic bones medially. It is cushioned by a layer of fibrocartilage (Becker et al., 2010). The pubic tubercle is a variably raised region of bone on the medial, superior, and anterior aspect of the pubic bone. It is the attachment site for the rectus abdominis muscle and the inguinal ligament (White et al., 2012). The preauricular sulcus, if present, appears as a groove of varying size and depth on the ilium, inferior to the auricular surface and posterior to the greater sciatic notch. This is an attachment site for the anterior sacroiliac ligament, which stabilizes the sacroiliac joint.

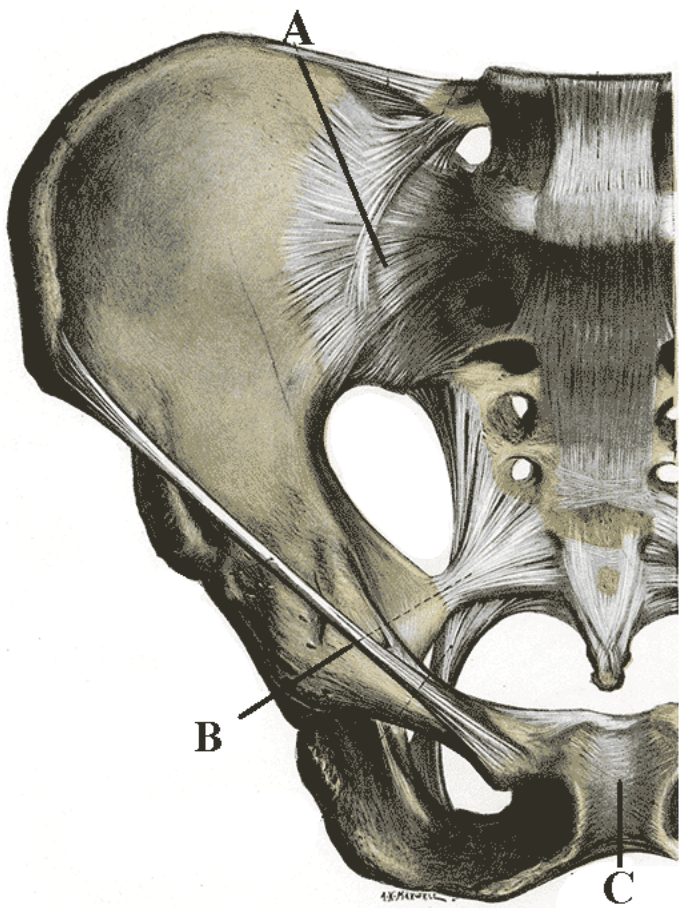

Figure 0.2 - Connective tissue of the pelvic girdle. Anterior view. A.) Anterior sacroiliac ligament; B.) Inguinal ligament; C.) Interpubic fibrocartilage (Gray, 1918).

The posterior pubic ligament, which stabilizes the pubic symphysis on the dorsal aspect of the pubic bone, may contribute to dorsal pubic pitting given its location (Figure 1.3). This ligament is not well discussed in the clinical literature (Becker et al., 2010).

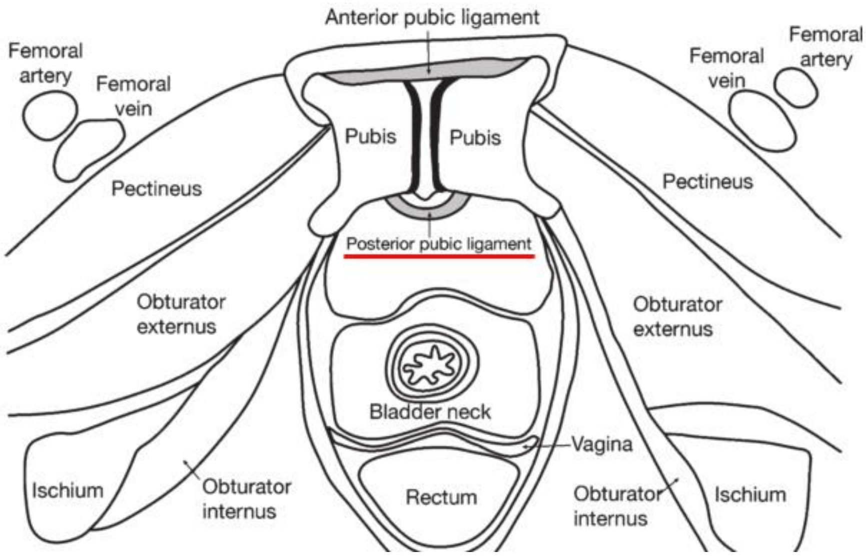

Figure 0.3 - Transverse illustration of the human female pelvis (Becker et al., 2010:481). The posterior pubic ligament is underlined.

Pelvic scarring and parity status

Several features of the pelvis, including dorsal pubic pitting, pubic tubercle extension, and preauricular sulcus morphology, have been linked to parity status in females (Angel, 1969; Putschar, 1976; McArthur et al., 2016). Although "scarring" is a misnomer for these features, they will be referred to as such for consistency with past studies. Early authors even claimed that scars could be used to estimate the number of births (Angel, 1969; Ullrich, 1975; Bergfelder and Herrmann, 1980; Tague, 1990). However, other studies have suggested that stress on the pelvic joints due to parturition is not the only cause of these traits. In fact, body mass index, pelvis shape, physical activity, and age have also been found to have an influence on the presence of pelvic scars, suggesting that pelvic instability is the primary cause of pelvic scarring (Maass and Friedling, 2014). As such, risk factors for pelvic instability, body mass, pregnancy, trauma, or physical activity may all contribute to pelvic scar formation (Andersen, 1986). With regard to age, parity-related scars may become obliterated by or made worse with age (Suchey et al., 1979; Tague, 1990).

Regarding dorsal pubic pitting, Holt (1978) demonstrated that it was present in nulliparous females with and without chronic inflammation as well as obese nulliparous females, indicating that parity was not the only cause for pitting. Andersen (1986) also found pelvic scars in nulliparous females and in some males. Likewise, Cox and Scott (1992) found no correlation between dorsal pubic pitting and the number of births, and Maass and Friedling (2014) observed dorsal pubic pits in 2.8% of male skeletons from the modern Cape Town collection. Snodgrass and Galloway (2003) examined a modern sample of females with known parity information and found that dorsal pubic pitting was correlated with parity in young females but not older females. In the older females (parous and nulliparous), dorsal pubic pitting correlated primarily with body mass index. This could indicate that pitting due to parity has remodeled with age, while obesity increases the likelihood of pit appearance later in life. However, a recent study of living patients showed a strong correlation between the presence of dorsal pubic pitting and vaginal births (McArthur et al., 2016). Of the females who had given birth vaginally in the McArthur and colleagues' (2016) study, 74% had observable dorsal pubic pits, while only 14% of females with no prior history of vaginal birth exhibited the trait. These studies show that dorsal pubic pitting has a complicated relationship with parity, age, and obesity.

There have also been mixed results in studies examining the relationship of pubic tubercle size and parity. Cox and Scott (1992) found a significant relationship between pubic tubercle size and parity status. However, a third of the nulliparous individuals in their sample also exhibited extended pubic tubercles. Later, Cox (2000) suggested the pubic tubercle is a strong indicator of parity given previous findings of significant dimorphism and that the size of the pubic tubercle was possibly attributable to increased stress to the rectus abdominis muscle during pregnancy. In direct opposition to this finding, Maass and Friedling (2014) found that pubic tubercle extension was in fact greater in males than in females, possibly due to differences in body size. They suggest that ligamentous stabilization of the pelvic girdle probably explains scars of parturition more than parity since many of these skeletal changes were also observed in larger males. This suggested that since the increased size of the pubic tubercle in males may be related to weight differences between the sexes, it could also present as more rugged in parous females. Snodgrass and Galloway (2003) also observed no relationship between the elongation of the pubic tubercle and parity. The pubic tubercle correlated with its distance from the pubic symphysis and the size of the arcuate angle, but not with number of births in their study.

Several studies have also attempted to link the preauricular sulcus to parity status. Houghton (1974) argued that a deep preauricular sulcus with a scooped-floor appearance was a good indicator of parity status; this type of scar (designated as the "groove of pregnancy" in this study) was only found in the females of this sample. However, in a review of the available research, Ubelaker and De La Paz (2012) noted several unsuccessful attempts at linking the preauricular sulcus in bioarchaeological studies and modern individuals of known status. For example, Spring et al. (1989) observed that 10% of nulliparous and 17% of parous females exhibited deep preauricular sulci in *in vivo* radiographs. In addition, Spring et al. (1989) observed pre- and post-birth radiographs in primigravidas females and found no change in preauricular sulcus presence. Tague's (1990) analysis of the preauricular sulcus in female rhesus macaques

(*Macaca mulatta*) and Maass and Friedling's (2014) of female human cadavers found a significant correlation between the morphology of the preauricular sulcus and parity status, though the sulcus was also present in males of both species.

Finally, Andersen's PhD dissertation (1986) found that pelvic scars are significantly related to sex regardless of parity status, though they still appear in some males. Andersen suggested that this could be due to the looser articulations of the female pelvis, as "tighter fitting female pelves tend to show less scarring" (1986:199). Therefore, increased pelvic flexibility could account for scar appearance in males, whether due to weakened pelvic floor muscles, habitual squatting, excess body weight, or trauma. As such, she called for "scars of parturition" to be renamed "scars of excess motion" (1986:201).

A recent meta-analysis by McFadden and Oxenham (2017) confirms that pelvic scar appearance is more related to sex than to parity. In general, the current research suggests that parity, which is a common source of pelvic instability, may be related to pelvic scars but is not the only factor. Any factor that causes pelvic instability may result in pelvic scarring. Therefore, there is a need to examine the relationship between pelvic instability and pelvic scars.

Parity status and age estimation

The influences of parity have also been explored in relation to age estimation. The aging process, and thus bone degeneration, is heavily influenced by increased body weight, along with hormone fluctuations and declining health. Bongiovanni (2016) investigated the effect of parity status on age estimation of the pubic symphysis. Using transition analysis, the author found that parous females transition to the next age cohort up to 14 years earlier than nulliparous females and males with the Todd method of aging the pubic symphysis (Todd, 1921), but only up to 7 years earlier with the Lovejoy method (Lovejoy et al., 1985) of the auricular surface (though not at all with the modified Buckberry-Chamberlain method). Bongiovonni (2016) suggested that this discrepancy is due to joint instability as a consequence of parity.

Similarly, Wescott and Drew (2015) found a tendency for obese individuals to be over-aged using the Buckberry and Chamberlain (2002) auricular surface method compared to individuals with a normal body mass index (BMI). They did not, however, find a significant difference in methods considering the pubic symphysis, suggesting biomechanical differences between obesity and parity. Finally, these authors also suggest that pelvic instability is a likely cause of the aging bias they reported.

The contrasts between Bongiovonni's (2016) and Wescott and Drew's (2015) studies suggest differences in how and how long weight is carried between parous and obese individuals, though they also highlight the impact of increased weight on the pelvic joints. Both studies suggest pelvic instability plays a role. Parity and obesity also result in changed gait marked by widened stance caused by widening of the pelvis and fat deposits in the thighs. Both conditions alter the center of mass, shifting it anteriorly, which results in a distinctive "waddle" in pregnancy (McCrory et al., 2014). Similarly, increased adiposity in the thighs contributes to gait instability due to increased knee abduction, and thus changes the way the pelvic joints bear weight (Wearing et al., 2006).

Risk factors for pelvic instability

Pelvic instability or dysfunction has been associated with different etiologies including pregnancy, obesity, sports-related trauma, and age. The clinical literature suggests that pelvic instability can be present in both sexes and vary with age. Pelvic instability is also linked with pelvic pain, osteoarthritis, and hypermobility. Walheim et al. (1984) investigated the degree of motion in the pelvic joints of living patients that included 11 parous females, one nulliparous and athletic female, and two males with pelvic trauma. The authors measured the degree of motion in the pubic joint with electromechanical pins, finding a significant correlation between a widened pubic symphysis and vertical motion in only two cases. Previous radiographic analysis showed erosion of the pubic symphysis or the auricular surface in all patients. A later radiographic study of the pelves of 45 living subjects found that multiparous females exhibited a mean of 3.1 mm of pubic joint translation compared to 1.6 mm in nulliparous females and 1.4 mm in males (Garras et al., 2008). Furthermore, gait changes during pregnancy due to weight gain and changes in weight distribution, shifting the body's center of gravity (Branco et al., 2014). As the hormone relaxin is excreted throughout pregnancy to loosen ligaments and thus prevent extreme strain and tearing (Björklund et al., 2000), it is possible that scars reported in parous females occurred due to post-partum pelvic instability, by which time relaxin levels had returned to normal.

Computed tomography and histomorphometry of bone

High-resolution computed tomography (HRTC) applies the same principles that have been the cornerstone of computed tomography since its infancy, but with increased resolution (Hounsfield, 1973). Histomorphometric analyses have long been applied to histological studies of bone (Parfitt et al., 1987). Microhistomorphometric analysis is generated by software plugins such as BoneJ for ImageJ and measures 2- and 3-dimensional bone qualities in scan data, such as bone density, trabecular connectivity, and trabecular orientation (Doube et al., 2010). These parameters are used to assess bone quality in clinical studies such as in osteoporosis and metabolic diseases (Kulak and

Dempster, 2010). In addition, trabecular microarchitecture has been utilized to draw conclusions about the biomechanics and behavior of extinct and living primates (Ryan and Shaw, 2013; Scherf et al., 2016; Chirchir et al., 2017; Milovanovic et al., 2017). Studies of non-primate mammals have shown that trabecular disorganization (high anisotropy) and trabecular bone volume increase with novel loading, then return to previous levels after the novel stimulus is removed (Huiskes et al., 2000). Recent research by Sylvester and Terhune (2017) highlights the importance of extracting a representative sample of bone for analysis. They found that extracting a single volume of interest (VOI) of trabecular bone risks missing the loading signal that may in fact be present in other bone regions. They advocate extracting multiple VOIs in order to achieve an accurate picture of trabecular quality throughout the bone.

The following parameters are defined by Parfitt et al. (1987) and in BoneJ by Doube et al. (2010). Connectivity density (Conn.D) examines the level of connection between trabecular bone struts. Bone volume (BV) detects the volume of bone within the VOI's total volume (TV). Trabecular spacing (Tb.Sp) measures the amount of space and distance between trabecular struts, and trabecular thickness (Tb.Th) is the thickness of the struts themselves. Degree of anisotropy (DA) measures the organization and directionality of trabeculae. These parameters reflect the overall strength and density of bone and can be used to interpret biomechanical loads.

Bone microstructure, age estimation, and lifestyle

Bone maintenance is a complicated process, trading between resorption and proliferation throughout life (Riggs et al., 2004). Joint erosion has a long history in radiological studies, and clinicians are increasingly utilizing HRCT to answer questions about bone degeneration at high resolution. Studies on mice (Botter et al., 2006) and dogs

(Sniekers et al., 2008) have detected significant cortical and trabecular thinning in the early stages of osteoarthritis. Likewise, anthropologists have investigated the microarchitecture of the pelvis for new ways to assess age in adults that offer insight into the normal degeneration of cortical and trabecular bone. Wade et al. (2011) discovered quantifiable age-related changes in trabecular microarchitecture with micro-CT in the pubic bone. Trabecular thickness and bone surface-to-volume ratio increased with age, while trabecular connectivity and density decreased. They also note that trabecular bone's heightened remodeling rate compared to cortical bone makes it far more vulnerable to age-related changes. Villa et al. (2013) also noted distinct qualitative age-related changes in trabecular bone density and joint fusion in the pubic bone through CT analysis.

Differences in bone density parameters between age cohorts of both sexes is hypothesized to be due to hormonal changes and stress that impact bone quality; trabecular bone remodeling tends to decrease and bone loss tends to increase with age (Kinney et al., 2005; Kulak and Dempster, 2010; Karsenty and Oury, 2012). Females are known to be at greater risk for osteoporosis as they age, and the hormonal effects have been explored with histology and histomorphometry (Kinney et al., 2005; Ensrud, 2013). However, recent histological studies of cortical bone have shown the opposite correlation with age (Gocha and Agnew, 2016). Agarwal et al. (2004) found great variation in correlations of histomorphometric results between age, sex, and physical activity.

Obesity has been proved to strengthen and improve bone microarchitecture, though as these gains are not proportional to weight gain, obesity is thought to contribute to bone fragility (Sornay-Rendu et al., 2013). Furthermore, osteoarthritis is commonly comorbid with obesity (Wearing et al., 2006). Although pelvic instability is not implicated by name, it is likely that the excess stress of obesity contributes to its development and exacerbates both bone weakness and osteoarthritis.

Changes in bone metabolism and microarchitecture have also been investigated in parous and lactating women. One literature review (Sanz-Salvador et al., 2015) found that while hormones involved in pregnancy can cause a period of relative bone weakness, the effects are temporary and do not predispose the individual for osteoporosis later in life. Similarly, bone density is not reduced during lactation or after (Kalkwarf, 1999; Aksakal et al., 2008). One study did suggest that pregnancy and lactation lead to increased bone mineral density (Wiklund et al., 2011). Clinical studies generally suggest that lactation and pregnancy improve bone strength, but there is great variation in samples and methodology (Salari and Abdollahi, 2014). More recent research, however, suggests that lactation has a long-term if not permanent detrimental impact upon bone microarchitecture (Bjørnerem et al., 2017).

Confounding variables

Several unknowable factors may impact results. Records do not include how long before death a donor had given birth, whether they breastfed, or how long they had been at their current weight. Many elderly donors arrive in an emaciated state. Furthermore, many individuals may have a BMI between 29 and 30, indicating they do not qualify as obese but are still overweight. Finally, if pelvic scar prevalence does differ significantly by sex, the exact etiology will still remain unknown.

Summary

Age and lifestyle both leave their mark on the human skeleton. Past research has shown that these changes occur on the gross and microscopic level. Understanding the influences of age, parity, and lifestyle on the human skeleton can aid anthropologists in learning about past populations, identifying individuals in forensic contexts, and improving our understanding of the biomechanics of gait under different stressors.

2. MATERIALS & METHODS

Sample

This study utilizes the Texas State University Donated Skeletal Collection (TXSTDSC), which has a robust sample of human remains of known sex, age, stature, body weight, self-reported race, and parity status. As of December 2016, when data collection concluded, there were 365 individuals donated to Texas State. Eliminating fetal remains, cremated remains, and individuals with postmortem damage, missing pelvic bones, fused pubic symphyses, or other excessive pathological processes to the pelvic girdle yielded a sample of 179 individuals. Of these, 101 were male and 78 were female. The mean age of the sample is 65.47 years with a range of 18-102 years. Summarized descriptive statistics are provided in Table 2.1. Body mass index (BMI) was calculated with the formula weight(kg)/height(m)^2 (Centers for Disease Control, 2018). BMI for this sample ranges from 13.47 to 62.89 with a mean of 28.37. Fifty-seven individuals (31 males and 26 females) have a BMI of at least 30, which is classified as obese by the US Centers for Disease Control and Prevention (2018). The range of pregnancies among parous females is 1-5. Parity status is not available for one female. Three parous females delivered by caesarian section.

Table 2.1 Sample characteristic means.

Group	*n*	Mean Known Age-at-death	Mean BMI*	Number Obese
Males	101	63.81	28.01	31
Females	78*	67.12	29.26	26
Nulliparous	31	63.64	30.11	14
Parous	46	69.19	28.96	12
N	179	65.47	28.37	57*

*Parity status was unavailable for one female, and body weight was unavailable for nine individuals.

Twenty-eight individuals from the 179 were chosen for HRCT to compare the pubic bone microarchitecture of individuals with and without a preauricular sulcus. The sulcus was targeted because it is the most frequently occurring pelvic scar in the TXSTDSC collection, but BMI, known age-at-death, age estimation error, pubic tubercle length, and dorsal pubic pitting will also be considered. The group of ten with a sulcus were all female; ten without a sulcus were male and eight were female. With only eight females without a preauricular sulcus in the TXSTDSC, age matching was not possible; this subsample is considerably older than the rest, which may have a major impact on results. The mean number of pregnancies is 1.11; nine are each parous and nulliparous. Mean ages and BMI are presented in Table 2.2.

Table 2.2 Descriptive statistics for HRCT sample, grouped by preauricular sulcus (PAS) presence or absence.

	With PAS (Female)	**Without PAS (Male)**	**Without PAS (Female)**	**Total Sample**
Age	65.6	54.4	78.12	65.19
BMI*	29.89	29.09	27.74	28.69
N	10	10	8	28

*Body weight was missing for two males and two females.

Data Collection & Analysis

Pelvic scarring

The left ossa coxae was analyzed for sample consistency. The length of the pubic tubercle and the presence of both dorsal pubic pitting and the preauricular were recorded for each available individual in the TXSTDSC collection. The pubic tubercle is a raised and roughened region of bone of varying size on the superior pubic ramus, lateral to the pubic symphysis (Snodgrass and Galloway, 2003). Pubic tubercle height was measured in millimeters using sliding calipers. The width of the pubic bone just lateral to the pubic tubercle was recorded and subtracted from the pubic tubercle measurement to determine the height of the tubercle alone (Figure 2.1). Dorsal pubic pits are lesions on the dorsomedial surface of the pubis (Suchey et al., 1979) (Figure 2.2). The preauricular sulcus is a groove of varying size and morphology on the posterior rim of the greater sciatic notch (Houghton, 1974; Dunlap, 1981) (Figure 2.3). These were recorded for presence or absence. Investigating the correlations and frequency of these scars with risk factors for pelvic instability will address the hypothesis that they are related to factors other than parity.

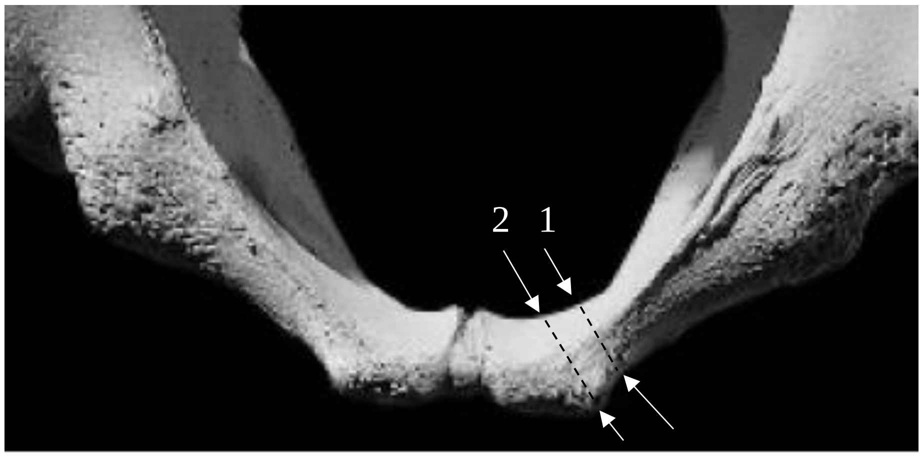

Figure 0.1 - Measurement sites for pubic tubercle length (White et al, 2012:417). 1.) Width of the iliopubic ramus. 2.) Width of the pubis, including the pubic tubercle.

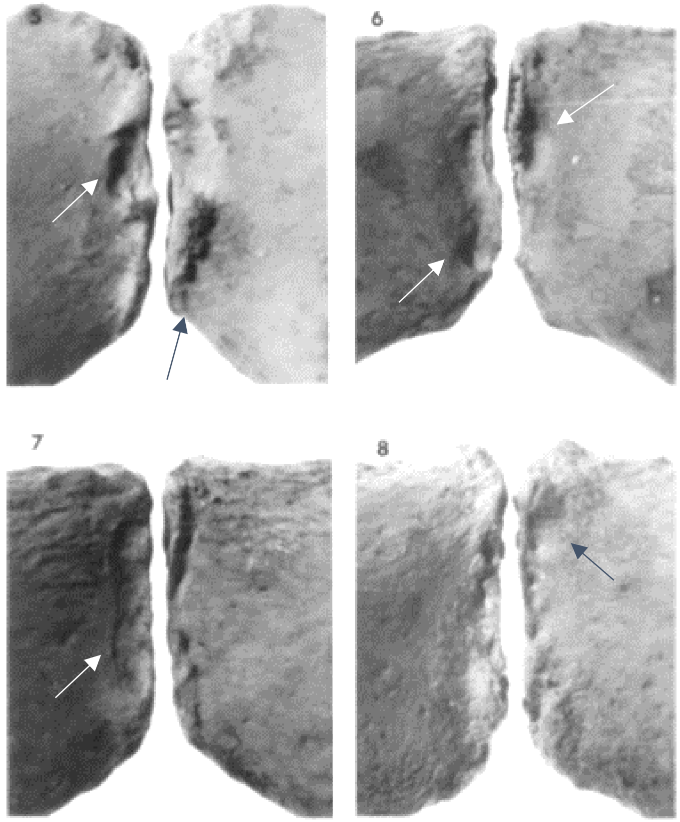

Figure 0.2 - Variations of dorsal pubic pitting (arrows) (Suchey et al., 1979:527).

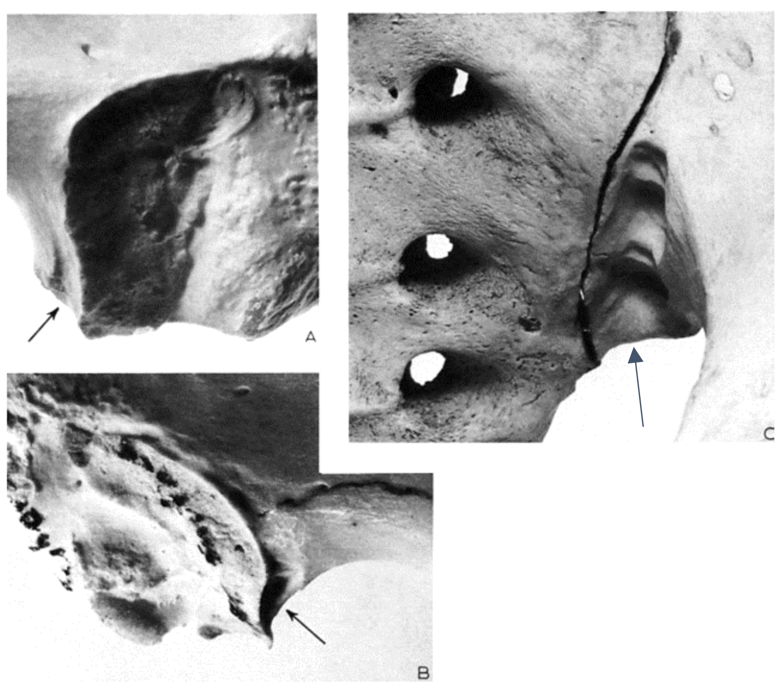

Figure 0.3 – Variations of the preauricular sulcus (arrows) (Houghton, 1974:387).

Age estimation of the pubic symphysis

The pubic symphysis, rather than the auricular surface, was chosen for investigating age estimation bias because the posterior ilium's morphology did not allow for a configuration that could be evaluated with HRCT at an appropriate resolution. The left pubic symphysis of each individual was scored as one of seven stages following Hartnett (2010). This method is a revision of the widely-used Suchey-Brooks method (Brooks and Suchey, 1990) and was chosen due to its inclusion of phases for older age groups, which are disproportionately represented in this thesis's sample. Table 2.3 describes the age-related phases used in the Hartnett's method (Hartnett, 2010:1151).

Table 2.3 Revised pubic bone phase descriptions for the Forensic Science Center collection (Hartnett, 2010:1151).

Phase 1	A clear ridge and furrow system extends from the pubic tubercle onto the inferior ramus. Ridges and furrows are deep and well-defined and do not look worn down. There is no dorsal lipping. Bone is of excellent quality and is firm, heavy, dense and smooth on the ventral and dorsal body. There is no rim formation. The dorsal plateau is not formed. The ridges and furrows extend to the dorsal edge.
Phase 2	The rim is in the process of forming, but mainly consists of a flattening of the ridges on the dorsal aspect of the face and ossific nodules present along the ventral border. Ridges and furrows are still present. The ridges and furrows may appear worn down or flattened, especially on the dorsal aspect of the face. The furrows are becoming shallow. The upper and lower rim edges are not formed. There is no dorsal lipping. The bone quality is very good and the bone is firm, heavy, dense, and smooth on the ventral and dorsal body, with little porosity. The pubic tubercle may appear separate from the face.
Phase 3	The lower rim is complete on the dorsal side of the face, and is complete until it ends approximately halfway up the ventral face leaving a medium to fairly large gap between the lower and upper extremities on the ventral face. This enlarged "V" is longer on the dorsal side than the ventral side. Some ridges and shallow furrows are still visible, but appear worn down. In some cases, the face is becoming slightly porous. The rim is forming both on the dorsal aspect of the face and the upper and lower extremities. In some cases, there is a rounded buildup of bone in the gap between the upper and lower extremities above the enlarged "V." Bone quality is good; the bone is firm, heavy, dense, and has little porosity. The dorsal surface of the body is smooth, and there are small bony projections near the medial aspect of the obturator foramen. The ventral aspect of the body is not elaborate. Very slight to no dorsal lipping. Quality of bone and rim completion are important deciding factors. Variant: In some cases, a deep line or epiphysis is visible on the ventral aspect parallel to and adjacent to the face (males only).

Table 2.3 continued. Revised pubic bone phase descriptions for the Forensic Science Center collection (Hartnett, 2010:1151).

Phase 4	In most cases, the rim is complete at this stage, but may have a small ventral hiatus on the superior and ventral aspect of the rim. The face is flattened and not depressed. Remnants of ridges and furrows may be visible on the face, especially on the lower half. The quality of bone is good, but the face is beginning to appear more porous. The dorsal and ventral surfaces of the body are roughened and becoming coarse. There is a slight dorsal lipping. In females with parturition pits, dorsal lipping can be more pronounced. The ventral arc may be large and elaborate in females.
Phase 5	The face is becoming more porous and is depressed, but maintains and oval shape. The face is not irregularly-shaped or erratic. The rim is complete at this stage. In general, the rim is not irregular. Ridges and furrows are absent on the face. There may be some breakdown of the rim on the ventral border, which appears as irregular bone (not rounded/solid). The ventral surface of the body is roughened and irregular, with some bony excrescences. The dorsal surface of the body is coarse and irregular. Projections are present on the medial aspect of the obturator foramen. Bone quality is good to fair; it is losing density and is not smooth. The bone is moderately light in weight. In females the ventral arc is prominent.
Phase 6	The face is losing its oval shape and is becoming irregular. The rim is complete, but breaking down, especially on the ventral border. The rim and face are irregular, porous, and macroporous. Bone quality is fair, and the bone is lighter and more porous, even with bony buildup on the ventral body surface. The rim is eroding. The dorsal surface of the bone is rough and coarse. There are no ridges and furrows. Dorsal lipping is present. Projections are present at the medial aspect of the obturator foramen. Bone weight is a major deciding factor between phases 6 and 7.
Phase 7	The face and rim are very irregular in shape and are losing integrity. The rim is complete but is eroding and breaking down, especially on the ventral border. There are no ridges and furrows. The face is porous and macroporous. Dorsal lipping is pronounced. Bone quality is poor, and the bone is very light and brittle. Bone weight is an important deciding factor. The dorsal surface of the bone is roughened. The ventral surface of the body is roughened and elaborate. Projections are present at the medial wall of the obturator foramen. The pubic tubercle is elaborate and proliferative. Bone weight is a major deciding factor between phases 6 and 7.
VARIANT	The rim is complete except for a lytic/sclerotic appearing hiatus at the superior ventral margin that extends toward the pubic tubercle and sometimes underneath the ventral rim, which should not be confused for a hiatus.

For investigating age estimation bias, this study's primary focus is in the degeneration of the symphyseal face, thus factors concerning its topography were given the most consideration. Regions of the pelvis with possible scars were obscured to avoid observation bias. The estimated Hartnett phase was recorded for each individual, who were later placed into their nearest age-appropriate phase. The actual phase was subtracted from the estimated phase to generate the error rate. A negative integer indicates under-aging, while a positive integer indicates over-aging. Over-aging in obese and parous individuals would support the hypothesis that both conditions can cause detectable pelvic instability in the skeleton.

High-resolution computed tomography

The sample chosen for HRCT was broken into three subgroups: ten female individuals with a preauricular sulcus, eight without, and ten males without a preauricular sulcus. Each specimen was scanned with the North Star x5000 HRCT scanner at the Grady Early Forensic Anthropology Research Laboratory at Texas State (GEFARL). Specimens were mounted and stabilized with a combination of radiolucent floral arrangement foam, rubber bands, and metal weights (Figures 2.4 and 2.5). The os coxae were oriented with the acetabulum down and the pubic symphysis up. This arrangement was placed on the scanner stage with the symphysis in the center in line with the x-ray source and rotating on an axis.

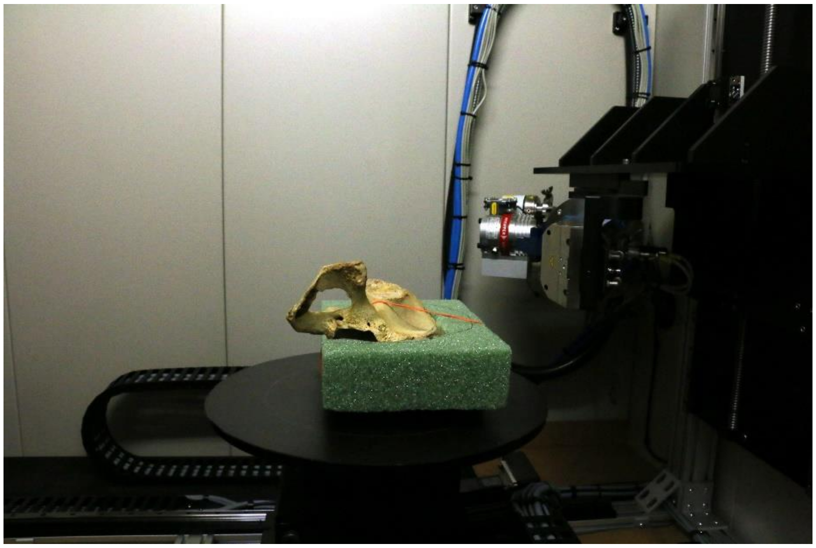

Figure 0.4 - View of a specimen mounted for scanning from outside the North Star scanner. X-ray source is to the right.

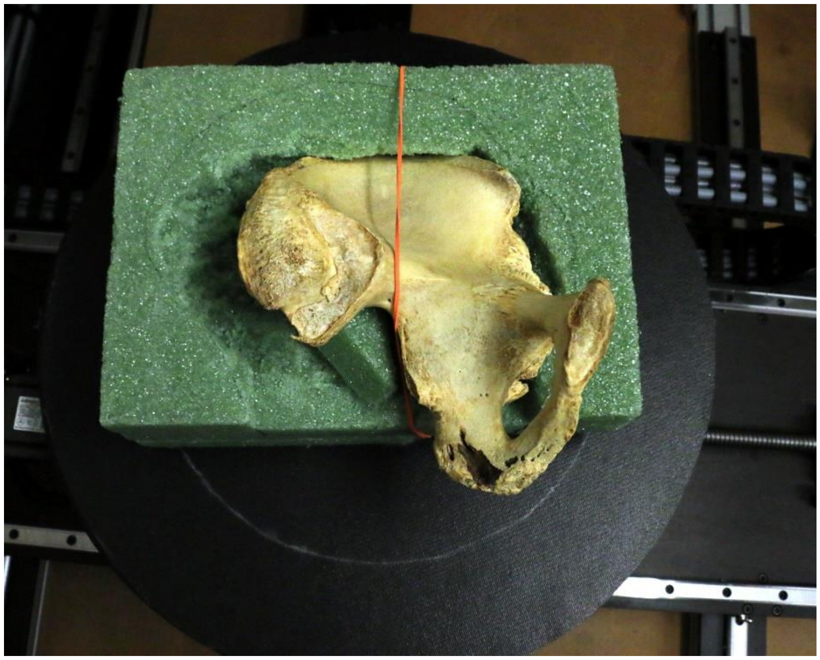

Figure 0.5 - Specimen mounted for scanning placed on the scanning stage in the North Star scanner. View from above. X-ray source is to the left.

Standard operating procedures for the scanner's software NSI EFxDR were followed for each scan's settings (North Star Imaging, Inc.). Technique development is a critical step in producing quality images and 3D reconstructions. For consistency the system voltage, current, and image resolution were set to 110 kV, 160 µA, and 39.45 µm for all scans. These parameters provide great sufficient penetration of the bone while allowing for satisfactory contrast. A resolution of less than 50 µm is needed to examine human trabeculae. Line profiles determine the number of slices a scan will produce, thus this setting varied by specimen (Figure 2.6). Each scan was then reconstructed into a three-dimensional format using the NSI efX_{CT} program (North Star Imaging, Inc.). Reconstruction allows the opportunity to remove excess data and noise and to orient the scan for optimal analysis in AVIZO Lite 9.2.0 general 3D visualization and analysis software (FEI Visualization Sciences Group).

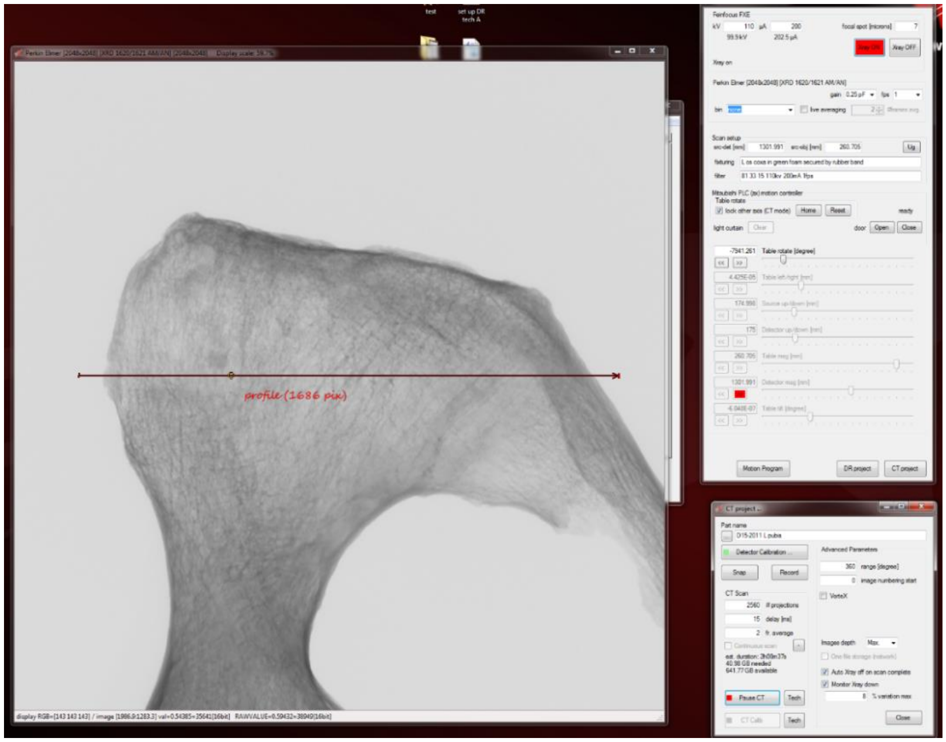

Figure 0.6 - Technique development window from the NSI EFxDR software showing the radiograph of a specimen prior to scanning.

Volume rendering and volume of interest extraction

The following protocol was followed for each scan dataset in AVIZO lite following guidelines created by Timothy Ryan (2015, personal communication). TIFF files for each scan were loaded into the software, creating a 3D project file. “Isosurface rendering” was selected to visualize the data in 3D. After adjusting the thresholding until the 3D image was visible, the “Isosurface” module was attached and the thresholding value copied. “Compactify” and “downsample” were selected. Three “Orthoslices” were also attached for each plane as guides. The “autoVOI_multi” script was attached to the dataset. Selecting “Create ROI” in the script’s view created a region of interest box encompassing the whole object. This was minimized to enclose only the pubic bone. With the vertical Orthoslice moved to the center of the pubic bone, Isosurface was turned off and the ROI boundaries brought in to form a tight rectangle around the pubic bone that avoided empty space and cortical bone, where possible. Then, the 3D measurement tool was used to draw lines to create roughly equal quadrants: Superior-Medial, Superior-Lateral, Inferior-Medial, and Inferior-Lateral (Figure 2.7). A volume of interest was created within each quadrant for each scan, taking up as much of the quadrant as possible (Figure 2.8). Overlap between VOIs was avoided to maintain independence of samples for each region of the pubic bone. This method ensures that the maximum amount of the pubic bone is considered given the available software, following the suggestions of Sylvester and Terhune (2017).

The autoVOI_multi script offers several options optimized for different bone regions, all of which create a VOI 50% of the size of the ROI. "Proximal tibia" under the VOI section in the script view was randomly selected for consistency. This was then adjusted to the maximum amount of a quadrant while still falling within the volume rendering. VOIs were not uniform in size due to high variability in size and shape within and between individual pubic bones. Selecting "create VOI" generated a VOI as a separate dataset, which was then saved as a DICOM file stack.

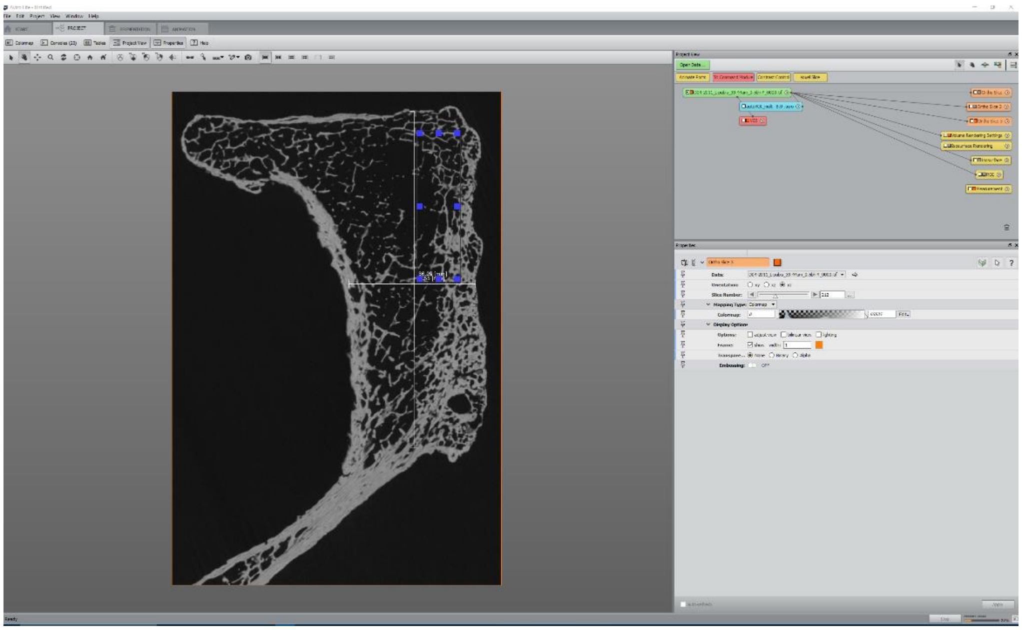

Figure 0.7 - Example of AVIZO project and the creation of a VOI in a pubic bone. Orthoslice view. Midcoronal view. Medial is right, inferior is up.

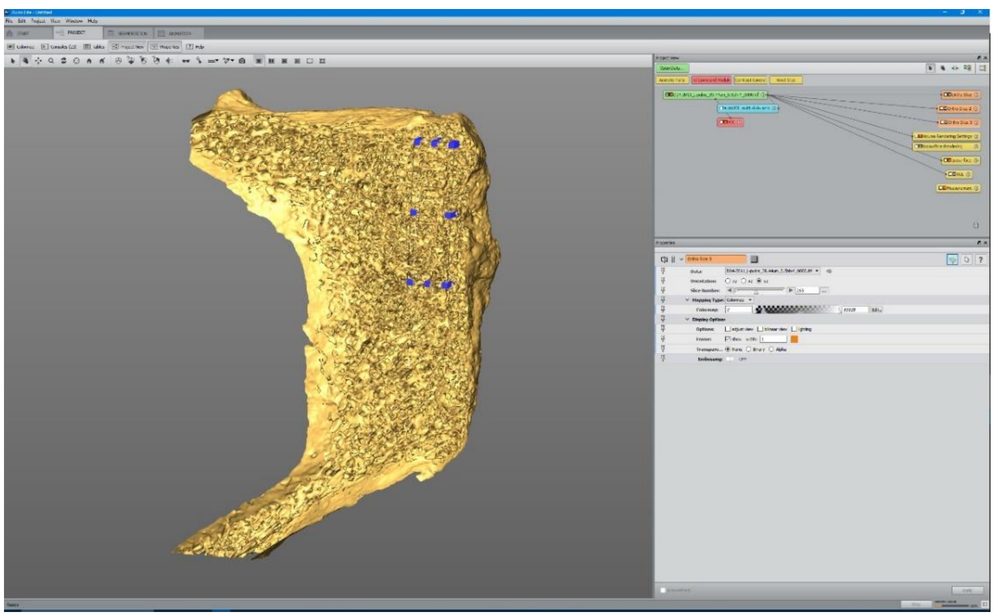

Figure 0.8 - VOI in 3D view (AVIZO Lite). Midcoronal view. Medial is right, superior is up.

BoneJ analysis

DICOM file stacks were imported into ImageJ, the open-source Image Processing and Analysis in Java program (Rasband, 1997-2016). The stacks were then analyzed with the plugin BoneJ (Doube et al., 2010) to assess measurements of trabecular quality and organization. This will test the hypothesis that obesity and parity affect trabecular microarchitecture as novel stimuli due to pelvic instability. The protocol for trabecular analysis was recommended by Timothy Ryan (2015, personal communication), who also developed a macro for executing the commands in batch mode (further edited by Devora Gleiber and the thesis author). These measurements are listed in the order of execution and briefly described in Table 2.4. (Complete descriptions can be found at http://www.bonej.org.)

Some image stacks uploaded with extremely low saturation. This was corrected in ImageJ through the Image menu > Adjust > Brightness/Contrast > Auto > Apply, and run through Optimise Threshold as usual. This correction was tested on other stacks already at an acceptable saturation and did not change measurement outputs.

Table 2.4 BoneJ commands and measurements (based on descriptions from http://www.bonej.org).

<table>
<tr><th>Command and Measurements</th><th colspan="2">Purpose</th></tr>
<tr><td>Optimise threshold
(“Threshold only” and “Apply Threshold” selected)</td><td colspan="2">Converts image stack into binary images</td></tr>
<tr><td>Volume fraction (BV/TV)
(Algorithm: Voxel)</td><td colspan="2">Volume of mineralized bone per unit</td></tr>
<tr><td>Bone volume (BV)</td><td colspan="2">Volume contained by surface mesh (mm³)</td></tr>
<tr><td>Total volume (TV)</td><td colspan="2">Volume from surface mesh around total volume (mm³)</td></tr>
<tr><td>(Trabecular) Thickness (Tb.Th)
(“Thickness” and “Spacing” selected)</td><td colspan="2" rowspan="2">Calculates mean and standard deviations from pixel values (millimeters)</td></tr>
<tr><td>Trabecular spacing (Tb.Sp)</td></tr>
<tr><td>(Degree of) Anisotropy (DA)
(Defaults)</td><td>Measures the degree of organization of trabeculae</td><td>0 = isotropic;
1 = anisotropic</td></tr>
<tr><td>Purify
(Labeling Algorithm: Multithreaded)</td><td colspan="2">Applied as a filter to remove small particles before Connectivity analyses</td></tr>
<tr><td>Connectivity density (Conn.D)</td><td colspan="2">Number of connected trabeculae per unit volume</td></tr>
</table>

Statistical analysis

The means of the BoneJ results were computed for each individual's four VOI regions. All statistical tests were performed using JMP Pro 12 (SAS Institute Inc., 2016). The preauricular sulcus (PAS) and dorsal pubic pitting (DPP) were coded for presence (P) or absence (A), and for some tests individuals were coded as obese (O), non-obese (NO), parous (P), or nulliparous (NP). These were treated as nominal data. Elsewhere, BMI and the pubic tubercle length (PT) were continuous and parity was ordinal. All BoneJ measurements are continuous data.

Significance was $\alpha = 0.05$ for all statistical tests for a 95% confidence level that the null hypothesis can be rejected if the test statistic is below 0.05. The following preliminary tests were performed to determine which tests would best compare the means of continuous variables. The Shapiro-Wilk test was performed to test for normality of distributions in each continuous measurement. Normally-distributed data fall symmetrically around the mean, forming a bell-curve. The null hypothesis of the Shapiro-Wilk test is that the independent and random-sampled data are normally distributed. Levene's test was performed to test the assumption that variances are equal between variables, or homoscedastic. This test was used in place of the F-test of variance, which is best used for normally-distributed data.

The following tests compare means of independent, randomly-sampled continuous data. These test the assumption that the means of two samples are similar. The Wilcoxon test was used to compare means of non-normal data. It should be noted that nonparametric tests are less statistically powerful than parametric tests. Student's t-test was used in cases of normal distribution and equal variances, while Welch's t-test was applied for unequal variances.

Linear regression tests whether an independent variable (*x*) predicts a dependent variable (*y*) in a linear relationship, with R^2 as the proportion of *x* that contributes to *y*. Chi square analyses tests expected versus observed frequencies between mutually exclusive categories of nominal data. This will test whether pelvic scars occur more frequently in groups with risk factors for pelvic instability.

3. RESULTS

Almost all variables were non-normal or had unequal variance following the Shapiro-Wilk and Levene's tests, respectively. The Wilcoxon test was used in these circumstances. For unequal variances only, Welch's t-test was used. Otherwise, Student's t-test, chi-square, and linear regressions were used. Significance was set to $\alpha = 0.05$. Box and whisker plots illustrate the median values of each sample (horizontal red lines, within boxes) compared to the grand mean (horizontal gray line). The "whiskers" represent the 25th and 75th percentiles. In regression plots, the red line is the "line of best fit." Significant and noteworthy results are presented below. Tables and figures for non-significant results are presented in Appendices A and B, respectively.

Pelvic Scarring and Gross Morphology

Pubic tubercle length (mm) and the frequency of the preauricular sulcus and dorsal pubic pitting were each examined by sex, parity status, age, obesity status, and body mass index for the whole sample (N = 179). This tests the hypotheses that the length of the pubic tubercle and the presence of pelvic scarring correlate with parity status and obesity status between sexes, and therefore whether pelvic instability increases the chance of their appearance. Missing data are indicated in each section. Error in age estimation using Hartnett's (2010) method for the pubic symphysis is also compared between these groups. This will test whether over-aging is associated with pelvic scarring and pelvic instability.

Dorsal pubic pitting analyses

Dorsal pubic pitting was less common than the preauricular sulcus in this sample; it was not observable in three individuals (N = 176). Contingency tables comparing its frequency between sexes, parity status, and obesity status are presented below. Chi-square analysis showed a significant difference in the frequency of pitting between the sexes, but not parity groups, with pitting far more common in females (Table 3.3). There was no difference between obese and non-obese individuals. The nonparametric Wilcoxon test examined mean differences in age-at-death and BMI between the presence and absence of dorsal pubic pitting (Table 3.4). Though neither pair was significantly different, age-at-death was markedly higher in those with pitting (p = 0.057).

Table 3.1. Descriptive statistics for the presence and absence of dorsal pubic pitting.

Group	*n*	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Absent	131	27.96	8.95	0.78	26.41	29.51
Present	36	28.95	8.29	1.38	26.15	31.76
N	167*	28.17	8.80	0.68	26.83	29.52

*Body weight was unavailable for 12 individuals

Table 3.2. Descriptive statistics for known age-at-death (years) between the absence and presence of dorsal pubic pitting.

Group	*n*	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Absent	138	64.01	15.28	1.30	61.44	66.59
Present	38	70.05	14.20	2.30	65.38	74.72
N	174	65.08	15.14	1.15	62.81	67.34

*DPP could not be assessed in nine individuals

Table 3.3. Dorsal pubic pitting: contingency analysis by sex and parity status. Chi-square = 58.54; DF = 2; **Prob = <0.000**; R^2 0.32. Significant difference between sexes, but not parity groups.

Group	*n*	Absent	Present
All females	75	39 (52.0%)	36 (48.0%)
All males	101	99 (98.02%)	2 (1.98%)
N	176	138 (78.41%)	38 (21.59%)

Table 3.4. Dorsal pubic pitting: nonparametric Wilcoxon test results for difference in mean body mass index and age-at-death between presence and absence (α = 0.05).

Variable	Score Mean Difference	Std Err Dif	Z	p-value
Known age-at-death (years)	17.74	9.33	1.90	0.057
Body mass index	7.26	9.10	0.80	0.425

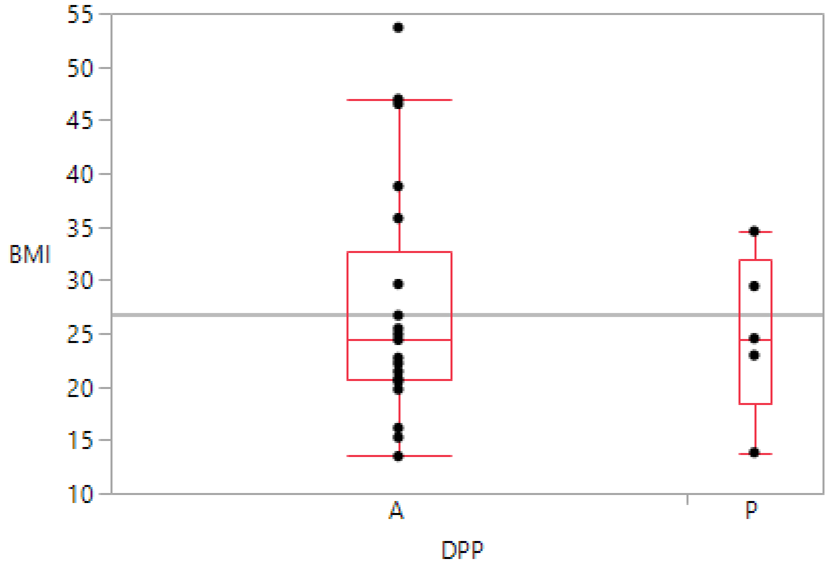

Figure 0.1 - Mean body mass index (BMI) boxplot comparison between the presence (P) and absence (A) of dorsal pubic pitting (DPP).

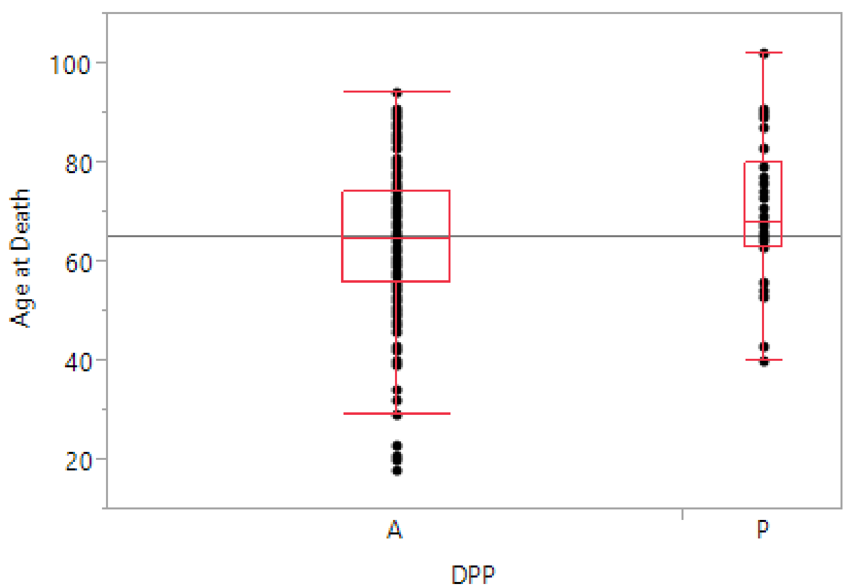

Figure 0.2 - Boxplot comparison of mean known age-at-death (years) between the presence (P) and absence (A) of dorsal pubic pitting (DPP).

Pubic tubercle analyses

The length of the pubic tubercle was non-normal in this sample. The pubic tubercle was not observable in five individuals (N = 174). Results for the Wilcoxon test for all groups are presented in Table 3.7. The Wilcoxon test of males to females and each parity group yielded a statistically significant difference only between males and parous females. The mean length of the pubic tubercle was significantly larger in males than in parous females. Parous females and nulliparous females were more different from each other than from nulliparous females and males (nulliparous females having a longer pubic tubercle), though this difference was not statistically significant. The same test of obese versus non-obese individuals also yielded insignificant results. Regressing pubic tubercle length against BMI yielded a very slight though insignificant inverse relationship (Figure 3.5). Pubic tubercle length was also regressed against age-at-death, returning a very slight though insignificant positive correlation (Figure 3.6).

Table 3.5. Descriptive statistics for pubic tubercle length by sex and parity status.

Group	*n*	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Males	99	3.30	2.16	0.22	2.87	3.73
Females	75*	2.88	1.76	0.20	2.47	3.28
Nulliparous	30	3.27	1.92	0.35	2.55	3.98
Parous	44	2.55	1.58	0.24	2.07	3.03
N	174	3.12	2.00	0.15	3.42	3.42

*Parity status was unavailable for one female.

Table 3.6. Descriptive statistics for pubic tubercle length by obesity status.

Group	*n*	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Non-obese	111	3.19	2.13	0.20	2.79	3.59
Obese	54	3.04	1.81	0.25	2.55	3.54
N	165*	3.14	2.03	0.16	2.83	3.46

*14 individuals could not be assessed due to missing body weight or pubic tubercle.

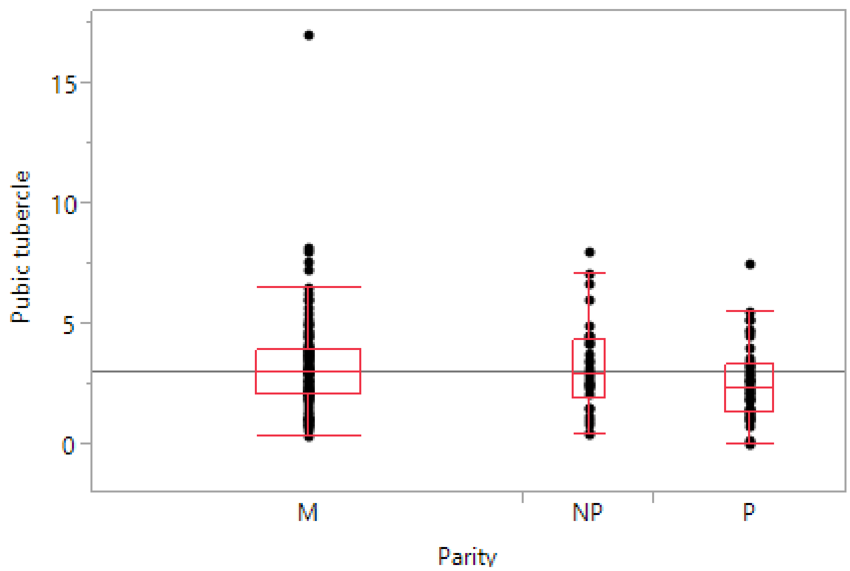

Figure 0.3 - Box plots of the length of the pubic tubercle (mm) by parity group and sex.

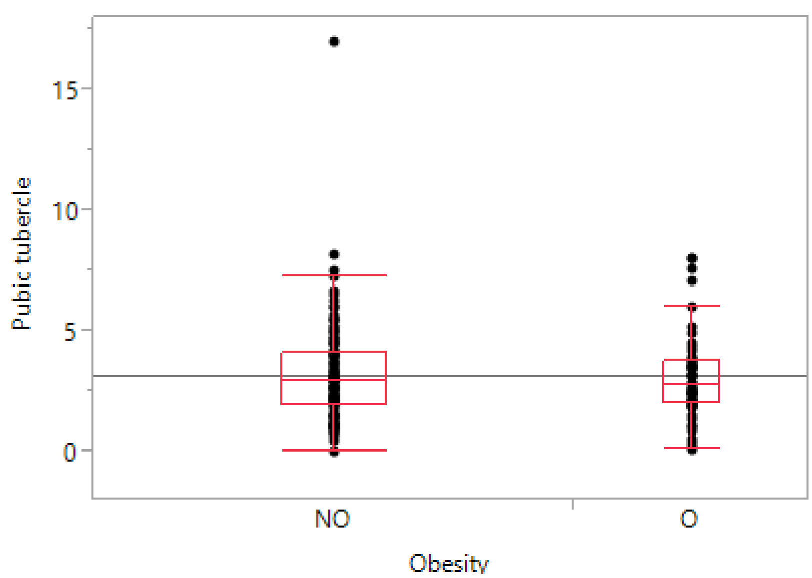

Figure 0.4 - Boxplots of lengths of the pubic tubercle (mm) between obese (O) and non-obese (NO) individuals.

Table 3.7. Nonparametric Wilcoxon test for difference of mean pubic tubercle length (mm) between males and females, parity groups, and obese and non-obese individuals (α = 0.05). Significant results are bolded with an asterisk.

Variable	Score Mean Difference	Std Err Dif	Z	p-value
Males/Females	10.52	7.711	-1.36	0.172
Parous/Nulliparous	-8.18	5.09	-1.61	0.108
Parous/Males	-16.56	7.50	-2.21	**0.027***
Nulliparous/Males	0.67	7.79	0.09	0.931
Obese/Non-obese	-2.61	7.93	-0.33	0.741

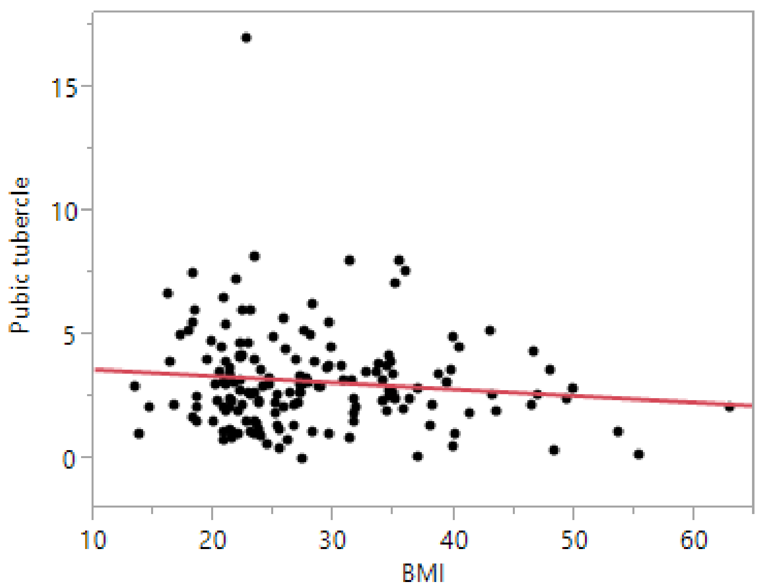

Figure 0.5 - Pubic tubercle length (mm) regressed on body mass index (BMI). $R^2 = 0.01$.

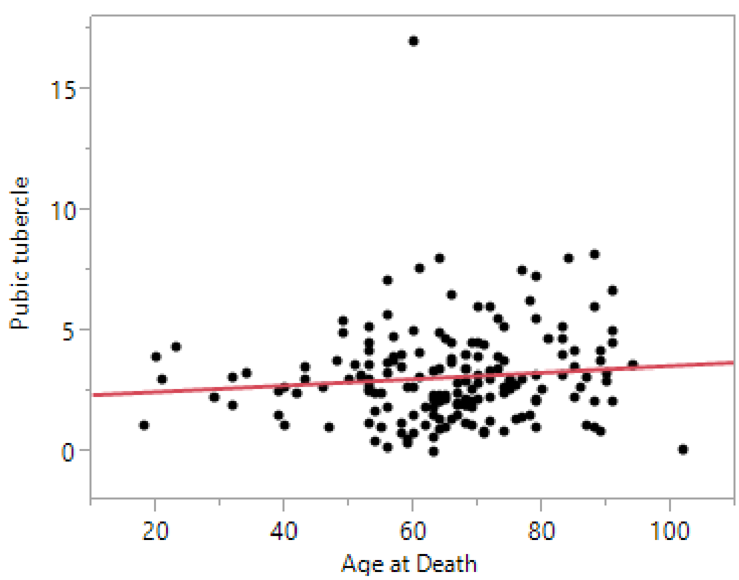

Figure 0.6 - Pubic tubercle length (mm) compared to age-at-death (years). $R^2 = 0.01$.

Preauricular sulcus

The frequency of the preauricular sulcus was examined by sex, parity group, obesity group, age, and BMI. Chi-square analysis yielded a significant difference between the sexes, being far more common among females, but not between parous and nulliparous females or obese and non-obese individuals (Table 3.10). Mean age-at-death and mean BMI were compared between those with a sulcus and those without through the Wilcoxon test (Table 3.11). Mean BMI approached statistically significant difference at $p = 0.055$.

Table 3.8. Descriptive statistics for known age-at-death (years) between presence and absence of the preauricular sulcus.

Group	*n*	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Absent	89	64.82	14.94	1.58	61.67	67.97
Present	90	66.12	15.53	1.64	62.87	69.38
N	179	65.47	15.21	1.14	63.23	67.72

Table 3.9. Descriptive statistics for body mass index between the absence and presence of the preauricular sulcus.

Group	*n*	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Absent	83	27.09	8.21	0.90	25.29	28.88
Present	87	29.59	9.83	1.05	27.49	31.68
N	170*	28.37	9.13	0.70	26.98	29.75

*Body weight was unavailable for nine individuals

Table 3.10. Contingency analysis of the preauricular sulcus by sex. Chi-square =89.09; DF = 1; **Prob = <0.000**; $R^2 = 0.36$; $\alpha = 0.05$.

Group	*n*	Absent	Present
All females	78	9 (11.5%)	69 (88.5%)
All males	101	80 (79.2%)	21 (20.8%)
N	179	89 (49.7%)	90 (50.3%)

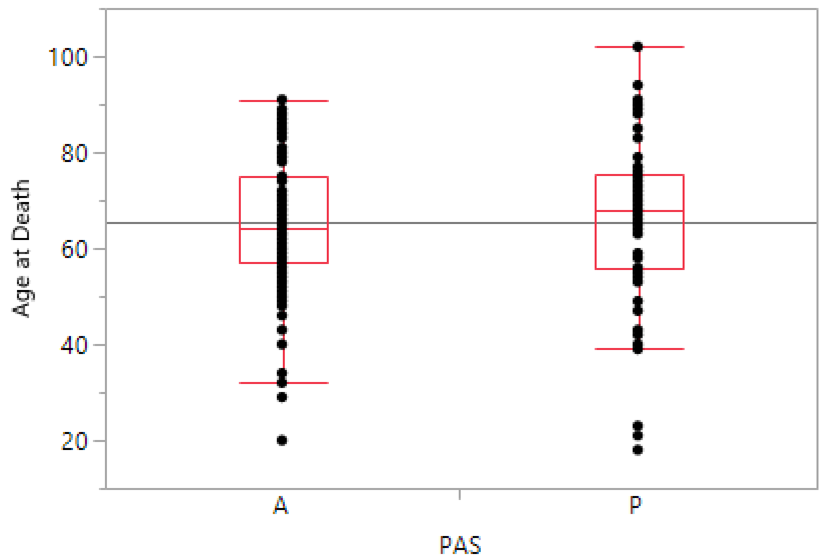

Figure 0.7 - Boxplots of age-at-death (years) between the presence (P) and absence (A) of the preauricular sulcus (PAS).

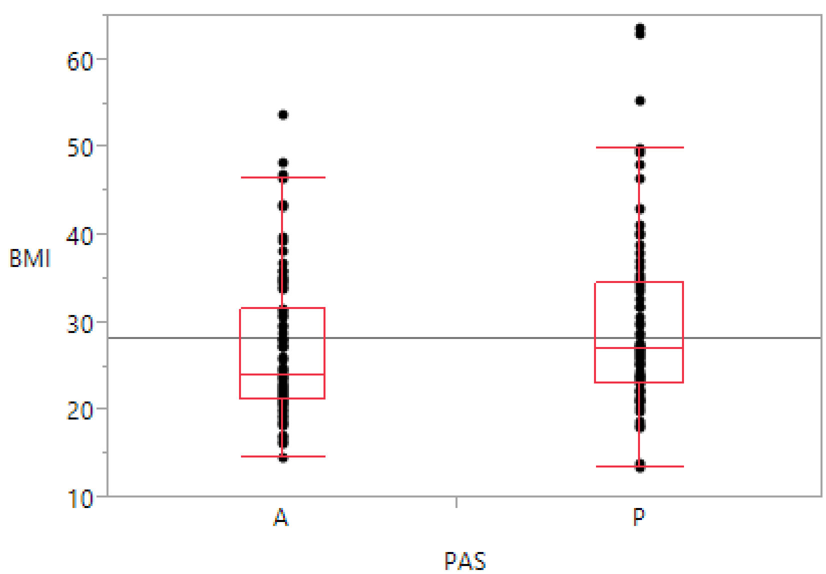

Figure 0.8 - Boxplots comparing body mass index (BMI) between the presence (P) and absence (A) of the preauricular sulcus (PAS).

Table 3.11. Nonparametric Wilcoxon test results for differences in mean body mass index and known age-at-death (years) between the presence and absence of the preauricular sulcus (α = 0.05).

Variable	Score Mean Difference	Std Err Dif	Z	p-value
Age-at-death	6.77	7.74	0.87	0.381
Body mass index	14.49	7.55	1.92	0.055

Age Estimation Differences between Groups

Age was estimated based on the morphology of the pubic symphysis following Hartnett (2010) for all but two individuals, who were unobservable (N = 177). Differences between the estimated phase and actual phase are reported below for each demographic group. A positive integer indicates over-aging, while a negative integer indicates under-aging. Descriptive statistics are presented in Tables 3.12 – 3.17. The Wilcoxon test returned a statistically significant difference between males and females but not between parity groups, obesity groups, or those with pelvic scars. Mean BMI was also not statistically different between individuals correctly estimated for age, over-estimated, and underestimated. Individuals with a preauricular sulcus were more likely to be over-aged, but not at the level of significance ($p = 0.062$), and this group was overwhelmingly female (Figure 3.10). Regressions of BMI and pubic tubercle length were also insignificant and returned very low R^2 values.

Table 3.12. Descriptive statistics of age estimation error by obesity status.

Group	*n*	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Non-obese	113	-0.06	0.71	0.07	-0.19	0.07
Obese	55	-0.11	0.99	0.13	-0.38	0.16
N	168*	-0.08	0.81	0.06	-0.20	0.05

*Body weight was unavailable for nine individuals

Table 3.13. Descriptive statistics of age estimation error by sex and parity status.

Group	*n*	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Males	101	-0.25	0.65	0.06	-0.38	-0.12
Females	76*	0.13	0.91	0.10	-0.08	0.34
Nulliparous	*30*	*0.23*	*1.04*	*0.19*	*-0.15*	*0.62*
Parous	*45*	*0.07*	*0.83*	*0.12*	*-0.18*	*0.32*
N	177	-0.08	0.80	0.06	-0.20	0.03

*Parity status was unavailable for one female

Table 3.14. Descriptive statistics of age estimation error by the presence and absence of the preauricular sulcus.

Group	*n*	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Absent	88	-0.20	0.59	0.06	-0.33	-0.08
Present	89	0.03	0.95	0.10	-0.16	0.23
N	177*	-0.08	0.80	0.06	-0.20	0.03

*Age could not be estimated in one individual

Table 3.15. Descriptive statistics of age estimation error by the presence and absence of dorsal pubic pitting.

Group	*n*	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Absent	137	-0.14	0.81	0.07	-0.27	0.00
Present	38	0.10	0.76	0.12	-0.14	0.36
N	175*	-0.08	0.80	0.06	-0.20	0.03

*Dorsal pubic pitting was unobservable in two individuals, and age could not be estimated in one

Table 3.16. Descriptive statistics for pubic tubercle length between age estimation bias groups.

Group	*n*	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Correct	134	3.11	2.05	0.18	2.75	3.46
Over-aged	13	2.95	1.20	0.33	2.22	3.68
Under-aged	27	3.26	2.12	0.41	2.42	4.11
N	174*	3.12	2.01	0.15	3.42	3.42

*The pubic tubercle could not be measured and age could not be estimated in four individuals

Table 3.17. Results for the nonparametric Wilcoxon test comparing mean age estimation error by sex, parity group, and preauricular sulcus ($\alpha = 0.05$). Significant results are bolded with an asterisk.

Variable	Score Mean Difference	Std Err Dif	Z	p-value
Males/Females	-16.46	5.69	-2.89	**0.0034***
Parous/Males	13.51	5.54	2.43	**0.015***
Nulliparous/Males	12.30	5.80	2.12	**0.034***
Preauricular sulcus presence/absence	10.53	5.63	1.87	0.062

Table 3.18. Contingency table for age estimation bias by sex. Chi-square = 9.32; DF = 2; Prob = 0.02; R2 = 0.04.

Group	*n*	Correct	Over-aged	Under-aged
All females	76	59 (77.63%)	10 (13.16%)	7 (9.21%)
All Males	101	78 (77.23%)	3 (2.97%)	20 (19.80)
N	177*	137 (77.40%)	13 (7.34%)	27 (15.25%)

*Age could not be estimated for two individuals

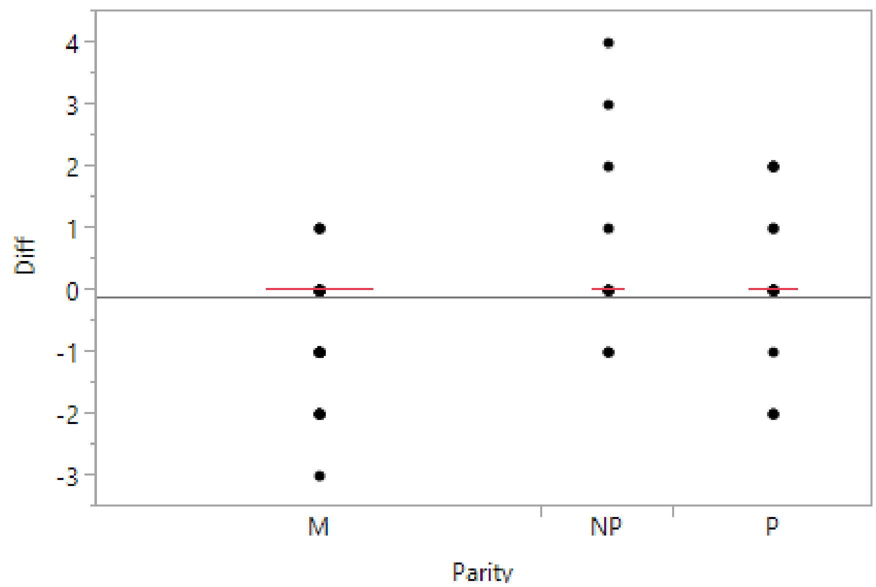

Figure 0.9 - Age estimation error (Diff) between males (M), nulliparous females (NP), and parous females (P).

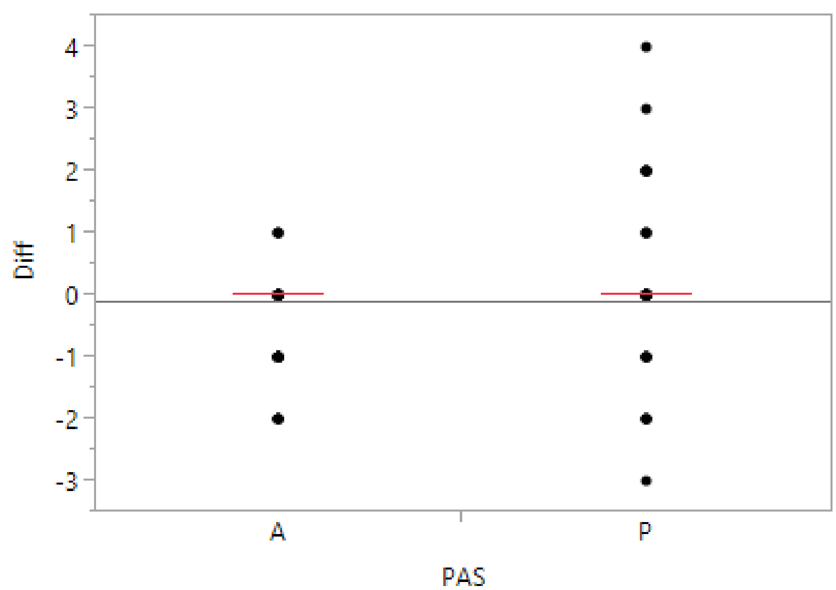

Figure 0.10 - Means of age estimation error (Diff) between the absence (A) and presence (P) of the preauricular sulcus (PAS).

Trabecular Microarchitecture

Degree of anisotropy, mean trabecular spacing, mean trabecular thickness, bone volume ratio, and connectivity density were tested against sex, parity status, obesity status (obese vs. non-obese), body mass index, age, and the presence of pelvic scars in a sample of pubic bones scanned with high-resolution computed tomography (HRCT) (N = 28). These analyses test the hypothesis that pelvic instability changes how loads are distributed within the pubic bone. Groups that are thought to be at risk for pelvic instability (obese individuals and parous females) are expected to have statistically significantly different measurements of trabecular bone quality from those that are not (males, non-obese individuals, and nulliparous females). This will also be corroborated by their association with pelvic scars. Controlling for age-at-death and body mass index through analysis of covariance did not meaningfully impact results, meaning the results are similar when the effects of these covariates are removed. All measurements were rounded to two significant figures.

Degree of anisotropy

This variable examines the degree of organization of trabecular struts. A value closer to 0 is more isotropic (organized) and a value closer to 1 is more anisotropic (disorganized). Descriptive statistics are provided in Tables 3.19 – 3.21. The results were normally distributed and each pair was equal in variance, thus Student's t-test was used ($\alpha = 0.05$). Body mass index, age-at-death, and pubic tubercle length were compared to degree of anisotropy through linear regression. Student t-test results are presented in Table 3.22. Statistically significant difference was reached between males and females of each subgroup, with males more anisotropic than females; there was no statistically significant difference between females of any group. A statistical difference was also found between those with and without dorsal pubic pitting, with anisotropy higher in the latter, though the scar is only present in females in this sample. Anisotropy was markedly higher in non-obese individuals, approaching statistical significance ($p = 0.052$). Finally, there was an inverse relationship between degree of anisotropy and increasing age and pubic tubercle length, but R^2 values were low ($R^2 = 0.07$ and $R^2 = 0.05$, respectively), indicating a weak influence on the dependent variable (Figures 3.14 and 3.15).

Table 3.19. Descriptive statistics of degree of anisotropy by sex, parity groups, and the presence of the preauricular sulcus (PAS).

Group	*n*	Mean	Std Dev	Std Error	Lower 95%	Upper 95%
Males/No PAS	10	0.43	0.05	0.02	0.39	0.46
Females	18	0.35	0.06	0.01	0.32	0.38
No PAS (Females)	8	0.34	0.05	0.02	0.30	0.38
PAS	10	0.35	0.06	0.02	0.32	0.39
Nulliparous	9	0.36	0.06	0.02	0.33	0.40
Parous	9	0.33	0.04	0.02	0.29	0.37
N	28	0.38	0.07	0.01	0.35	0.40

Table 3.20. Descriptive statistics for degree of anisotropy between obese and non-obese individuals.

Group	*n*	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Non-obese	20	0.39	0.06	0.01	0.36	0.42
Obese	6	0.33	0.08	0.03	0.25	0.41
N	26*	0.37	0.07	0.01	0.35	0.40

*Body weight was unavailable for two individuals

Table 3.21. Descriptive statistics of degree of anisotropy between individuals with and without dorsal pubic pitting (DPP).

Group	*n*	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
DPP absent	23	0.39	0.06	0.01	0.36	0.42
DPP present	5	0.32	0.05	0.02	0.26	0.39
N	28	0.38	0.07	0.01	0.35	0.40

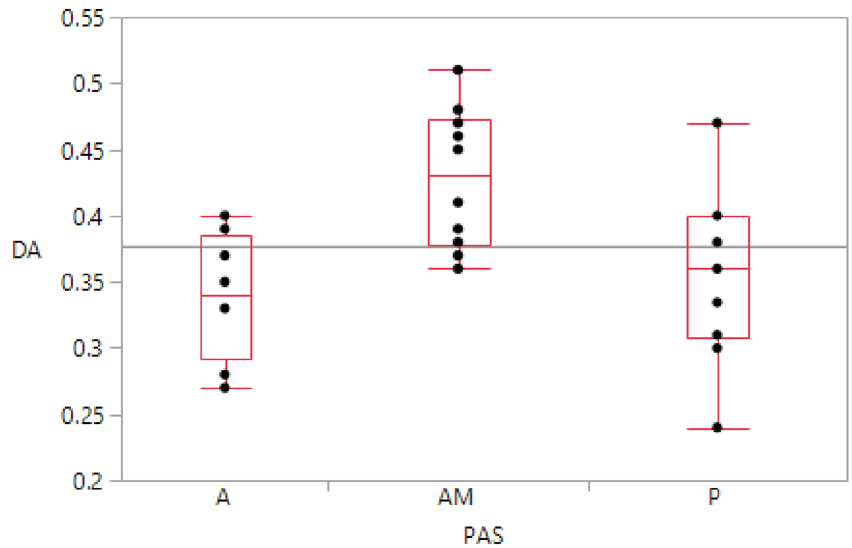

Figure 0.11 - Box plots comparing degree of anisotropy between the presence (P) and absence (A = females, AM = males) of the preauricular sulcus (PAS).

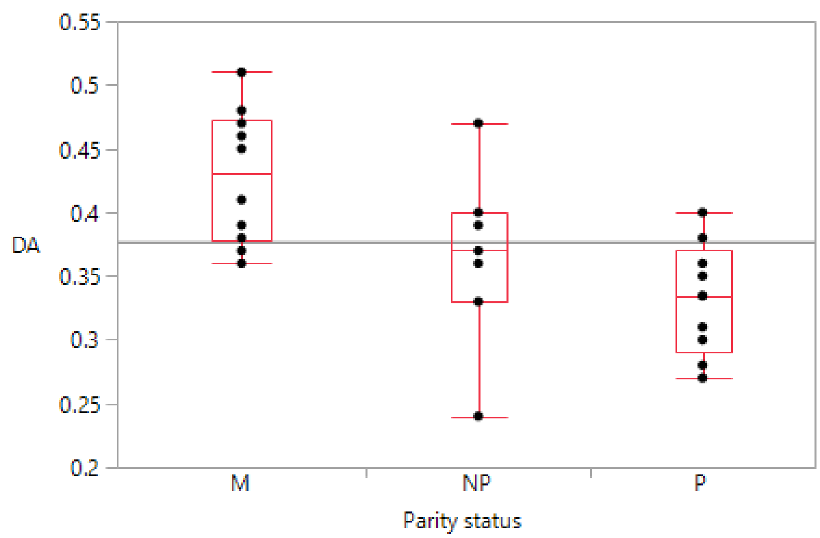

Figure 0.12 - Box plots comparing degree of anisotropy between parous (P), nulliparous (NP) females, and males (M).

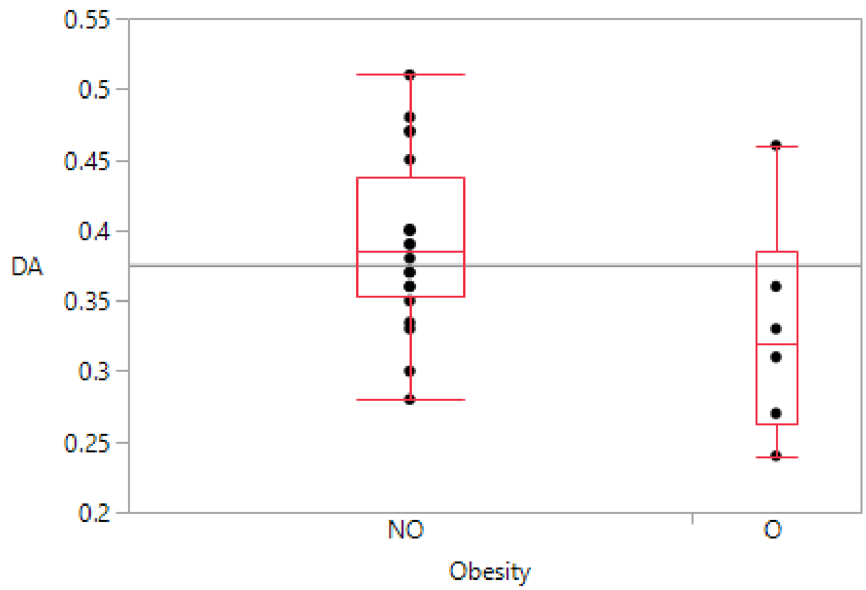

Figure 0.13 - Box plots of degree of anisotropy (DA) between non-obese (NO) and obese (O) individuals.

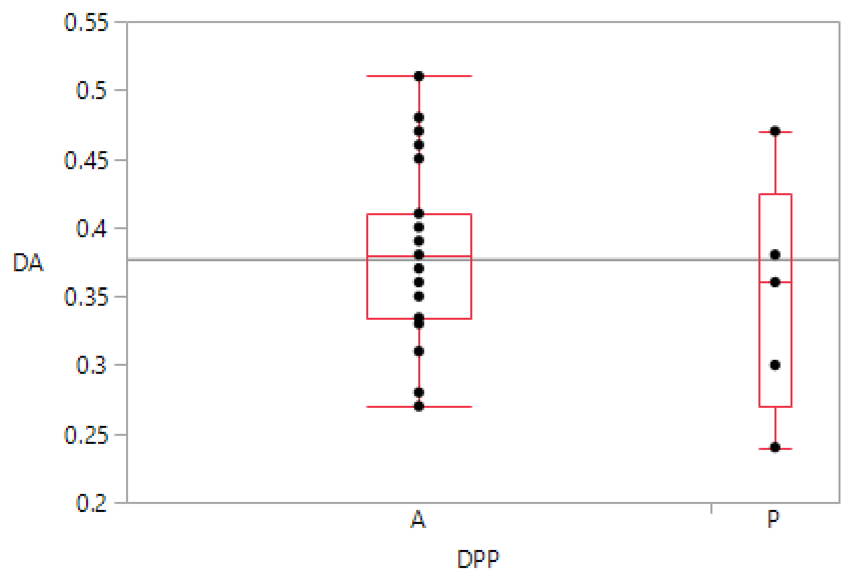

Figure 0.14 - Box plots of degree of anisotropy (DA) between individuals with (P) and without (A) dorsal pubic pitting (DPP).

Table 3.22. Results of Student's t-test comparing degree of anisotropy by sex, parity status, obesity status, and the presence and absence of the preauricular sulcus (PAS) and dorsal pubic pitting (DPP). Significant results are bolded with an asterisk.

Variables	Difference	Std Error Dif	Lower CL	Upper CL	p-Value
Male/Female	0.08	0.02	0.03	0.12	**0.001***
Parous/Nulliparous	0.03	0.02	-0.02	0.09	0.195
Parous/Males	0.10	0.02	0.04	0.15	**0.001***
Nulliparous/Males	0.06	0.02	0.01	0.11	**0.019***
Obese/Non-obese	0.06	0.03	0.00	0.12	**0.052***
PAS present (females)/PAS absent (males)	0.07	0.02	0.02	0.12	**0.007***
PAS present/PAS absent (females)	0.01	0.03	-0.04	0.07	0.563
PAS absent (males)/PAS absent (females)	0.09	0.03	0.03	0.14	**0.003***
DPP present/absent	0.06	0.03	0.00	0.13	**0.047***

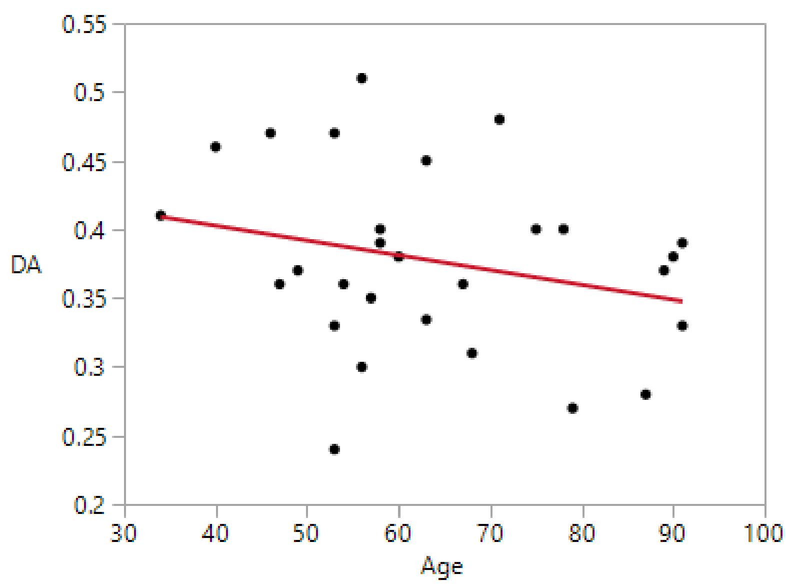

Figure 0.15 - Regression comparing degree of anisotropy (DA) to known age-at-death (years). $R^2 = 0.07$.

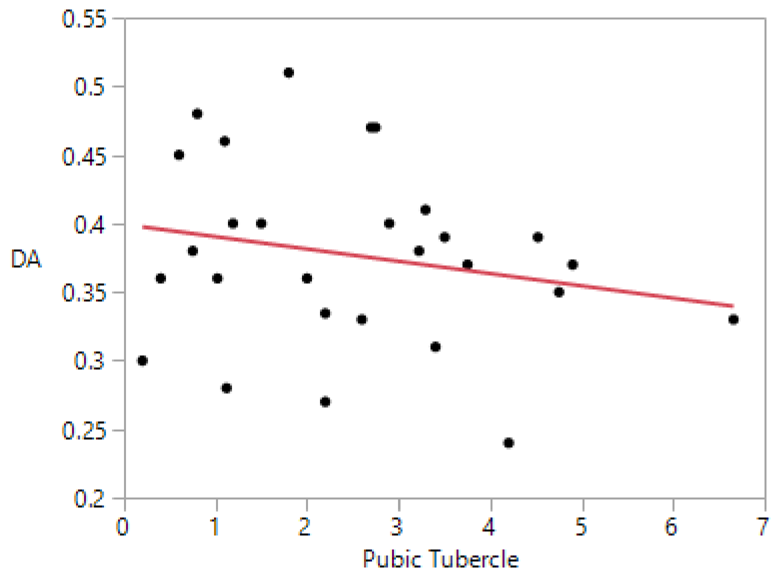

Figure 0.16 – Regression comparing degree of anisotropy (DA) to pubic tubercle length (mm). $R^2 = 0.05$.

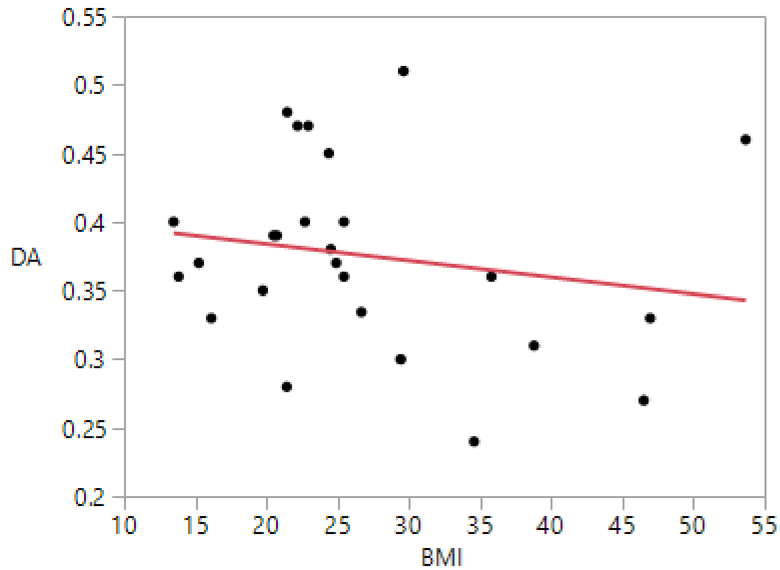

Figure 0.17 – Regression comparing degree of anisotropy (DA) to body mass index (BMI). $R^2 =$ 0.03.

Mean trabecular spacing

Trabecular spacing measures the mean space between trabecular struts within a volume of interest in micrometers (µm). This measurement was normally distributed and equal in variance between each pair of variables, thus Student's t-tests were used ($\alpha =$

0.05). Pairs of continuous traits (body mass index, age-at-death, and pubic tubercle length) were compared through regressions. Descriptive statistics are provided in Tables 3.23 – 3.25. Trabecular spacing was only significantly different between obese and non-obese individuals, with far greater average spacing in the non-obese (Table 3.26). There were also marked differences between females with and without a preauricular sulcus, and between males and females without, approaching statistical significance (p = 0.070 and p = 0.088, respectively). Parous females and females without a preauricular sulcus both had greater trabecular spacing. Trabecular spacing also increased significantly with age-at-death though less so with pubic tubercle length, but decreased with rising body mass index (Figures 3.19 – 3.21).

Table 3.23. Descriptive statistics of mean trabecular spacing (µm) between parity groups, sex, and the presence and absence of the preauricular sulcus (PAS).

Group	*n*	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Males	10	1.03	0.26	0.08	0.84	1.21
Females	18	1.13	0.33	0.08	0.96	1.29
No PAS (females)	8	1.28	0.41	0.14	0.94	1.61
PAS	10	1.01	0.21	0.07	0.86	1.16
Nulliparous	9	1.16	0.31	0.10	0.92	1.40
Parous	9	1.10	0.36	0.12	0.82	1.38
N	28	1.09	0.31	0.06	0.97	1.21

Table 3.24. Descriptive statistics of mean trabecular spacing (µm) between the presence and absence of dorsal pubic pitting (DPP).

Group	*n*	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
DPP absent	23	1.09	0.31	0.06	0.95	1.22
DPP present	5	1.11	0.32	0.14	0.71	1.50
N	28	1.09	0.31	0.06	0.97	1.21

Table 3.25. Descriptive statistics for mean trabecular spacing (µm) between non-obese and obese individuals.

Group	*n*	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Non-obese	20	1.19	0.30	0.07	1.05	1.33
Obese	6	0.90	0.14	0.06	0.75	1.04
N	26*	1.12	0.30	0.06	1.00	1.24

*Body weight was unavailable for two individuals

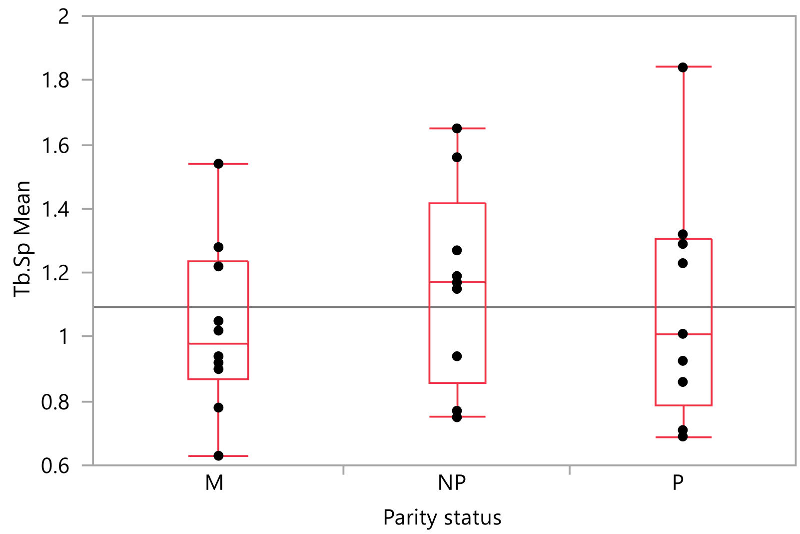

Figure 0.18 - Box plots comparing trabecular spacing (Tb.Sp, µm) between the presence (P) and absence (A = females, AM = males) of the preauricular sulcus (PAS).

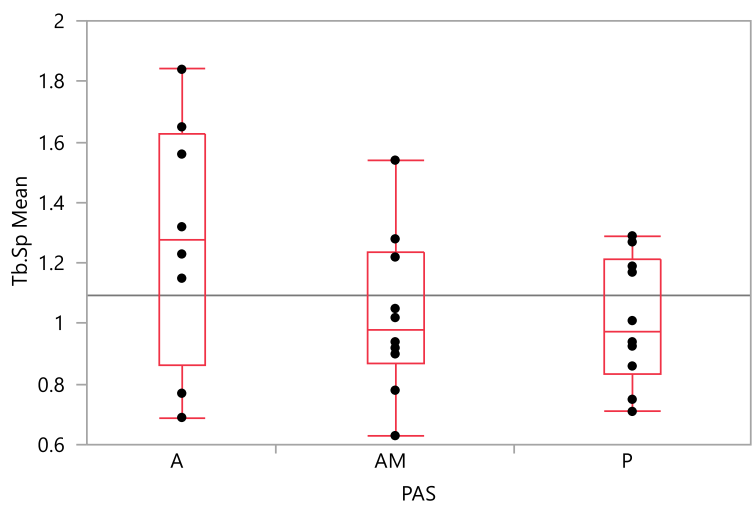

Figure 0.19 - Box plots comparing trabecular spacing (Tb.Sp, µm) between parous (P), nulliparous (NP) females, and males (M).

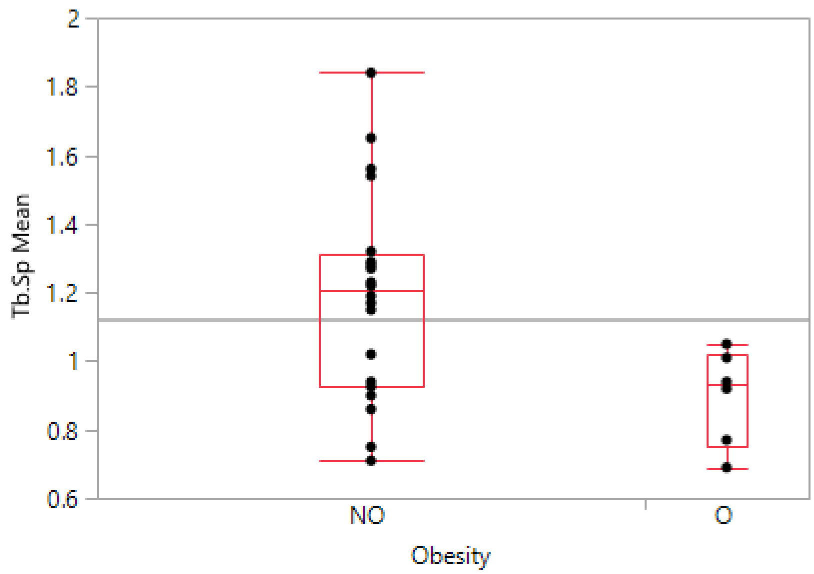

Figure 0.20 - Boxplots of mean trabecular spacing (Tb.Sp, µm) between non-obese (NO) and obese (O) individuals.

Table 3.26. Student's t-test results for mean trabecular spacing (α = 0.05). Statistical significance is denoted by bold text and asterisk.

Variables	Difference	Std Error Dif	Lower CL	Upper CL	p-Value
Obese/Non-obese	0.29	0.13	0.03	0.56	**0.031***
PAS present/PAS absent (females)	0.26	0.14	-0.02	0.55	0.070
PAS absent (males)/PAS absent (females)	0.25	0.14	-0.04	0.54	0.088

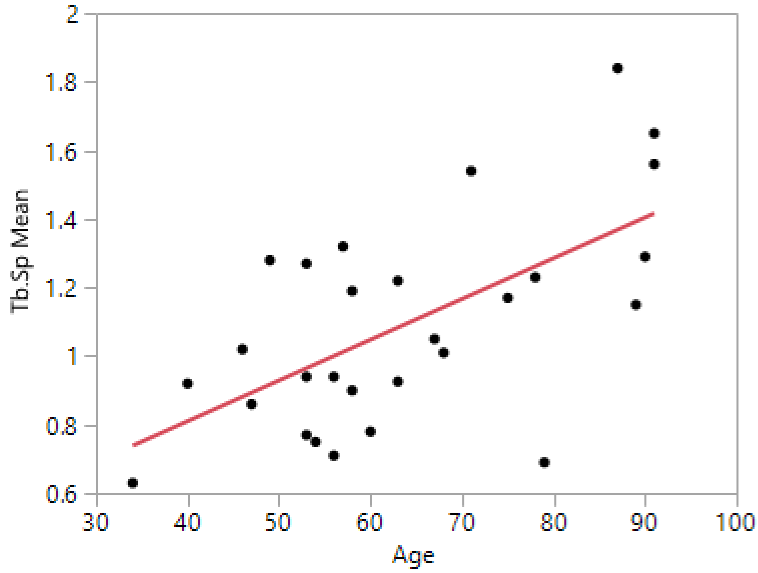

Figure 0.21 - Regression comparing trabecular spacing (Tb.Sp, µm) mean to age-at-death (years). $R^2 = 0.38$.

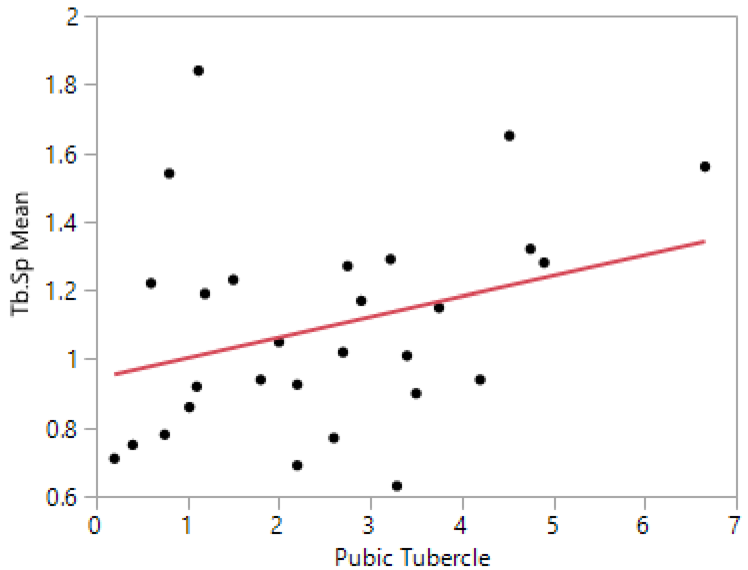

Figure 0.22 - Regression comparing trabecular spacing (Tb.Sp, µm) to pubic tubercle length (mm). $R^2 = 0.09$.

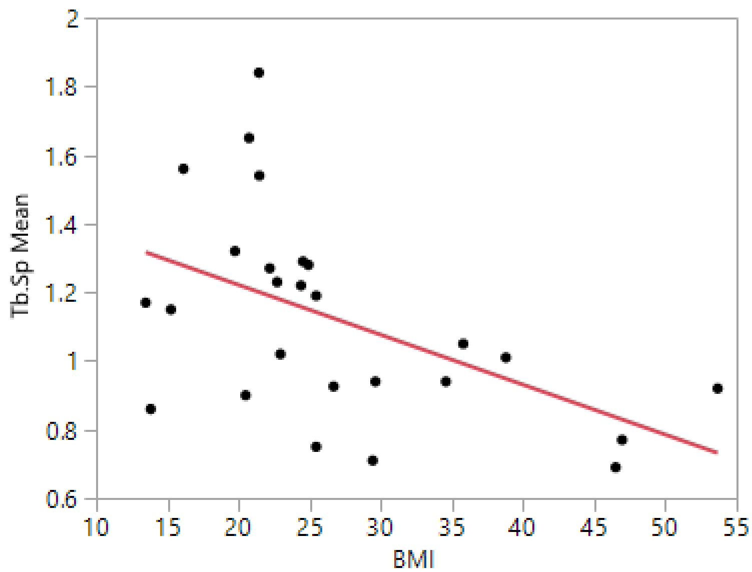

Figure 0.23 - Regression comparing trabecular spacing (Tb.Sp, µm) to body mass index (BMI). $R^2 = 0.25$.

Trabecular thickness

Trabecular thickness measures the mean thickness of trabecular struts in micrometers (µm) within a volume of interest. This measurement was not normally distributed, so the Wilcoxon test was used to test means between each demographic group ($\alpha = 0.05$; Table 3.29). Only males and females without a preauricular sulcus were significantly different, with males having a higher mean trabecular thickness. Parous females and females generally had a higher mean trabecular thickness than males, though these differences only approached statistical significance ($p = 0.087$ and 0.059, respectively). Regressions with age-at-death, body mass index, and pubic tubercle length were not significant (Appendix B). Removing the outlier did not meaningfully impact results.

Table 3.27. Descriptive statistics for mean trabecular thickness (µm) between parity groups.

Group	*n*	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Males	10	0.22	0.02	0.01	0.21	0.23
Females	18	0.23	0.13	0.03	0.17	0.29
PAS absent	8	0.19	0.03	0.01	0.17	0.23
PAS present	10	0.26	0.17	0.05	0.14	0.38
Nulliparous	9	0.26	0.17	0.06	0.13	0.39
Parous	9	0.20	0.06	0.02	0.16	0.25
N	28	0.23	0.10	0.02	0.19	0.27

Table 3.28. Descriptive statistics for mean trabecular thickness (µm) by obesity status.

Group	*n*	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Non-obese	20	0.23	0.12	0.03	0.18	0.28
Obese	6	0.22	0.06	0.02	0.16	0.28
N	26*	0.23	0.10	0.02	0.19	0.27

*Body weight was unavailable for two individuals

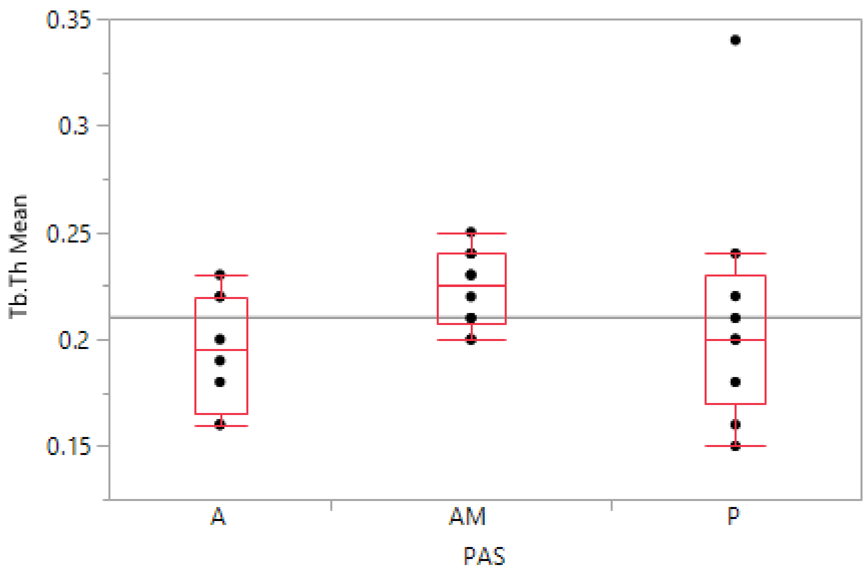

Figure 0.24 - Box plots of trabecular thickness (µm) between the presence (P) and absence (A) of the preauricular sulcus (PAS) and males without a preauricular sulcus (AM). Outlier removed (no PAS, Tb.Th = 0.71 µm).

Table 3.29. Nonparametric Wilcoxon test results for trabecular thickness (α = 0.05). Statistical significance is denoted by bold text and asterisk.

Variable	Score Mean Difference	Std Err Diff	Z	p-Value
Male/Female	5.52	3.22	1.71	0.087
Parous/Males	-4.85	2.57	-1.89	0.059
PAS absent (males)/PAS absent (females)	5.29	2.51	2.10	**0.035***

Bone volume ratio

Bone volume ratio is the proportion of bone volume to total volume within the volume of interest (μm^3). Descriptive statistics are provided in Tables 3.30 – 3.32. This measurement was not normally distributed, so the Wilcoxon test was used to compare means between each demographic group ($\alpha = 0.05$, Table 3.33). Linear regression compared bone volume ratio to body mass index, age-at-death, and pubic tubercle length. Means were only significantly different between obese and non-obese individuals (p = 0.028). There were notable differences between preauricular sulcus presence and absence between males and females approaching statistical significance (p = 0.060 and 0.067, respectively). There was also a significant inverse correlation with age-at-death and a positive relationship with body mass index (Figures 3.26 – 3.28).

Table 3.30. Descriptive statistics for sex, preauricular sulcus (PAS) presence and absence, and parity status.

Group	*n*	Mean	Std Dev	Std Error Mean	Lower 95%	Upper 95%
Males	10	0.14	0.05	0.01	0.10	0.17
Females	18	0.12	0.05	0.01	0.09	0.15
PAS absent	8	0.10	0.05	0.02	0.06	0.14
PAS present	10	0.14	0.05	0.02	0.10	0.18
Nulliparous	9	0.11	0.05	0.02	0.08	0.15
Parous	9	0.12	0.06	0.02	0.08	0.17
N	28	0.13	0.05	0.01	0.11	0.15

Table 3.31. Descriptive statistics of bone volume ratio between the presence and absence of dorsal pubic pitting (DPP).

Group	*n*	Mean	Std Dev	Std Error Mean	Lower 95%	Upper 95%
DPP absent	23	0.13	0.05	0.01	0.10	0.15
DPP present	5	0.13	0.05	0.02	0.06	0.20
N	28	0.13	0.05	0.01	0.11	0.15

Table 3.32. Descriptive statistics for bone volume ratio between obese and non-obese individuals.

Group	*n*	Mean	Std Dev	Std Error Mean	Lower 95%	Upper 95%
Non-obese	20	0.11	0.05	0.01	0.09	0.13
Obese	6	0.16	0.04	0.02	0.11	0.20
N	26*	0.12	0.05	0.01	0.10	0.14

*Body weight was unavailable for two individuals

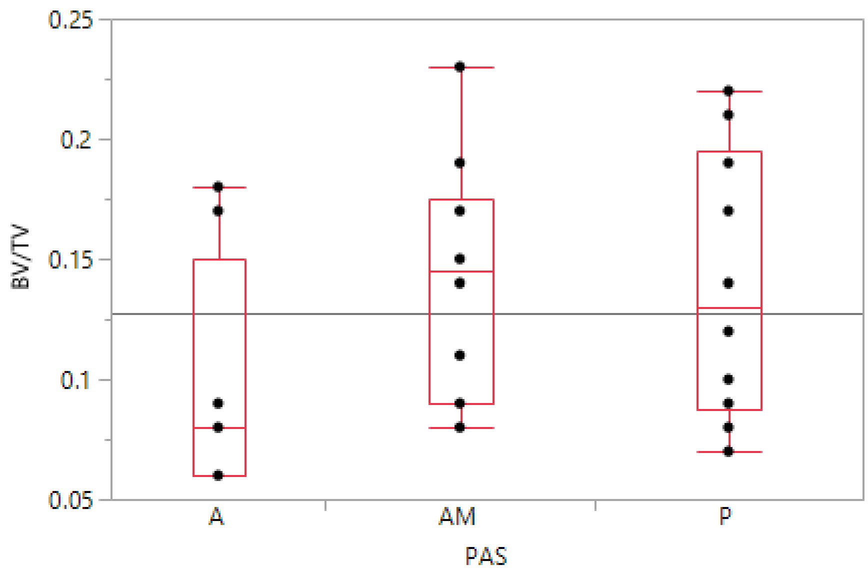

Figure 0.25 - Box plots of bone volume ratio (BV/TV) between the presence and absence of the preauricular sulcus (PAS). (A = absent, females; AM = absent, males; P = present, females.)

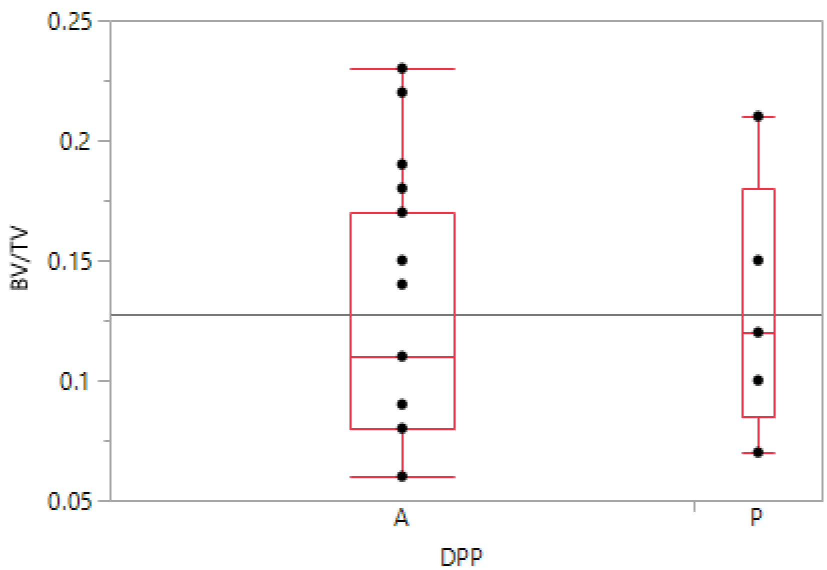

Figure 0.26 - Box plots of bone volume index (BV/TV) between the presence (P) and absence (A) of dorsal pubic pitting (DPP).

Table 3.33. Results for the nonparametric Wilcoxon test for bone volume ratio (α = 0.05). Statistical significance is denoted by bold text and asterisk.

Variable	Score Mean Difference	Std Err Diff	Z	p-Value
Obese/Non-obese	7.80	3.54	2.20	**0.028***
PAS present/PAS absent (females)	4.61	2.52	1.83	0.067
PAS absent (males)/PAS absent (females)	4.72	2.51	1.88	0.060

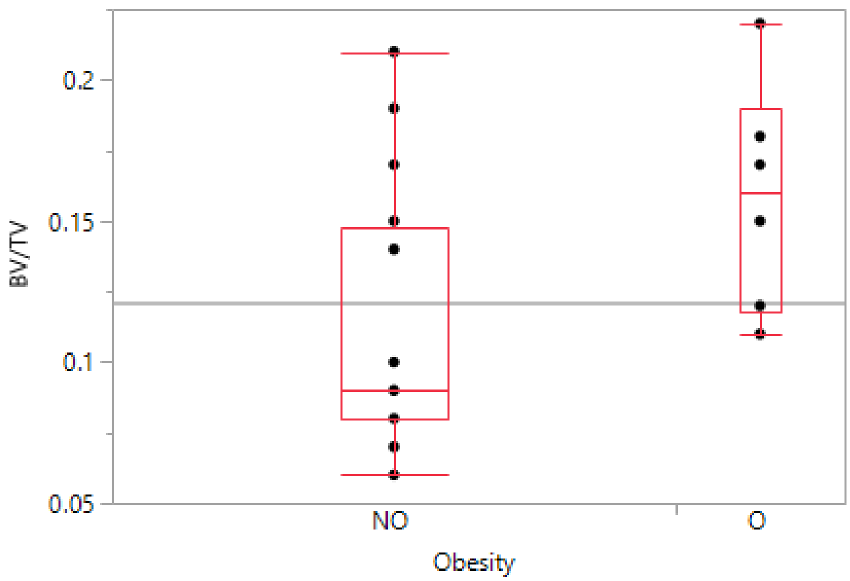

Figure 0.27 - Box plots for bone volume ratio between obese and non-obese individuals.

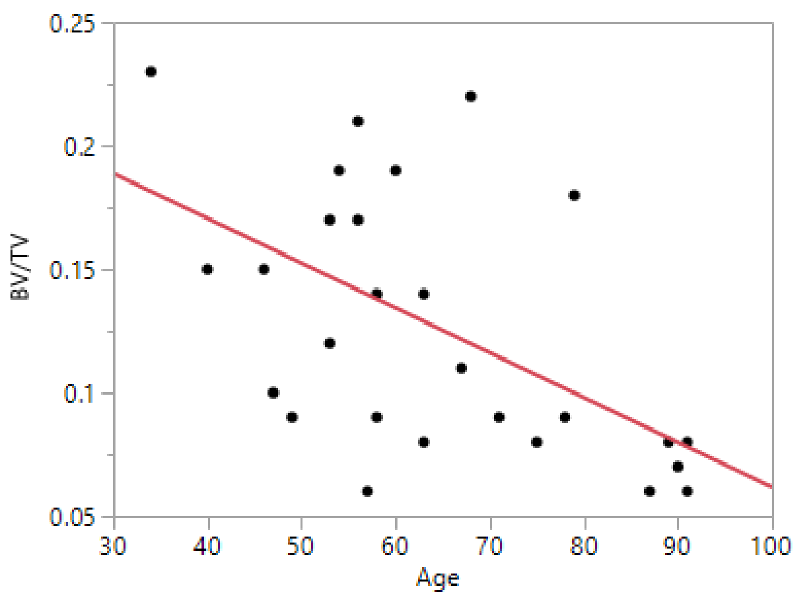

Figure 0.28 - Regression comparing bone volume ratio (BV/TV) to age-at-death (years). R^2 = 0.30.

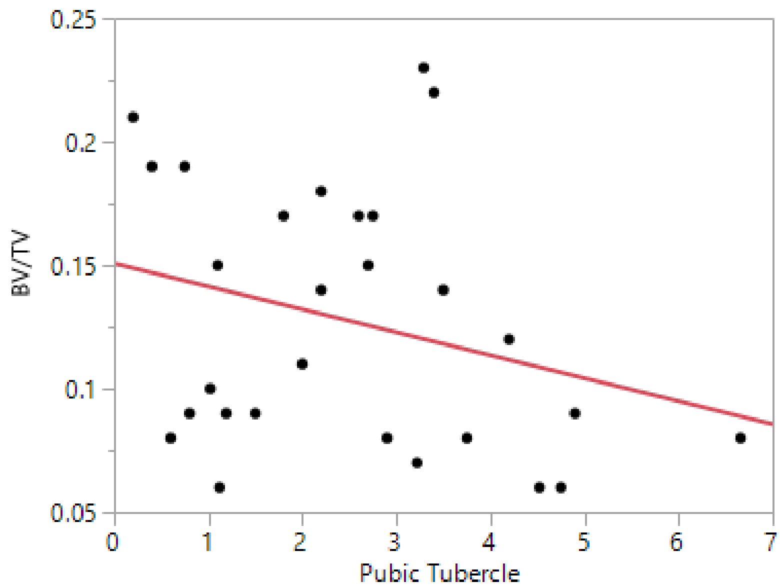

Figure 0.29 - Regression comparing bone volume ratio (BV/TV) to pubic tubercle length (mm). $R^2 = 0.08$.

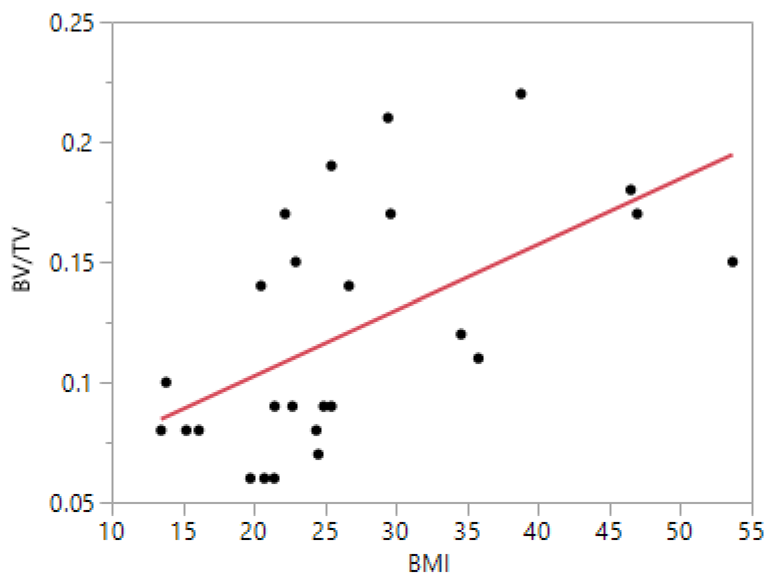

Figure 0.30 - Regression comparing bone volume index (BV/TV) and body mass index (BMI). $R^2 = 0.33$.

Connectivity density

Connectivity density reports the number of connected trabecular struts within a volume of interest. Descriptive statistics are provided in Tables 3.34 – 3.36. These data were also non-normal and the Wilcoxon test was used ($\alpha = 0.05$), with linear regressions between pairs of continuous variables. Only obese and non-obese individuals were significantly different (p = 0.019), with obese individuals showing much higher mean connectivity density (Figure 3.29), and there was a notable inverse relationship with age-at-death and a positive relationship with body mass index (Figures 3.30 and 3.32).

Table 3.34. Descriptive statistics for connectivity density by sex, preauricular sulcus (PAS) presence and absence, and parity status.

Group	*n*	Mean	Std Dev	Std Error Mean	Lower 95%	Upper 95%
Males	10	3.47	1.91	0.60	2.10	4.84
Females	18	3.50	2.05	0.48	2.47	4.52
PAS present	10	3.79	1.71	0.54	2.56	5.01
PAS absent	8	3.13	2.49	0.88	1.05	5.22
Nulliparous	9	3.01	1.76	0.59	1.66	4.37
Parous	9	3.98	2.31	0.77	2.20	5.75
N	28	3.49	1.97	0.37	2.72	4.25

Table 3.35. Descriptive statistics for connectivity density by dorsal pubic pitting (DPP) presence and absence.

Group	*n*	Mean	Std Dev	Std Error Mean	Lower 95%	Upper 95%
DPP absence	23	3.31	2.02	0.42	2.44	4.19
DPP presence	5	4.28	1.67	0.74	2.21	6.35
N	28	3.49	1.97	0.37	2.72	4.25

Table 3.36. Descriptive statistics for connectivity density for obese and non-obese individuals.

Group	*n*	Mean	Std Dev	Std Error Mean	Lower 95%	Upper 95%
Non-obese	20	2.86	1.56	0.34	2.13	3.59
Obese	6	4.60	2.03	0.83	2.46	6.73
N	26*	3.26	1.80	1.80	2.53	3.98

*Body weight was unavailable for two individuals

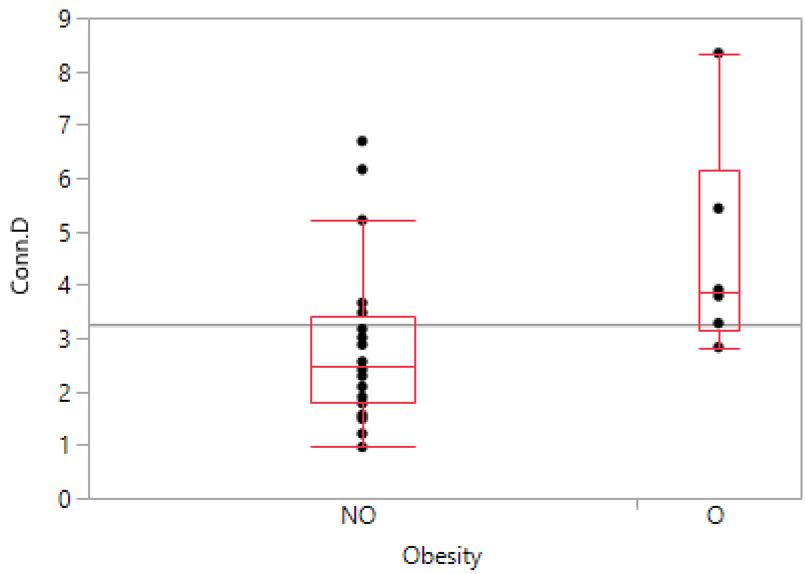

Figure 0.31 - Box plots of connectivity density (Conn.D) between non-obese (NO) and obese (O) individuals.

Table 3.37. Results for the nonparametric Wilcoxon test for connectivity density (α = 0.05). Statistical significance is denoted by bold text and asterisk.

Variable	Score Mean Difference	Std Err Diff	Z	p-Value
Obese/Non-obese	8.34	3.56	2.34	**0.019***

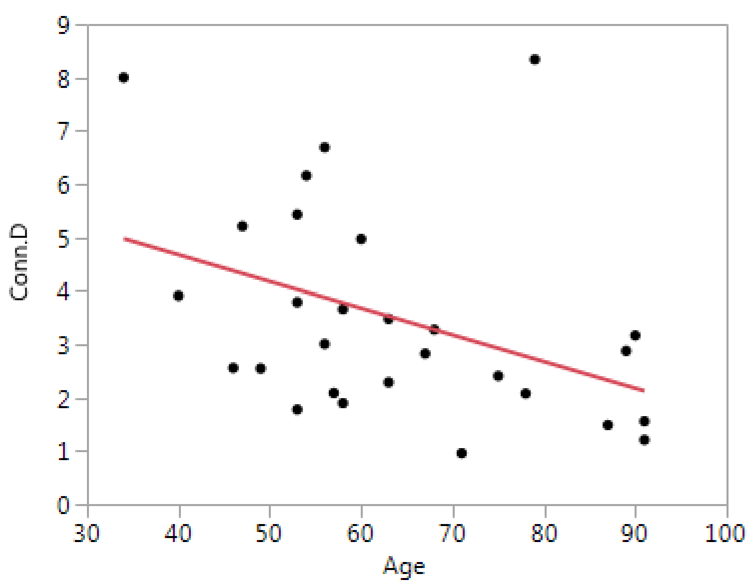

Figure 0.32 - Regression of connectivity density (Conn.D) against age-at-death (years). R^2 = 0.16.

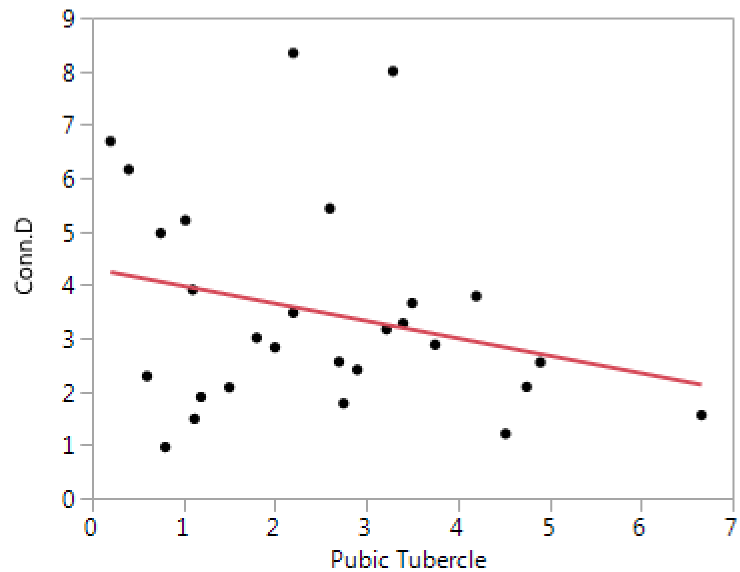

Figure 0.33 - Regression of connectivity density (Conn.D) against pubic tubercle length (mm). $R^2 = 0.07$.

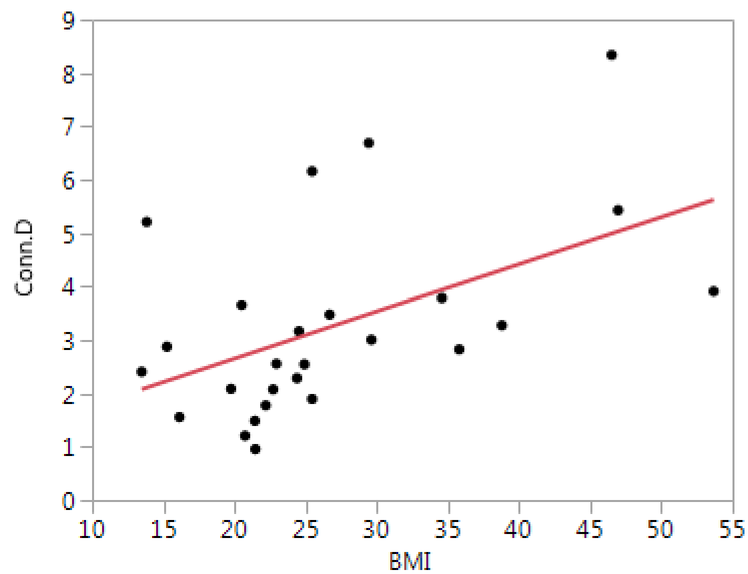

Figure 0.34 - Regression of connectivity density (Conn.D) against body mass index (BMI). $R^2 = 0.26$.

4. DISCUSSION & CONCLUSION

This study sought to address the question of pelvic scarring in relation to parity and obesity, together considered risk factors for pelvic instability. The results confirm some quantifiable and statistically significant macroscopic and microscopic differences between parity groups and obesity groups, though most predicted differences only occurred between males and females as a whole. This suggests that while pelvic instability may be a factor linking parity and obesity to the appearance of pelvic scars, the greater difference is between males and females, parous or not. As argued by Andersen (1986) and McFadden and Oxenham (2017), pelvic scars, while not an indicator of parity status, are related to sex and therefore reflect pelvic anatomy more than pelvic instability.

Detecting Pelvic Instability

It was hypothesized that pelvic instability could be detected by examining excessive wear in the pubic symphysis joint relative to known age. The hypothesis was that over-aging using the pubic symphysis would be more common in individuals with pelvic instability risk factors, such as parity and obesity, due to increased friction of the symphyseal face. There was no relationship between body mass index and the accuracy of age estimation in the pubic symphysis, unlike Wescott and Drew's (2015) results. Those with a preauricular sulcus, who were overwhelmingly female, were more likely to be over-aged, though not significantly ($p = 0.062$). These findings confirm the null hypothesis that individuals with a sulcus were not more likely to be over-aged.

Females were more likely to be over-aged compared to males, especially nulliparous females. These results contradict previous findings that parous females are more likely to be over-aged compared to nulliparous females (Bongiovonni, 2016). Age estimation methods do offer different scales for males and females to accommodate the tendency to over-age females, which has been considered a consequence of parity (Bongiovonni, 2016). The fact that nulliparous females were the most likely to be over-aged may be due to increased physical activity unhampered by postpartum pelvic pain. Garras et al. (2008) noted increased pelvic instability and motion of the pubic symphysis between males and females, and parous and nulliparous females, which suggests increased cortical wear should be observable in the pubic symphysis. Therefore, the results of this study suggest that it may not be possible to detect pelvic instability in skeletal remains or that parity status or obesity do not contribute to pelvic instability to an extent that would be observable in skeletal remains.

Macroscopic Morphology

The frequency of the preauricular sulcus and dorsal pubic pitting and the length of the pubic tubercle were investigated to test the hypotheses that they would increase in obese or parous individuals due to pelvic instability. Chi-square analyses showed a significant difference in preauricular sulcus and dorsal pubic pitting frequency between males and females, but not parity groups or obesity status. These results largely confirm the null hypothesis that there is no difference in scar prevalence among parous females or obese individuals, nor is there a pattern in anterior versus posterior scarring. Scar frequencies in this study are comparable to previous studies' results prior to 2017 (Tables 4.1 and 4.2). The most notable difference is in the frequency of the sulcus in males: rates were far higher in previous studies, though females' rates are similar. Dorsal pubic pitting was also much more common in other studies, though most samples only included females. This could reflect different age-at-death distributions between samples if pitting resorbs over time. However, while age-at-death distributions were not stated in all studies, some noted that there was no relationship with age. In addition, depending on the time period represented in the samples, this may also or a kind of secular change in how stress to the pelvic joints is expressed, perhaps due to changes in levels of manual labor over time. Furthermore, the preauricular sulcus was far more common than dorsal pubic pitting in this sample, repeating findings from previous work. This indicates that different mechanisms must be at play in their appearance.

Table 4.1. Comparison of frequencies of the preauricular sulcus (% present) in the literature.

	This study (Galea, 2018)	**Karsten (2017)**	**Maass & Friedling (2014)**	**Cox & Scott (1992)**	**Andersen (1986)**	**Holt (1978)**	**Houghton (1974)**
Collection	TXSTDSC	Hamann-Todd	Univ. of Cape Town, Univ. of Stellenbosch	Spitafields	Hamann-Todd	Hamann -Todd	Univ. of Otago
Males	21 (N = 101)	37 (N = 261)	52 (N = 184)	N/A	94 (N = 87)	N/A	81 (N = 54)
Females	88 (N = 78)	90 (N = 239)	81 (N = 126)	87 (N = 138)	77 (N = 151)	70 (N = 68)	92 (N = 65)

Table 4.2. Comparisons of frequencies of dorsal pubic pitting in females in the literature.

	This study (Galea, 2018)	**McArthur et al. (2016)**	**Maass & Friedling (2014)**	**Cox & Scott (1992)**	**Andersen (1986)**	**Suchey et al. (1979)**
Collection	TXSTDSC	Radiographs of American hospital patients	Univ. of Cape Town, University of Stellenbosch	Spitafields	Hamann-Todd	L.A. Co. Dept. of the Coroner
% Present	48	74	33	38	64	87
N	75	311	126	138	151	486

This study confirmed that the presence of pelvic scarring is related to being female. Previous studies report a range of results, some of which agree with this thesis's findings. Andersen (1986) found no relationship with parity but a strong correlation with the female sex, noting that the female pelvis is twice as flexible as males based on measurements of the articulated pelvis before and after expanding the joints to their bony limits. Spring et al. (1989) concurred, concluding that pelvic scars are "specific for female gender" (1989:252). Maass and Friedling (2014) reported that preauricular sulcus and dorsal pubic pitting presence and severity were only related to sex. Novak et al. (2012) and Karsten (2017) concluded that the absence of the sulcus is a strong indicator of the male sex, rather than relying on its variable presence in females. Snodgrass and Galloway (2003) determined that degree of dorsal pubic pitting is highly correlated with number of births only in women under 50 years of age, which could reflect remodeling with age. McArthur et al. (2016) found a strong relationship between degree of dorsal pubic pitting and vaginal delivery, particularly among females of non-white ancestry. However, they found no relationship between preauricular sulcus presence and parity, nor did they include males in their research.

Mean body mass index (BMI) was nearly significantly higher in those with a preauricular sulcus (p = 0.055), but there was no relationship with dorsal pubic pitting. However, the two males with dorsal pubic pitting were both obese. While this does appear to support the hypothesis that obesity could be a factor, the sample size is far too small to be of any practical significance. Furthermore, there was no association between BMI and scarring in females of either group or combined. Snodgrass and Galloway (2003) found a positive correlation only between pitting and BMI in women over 50. Despite a paucity of research linking BMI with pelvic scarring, several researchers suggest that rising BMI could account for scar appearance in males (Andersen, 1986; Cox and Scott, 1992; Maass and Friedling, 2014). With the BMI of many individuals from the TXSDSC falling just short of 30, it may be worthwhile to include those who fall into the "overweight" category (25-29) in future studies.

The relationship between pelvic scarring and age-at-death appears to be complex. Average age was higher in those with dorsal pubic pitting, approaching statistical significance (p = 0.057), while all females without a preauricular sulcus were over 60 years old. Previous research has produced conflicting results. Andersen (1986) noted a positive association between age and scar appearance, suggesting that pelvic instability increases with age. Spring et al. (1989) and Karsten (2017) found no association between age and the preauricular sulcus. Suchey et al. (1979) noted that dorsal pubic pitting was more common in females over 30. Similarly, McArthur et al. (2016) found that parous females with pitting were most often over the age of 50, while Snodgrass and Galloway (2003) found the opposite. Snodgrass and Galloway also found that the correlation with number of births disappeared in women over 50, but that pits deepened with age. As the sites of the preauricular sulcus and dorsal pubic pitting are ligamentous attachment sites (Andersen, 1986; Maass and Friedling, 2014), their increasing frequency with age could be attributed to the same phenomenon that leads to larger musculoskeletal sites with age (Villotte and Knüsel, 2013; Yonemoto, 2016). However, scar disappearance with age could be due to bone remodeling. Either could be true due to individual activity levels and bone maintenance. In sum, research on the relationships between scar appearance and age are contradictory: either scars worsen with age or disappear.

For pubic tubercle length, only males and parous females were statistically different, with males significantly larger. Nulliparous females fell between the two. This confirms the null hypothesis that there is no significant difference between parity groups or obesity groups. It also confirms previous studies that found no correlation with parity (Snodgrass and Galloway, 2003), and those that reported larger pubic tubercles in individuals over 50 years of age and males due to their larger body size (Maass and Friedling, 2014). As a muscle and ligamentous attachment site, a larger pubic tubercle suggests more rectus abdominis muscle and inguinal ligament stress (Maass and Friedling, 2014). Pregnancy, however, results in muscle weakness (McCrory et al., 2014).

Limitations

Some limiting factors involve the completeness of donated individuals' biographical information. Time elapsed since parous females' last pregnancy is unknown; this may be a significant factor as Suchey et al. (1979) found that the degree of dorsal pubic pitting increased with time since last birth, though this may simply be another relationship with age. Body mass index was calculated based on weight and stature taken after death at Texas State University and may not reflect what was typical in life due to a combination of lifestyle and health changes in the years before death. Regarding age estimation of the pubic symphysis, phases for adults are large and tend to overlap, which minimizes error. As such, traditional age estimation methods may not be the most precise proxy for measuring cortical deterioration. In addition, in the interest of time, this study did not distinguish between grades or types of the preauricular sulcus or dorsal pubic pitting, as explored in previous studies (Houghton, 1974; Andersen, 1986; Ubelaker, 2012).

Trabecular Microarchitecture

Investigating trabecular structure parameters tests the hypothesis that parity and obesity impact the organization and quality of trabeculae in the pubic bone as it adapts to the novel loads and changes in gait associated with pelvic instability (Greve et al., 2007; McCrory et al., 2014; Kivell, 2016). This thesis's results did not provide consistent support for these hypotheses. As bone microarchitecture has been shown to return to its previous state after the load is removed (Huiskes et al., 2000), it is possible that any changes caused by parity or past obesity remodeled by the time of death.

Degree of anisotropy (DA) was significantly higher (more anisotropic and less directionally organized) in males than females, and even more so between parous females and males, as was expected. Non-obese individuals were notably more anisotropic than the obese, which approached statistical significance ($p = 0.052$). This contradicts the hypothesis that trabeculae would be less organized in parous females and obese individuals due to increased stress on the pubic bone. High anisotropy has been associated with accommodating novel loads (Huiskes et al., 2000), so it is possible that the relatively high anisotropy in males and non-obese individuals in this sample is due to higher levels of novel daily activity. Shaw and Ryan (2012) found that DA was higher in the femoral head than in the humeral head in humans and quadrupedal primates, indicating that more loading is occurring in the hip than in the shoulder.

Trabecular spacing (Tb.Sp) measures the average amount of space between trabecular struts, usually in millimeters. Results indicate that it was significantly greater in non-obese individuals. Regressing with body mass index showed a notable decline in Tb.Sp with rising BMI ($R^2 = 0.25$). However, Tb.Sp has also been shown to increase with loading but decrease with body size (Ryan and Shaw, 2013). Less space between trabeculae usually occurs with an increase in bone mass. This could in fact be consistent with this study's results if obesity is considered a novel stimulus and not what is considered normal body weight that the human skeleton is adapted to accommodate. Therefore, obese individuals in this study could be demonstrating increased Tb.Sp for their body size due to the novel loading of excess anterior body fat.

Trabecular thickness (Tb.Th) measures the mean thickness of trabecular struts (µm), and was significantly higher in females with a preauricular sulcus compared to males without. There was also a notable but insignificant increase in males over parous females (p = 0.059). A large outlier was a 53-year-old non-obese, nulliparous female with a sulcus (Tb.Th = 0.71 µm; sample mean = 0.22 µm), which may be due to cancer reported as cause of death or light daily exercise. Higher Tb.Th is associated with higher activity levels and stress to joints (Huiskes et al., 2000; Ryan and Shaw, 2015). Increased thickness in females with a preauricular sulcus supports the hypothesis that the sulcus results from heightened pelvic joint mobility, but the higher Tb.Th in males compared to parous females contradicts the hypothesis that increased pelvic joint mobility in parous females would be reflected in trabecular thickness. This may be due to documented loss of bone volume in postmenopausal and lactating females (Riggs et al., 2004; Sanz-Salvador et al., 2015; Bjørnerem et al., 2017).

Connectivity density (Conn.D) measures the number of connected trabeculae; it was significantly higher in obese individuals (p = 0.019), and as such increased modestly with rising BMI (R^2 = 0.26). This is consistent with the hypothesis and previous studies showing that bone volume increases with the greater load of obesity (Shaw and Ryan, 2012; Sornay-Rendu et al., 2013; Ryan and Shaw, 2015; Kivell, 2016). Scherf et al. (2016) also reported higher Conn.D in Neolithic Europeans compared to modern Europeans, which they attributed to “a specific response to functional demands” (2016:112).

Bone volume ratio (BV/TV) measures the proportion of bone volume within the total volume. It was only significantly higher in obese individuals versus non-obese (p = 0.028). Accordingly, BV/TV increased modestly with BMI (R^2 = 0.33), refuting the null hypothesis that bone volume does not increase in the obese. BV/TV was also notably higher in females with a preauricular sulcus and males without a sulcus compared to females without, though only approaching statistical significance (p = 0.067 and 0.060, respectively). This suggests that females with a sulcus and males without place more stress on the pubic bone, in part rejecting the null hypothesis that the presence of pelvic scarring is not related to increased trabecular bone volume. In other words, obese individuals, females with a sulcus, and males have more relative bone volume. This in part refutes the null hypothesis that obese individuals would not have greater trabecular bone volume. However, no differences were seen between parity groups, which supports the null hypothesis that there is no bone volume difference between parous and nulliparous females.

Trabecular thickness, connectivity density, and trabecular spacing all contribute to bone volume. In this thesis, lower Tb.Sp in obese individuals is consistent with their higher Conn.D and BV/TV, and females with a preauricular sulcus and males without had higher Tb.Th compared to females without the sulcus. This indicates that these groups' pubic bones are comprised of more robust trabeculae. Higher relative bone volume has previously been associated with increased mechanical stress. Shaw and Ryan (2012) found that the femoral head had higher BV/TV than the humeral head in human and quadrupedal primates, indicating greater load bearing in the former. Similarly, Scherf et al. (2016) reported much more robust trabecular bone in Neolithic Europeans compared to modern Europeans due to higher levels of manual labor. This suggests that females with a sulcus and males without are placing higher loads on their pubic bones compared to females without a sulcus, though the females without a sulcus were older on average. Similarly, obese individuals may be placing more stress on the pubic bone than the non-obese. This in part supports the hypothesis that obesity and the presence of a preauricular sulcus would predict high levels of trabecular bone parameters in the pubic bone associated with increased loading. However, while these results are consistent with increased joint stress, they do not necessarily predict pelvic instability.

Limitations

Sample size was one of the most salient limiting factors for this section of this study. The time required for scanning each specimen and processing the data was a considerable constraint. In addition, only eight females in the study sample (N = 179) had a preauricular sulcus. Not only is this two fewer than the other two groups selected for scanning, this group is significantly older than the remaining sample. This also prevented the analysis of age estimation error with bone microarchitecture. In addition, volume of interest selection was not standardized, nor was it possible to avoid cortical bone completely, due to variations in pubic bone size and shape. Thus, more cortical bone was likely erroneously selected in smaller individuals in an attempt to sample as much trabecular bone as possible. In addition, while HRCT successfully detected differences in the pubic bone's trabecular microarchitecture that are associated with increased load bearing, it is not possible to conclusively assign the cause to pelvic instability.

Finally, some biographical data were not provided by donors, such as the length of time since last pregnancy, the weight of the neonate at birth, and whether parous females breastfed. As previously discussed, trabecular architecture has been shown to return to its original state after a novel load is removed (Huiskes et al., 2000). With a mean known age-at-death of 69.44 years for parous females in this sample (n = 9) and the youngest at 47 years, it is highly likely that it had been years if not decades since their last pregnancy. Furthermore, breastfeeding has been associated with increased trabecular thickness and separation and decreased bone volume ratio (Bjørnerem et al., 2017), so it is impossible to know whether this is influencing the results without that information.

Future research

This study hypothesized that females, especially parous females, and obese individuals were more likely to be over-aged based on the pubic symphysis. It was thought that the excess cortical wear to the symphyseal face may indicate pelvic instability, as females and obesity are risk factor groups. However, only females were consistently over-aged, particularly nulliparous females. The addition of age estimation of the auricular surface could provide a more complete picture of pelvic joint stress, as shown with obese individuals by Wescott and Drew (2015). Furthermore, standardizing pubic tubercle height by body size may illuminate previously hidden relationships with obesity and parity.

Comparing the microarchitecture of the pubic bones of males and females, obese and non-obese individuals, parous and nulliparous individuals, and individuals with and without pelvic scars has significant potential for revealing clues about load distribution in the pelvis. This study’s results could be improved first and foremost with a larger sample size, particularly more females without scars and including males with scars. In addition, volumes of interest were created in quadrants of each pubic bone to create a representative sample. Comparing these quadrants within and between interest groups could reveal more insights into how loads are distributed, as would applying Sylvester and Terhune's (2017) geometric morphometric mapping technique to the pubic symphysis.

Conclusions

This thesis adds to the growing body of evidence against the preauricular sulcus and dorsal pubic pitting as unequivocal evidence of parity; they were overwhelmingly present in parous and nulliparous females alike. Mean BMI was notably higher in individuals with a preauricular sulcus, though not significantly. Females, particularly nulliparous females, were also more likely to be over-aged using the pubic symphysis than males, while males had a larger mean pubic tubercle length than parous females. Although pregnancy and obesity are documented risk factors of pelvic instability, the preauricular sulcus was only weakly associated with obesity. This fails to demonstrate a clear connection between pelvic scarring and pelvic instability. The question remains why pelvic scarring occurs in females so much more than males, and why females are consistently over-aged even with different phase scales for each sex (Franklin, 2010; Hartnett, 2010; Garvin and Passalacqua, 2012). This may be related to greater average pelvic flexibility in females, as suggested by Andersen (1986). Greater than average pelvic flexibility may account for the occasional scar appearance in males.

Most microarchitectural differences occurred based on sex, obesity, and age, following previous studies, but no consistent connections could be made between obesity, parity, and pelvic scar appearance. Females had lower anisotropy than males, and females with a preauricular sulcus showed increased Tb.Th compared to males and increased bone volume compared to females without. Parous females had lower Tb.Th than males. Obese individuals presented with lower anisotropy and trabecular spacing, and higher bone volume ratio and connectivity density. Increased BV/TV links obesity and preauricular sulcus presence, and each group had an additional elevated measurement associated with novel bone loading (Conn.D and Tb.Th, respectively), suggesting these groups are experiencing more stress to the pelvis. The decrease in Tb.Th in parous females could be explained by enduring bone resorption associated with lactation. Lower anisotropy in parous females and obese individuals may be due to decreased activity levels compared to nulliparous females and individuals of healthy weight. Future studies with a larger sample and more complete biographical information may strengthen these associations. In addition, comparing these microarchitectural measurements between regions of the pubic bone, rather than comparing means of multiple volumes of interest, may show differences in how loads are distributed between each group.

This thesis intended to link parity and obesity to pelvic scarring and microarchitectural changes as a means of documenting the impact of pelvic instability on the human pelvis. Although results were ambiguous, they did confirm previous findings that the preauricular sulcus and dorsal pubic pitting have more complex etiologies than parity alone. Furthermore, this thesis builds upon a growing body of literature that utilizes high-resolution computed tomography to understand behavior and adaptation through the microarchitecture of human bone. With further study, this topic could have significant implications for the analysis of human remains in past societies as well as forensic investigations.

APPENDIX SECTION

APPENDIX A: Tables for Non-Statistically Significant Results

Table A.1. Dorsal pubic pitting: contingency analysis by sex and parity status. Chi-square = 58.54; DF = 2; **Prob = <0.000**; R^2 = 0.32. Significant difference between sexes, but not parity groups. Obese/non-obese males: Chi-square = 4.22; DF = 1; **Prob = 0.04**.

Group	*n*	Absent	Present
All females	75	39 (52.0%)	36 (48.0%)
Parous females	44	23 (52.27%)	21 (47.27%)
Nulliparous females	30	16 (53.33%)	14 (46.67%)
Obese Parous females	12	8 (66.67%)	4 (33.33%)
Obese Nulliparous females	13	5 (38.46%)	8 (61.54%)
All Males	101	99 (98.02%)	2 (1.98%)
Obese Males	31	29 (93.55%)	2 (6.45%)
Non-Obese Males	64	64 (100%)	0 (0%)
N	176	138 (78.41%)	38 (21.59%)

Table A.2. Dorsal pubic pitting: contingency analysis by obesity status. Chi-square = 0.58; DF = 1; Prob = 0.45.

Group	Absent (%)	*n*	Present (%)	*n*	Total (%)	N
Non-obese	53.29	89	13.17	22	66.47	111
Obese	25.15	42	8.38	14	33.53	56
N	78.44	131	21.56	36	100	167*

*Body weight was unavailable for nine individuals

Table A.3. Contingency analysis of the preauricular sulcus by sex, parity status, and obesity status. Significant between sexes: Chi-square =89.09; DF = 1; **Prob = <0.00**; R^2 = 0.36; α = 0.05.

Group	*n*	Absent	Present
All females	78	9 (11.5%)	69 (88.5%)
Parous females	46	5 (10.2%)	41 (89.1%)
Nulliparous females	31	4 (12.9%)	27 (87.1%)
Obese Parous females	12	2 (16.7%)	10 (83.3%)
Obese Nulliparous females	14	1 (7.1%)	13 (92.9%)
All Males	101	80 (79.2%)	21(20.8%)
Obese Males	31	22 (71.0%)	9 (29.0%)
Non-Obese Males	64	53 (82.8%)	11 (17.2%)
N	179	89 (49.7%)	90 (50.3%)

*Parity status was unavailable for one female

Table A.4. Results for the nonparametric Wilcoxon test comparing age-at-death (years) between the presence and absence of the preauricular sulcus (α = 0.05).

Group	- Group	Score Mean Difference	Std Err Dif	Z	p-Value
Present	Absent	6.771161	7.743125	0.8744739	0.3819

Table A.5. Contingency analysis of the preauricular sulcus by obesity status. No significant difference. Chi-square = 0.85; DF = 1; Prob = 0.36; R^2 = 0.004; α = 0.05.

Group	*n*	Absent	Present (%)
Non-obese	113	58 (34.1%)	55 (32.3%)
Obese	57	25 (14.7%)	32 (18.8%)
N	170*	83 (48.8%)	87 (51.2)

*Body weight was unavailable for nine individuals

Table A.6. Results for the nonparametric Wilcoxon test comparing mean age estimation error by sex, parity group, obesity group, and pelvic scars (α = 0.05).

Variable	Score Mean Difference	Std Err Dif	Z	p-value
Parous/Nulliparous	-0.14	3.76	-0.04	0.971
Obese/Non-obese	-2.68	5.85	-0.46	0.647
Dorsal pubic pitting presence/absence	11.04	6.82	1.62	0.106
Preauricular sulcus presence/absence	10.53	5.63	1.87	0.062

Table A.7. Contingency table for age estimation bias by sex, parity status, and obesity status. Significant between sexes. Chi-square = 9.32; DF = 2; **Prob = 0.01**; R^2 = 0.04.

Group	*n*	Correct	Over-aged	Under-aged
All females	76	59 (77.63%)	10 (13.16%)	7 (9.21%)
Parous females	30	23 (76.67%)	4 (13.33)	3 (10.00%)
Nulliparous females	45	35 (77.78%)	6 (13.33%)	4 (8.89%)
Obese Parous females	11	8 (72.72%)	2 (18.18%)	1 (9.10%)
Obese Nulliparous females	13	10 (76.92%)	3 (23.08%)	0
All Males	101	78 (77.23%)	3 (2.97%)	20 (19.80)
Obese Males	31	20 (64.52%)	1 (0.03%)	10 (32.26%)
Non-obese Males	64	52 ((81.25%)	2 (3.13 %)	10 (15.63%)
N	177*	137 (77.40%)	13 (7.34%)	27 (15.25%)

*Age could not be estimated for two individuals; body weight was unavailable for 9 individuals; parity status was unavailable for one female

Table A.8. Wilcoxon test for difference in mean body mass index between individuals correctly estimated for age, over-aged, and under-aged (α = 0.05).

Variables	Score Mean Difference	Std Err Dif	Z	p-Value
Over-aged/Correct	12.65	12.05	1.05	0.29
Under-aged/Correct	1.17	9.80	0.12	0.90
Under-aged/Over-aged	-3.51	3.78	-0.92	0.35

Table A.9. Contingency table for age estimation bias by presence and absence of the preauricular sulcus. No significant difference. Chi-square = 4.70; DF = 2; Prob = 0.09; $R^2 = 0.02$; $\alpha = 0.05$.

Group	*n*	Correct	Over-aged	Under-aged
Absent	88	69 (78.41%)	3 (3.41%)	16 (18.18%)
Present	89	68 (76.40%)	10 (11.24%)	11 (12.36%)
N	177	137 (77.40%)	13 (7.34%)	27 (15.25%)

Table A.10. Contingency analysis for age estimation bias by the presence and absence of dorsal pubic pitting. No significant difference. Chi-square = 2.54; DF = 2; Prob = 0.28; $R^2 = 0.01$; $\alpha = 0.05$.

Group	*n*	Correct	Over-aged	Under-aged
Absent	137	104 (75.91%)	9 (6.57%)	24 (17.52%)
Present	38	31 (80.58%)	4 (10.53%)	3 (7.89%)
N	175	135 (77.14%)	13 (7.43%)	27 (15.43%)

Table A.11. Results for nonparametric Wilcoxon test comparing mean pubic tubercle length between age estimation bias groups. $\alpha = 0.05$.

Group	Score Mean Difference	Std Err Dif	Z	p-Value
Under-aged/Correct	0.87	9.83	0.09	0.930
Over-aged/Correct	0.72	12.37	0.06	0.954
Under-aged/Over-aged	-1.25	3.95	-0.32	0.751

Table A.12. Student's t-test results for mean trabecular spacing ($\alpha = 0.05$).

Variables	Difference	Std Error Dif	Lower CL	Upper CL	p-Value
Male/Female	0.10	0.12	-0.15	0.35	0.414
Parous/Nulliparous	0.06	0.15	-0.24	0.37	0.670
Parous/Males	0.07	0.14	-0.23	0.37	0.635
Nulliparous/Males	0.13	0.14	-0.16	0.43	0.365
PAS present (females)/PAS absent (males)	0.02	0.13	-0.25	0.29	0.902
PAS present/PAS absent (females)	0.26	0.14	-0.02	0.55	0.070
PAS absent (males)/PAS absent (females)	0.25	0.14	-0.04	0.54	0.088
DPP present/absent	0.02	0.15	-0.30	0.34	0.895

Table A.13. Nonparametric Wilcoxon test results for trabecular thickness (α = 0.05).

Variable	Score Mean Difference	Std Err Diff	Z	p-Value
Male/Female	5.52	3.23	1.71	0.087
Parous/Nulliparous	-2.44	2.50	-0.98	0.329
Parous/Males	-4.85	2.57	-1.89	0.059
Nulliparous/Males	-2.53	2.57	-0.99	0.324
Obese/Non-obese	-0.22	3.54	-0.06	0.951
PAS present (females)/PAS absent (males)	-2.30	2.63	-0.87	0.381
PAS present/PAS absent (females)	1.80	2.52	0.71	0.475
DPP present/absent	2.43	4.04	0.60	0.546

Table A.14 Results for the nonparametric Wilcoxon test for bone volume ratio (α = 0.05).

Variable	Score Mean Difference	Std Err Diff	Z	p-Value
Male/Female	3.58	3.23	1.11	0.268
Parous/Nulliparous	0.56	2.50	0.22	0.824
Parous/Males	-1.90	2.58	-0.73	0.461
Nulliparous/Males	-2.85	2.56	-1.11	0.266
PAS present (females)/PAS absent (males)	-0.30	2.64	-0.11	0.909
PAS present/PAS absent (females)	4.61	2.52	1.83	0.067
PAS absent (males)/PAS absent (females)	4.72	2.51	1.88	0.060
DPP present/absent	0.85	4.04	0.21	0.833

Table A.15. Results for the nonparametric Wilcoxon test for connectivity density (α = 0.05).

Variable	Score Mean Difference	Std Err Diff	Z	p-Value
Male/Female	0.70	3.24	0.21	0.829
Parous/Nulliparous	2.44	2.52	0.97	0.331
Parous/Males	0.74	2.58	0.28	0.775
Nulliparous/Males	-1.79	2.58	-0.69	0.488
PAS present (females)/PAS absent (males)	1.10	2.64	0.41	0.678
PAS present/PAS absent (females)	3.26	2.53	1.29	0.198
PAS absent (males)/PAS absent (females)	2.36	2.53	0.93	0.351
DPP present/absent	5.84	4.06	1.43	0.150

APPENDIX B: Figures for Non-Statistically Significant Results

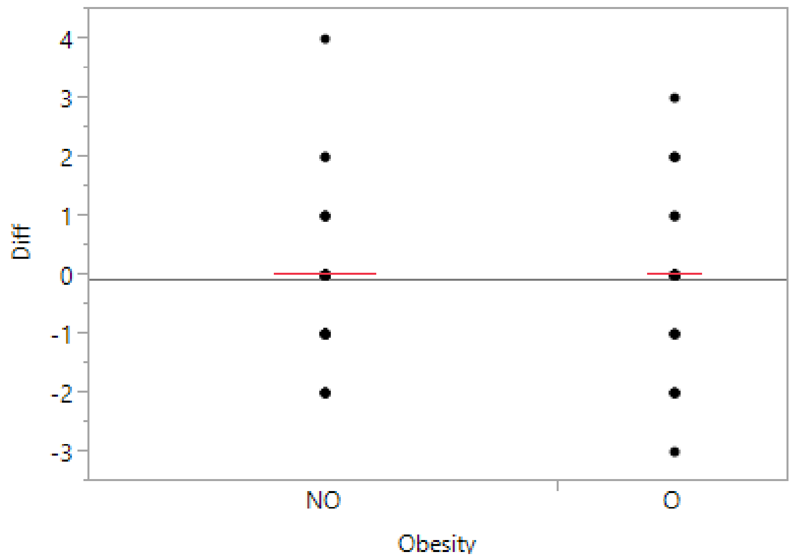

Figure B.1 - Age estimation error (Diff) between obese (O) and non-obese (NO) individuals.

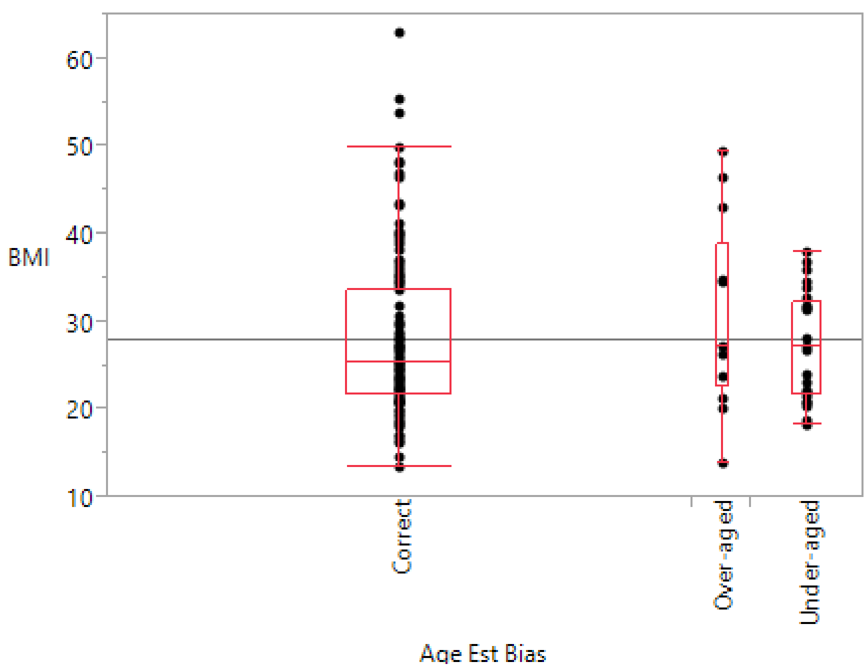

Figure B.2 - Mean body mass index (BMI) between individuals correctly estimated for age, over-aged, and under-aged.

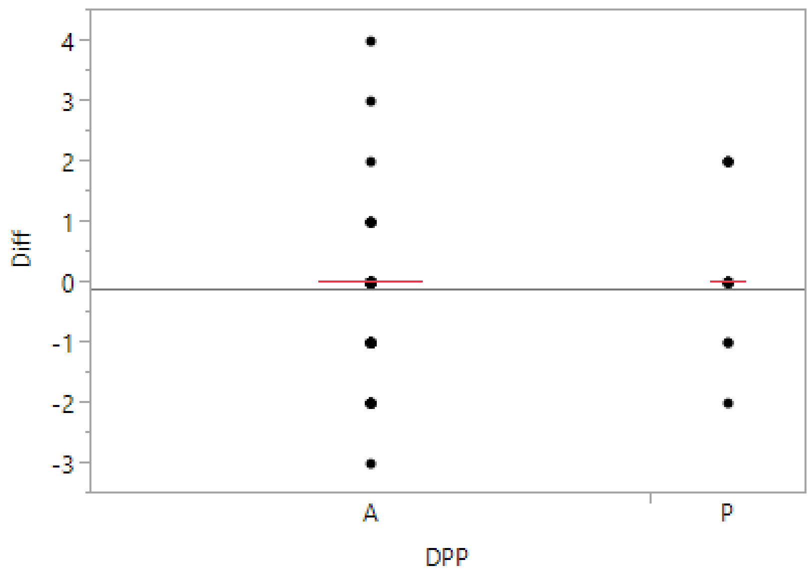

Figure B.3 - Means of age estimation error (Diff) between the absence (A) and presence (P) of dorsal pubic pitting (DPP).

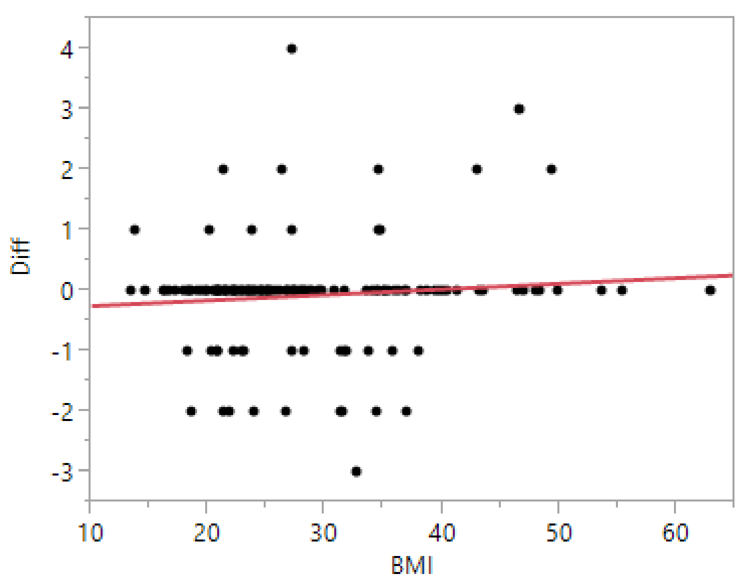

Figure B.4 – Age estimation error rates (Diff) regressed on body mass index (BMI). $R^2 = 0.01$.

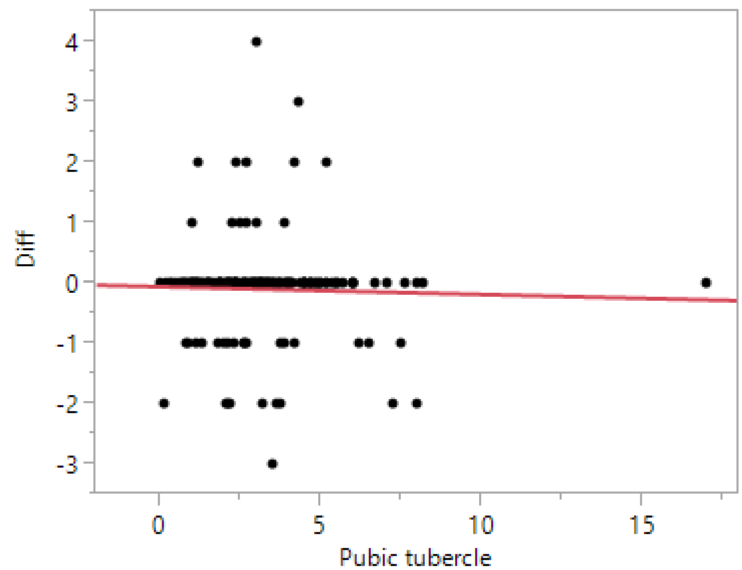

Figure B.5 – Age estimation error rate (Diff) regressed on pubic tubercle length (mm). $R^2 = 0.00$.

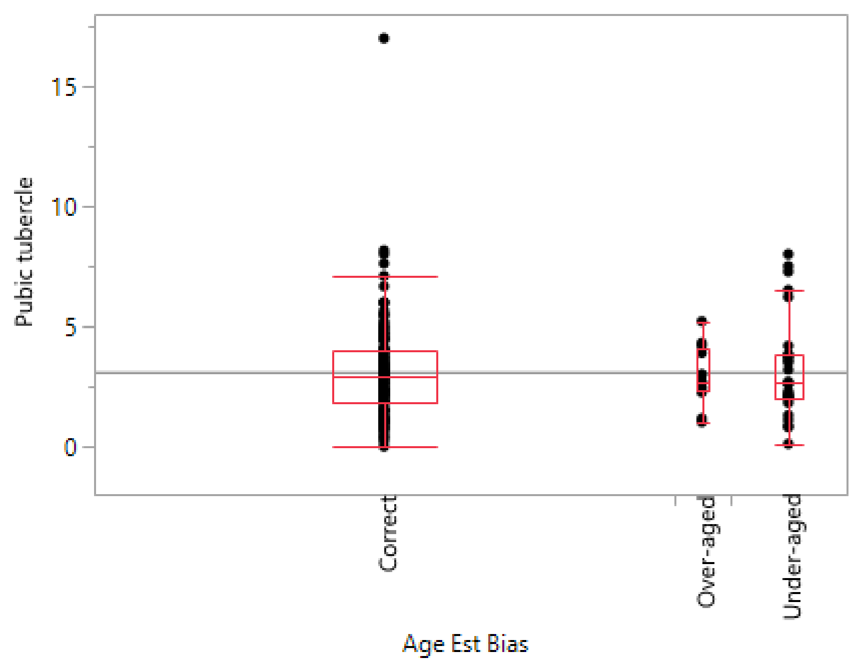

Figure B.6 – Pubic tubercle length (mm) compared by age estimation bias (Age Est Bias) groups.

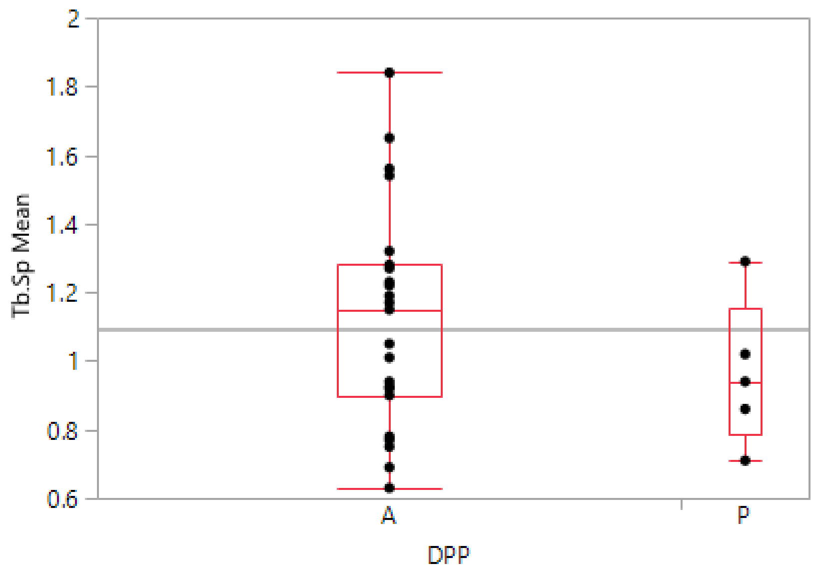

Figure B.7 - Box plots of mean trabecular spacing (Tb.Sp, µm) between the presence (P) and absence (A) of dorsal pubic pitting (DPP).

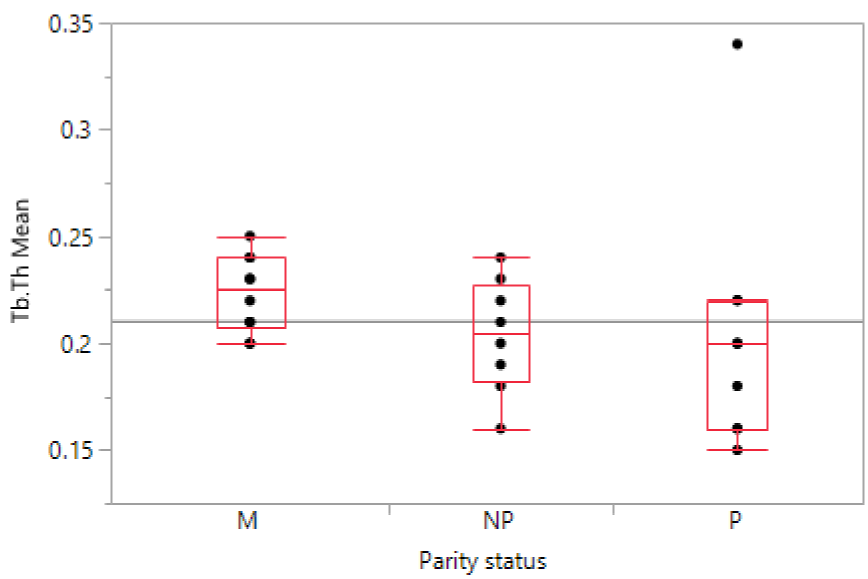

Figure B.8 - Box plots of trabecular thickness (µm) between parous (P) and nulliparous (NP) females and males (M). Outlier removed (NP, Tb.Th = 0.71 µm).

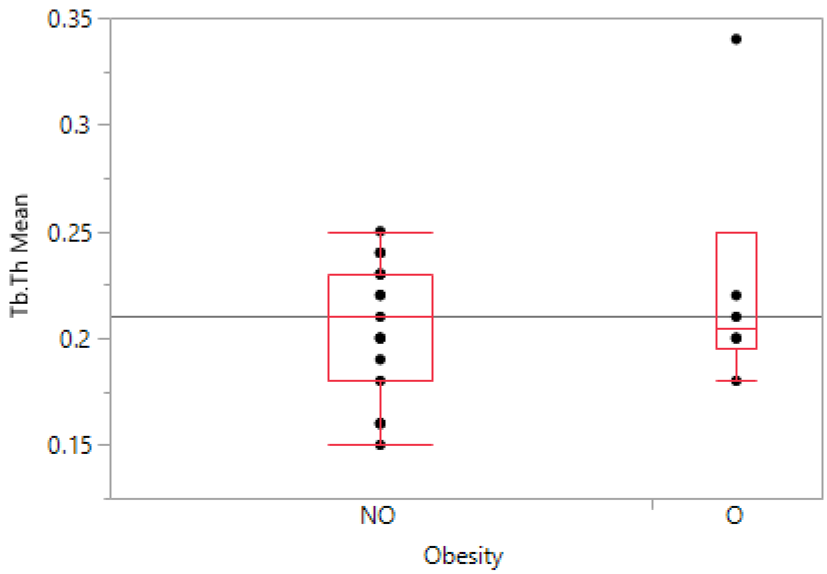

Figure B.9 - Box plots of trabecular thickness (µm) between non-obese (NO) and obese (O) individuals. Outlier removed (NO, Tb.Th = 0.71 µm).

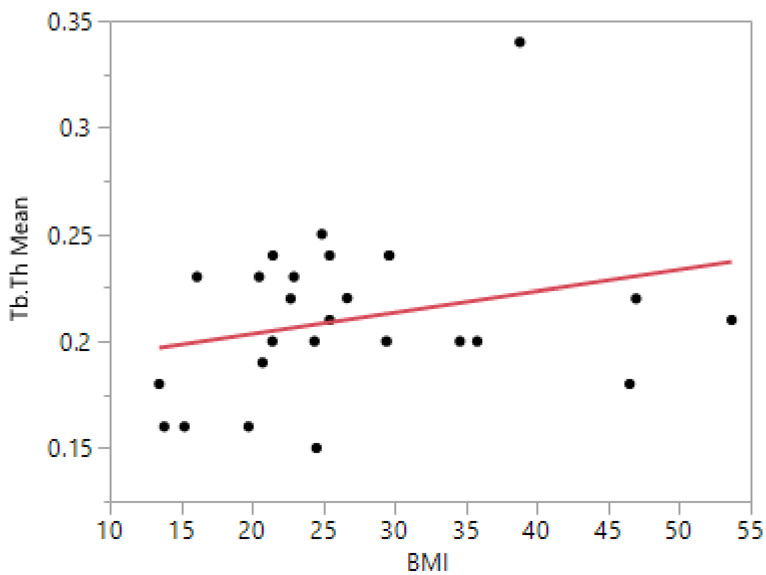

Figure B.10 - Regression of mean trabecular thickness (Tb.Th Mean, µm) and body mass index (BMI). $R^2 = 0.00$. Outlier removed (BMI = 22.19; Tb.Th = 0.71 µm).

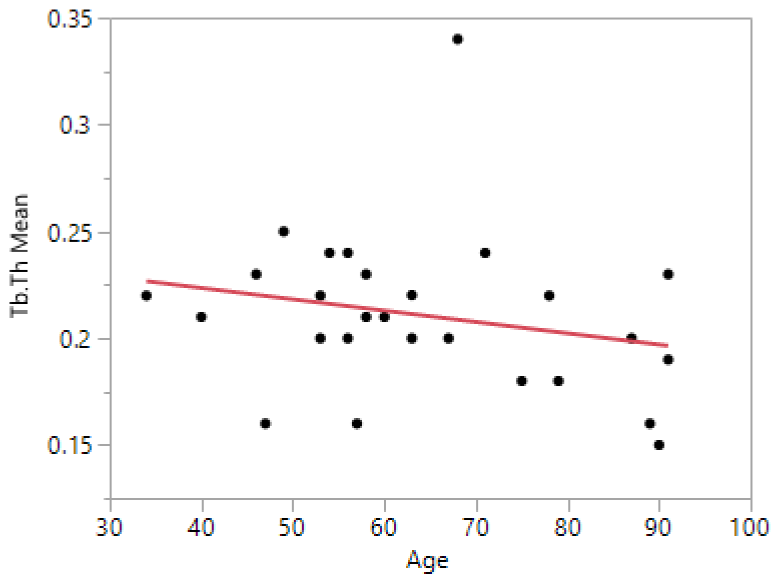

Figure B.101 - Regression of trabecular thickness mean (Tb.Th Mean, µm) and age-at-death (years). R^2 = 0.04. Outlier hidden (Tb.Th = 0.71 µm; Age = 53 years).

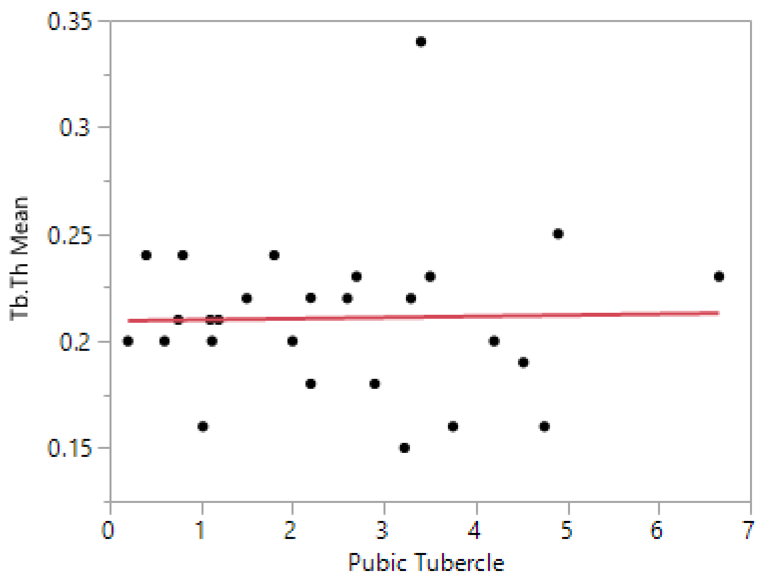

Figure B.112 - Regression of mean trabecular thickness (Tb.Th Mean, µm), and pubic tubercle length (mm). R^2 = 0.00. Outlier hidden (Tb.Th = 0.71 µm; pubic tubercle length = 2.75 mm).

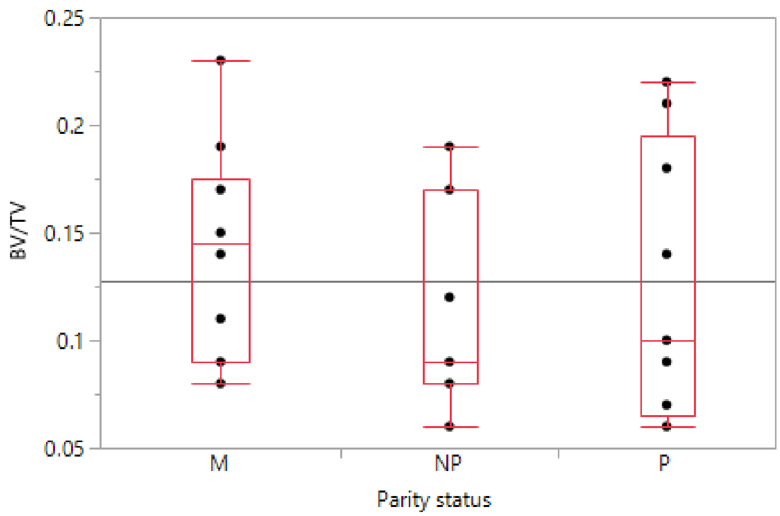

Figure B.13 - Box plots of bone volume ratio (BV/TV) between males (M), parous females (P), nulliparous females (NP).

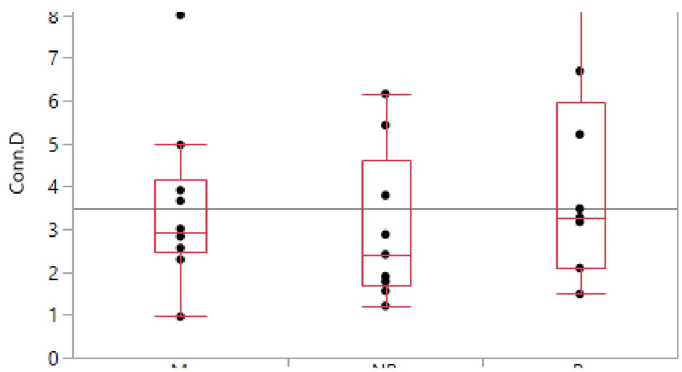

Figure B.14 - Box plots comparing connectivity density (Conn.D) between the presence (P) and absence (A = females, AM = males) of the preauricular sulcus (PAS).

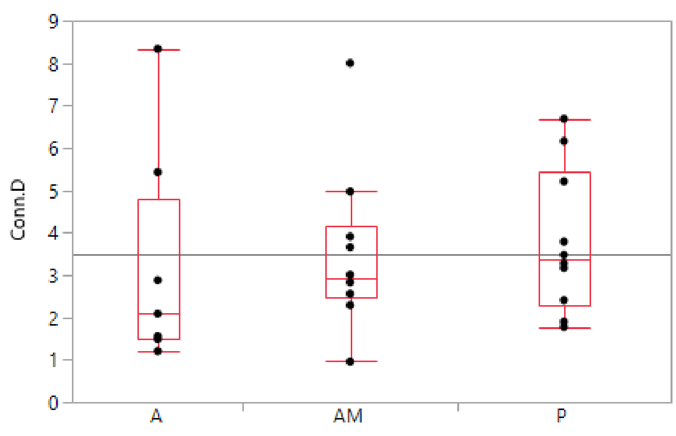

Figure B.15 - Box plots comparing connectivity density (Conn.D) between parous (P), nulliparous (NP) females, and males (M).

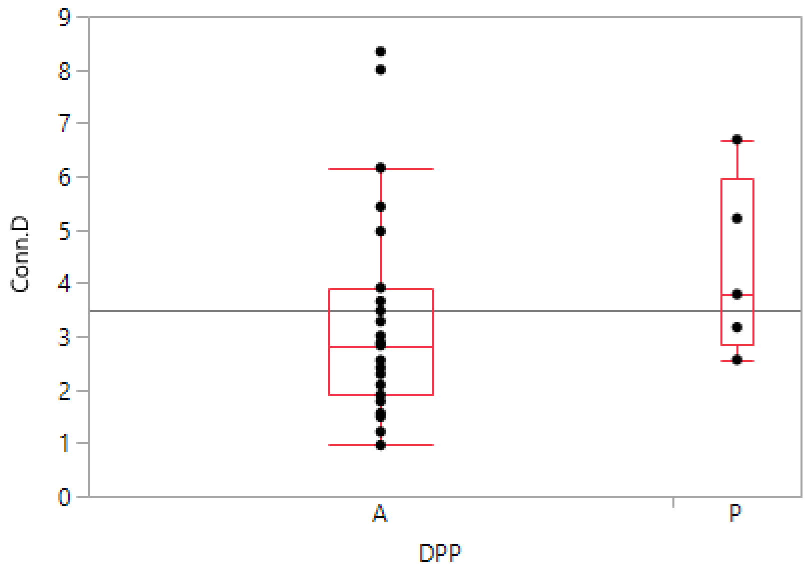

Figure B.16 - Box plots for connectivity density (Conn.D) by the absence (A) and presence (P) of dorsal pubic pitting (DPP).

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