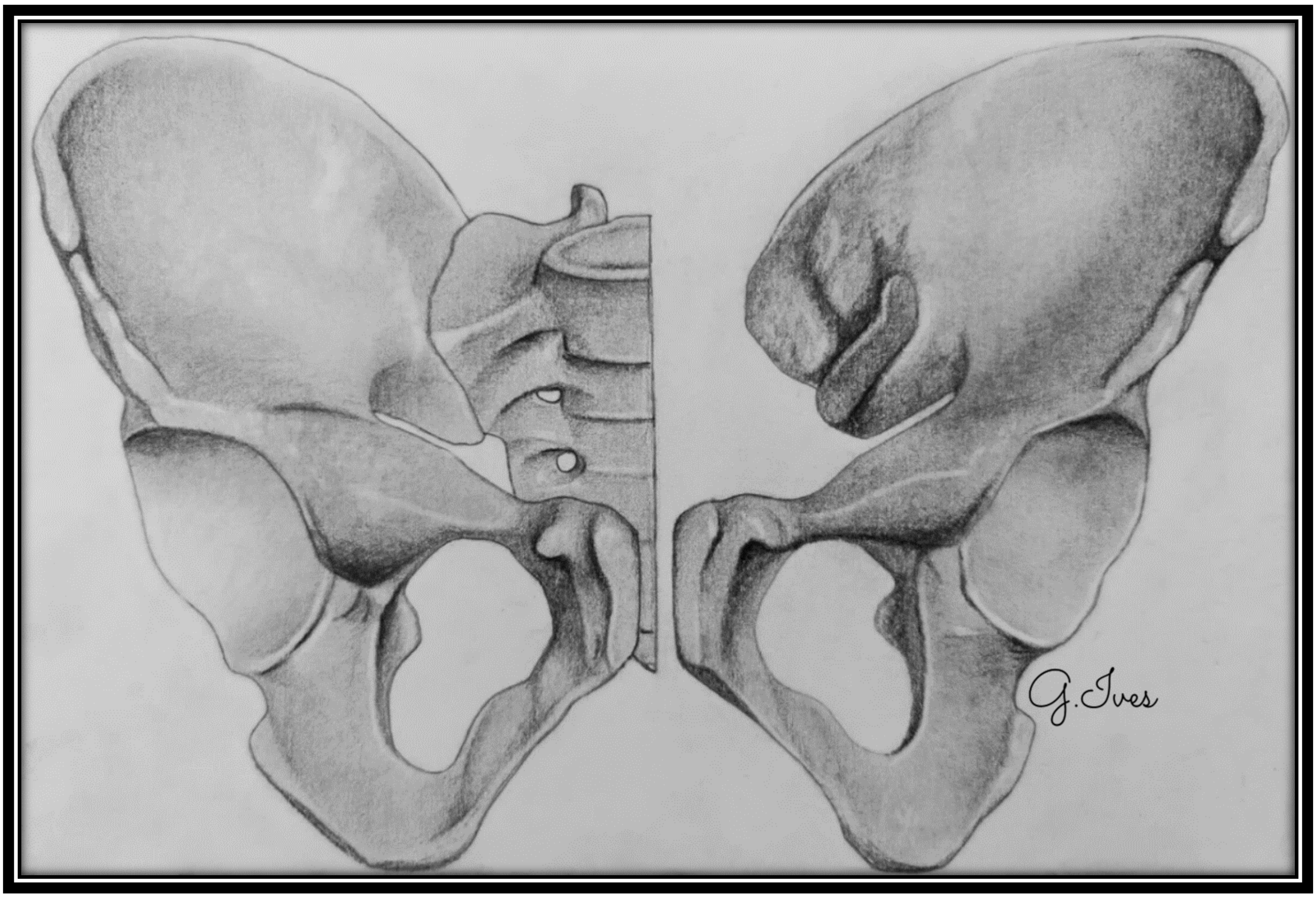


Pelvic Scarring: What Can it Tell Us?

Georgina Ives

School of Anthropology and Conservation

University of Kent

This thesis was submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in Anthropology at the University of Kent.

Submission: September 2024

Word Count (excluding references and appendix)**: 52,769**

Number of pages: 162

Associated publications:

1. Ives. G, Johns, S. E., and Deter, C. (2024) Sexual Dimorphism of Pelvic Scarring: A New Method of Adult Biological Sex Estimation. *Journal of Forensic Sciences*. https://doi.org/10.1111/1556-4029.15587

2. Ives. G, Johns, S. E., and Deter, C. (In press) Pelvic Scarring: A Result of Gravidity and Parity, or Simply Evidence of Biological Potential?.*Journal of Archives of Biology & Life Sciences.*

3. Ives G, Johns, S. E., Deter, C. Do Age, Height, and Weight Influence the Development of Pelvic Scarring? (**Ready for journal submission**).

Lead author for all publications: **Georgina Ives** – responsible for manuscript research, data collection, data analysis and interpretation, manuscript writing, publication correspondence, and manuscript revisions. Thesis supervisors and publication co-authors: **Sarah E. Johns** and **Chris Deter** – responsible for guidance - particularly regarding methodology (Chris Deter) and statistical analysis (Sarah E. Johns), manuscript review (both), and approval of final drafts (both).

Acknowledgements

I would first like to thank my PhD supervisors – **Chris Deter** and **Sarah Johns** – for their constant guidance throughout this long but wonderful journey. **Sarah**, thank you for your kind words and invaluable support for all things academic. You always found time for me even when I knew you were super busy, and I genuinely appreciate it. **Chris**, thank you for always believing in me and pushing me to improve. I will forever be grateful.

I would also like to thank **Chris Dunmore** for sharing his expert statistics knowledge (sorry for the endless questions) - but, most importantly, for his friendship, which I shall cherish always. Similarly, thank you to **Charlotte** and **Petrina**, who are two of the most beautifully intelligent women I know and will forever be some of my closest friends. Thank you for your unwavering support and for making my PhD experience so positive and memorable. I cannot wait to see what amazing things you both do when you finish your PhD journeys.

Finally, thank you to my favourite people – my **Mum** and my partner, **Anthony**. **Anthony**, I could not ask for a more patient and understanding partner. Thank you for always supporting me and being my number one fan when I needed it the most. I apologise for all the times you had to sit through me talking *at* you about my research. **Mum**, I could not have gotten through this process without you. You believed in me from the start and have been my absolute rock, and thank you for being my personal proofreader (I am sorry about making you read everything a million times). I am so lucky to have such a beautifully kind and intelligent Mum.

None of this would have been possible without you all. Thank you.

Abstract

Over a span of almost 60 years, pelvic scarring has been extensively studied with the intention of developing or refining methods for biological profile estimation. Despite this, some challenges persist in linking pelvic scarring with specific biological variables, necessitating continued investigation to enhance forensic and anthropological methodologies. This thesis re-examines the potential associations between biological factors and pelvic scar sites, using samples from the Texas State Donated Skeletal Collection (n = 220). Where required, validation analyses were later conducted using individuals from the Spitalfields collection (n = 86).

This research identified significant relationships between biological sex and scar sites, introducing a novel metric-based sex estimation method using the approximate volumes of the preauricular sulcus and newly defined inferior interosseous cavity. This method achieved 97.1% accuracy in the development sample, with 90.7% accuracy upon validation. In revisiting the debated link between pelvic scarring and obstetric events, significant associations were observed with all scar features in the combined sex sample. However, excluding males reduced statistical obstetric significance, except for the preauricular sulcus and superior interosseous cavity. Finally, this study examined the impact of age, height, and weight on pelvic scarring, identifying only a small number of weak associations across both full and single-sex samples.

This research highlights the consistent sexual dimorphism of pelvic scarring, with particularly high accuracy and forensic potential demonstrated in posterior pelvic scar analysis. While obstetric events may contribute to sulcus development, biological sex plays a more significant role in scar formation, whereas the superior interosseous cavity appears most affected by pregnancy-related biomechanical stress. In contrast, age, height, and weight were not found to significantly influence pelvic scar presentation for the purposes of biological profile estimation. Overall, this research advances forensic anthropology by providing a more accurate and accessible method for sex estimation, while also deepening current understanding of pelvic scar formation. Furthermore, while designed for practical application, the method also offers scope for future refinement through advanced technologies such as 3D imaging and machine learning, supporting continued innovation in forensic and archaeological analysis.

Glossary

Pelvic Scarring: In this study, pelvic scarring refers to any area of the pelvis that commonly presents with cortical bone changes (either lytic or proliferative) at the site of tendon or ligament attachment.

Gravidity: The number of pregnancies, regardless of the outcome.

Gravid: Having been pregnant

Nulligravid: Never having been pregnant

Parity: the number of times a woman has given birth to a live neonate (any gestation) or at 24 weeks or more, regardless of whether the child was viable or non-viable (i.e. stillbirths). In this study, it refers to vaginal births, specifically.

Parous: Having given birth to one or more offspring. In this study, it refers to vaginal births, specifically.

Nulliparous: Never having given birth to offspring. In this study, it refers to vaginal births, specifically. Therefore, a female may have been gravid but remain nulliparous (i.e., in the caesarean section).

Table of Contents

Tables

Figures

Chapter 1: Introduction

The analysis of human skeletal remains is a crucial process in both forensic and archaeological investigations, helping to identify unknown individuals in modern cases and establish group demographics and biological factor interactions of past populations (White et al., 2012; Katzenberg & Grauer, 2019). The pelvis is one of the most frequently analysed skeletal structures, proving highly valuable in estimating biological age and sex (White et al., 2012; Christensen et al., 2014). Over the last five decades, one aspect of the pelvis of particular interest has been pelvic scarring – first referred to as "scars of parturition" (Stewart, 1970, p.127). This term was adopted based on Angel's (1969) hypothesised connection between dorsal pubic pitting and the birthing process. Studies have since identified further common sites of scarring, such as the preauricular sulcus, interosseous groove, pubic tubercle extension, and iliac tuberosity extension (e.g., Andersen, 1986; Cox, 2000; Maass, 2012; Waltenberger et al., 2021;2022a;2022b).

Early parturition scar research focused on the theory of obstetric association. It is thought that pregnancy hormones induce skeletal laxity while the physical changes associated with foetal growth and birth exert significant musculoskeletal strain, promoting active bone remodelling (Andersen, 1986; Maass, 2012). However, an issue with the term "scars of parturition" arises in that it implies a definitive association between pelvic scarring and obstetric events (specifically birth). Later research suggests that the osteological relationship between obstetrics and pelvic scarring is less clear. Ullrich (1975), Cox & Scott (1992), McArthur et al. (2016), and Igarashi et al. (2019) have explored the relationship between pelvic scars and obstetric factors or the number of childbirth events, and indeed indicate that analysis of pelvic scar sites can potentially reveal information about obstetric history. However, in contrast, Kelley (1979), Suchey et al. (1979), Andersen (1986), Spring et al. (1989), and Canty (2020) have documented pelvic scarring in nulliparous or nulligravid females, suggesting that reproductive events are at least not the exclusive cause of pelvic scarring.

By incorporating a male sample, some research explores the theory that pelvic scar occurrence or severity may simply be an expression of biological sex, arising as a consequence of mature pelvic dimorphism. Such studies historically produce varying results (Houghton, 1974; Ullrich, 1975; Işcan & Derrick, 1984; Andersen, 1986; Spring et al., 1989; Novak et al., 2012; Gohil et al., 2014; Maass & Friedling, 2016; McArthur et al., 2016; Mahadevappa & Shivalingaiah, 2017; Karsten, 2018; Praxmarer et al., 2020; Waltenberger et al., 2021;2022a), although those that observe scarring in a significant percentage of males support those studies that refute obstetric scar aetiology. Although, when considering scar severity on a graded scale (e.g. Houghton, 1974; Ullrich, 1975; Andersen, 1986; Maass & Friedling, 2016; Canty, 2020; Praxmarer et al., 2020; Waltenberger et al., 2021;2022a), it is generally agreed that scarring is dimorphic across the pelvis, with male scarring less severe than that typical in females - with the exception of pubic tubercle extension. Despite these observations, no widely adopted methods of sex estimation using pelvic scarring have been developed to date (Canty, 2020).

In agreement with McFadden (2020), this research identifies difficulty in cross-study comparison, often hindered by an inconsistency in the number of scar variables analysed, with frequent variation in the analysis methods employed. Many existing studies rely on basic morphological and categorical systems, disregarding early caution expressed by Suchey et al. (1979) concerning the arbitrary nature of scar categorisation. Some research, such as that conducted by Stewart (1970), Houghton (1974), Ullrich (1975), Novak et al. (2012), McArthur et al. (2016), Karsten (2018), and Igarashi et al. (2019) has subsequently sought to enhance the precisions of basic binary methods by including categorical grades. However, this is often inappropriate for assessing binary aspects of the biological profile, and analysis remains limited compared to metric investigation. Furthermore, grading can promote subjectivity when introducing more groups to enhance precision. In recognition of these issues, Maass & Friedling (2016) advocate for the inclusion of metric elements in scar categorisation, later adopted by Praxmarer et al. (2020) and Waltenberger et al. (2021; 2022a; 2022b). However, caution is necessary as this can result in the heterogeneous, unmodified use of different existing scar analysis methods in assessing multiple features, leading to methodological inconsistencies and rendering intra-study comparisons difficult.

McFadden (2020) first drew attention to the degree of variability in both the quality and quantity of biological data available across osteological scar studies. This research identifies how, in some cases (Houghton, 1974; Ullrich, 1975; Maass, 2012; Maass & Friedling, 2016; Canty, 2020; Praxmarer et al., 2020; Waltenberger et al., 2021), even biological sex is unknown for at least part of the sample - leaving results susceptible to the inaccuracies associated with the estimation methods used. Moreover, a historical challenge in identifying skeletal samples accompanied by records of pregnancies and births may invalidate inferences of an obstetric association with scarring. Related to this, even in studies where obstetric history was known (e.g., Holt (1978), Kelley (1979), and Igarashi et al. (2019), there was no differentiation between pregnancy and birth when interpreting results, thus limiting investigative potential.

Given these challenges, it is imperative to utilise a sample with known biological sex and detailed obstetric history, justifying further research. Additionally, a consideration of other biological factors, as advocated by researchers such as Andersen (1986), Mass (2012), and Waltenberger et al. (2022a; 2022b), is essential to understand the potential multifactorial influence on scar development. It is also important to use a consistent and robust system of scar analysis, including metric assessment applicable to multiple scar sites, to facilitate appropriate cross-scar comparison as far as possible.

1.1. Study Overview

This research examines the aetiology and predictive potential of pelvic scarring by analysing the occurrence and presentation of osteological changes at commonly observed scar sites using a known mixed-sex skeletal sample. Scar analysis will begin with a macromorphological assessment of scar features, enabling direct comparison with existing findings. This will be supplemented by a metric analysis of all scar features, thereby avoiding the categorical restriction of continuous measures and reducing methodological subjectivity. Conclusions will be drawn regarding the relationships between pelvic scarring and known biological factors, including sex, obstetric event occurrence – including gravidity (pregnancy) and parity (birth), age at death, height, and weight. This study ultimately aims to advance our understanding of pelvic scarring and its implications in the assessment of the biological profile within a modern human population. Furthermore, it seeks to develop new methods of scar-based biological profile estimation, where significant relationships are identified.

1.1.1. Research Questions

1. Can biological sex be estimated through pelvic scar analysis?
2. Is there a significant difference in the occurrence rate or severity of pelvic scarring between males and females?
3. Is there a significant difference in the occurrence rate or severity of pelvic scarring between nulligravid and gravid females?
4. Is there a significant difference in the occurrence rate or severity of pelvic scarring between nulliparous and parous females?
5. Assuming significant differences in either scar occurrence or presentation in obstetric groups, can this be used to estimate gravidity or parity event occurrence?
6. Does the occurrence or severity of scarring across pelvic sites differ significantly with age, height, or weight?

1.1.2. Hypotheses

H1. The rate of scar occurrence between sexes will not vary significantly, but there will be a statistically significant difference when assessing scar severity across all pelvic sites.

H2. Pelvic scarring between sexes will differ most significantly in areas where the female pelvis experiences lateral stress due to its broader and more flexible structure.

H3. Pelvic scar incidence and severity will not differ significantly between obstetric groups.

H4. Pelvic scar incidence will not differ significantly with age, but the severity will reduce in females due to menopause-induced pelvic changes.

H5. Neither height nor weight will significantly affect scar incidence or severity across all scar sites.

1.2. Ethics Statement

Ethical approval was obtained through the School of Anthropology and Conservation ethics team and was valid for the duration of the data collection period (Ethics ID = 2022164607329563). In the discussion of the skeletal collection(s) used, information surrounding donor procurement and data availability has been outlined in the materials and methodology section to ease any additional concerns that might arise when using human skeletal remains.

Chapter 2: Pelvic Structure and Scarring

This chapter offers a comprehensive overview of skeletal pelvic anatomy, establishing a foundation for the detailed examination of individual scar sites. It begins with an in-depth discussion of pelvic growth and development, including a general timeline of ontogenetic events, to contextualise how the pelvis matures and the key milestones that may influence the formation of pelvic scars. The standard morphology of the adult pelvis is then outlined, detailing its anatomical features and functional significance. Finally, this chapter focuses on common pelvic scar sites to provide further context for the study.

2.1. Pelvic Anatomy

2.1.1. Pelvic Growth and Development

Early pelvic development begins in utero between the end of the second and fifth foetal months, characterised by the appearance of the first to fifth sacral ossification centres and the three primary os coxae ossification centres – corresponding to the ilium, ischium, or pubis (Schwartz, 2007; Wall-Scheffler et al., 2020a). At the posterior pelvis, the ossification sites for the sacrum appear slightly later, between the fourth and eighth foetal months (Lierse et al., 2012). By full term, the sacrum (excluding the coccyx) and the three elements of the os coxae are indicative of their final adult morphology, and this includes almost all soft tissue attachment sites (Cunningham et al., 2016; Wall-Scheffler et al., 2020a).

Primary ossification centres continue to metabolise postnatally, and secondary ossification sites appear (Schwartz, 2007; Wall-Scheffler et al., 2020a). Initially, the ilium, ischium, and pubis are connected by triradiate cartilage, with central acetabular development commencing between the second and sixth postnatal months (Schwartz, 2007). Fusion between the inferior pubic ramus and ischial ramus typically starts by age six and is complete by the age of eight, thereby defining the obturator foramen (Schwartz, 2007). The eighth year includes the fusion of the transverse and costal elements of the sacrum (Lierse et al., 2012). Union of each of the three pelvic elements at the acetabulum commences between the ages of nine and twelve – first between the pubis and ilium, then the ilium and ischium, before finally completing between the ischium and pubis (Wall-Scheffler et al., 2020a). On average, this process is complete between the ages of fourteen and sixteen - but in females specifically, fusion occurs between eleven and fifteen, while in males, it is between fourteen and seventeen (Schwartz, 2007; Cunningham et al., 2016; Verbruggen & Nowlan, 2017).

The initiation of secondary ossification coincides with pubertal onset, which is typically between twelve and thirteen in females and fourteen and fifteen in males (Scheuer & Black, 2004), resulting in overall earlier fusion in biological females (Wall-Scheffler et al., 2020a). This process sees the development of further ossification centres across five additional os coxae sites: the anterior superior and inferior iliac spines, iliac crest, ischial tuberosity, and superior pubis (Cunningham et al., 2016; Wall-Scheffler et al., 2020a). The union between these secondary sites and the body of the os coxae commonly starts around the age of sixteen or seventeen but can continue until age twenty-five (Scheuer & Black, 2004). Meanwhile, the appearance of sacral body epiphyses occurs anywhere between the ages of ten and fifteen, delaying the complete fusion of the inferior sacral bodies to between eighteen and twenty years – with fusion of the S1 and S2 vertebrae completing by the twenty-fifth year (Lierse et al., 2012; Verbruggen & Nowlan, 2017) in line with the standard completion of os coxal maturation.

2.1.2. The Adult Pelvis

Now fully developed, the adult pelvic girdle is formed of three bones – the sacrum and two paired os coxa (Andersen, 1986; Scheuer & Black, 2004; White et al., 2012) (see Figure 1). The sacrum is a large triangular-shaped bone that sits posteromedially within the pelvic girdle, and the two pelvic bones are positioned on each side of the sacrum posteriorly (White et al., 2012). Each pelvic bone is irregular in shape and curves anterolaterally to complete the characteristic basin shape of the pelvis, forming the pubic joint at the midline of the anterior border (Andersen, 1986). As discussed in section 2.1.1, each of the pelvic bones comprises three distinct parts: the ilium, the ischium, and the pubis. These components fuse at the acetabulum during development, forming the deep socket that articulates with the head of the femur (Andersen, 1986). Despite their fusion, osteological texts frequently refer to each of these bones individually, along with the sacrum, to facilitate discussions or analyses of the intricate pelvic structure.

The sacrum is a large symmetrical bone formed of five fused vertebrae decreasing in size inferiorly (Andersen, 1986; Scheuer & Black, 2004). This bone protects the inferior spinal nerves (Cunningham et al., 2016). The fifth lumbar vertebra is superior to the sacrum, forming the lumbosacral joint (Andersen, 1986). On each side of the sacrum, the ilium of each of the pelvic bones connects, creating the two synovial sacroiliac joints (Walker, 1992). The bony contact point of this joint is called the auricular surface, which presents as a distinctive dual demi face shape upon the corresponding surface of each pelvic element. Surrounding the sacroiliac joint are multiple ligamentous structures (interosseous, ventral sacroiliac, and dorsal sacroiliac ligaments) responsible for the high level of joint stability, which is crucial in the effective bipedalism of modern humans (Walker, 1992; Cunningham et al., 2016).

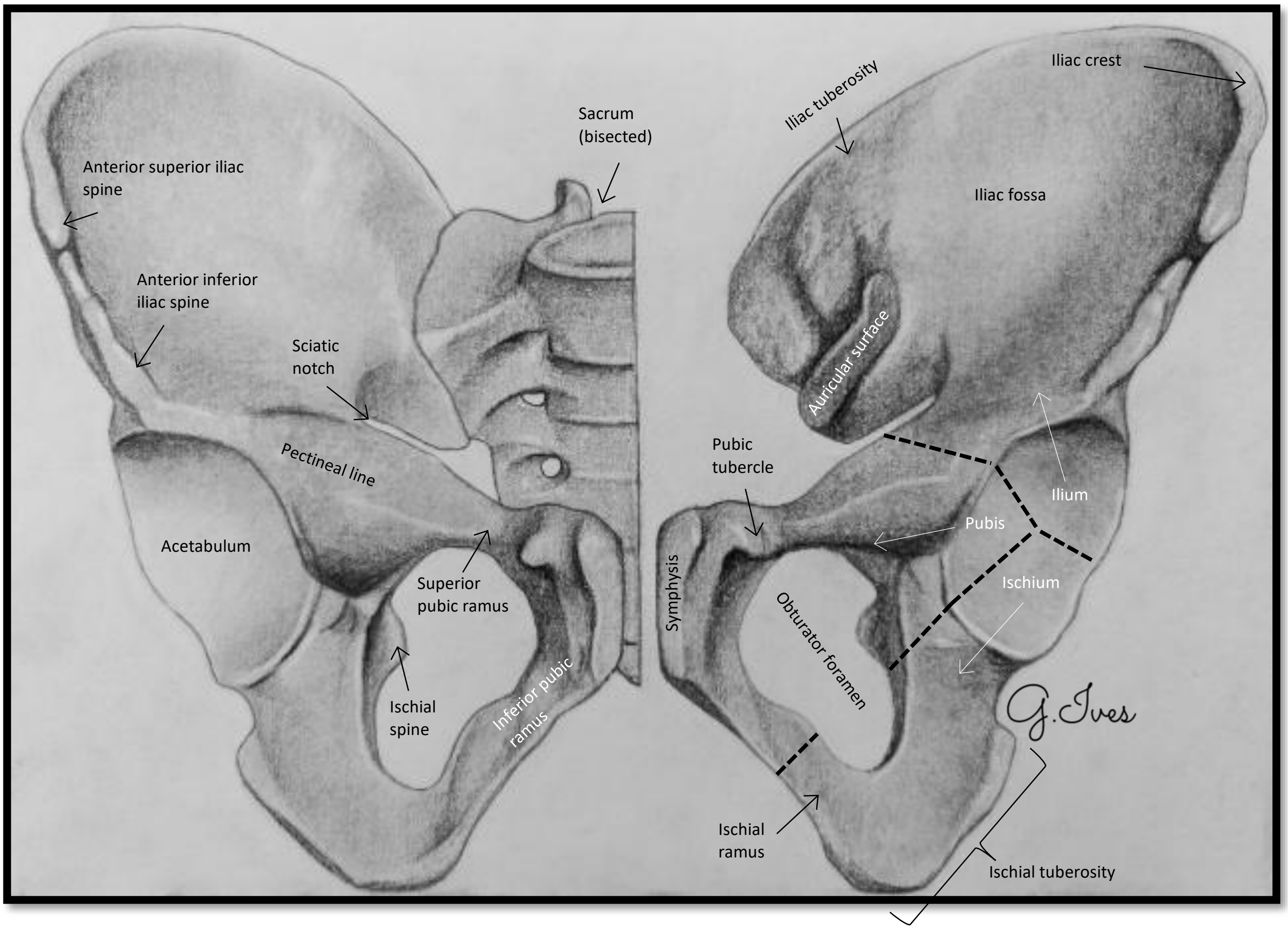


Figure 1. Annotated drawing of the adult pelvis, with the left side of the sacrum removed to reveal the auricular area of the left os coxa.

The ilium is the largest of the three pelvic sections, accounting for roughly two-fifths of the pelvic bone (Andersen, 1986). Continuing superiorly from the auricular surface leads to the thick iliac crest atop the wing of the ilium – stretching from the posterior superior iliac spine to the anterior superior iliac spine (Andersen, 1986; Cunningham et al., 2016). The anterior inferior spine follows a concavity along the anterior border (Cunningham et al., 2016). The lateral half of the iliac crest surrounds the iliac fossa of the inner surface of the ilia, between which and the superior demi face of the auricular surface, the arcuate line can be traced (Andersen, 1986). This line continues from the iliac crest to the pubic symphysis. Upon the posterior surface of the iliac wing, there are few key features aside from the superior third of the acetabulum beginning at the inferior margin of the ilium. The final key feature of the ilium is the sciatic notch, presenting as a considerable indentation into the posterior aspect from the posterior inferior iliac spine onto the ischium (Andersen, 1986; White et al., 2012).

The ischium is the strongest bone of the pelvis, occupying the inferoposterior section of the pelvic bone and commencing superiorly at the acetabulum to form the inferolateral third of the socket (Andersen, 1986; Scheuer & Black, 2004). Close to this, the superior edge of the ischial tuberosity can be found upon the superior ramus, representing the inferior point of the sciatic notch (White et al., 2012). The superior ramus continues down into the body of the ischium and the area of rugosity of the ischial tuberosity at the posterior edge (Andersen, 1986; White et al., 2012). The ischial body then narrows into the inferior ramus, completing the posterior border of the obturator foramen and morphing into the inferior pubic ramus anteriorly (Andersen, 1986; White et al., 2012).

Finally, the pubis bone forms the anterior-most area of the pelvic bone, completing the obturator foramen, providing the final anterior section of the acetabulum, and facilitating the closure of the 'osteoarticular ring' of the pelvis anteriorly at the symphyseal surface (Andersen, 1986; Scheuer & Black, 2004). The symphyseal surface of each of the os coxae forms the cartilaginous pubic symphysis joint responsible for pelvic stability in combination with the posterior sacroiliac joint (White et al., 2012; Cunningham et al., 2016). Two rami extend from the superior and inferior ends of the symphyseal surface – the inferior pubic ramus, which can be traced inferolaterally, leads into the inferior ramus of the adjacent ischium, while the superior pubic ramus follows the pectineal line extending towards the iliac body and the acetabulum (White et al., 2012). The pubic crest and pubic tubercle serve as clear landmarks of the superior ramus of the pubis, with the crest observable as a thickened mount immediately superior to the pubic symphysis – extending laterally to form the variably sized tubercle (White et al., 2012).

2.2. Pelvic Scar Sites

Pelvic scarring refers to sites of naturally occurring cortical bone alteration as a result of ligament or tendon stress, similar to entheseal changes that may be observed throughout the skeleton. Like common entheseal changes, these bony alterations may be lytic - resulting in bone loss, or proliferative - leading to new bone growth. This section provides detail of typical scar feature presentations at each of the common scar sites.

The most frequently reported scar site features are dorsal pubic pitting, the preauricular sulcus, and pubic tubercle extension (Cox & Mays, 2000; Maass, 2012). Although, additional scar sites have been identified on the retroauricular surface as an extension of the iliac tuberosity (Işcan & Derrick, 1984; Andersen, 1986) and retroauricular surface indentation (Houghton, 1974; Işcan & Derrick, 1984; Andersen, 1986). Scarring has more recently been identified as pitting adjacent to the ventral aspect of the pubic symphysis (Figures 2 and 3) (Rebay-Salisbury et al., 2018; Waltenberger et al., 2021, 2022b).

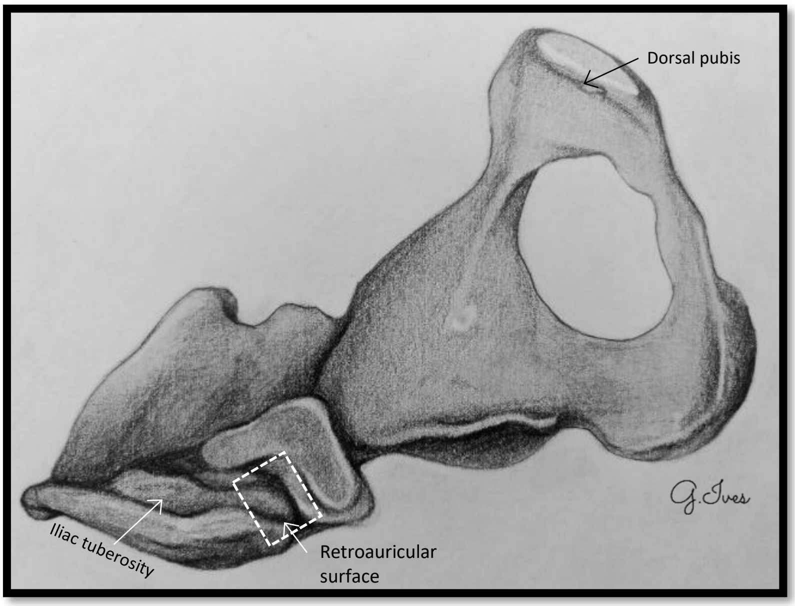


Figure 2. Drawing of the medial view of the left os coxa highlighting the dorsal pubic surface, the retroauricular surface, and the iliac tuberosity.

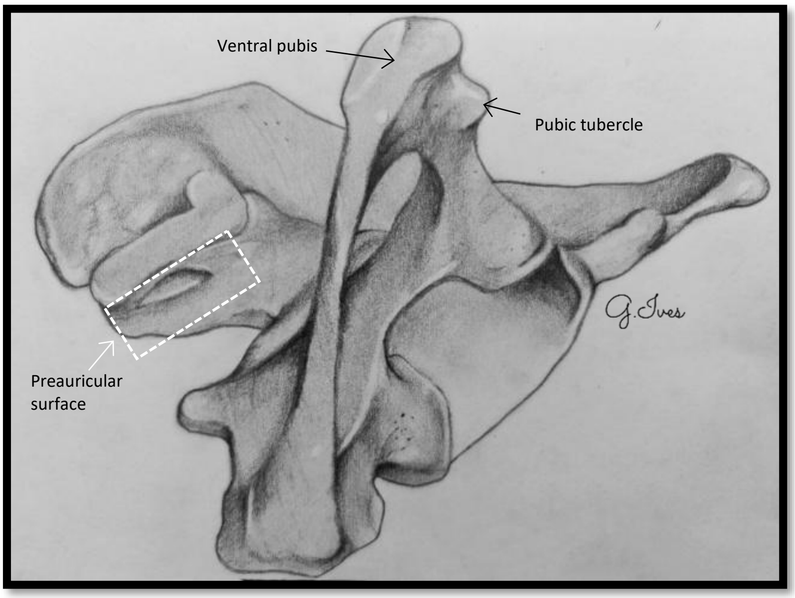


Figure 3. Drawing of the inferior view of the left os coxa highlighting the pubic tubercle, the preauricular surface, and the ventral pubic surface.

2.2.1. Dorsal Pubic Pitting

Angel (1969) first detailed observable changes on the dorsal pubic surface adjacent to the dorsal edge of the pubic symphyseal surface of the pubis, which has been a focal point in a vast number of studies (McFadden, 2020). This area of the pubis can be directly associated with pelviabdominal muscle origins, such as that of the abdominus rectus and pyramidalis muscles, and the anterior muscles of the pelvic floor. The posterior ligament spans the width of the pubic symphyseal gap, attaching to the dorsal aspect of the pubis and assisting in the stabilisation of the anterior pelvis (Andersen, 1986; Maass, 2012). Changes at the dorsal pubic surface can be described as a fossa, depression, groove, cavity, or pit (Angel, 1969; Stewart, 1970; Holt, 1978; Suchey et al., 1979; Andersen, 1986; Cox & Scott, 1992; Snodgrass & Galloway, 2003; Maass & Friedling, 2016; McArthur et al., 2016; Praxmarer et al., 2020). However, the term 'pit' remains the most widely used descriptor within the osteological literature. Although dorsal pitting is not always immediately apparent, it often accentuates existing osteophytic lipping along the symphyseal border, aiding its identification. In positive cases, while multiple pits are possible, a single pit is most commonly observed, which may represent a minor expression or a coalescence of multiple smaller pits forming a single, larger indentation.

2.2.2. Preauricular Sulcus

The preauricular sulcus is the single most frequently analysed example of pelvic scarring. Early discussion of this feature can be found in the works of Fraser (1958) and Davivongs (1963), but it was brought to the forefront of osteological research by Houghton (1974). Frequently termed the preauricular groove in these early studies before the move towards the term sulcus (Andersen, 1986; Novak et al., 2012; Maass & Friedling, 2016; Karsten, 2018; Canty, 2020; Praxmarer et al., 2020), this feature occurs at the site of the ventral sacroiliac ligament attachment and is characterised by cavitation upon the preauricular surface - parallel to the anterior border of the auricular surface (Houghton, 1974) (see Figure 3).

2.2.3. Pubic Tubercle Extension

The pubic tubercle is found along the superior border of the pubis. This feature acts as an anchor for the inguinal ligament, internal oblique, and transversus abdominus muscles (White et al., 2012). It is also an attachment site for the superior pubic ligament (Andersen, 1986). This feature is commonly assessed as the extension of the tubercle beyond the natural curve of the arcuate line (Bergfelder & Herrmann, 1980; Cox & Scott, 1992; Snodgrass & Galloway, 2003; Maass & Friedling, 2016), however, some individuals do not present with any apparent elongation. First observed by Angel (1969), it was determined that the extension of this area occurs due to the force exerted upon it by the associated muscles, resulting in enthesopathic extension, but Waltenberger et al. (2021) note variations in the exact definition of this scar feature.

2.2.4. Interosseous Groove (and auricular lipping)

The interosseous groove is found on the retroauricular surface of the ilium. The focus on the interosseous groove developed primarily from Houghton's (1974) observations of pitting on the retroauricular area, and defined by its ability to produce a platform at the dorsal auricular edge. Işcan and Derrick (1984) clearly define the interosseous groove as the visible indentation that may start at the dorsal aspect of the superior demi face, or ramus, of the auricular surface, extending along the inferior dorsal border, terminating before the posterior inferior iliac spine. This indentation develops at the site of the interosseous ligament, although the ligamentous attachment site is not always as obvious as that relating to the preauricular sulcus (Houghton, 1974; 1975). Houghton (1974; 1975) explains that the rugged nature of the retroauricular area of the medial iliac surface can make detection of the complete attachment site of the interosseous ligament difficult. However, the anterior-most point of insertion is often noticeable due to the formation of lipping along the dorsal edge of the inferior auricular surface. Similar lipping can appear along the shorter superior border of the auricular surface, but this is not always present.

2.2.5. Further Sites

Although not a focal point of this research, some studies also assess variation in iliac tuberosity extension (Andersen, 1986; Maass & Friedling, 2016) first noted by Işcan and Derrick (1984), which has been linked to any stress exerted on, or changes to, the interosseous sacroiliac ligament. In addition, Rebay-Salisbury et al. (2018) and Waltenberger et al. (2021; 2022a; 2022b) observe pitting on the ventral plane of the pubis, comparable to dorsal pubic pitting. This corresponds with the anterior symphyseal ligament but is the least frequently discussed, given its comparatively recent identification.

Chapter 3: Research Background and Literature

Pelvic scarring has been a topic of considerable interest within forensic anthropology, bioarchaeology, and anatomy for over five decades and remains a subject of debate to the present day. The significance of pelvic scarring surpasses the simple consideration of the physical manifestations by serving as potential indicators of physiological processes (Maass, 2012; Praxmarer et al., 2020; Waltenberger et al., 2022b). This chapter investigates the primary aetiological theories of pelvic scarring, providing a basis for later chapters. Each causational theory section within this chapter will be accompanied by an overview and synthesis of existing osteological investigations to provide a robust foundation for this study. in seeking to provide the most accurate and detailed literature review possible, those studies utilised are examples of highly detailed doctoral theses or peer-reviewed publications, only. Table 1 below provides a reference for each of the biological and scar feature variables discussed in each key osteological study. The terminology used in the table and the discussion of studies has been standardised to enhance cross-study understanding.

3.1. Biological Sex

The modern human pelvis has evolved to support efficient bipedalism while accommodating the simultaneous increase in foetal cranial size, rendering the process of childbirth notably more challenging when compared to our quadrupedal ancestors (Trevathan, 2017; Mitteroecker & Fischer, 2022). During the transition to bipedal locomotion, the pelvis became shorter and wider, with increased iliac flare to manage the weight distribution associated with a permanently upright posture (Wall-Scheffler et al., 2020b). However, these morphological adaptations also reduced the anteroposterior diameter of the pelvic inlet (Wall-Scheffler et al., 2020; Mitteroecker & Fischer, 2022). To mitigate the birthing difficulties introduced by bipedalism, further adaptations were required in the female pelvis, accounting for the pronounced pelvic dimorphism observed in modern humans (Mitteroecker & Fischer, 2022).

Sexual dimorphism refers to the differences in phenotypic expression between sexually mature males and females of a species and is particularly evident in human skeletal morphology (Klales, 2020). In the context of pelvic scar development, some research proposes that pelvic maturation may play a role in the pattern and severity of scarring, with further theory that osteological changes across scar sites might be influenced by the adult female hormone cycle, introducing regular periods of musculoskeletal pelvic stress. This subsection explores the biological sex theory of scar causation, alongside osteological studies that both support and challenge the proposed relationship between biological sex and scarring.

3.1.2. Sex Estimation

Given the evolutionary adaptations of the female pelvis in response to reproductive demands, the pelvis has become a critical anatomical region for sex estimation in forensic anthropological and archaeological contexts. The pronounced differences in male and female pelvic morphology provide several anatomical landmarks useful for estimating biological sex with variable degrees of accuracy (Lovell, 1989; Bytheway & Ross, 2010; White et al., 2012). Traditionally, pelvis-based sex estimation methods have focused on structural aspects adopting a morphological approach, with the Phenice (1969) method being a prime example. This method evaluates three features of the anterior pelvis, demonstrating an initial accuracy of 96%. However, subsequent validation studies reported reduced accuracies ranging from 59% to 88.4% (Lovell, 1989; Maclaughlin & Bruce, 1990; Ubelaker & Volk, 2002). Despite these variations, the Phenice (1969) method remains the most widely used sex estimation technique today (Klales, 2020).

Walker (2005) raised concerns about the reliance on the anterior pelvis, particularly when analysing archaeological remains, with this region prone to postmortem damage in up to 90% of cases. To address this limitation, Walker (2005) developed an alternative method focusing on the dimorphism of the greater sciatic notch. This method employs a graded visual guide similar to the Phenice (1969) approach but offers a lower overall accuracy of 80%, improving to 89% when excluding androgynous samples (Walker, 2005). These results align with recent method testing by Bonczarowska et al. (2019), achieving 81% accuracy, and DesMarais et al. (2023), reporting 87.5% accuracy.

While existing methods demonstrate high accuracy, the successful application of both the Phenice (1969) and Walker (2005) techniques are vulnerable to postmortem damage due to their focus on large pelvic regions, potentially limiting their applicability (Walker, 2005). Additionally, these methods are predominantly morphological and categorical - which, while straightforward to apply, may reduce precision and introduce subjectivity (Brothwell & Zakrzewski, 2004; McFadden, 2020; Verma et al., 2020). This highlights the need for sex estimation methods that target smaller pelvic features, such as pelvic scar sites, which are less likely to sustain postmortem damage and can be easily assessed both morphologically and metrically.

3.1.3. Pelvic Dimorphism and Flexibility

The mature female pelvis is not only more gynaecoid in shape and proportionally larger relative to body size than the male pelvis, but also exhibits greater flexibility (Andersen, 1986; Maass, 2012; Wall-Scheffler et al., 2020; Fischer et al., 2021; Mitteroecker & Fischer, 2022). These adaptations result from hormone-driven pubertal changes that increase pelvic mobility in biological females (Andersen, 1986; Maass, 2012), facilitating the biomechanical demands of reproduction. However, this increased mobility may also predispose the pelvis to more frequent or pronounced skeletal stress.

Andersen (1986) described pelvic scarring as "scars of excess motion" (p. 184), suggesting that such scarring develops directly due to movement-induced tension. The natural flexibility of the female pelvis necessitates robust ligamentous stabilisation, as emphasised by Işcan & Derrick (1984) and Maass (2012). All common pelvic scar sites align with ligamentous and tendinous attachment points, rendering them particularly susceptible to musculoskeletal tension from the point of dimorphic development onwards (Maass, 2012). Evidence from Andersen (1986) and Waltenberger et al. (2022a) further supports this theory, with cases of pelvic scarring identified in individuals shortly after puberty, when alternative causes of scarring are less likely.

This correlation between pelvic morphology and biomechanical stresses indicates that female pelvis flexibility may therefore initiate a cortical response at skeletal attachment sites (Işcan & Derrick, 1984; Maass, 2012). Furthermore, if a broader pelvis contributes to increased musculoskeletal tension, scar presentation might vary depending on whether individuals exhibit typically gynaecoid or more androgynous skeletal traits. Such considerations underscore the need for continued investigation into how pelvic morphology influences the development and presentation of scarring.

3.1.4. The Female Menstrual Cycle

There is increasing evidence that the monthly female hormone cycle may exacerbate pelvic stress, which may in-turn advance scar presentation. This complex cycle, spanning approximately 28 days, involves multiple hormones and can be divided into three primary phases: follicular, ovulatory, and luteal (Ferin et al., 1993; Mihm et al., 2011; Reed & Carr, 2018). While the cycle primarily regulates menstruation, it also influences numerous other body systems, including the musculoskeletal system (Micussi et al., 2015; Chidi-Ogbolu & Baar, 2019).

In an early study, Maxwell (1938) investigated the effect of the menstrual cycle on the female pelvis using X-ray analysis. The findings revealed that periods of heightened oestrogen, such as during the mid-follicular and mid-luteal phases, lead to the relaxation of pelvic connective tissues and articular diastasis, particularly in the sacroiliac area (Maxwell, 1938). Further research by Chidi-Ogbolu & Baar (2019) demonstrated that cyclical oestrogen surges could soften pelvic ligaments to the extent that serious musculoskeletal injuries become possible. Micussi et al. (2015) also identified hormone-induced variations in pelvic floor tension, with muscle tone increasing during the follicular and luteal phases. Notably, this increase in muscle tone coincides with the periods of connective tissue laxity described by Maxwell (1938), creating a cyclical pattern of heightened biomechanical stress on the pelvis. Therefore, the female pelvis is not only inherently more flexible than that of biological males but also undergoes monthly cycles of increased tension at common pelvic scar sites due to hormone-induced pelvic laxity. These hormonal influences may contribute to the development and progression of pelvic scarring, particularly where ligamentous and tendinous attachments are subjected to repetitive stress.

3.1.5. Summary of the Biological Sex Theory

The biological sex theory of pelvic scar causation integrates the interplay of biomechanical stressors and hormonal cycles unique to biological females. Key evidence suggests that the enhanced flexibility and broader morphology of the female pelvis, driven by reproductive adaptations, contribute to increased musculoskeletal tension and, subsequently, pelvic scarring (Andersen, 1986; Maass, 2012). Additionally, hormonal influences, particularly the cyclical surges of oestrogen, exacerbate pelvic stress through ligamentous laxity and fluctuating muscle tone (Maxwell, 1938; Micussi et al., 2015; Chidi-Ogbolu & Baar, 2019).

From a biomechanical perspective, the gynaecoid pelvis, characterised by its wider dimensions and increased mobility, experiences greater ligamentous strain in general. This strain is further amplified by hormonal modulation, as oestrogen-induced laxity in connective tissues leads to increased stress at musculoskeletal attachment points. This cyclical biomechanical stress may lead to repeated microtrauma, contributing to the development and progression of scarring over time (Maass, 2012; Waltenberger et al., 2022a).

Collectively, this theoretical framework provides a critical lens through which existing studies on sexual dimorphism and pelvic scarring can be assessed. By combining biomechanical and hormonal theories, it offers an enhanced understanding of how pelvic scarring may serve as a marker for biological sex, thus informing osteological investigations.

Table 1. Existing research reference table, indicating the biological and scar variables directly investigated in each study.

Study	Sex	Obstetrics	Age	Height/ stature	Body size/mass	Preauricular sulcus	Interosseous groove	Dorsal pubic pitting	Pubic tubercle extension	Iliac tuberosity extension
Stewart (1970)		X	X					X		
Houghton (1974)	X	X				X	X			
Ullrich (1975)	X					X		X	X	
Holt (1978)		X						X		
Kelley (1979)		X	X			X	X	X		
Suchey et al. (1979)		X	X					X		
Işcan & Derrick (1984)	X						X			X
Andersen (1986)	X	X	X			X	X	X		X
Spring et al. (1989)	X	X	X			X				
Cox & Scott (1992)		X	X			X		X	X	
Snodgrass & Galloway (2003)		X	X	X	X			X	X	
Novak et al. (2012)	X		X			X				
Gohil et al. (2014)	X					X	X			X
Maass & Frielding (2016)	X		X			X	X	X	X	X
McArthur et al. (2016)	X	X				X		X		
Mahadevappa & Shivalingaiah (2017)	X		X				X			
Karsten (2018)	X		X			X				
Igarashi et al. (2019)		X	X			X				
Canty (2020)	X	X	X	X	X	X				
Praxmarer et al. (2020)	X		X	X	X	X		X	X	
Waltenberger et al. (2021)		*	X	X	X	X		X	X	
Waltenberger et al. (2022a)	X		X			X		X	X	
Waltenberger et al. (2022b)		X	X	X	X	X		X	X	

** Waltenberger et al. (2021) focus on pelvic size and shape, offering indirect inferences to obstetrics, highlighted further on as relevant.*

3.1.6. Biological Sex and Pelvic Scarring

Building upon aspects of the dimorphic theory of scar causation, existing osteological studies have sought to quantify and analyse these differences with diverse results (Houghton, 1974; Ullrich, 1974; Andersen, 1986; Işcan & Derrick, 1984; Spring et al., 1989; Novak et al., 2012; Gohil et al., 2014; Maass & Friedling, 2016; McArthur et al., 2016; Mahadevappa & Shivalingaiah, 2017; Karsten, 2018; Canty, 2020; Praxmarer et al., 2020). The following section closely examines these key research examples, exploring the extent to which pelvic scarring exhibits sexual dimorphism and how each aligns with or challenges the proposed theoretical framework. Despite some challenges concerning sample, variable, and methodological heterogeneity, these studies contribute valuable insights into pelvic scarring and its implications for osteological investigation.

Preauricular Sulcus

The preauricular sulcus is most frequently analysed in the study of scar dimorphism. Most studies agree that the mere binary assessment of sulcus presentation cannot confidently estimate biological sex (Andersen, 1986; Canty, 2020; Gohil et al., 2014; Houghton, 1974; Karsten, 2018; Novak et al., 2012; Spring et al., 1989). However, dimorphism in sulcus severity has been widely reported in both morphological studies (Houghton, 1974; Novak et al., 2012; Karsten, 2018; Canty, 2020) and metric studies (Andersen, 1986; Maass & Friedling, 2016; Praxmarer et al., 2020) - indicating an association between female sex and advanced preauricular sulcus development.

Houghton (1974) was the first to propose a focus on scar presentation on the ilia, analysing 119 unknown individuals. In doing so, Houghton identified the sulcus in 92% of females - 71% of whom presented with the more severe ‘groove of pregnancy’ (GP) sulcus, characterised by a deep, complex indentation. The remaining 21% had the less severe groove of ligament (GL) variation. 81% of males also exhibited a sulcus, although, when present, it was consistently categorised as the milder GL form (Houghton, 1974). Thus, it was concluded that while a severe sulcus is indicative of being biologically female, all other variations cannot be confidently used in the estimation of biological sex.

In 1975, Ullrich continued the investigation of the preauricular sulcus alongside the pubis (dorsal and ventral) and pubic tubercle, looking at individuals exhumed from a late Slavic cemetery. Unfortunately, this is the only study included in this review for which the full details were not accessible at the time of research, however it was retained due to its influence on later studies. This study involved the analysis of pelvic sections from 77 individuals (39 estimated males and 38 estimated females), including 49 sacra, 70 ilia, and 63 pubic bones (Ullrich, 1975). It is unclear if these were paired. According to Andersen (1969), Ullrich’s (1975) sample also included an undisclosed number of juvenile bones. Scarring at each site was categorised morphologically, with the lowest associated with an absence of scarring (presumed to indicate that an individual is either male or nulliparous female), and subsequent grades increasing with scar severity (Ullrich, 1975). It was concluded that the sulcus was one of two sites to be a reliable indicator of sex, presumed to relate to obstetric events in females (Ullrich, 1975), but this could not be verified nor quantified as part of the study due to the nature of an unknown sample (Andersen, 1969).

Noting these issues, Andersen (1986) utilised multiple measurements in a more comprehensive analysis of four pelvic scar features – including the preauricular sulcus – using 238 known adult individuals (151 females and 87 males). The sulcus was assessed using an adaptation of Houghton's (1974) method. This consisted of five categories grading scar presentation, with the first two associated with GL scarring and the latter three consistent with variations of the more severe GP scarring. Sulcus depth and length measurements were also recorded (Andersen, 1986). ~75% of both parous and nulliparous groups presented with severe preauricular scarring (Andersen, 1986). Andersen found that 22.3% of males did not show signs of a sulcus, compared to just 5.7% of females. An even smaller percentage of females (4.9%) presented with a mild sulcus presentation – leaving 89.4% with a significant sulcus (Andersen, 1986). This suggests that females are highly likely to have a preauricular sulcus, which is most likely significant in its presentation; however, the general presence of a sulcus is not specific to biological females (Andersen, 1986). Furthermore, males were far more likely to not present with any sulcus, meaning that sulcus absence would be likely indicative of an individual being male (Andersen, 1986).

In contrast, Spring et al. (1989) found advanced sulcus presentation in only 15.3% of females as part of their radiographic study of 300 known adults (190 females; 110 males). All individuals were over 17 years of age, and any with pelvic pathology were excluded (Spring et al., 1989). When grading sulcus appearance, a five-stage method was used, whereby stage 1 was defined as a significant sulcus of at least 1 cm across (posterior–anterior) and 0.5 cm perpendicular; stage 2 indicated a smaller sulcus; stage 3 indicated no sulcus; stages 4 and 5 related to any bony extension beyond the sciatic notch border - but still highlighted a lack of sulcus (Spring et al., 1989). While only 55 females (28.95%) had evidence of a typical sulcus (stage 1 or 2), the same was apparent in only 3 males (2.73%) (all stage 2), and only 15.3% of females presented with deep sulci. This highlights that, while Spring et al. (1989) found that a sulcus was rare in males, it was still not typical in females. Although, Spring et al.'s (1989) study is the only purely radiographic example, which may explain the lower sulcus occurrence in females compared to previous studies, as scarring is known to be more challenging to interpret radiographically (Young, 1940; Walker, 2005). Thus, sulcus presence was not deemed to be a sex indicator, although Spring et al. (1989) believed that a deep sulcus could accurately indicate that an individual is female.

Novak et al. (2012) conducted a study using a sample of 198 known-sex adults (97 males and 101 females) free from extreme pathology or displaying grossly atypical morphology. The sulcus was assessed using guidelines from Buikstra & Ubelaker (1994), with a score of 0 in the absence of a sulcus, 1 or 2 indicating a wide but shallow or deep sulcus, respectively, and 3 or 4 associated with a narrow sulcus but again – shallow or deep – respectively (Novak et al., 2012). Novak et al. (2012) found that 63.4% of females had a preauricular sulcus, while just 5% of males exhibited the same, leading to the same conclusion as Houghton (1974) and Spring et al. (1989), in that the simple presence or absence of a sulcus alone is not valuable in sex estimation. However, in further agreement with previous studies, there was a significant difference noted in severity classifications – with the 5% of males all having the mildest expression (shallow with imperfect formation), and all 63.4% of females presenting with sulci that were broad, deep, or a combination. In this case, a significant sulcus indicated that the individual was biologically female and vice-versa, thereby allowing Novak et al. (2012) to correctly sex 100% of individuals who presented with a sulcus. This led to an accuracy rate of 94.7% in the full original sample, although this was reduced to just 63.4% in the female sample, as the other 36.6% did not have any evidence of a sulcus (Novak et al., 2012).

In 2014, Gohil et al. utilised another small non-pathological known-sex sample of 27 males and 27 females drawn from a medical anatomy college collection. Taking a simpler approach than their predecessors, their analysis involved the basic assessment of each feature as either present or absent (Gohil et al., 2014). Through this, Gohil et al. (2014) identified a preauricular sulcus in almost 50% (48.14%) of males and 68.51% of females. This presented only a weak sex association and supported the general findings of other binary preauricular sulcus studies.

Two years later, Maass & Friedling (2016) presented a detailed analysis of the same four features observed by Andersen (1986), with additional pubic tubercle analysis. Their sample consisted of 312 non-pathological adult skeletal remains (128 females; 184 males) from one known donated collection and one forensic collection - the latter of which required osteological age and sex estimation (Maass & Friedling, 2016). The method of preauricular sulcus assessment was entirely novel (Maass & Friedling, 2016) – classed as follows: absent or broad-shallow (< 3 mm deep), narrow-shallow (3-5 mm deep), defined (> 5 mm deep; < 10 mm wide), or complex (> 5 mm deep; > 10 mm wide). Females more regularly presented with a preauricular sulcus, which was generally more severe (21.3% of female sulci were classed as defined and 30.7% as complex, versus 11.5% and 2.3% of males classed as defined or complex, respectively) (Maass & Friedling, 2016). Conversely, 48.3% of males had an absent or broad-shallow sulcus compared to 18.9% of females. However, by not separating absent and mild sulcus groups, these findings are difficult to directly compare to previous studies beyond the confirmation that preauricular scarring is generally more common and severe in females.

Karsten (2018) further considered preauricular sulcus variation within a large known-sex mixed sample (261 adult males; 239 adult females). For each of the 500 individuals in the sample, the preauricular sulcus was assessed using Buikstra & Ubelaker's (1994) categorical guidelines. Karsten (2018) observed 89.96% of females and 37.12% of males with evidence of a preauricular sulcus. Karsten further deduced that focusing on those without any sulcus and assuming they are biologically male produces an accuracy rate of 87.2%. Therefore, concurring with multiple previous studies, Karsten (2018) concluded that a lack of sulcus suggests that the individual is more likely to be male but that the existence of a sulcus should not be used to infer biological sex either way.

More recently, Canty (2020) developed and tested another novel method of preauricular sulcus analysis. Canty (2020) used adult samples from six different skeletal collections and one CT scan database previously created using living individuals - equating to 894 specimens. 159 individuals were from the two undocumented collections, thus requiring osteological age and sex estimation (Canty, 2020). All but one of the collections allowed for the consideration of scar dimorphism due to the inclusion of both sexes (n = 817), although the final sex distribution across all samples was not clear. Canty (2020) focused on non-metric sulcus depth, defining a five-category grading system, ranging from 0 (indicating sulcus absence) to 4. Grade 1 represents a slight and even indentation which may not be discernible by eye, while grade 2 sulci present with a subtle change in depth, causing an uneven floor. Grade 3 cannot be awarded unless multiple pits are present, and there may or may not be a smooth transition between these. The most significant grade was assigned in cases where the sulcus was very deep and highly pitted, with a rough surface texture (Canty, 20202) - similar to Houghton's (1974) definition of the GP sulcus. 22-51% of males across the samples (average 39.83%) were found to present with any form of sulcus, compared to an average of 88.5% of females across collection samples (Canty, 2020). The lowest percentage for females was found through scan analysis, indicating potential difficulty in discerning sulci through scan assessment alone. None of the males presented with grade 4 scarring, and a maximum of 1% of males presented with grade 3 in any of the six samples (Canty, 2020). Within four female samples, the highest percentage of each group was defined as grade 3, and for one group, grade 4. The only exception was the scan group, with the highest percentage of both sexes classed as group 0 or 1. These findings support those of previous studies, indicating significant dimorphism within scar presentation, with females more likely to present with more significant sulci (Canty, 2020).

Using Canty's (2020) method, Praxmarer et al. (2020) also investigated sulcus presentation alongside two other scar features in 167 estimated adult male and 129 estimated adult female non-pathological pelves from two archaeological collections. The sulcus was found to be one of two significantly dimorphic scar features, with presentation more severe in females in agreement with previous research. Grades 2 – 4 were most frequent in females, and just four females were void of any sulcus, while 0% of males displayed defined or complex examples (Praxmarer et al., 2020). 77.7% of female sulci were rugged, and 84.9% of males that presented with a sulcus (78.3%) had a smooth-floored variation (Praxmarer et al., 2020). These findings concur with those from Canty in the same year.

The most recent research including the analysis of the preauricular sulcus has been conducted by Waltenberger and colleagues (Waltenberger et al., 2021, 2022a, 2022b). Across all studies, the preauricular sulcus was analysed following methods established by Houghton (1974; 1975) and Cox (1989). Waltenberger et al.'s first study in 2022 used an anonymised adult CT sample to focus on age-dependent pelvic shape variation and scarring (2022a), enabling the investigation of sex-based differences. In this study, the sample included scans from 45 nulliparous, 45 primiparous, and 45 multiparous adult females – alongside a comparative sample of 45 adult males (Waltenberger et al., 2022a). Waltenberger et al. (2022a) observed a continuous change in female pelvic shape, and subsequently scarring, with age - with trajectory variation linked to the average periods of puberty and menopause. This will be discussed in detail in the discussion of scarring and age later in this review. However, there was less variation in the male sample, with limited changes to pelvic morphology and a very weak increase in scarring over time (Waltenberger et al., 2022a). Therefore, it could be concluded that more significant scarring would be likely in females, but that the cause may be hormonal or obstetric in nature.

Dorsal Pubic Pitting

Ullrich (1975) was the first to investigate the dimorphism of dorsal pubic pitting in his investigation of the pelvic bones from the late Slavic cemetery. Alongside the preauricular sulcus, this scar feature was identified as the most reliable indicator of sex, again presumed to relate to obstetric events (Ullrich, 1975). Following this, as part of Andersen's extensive (1986) study of 238 known-sex individuals, dorsal pubic pitting was assessed using an early method established by Stewart (1970), in which such is categorised as 'absent', 'trace to small', or 'medium to large'. Andersen (1986) adapted this to specify the classification of 'trace-small' pits as those that do not exceed 2 mm in diameter. Pitting was found in 51.3% to 56.7% of females, depending on parity status (Andersen, 1986). Meanwhile, just 2.4% of males had any evidence of pitting, and in all cases, pits were small (Andersen, 1986). Andersen (1986) adds that pubic pitting in females was more likely to be medium to large than trace to small (as was consistently observed in the small percentage of males), at least strengthening estimation potential where the feature is present.

Maass & Friedling (2016) also recorded dorsal pitting in a small percentage of males, resulting in a significant sex association. Maass & Friedling's study concentrated on the largest dorsal pit in each case, while following Andersen's (1986) method of categorisation. Pitting was noted in only 2.8% of males, although these cases were all classed as medium/large pitting. However, only 33.3% of females also presented with any pitting, and for either sex, no distinction between medium and large examples was offered. In support of this, McArthur et al. (2016) conducted a CT scan analysis on 359 living individuals, including 311 females and 48 males. Dorsal pubic scarring was assessed using the method first detailed by Ullrich (1975), with the primary aim of analysing pitting in association with obstetric data. However, a sex association was identified with pitting noted in 64.6% of females but complete absence in the male sample - further supporting conclusions from Andersen (1986).

Praxmarer et al. (2020) offered general support of previous pitting-based studies. In their study, pits were counted as single, double, or groove (combined pits), and the somewhat subjective method developed by Bergfelder & Herrmann's (1980) in the investigation of obstetric pitting variation, was further utilised. This grades pits as 0 (absent), 1 (barely perceptible), 2 (confidently perceptible), or 3 (prominent) (Bergfelder & Herrmann, 1980; McArthur et al., 2016). According to Praxmarer et al. (2020), females showed evidence of pitting significantly more often than males. 81% of the 100 female sample presented with some degree of pubic pitting, with 71% having two or more pits and 64.8% classed as confidently perceptible or prominent (Praxmarer et al., 2020). Over 75.7% of males had no perceptible pitting (with only 6.9% having two or more pits) and only 4.2% confidently perceptible but no prominent examples (Praxmarer et al., 2020).

In Waltenberger et al.'s (2022a) study, dorsal pitting was assessed following guidelines from Stewart (1970) and Ullrich (1975), with the addition of maximum height, width, and depth measures to facilitate approximate cubic calculations. As detailed in the discussion of preauricular sulcus presentation, scarring was found to be more significant in females than males but showed an increase over time with the potential for both hormonal and obstetric associations (Waltenberger et al., 2022a). Unfortunately, the full discussion of pelvic scarring was limited, providing no details for individual scar presentation. However, the general conclusion that dorsal pitting was more significant in females offers support to previous studies (Andersen, 1986; McArthur et al, 2016; Praxmarer et al., 2020).

Interosseous Groove

Early recognition of the interosseous groove by Houghton (1974) concluded that this feature was less significant in the estimation of biological sex, with most of the study focusing on the analysis of the preauricular sulcus. Nonetheless, a decade later, Işcan & Derrick (1984) returned to this scar feature, using a small mixed-sex sample of 27 modern forensic specimens (17 known males and 10 known females), including one thirteen-year-old male and two fifteen-year-old females. Unfortunately, this study does not explicitly detail the full analysis methods but does mention the inclusion of a basic depth measurement of the interosseous groove, aside from which a simple morphological categorical system was adopted. In this study, the postauricular space was found to be the most consistent measure of biological sex (Işcan & Derrick, 1984). However, focusing on pelvic scar features, the interosseous groove proved to be the most significant - observed in 90% of females, with an average depth of 2 mm. Conversely, this feature was only found in 5.9% of the male sample (depth unspecified) (Işcan & Derrick, 1984). This suggests that the presence of the interosseous groove is highly indicative of being biologically female and vice versa.

Just two years later, Andersen (1986) sought to investigate this proposed association as part of their study, categorising the interosseous groove based on general morphology, length, and depth. Unlike Işcan & Derrick (1984), no such association with sex was observed (Andersen, 1986). This was later further investigated by Gohil et al. (2014), in their small-scale study, through which they observed only a weak association between interosseous groove development and biological sex – again contradicting the earlier findings of Işcan & Derrick (1984). The study assessed the presence or absence of the groove and found it in 72.22% of females and nearly one-third of males (29.62%), illustrating a notable overlap between sexes and concluding that this scar feature is not appropriate as an indicator of sex.

Maass & Friedling (2016) identified a stronger association. Like their earlier sulcus analysis, Maass & Friedling's (2016) method of Interosseous groove analysis was novel. In this case, the interosseous groove was categorised as either shallow (< 3.0 mm deep; < 5.0 mm wide), moderate (> 3.0 mm deep; 5-10 mm wide), or developed (> 3.0 mm deep; > 10.0 mm wide). It was found that 90% of males presented with a shallow groove and only 3.3% had a developed groove (Maass & Friedling, 2016). This is compared to 56.7% of females presenting with a developed groove, and a further 15.9% with a moderate groove – leaving just 27.4% with shallow presentation. This suggests that a highly developed groove is strongly associated with females, while a shallow groove is more indicative of males. However, caution should be taken with the latter, as more than a quarter of females were found to share this groove type. Notably, Maass & Friedling's study did not include an 'absent' category, indicating that all 312 samples exhibited some evidence of an interosseous groove - an observation starkly contrasting with Gohil et al. (2014), who recorded absent grooving in a significant proportion of their sample.

Most recently, Mahadevappa & Shivalingaiah (2017) used a sample of complete pelves from 250 medical cadavers (120 males and 130 females – including 50 non-adults), for which it is assumed that biological sex and age were known. Groove assessment was straightforward, requiring only a record of presence and, if present, classification as ‘prominent’ or ‘less prominent’ (Mahadevappa & Shivalingaiah, 2017). However, it must be noted that no clear definition is provided for the severity categories in this study. Nonetheless, Mahadevappa & Shivalingaiah (2017) discovered groove absence in 83.3% of males, while it was present in the same percentage of females. Considering only prominent grooves, just 1.7% of males fall into this category, compared to 64.1% of females (Mahadevappa & Shivalingaiah, 2017). This suggests that an absence of an interosseous groove is more commonly associated with being biologically male, but a prominent groove indicates the individual is biologically female. These findings are most representative of Işcan & Derrick’s (1984) results while enhancing previous results presented by Gohil et al. (2014) and Maass & Friedling (2016).

Pubic Tubercle and Iliac Tuberosity

Pubic tubercle extension was not formally investigated in association with biological sex again until Maass & Friedling’s (2016) study, in which the tubercle was classified based on the extension beyond the ventral surface of the pubis as follows: small = < 1.0 mm, medium = 1.0 mm – 3.0 mm, or large = > 3.0 mm. This analysis revealed that most individuals fell into the intermediate category (females = 66.7%; males =79.2%), but only 6.4% of females presented with a prominent tubercle while just 7.3% of males had evidence of a smaller tubercle (Maass & Friedling, 2016). This means that individuals with smaller tubercles are more likely to be female, and vice versa; however, with the majority of individuals presenting with tubercles between 1.0 mm and 3.0 mm, tubercle assessment would not be appropriate for the estimation of sex overall. Although, utilising the same analysis method, Praxmarer et al. (2020) found that a considerable 50% of males did not present with any tubercle extension alongside 14.9% of females, while 21.4% of male tubercles and 11.1% of female tubercles were classified as small. In the case of medium and large classifications, the percentage of females were higher than males – with a considerable 62.9% of females and a further 24.1% of males presenting with a medium tubercle versus 11.1% and 7.2% with a large (Praxmarer et al., 2020). This provides an opposing conclusion to that established by Maass & Friedling (2016).

Regarding the iliac tuberosity, and Işcan & Derrick (1984) were the first to consider dimorphism. Işcan & Derrick (1984) described four categories: absent, a fossa without bony prominence, a pointed crest, or a mound. The latter was consistently observing in all 17 males, while 5 females presented as absent and the other 5 as either a fossa or pointed crest (Işcan & Derrick,1984). This enabled the confident determination of biological sex, albeit in a very small sample. In contradiction to this, Andersen (1986) failed to observe an association between iliac tuberosity extension and biological sex, despite using the same method as Işcan & Derrick (1984). It was not until 2014, when Gohil et al. conducted further analysis – recording absence of this feature in 31.49% of females, indicating a lower rate than Işcan &

Derrick (1984). However, Gohil et al. (2014) also noted an absence in 9.26% of males. This resulted in only a weak association between tuberosity extension absence and female sex. Maass & Friedling (2016) provided the most recent analysis of this feature, following Andersen's (1986) guidance with additional categorical measurements as follows: extension absence (< 20 mm), moderate extension (20-25 mm), and significant extension (> 25 mm). No significant association between tuberosity extension and biological sex was identified, concurring with Andersen's findings 30 years prior.

Accumulative Scar Analysis

While detailed discussion of individual features in Andersen's (1986) study focused on dorsal pubic and preauricular scarring, the occurrence of these features was considered alongside that of the interosseous groove in a cumulative approach to predicting sex and obstetric events. Resultantly, Andersen (1986) was able to emphasise sex differences based on feature combination frequencies, identifying that 72.4% of females presented with two to three features to some degree, and just 7% of females did not present with any of the three features. Meanwhile, just 5.7% of males had more than one of the three features, with a considerable 65.43% absent of all scars. Thus, it is possible to associate an absence of any scarring with males and the presence of all features with females – although many individuals would fall within the intermediate range, where sex estimation would become less accurate.

More recently, Gohil et al. (2014) found the accumulative analysis of the number of pelvic features (tubercle extension, interosseous groove, preauricular sulcus) to better indicate biological sex than the analysis of individual scar presence. This analysis also included consideration of the postauricular space, with a broader area classed as 'present' in the binary assessment. In males, 1.85% were absent of all features, 12.96% had just one feature, 37.04% presented with two, 46.3% with three, and just 1.85% with all four (Gohil et al., 2014). In the female sample, one individual (again, accounting for 1.85%) presented without any of the four features, 7.4% had just one feature, 24.07% had two, 44.44% had three features, and 22.22% had all four (Gohil et al., 2014). Therefore, males were more likely to have one or two of the four features, while females were more likely to have all four.

3.2. Obstetric Events

The concept that the pelvis of a biological female can reveal their pregnancy and childbirth history (gravidity and parity) was first introduced by Hippocrates in the 4th century BC (Gharib & Aglan, 2018). This has since been the focus of many medical, forensic, and archaeological studies. In an osteological context, it was first theorised that evidence of bony scarring across multiple pelvic sites might arise due to obstetric events as an explanation for the early observation of scar feature dimorphism (Angel, 1969; Stewart, 1970; Houghton, 1974; Ullrich, 1975). Since then, obstetric factors have remained a frequent consideration in pelvic scar analysis. This subsection explores the hormonal and physical changes associated with pregnancy and birth and how these could potentially result in pelvic scarring, before highlighting the general findings drawn from relevant research.

3.2.1. Pregnancy Hormones and the Pelvis

Progesterone, oestrogen, and relaxin are all crucial hormones associated with obstetric processes (Kumar & Magon, 2012). These hormones facilitate pelvic adaptations during pregnancy and birth by promoting ligament laxity, joint widening, and increased mechanical flexibility to accommodate foetal growth and delivery (Houghton, 1974; Anderson, 1986; Kumar & Magon, 2012). Relaxin, in particular, has been shown to contribute to the loosening of the sacroiliac and pubic symphysis joints, which, in combination with mechanical stresses, may result in scar feature development (Waltenberger et al., 2022a). According to obstetric scar theory, these hormonally driven adaptations, while critical for gravidity and parturition, may manifest as observable pelvic scarring over time.

Progesterone levels reach up to thirty times that of a non-pregnant female (Suresh & Radfar, 2004) - peaking during the first ten weeks, and again from the 32nd week of pregnancy. Progesterone is primarily responsible for successful embryo implantation and preventing premature foetal rejection (Kumar & Magon, 2012). More importantly, it stimulates osteoblastic growth and enhances bone formation (Cable & Grider, 2023) while strengthening the pelvic floor muscles until birth (Kuzmar, 2021). Oestrogen has been found to increase tenfold during pregnancy (Suresh & Radfar, 2004) and is fundamental for foetal development from a very early stage. Kuzmar (2021) also explains that oestrogen softens crucial ligaments while, at the same time, suppressing bone resorption by reducing osteoclastic activity (Ott, 2008).

The third hormone, relaxin, is a pregnancy-specific hormone crucial in repairing ligaments and muscle tissue, as well as regulating bone metabolism in pregnancy by increasing osteoclastic activity, which is reduced by the other two primary pregnancy hormones (Dehghan et al., 2014). Studies show that relaxin is mainly responsible for the widespread skeletal laxity of the mother during pregnancy and birth by activating collagenase to soften cartilage, ligaments, and tendons (Dehghan et al., 2014; Mitteroecker & Fischer, 2022), and is thus implicated in commonly associated musculoskeletal changes (Sneag & Bendo, 2007; Talbot & Maclennan, 2016). Gharib & Aglan (2018) state that the degree of laxity can even be so significant that it results in biomechanical changes which may or may not be symmetrical. However, without these hormones, the mother's body would not be able to respond to foetal growth appropriately – nor give birth without caesarean intervention (Mitteroecker & Fischer, 2022).

3.2.2. Foetal Growth and Musculoskeletal Stress

Research suggests that the increase in musculoskeletal strain in the latter stage of pregnancy can be directly related to the growth of the foetus itself (MacEvilly & Buggy, 1996; Talbot & Maclennan, 2016; Gharib & Aglan, 2018). This coincides with an increase in skeletal load-bearing, postural changes in the mother, and stress on the associated muscles and their attachment sites (MacEvilly & Buggy, 1996; Talbot & Maclennan, 2016; Gharib & Aglan, 2018). The abdominal and pelvic floor muscles undergo considerable strain as the foetus grows - particularly towards the third trimester (Theodorsen et al., 2019; Veljovic et al., 2019), despite increased tendinous laxity (Maass, 2012). This is further exacerbated by foetal weight (Wesnes & Seim, 2020; Zhu et al., 2023). Significant stress on muscles is often evident at the attachment and insertion points of the bones, known as entheses (Villotte & Knusel, 2013), and this is where the potential to see physical evidence of this on the pelvis becomes apparent.

Several muscles are of particular interest when discussing changes during pregnancy and pelvic scarring, including the rectus abdominis, external abdominal obliques, transversus abdominis, and pelvic floor muscles (Gilleard & Brown, 1996; Calais-Germain, 2003). The levator ani, or pelvic floor, forms the thick basin-shaped support for the visceral pelvic contents and the foetus during pregnancy (Netter, 2017; Theodorsen et al., 2019). These muscles therefore need to be particularly strong and attach at multiple sites around the pelvic inlet, one of which is the dorsal surface of the pubis (Netter, 2017; Theodorsen et al., 2019). Theodorsen et al. (2019) explain that this muscular structure and the associated tendons become strained as the weight load increases during pregnancy. Additionally, the external obliques attach to the pubic tubercle, while the transversus abdominus inserts into the pubic crest and pectineal line of the pubis (Netter, 2017). With the muscle fibres running medially, both undergo significant strain by the peak of pregnancy when the abdominal diameter increases (Gilleard & Brown, 1996).

However, the rectus abdominis muscle - originating at the pubic symphysis and pubic crest - is the muscle most frequently observed in obstetric research, as it succumbs to the most physical stress during pregnancy (Gilleard & Brown, 1996; Coldron et al., 2008; Opala-Berdzik & Dăbrowski, 2009; Theodorsen et al., 2019). The rectus abdominis length increases dramatically as the foetus grows (Gilleard & Brown, 1996). As this muscle stretches vertically, alterations can be observed as a lateral separation of the abdominus muscles (Gilleard & Brown, 1996), facilitated by softening of the linea alba (Coldron et al., 2008). As a result, areas around the pubis are of particular interest when estimating gravidity history, especially considering that this area also serves as an attachment site for the pelvic floor and transversus abdominus muscles.

Pelvic girdle stability is primarily maintained by the pubic joint anteriorly and the robust sacroiliac joints posteriorly (Cunningham et al., 2016). However, when the associated ligaments soften during pregnancy, these joints become unstable, altering the attachment angle and resulting in microtrauma and joint inflammation (Fiani et al., 2021; Pany-Kucera et al., 2021). Damen et al. (2001) and Fiani et al. (2021) suggest that this is worsened by increased abdominal volume and weight, and resultant postural changes – leading to significant joint dysfunction. Later stages of pregnancy can cause considerable strain on the ligaments of the ordinarily inflexible sacroiliac joint, particularly with pregnancy-induced laxity facilitating uterine shift and causing increased pressure on the lower back and posterior pelvis (Ritchie, 2003). This can promote the widening of the sacroiliac joint during pregnancy by up to 4mm (Garagiola et al., 1989). Houghton (1974) and Maass (2012) detail the ligament remodelling and repair process with a postpartum reduction in relaxin levels, returning to their pre-pregnancy state just a few months after the event. However, Houghton (1975) highlights that areas of cortical bone remodelling associated with pregnancy-related ligament changes can take many years to reverse.

In fact, the cumulative impact of musculoskeletal strain, ligamentous laxity, and biomechanical adjustments during pregnancy not only influences immediate physical adaptations but can also manifest as clinical symptoms, particularly in the later stages of gestation. These physiological demands often contribute to significant discomfort and pain, underscoring the complex interplay between anatomical changes and maternal health outcomes. In this context, research highlights that posterior pelvic pain (PPP) incidence is particularly high in the last trimester of pregnancy, with approximately 22% of women affected, of which 5-8% classify their pain as severe (Daly et al., 1991; McIntyre & Broadhurst, 1996). More recent studies report that a significant percentage of pregnant women experience general pelvic girdle pain, which often continues postpartum (Wu et al., 2004; Kovacs et al., 2012; Kesikburun et al., 2018). The aetiology of pregnancy-induced pelvic pain is complex and generally considered to be multifactorial, involving factors such as pre-existing pelvic asymmetry, biomechanical abnormalities, musculoskeletal strain, and general pelvic laxity due to pregnancy hormones (Smith et al., 2008; Keriakos et al., 2011; Gharib & Aglan, 2018).

3.2.3. Parity and Pelvic Trauma

Ligament tension at the anterior and posterior pelvis further increases during the birthing process due to the pelvic expansion required for successful vaginal delivery (Dehghan et al., 2014; Fiani et al., 2021), which involves diastasis of the joints (Morino et al., 2019). This is particularly pronounced at the pubis, which can result in traumatic pelvic distortion through joint rupture (Morino et al., 2019; Seidman et al., 2019). Seidman et al. (2019) state that pubis separation exceeding just 1 cm can be skeletally significant. Posteriorly, sacroiliac joint nutation occurs during the late stages of labour (Kiapour et al., 2020), when the superior end of the sacrum shifts anteriorly and the coccyx shifts posteriorly, opening the pelvic outlet. This exacerbates sacral tension already exerted during pregnancy (Pany-Kucera et al., 2019). This tension is most considerable during the first pregnancy and birth, with research indicating an increase in hormone-induced joint laxity (and resultant reduced tension) from the second pregnancy onwards (Calguneri et al., 1982). However, Williams (1995) explains that persistent sacroiliac malalignment can occur when ligaments tighten as hormones return to pre-pregnancy levels – which could produce a permanent state of sacroiliac ligament tension.

The levator ani muscle must adapt and stretch remarkably during the expulsion phase of the delivery process (Ashton-Miller & DeLancey, 2007, 2009; Rostaminia et al., 2016; Shek & Dietz, 2019). This robust muscle can stretch by a factor of up to 3.3 (Rostaminia et al., 2016; Shek & Dietz, 2019), which extends far beyond the standard stretch ratio threshold for striated skeletal muscle of 1.5 (Ashton-Miller & DeLancey, 2009; Rostaminia et al., 2016; Shek & Dietz, 2019). Distension of the levator ani is often so extreme that it causes significant strain on the muscle-bone interface and frequently leads to tearing of the muscle tissue (Shek & Dietz, 2019). Shek & Dietz (2019) even observed detachment of the puborectalis, which lies centrally within the levator ani, in one-third of primiparous women. This is statistically influenced by the frequent use of instruments to aid newborn extraction (Shek & Dietz, 2019).

3.2.4. Summary of the Obstetric Theory

The obstetric theory of pelvic scar causation centres on the significant hormonal and biomechanical adaptations that occur during pregnancy and childbirth. Pregnancy-specific hormones (primarily progesterone, oestrogen, and relaxin) facilitate necessary pelvic flexibility and ligamentous laxity, enabling foetal growth and birth. However, these hormonal effects, particularly when combined with increased musculoskeletal strain in late pregnancy, may contribute to pelvic scarring through microtrauma and bone remodelling (Waltenberger et al., 2022a; Maass, 2012). From a biomechanical perspective, the physical demands of foetal growth place substantial strain on the pelvic floor and associated muscles, particularly at their entheseal attachment points. The expulsion phase of childbirth further exacerbates this strain, often leading to significant trauma at the muscle-bone interface and, in severe cases, ligament rupture and joint diastasis (Shek & Dietz, 2019; Morino et al., 2019).

This theoretical framework suggests that the cumulative impact of hormonal modulation, mechanical stress, and pregnancy and birth-related trauma could result in observable osteological changes. It provides a basis for interpreting pelvic scarring as a potential indicator of obstetric history, guiding subsequent research into the relationship between pregnancy, childbirth, and skeletal markers. The following section reviews the primary osteological studies which have assessed this relationship to date.

3.2.5. Obstetric Events and Pelvic Scarring

The relationship between obstetric events and pelvic scarring has been a topic of considerable interest and debate over recent decades and can be seen to be the main focus of key osteological scar studies until the early 21st century. Early interpretations suggest pelvic scarring to be a reliable indicator of obstetric history, with scarring patterns believed to reflect the physiological changes primarily associated with childbirth; however, some fundamental studies have questioned this, presenting inconsistencies and complexities in aetiological association (Stewart, 1970; Houghton, 1974; Holt, 1978; Kelley, 1979; Suchey et al., 1979; Andersen, 1986; Spring et al., 1989; Cox & Scott, 1992; Snodgrass & Galloway, 2003; McArthur et al., 2016; Igarashi et al., 2019; Canty, 2020; Waltenberger et al., 2022a; 2022b).

Dorsal Pubic Pitting

Dorsal pubic pitting analysis dominated pre-21st century obstetric scar research. Early rudimentary studies from Stewart (1970) and Holt (1978) were based on the theory of a direct correlation between dorsal pubic pits and parturition. Stewart's (1970) research was the first to propose the term 'scars of parturition' when discussing scar features. This study involved the graded morphological analysis of the dorsal pubic surface of 170 known-sex females for which obstetric history was undetermined, with pitting assessed as either 'absent', 'trace to small', or 'medium to large' (Stewart, 1970). Interestingly, Stewart (1970) found that just 50% of the female sample presented with any degree of pitting at all, with significant examples observed in only 17%. It was concluded that it would be improbable that 50% of the entire female sample had never given birth, and thus, Stewart (1970) recommended caution in linking scarring and parturition.

Utilising the same methodology as Stewart (1970), Holt (1978) conducted a study including just 68 known biological females; however, this study was the first for which both biological sex and parity status for all individuals were recorded. Holt (1978) explains that birth history was previously garnered based on soft tissue analysis and medical records. Thus, obstetric history was confidently ascertained, and details of pregnancy (gravidity) and birth were included, although pregnancy in the absence of natural birth (caesarean section) was not investigated separately. Holt acknowledged that errors may still have been possible, especially in cases of less certain obstetric status, for examples, where such was assigned from soft tissue observations alone. Holt (1978) presented findings as the percentage of individuals falling into each scar category, but did not specify the number of females belonging to each parity group. This can make result interpretation difficult, but upon discussion, Holt (1978) explains that scarring was found in nulliparous individuals - and conversely, some gravid or parous females had no evidence of scarring at all. Additionally, there was little difference in scar severity across obstetric groups (Holt, 1978). This reinforces the question of whether pubic scarring is, in fact, the result of pregnancy or the vaginal birthing process at all.

A study by Kelley (1979) focused on both dorsal pubic pitting and scarring around the auricular surface. Additional features were considered but subsequently discounted due to statistical insignificance. Kelley (1979) utilised a sample of 198 adult known females from the same collection used by Holt (1978) but decided to include only those for which parity status was confidently assessed as either "certainly has" or "certainly has not" had children, to limit possible obstetric grouping errors. Once again, this meant that this sample included females with a positive gravidity history, although they may not have given birth naturally (making them nulliparous). Unfortunately, this was not specified. Kelley's dorsal pitting analysis followed the method previously outlined by Stewart (1970) without adaptation. Moderate-severe dorsal pitting was observed in just 1% of nulliparous females and only 20.9% of the alternate group. Slight pitting was found in a comparable percentage of both groups (~23%), meaning that a larger percentage of nulliparous than parous females presented without any pitting (76.6% and 56%, respectively). This suggests that while it may be possible to confirm pregnancy occurrence in those with particularly severe pitting, parity status cannot be estimated otherwise.

Suchey et al. (1979) conducted an extensive study using 486 known females from a contemporary autopsied sample, focusing only on dorsal scarring. Suchey and colleagues benefitted from access to obstetric data - including number of births and offspring, as well as the spacing between each or since the last birth. In each case, this information was provided by friends or family of the deceased (Suchey et al., 1979). Using the Stewart (1970) method, Suchey et al. (1979) indicated that pitting was strongly associated with pregnancy and birth, with 93.5% of positive cases presenting with dorsal changes. However, 73.65% of nulligravid females did also, thereby reducing its value in estimating obstetric event occurrence based on presence alone. Suchey et al. (1979) did not indicate further significance when isolating pit grades between positive and negative groups. Still, they did find a statistically significant but weak association between pitting severity and the number of births, with 17 nulligravid females presenting with moderate to severe scarring, but just 22 of 302 gravid females (who experienced between one and five pregnancies) presented with the same. The remaining 36 gravid females, who all experienced more than five pregnancies, exclusively presented with pitting. Overall, this indicates that females who experience full-term pregnancy are likely to present with pitting, becoming highly likely if they have six or more separate pregnancies – but feature presence cannot prove that the female has at any point been pregnant. Furthermore, when considering pregnancy interval, Suchey et al. (1979) noted that females were more likely to have extensive pitting if their last pregnancy was over 15 years previously.

Andersen (1986), as the first to utilise multiple measurements in the analysis of four pelvic scar features, included 151 adult females in their study for whom obstetric history was determined through record consultation. But, unlike in Kelley's (1979) study using the same skeletal collection, 'probable' obstetric grouping was included. Analysed using the same method used to assess the dimorphic presentation of dorsal pubic pitting, Andersen (1986) found pitting in 51.3% of women who had been classified as probably or definitely had never been pregnant – almost 60% of which were moderate to severe examples. However, just 56.7% of the opposing group presented with pitting to any degree, highlighting no significant association between dorsal pitting and obstetric events.

Cox & Scott (1992) presented key findings following the research undertaken by Cox in 1989. This research focused on the variation of three scar sites including the dorsal pubis using a sample of 138 known females identified through associated coffin plates. The sample included 94 females with personal records, including the number of children borne by them, their dates of birth, and, subsequently, the spacing between each birth (Cox & Scott, 1992). Only individuals for whom the obstetric history could be confidently deduced were included in the study of obstetric variables. Pitting was scored in terms of presence and pit count, through which it was deduced that neither pubic pitting occurrence nor severity was significantly associated with parity. Pitting was present in 33.33% of nulliparous females (3 of 9) – of which all cases were single pit examples - but it was also present in just 40% of parous females (62.5% of which were single pit, 18.75% double pit, and just 18.75% 3-4 pit).

In 2003, Snodgrass and Galloway conducted a study using the pelves of 148 known modern females using a randomly selected subsection of Suchey et al.'s (1979) investigation sample, for which relatives of each decedent had provided parity information. Snodgrass and Galloway (2003) used Ullrich's (1975) classification system to record pitting, observing a strong positive correlation between pitting and the number of births, but only for individuals up to 50 years old. In individuals over 50 years old at the time of death, 22% of those with pitting were nulliparous, which subsequently diminished the significance between parity groups (Snodgrass & Galloway, 2003). Overall, despite some positive results, Snodgrass and Galloway (2003) were forced to describe skeletal obstetric indicators as "highly desirable yet elusive" (p. 1226), stating that pelvic scarring cannot determine parity accurately enough – at least for forensic applications (Snodgrass & Galloway, 2003).

It was not until over a decade later that McArthur et al. (2016) conducted a CT scan analysis on 311 living females with known vaginal birth data, again using the method established by Ullrich (1975). Data was collected directly from the study participants, with the number of births categorised as 'none', 'one', or 'two or more'. There was found to be a significant statistical association with vaginal birth – with 194 cases of scarring among the 262 females recorded as having given birth vaginally, equating to 74.05% (McArthur et al., 2016). Although, of the small number of females (49) who had not given birth, 14.29% also exhibited pelvic scarring; however, there was no detail as to whether these were cases of pregnancy termination, caesarean cases, or completely unrelated to any aspect of pregnancy. Contradictory to previous studies, McArthur et al. (2016) highlight that pitting severity and number of births were not significantly correlated.

Waltenberger et al. (2021) investigated dorsal pubic scarring and other scar features associated with pelvis size and shape, involving the analysis of 73 adult pelves from two archaeological collections (Waltenberger et al., 2021). 19 individuals (12 males and 7 females) were from an unknown collection. The remaining 27 male and 27 female pelves were from a collection for which basic biological data was known (Waltenberger et al., 2021). In assessing dorsal scarring, Waltenberger et al. (2021) adapted methods from Stewart (1970) and Ullrich (1975). While this study did not seek to directly analyse scarring in association with obstetrics, it did facilitate indirect inferences. Waltenberger et al. (2021) observed an inverse relationship between pelvic size and general pelvic scarring in females only, leading to the conclusion that scarring is associated with obstetric events – putting more strain on smaller female pelves.

Waltenberger et al. (2022b) most recently sought to confirm this relationship using the same anonymised CT sample and scar analysis method as used in the Waltenberger et al. (2022a) study. The scan repository included information on the number of pregnancies and births, obtained through a combination of a consultation with medical examiner records and decedent interviews (Waltenberger et al., 2022b). This study used a sample including scans from 45 nulliparous, 45 primiparous, and 45 multiparous adult females, alongside a sample of 15 juveniles (Waltenberger et al., 2022b). Waltenberger et al. (2022b) found a significant relationship between dorsal pitting severity and obstetric events, only – Although this feature was present in just 27% of the sample. Nonetheless, this refutes the general conclusions drawn from the Waltenberger et al. (2021) study. Still, when utilising pitting expression as the geometric mean of all three pitting measures, the predictive potential was low for single individuals (Waltenberger et al., 2022b). Due to a lack of significance noted with all other scar features, it was concluded that dorsal pitting is the only 'true' parturition scar but that pit measurements should only be used in the assessment of average group gravidity or parity count for a population with the consideration of age across the sample (Waltenberger et al., 2022b).

Preauricular Sulcus

The preauricular sulcus has been extensively examined as an indicator of obstetric history. The early study by Houghton (1974) observed a notable association between sulcus development and parity. Houghton recorded sulcus presence in 92% of females, with the severe GP sulcus occurring in 71% of parous females, suggesting an obstetric association. However, these studies assumed parity status, which has prompted later caution regarding their reliability. Following Houghton's (1974) method, Kelley (1979) observed mild presentation in over 50% of the females without a positive pregnancy history versus just 20.9% of parous females. On the other hand, a highly developed sulcus was noted in twice as many parous females (43.9%). However, this was also present in 20.6% of nulligravid/nulliparous females (Kelley, 1979), reducing its value as an obstetric indicator. Interestingly, there was no inclusion of an absent category for this feature, suggesting that all females presented with some degree of sulcus cavitation.

In Andersen's (1986) study, the results for the preauricular sulcus were similar across female obstetric groups, with ~75% of both presenting with severe preauricular scarring and less than 6% having none (Andersen, 1986). An even smaller percentage of females (4.9%) presented with a mild sulcus presentation – leaving 89.4% with a significant sulcus indentation (Andersen, 1986). This suggests that females are highly likely to have a preauricular sulcus, which is most likely significant in its presentation – regardless of obstetric history. Similarly, Spring et al. (1989) deduced that the severity of the sulcus could not be used as an indicator of positive pregnancy history, at least through radiographic assessment, with just 25 (17%) parous and 4 (10%) nulliparous females presenting with well-defined sulci (stage 1). Spring et al. (1989) conducted an additional analysis using x-rays taken from six females pre- and post-pregnancy, through which they observed no changes, thereby further validating their conclusion.

Cox & Scott (1992) also analysed the preauricular sulcus with reference to historical obstetric data. Sulci were graded 1-4, with the first two grades corresponding with Houghton's (1974) classifications (GL and GP) – the third and fourth grades corresponded with those defined by Dunlap (1981) and Derry (1909), respectively. Maximum length and width were also recorded for this feature (Cox &

Scott, 1992). According to Cox & Scott, complete absence of this scar was observed in 22.2% of nulliparous and 9.5% of parous females. Grades 1 – 3 were found across both nulliparous and parous groups, with only two parous cases identified as the most severe type. Furthermore, mean sulcus length and width were not significantly different between obstetric groups (Cox & Scott, 1992). Subsequently, it was concluded that there were no significant differences between obstetric groups for sulcus presence, type, or measurements – supporting Andersen (1986) and Spring et al. (1989).

More recently, Igarashi et al. (2019) conducted a rigorous investigation focused on scarring of the preauricular area, using a sample of 233 known adult female cadavers donated to medical universities. Highly detailed obstetric information was later obtained from relatives for 90 individuals - including the number of pregnancies and births, the type of birth (caesarean, assisted natural birth, unassisted natural birth), and even the length or difficulty of each birth (Igarashi et al., 2019). Igarashi et al. (2019) identified five distinct non-metric categories based on severity, considering depression depth, margin description, and the inclusion of sub-pitting within the sulcus. Types four and five were classed as the most severe, observed in only females within the larger 'early-modern' sample used in developing the method, while types one through three were found in both sexes (Igarashi et al., 2019). Igarashi et al. (2019) found that 90% of modern females presented with scarring indicative of positive obstetric history (types 4 or 5) – with 65.15% of those falling into the less-severe of the two. When considering correlations with known pregnancies and births, a further score system was established, with 0 assigned where scar types 1-3 were observed (indicating no obstetric history), 1 related to type 4 scarring, and 2 to the most severe scar type (Igarashi et al., 2019). It was determined that individuals without scarring had never been pregnant or given birth, minimal obstetric-related scarring (combined score 1-2) indicated a low incidence of births or pregnancies, and considerable scarring (combined score 3-4) could be associated with a higher number of obstetric events (Igarashi et al., 2019). Reversing the result pattern evident in many previous studies, this method correctly identified the 4 nulliparous females, misidentifying just 11.63% of parous individuals as otherwise. Further analyses indicated that considerable scar scores were distributed across larger pregnancy and birth values (Igarashi et al., 2019).

Canty's (2020) research halts the trend identified by Igarashi et al. (2019). Canty's (2020) analysis enabled obstetric group assessment using three collections, including two historical samples and one CT scan repository (n = 158). Obstetric information for the two skeletal samples was obtained through consultation with historical records, while data accompanying the scan sample was previously acquired through direct patient interviews (Canty, 2020). No significant difference in scar presentation was observed between parity groups (Canty, 2020), with the most substantial difference between parous and nulliparous females in any of the three samples being 10%. Therefore, the overall findings suggest that preauricular sulcus development may be more significant in females, but obstetric events do not likely influence the presentation (Canty, 2020). In agreement, Waltenberger et al. (2022b) failed to identify any association between preauricular scarring and obstetric events according to methods developed by Houghton (1974;1975) and Cox (1989). In this study, a sulcus was identified in 93.7% of all females, regardless of parity status – with no further association between parity and scar severity. To reiterate earlier observations, this opposes the inference of a potential obstetric-scar relationship highlighted by Waltenberger et al. (2021).

Interosseous Groove, Pubic Tubercle and Iliac Tuberosity

Kelley's (1979) study further included the analysis of the post-auricular interosseous groove. Kelley (1979) found that nulligravid females were less likely to have an interosseous groove, with a prevalence of 67.3%; slight or moderate grooving was found in 15.9% and 16.8% of the remainder of the group, respectively. Meanwhile, similar percentages of the gravid sample fell into each of the three interosseous categories (31.9% – 36.2%) (Kelley, 1979). These results follow a similar pattern to that observed by Kelley regarding the preauricular sulcus, thereby refuting an obstetric-scar association. Offering agreement, Andersen (1986) did not identify an association between obstetric events and the interosseous groove leading to the exclusion of detailed results from their discussion, although this scar feature was included in their accumulative analysis.

Cox & Scott (1992) identified a significant positive correlation between tubercle extension and not only parity occurrence, but also parity count. In this study, extension was first identified as present or absent and then graded according to Bergfelder & Herrmann (1980) as appropriate. Within the nulliparous females, 33.33% had any extension, accounting for just 12.5% of the full female sample that presented with such (cox & Scott, 1992). Furthermore, while nulliparous females represent a more significant percentage of extension grades 1 and 2, the more severe grade 3 was attributed to parous females only (Cox & Scott, 1992). The grade was found to be significantly associated with the number of births, with those with the most advanced grade having a median parity count of five (Cox & Scott, 1992). However, later studies failed to replicate these findings. In Snodgrass & Galloway's (2003) research, using the same grading method as Cox & Scott (1992), absolutely no correlation with extension severity was found. Waltenberger et al. (2022b) later utilised a simple present/absent method following suggestions from Maass (2012) and Pany-Kucera et al. (2019) – but again, failed to identify of infer any relationship between extension and obstetric events.

Finally, Andersen (1986) conducted the only research covered in this review which also analysed potential iliac tuberosity alterations in response to obstetric events. Similar to previously highlighted findings, no association was noted nor discussed (Andersen, 1986). Notably, this feature was also excluded from any accumulative scar investigations.

Accumulative Scar Analysis

In addition to the investigation of single-scar obstetric relationships, Kelley (1979), Andersen (1986), and Waltenberger et al. (2021) all conducted analysis of simultaneous scar features. Kelley (1979) concluded that no single scar feature could provide sufficiently reliable indication of obstetric history. However, increased estimation accuracy was obtained with the combined consideration of the occurrence and severity of dorsal pitting, the preauricular sulcus, and the interosseous groove. With each categorised as 'absent', 'trace', or 'present', Kelley (1979) devised an estimation table where an absence of two or more features, or the absence of one where both others are trace, indicates nulliparity. All alternative combinations indicate positive parity history (Kelley, 1979). This led to an 80.37% accuracy in identifying nulliparous females, but only a 58.24% accuracy for parous female identification. This method demonstrates reasonable accuracy in identifying nulliparous females; however, it misclassifies a significant proportion of parous females. Kelley (1979) also contends that the approach is particularly effective in identifying multiparous females, as those exhibiting two or more definitive scar features; although no specific supporting data was provided to substantiate this claim.

Andersen (1986) adapted Kelley's (1979) approach using the same scar features. Andersen introduced an intermediate zone. This includes the consistent trace grouping, two trace and one present, or one of each (present, trace, absent) (Andersen, 1986). The lower boundary includes all groupings where two or more features are present, appearing to separate groups efficient in identifying multipara females as claimed by Kelley (1979). Focusing on those females for which obstetric history was definite, Andersen observed a reduction in accuracy compared to Kelley (1979). Only 35.71% of nulliparous females were correctly identified, alongside 26.32% of parous females (Andersen, 1986). Within the areas of the table seeking to identify parous females, resided 42.9% of the nulliparous group and 47.37% of the parous group (Andersen, 1986). This highlights a considerable lack of distinction between obstetric groups based on this accumulative assessment, emphasising that observed by Kelley (1979).

Most recently, in the investigation of scarring and pelvic shape, Waltenberger et al. (2021) note that regression analysis presented interesting results for the combined analysis of the preauricular sulcus and corresponding grooving on the sacrum less frequently assessed in scar studies. Waltenberger et al., (2021) found there to be a weaker scar expression in females with more typical gynaecoid pelves compared to more android pelves. This further supports the theory of a link to obstetric events, with more strain placed on a less well-adapted, narrower, android pelvis – resulting in more significant pelvic scarring (Waltenberger et al., 2021).

3.3. Additional Biological Factors

Many examples of osteological pelvic scar research consider the influence of age (Stewart, 1970; Kelley, 1979; Suchey et al., 1979; Andersen, 1986; Spring et al., 1989; Cox & Scott, 1992; Snodgrass & Galloway, 2003; Maass & Friedling, 2016; Mahadevappa & Shivalingaiah, 2017; Karsten, 2018; Igarashi et al., 2019; Canty, 2020; Praxmarer et al., 2020; Waltenberger et al., 2021;2022a;2022b), with a small number of those further investigating any association between scar presentation and body size or mass (Snodgrass & Galloway, 2003; Canty, 2020; Praxmarer et al., 2020; Waltenberger et al., 2021;2022b). This section first reviews how increasing age may influence scar feature presentation, focusing on the two main reproductive hormones and how reductions in these during the ageing process might affect pelvic structures and scarring. This is followed by a review of body size and mass as further potentially causational or influential biological factors.

3.3.1. Age

Ageing is associated with a reduction in sex hormone levels over time. While both sexes experience age-related skeletal changes, inherent dimorphism in hormonal profiles, pelvic architecture, and biomechanical loading patterns remain. Testosterone and oestrogen are crucial for the development of sex characteristics in biological males and females, respectively, but both hormones assist in musculoskeletal maintenance in both sexes (Guggenbuhl, 2009; Lang, 2011; Hammes & Levin, 2019). Male testosterone levels peak between ages 20 and 30 and slowly decline throughout life, with a reduction in oestrogen levels commencing in later years (Barron & Pike, 2013; Horstman et al., 2012; Pataky et al., 2021). Comparatively, females lose up to 80% of oestrogens within the first year of menopause, commonly commencing during the fourth life decade and continuing at the same rate annually (Burger et al., 2002; Vina et al., 2006). Females also experience age-related decline in testosterone at the same time (Horstman et al., 2012), generally reducing to just 15% of premenopausal levels (Longcope & Johnston, 1988; Horstman et al., 2012).

Hormonal changes during menopause can cause rapid physiological changes in females, typically more significant than in males (Pietschmann et al., 2009; Lang, 2011). The decrease in female oestrogen levels is linked to accelerated bone loss, compromised tissue healing, and a shift towards a more androgynous pelvic structure (Burger et al., 2002; Russo et al., 2003; Cauley, 2015; Pataky et al., 2021; Waltenberger et al., 2022a). Lang (2011) notes the reduction in mechanosensitivity accompanying menopause, while Moalli et al. (2004) highlight an increased post-menopause pelvic floor laxity, subsequently reducing load-bearing capability and increasing strain across ligamentous attachment sites. It has been noted that oestrogen loss can affect male bone health in later years (Lang, 2011). However, male mechanosensitivity reduction is comparatively less significant, meaning that mechanical loading is more likely to mitigate bone loss related to male oestrogen reduction (Lang, 2011). Furthermore, numerous studies have shown a correlation between decreased testosterone levels and a decline in bone density in older males; however, this correlation is not significant until around two decades after any negative age-related changes are observed in females (Fink et al., 2006; Riggs et al., 1981; Pataky et al., 2021). Due to lower pre-menopausal levels, the impact of reduced female testosterone may be less pronounced than in males, but Lang (2011) has observed exacerbated skeletal deterioration in females with notably low testosterone levels, further enhancing the significant oestrogen-deficiency-induced changes.

Regarding pelvic scarring, age-induced osteoporosis significantly slows bone healing and repair processes, potentially exacerbating the persistence and severity of osteological changes at scar sites across the pelvis (Maass, 2012). Osteoporosis is a condition marked by reduced bone density and quality, arising from an imbalance in the bone remodelling process where bone resorption outpaces formation. In osteoporotic bone, the activity of osteoblasts - the cells responsible for building new bone - is diminished, while osteoclast activity, which breaks down bone tissue, is increased (Ferretti et al., 2003; Rodriguez et al., 2019; Umur et al., 2024). This imbalance results in a weakened skeletal structure that not only is more fragile but also heals more slowly after injury.

Moreover, osteoporosis is associated with reduced vascularity (i.e., a diminished blood supply), essential for effective bone repair. The impaired vascularisation means that nutrients and oxygen are delivered less efficiently to the repair sites, while changes in signalling molecules further disrupt the normal healing cascade (Rodriguez et al., 2019; Umur et al., 2024). Together, these factors mean that any damage to the pelvic bone may persist longer and appear more pronounced. This delayed healing can be especially significant in the pelvis, where age-induced bone loss, combined with pelvic laxity, increases musculoskeletal stress at scar sites. As a result, the severity of pelvic scarring may be intensified in older individuals. Alternatively, from an obstetric perspective, older females might display more pronounced scarring due to a higher cumulative number of pregnancies, thereby exacerbating scarring.

3.3.2. Age and Pelvic Scarring

Dorsal Pubic Pitting

Stewart (1970) and Kelley (1979) were among the early researchers to identify an association between dorsal pitting and age in female-only samples. In Stewart's (1970) study, which examined skeletal remains from individuals estimated to be between 20 and 109 years old at death, a general decline in pitting severity was observed with advancing age - though this reduction only became statistically significant after the age of 80. This suggests the occurrence of age-related bony changes that reduce scar presentation on the dorsal pubis, becoming most significant in advanced decades. Kelley (1979) evaluated individuals aged 15 and older and reported age-related outcomes for three key scar features (dorsal pitting, preauricular changes, and interosseous grooving) as a combined measure, which prevented an assessment of each feature separately. Nonetheless, their overall results revealed that nulliparous females exhibited consistent scarring throughout life, aside from a slight dip in the fourth decade (Kelley, 1979). Meanwhile scarring in parous females rose sharply beyond that of nulliparous females until the third decade, remaining at that level with a slight reduction in severity mirroring that in nulliparous females, before a decline from the fifth decade – reaching the average scar presentation in nulliparous females by the age of 70 (Kelley, 1979). This shows a peak in scar presentation in parous females during primary childbirth years, with the obliteration process beginning from the age of menopause. This indicates an obstetric-scar relationship, although the presence and variation of pitting in nulliparous females indicates a concurrent effect of age on scar presentation in advanced years.

Providing alternative findings, Suchey et al. (1979) found that the incidence of pitting increased consistently from the age of 10 to 99, identifying the second decade as the onset of pitting increase without evidence of later obliteration. In females under the age of 20, 70.97% did not present with pitting (Suchey, et al., 1979), meanwhile, in the 20-29 category, this reduced to 23.73%, and again to 3.26% of those 30 years or over. The onset of this trend can be associated with the first full decade of reproductive ability in females, suggesting a possible hormone-related cause of scarring. Suchey et al. (1979) further observed a relationship with the number of pregnancies but were able to establish an independent effect of age on scarring due to a similar trend observed in nulliparous female group.

A decade later, Andersen (1986) examined a sample of individuals aged 18 to 93 at the time of death, noting a slight reduction in pitting severity among those over 60 - about ten years after the initial reduction reported by Kelley (1979). Although this decrease was not statistically significant in Andersen's study, it is noteworthy that the only two males displaying pitting were both over 80, hinting at a possible association between very advanced age and dorsal pitting in males. Similarly, Cox and Scott (1992) found no significant link between dorsal pubic pitting and age in a sample ranging from 12 years old upwards (with an average age of 56). These results are consistent with later research by Maass and Friedling (2016), who studied individuals aged 20 and over, as well as by Waltenberger et al. (2021), whose sample included individuals who died between the ages of 19 and 77.

In line with Suchey et al. (1979), Snodgrass and Galloway (2003) found that pitting severity increased significantly with age in a sample ranging in age (at death) from 17 to 99. Their results imply that the progression of skeletal aging may intensify scar presentation, countering earlier claims that skeletal deterioration might obliterate or obscure such scarring. Notably, the group with no pitting had a mean age of 40.7 years, while the mean ages for grades 1 through 4 were 40.0, 49.9, 53.4, and 60.7 years, respectively (Snodgrass & Galloway, 2003) - indicating a later onset of advanced pitting than that observed by Suchey et al. Although, contrary to Kelley's (1979) conclusions, Snodgrass & Galloway (2003) did not observe any interrelation with parity status, suggesting that obstetric history does not impact scar presentation in combination with age.

Using a sample of individuals aged 20 or over at the time of death, Praxmarer et al. (2020) noted a significance difference in scarring between female age groups specifically. Older females were found to present with more frequent and severe pitting - offering further support of the preceding research. For example, the percentage of females with converged pits increased from 26.1% in the 'young' group to 72% of the 'very old' group. Similarly, there was an increase in the percentage of prominent pitting from 8.7% of 'young' females, to 54.1% of the 'very old' females. Conversely, there was a significant reduction in the frequency and severity of dorsal pitting in the male sample (Praxmarer et al., 2020). While 61.5% of 'young' males had no evidence of pitting, this was the case in a significant 88.2% of the 'very old' sample, and zero males in the older group had any pitting beyond 'barely perceptible'.

Providing the latest research, Waltenberger et al. (2022a; 2022b) also identified some noteworthy associations based on the same sample with an age at death range of 12 to 92. Waltenberger et al. (2022a) noted a significant association with dorsal pitting in females until the age of 37 to 40. This range encompasses standard reproductive years, enabling inferences about a positive fertility-scar relationship, or obstetric relationship. From age 50, the pelvis became more android in shape as associated with menopausal events, and the positive trend in scar presentation plateaued (Waltenberger et al., 2022a). This trend aligns with broader age-related physiological changes, particularly the decline in bone plasticity and hormonal influences post-menopause. This further supports the fertility or obstetric theory given the cessation of scar development in the absence of obstetric event potential. Male pelvis shape was found to be less variable, with android traits most obvious up until age 45 and only an increase in anteroposterior diameter and coxal length thereon (Waltenberger et al., 2022a). Although, age was weakly correlated with male scar presentation (Waltenberger et al., 2022a) confirming that obstetric events cannot be solely responsible for dorsal pubic scarring and that such may be a product of, or at least exacerbated by, the aging process itself. However, according to the later study by Waltenberger et al. (2022b), the expression of all scar features – including dorsal pitting - was stronger in individuals under 45. This presents a reduction in scar presentation from around the time of menopause onwards (Waltenberger et al., 2022b), directly contradicting Waltenberger et al.'s (2022a) age-based findings. This is particularly interesting given that the same sample was used in both studies.

Preauricular Sulcus

The preauricular sulcus similarly exhibits varied age-related trends across studies. Reiterating Kelley's (1979) findings in combining the results of preauricular, interosseous, and dorsal pubic changes, it is inferred that preauricular sulcus severity also increases in earlier decades in response to age and obstetric events. This is due to a sharper increase in scar presentation in parous females compared to nulliparous females during primary childbearing years, decreasing from the time of menopause onwards in all females (Kelley, 1979). Meanwhile, Andersen (1986) identified only a weak correlation between chronological age and the presence of a preauricular sulcus, with a statistically significant relationship emerging solely in cases where the sulcus was markedly pronounced. These findings suggest that age-related changes are primarily associated with advanced age only.

Subsequent studies have examined the association between chronological age and the development of the preauricular sulcus, yet most found no significant relationship. Spring et al. (1989) analysed a sample aged 32 to 87, Cox and Scott (1992) included individuals aged 12 and older, Novak (2012) and Maass and Friedling (2016) both focused on subjects aged 20 and above, Karsten (2018) studied individuals between 15 and 99, Igarashi et al. (2019) examined a range of 14 - 106 (varying by sample and sex), and Canty (2020) focused on those aged 18 and over – but none observed any age-based correlations. Disputing these findings, Praxmarer et al. (2020) reported that the incidence and severity of the preauricular sulcus increased with age in females. In line with Andersen's (1986) observations, they found that the sulcus floor was significantly more likely to be pitted in older females: while 56% of 'young' females exhibited a pitted sulcus, this percentage increased to 85.7% in the 'old' group and 82.1% in the 'very old' group (Praxmarer et al., 2020). Furthermore, where 75% of 'young' females showed a sulcus graded 2 or below, approximately 70% of older females presented with more severe grades - 71.4% in the 'old' group and 67.9% in the 'very old' group. In contrast, there was little variation in both the occurrence and severity of the sulcus among males, with none exhibiting a well-defined or complex sulcus (Praxmarer et al., 2020).

Finally, while Waltenberger et al. (2021) failed to identify a significant relationship between chronological age and the preauricular sulcus, Waltenberger et al. (2022a) again found an association for females under 40 years of age, with sulcus development appearing to stabilise thereafter - attributed to reduced hormonal and mechanical stresses following menopause. Mirroring trends noted for dorsal pubic pitting, the same study found only a weak correlation between age and male scar manifestation (Waltenberger et al., 2022a), but this continues to dispute a solely obstetric cause of scarring. Most recently, Waltenberger et al. (2022b) observed that overall scar feature expression was notably greater among individuals under 45, suggesting a decline in sulcus presentation coinciding with the onset of menopause, thereby challenging the plateau proposed in their 2022a investigation.

Pubic Tubercle

The earliest investigation into age-related changes of the pubic tubercle was conducted by Cox and Scott (1992), who reported no discernible association. Likewise, Snodgrass and Galloway (2003) found no correlation between age and pubic tubercle expression, despite identifying a strong link between age and dorsal pubic pitting. In contrast, Maass and Friedling (2016) identified significant age-related variation in tubercle size, demonstrating that older individuals generally exhibit larger tubercles. Specifically, 42.9% of 'young' and 39.1% of 'middle' females in their sample presented with a small tubercle, compared to only 21.4% of 'old' and 11.1% of 'very old' females, and this pattern was reflected in both male and pooled samples.

Deviating from their conclusions pertaining to dorsal pitting and the preauricular sulcus, Praxmarer et al. (2020) observed no association between pubic tubercle extension and age in females. However, it was reported that tubercle dimensions increased with age within the male group (Praxmarer et al., 2020). While 81.3% of 'young' males exhibited only a small tubercle extension (if any), this was true of only 42.8% of the 'very old' age group, translating to 57.2% of older males manifesting medium to large tubercle extensions (Praxmarer et al., 2020).

In their 2021 study, Waltenberger et al. again found no association between age and scarring, in this case pubic tubercle extension. However, in subsequent work, Waltenberger et al. (2022a; 2022b) reported similar findings to dorsal pubic pitting and preauricular sulcus development. Waltenberger et al. (2022a) identified a correlation between female age and tubercle extension up to approximately 40 years of age - after which a plateau was observed - suggesting a combined influence of age and obstetric events. In contrast, only a weak association was observed among males. Likewise, Waltenberger et al. (2022b) consistently found higher rates of scarring in individuals younger than 45 years. Notably, this feature was exclusively observed within that younger cohort.

Interosseous Groove and Iliac Tuberosity

The interosseous groove and iliac tuberosity have received less attention compared to the other common scar sites in terms of age-related variation. Both first considered in combination with age by Andersen (1986), we can assume no significant age-scar relationship for either feature, given their complete absence in the discussion. The same conclusion was reached for the interosseous groove by Maass & Friedling (2016); however, they did observe a significant relationship between age and iliac tuberosity development comparable to their pubic tubercle observations. Maass & Friedling (2016) found that the iliac tuberosity was more pronounced in older individuals in the full sample and both single-sex samples. For example – across the full sample – 53.3% of 'young' and 64.7% of 'middle' aged individuals presented with any eminence, versus 76% of 'old' and 87.2% of 'very old' individuals (Maass & Friedling, 2016)

Mahadevappa and Shivalingaiah (2017) conducted the only study to date that indicates an association between interosseous groove presentation and age. Unfortunately, they provided only a vague overview of their sample age at death - stating that it ranged from birth to "more than 45 years" (Mahadevappa and Shivalingaiah, 2017, p.117) (seeming to reference the age groups rather than the full age range). Nonetheless, it was concluded that the presentation of this feature reduces with age, believed to be a result of age-related collapse of the sacral auricular elevation. This relationship is evident in the female group, with 93.3% females up to 45 years old having advanced indentation, reduced to 68.9% of females over 45. Only 11.54% of 23 non-adult females had any evidence of interosseous groove development, none of which presented with advanced changes. As detailed in chapter 3.1.6, just 20 males (16.7%) had evidence of interosseous changes, impeding detailed age-related analysis.

3.3.3. Stature and Body Mass

Taller individuals generally have larger pelves (Holland et al., 1982; Tague, 2000), although this must account for existing pelvic dimorphism. For example, taller females have larger pelves than shorter females, and the same can be observed in males, but we know that females have broader pelves with larger rounded inlets than typical males. When isolated, the pelvis of taller individuals is proportionally taller relative to width, with longer iliac blades and a more vertically ovoid inlet (Fischer & Mitteroecker, 2015). This is consistent with dimorphic variation, as males are generally taller than females. However, a discrepancy in stature versus pelvic capaciousness ratio can arise in older individuals due to skeletal compression that occurs with age – with older adults expected to be shorter than they were in mid-adulthood (Snodgrass & Galloway, 2003).

The basic stature theory of scar influence would dictate that taller individuals suffer more strain across pelvic scar sites due to having a larger pelvis and increased tension at sites of ligamentous attachment. Furthermore, scar sites prone to vertical strain - such as the anteroposterior attachment site of the levator ani, or primary abdominal muscles - may present as more developed in particularly tall individuals. If we combine this theory with the theory of dimorphism, whereby scar features develop because of puberty and female cyclical hormonal changes, it is therefore plausible that taller females could present with more pronounced scar features than shorter females. Furthermore, the consideration of height and pelvic dimensions within the obstetric theory presents an alternative hypothesis based on the idea that a shorter female would have a smaller, less capacious pelvis. This would reduce the birth canal and make the birth process more difficult (Cox, 1989; Maass, 2012), thereby exerting extreme stress on the pelvic structures. Cox (1989) suggests that such an event could result in more significant scarring compared to females with broader pelvic architecture.

Further focusing on a potential association between body mass and scarring first reveals a connection between weight and primary sex hormones, with research showing that increased body fat correlates with oestrogen levels, explaining typical male weight gain during early andropause when oestrogen levels rise relative to testosterone (Orwoll et al., 2006; Pataky et al., 2021). This body fat increase is most evident in the torso, mirroring typical adult female weight gain due to their higher baseline oestrogen levels (Horstman et al., 2012; Pataky et al., 2021). A significant increase in central mass in turn increases intra-abdominal pressure (Mengert, 1936; Ulfelder, 1956; Lambert et al., 2005; Tim & Mazur-Bialy, 2021) - in extreme cases mimicking the musculoskeletal effect of pregnancy by placing strain on the anterior abdominal muscles (Mengert, 1936; Ramalingam & Monga, 2015) and pelvic floor (Greer et al., 2008; Ramalingam & Monga, 2015). The strain on associated pelvic attachment sites could produce bony changes in significantly overweight individuals. However, unlike in pregnancy, the associated pelvic strain in obese individuals can be chronic. Therefore, any evidence of osteological response at pelvic sites might present as more severe, either due to prolonged musculoskeletal stress or the absence of post-stress skeletal recovery observed post-pregnancy (Karlsson et al., 2005; Winter et al., 2020). Conversely, being underweight can equally influence skeletal health. Significant weight loss below 60% induces significant oestrogen loss, leading to musculoskeletal changes akin to those observed during and after menopause, including bone and muscle density loss, soft tissue weakness, collagen synthesis disruption, and levator ani dysfunction (Tim & Mazur-Bialy, 2021).

3.3.4. Stature, Body Mass, and Pelvic Scarring

Anthropometric factors - specifically height and weight - have received considerably less attention than other variables discussed in this review. Nevertheless, they warrant consideration, given their potential interaction with other factors which may influence the development of pelvic scarring. Houghton (1974) was the first to formally hypothesise that, because taller individuals experience greater mechanical stress across the pelvic region due to increased skeletal length, which may contribute to scar presentation. Shortly thereafter, Holt (1978) suggested a link between obesity and scar development as a justification for the scarring observed in biological males. However, these theories were not investigated until many decades later, focusing on the preauricular sulcus (Canty, 2020), and/or dorsal pubic pitting and pubic tubercle development (Snodgrass & Galloway, 2003; Praxmarer et al., 2020; Waltenberger et al., 2021; 2022b). To date, there has been no research into potential associations between anthropometric factors and interosseous or iliac tuberosity changes.

Preauricular Sulcus

Canty (2020) initiated the investigation of height and weight factors in association with the posterior pelvis, using the known CT scan sample (n = 75) which formed part of their larger research. The author did not provide the height and weight data for the sample, instead presenting such as combined BMI data – although with the majority of individuals classed as 'healthy', we can assume cases of extreme height or weight were minimal. Regardless, Canty (2020) found no discernible link between these anthropometric variables and preauricular sulcus development. In contrast, Praxmarer et al. (2020) estimated height and weight using sex-specific osteological formulae, though they too did not detail the full anthropometric ranges. Notably, however, they identified a negative association between female height and sulcus length, observing a weak negative correlation between weight and both sulcus length and width in females (Praxmarer et al., 2020). Together, these results hint at a relationship between smaller female stature and more pronounced sulcus development.

Waltenberger et al. (2021) assessed body size measures in their sample, reporting a height range of 144–163 cm for females (n = 39) and 150–187 cm for males (n = 34), yielding an overall height range of 144–187 cm. Although weight was recorded for 54 individuals within the study sample, a full weight range was not provided; the authors noted that most were underweight at the time of death due to illness. In a subsequent study, Waltenberger et al. (2022b) reported complete height (145–185 cm) and weight (33.57–107 kg) ranges for their CT scan sample of 150 individuals. In either study, no significant association between body size (height or weight) and sulcus development or severity was observed.

Dorsal Pubic Pitting

Previous research into anthropometric influences on dorsal pubic pitting to date consistently reports minimal impact of height or weight. Snodgrass and Galloway (2003) conducted one of the earliest studies incorporating anthropometric data into pelvic scar analysis. Using a known sample, they examined height in a sample of 142 individuals (ranging from 132.1 cm to 190.5 cm) and body weight in 139 individuals (ranging from 36.3 kg to 142.4 kg). They also used this data to produce BMI figures for further analysis of the 139 individuals for which both height and weight data were available. Their findings revealed no significant correlation between body weight and dorsal pubic pitting, leading them to conclude that parity and age are far stronger predictors of pitting prevalence and severity (Snodgrass & Galloway, 2003). Similarly, dorsal pubic pitting demonstrated no measurable height-related trends (Snodgrass & Galloway, 2003). These observations have been confirmed by Praxmarer et al. (2020), Waltenberger et al. (2021) and Waltenberger et al. (2022b).

Pubic Tubercle Extension

Regarding the pubic tubercle, Snodgrass and Galloway (2003) found no significant relationship between height or weight and the expression of this feature. In contrast, Praxmarer et al. (2020) identified an anthropometric association in their male sample, reporting a significant correlation between tubercle width and male height. Although no similar correlation was observed in the female sample, Praxmarer et al. (2020) did note a weak negative association between female body mass and tubercle expression. Additionally, Waltenberger et al. (2021) reported an association between the degree of tubercle extension and both weight and height when considering the full sample. However, this relationship was not replicated in their later study (Waltenberger et al., 2022b). These mixed findings suggest that while anthropometric factors may influence pubic tubercle characteristics, there is certainly a degree of dimorphic influence as highlighted in section 3.1.6.

3.4. Chapter Summary

Common scar sites are found on the pubis and ilium of the pelvis and most often present as lytic lesions - although the pubic tubercle, for example, develops as a proliferative extension. Interosseous bone scarring has both lytic and proliferative tendencies, with cavitation of the retroauricular surface and the neighbouring edge of the auricular surface, while promoting bony growth along the auricular surface edge. As discussed in this chapter, multiple theories exist regarding the causes or influences of these bony changes, primarily focusing on biological sex and obstetric factors. Nevertheless, following a review of existing research, it remains challenging to form definitive conclusions regarding the cause or predictive potential of pelvic scarring - with numerous studies producing conflicting or uncertain results, and many restricted by their methodologies. This emphasises the complexity of pelvic scar analysis, underscoring the need for further research.

Taking an advanced approach, this research will clarify the causes, influences, and value of pelvic scarring. This will involve assessing preauricular, interosseous, dorsal pubic, and pubic tubercle changes - all of which previous studies indicate are most likely associated with biological factors. This process requires an in-depth examination of a contemporary skeletal collection with known biological data and sees a move away from the solely categorical grading systems of many previous studies. Scar features will be assessed individually and in combination where appropriate, while maintaining awareness of the issues associated with existing multi-feature methods. The following chapter (4) provides a detailed overview of the materials and methods used in this research before presenting the results in Chapter 5 – including the novel consideration of interosseous changes in relation to height and weight.

Chapter 4: Materials and Methods

This chapter outlines the materials used and methodology followed in this study, providing a comprehensive framework of the research process. The chapter begins with an overview of the skeletal samples, including demographic information and relevant collection background details. Following this, the chapter provides a clear and precise description of the scar analysis process. This section is designed to facilitate replication and includes step-by-step procedures, descriptions of the tools and techniques used, and criteria for evaluating scar features.

4.1. Primary Skeletal Collection

This research required a skeletal collection associated with an extensive record of personal data that might influence changes to pelvic feature morphology. For this reason, this study used the Texas State Donated Skeletal Collection (TXSTDSC), comprised of modern individuals from the United States who had either preregistered to donate their body to the Forensic Anthropology Center at Texas State (FACTS) when they die or had their body donated by their next of kin after death (Gocha et al., 2021; FACTS, 2022). FACTS donors are used to study human decomposition under various conditions and general skeletal biology (FACTS, 2022). The facility accepts autopsied cadavers and those who have donated organs. However, they will not take individuals who weigh over 500 lbs (226.8kg) or those with any active transmissible disease at the time of death.

4.1.1. TXSTDSC Donation Statistics and Research Availability

At the time of publication, Gocha et al. (2021) noted 710 body donations in the 13 years the facility had been active. The collection continues to grow, averaging 65 donations each year, with a slight reduction in contributions to the collection due to the COVID-19 pandemic. A more recent publication from Olsen (2023) suggests that the current donor figure is roughly 850 – with as many as 1,500 living pre-registered donors. However, it is essential to note that the number of individuals available in the donated skeletal collection only partially reflects the total number of donors. According to Gocha et al. (2021), donor remains are usually in the outdoor facility for at least two years before being added to the skeletal collection (TXSTDSC) for research. Therefore, the number of curated adult individuals available within the TXSTDSC at the time of this research was only 465 (186 females; 279 males).

4.1.2. Donor Demographics

The TXSTDSC includes individuals ranging from 21 weeks gestation to 103 years old at the time of death, comprised of more biological males than females at 58% and 42%, respectively (Gocha et al., 2022). There is a slight bias towards older individuals within the FACTS collection, with a median age of 68 and a mean age of 66. See Figure 4 for a visual representation of this data, as provided by Gocha et al. (2022). There is further biological ancestry bias, with curated individuals predominantly coming from the central Texas area, with just 11% from American states further afield (Gocha et al., 2022). Gocha et al. (2022) note that 90% of the sample classed themselves as White (non-Hispanic), while 4.5% identified as white-Hispanic, and 5.5% of the total collection included individuals of Black, Asian, or combined ancestries.

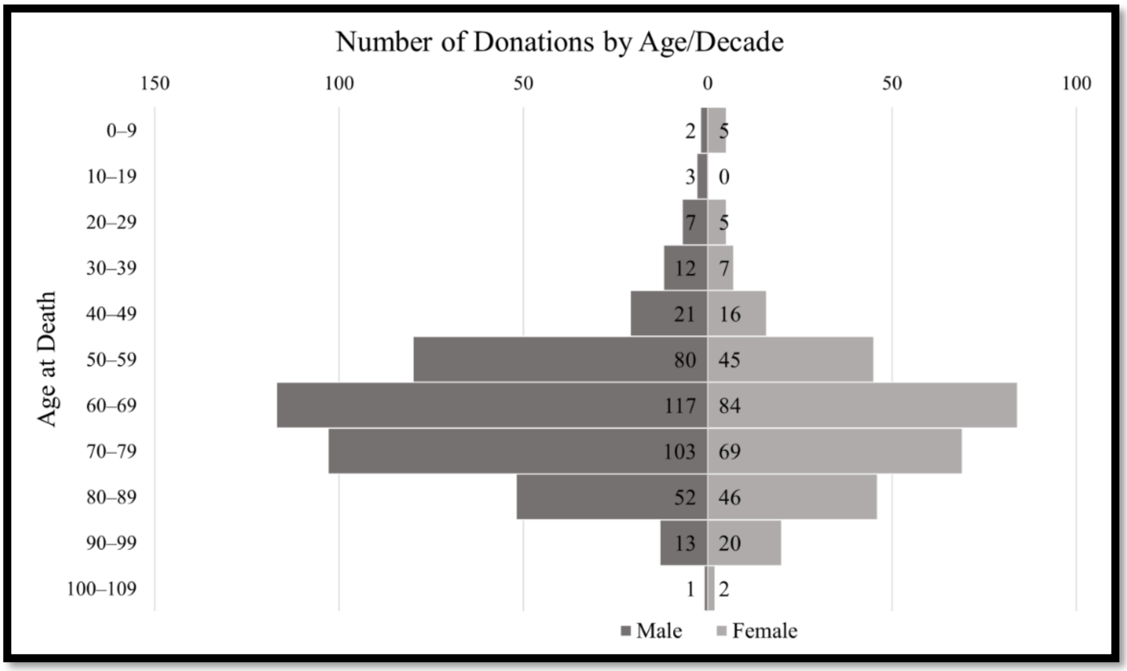


Figure 4. Distribution of TXSTDSC age-at-death categories, separated by biological sex (Gocha et al., 2021).

Upon receipt of donor bodies, FACTS collects additional information including the height and weight of the cadaver (not to be confused with self-reported height and weight data), waist circumference, and foot length (Gocha et al., 2022). Gocha et al. (2022) provide information on general cadaver height and weight records; the full range in recorded height is 1.27m to 1.98m, with an average measurement of 1.68m. The average weight of the donors is 75.7kg, spanning a range of 26.7kg to 221.8kg.

Since 2010, FACTS has been granted access to the State of Texas' death certificate system and thus can officially record any associated information (Gocha et al., 2022). This information includes the date and location of birth (and by proxy, their age-at-death), full legal name of the donor (and spouse if relevant), name of both parents, sex, race, education level, and lifelong occupation (Gocha et al., 2022). Although, most of this information is not made available to researchers to maintain donor anonymity. Any personal data associated with each donor, unrelated to that required for death certification, is provided by the donor upon registration or by their next of kin upon post-mortem donation (FACTS, 2022). Data recorded for each donor at this stage includes medical and occupation histories, drug and alcohol habits, and handedness.

With consideration of any biological factors that may relate to pelvic scarring, FACTS kindly provided the following information in association with the individuals utilised for this research: biological sex, age at death, ancestry, cadaver stature and weight, and complete obstetric data – including both the number of pregnancies and the number of births. Regarding obstetric data, FACTS houses the only known sizeable skeletal collection of modern individuals for which pregnancy and birth information is explicitly recorded. Medical and occupation history was obtained for each donor for reference should any unusually significant outliers be noted during the analysis process.

4.1.3. Ethical Considerations

FACTS does not accept donations from estranged family members or utilise unclaimed bodies - using only individuals happy to serve as donors in post-mortem research (Gocha et al., 2021), thereby avoiding the potentially unethical procurement of remains. The only exception would be foetal or juvenile donations, where the decision to donate would be that of the individual's guardian(s). FACTS requires the completion of a donor release form signed by either the donor or next of kin before they can accept a body (Gocha et al., 2022). This form permits the intake of the deceased into the facility and permits FACTS to carry out any necessary forensic studies, such as trauma research. Gocha et al. (2022) explain that explicit detail of the latter is not a requirement of the Texas Anatomical Gift Act to which they must adhere but that FACTS includes it anyway in the spirit of informed consent.

The skeletal remains of all the individuals used in the development of this research were handled with extreme care and respect throughout. Caution was taken to ensure that all skeletal elements were returned to their associated box, and these were positioned in the box in such a way as to avoid damage to more delicate bones by those heavier. Donor anonymity was maintained throughout, with individuals identifiable only by their donation number. Furthermore, personal donor information, as provided, was restricted only to that which was relevant to this research.

4.2. Sample Selection and Demographics

This section details the primary demographic distribution of the research sample, including age and age groups, sex, height, weight, and both gravidity and parity. FACTS kindly provided ancestry information for this research; however, as earlier discussed, there is considerable weighting towards those of white ancestry in the complete donor collection. Unfortunately, this issue was unavoidable in the research sample, with white individuals accounting for 90% of the sample. Therefore, ancestry data was deemed unsuitable for statistical investigation in this study and has not been further detailed in this section.

4.2.1. Inclusion and Exclusion Criteria

All curated adult females 18 or over at the time of death, free from direct trauma to each analysis site on at least one side of the pelvis and without evidence of any impactful osteophytic development or disease, were used (n = 169). For details of the available TXSTDSC females excluded from the research sample in this study (n = 18), see Appendix B. A smaller comparative sample of adult males was used – meeting these same criteria (n = 51), increasing nulligravid and nulliparous sample sizes and facilitating sex-based analyses. To ensure a diverse range of individuals, the male sample was chosen based on their height and weight, allowing for the largest possible anthropometric data size and ranges. As height and weight information was lacking for some females, gathering comprehensive coverage for the male sample was especially important. Table 4 shows where the male sample was able to enhance these ranges.

4.2.2. Age Demographics

The full research sample age-at-death range was 21-103, with female ages extending through the entire range and males confined to a slightly reduced range of 29-97 (see Table 2 and Figure 5) – although the official age-at-death was unavailable for six males. Age-at-death categories have been established for this research, with details provided in Table 3 and Figure 6. These categories were designed to include the youngest individual with a known age-at-death (21 years), with each category spanning two decades to ensure adequate sample sizes for statistical analysis. Consequently, one category encompasses the 40-59 age range, which aligns with the typical onset of menopause. This design facilitates an effective investigation of the relationship between age, hormonal changes, and the development of scarring in biological females.

Table 2. Age-at-death statistics for the TXSTDSC full, female, and male research samples.

	n	Age range	Mean age	Std. Dev
Full sample	214	21 – 103	68.2	14.62
Female sample	169	21 – 103	67	14.87
Male sample	45	29 – 97	69.2	13.75

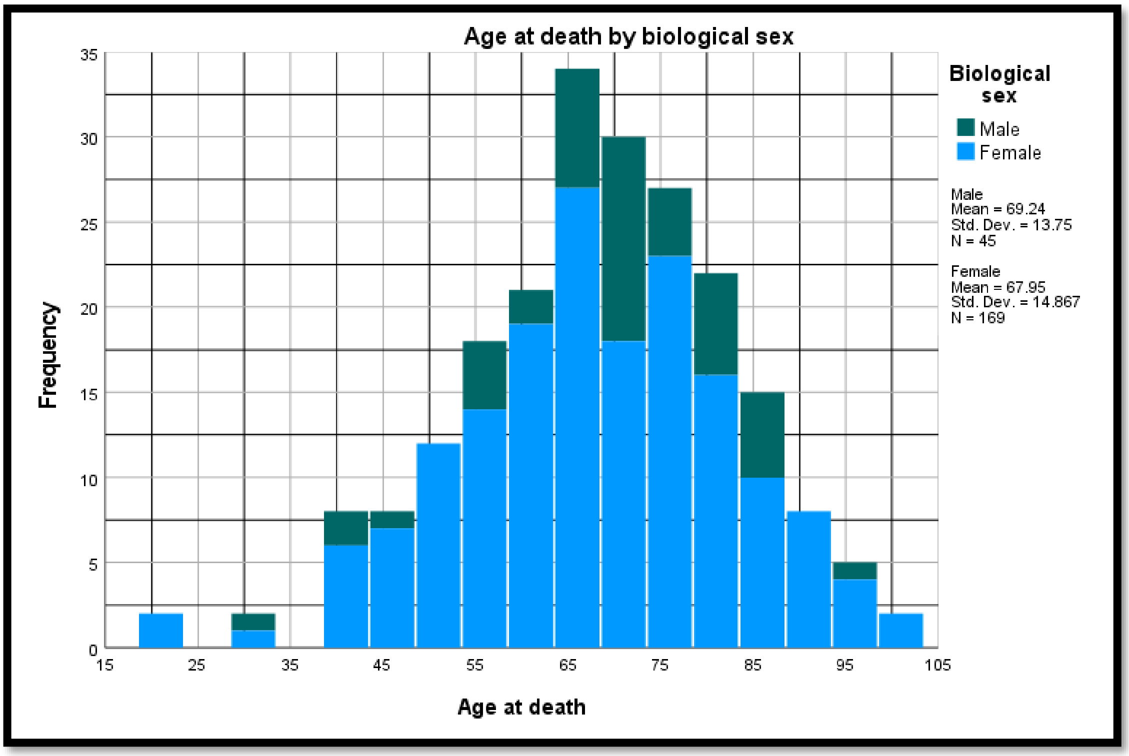


Figure 5. TXSTDSC full research sample age-at-death distribution.

Table 3. Age-at-death group statistics and cumulative percentages for the full, female, and male research samples.

	Age Group				
	Unknown	20 – 39	40 – 59	60 – 79	80+
Full sample	6	8	49	109	48
Female sample	0	6	43	83	37
Male sample	6	2	6	26	11

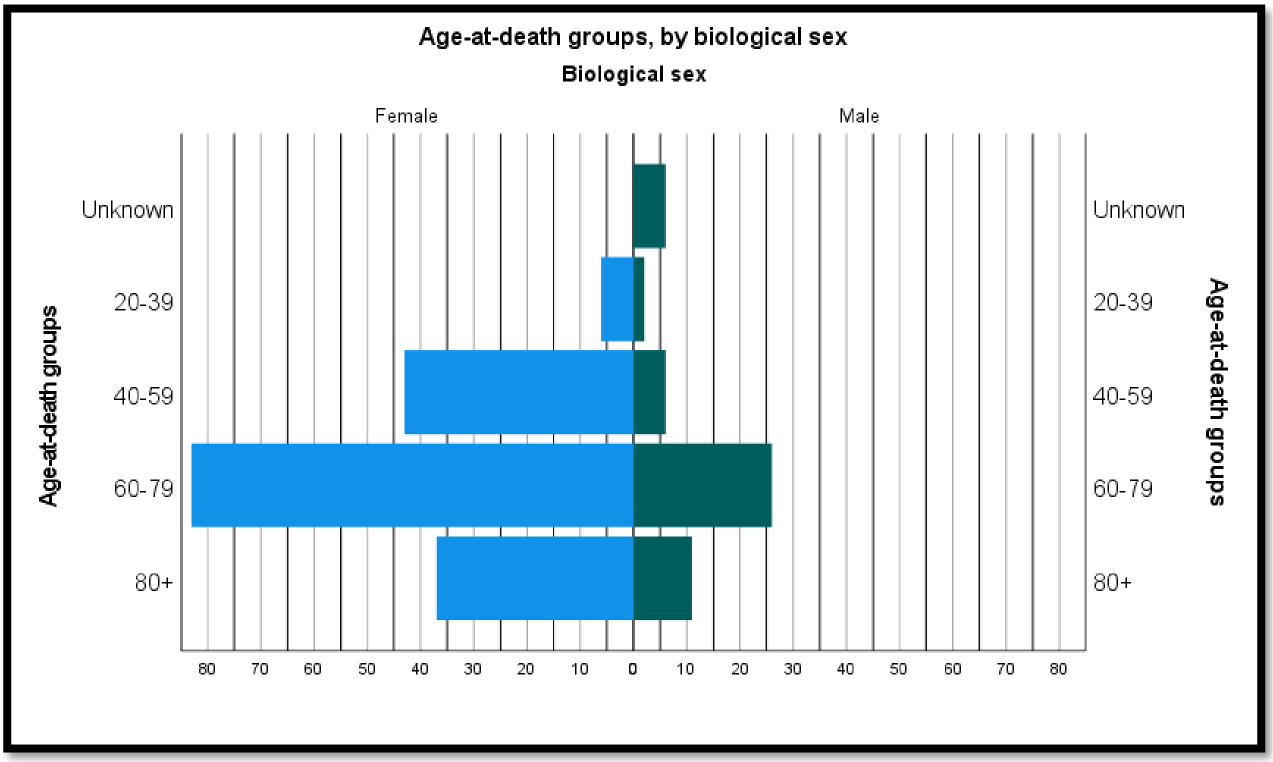


Figure 6. TXSTDSC full research sample age-at-death group distribution, separated by sex.

4.2.3. Height and Weight Demographics

The height and weight ranges for the entire mixed-sex research sample are 1.27m – 1.89m and 32.2kg – 184.13kg, respectively. The height and weight statistics for this sample are comparable to those of FACTS' complete donor sample. Table 4 presents comprehensive data on the height and weight across the entire research sample as well as male and female groups separately (see Figures 7 – 9 for associated infographics).

Table 4. Height and weight statistics for the TXSTDSC full, female, and male research samples.

	Height (m)				Weight (kg)			
	n	Range	Mean	Std. Dev	n	Range	Mean	Std. Dev
Full sample	212	1.27 – 1.89	1.63	0.1	150	32.2 – 184.13	72.43	31.33
Female sample	162	1.27 – 1.75	1.6	0.07	100	32.65 – 184.13	65.51	25.6
Male sample	50	1.35 – 1.89	1.74	0.11	50	32.2 – 172.79	86.26	36.99

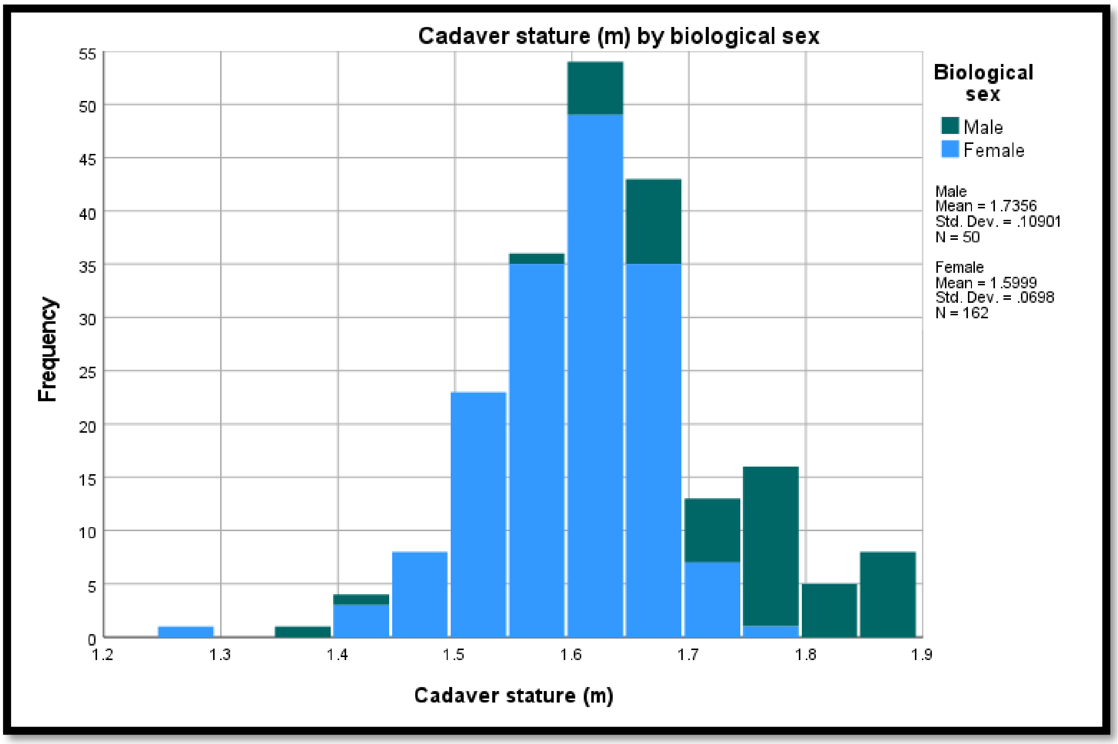


Figure 7. TXSTDSC full research sample height distribution.

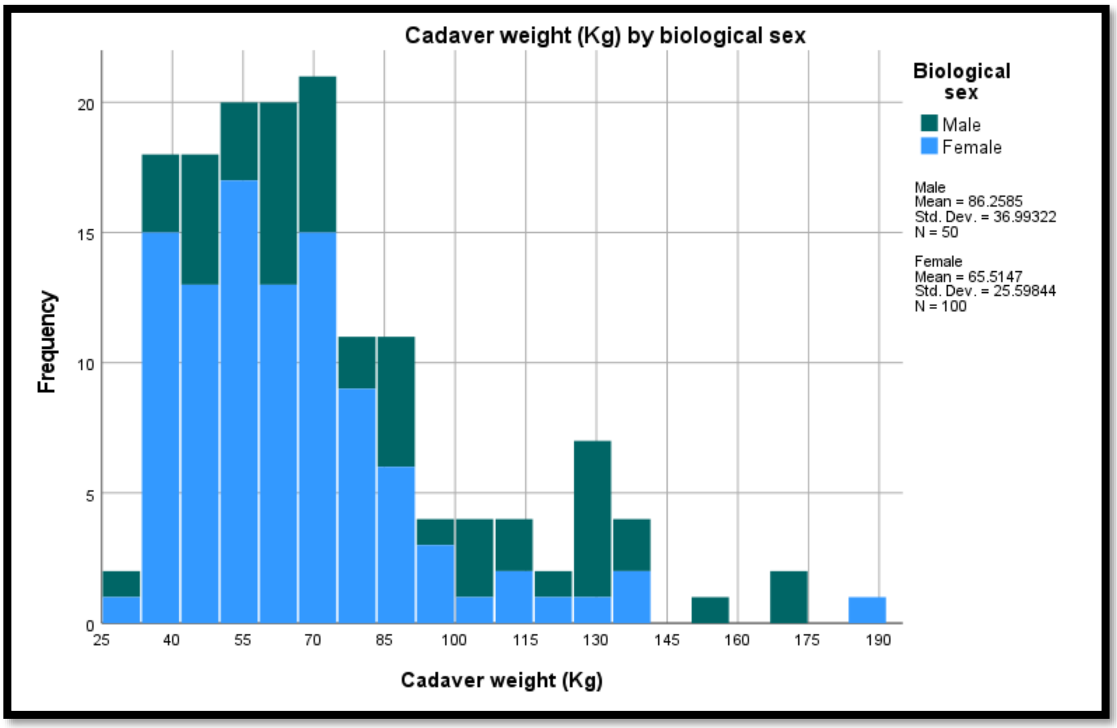


Figure 8. TXSTDSC full research sample weight distribution.

4.2.4. Obstetric Demographics

43 females were recorded as having never experienced a viable pregnancy (nulligravid). This brings the total number of nulligravid individuals (including males) to 94. 126 females had experienced at least one full-term pregnancy, with the highest recorded number of 7 pregnancies. Full details of obstetric data can be found in Table 5, as presented in Figures 9 and 10. This data indicates cases of natural vaginal birth, with a higher number of parous than gravid cases. Cases of caesarean section were identified through the analysis of donor medical histories, resulting in a nulliparous female sample of 48 (99, including the male sample). There were no instances of a higher birth rate compared to the number of pregnancies – implying no cases of multiple-foetus pregnancies within this sample. However, it is possible that multiple births resulting from a single pregnancy were grouped during the completion of the obstetric section of the donor questionnaire.

4.2.5. Estimation Method Validation Sample

A skeletal sample was used from the Christ Church Spitalfields Collection to validate the sex estimation method developed as part of this research. This collection comprises almost 1000 individuals interred in Spitalfield's, London, across the 18th and 19th centuries (Molleson et al., 1993). 387 individuals were identifiable by coffin plates, providing their names, ages at death, and social background through associated record consultation. Social reconstruction showed that many individuals were of French descent (41.6%), 33.1% were most likely of English descent, and the majority were believed to reflect the 'middling sort' of the eighteenth-century (Molleson et al., 1993). 'Middling sort' refers to middle class individuals, neither very wealthy nor very poor, with moderate social standing and income.

The validation sample utilised in this study comprised 86 known individuals from the Spitalfields Collection, including an even number of biological males and biological females. The ages at time of death across the entire sample ranged from 21 to 89, with an average age of 54.7. Among the male sample age-at-death spanned from 21 to 81, with a mean age of 53.1. In contrast, the female sample age-at-death ranged from 23 to 89, with a mean age of 56.3.

Biological information for each individual was established based on the coffin plate associated with them. However, this method presents certain challenges, particularly regarding the reliability of biological data. For instance, forenames inscribed on coffin plates may lead to ambiguous assumptions about sex or gender identity, especially if the names have gender-neutral or culturally variable usage. These potential uncertainties must be acknowledged when interpreting the data. Nevertheless, all individuals included in the sample were well-preserved and conformed to the exclusion criteria established with the initial sample.

Table 5. Gravidity and parity statistics with cumulative percentages for the TXSTDSC female and full research samples.

	Gravidity and parity count									
	0	1	2	3	4	5	6	7	Mean	Std. Dev
Gravidity (n)	43	36	38	28	15	8	0	1	1.79	1.52
	(94 incl. males)								1.38	1.53
Cumulative percentage (female only)	25.4	46.7	69.2	85.8	94.7	99.4	/	100	/	/
Cumulative percentage (incl. males)	42.7	59.1	76.4	89.1	96.9	99.5	/	100	/	/
Parity (n)	48	36	36	27	15	6	0	1	1.69	1.5
	(99 incl. males)								1.3	1.5
Cumulative percentage (female only)	28.4	49.7	71	87	95.9	99.4	/	100	/	/
Cumulative percentage (incl. males)	45	61.4	77.7	90	96.8	99.5	/	100	/	/

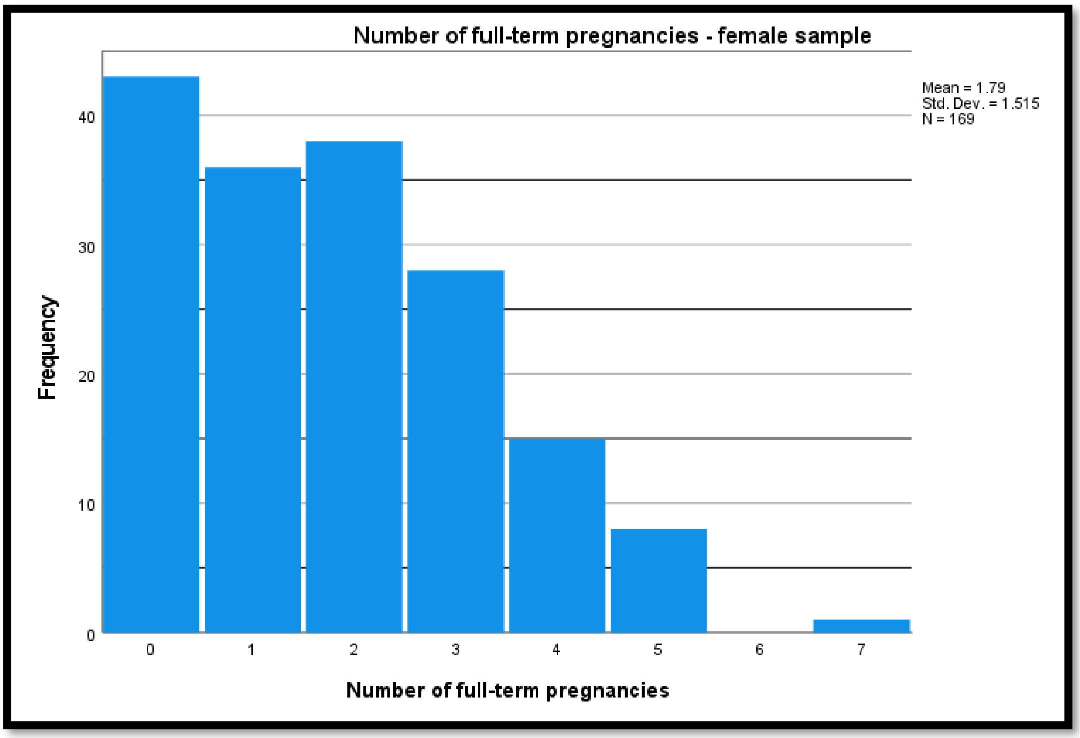


Figure 9. Distribution of the number of full-term pregnancies amongst TXSTDSC research sample gravid females.

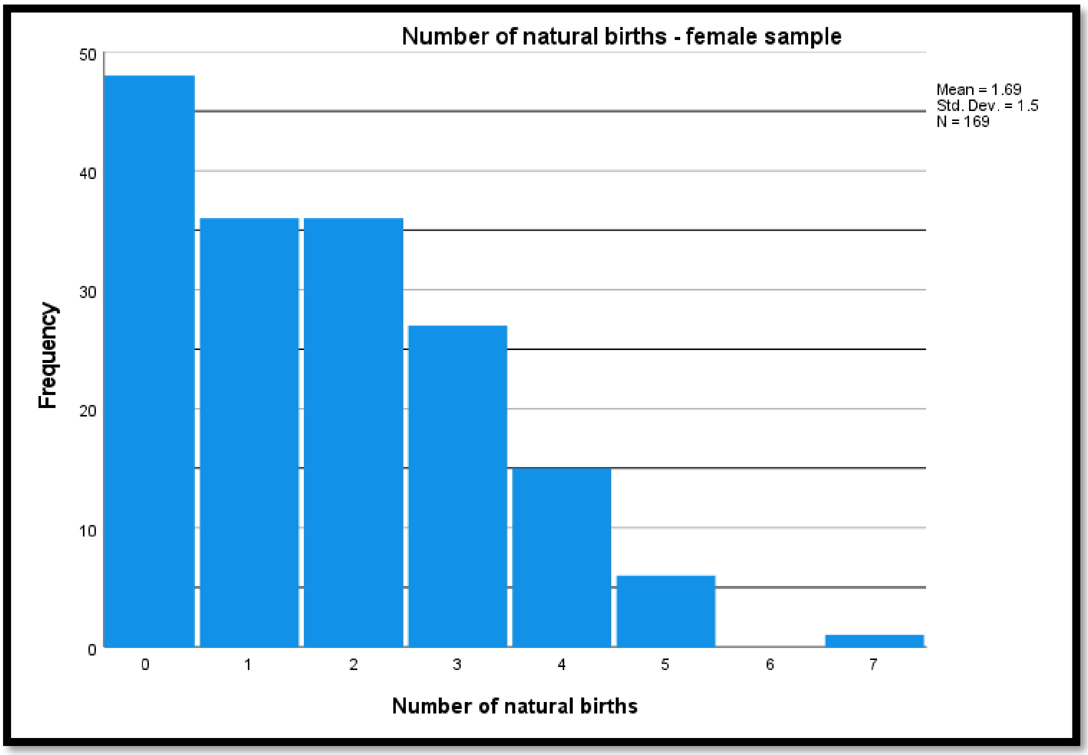


Figure 10. Distribution of the number of vaginal births amongst TXSTDSC research sample parous females.

4.3. Metric Analysis

In this study, morphological and metric analysis of pitting on the dorsal pubis, the extension of the pubic tubercle, the preauricular sulcus, and changes associated with the attachment of the interosseous ligament were carried out. The initial assessment of each scar feature involved recording each as either present or absent for every individual. Where the feature was present, metric data was recorded in millimetres using the same set of digital callipers for all individuals across both skeletal samples. In this research, 150 mm Proster Vernier callipers were used, proving a standard accuracy of 0.02mm for all measurements.

When feasible, the left os coxa was utilised for all analyses, which is common within pelvic scar studies (e.g., Novak et al., 2012; Maass & Friedling, 2016; Karsten, 2018; Canty, 2020). However, Maass (2012) and Igarashi et al. (2019) observed no difference in scar presentation between the left and right os coxa. Therefore, where features on the left side were damaged or obscured, or if the left side was missing in its entirety, the right os coxa was examined instead. Some pelvic features required only a single measurement, while others involved length, width, and depth measurements – bringing the total number of direct measurements for any individual in the initial sample to up to fourteen. To ensure consistency in measuring small scar sites on the bony pelvis, digital callipers were calibrated using standard measurements before each set of measurements to ensure accuracy. A consistent technique was employed throughout, guaranteeing uniformity in the process. Additionally, an intra-observer study was conducted, where measurements were checked using Cronbach's Alpha, revealing high consistency. Detailed documentation was maintained to ensure reproducibility. Each of the following subsections acts as a guide for measuring each scar site with reference to existing methods and details any adaptations particular to this research.

Measurement reference photos can be found in each associated section, which were taken using a Nokia 8.3 smartphone during the initial data collection. Reference lines were later added using the Microsoft Shape tool.

4.3.1. Dorsal Pubic Pitting

Maximum pitting measurements on the dorsal surface of the pubis were recorded following a similar process to that outlined by Waltenberger et al. (2022), adapted from the work of Stewart (1970) and Ullrich (1975). Pit width was recorded as the measurement perpendicular to the symphyseal surface, and length (used instead of ‘height’ in this study to maintain consistency across all pelvic sites) was measured as the maximum distance of the pit parallel to the surface of the symphysis (see Figure 11). Pitting depth was determined as the maximum distance from the dorsal pubic surface to the base of the deepest pit. In developing Waltenberger et al.’s (2022) methodology, the evaluation of independent multi-pit examples (see Figure 11, photo 5) involved taking a length measurement of the largest individual pit as well as a measurement across the full range of pits. Here, a single pit is defined as an isolated, clearly defined depression on the pubic surface, whereas multiple pits refer to several distinct depressions occurring in close proximity. This dual approach—measuring both the largest, isolated pit (single-pit approach) and the collective extent of pitting (multi-pit approach)—permits a more nuanced examination of correlations between demographic factors and pubic pitting.

4.3.2. Pubic Tubercle Extension

When measuring the pubic tubercle extension, the previously established methodology developed by Snodgrass and Galloway (2003), as used in the research of Maass (2012) and Mass and Friedling (2016), was followed with minimal deviations. Measurement was taken from the line of the natural curve of the pubis to the tip of the tubercle extension (Figure 12). However, unlike previous studies, this research does not place tubercle extension measurements into general descriptive categories. Instead, this research focuses on scale variables to facilitate later in-depth data analysis.

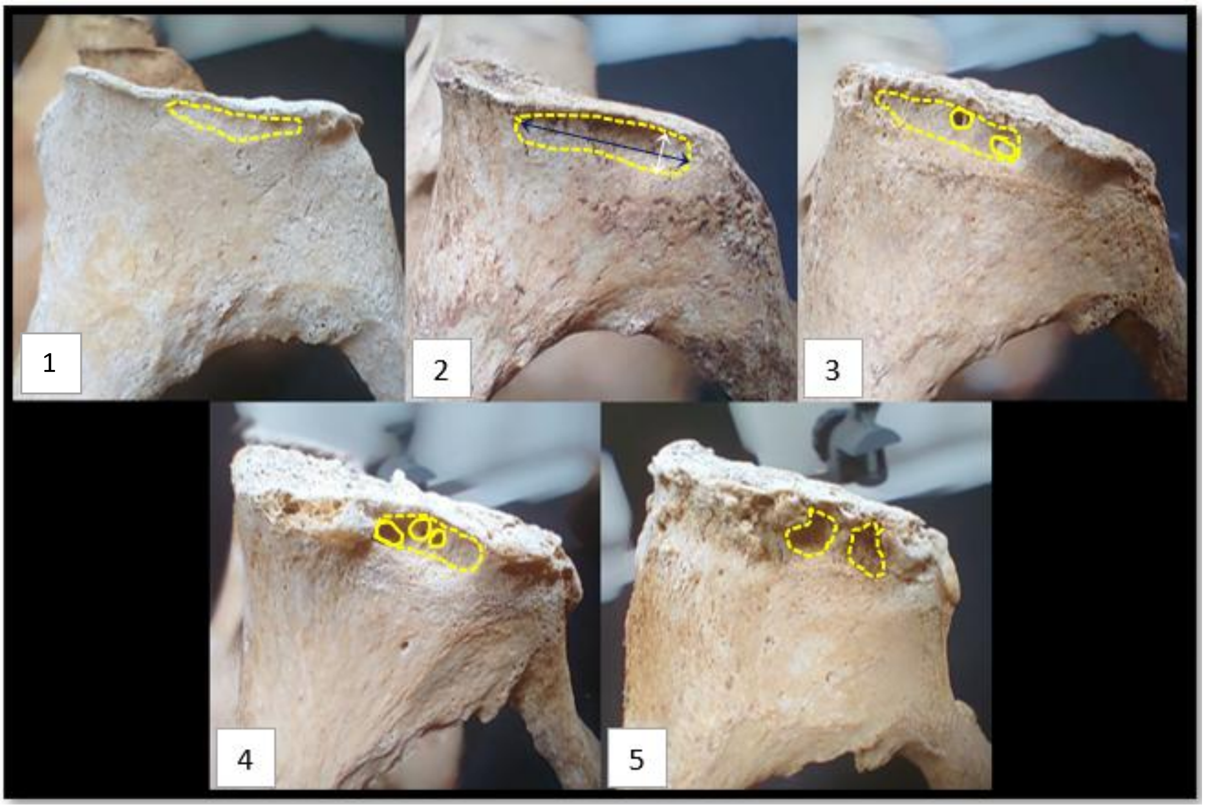


Figure 11. Examples of dorsal pubic pitting from the TXSTDSC research sample. The yellow dotted line identifies the outer perimeter of any pitting, while smaller pits within that area have been highlighted using a bold line of the same colour. Photos 1 and 2 show simple single pits, while 3 to 5 provide multi-pit examples. Examples 3 and 4 present relatively shallow pits, encompassing smaller, deeper pits, and photo 5 shows a case of two independent deep pits. Photo 2 shows maximum length (blue line) and width (white line) measurements.

4.3.3. Preauricular Sulcus

was recorded as the deepest point of the sulcus floor from the unaffected surface level. In this research, an additional measurement of maximum length was taken, which was observed as the maximum measurement of the depression as it runs parallel to the inferior ramus of the auricular surface (see Figure 13). Note that in most cases, this depression should be clearly visible - but where it is particularly shallow, the edges of the sulcus should still be palpable. This is the first known study to utilise all three measurements from the preauricular sulcus.

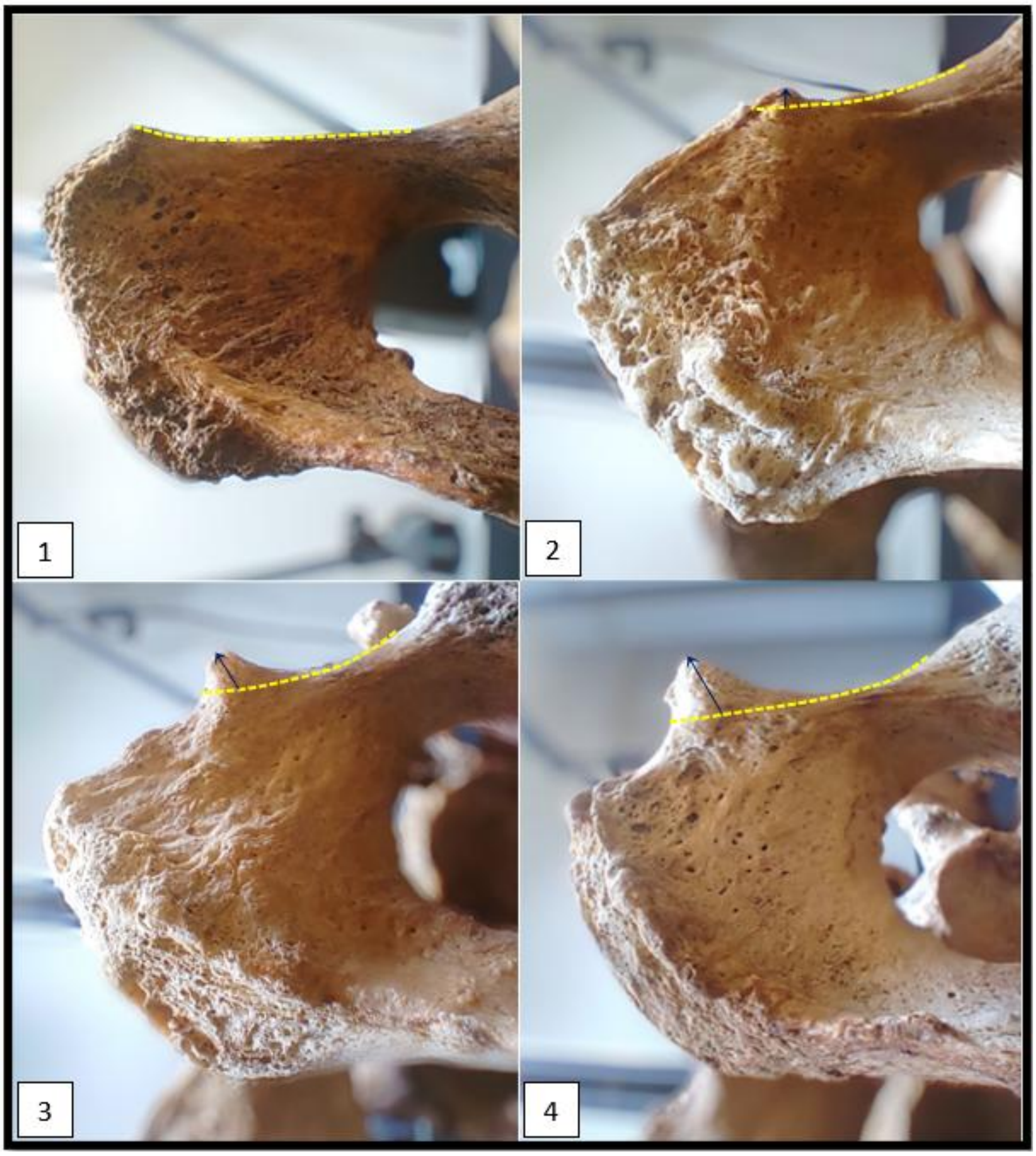


Figure 12. Examples of tubercle extension range within the TXSTDSC sample – from no extension (photo 1) to a significant extension (photo 4). In each case, the yellow dotted line represents the natural curve of the pubis, and the blue arrow indicates the extension (photo 4). In each case, the yellow dotted line represents the natural curve of the pubis, and the blue arrow indicates the extension measurement line through the centre of the mound.

4.3.4. Interosseous Groove (cavity)

This research approached the analysis of the interosseous groove in a novel way. Traditionally, the study of this feature involves width and depth assessment across the full attachment site of the interosseous ligament (Houghton, 1975a; Işcan & Derrick, 1984b; Maass, 2012; Ullrich, 1975; Waltenberger et al., 2021, 2022b). However, as discussed in Section 2.2.4, interosseous scarring on the retroauricular surface can be challenging to identify and analyse. Subsequently, interosseous scar analysis in this research focuses solely on the cavity formed by auricular surface lipping at the dorsal edge(s) first mentioned by Houghton (1974) (hereon referred to as the interosseous cavity, or interosseous cavitation). When discussing auricular characteristics associated with the interosseous ligament, this study utilises the same vocabulary as Wescott's (2015) research on auricular elevation. (see Figure 14).

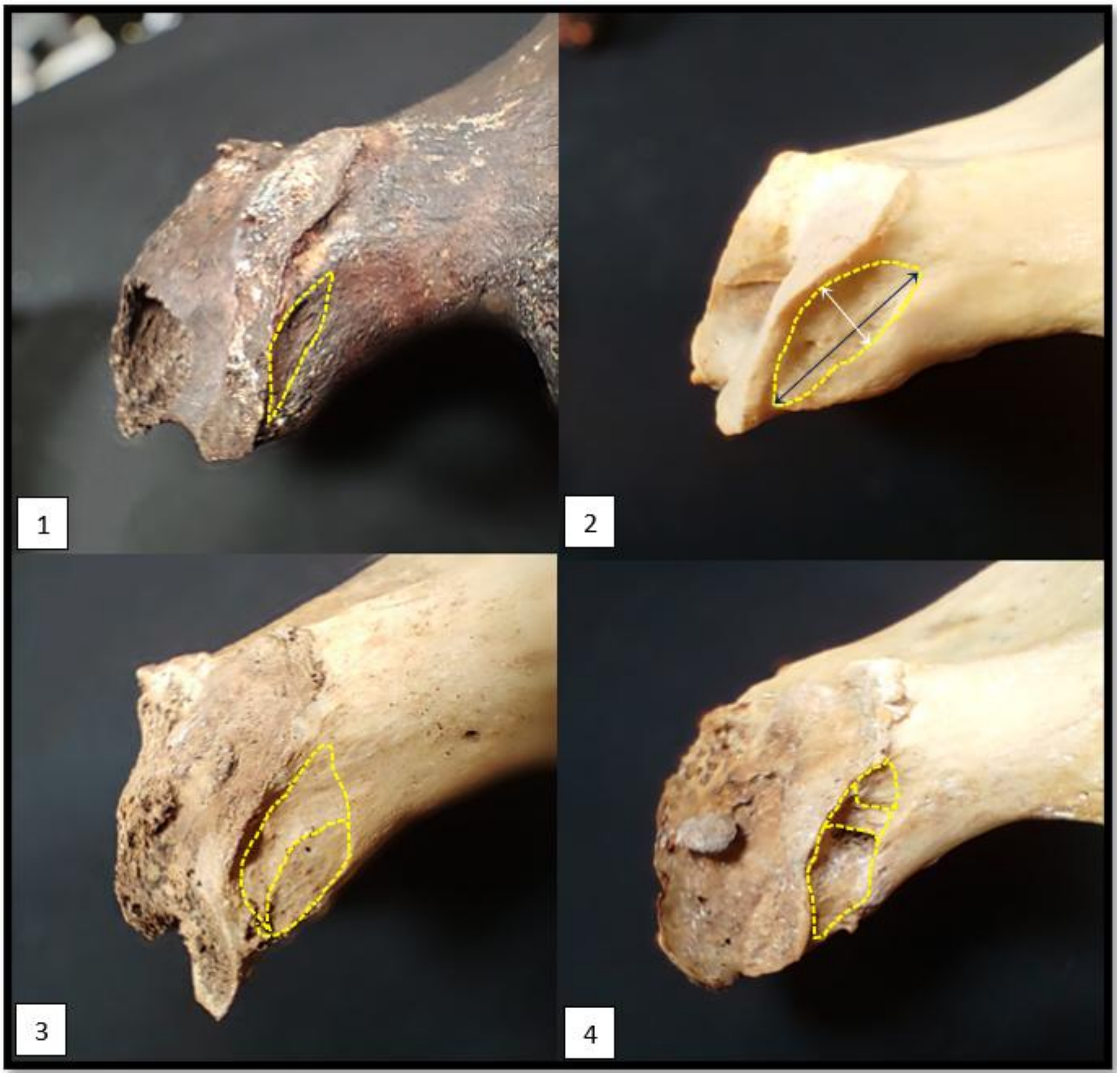


Figure 13.Examples of a range in preauricular sulcus depth and complexity noted within the TXSTDSC research sample. The yellow dotted line identifies the outer perimeter of each. Photos 1 and 2 show superficial and relatively shallow sulci, although 2 is significantly wider. Photos 3 and 4 provide more complex examples, with variable depths within the perimeter of each sulcus, each identified and separated by additional dotted lines. Photo 2 shows the standard maximum length (blue line) and maximum width (white line) measurements applied to all examples.

Figure 14. Auricular surface features (left os coxa) – identified on an individual from the TXSTDSC.

Continuing to move away from the primarily descriptive methods of previous research, length, width, and depth measurements were taken. Figure 15 highlights the maximum length measurement, comparable to Maass's (2012) interosseous analysis method. This accounts for the entire length of the inferior ramus cavity, as seen in all three photos. Specific to this research, a second measurement was taken along the superior dorsal edge where a cavity was present. This was not present in all donors, but where it was, it presented a continuation of the inferior cavity - always following a small, although variable, hiatus. Note that auricular surface lipping can be extreme and obscure the full length of the cavity area(s), so caution must be taken to analyse this section effectively. In cases where cavitation is especially shallow or narrow, small interruptions may appear along the inferior or superior lengths as a result of bridging between the post-auricular surface and auricular lipping. To simplify maximum length measurement and ensure measurement consistency, these bridges were disregarded.

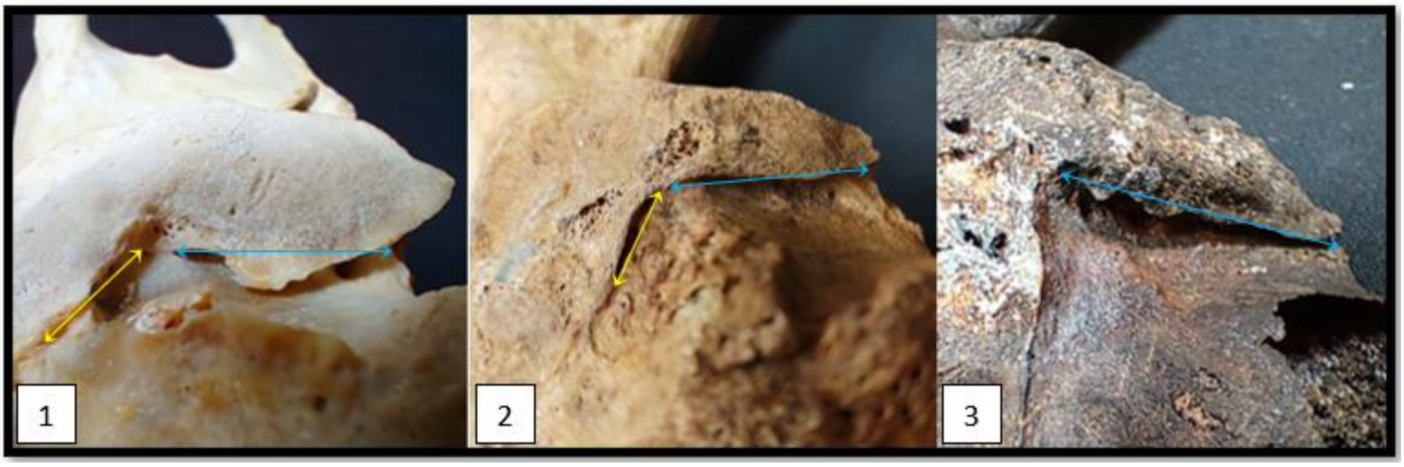


Figure 15. Examples of interosseous cavity length identified in the TXSTDSC research sample. All three shown here present with an inferior cavity, the maximum length of which was measured as depicted by the pale blue line. Photos 1 and 2 show the less commonly present superior cavity – measured in length as represented by the yellow line. Although a small degree of lipping is evident across the superior angle of the auricular surface in photo 3, this does not extend enough to facilitate measurements.

Figure 16 shows the two additional measurements: maximum width and maximum depth. Even in minor cases, the auricular lip facilitates a maximum width measurement between it and the retroauricular floor over which it extends. Maximum depth was defined as the measurement from the edge of the auricular lip to the deepest point into the cavity.

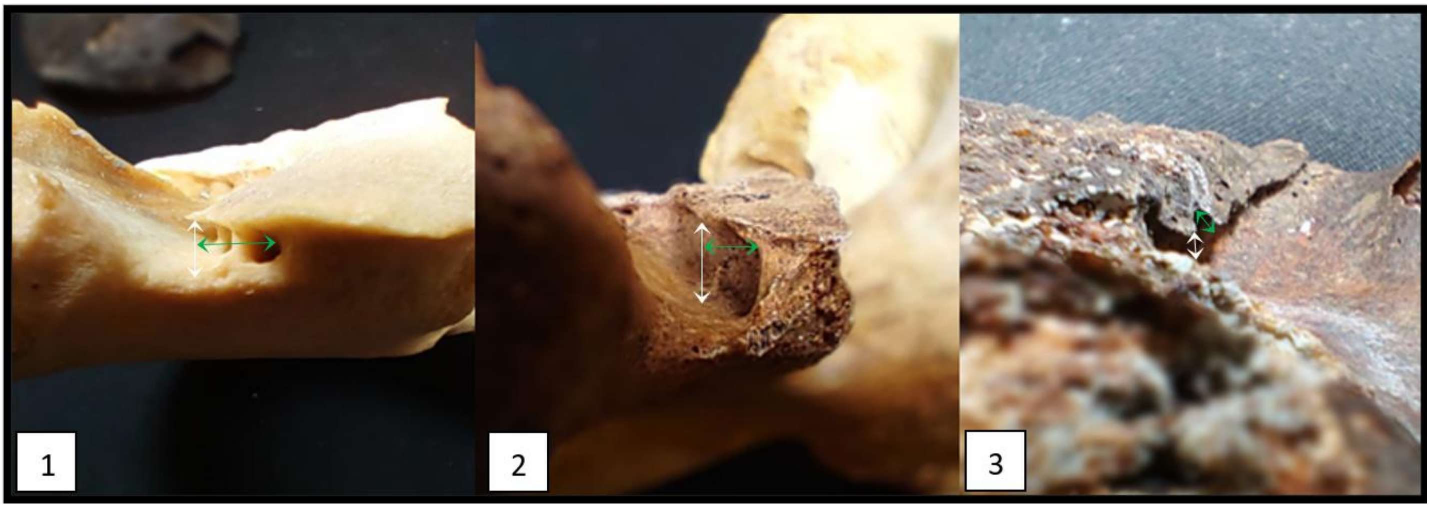


Figure 16. Examples of maximum interosseous cavity width (white line) and maximum cavity depth (green line) measurements using three examples from the TXSTDSC sample. These images depict measurements of the inferior interosseous cavity. Superior cavitation was measured in the same way.

4.4. Hypothesis Testing

All measurements were systematically taken and carefully input into an Excel spreadsheet alongside the demographic information provided by FACTS. Each measurement was checked twice before moving on to the next one to ensure accuracy during both data collection and entry. Initially, the inclusion and exclusion criteria were applied to all available female skeletons to assess their suitability for analysis of the full range of pelvic features. Once this process was complete, the male skeletons were selected based on additional anthropometric considerations as outlined in section 4.2.1. After the final sample was determined, sex information for all 220 donors was hidden, and the samples were randomised to minimise potential bias during analysis. In total, 14 direct measurements were recorded for each sample, after which additional variables were calculated using basic Excel formulae. Furthermore, simple present/absent variables were established, and the age group variable was set during this stage of data processing.

All statistical analyses were conducted using IBM SPSS Statistics version 28 due to extensive user experience. All variables were set to a scale or ordinal category, requiring some variables to be coded. For binary variables, such as sex or feature presence, a standard dichotomous ‘0/1’ coding system was adopted, as outlined by Wilson and Lorenz (2015). For age groups, ‘0’ indicates that the group is unknown and ‘1’ is awarded to the lowest value group - increasing to a maximum of ‘4’ representing the highest value groups. To facilitate clear statistical test output, all coded variables were appropriately labelled.

4.4.1. Analytical Strategy

All variables were first explored to gain insight into the fundamental characteristics of the data. This analysis generates useful frequency and distribution summaries, as well as boxplots revealing any outliers (Marsh & Elliot, 2008). Such information is essential in selecting the best statistical analyses for the data. In determining distribution normality and the outcome of any subsequent tests, statistical significance was established at the standard threshold of $p < 0.05$ (Marsh & Elliot, 2008). This threshold corresponds to a 95% confidence level, which is commonly used in biological and forensic research to strike a balance between reliability and minimising error. At this level, there is a 95% probability that observed results are not due to random chance, thereby reducing the risk of false positives. This level also ensures that the statistical tests maintain sufficient power to detect meaningful relationships, without being so stringent that false negatives become a concern. For this study, the 95% confidence level provided an appropriate balance, supporting the reliability of findings while remaining practical for evaluating the correlations between pelvic features and demographic factors.

For the examination of dichotomous variable interactions, such as sex or obstetric event occurrence against pelvic feature presence or absence variables, chi-square χ2(1) tests were performed, as is common in this area of research (Andersen, 1986; Spring et al., 1989; Cox & Scott, 1992; Holt, 1978; Igarashi et al., 2019; Kelley, 1979; Maass, 2012; Maass & Friedling, 2016; McArthur et al., 2016; Praxmarer et al., 2020; Wescott, 2015). This test allows for the examination of cross-tabulated data and the detection of significant associations through Chi-square results – the strength of which can be determined based on the Phi coefficient (ϕ) (Field, 2009; Morgan et al., 2011). The strength of Phi association in this study was based on the criteria established by Rea & Parker (2014). The categories are as follows: negligible (< 0.099), weak (0.1 - 0.199), moderate (0.2 – 0.399), moderately strong (0.4 – 0.599), strong (0.6 – 0.799), and very strong (> 0.8). Notably, Chi-square testing has fewer assumptions than many other tests of association. Nonetheless, it requires two categorical variables and independence of observations (Morgan et al., 2011). Fortunately, the data met these assumptions without the need for adaptation.

Correlation tests were run to measure potential relationships between pelvic feature measurements and continuous biological variables, as seen in the research by Cox and Scott (1992), Snodgrass and Galloway (2003), Novak et al. (2012), McArthur et al. (2016), and Waltenberger et al. (2021). This study used non-parametric Spearman's correlation rank (ρ) testing when analysing continuous biological variables. This test was selected because all pairs were monotonic, but at least one variable in each pairing failed the test assumption of either a normal distribution or freedom from outliers, as required for the parametric alternative (Cronk, 2020; Morgan et al., 2011; Verma & Abdel-Salam, 2019). The decision was made to retain any outliers and use non-parametric testing at this stage since the data is solely biological and reflective of natural variation. The non-parametric Kendall's tau-b correlation (τb) test was employed to evaluate correlations between measurement and biological group variables. This test is the most suitable for this type of variable combination, and like the Spearman's rank test, abnormal data distribution or outliers do not affect it (Morgan et al., 2011).

The selection of variable pairings for further testing was based on correlation strength, with only those identified as strong being utilised. The guidelines outlined by Cronk (2020) were adhered to when analysing Spearman's Rank results, defining strong correlations as any result exceeding 0.7. Interestingly, as Sharma (2019) highlights, the correlation boundaries for tau-b tests are considerably lower than those of Spearman's correlations. In this case, a strong correlation is classified as 0.3 or higher. Hence, this threshold was utilised to evaluate biological group correlations and identify the most valuable pairings. Those selected variable combinations then underwent regression analysis to assess the predictive capabilities of independent variables – a process noted in previous studies by Andersen (1986), Novak et al. (2012), Bonczarowska et al. (2019), McArthur et al. (2016), and

Waltenberger et al. (2022). As discussed in the upcoming results chapters, all pairings that indicated strong prediction potential involved binomial biological variables. Therefore, logistic regression testing was utilised.

These identified variables naturally met all logistic regression study design assumptions outlined by Stevens (2002), given the existence of one dichotomous dependent variable alongside one or more nominal or continuous variables, independence of observations, dependent categories and independent variables' mutual exclusivity, and a minimum of 15 cases for each independent variable. The existence of linearity in the logit for continuous independent variables is another test assumption highlighted by Stevens – which was confirmed for all final model predictor variables using the Box-tidwell procedure (Box & Tidwell, 1962) with Bonferroni correction (Tabachnick & Fidell, 2014).

Stevens (2002) emphasises the importance of avoiding multicollinearity in multiple regression analyses, as this can obscure the relative potential of each predictor variable – to which Pedhazur (1997) adds can reduce or even produce false negatives for predictor significance. Furthermore, Stevens explains how multicollinearity lowers predictor precision, often manifesting as significant coefficient standard errors and an overall reduction in test power. To avoid these issues, potential collinearity was checked through the assessment of inter-variable correlation statistics (with a recommendation of caution around $r = 0.8$ or over) alongside collinearity diagnostics, usually utilised as a part of linear regression analysis, as detailed by Field (2009).

Finally, to ensure the model's predictive abilities are not significantly reduced, at this stage it becomes crucial to eliminate any outliers that might be strongly influential to the results. This test assumption was met when conducting initial logistic regression analyses, whereby case-wise diagnostics revealed potential outliers that exceeded the standardised residuals of ±2. Although it is common for some cases to fall outside this range (Menard, 2010), and some studies even suggest extending the residual allowance to ±3 (Field, 2009). As a result, this research used a median cut-off of ±2.5 as Filler and DiGabriele (2012) recommend. Therefore, in developing the final regression models, standardised residuals exceeding ±2.5 (rounded to 1.d.p) were identified as outliers and removed accordingly.

4.4.2. Graphical Presentation of Predictive Models

In presenting important models, any single variable regressions have been displayed using a simple graph plotting the measurement variable against predictive probability, with an interpolation line highlighting the natural data curve. Grid lines have been added to single variable plots to enable the accurate tracing of a known measurement to the predicted probability at the line intersection. Significant multiple variable models have been plotted as a scatter graph, accounting for two simultaneous independent measurement variables and predictive probability around a 50% (0.5) threshold. All graphs accompany the logistic regression equation - offering two methods of predicting group affinity using measurements from an unknown individual.

Employing the single-predictor method, biological sex probabilities can be identified with reference to grid lines incorporated to emphasise percent probability intersections at 10, 25, 50, 75, and 90 percent (where available). The intersection lines can be traced to the associated measurement of the predictor variable. As standard, any measurement corresponding with a probability of over 0.5/50% is associated with the positive group (in this case, female), and any below this level would be predicted as belonging to the negative group (male). However, as measurement interceptions move further from this central point, the probability of belonging to the associated group increases. To clarify, if a measurement aligns with the 75% line or produces a result of 0.75 if using the regression equation, it has a 75% probability of falling within the female group. On the other hand, a result of 10% or 0.1 implies a 90% likelihood of the case being associated with the male group.

When utilising a two-predictor model graph, group prediction is based on the intersection point of the two measurements for a single individual, which falls on either side of the diagonal 50% prediction threshold line. As with single-predictor models, where cases reside on the left of the prediction line (< 0.5), they are identified as male, and the opposite is assumed should the case fall to the right (> 0.5). Again, dotted lines on either side of the 50% threshold have been drawn to assist with result interpretation, indicating 10, 25, 75, and 90 percent prediction ranges.

Chapter 5: Results

This chapter presents the results of all analyses conducted to address the research questions and hypotheses central to this study. The chapter begins with a comprehensive overview of the full sample descriptive statistics, establishing a baseline understanding of pelvic scar feature measurements across the entire TXSTDSC research sample. This is followed by an intraobserver analysis, evaluating the consistency of measurement techniques and ensuring reliability in data collection and results. Subsequent sections focus on hypothesis-driven analyses, examining the influence of biological sex, obstetric history, age, height, and weight on pelvic scar presentation. These analyses are presented in thematic sections, allowing for a clear comparison of how different factors contribute to scar morphology. Significant findings are highlighted to establish key trends, later expanded upon in the subsequent discussion chapter.

5.1. Full Descriptive Statistics and Intra-observer Error Testing

Table 6 presents the descriptive statistics and percentage frequencies for all pelvic scar feature measurements across the full TXSTDSC research sample. Dorsal pubic pitting was present in just 20% of the entire sample. As expected, multi-pit length exhibited the greatest maximum value (26.36 mm) and highest mean value (1.66 mm) when compared to a maximum single pit length of p18.78 mm and mean of 1.28 mm. Pitting width and depth had lower maximum values (6.47mm and 4.54mm, respectively), with mean values of 0.61mm and 0.32 mm, reflecting the general shape of pitting on the dorsal pubic surface. Conversely, the preauricular sulcus demonstrated a high prevalence within the sample, present in 84.5% of individuals. Sulcus length exhibited the largest maximum value of all scar features (54.06 mm), with a mean of 20.38 mm and a standard deviation of 12.01 mm, suggesting considerable variability in sulcus presentation. Sulcus width and depth also showed substantial measurements, with maximum values of 18.75 mm and 4.76 mm, and mean values of 5.25 mm and 1.31 mm, respectively.

The inferior cavity was present in 93.6% of the sample, compared to 29.1% for the superior cavity. Inferior cavity length had the second-largest maximum measurement across all scar features (36.62 mm), with a mean of 19.16 mm and a standard deviation of 8.78 mm, indicating high variability. The inferior cavity width and depth showed maximum values of 7.51 mm and 8.94 mm, with mean values of 2.33 mm and 2.4 mm, respectively. Superior cavity measurements were notably smaller, with the highest maximum recorded for cavity length (29.24 mm) but with a much lower mean (3.32 mm), and width and depth maximum values of 4.61 mm and 4.37 mm, respectively, with mean values of 0.5 mm and 0.42 mm. The differences between superior and inferior cavitation are representative of the shape of the auricular surface bordering the retroauricular space.

Pubic tubercle extension was the most universally present scar feature, identified in 98.6% of the sample. The maximum measurement for pubic tubercle extension was 9.18 mm, with a mean of 3.35 mm and a standard deviation of 1.7 mm, indicating some variability in presentation, albeit with lower overall values compared to other scar features. Overall, scar feature presence varied widely across the sample, with high prevalence in preauricular sulcus, inferior interosseous cavity, and pubic tubercle extension, contrasting with the lower occurrence of dorsal pubic pitting and superior interosseous cavity features. The range of maximum and mean measurements suggests considerable variability in scar morphology, with sulcus length and inferior cavity length presenting as the most variable dimensions.

Table 6. Descriptive statistics for the full TXSTDSC research sample scar feature variables.

Scar site	Measurement variable	Scar feature present (%)	Scar feature absent (%)	Maximum value (mm)	Mean value (mm)	Std. Deviation
Dorsal pubic pitting	Pit length – Single	20	80	18.78	1.28	3.42
	Pitting length – Multi			26.36	1.66	4.37
	Pitting width			6.47	0.61	1.42
	Pitting depth			4.54	0.32	0.76
Preauricular sulcus	Sulcus length	84.5	15.5	54.06	20.38	12.01
	Sulcus width			18.75	5.25	3.47
	Sulcus depth			4.76	1.31	1.02
Interosseous cavitation	Superior cavity length	29.1	70.9	29.24	3.32	6.04
	Superior cavity width			4.61	0.5	0.92
	Superior cavity depth			4.37	0.42	0.85
	Inferior cavity length	93.6	6.4	36.62	19.16	8.78
	Inferior cavity width			7.51	2.33	1.31
	Inferior cavity depth			8.94	2.4	1.75
Pubic tubercle extension		98.6	1.4	9.18	3.35	1.7

To ensure that the subsequent analyses are robust and reliable, error testing was conducted to validate the consistency of scar feature measurements. While interobserver testing was not feasible due to time and logistical constraints, intra-observer analysis provided a critical evaluation of measurement precision, supporting the integrity of the dataset used in all further analyses. This process enhances the validity of the findings by demonstrating that any minor variations in scar measurements were not due to inconsistencies in data collection.

Direct measurements were duplicated for the first 20 samples, with a one-week interval between the initial and secondary measurements. The second set of measurements was recorded blindly to prior results to prevent bias. Once both data sets were obtained, intra-observer error was assessed using Cronbach's Alpha internal consistency test (Cronbach, 1951), a widely recognised method for evaluating the reliability of repeated data sets (Dimitrov, 2002). The test yielded an exceptionally high Cronbach's Alpha of 0.99 (see Table 7), indicating near-perfect consistency between the two sets of measurements (Zeller, 2005).

Table 7. Intra-observer results for all basic scar feature measurements, presented as the average measurements across the first 20 TXSTDSC cases.

Measurement variable	Measure 1 (mm)	Measure 2 (mm)	Absolute difference	Relative difference (%)
Pit length – Single pit	0.94	0.92	0.02	2.12
Pitting length – Multi pits	1.84	1.83	0.01	0.54
Pitting width	0.63	0.71	0.08	12.7
Pitting depth	0.27	0.26	0.01	3.7
Sulcus length	2.91	2.91	0	0
Sulcus width	17.12	17.70	0.58	3.39
Sulcus depth	4.84	4.98	0.14	3
Superior cavity length	1.45	1.33	0.12	8.28
Superior cavity width	19.26	19.43	0.17	0.88
Superior cavity depth	2.74	2.61	0.13	4.74
Inferior cavity length	2.76	2.85	0.09	3.26
Inferior cavity width	3.54	3.57	0.03	0.85
Inferior cavity depth	0.70	0.69	0.01	1.43
Pubic tubercle extension	0.67	0.67	0	0

Table 7 shows the mean values for each scar measurement variable across the 20 samples. The maximum absolute difference was 0.58 mm for sulcus width, and the maximum relative difference was 12.7% for pit width. Despite these variations, repeat testing for all scar variables consistently produced a high Cronbach's Alpha of 0.99, demonstrating excellent measurement precision. For the 20 samples in the intra-observer study, the median of the two measurements was used in subsequent analyses. However, due to the minimal variation observed and the statistically insignificant intra-observer error, it was determined that incorporating specific error adjustments into the final statistical models was unnecessary. The high reliability coefficient indicated that measurement errors were controlled within acceptable limits, minimising their impact on data analysis. As a result, no further error terms related to intra-observer variation were included in the final statistical models. This decision aligns with best practices in quantitative research, where additional error terms are only warranted when measurement variability exceeds a threshold that may compromise data integrity (Dimitrov, 2002). Including unnecessary error terms could risk overfitting the data, potentially reducing the overall robustness of the analysis.

5.2. Sexual Dimorphism and Pelvic Scarring

This section presents the results of analyses examining sexual dimorphism in pelvic scar feature presentation, using Tables 8–16 to explore both non-metric and metric data. The objective is to determine whether biological sex significantly influences the occurrence and dimensions of pelvic scar features and to evaluate their predictive capacity, providing insights into sex-based morphological variation within the pelvis. The analysis begins with an evaluation of scar feature presence, comparing male and female samples to identify dimorphic patterns. This includes frequency analyses of scar feature occurrence and statistical testing to assess significant sex-based differences. Subsequent analyses incorporate descriptive statistics and examine metric associations with biological sex, applying statistical tests and logistic regression models to evaluate the predictive strength of scar feature dimensions for biological sex estimation.

5.2.1. Scar Feature Presence

Tables 8 and 9 detail any associations between biological sex and the presence of each of the five pelvic scar features separately, indicating all but pubic tubercle extension as being statistically significant to varying degrees. Cross-tabulation revealed that 158 of 169 females exhibited a preauricular sulcus, although over half of the males (54.9%) also presented with the feature, resulting in a moderately strong feature-sex association ($\phi = 0.451$). Presenting a reduced association strength, inferior interosseous cavitation was present in 165 females, but also 41 of the 51 males ($\phi = 0.298$). Dorsal pubic pitting was present in just 3 males and 41 females, producing a weak association of $\phi = 0.194$. Presenting the weakest of the statistically significant associations, 56 of 169 females had evidence of superior interosseous cavitation, while only 8 males exhibited it ($\phi = 0.162$).

Table 8. Cross-tabulated data for individual scar feature occurrence - presented for the TXSTDSC full and single-sex samples.

Pelvic scar feature		Scar feature absent count	Scar feature present count
Dorsal pubic pitting	Male	48 (94.1%)	3 (5.9%)
	Female	128 (75.7%)	41 (24.3%)
	Total	176 (80%)	44 (20%)
	Correct prediction (IF M = absent; F = present)	89 (40.5%)	
Preauricular sulcus	Male	23 (45.1%)	28 (54.9%)
	Female	11 (6.5%)	158 (93.5%)
	Total	34 (15.5%)	186 (84.5%)
	Correct prediction (IF M = absent; F = present)	181 (82.3%)	
Superior interosseous cavity	Male	43 (84.3%)	8 (15.7%)
	Female	113 (66.9%)	56 (33.1%)
	Total	156 (70.9%)	64 (29.1%)
	Correct prediction (IF M = absent; F = present)	99 (45%)	
Inferior interosseous cavity	Male	10 (19.6%)	41 (80.4%)
	Female	4 (2.4%)	165 (97.6%)
	Total	14 (6.4%)	206 (93.6%)
	Correct prediction (IF M = absent; F = present)	175 (79.5%)	
Pubic tubercle extension	Male	0 (0%)	51 (100%)
	Female	3 (1.8%)	166 (98.2%)
	Total	3 (1.4%)	217 (98.6%)
	Correct prediction (IF M = absent; F = present)	166 (75.5%)	

Table 9. Chi-square and Phi strength of association results for each scar feature occurrence within the full TXSTDSC sample.

Pelvic scar feature	Chi-square value (χ2)	Strength of association (ϕ)	Test significance (*p*)
Dorsal pubic pitting	8.27	0.194	0.004
Preauricular sulcus	44.65	0.451	< 0.001
Superior interosseous cavity	5.783	0.162	0.016
Inferior interosseous cavity	19.544	0.298	< 0.001
Pubic tubercle extension	0.918	-0.065	0.338

Tables 10 and 11 focus on potential association between the total number of scars present and biological sex ($\phi = 0.504$). There was an initial increase in scarring in males, from just 3 males with one scar feature, to up to three features observed in 22 males. There was a significant reduction in the number of males with four of five scar sites, with none having all five scar features. Conversely, no biological females had just one feature, and just 11 females presented with only two. A similar percentage of females as males presented with three features. However, a considerably higher percentage of females than males were observed to have four of five features, and 14 females (8.3%)

had all five, including cavitation at inferior and superior dorsal auricular borders. Note that all individuals across the full sample had at least one of the scar features.

Table 10. Cross-tabulated data for the total number of pelvic scar features - presented for the TXSTDSC full and single-sex samples.

	Total number of pelvic scar features present				
	1	2	3	4	5
Male	3 (5.9%)	21 (41.2%)	22 (43.1%)	5 (9.8%)	0 (0%)
Male (accumulative 1 - 4)	3 (5.9%)	24 (47.1%)	46 (90.2%)	51 (100%)	
Female	0 (0%)	11 (6.5%)	83 (49.1%)	61 (36.1%)	14 (8.3%)
Female (accumulative 5 - 2)		169 (100%)	158 (93.5%)	75 (44.4%)	14 (8.3%)

Table 11. Chi-square and Phi strength of association results for the total number of pelvic scar features within the full TXSTDSC sample.

Chi-square value (χ2)	Strength of association (ϕ)	Test significance (*p*)
55.856	0.504	< 0.001

5.2.2. Scar Feature Measurements

Table 12 presents the descriptive statistics for all individual scar measurements for both male and female groups separately, including maximum, mean, and standard deviation values. Complementing the above results, the percentage of males and females for which each feature was absent has been presented in place of the minimum value, as this was zero in all cases. This table shows almost no dimorphic variation in pubic tubercle extension absence. All remaining features were absent in a higher percentage of males than females, although the absence count was high for dorsal pubic pitting and superior interosseous cavity, and low for inferior interosseous cavity across both sexes. The preauricular sulcus absence was most dimorphic, with a percentage-point difference of 38.6. Meanwhile, Scar feature measurements were consistently larger in females than in males across all variables, except for pubic tubercle extension, where males exhibited a higher mean value. Differences were particularly pronounced in features surrounding the sacroiliac joint and pelvic cavities, with females displaying substantially larger scar dimensions in both maximum and mean values.

The largest sex difference was observed in sulcus length, where the maximum measured 54.06 mm in females, compared to just 26.23 mm in males. Mean values reflected an equally stark contrast, with females averaging 24.04 mm, while males averaged just 8.23 mm. Sulcus width followed a similar pattern, with maximum values of 18.75mm in females versus 5.26 mm in males, and mean values of

6.38mm and 1.52 mm, respectively. The second most substantial sex difference occurred in superior cavity length, which had a maximum of 29.24 mm in females but only 11.27 mm in males. Mean values showed an even greater disparity, with females measuring 4.02 mm on average, compared to just 0.99 mm in males.

Another clear example of sex-based variation was found in inferior cavity depth, where the maximum was 8.94 mm in females but only 2.86 mm in males. Mean values similarly reflected this difference, at 2.87 mm and 0.84 mm, respectively. Pit measurements also showed a notable difference between sexes. Single-pit length had a maximum of 18.78 mm in females and 9.45 mm in males, with mean values of 1.53 mm and 0.44 mm, respectively. Multi-pit length followed a similar trend, with maximum values of 26.36 mm in females and 9.45 mm in males, and mean values of 2 mm and 0.55 mm. These findings indicate that males are less likely to develop extensive pitting scars than females.

A notable exception to this pattern was observed in pubic tubercle extension. While males had a lower maximum value (7.52 mm) than females (9.18 mm), their mean measurement was higher (4 mm in males compared to 3.16 mm in females). This was the only feature where males exhibited a greater average value, suggesting that while females occasionally develop larger pubic tubercle extensions, males display more consistent development of this scar feature.

5.2.3. Metric Analysis

All tau-b correlations between variable measurements and biological sex were statistically significant ($p = < 0.05$) (see Table 13). The most prominent feature was the preauricular sulcus, which presented a strong correlation ($\tau b > 0.3$) with biological sex across all three measurements. This was followed by the inferior interosseous cavity, where width and depth displayed strong correlations ($\tau b = 0.448$ and 0.444), while the length was moderately correlated ($\tau b = 0.223$). Consequently, these scar features were selected as the focus of further analysis.

Ahead of logistic regression analysis, key measurements were assessed for multicollinearity, a condition where independent variables are highly correlated, potentially distorting statistical models by inflating standard errors and weakening the reliability of regression coefficients. Collinearity diagnostics showed no significant findings overall, but strong intercorrelations were detected between the most statistically valuable dimension pairs for both the sulcus and inferior cavity, with correlation coefficients of $r = .781$ and $r = .721$, respectively. While not critical enough to entirely invalidate the regression analysis, these correlations posed a risk of discreet multicollinearity, which could affect model performance.

Table 12. Descriptive statistics for the full TXSTDSC sample (n = 220), male-only sample (n = 51), and female-only sample (n = 169).

Measurement variable	Scar feature absent count			Maximum value (mm)		Mean value (mm)			Std. Deviation		
	Full sample	Males	Females	Males	Females	Full sample	Males	Females	Full sample	Males	Females
Pit length – Single	176 (80%)	48 (94.1%)	128 (75.7%)	9.45	18.78	1.28	0.44	1.53	3.42	1.88	3.73
Pitting length – Multi				9.45	26.36	1.66	0.55	2	4.37	2.21	4.79
Pitting width				2.43	6.47	0.61	0.11	0.76	1.42	0.46	1.57
Pitting depth				1.34	4.54	0.32	0.07	0.4	0.76	0.27	0.84
Sulcus length	34 (15.5%)	23 (45.1%)	11 (6.5%)	26.23	54.06	20.38	8.23	24.04	12.01	8.46	10.41
Sulcus width				5.26	18.75	5.25	1.52	6.38	3.47	1.59	3.07
Sulcus depth				3.54	4.76	1.31	0.55	1.54	1.02	0.7	0.99
Superior cavity length	156 (70.9%)	43 (84.3%)	113 66.9%)	11.27	29.24	3.32	0.99	4.02	6.04	2.61	6.58
Superior cavity width				1.90	4.61	0.5	0.2	0.59	0.92	0.51	0.99
Superior cavity depth				2.41	4.37	0.42	0.18	0.49	0.85	0.48	0.93
Inferior cavity length	14 (6.4%)	10 (19.6%)	4 (2.4%)	32.18	36.62	19.16	14.18	20.66	8.78	9.96	7.82
Inferior cavity width				2.40	7.51	2.33	1.16	2.68	1.31	0.715	1.25
Inferior cavity depth				2.86	8.94	2.4	0.84	2.87	1.75	0.77	1.69
Pubic tubercle extension	3 (1.4%)	0 (0%)	3 (1.8%)	7.52	9.18	3.35	4	3.16	1.7	1.39	1.74

Note: Minimum values are absent from the above table, as the minimum is 0.0 mm for all variables except for male pubic tubercle extension, at 1.52 mm. The full sample maximum value data is absent as it is consistently represented by the female value.

To mitigate this issue and preserve all relevant dimensional data without discarding any variables, a practical solution was adopted: the measurements were cubed to approximate a volume variable. This transformation served two key purposes. First, it reduced the risk of multicollinearity by integrating correlated measurements into a single composite variable, thus simplifying the dimensional data structure. Second, it allowed the use of all key measurements in regression without redundancy, enhancing the model's predictive capability for sex estimation.

It is acknowledged that the structures being measured are not perfectly cubic in shape, and the resulting volume is an approximation rather than an anatomically precise value. However, the focus was not on obtaining an exact physical representation of volume but on leveraging a proxy measure to maximise statistical validity. By combining multiple dimensions in this manner, the statistical model effectively accounted for variations in overall size and shape, reducing collinearity without compromising data integrity. Correlation statistics for these two new variables can be found in Table 13 (highlighted in bold).

Further descriptive statistics for the two new approximate volume variables are presented in Table 14. A clear disparity exists between males and females, directly linked to the larger measurements recorded for the female population (refer to Table 12). The maximum and mean values for females are significantly higher than those for males, and larger values inherently produce a greater spread in the data, leading to a higher standard deviation. This effect is further amplified by the cubic scaling, where even moderate differences in individual measurements result in disproportionately larger variations in the calculated volume. Overall, the tenfold difference in standard deviation reflects both the inherent differences in dimensional measurements between sexes and the statistical effects of cubing those values. This disparity does not indicate error or bias in the data but rather highlights natural and proportional differences in the scale and variability of pelvic morphology across the male and female samples.

Table 13. Kendall's tau-b correlation results for all individual scar feature measurements in the TXSTDSC sample (n = 220).

Measurement variable	Correlation (τb)	sig. (*p*)
Pit length – Single pit	0.179	0.005
Pitting length – Multi pits	0.179	0.005
Pitting width	0.189	0.003
Pitting depth	0.188	0.004
Sulcus length	0.457	< 0.001
Sulcus width	0.504	< 0.001
Sulcus depth	0.39	< 0.001
Superior cavity length	0.177	0.005
Superior cavity width	0.163	0.01
Superior cavity depth	0.154	0.014
Inferior cavity length	0.223	< 0.001
Inferior cavity width	0.448	< 0.001
Inferior cavity depth	0.444	< 0.001
Pubic tubercle extension	-0.202	< 0.001
Sulcus approximate volume	**0.505**	**< 0.001**
Inferior cavity approximate volume	**0.445**	**< 0.001**

Table 14. Approximate volume variable descriptive statistics for the TXSTDSC full sample (n = 220), male-only sample (n = 51), and female-only sample (n = 169).

Measurement variable	Maximum value (mm)			Mean value (mm)			Std. Deviation		
	Full sample	Males	Females	Full sample	Males	Females	Full sample	Males	Females
Sulcus approximate volume	3074.6	218.79	3074.6	250.11	23.04	318.63	354.74	36.98	378.5
Inferior cavity approximate volume	968.05	138.95	968.05	164.4	25.1	206.44	197.64	30.72	207.29

5.2.4. Single-variable Logistic Regression Models

Data regarding the single-variable logistic regression models generated using the newly computed approximate volume variables can be found in Tables 15 and 16 (data not in bold). Both single-variable models were highly statistically significant ($p < 0.001$). The approximate volume of the preauricular sulcus alone explains a substantial proportion of the variation in biological sex (67.9%). This model revealed that a 1 mm increase in sulcus volume is associated with a 4.7% increase in the odds of an individual being biologically female and accurately classified 86.5% of cases, with higher sensitivity than specificity.

In the context of this work, sensitivity refers to the proportion of biological females correctly predicted by the model, while specificity refers to the proportion of biological males correctly predicted. Higher sensitivity than specificity indicates that the model more effectively predicts biological females than males. While this may reduce the accuracy of male classification, it ensures greater reliability in identifying females, which can be beneficial depending on the forensic or biological profile application.

The inferior interosseous cavity model showed a lower odds ratio, with a 3.9% increase in the odds of being biologically female per 1 mm increment. This model explained a slightly lower proportion of biological sex variation (52.2%) than the sulcus volume model. In this case, specificity was reduced to just over 56%, leading to a decrease in the overall classification accuracy to 80.2%. Both single-variable prediction graphs produced using these regression models are presented as Figures 17 and 18.

5.2.5. Multi-variable Logistic Regression Model

A final regression model was developed using 210 individuals from the original sample after removing residuals >±2.5. This involved assessing both key features in combination, conforming to the same biological sex threshold as the single-variable models. The information in Tables 15 and 16 in bold provides the final regression model statistics, and Figure 19 offers the prediction graph corresponding with the multivariable equation statistics in bold in Table 16. This graph can be used to estimate unknown samples by plotting the intersecting measurement point, or alternatively, the standard logistic regression equation can be used:

$$\text{Probability} = P = \frac{1}{1 + e^{-(\beta 0+\beta 1X1+\beta 2X2)}}$$

In this equation, the constant coefficient (β0) is -8.739, and the approximate volume variable coefficients (β1 and β2) are 0.091 for the preauricular sulcus and 0.095 for the inferior interosseous cavity, respectively. X1 and X2 refer to the corresponding input measurements for each case.

Cases where one of the two regression variables was absent were included in the analysis. Just three males did not present with either of the final key scar features, equating to only 5.9% of the male sample. Meanwhile, just one female had neither scar feature (0.6% of the female sample) – although this female was one of 10 samples excluded as residuals in the development of the final model. Combining the two variables produced the most robust prediction model, again highly statistically significant (*p* = < 0.001). When both approximate volume measurements were utilised simultaneously, the data analysis identified that for every 1 mm increase in sulcus volume, there was a 9.5% increase in the odds of the individual being biologically female, while the same measurement increase in inferior cavity volume was linked to a 10% increase in the odds of being biologically female. This model produced a final accuracy of 97.1%, reducing the disparity between sensitivity and specificity percentages – both of which were over 91%.

5.2.6. Method Validation – Application of the Final Predictive Model

Table 17 presents the results of the final sex estimation method as applied to the validation sample. These results have been categorised based on the likelihood of each individual being female, given their approximate preauricular sulcus and inferior interosseous cavity volume measurements. Individuals identified as 'very likely' male fell within the less than 10% probability range for being female, while 'likely' males were classified as just 10-25% likely to be female. Conversely, 'likely' females were identified based on a 75-90% predicted likelihood of being female, while an over 90% likelihood indicated that an individual is 'very likely' female. Around the 50% separation line, individuals over 25% but less than 50% likely to be female were categorised as 'most likely' male, versus those categorised as 'most likely' female at between 50% and 75% likely to be female.

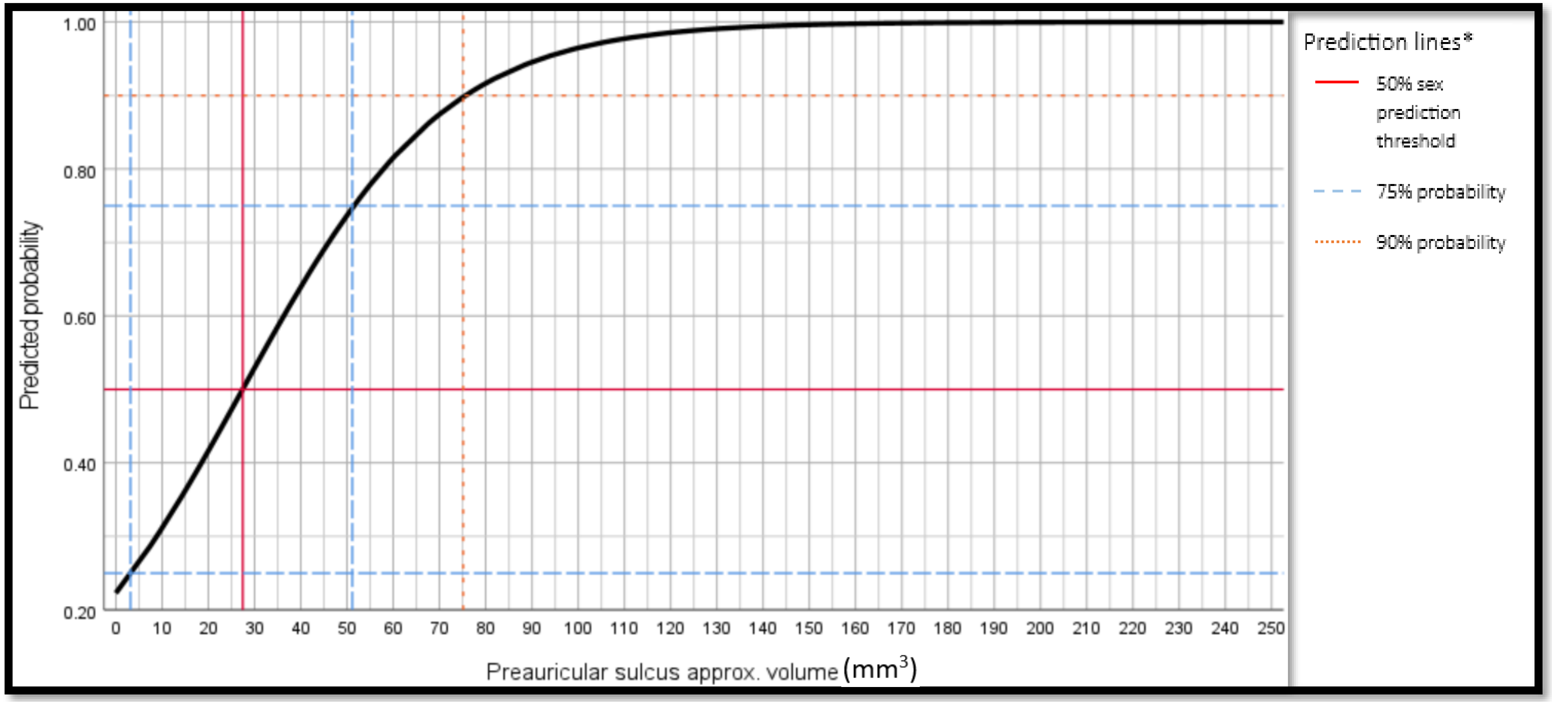
Table 17 reveals a final estimation accuracy of 90.7% across the sample - with a higher accuracy rate for males than females, at 97.67% (42 of 43) and 83.73% (36 of 43), respectively. This equates to the incorrect biological sex estimation of just one male and seven females around the 50% predicted probability line assigned by the method. Focusing on the male sample only, over 86% of all biological males, and 88.1% of those correctly estimated, were categorised as very likely male. 76.74% of the total number of biological females, or 91.7% of all of those correctly estimated, fell into the very likely female category.

Table 15. Summary and classifications for single-predictor and combined logistic regression models (sulcus approximate volume and inferior cavity approximate volume).

Predictor variable(s) for the model	Sample (n)	Max ZResid. (1.d.p)	Chi-square (χ2)	Sig. (*p*)	Nagelkerke (R^2)	% males (0) correctly predicted (specificity)	% females (1) correctly predicted (sensitivity)	Total % correctly predicted	Positive predictive value (%)	Negative predictive value (%)
Sulcus approx. volume	215	none	99.221	< 0.001	0.679	73.9% (34 of 46)	89.9% (152 of 169)	86.5%	92.7%	66.7%
Inferior cavity approx. volume	217	none	90.437	< 0.001	0.522	56.3% (27 of 48)	87% (147 of 169)	80.2%	87.5%	55.1%
Sulcus approx. volume and inferior cavity approx. volume	**210**	**none**	**200.795**	**< 0.001**	**0.935**	**91.7% (44 of 48)**	**98.8% (160 of 162)**	**97.1%**	**97.6%**	**95.7%**

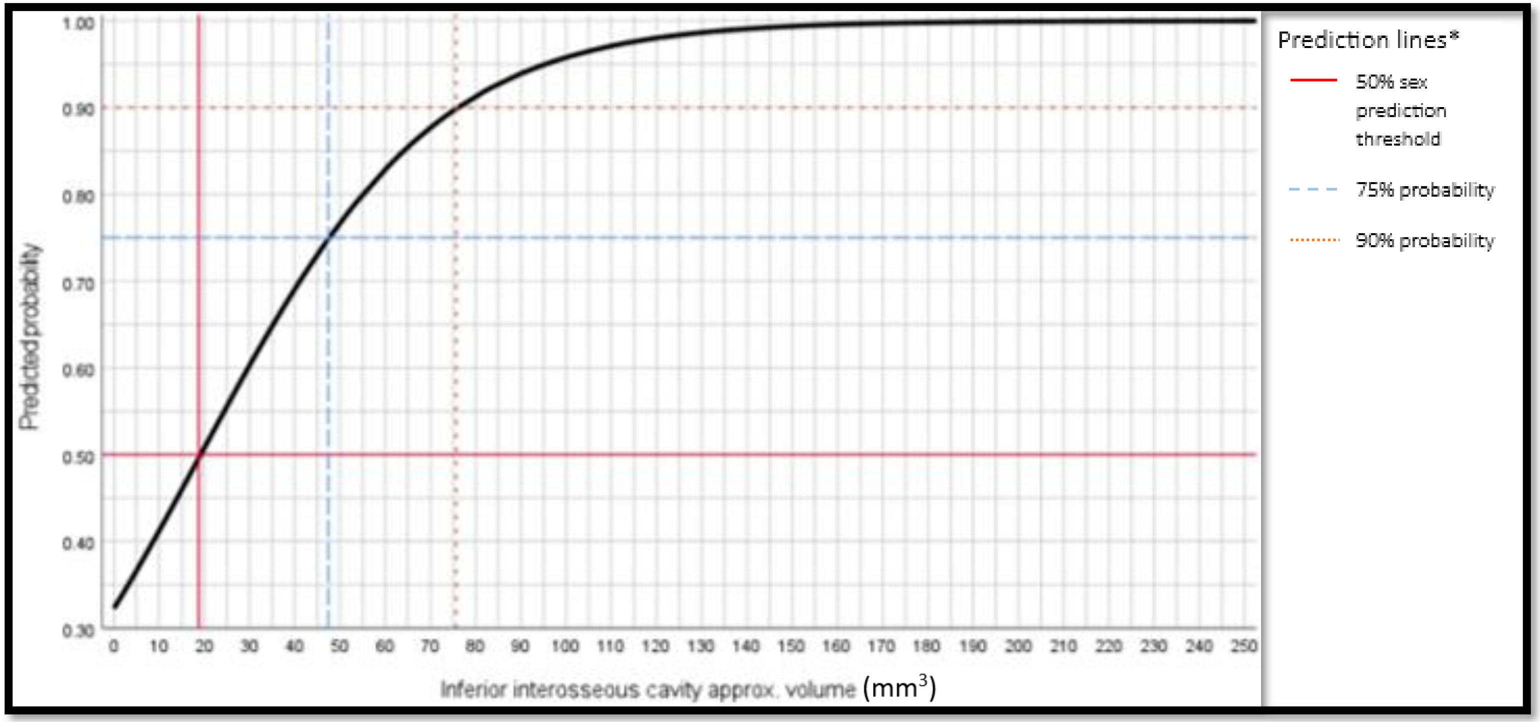
Table 16. Variables in the equation for single-predictor and combined logistic regression models (sulcus approximate volume and inferior cavity approximate volume).

Predictor variable for model	Equation variable	B	S.E.	Wald	Sig. (*p*)	Exp (B)	95% C.I. for Exp (B) – lower and upper boundaries	
Sulcus approx. volume	Predictor	0.046	0.009	27.247	< 0.001	1.047	1.029	1.065
	Constant	-1.249	0.333	14.068	< 0.001	0.287		
Inferior cavity approx. volume	Predictor	0.039	0.008	24.873	< 0.001	1.039	1.024	1.055
	Constant	-0.741	0.294	6.376	0.012	0.476		
Sulcus approx. volume and inferior cavity approx. volume	**Sulcus vol. (predictor 1)**	**0.091**	**0.025**	**13.311**	**< 0.001**	**1.095**	**1.043**	**1.15**
	Inferior cavity vol. (predictor 2)	**0.095**	**0.028**	**12.035**	**< 0.001**	**1.1**	**1.042**	**1.161**
	Constant	**-8.739**	**2.499**	**12.231**	**< 0.001**	**0.000**		



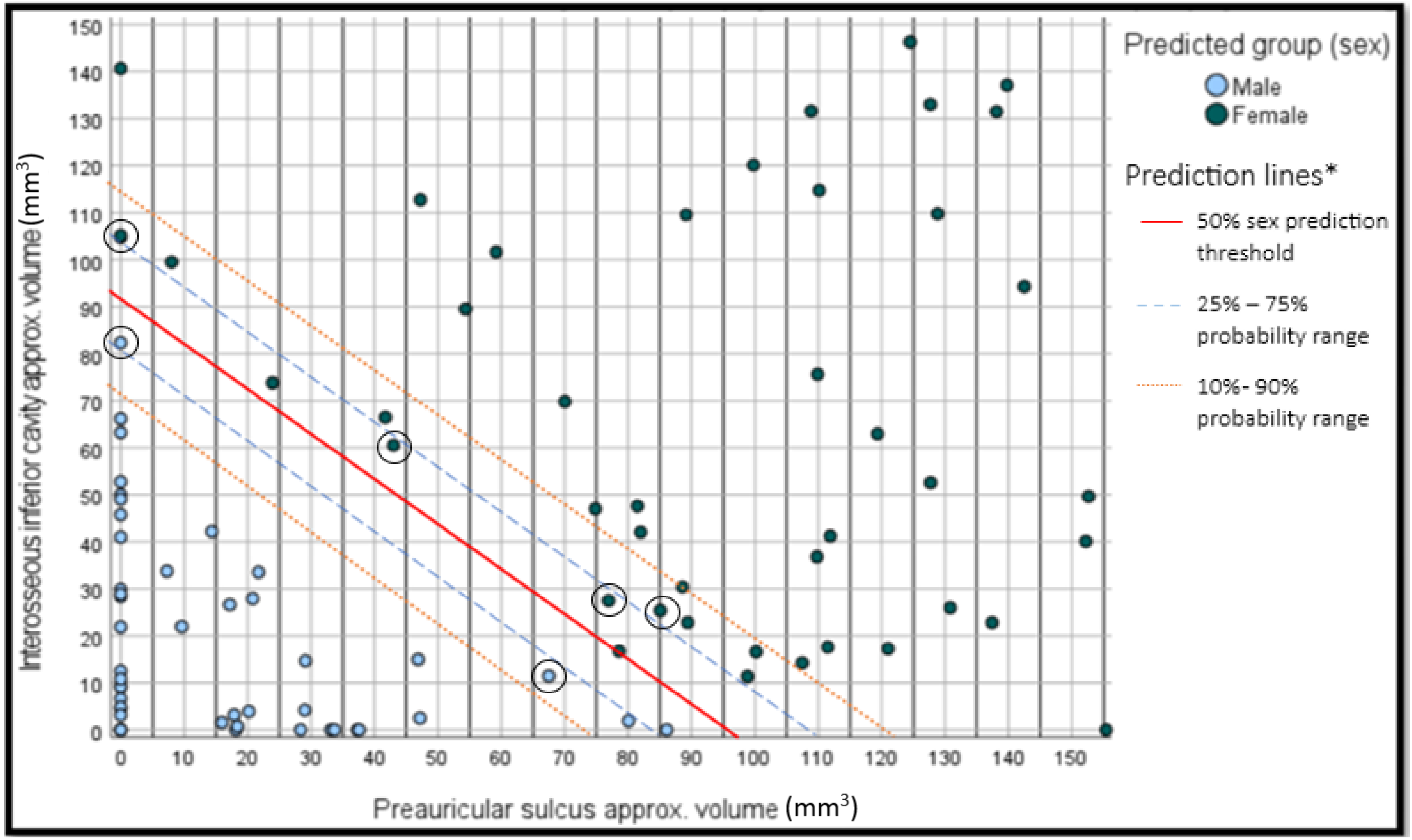
* Note: *50% sex prediction threshold (< 50% = male; > 50% = female). The 25% - 75% range represents the probability of being female but can be reversed to represent the probability of being male. Similarly, the 90% probability of being female can be considered a 10% probability of being male.*

Figure 17. Graphical presentation of the predicted probability of being female based on the approximate volume of the preauricular sulcus - limited to 250mm to aid intersection interpretation. The solid red line represents the intersection between sulcus volume and 50% probability (< 50% = male; > 50% = female), the blue dashed lines highlight measurements associated with 25% and 75% probabilities, and the dotted orange line represents the point from which there is a 90%+ probability of being female.



** Note: 50% sex prediction threshold (< 50% = male; > 50% = female). The 75% probability of being female can be reversed to represent a 25% probability of being male. Similarly, the 90% probability of being female can be considered a 10% probability of being male.*

Figure 18. Graphical presentation of the predicted probability of being female based on the approximate volume of the inferior interosseous cavity - limited to 250mm to aid prediction intersection interpretation. The solid red line represents the intersection between inferior cavity volume and 50% probability (< 50% = male; > 50% = female), the blue dashed line highlights the measurement associated with a 75% probability, and the dotted orange line represents the point from which there is a 90%+ probability of being female.



* Note: 50% sex prediction threshold (<50% = male; >50% = female). 25% - 75% and 10% - 90% ranges represent the probabilities of being female, but each range can be reversed to represent the probability of being male.

Figure 19. Graphical presentation of biological sex prediction using the TXSTDSC sample, based on interactions between the approximate volume of the inferior interosseous cavity and the approximate volume of the preauricular sulcus (Table 16). The axis measurements have been limited to 150mm to aid prediction boundary interpretation. Circled cases indicate those that were incorrectly estimated by the model.

Table 17. Validation sample (n =86) classifications for male and female groups, based on the probability of being female according to the final estimation method.

	Classification ranges					
Sample	Very likely male (<10%)	Likely male (10% - 25%)	Most likely male (25% - 50%)	Most likely female (50% - 75%)	Likely female (75% - 90%)	Very likely female (>90%)
Biological males (n = 43)	37	4	1	0	0	1
Accumulative male accuracy (left to right)	86.05%	95.35%	97.67%			
Biological females (n = 43)	4	2	1	3	0	33
Accumulative female accuracy (right to left)				83.73%	76.74%	76.74%
Total (n = 86)	41	6	2	3	0	34

Total accuracy = 90.7%

5.3. Obstetric Events and Pelvic Scarring

Using Tables 18–21, this section explores whether gravidity and parity significantly affect the occurrence and dimensions of pelvic scar features, providing insights into how pregnancy and childbirth may contribute to pelvic morphological changes. The analyses begin with an evaluation of scar feature presence, comparing gravid and nulligravid females as well as parous and nulliparous females, with the full sample included to assess potential sex-based differences. This includes frequency analyses and statistical testing. The chapter then progresses to metric analyses, incorporating descriptive statistics for scar feature measurements across obstetric groups. These analyses examine maximum, mean, and variability data to assess whether obstetric events influence scar dimensions. Finally, statistical tests and correlation analyses are employed to determine the strength of associations between obstetric status and scar feature measurements, offering a comprehensive assessment of if, or how, pregnancy and childbirth affect pelvic scarring.

5.3.1. Scar Feature Presence

Tables 18 and 19 provide data on the presence of each scar feature in association with gravidity and parity across the complete and female-only samples. Analysis indicated moderate associations between the presence of scar features and obstetric events in the combined sex sample, excluding pubic tubercle presence. The preauricular sulcus presence was most strongly associated with gravidity ($\chi 2(1) = 29.777$, $\phi = 0.368$), present in 121 of 126 gravid individuals, but also 65 of 94 nulligravid individuals (including biological males). The same feature presented the strongest relationship with parity ($\chi 2(1) = 26.381$, $\phi = 0.346$), appearing in 116 of 121 parous individuals and 70 of 99 nulliparous.

Removing the male sample reduced the number and strength of associations, with only the preauricular sulcus and superior interosseous cavity presence remaining associated with gravidity and parity. For females, the sulcus presence was weakly associated with gravidity ($\chi 2(1) = 5.253$, $\phi = 0.176$), present in 36 of 43 nulligravid females, and even less so with parity ($\chi 2(1) = 3.954$, $\phi = 0.153$), seen in 42 of 48 nulliparous females. Superior interosseous cavitation was moderately related to gravidity ($\chi 2(1) = 9.579$, $\phi = 0.238$), present in 50 of 126 gravid females and 14 of 94 nulligravid females, and moderately associated with parity ($\chi 2(1) = 8.207$, $\phi = 0.22$), found in 48 of 121 parous females and 8 of 48 nulliparous females. The associations for superior cavitation were weaker in females compared to the mixed-sex sample for both obstetric groups.

5.3.2. Scar Feature Measurements

Table 20 provides descriptive statistics for scar feature measurements across obstetric groups, structured to assess the influence of gravidity and parity on pelvic scarring, while also controlling for sex-based effects.

Positive and Negative Obstetric Comparisons

Scar feature measurements generally increased from negative to positive obstetric groups, with both maximum and mean values tending to be higher in gravid and parous females than in their nulligravid and nulliparous counterparts. For most features, maximum values increased across obstetric group pairings (gravid and nulligravid; parous and nulliparous). Superior cavity length, for example, increased from 22.66 mm in nulligravid and nulliparous females to 29.24 mm in both gravid and parous females. Similarly, sulcus width showed an increase from 12.13 mm in negative obstetric groups to 18.75 mm in both positive obstetric groups. The largest increase observed was in pit width, which rose from 3.01 mm to 6.47 mm in the gravidity pairing and from 4.29 mm to 6.47 mm in the parity pairing. Mean values followed a similar trend, with increases across positive obstetric groups. Superior cavity length nearly doubled in mean value, rising from 2.28 mm (nulligravid) and 2.26 mm (nulliparous) to 4.61 mm (gravid) and 4.72 mm (parous). Sulcus width also increased in mean value from 5.75 mm (nulligravid) and 5.82 mm (nulliparous) to 6.6 mm in both gravid and parous groups. The pattern observed in pit width was also reflected in mean values, rising from 0.32 mm to 0.91 mm in the gravidity analysis and 0.38 mm to 0.92 mm in the parity analysis.

Table 18. Scar occurrence in obstetric groups cross-tabulation within the TXSTDSC full sample (n = 220), female sample (n = 169), and comparative male sample (n =51).

		Gravidity				Parity				Male-only Sample (n = 51)	
		Full Sample (n = 220)		Female-only Sample (n = 169)		Full Sample (n = 220)		Female-only Sample (n = 169)			
Pelvic scar feature		Feature absent	Feature present	Feature absent	Feature present	Feature absent	Feature present	Feature absent	Feature present	Feature absent	Feature present
Dorsal pubic pitting	Negative Group*	**84** (89.4%)	**10** (10.6%)	**36** (83.7%)	**7** (16.3%)	**88** (88.9%)	**11** (11.1%)	**40** (83.3%)	**8** (16.7%)	n/a	
	Positive Group*	**92** (73%)	**34** (27%)	**92** (73%)	**34** (27%)	**88** (72.7%)	**33** (27.3%)	**88** (72.7%)	**33** (27.3%)		
	Total	**176** (80%)	**44** (20%)	**128** (75.7%)	**41** (24.3%)	**176** (80%)	**44** (20%)	**128** (75.7%)	**41** (24.3%)	**48** (94.1%)	**3** (5.9%)
	Correctly Predicted	**118** (53.6%)		**70** (41.4%)		**121** (55%)		**73** (43.2%)		n/a	
Preauricular sulcus	Negative Group*	**29** (30.9%)	**65** (69.1%)	**6** (14%)	**37** (86%)	**29** (29.3%)	**70** (70.7%)	**6** (12.5%)	**42** (87.5%)	n/a	
	Positive Group*	**5** (4%)	**121** (96%)	**5** (4%)	**121** (96%)	**5** (4.1%)	**116** (95.9%)	**5** (4.1%)	**116** (95.9%)		
	Total	**34** (15.5%)	**186** (84.5%)	**11** (6.5%)	**158** (93.5%)	**34** (15.5%)	**186** (84.5%)	**11** (6.5%)	**158** (93.5%)	**23** (45.1%)	**28** (54.9%)
	Correctly Predicted	**150** (68.2%)		**127** (75.1%)		**145** (65.9%)		**122** (72.2%)		n/a	
Superior interosseous cavity	Negative Group*	**80** (85.1%)	**14** (14.9%)	**37** (86%)	**6** (14%)	**83** (83.8%)	**16** (16.2%)	**40** (83.3%)	**8** (16.7%)	n/a	
	Positive Group*	**76** (60.3%)	**50** (39.7%)	**76** (60.3%)	**50** (39.7%)	**73** (60.3%)	**48** (39.7%)	**73** (60.3%)	**48** (39.7%)		
	Total	**156** (70.9%)	**64** (29.1%)	**113** (66.9%)	**56** (33.1%)	**156** (70.9%)	**64** (29.1%)	**113** (66.9%)	**56** (33.1%)	**43** (84.3%)	**8** (15.7%)
	Correctly Predicted	**130** (59.1%)		**87** (51.5%)		**131** (59.5%)		**88** (52.1%)		n/a	
Inferior interosseous cavity	Negative Group*	**12** (12.8%)	**82** (87.2%)	**2** (4.7%)	**41** (95.3%)	**12** (12.1%)	**87** (87.9%)	**2** (4.2)	**46** (95.8%)	n/a	
	Positive Group*	**2** (1.6%)	**124** (98.4%)	**2** (1.6%)	**124** (98.4%)	**2** (1.7%)	**119** (98.3%)	**2** (1.7%)	**119** (98.3%)		
	Total	**14** (6.4%)	**206** (93.6%)	**4** (2.4%)	**165** (97.6%)	**14** (6.4%)	**206** (93.6%)	**4** (2.4%)	**165** (97.6%)	**10** (19.6%)	**41** (80.4%)
	Correctly Predicted	**136** (61.8%)		**126** (74.6%)		**131** (59.5%)		**121** (72%)		n/a	
Pubic tubercle extension	Negative Group*	**0** (0%)	**94** (100%)	**0** (0%)	**43** (100%)	**0** (0%)	**99** (100%)	**0** (0%)	**48** (100%)	n/a	
	Positive Group*	**3** (2.4%)	**123** (97.6%)	**3** (2.4%)	**123** (97.6%)	**3** (2.5%)	**118** (97.5%)	**3** (2.5%)	**118** (97.5%)		
	Total	**3** (1.4%)	**117** (98.6%)	**3** (1.8%)	**163** (98.2%)	**3** (1.4%)	**117** (98.6%)	**3** (1.8%)	**163** (98.2%)	**0** (0%)	**51** (100%)
	Correctly Predicted	**123** (55.9%)		**123** (72.8%)		**118** (53.6%)		**118** (69.8%)		n/a	

* Groups: Gravidity (negative = nulligravid; positive = gravid), Parity (negative = nulliparous; positive = parous)

Table 19. Chi-square and Phi strength of association results for each scar feature occurrence, comparing the TXSTDSC full (n = 220) and female-only (n = 169) results across gravidity and parity groups.

Pelvic scar feature	Gravidity						Parity					
	Full Sample			Female-only Sample			Full Sample			Female-only Sample		
	Chi-square value (χ2)	Strength of association (ϕ)	Test sig. (*p*)	Chi-square value (χ2)	Strength of association (ϕ)	Test sig. (*p*)	Chi-square value (χ2)	Strength of association (ϕ)	Test sig. (*p*)	Chi-square value (χ2)	Strength of association (ϕ)	Test sig. (*p*)
Dorsal pubic pitting	8.99	0.202	0.003	1.999	0.109	0.157	8.889	0.201	0.003	2.104	0.112	0.147
Preauricular sulcus	29.777	0.368	< 0.001	5.253	0.176	0.022	26.381	0.346	< 0.001	3.954	0.153	0.047
Superior interosseous cavity	16.037	0.27	< 0.001	9.579	0.238	0.002	14.587	0.257	< 0.001	8.207	0.22	0.004
Inferior interosseous cavity	11.29	0.227	< 0.001	1.302	0.088	0.254	10.014	0.213	0.002	0.94	0.075	0.332
Pubic tubercle extension	2.269	-0.102	0.132	1.042	-0.079	0.307	2.488	-0.106	0.115	1.212	-0.085	0.271

Two features exhibited opposing trends, where maximum values decreased from negative to positive obstetric groups, with variation in mean values. Sulcus length showed a reduction in maximum value from 54.06 mm (nulligravid and nulliparous) to 52.52 mm (gravid and parous), although the mean increased from 20.4 mm (nulligravid) to 25.29 mm (gravid) and 20.75 mm (nulliparous) to 25.35 mm (parous). Pubic tubercle extension followed the same pattern for maximum values, decreasing from 9.18 mm to 8.31 mm. Mean values also decreased in both comparisons, from 3.4 mm (nulligravid) to 3.07 mm (gravid) and from 3.28 mm (nulliparous) to 3.11 mm (parous).

Gravid and Parous Female Comparisons

Comparisons between positive obstetric groups revealed that all maximum values remained stable across scar features, while the majority of mean values showed slight increases in parous groups. For example, maximum values for sulcus measurements (width, depth, and length) exhibited no change, remaining at 18.75 mm, 4.76 mm, and 52.52 mm, respectively. However, mean sulcus depth increased marginally from 1.62 mm to 1.63 mm, and sulcus length from 25.29 mm to 25.35 mm. Pitting, cavitation, and tubercle measurements presented similarly, with just single pit length and superior cavity width not exhibiting a mean increase, alongside sulcus width. The largest difference can be seen in inferior cavity length, with a mean increase of 0.23 mm from gravid to parous female groups.

5.3.3. Metric Analysis

Table 21 presents Kendall's tau-b correlation results for scar feature measurements across both the full sample and the female-only sample, assessing the relationships between scar features and obstetric variables. All scar measurements were correlated with gravidity and parity in the mixed-sex sample, with most associations at least moderate ($\tau b > 0.2$). Exceptions to this pattern included single pit length, inferior cavity length, tubercle extension, and multi-pit length in the parity assessment, where correlations were weaker. The strongest correlations were observed for preauricular sulcus measurements, with maximum sulcus length producing the highest correlation with both obstetric variables (gravidity: $\tau b = 0.399$; parity: $\tau b = 0.387$). Other sulcus measurements, and all but the length measurement for the inferior interosseous cavity, also demonstrated moderate-to-strong associations with both gravidity and parity. Superior cavity measurements were also moderately correlated with obstetric history, particularly superior cavity depth (gravidity: $\tau b = 0.258$; parity: $\tau b = 0.251$). When analysing the female-only sample, statistically significant correlations were reduced. Sulcus length and width remained correlated with obstetric status, but at a lower strength than in the full sample. The only variable to retain a moderate correlation with both gravidity ($\tau b = 0.226$) and parity ($\tau b = 0.216$) was superior cavity depth.

Table 20. Scar measurement data for obstetric groups within the TXSTDSC full sample (n = 220), female sample (n = 169), and comparative male sample (n =51).*

Measurement variable	Gravid			Nulligravid (females)			Parous			Nulliparous (females)			Males only		
	Max (mm)	Mean (mm)	Std. dev	Max (mm)	Mean (mm)	Std. dev	Max (mm)	Mean (mm)	Std. dev	Max (mm)	Mean (mm)	Std. dev	Max (mm)	Mean (mm)	Std. dev
Pit length – Single	18.78	1.82	4.02	15.97	0.75	2.61	18.78	1.82	4.02	15.97	0.84	2.69	9.45	0.44	1.88
Pitting length – Multi	26.36	2.42	5.28	15.97	0.69	2.53	26.36	2.45	5.28	15.97	0.79	2.63	9.45	0.55	2.21
Pitting width	6.47	0.91	1.74	3.01	0.32	0.78	6.47	0.92	1.74	4.29	0.38	0.94	2.43	0.11	0.46
Pitting depth	4.54	0.47	0.93	1.91	0.19	0.47	4.54	0.48	0.92	1.91	0.2	0.49	1.34	0.07	0.27
Sulcus length	52.52	25.29	9.65	54.06	20.4	11.75	52.52	25.35	9.65	54.06	20.75	11.25	26.23	8.23	8.46
Sulcus width	18.75	6.6	2.89	12.13	5.75	3.53	18.75	6.6	2.89	12.13	5.82	3.47	5.26	1.52	1.59
Sulcus depth	4.76	1.62	1.01	3.55	1.28	0.9	4.76	1.63	1.01	3.55	1.31	0.88	3.54	0.55	0.7
Superior cavity length	29.24	4.61	6.68	22.66	2.28	6.04	29.24	4.72	6.68	22.66	2.26	5.77	11.27	0.99	2.61
Superior cavity width	4.61	0.7	1.05	2.87	0.28	0.73	4.61	0.7	1.05	2.87	0.32	0.75	1.90	0.2	0.51
Superior cavity depth	4.37	0.61	1.02	1.47	0.14	0.38	4.37	0.62	1.02	1.47	0.16	0.4	2.41	0.18	0.48
Inferior cavity length	36.62	20.61	7.68	36.44	20.8	8.29	36.62	20.84	7.68	36.44	20.22	8.64	32.18	14.18	9.96
Inferior cavity width	7.51	2.76	1.27	6.04	2.5	1.18	7.51	2.79	1.27	6.04	2.42	1.2	2.40	1.16	0.72
Inferior cavity depth	7.94	2.96	1.75	6	2.58	1.47	7.94	3.01	1.75	6	2.52	1.46	2.86	0.84	0.77
Pubic tubercle extension	8.31	3.07	1.7	9.18	3.4	1.86	8.31	3.11	1.7	9.18	3.28	1.8	7.52	4	1.39

**Minimum values are absent, as variable absence occurs in all variables across all groups with the exception of pubic tubercle extension, presenting with a minimum value of 0.62 mm in nulligravid and nulliparous female groups, and 1.52 mm in males.*

Table 21. Kendall's tau-b correlation results for all scar feature measurements, comparing the TXSTDSC sample full (n = 220) and female-only (n = 169) results for gravidity and parity group associations.

	Gravidity				Parity			
	Full Sample		Female-only Sample		Full Sample		Female-only Sample	
Variable measurements (mm)	Correlation (τb)	sig. (*p*)	Correlation (τb)	sig. (*p*)	Correlation (τb)	sig. (*p*)	Correlation (τb)	sig. (*p*)
Pit length – single	0.198	0.002	0.118	0.104	0.196	0.002	0.118	0.106
Pit length – multi	0.2	0.002	0.121	0.097	0.199	0.002	0.122	0.094
Pit width	0.207	0.001	0.122	0.094	0.204	0.001	0.121	0.096
Pit depth	0.204	0.002	0.117	0.107	0.202	0.002	0.119	0.102
Sulcus length	0.399	< 0.001	0.168	0.008	0.387	< 0.001	0.168	0.008
Sulcus width	0.382	< 0.001	0.083	0.189	0.37	< 0.001	0.087	0.167
Sulcus depth	0.329	< 0.001	0.122	0.055	0.315	< 0.001	0.116	0.068
Superior cavity length	0.256	< 0.001	0.192	0.007	0.253	< 0.001	0.191	0.007
Superior cavity width	0.248	< 0.001	0.198	0.005	0.237	< 0.001	0.184	0.01
Superior cavity depth	0.258	< 0.001	0.226	0.001	0.251	< 0.001	0.216	0.002
Inferior cavity length	0.136	0.014	-0.011	0.857	0.147	0.008	0.014	0.826
Inferior cavity width	0.328	< 0.001	0.068	0.282	0.335	< 0.001	0.094	0.137
Inferior cavity depth	0.324	< 0.001	0.074	0.24	0.331	< 0.001	0.101	0.109
Pubic tubercle extension	-0.161	0.004	-0.048	0.45	-0.134	< 0.001	-0.017	0.79

5.4. Age, Height, Weight, and Pelvic Scarring

5.4.1. Scar Feature Presence – Age Groups

Table 22 presents the occurrence of scar features across age groups for those of known age-at-death within the full, female-only, and male-only samples. In the female sample, the preauricular sulcus was highly prevalent across all age groups, with occurrence rates exceeding 93%, except for the 80+ category, where it declined slightly to 89.2%. The inferior interosseous cavity followed a similar pattern, maintaining an occurrence rate above 83.3% in all female age groups, maintaining an occurrence rate of over 97.3% from the age of 40 onwards. Superior interosseous cavity occurrence peaked in the female 60–79 group (38.6%) before declining to 29.7% in the 80+ group. In the male sample, the superior interosseous cavity displayed a slight increase in occurrence across age groups, rising from 16.7% in the 40–59 group to 27.3% in the 80+ group. However, overall occurrence remained lower than in the female sample. Dorsal pubic pitting demonstrated a clear age-related trend in females, with 33.7% of individuals aged 60–79 exhibiting the feature, but a decline to 16.2% in females aged 80+ – comparable to that in the 20-39 female age group. The male sample exhibited much lower overall dorsal pubic pitting occurrence, with no recorded cases in individuals under 80, and only two occurrences in males aged 80+ (18.2%). Pubic tubercle extension was present in over 96% of females across all age groups and in 100% of males, indicating no clear relationship with age.

5.4.2. Scar Feature Measurements and Metric Analysis - Age

Tables 23–25 present the descriptive statistics for pelvic scar feature measurements by age group, detailing the full sample, female-only sample, and male-only sample separately. These tables provide insights into how scar feature dimensions vary with age, highlighting key trends in maximum, mean, and variability measurements across the 20–39, 40–59, 60–79, and 80+ age groups. Table 26 provides the results of the correlative analysis, highlighting any significant relationships between those measurements and age groups.

Full Sample

Table 23 presents the metric data for pelvic scar feature measurements across all age groups in the full sample, revealing age-related trends and overall variability in scar feature presentation.

Dorsal pubic pitting exhibited no clear trend in single-pit length, with no differences between single and multi-pit length values in the 20–39 and 40–59 age groups, suggesting either a single pit presence or secondary pitting within a larger one. Multi-pitting was observed in the 60–79 and 80+ groups, with maximum multi-pit length increasing from 20.86mm to 26.36mm, while mean values reduced from

2.02 mm (60–79) to 1.82 mm (80+), both lower than the mean for the 20–39 group (2.35mm). Pitting width and depth increased with age, with maximum width rising from 4.44mm (20–39) to 6.47 mm (60–79), before reducing to 6.07 mm (80+), while mean values were irregular, peaking at 0.82mm (60–79). Pitting depth rose steadily from 1.66 mm (20–39) to 4.54mm (80+).

The preauricular sulcus exhibited a general increase in maximum length, peaking at 54.06 mm (60–79), before declining slightly to 52.52 mm (80+). Mean sulcus length showed a more defined trend, increasing to a peak of 22.18 mm (40–59), and then reducing to 21.48 mm (60–79) and 17.8 mm (80+). Sulcus width increased from 9.92mm (20–39) to 18.75 mm (60–79), before dropping to 12.06 mm (80+), with mean values peaking at ~5.9mm in the 20–39 and 40–59 age groups. Sulcus depth increased from 2.11 mm (20–39) to over 4mm in subsequent age groups, while mean values remained steady between 1.24 mm and 1.34 mm.

Considering interosseous cavitation, superior cavity length increased from 8.9 mm (20–39) to 29.24 mm (60–79), before declining to 22.66 mm (80+), mirrored in the mean trend. Superior cavity width rose from 1.2mm to 4.61mm in the 80+ group, while depth values increased consistently, peaking at 4.06mm. Inferior cavity length remained high, with maximum values above 36mm across all age groups, while mean length ranged from 15.66 mm (20–39) to 20.03 mm (80+). Inferior cavity width increased to 7.51 mm (40–59), then reduced to 5.01 mm (80+). Inferior depth rose from 5.22 mm (20–39) to 8.94 mm (60–79) before reducing to 6.69 mm (80+), with mean values remaining stable.

Pubic tubercle extension reached a maximum of 9.18 mm (60–79), before decreasing to 7.52 mm (80+), showing a comparable trend to the youngest group (7.02 mm). Mean values were highest in the youngest group (3.92 mm), dropping to ~3.3mm in the remaining age groups.

Single-Sex Samples

Tables 24 and 25 present the metric data for pelvic scar feature measurements by age group in the female-only and male-only samples, highlighting key trends and differences compared to the full sample (Table 23). This section provides a comprehensive synthesis of all scar variables, offering insights into sex-based differences in scar feature presentation.

Single-pit and multi-pit length trends in females were consistent with the full sample, with identical maximum values across all age groups, while mean values were generally higher in females, particularly in younger groups. For example, the mean single-pit length in females reached 3.13 mm (20–39), compared to 2.35 mm in the full sample. Multi-pit length also showed identical maximums to the full sample, increasing to 26.36 mm (80+), while female mean values remained consistently higher, indicating greater pitting severity. In males, single-pit and multi-pit lengths remained 0.00 mm across all age groups until the 80+ group, where maximum values of 9.45 mm were recorded for both variables. Mean values were consistently low, at 1.21 mm (single-pit) and 1.72 mm (multi-pit), showing minimal pitting development compared to the full and female samples. Pitting width and depth followed similar trends, with maximum values of 1.72 mm for width and 1.34 mm for depth appearing only in the 80+ group, while mean measurements remained very low, at 0.3 mm (width) and 0.21 mm (depth), reflecting significantly reduced pitting presentation.

The preauricular sulcus in females exhibited maximum length values identical to the full sample, peaking at 54.06mm (60–79) and declining to 52.52 mm (80+), demonstrating comparable extreme sulcus length across mixed-sex and female samples. However, mean sulcus length in females was higher, reaching 25.25 mm (60–79) compared to 21.48 mm in the full sample, and declining to 21.44 mm (80+) (17.8 mm in the full sample). Sulcus width and depth followed full sample trends in females, with maximum width at 18.75 mm (60–79) and maximum depth at 4.76 mm, while mean values were also higher, peaking at 7.49 mm (width) and 1.61 mm (depth), suggesting broader and deeper sulcus presentation in females. In males, maximum sulcus length peaked at 26.23 mm (60–79), then declined to 14.32 mm (80+), presenting significantly lower measurements than in females and the full sample. Mean sulcus length remained consistently lower, not exceeding 9.45 mm (60–79) and dropping to 5.55 mm (80+), highlighting a reduced average sulcus length in older males. Sulcus width in males increased gradually, with maximum values of 5.26 mm (80+), while mean width stayed low, peaking at 1.56 mm, then declining to 1.31 mm (80+). Sulcus depth in males exhibited reduced measurements, with maximum depth increasing from 0.48 mm (20–39) to 3.54 mm (80+), while mean values remained under 0.7mm, underscoring minimal sulcus depth development.

For superior and inferior interosseous cavities, female measurements were largely consistent with the full sample, with maximum superior cavity length reaching 29.24 mm (60–79) and inferior cavity length exceeding 36 mm across most age groups. The single exception was observed in the 20–39 group, where female inferior cavity length was lower (25.37 mm) compared to 29.47 mm in the full sample. All mean values for superior and inferior interosseous cavity measurements were higher in females, with mean superior cavity length at 1.48 mm (20–39) compared to 1.11 mm in the full sample, reflecting greater average scarring potential in females. In males, superior cavity length reached only 11.27 mm (80+ group), significantly lower than in females and the full sample, with mean values remaining low, peaking at 1.75 mm (80+). Maximum superior cavity width and depth were also lower in males, at 1.9 mm (width) and 2.41 mm (depth), with mean values consistently minimal, peaking at 0.42 mm (width) and 0.45 mm (depth). Inferior cavity length in males ranged from 25.11 mm (40–59), peaking at 32.18 mm (60–79), with mean values showing reduced variability, averaging 15.8 mm (80+) – thus demonstrating limited scarring development.

Pubic tubercle extension results in females were almost identical to the full sample, with maximum values of 9.18 mm (60–79), but the female 80+ sample maximum reduced to 6.56 mm, compared to 7.52 mm in the full sample. Mean values remained stable, ranging between 3.21 mm and 3.8 mm, showing marginally lower averages than the full sample. In males, maximum values peaked at 7.52 mm (80+), lower than the 9.18 mm maximum in the female and full samples, while mean values remained consistently higher than in females, averaging around 4 mm, showing reduced variability but higher consistency in males.

Correlations

Through the presentation of Chi-square and Phi results, Table 26 confirms a lack of significant relationships between age groups and scar feature occurrence in the full sample or male sample. However, in the female-only sample, a significant association was identified between age groups and dorsal pubic pitting presence ($\chi^2 = 8.032$, $p = 0.045$), supporting an age-related trend in females. Meanwhile, Table 27 presents the results of linear correlation analyses between biological age and scar feature measurements for full and single-sex groups. This table reveals a weak positive correlation between male age and all dorsal pubic pitting measurements ($\rho = 0.328$, $p = 0.028$), however, this correlation is based on a small number of older males with pitting (n = 2). Despite the significant categorical association in Table 22, no significant correlations were found between continuous age and scar feature measurements in the female-only sample.

5.4.3. Metric Analysis - Height and Weight

Table 27 further presents the results of linear correlation analyses between scar feature measurements and height and weight variables. Weak negative correlations were identified between height and all sulcus measurements ($\rho = -0.236$ to -0.332, $p < 0.001$), as well as inferior cavity width ($\rho = -0.337$, $p < 0.001$) and inferior cavity depth ($\rho = -0.282$, $p < 0.001$). In contrast, a positive correlation was observed between height and pubic tubercle extension ($\rho = 0.252$, $p < 0.001$), suggesting that taller individuals exhibited greater pubic tubercle extension. Weak negative correlations were observed between weight and sulcus length ($\rho = -0.200$, $p = 0.014$), inferior cavity width ($\rho = -0.185$, $p = 0.023$), and inferior cavity depth ($\rho = -0.213$, $p = 0.009$). These findings indicate that individuals with lower body mass tend to exhibit a longer sulcus and a wider and deeper inferior interosseous cavity. No significant correlations were found within the individual-sex samples, including those identified as significant in the full sample.

Table 22. Cross-tabulated data showing the occurrence of scar features by age-at-death groups within full and single-sex TXSTDSC samples.

Pelvic Scar Feature (**P** = present; **A** = absent)		Full Sample					Female Sample					Male Sample				
		20 – 39 (n = 8)	40 – 59 (n = 49)	60 – 79 (n = 109)	80+ (n = 48)	Total (n = 220)	20 – 39 (n = 6)	40 – 59 (n = 43)	60 – 79 (n = 83)	80+ (n = 37)	Total (n = 169)	20 – 39 (n = 2)	40 – 59 (n = 6)	60 – 79 (n = 26)	80+ (n = 11)	Total (n = 51)
Dorsal pubic pitting	**P**	1 (12.5%)	6 (12.2%)	28 (25.7%)	8 (16.7%)	44 (20%)	1 (16.7%)	6 (14%)	28 (33.7%)	6 (16.2%)	41 (24.3%)	0 (0%)	0 (0%)	0 (0%)	2 (18.2%)	3 (5.9%)
	A	7 (87.5%)	43 (87.8%)	81 (74.3%)	40 (83.3%)	176 (80%)	5 (83.3%)	37 (86%)	55 (66.3%)	31 (83.8%)	128 (75.7%)	2 (100%)	6 (100%)	26 (100%)	9 (81.8%)	48 (94.1%)
Preauricular sulcus	**P**	7 (87.5%)	43 (87.8%)	94 (86.2%)	38 (79.2%)	186 (84.5%)	6 (100%)	40 (93%)	79 (95.2%)	33 (89.2%)	158 (93.5%)	1 (50%)	3 (50%)	15 (57.7%)	5 (45.5%)	28 (54.9%)
	A	1 (12.5%)	6 (12.2%)	15 (13.8%)	10 (20.8%)	34 (15.5%)	0 (0%)	3 (7%)	4 (4.8%)	4 (10.8%)	11 (6.5%)	1 (50%)	3 (50%)	11 (42.3%)	6 (54.5%)	23 (45.1%)
Superior interosseous cavity	**P**	1 (12.5%)	13 (26.5%)	36 (33%)	14 (29.2%)	64 (29.1)	1 (16.7%)	12 (27.9%)	32 (38.6%)	11 (29.7%)	56 (33.1%)	0 (0%)	1 (16.7%)	4 (15.4%)	3 (27.3%)	8 (15.7%)
	A	7 (87.5%)	36 (73.5%)	73 (76%)	34 (70.8%)	156 (70.9%)	5 (83.3%)	31 (72.1%)	51 (61.4%)	26 (70.3%)	113 (66.9%)	2 (100%)	5 (83.3%)	22 (84.6%)	8 (72.7%)	43 (84.3%)
Inferior interosseous cavity	**P**	6 (75%)	48 (98%)	102 (93.6%)	46 (95.8%)	206 (93.6%)	5 (83.3%)	43 (100%)	81 (97.6%)	36 (97.3%)	165 (97.6%)	1 (50%)	5 (83.3%)	21 (80.8%)	10 (90.9%)	41 (80.4%)
	A	2 (25%)	1 (2%)	7 (6.4%)	2 (4.2%)	14 (6.4%)	1 (16.7%)	0 (0%)	2 (2.4%)	1 (2.7%)	4 (2.4%)	1 (50%)	1 (16.7%)	5 (19.2%)	1 (9.1%)	10 (19.6%)
Pubic tubercle extension	**P**	8 (100%)	49 (100%)	106 (97.2%)	48 (100%)	217 (98.6%)	6 (100%)	43 (100%)	80 (96.4%)	37 (100%)	166 (98.2%)	2 (100%)	6 (100%)	26 (100%)	11 (100%)	51 (100%)
	A	0 (0%)	0 (0%)	3 (2.8%)	0 (0%)	3 (1.4%)	0 (0%)	0 (0%)	3 (3.6%)	0 (0%)	3 (1.8%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)

Table 23. Scar measurement data for known age groups within the TXSTDSC full sample (n = 214)*

Measurement variable	20 – 39 (n = 8)			40 – 59 (n = 49)			60 – 79 (n = 109)			80+ (n = 48)		
	Max (mm)	Mean (mm)	Std. dev	Max (mm)	Mean (mm)	Std. dev	Max (mm)	Mean (mm)	Std. dev	Max (mm)	Mean (mm)	Std. dev
Pit length – Single	18.78	2.35	6.64	15.97	0.61	2.42	17.88	1.55	3.62	12.84	1.14	3.06
Pitting length – Multi	18.78	2.35	6.64	15.97	0.61	2.42	20.86	2.02	4.6	26.36	1.82	4.99
Pitting width	4.44	0.56	1.57	4.46	0.27	0.82	6.47	0.82	1.65	6.07	0.54	1.35
Pitting depth	1.66	0.21	0.59	1.8	0.14	0.42	3.12	0.38	0.73	4.54	0.41	1.06
Sulcus length	32.16	19.74	9.94	46.84	22.18	11.39	54.06	21.48	11.92	52.52	17.8	12.59
Sulcus width	9.92	5.89	3.41	13.79	5.9	3.5	18.75	5.37	3.51	12.06	4.65	3.29
Sulcus depth	2.11	1.24	0.73	4.76	1.34	1.04	4.71	1.34	1.01	4.13	1.29	1.08
Superior cavity length	8.9	1.11	3.15	23.22	3.32	6.21	29.24	3.8	6.47	22.66	3.0	5.45
Superior cavity width	1.2	0.15	0.42	2.95	0.42	0.79	3.78	0.57	0.96	4.61	0.55	1.04
Superior cavity depth	0.27	0.03	0.1	2.51	0.3	0.57	4.37	0.48	0.9	4.06	0.54	1.05
Inferior cavity length	29.47	15.66	11.01	36.09	19.56	8.44	36.44	19.28	8.61	36.62	20.03	8.66
Inferior cavity width	4.87	1.99	1.7	7.51	2.48	1.27	6.27	2.37	1.42	5.01	2.27	1.03
Inferior cavity depth	5.22	2.11	2.06	7.34	2.8	1.84	8.94	2.28	1.7	6.69	2.52	1.7
Pubic tubercle extension	7.02	3.92	2.24	8.31	3.33	1.65	9.18	3.28	1.8	7.52	3.43	1.54

**Minimum values are absent as all values were 0.0 mm, except for pubic tubercle extension in the 20-30, 40-59, and 80+ age groups, recorded as 0.91 mm, 0.82 mm, and 0.56 mm, respectively.*

Table 24. Scar measurement data for known age groups within the TXSTDSC female sample (n = 169).

Measurement variable	20 – 39 (n = 6)				40 – 59 (n = 43)				60 – 79 (n = 83)				80+ (n = 37)			
	Min (mm)	Max (mm)	Mean (mm)	Std. dev	Min (mm)	Max (mm)	Mean (mm)	Std. dev	Min (mm)	Max (mm)	Mean (mm)	Std. dev	Min (mm)	Max (mm)	Mean (mm)	Std. dev
Pit length – Single	0.00	18.78	3.13	7.67	0.00	15.97	0.7	2.58	0.00	17.88	2.04	4.03	0.00	12.84	1.11	3.12
Pitting length – Multi	0.00	18.78	3.13	7.67	0.00	15.97	0.7	2.58	0.00	20.86	2.65	5.12	0.00	26.36	1.85	5.34
Pitting width	0.00	4.44	0.74	1.81	0.00	4.46	0.3	0.87	0.00	6.47	1.07	1.81	0.00	6.07	0.61	1.5
Pitting depth	0.00	1.66	0.28	0.68	0.00	1.8	0.16	0.44	0.00	3.12	0.49	0.8	0.00	4.54	0.47	1.18
Sulcus length	14.1	32.16	23.63	6.31	0.00	46.84	24.01	10.34	0.00	54.06	25.25	10.04	0.00	52.52	21.44	11.64
Sulcus width	4.62	9.92	7.49	1.88	0.00	13.79	6.51	3.25	0.00	18.75	6.57	3.08	0.00	12.06	5.64	2.96
Sulcus depth	0.98	2.11	1.58	0.43	0.00	4.76	1.45	1.04	0.00	4.71	1.61	0.99	0.00	4.13	1.47	1.02
Superior cavity length	0.00	8.9	1.48	3.63	0.00	23.22	3.58	6.48	0.00	29.24	4.71	7.07	0.00	22.66	3.37	5.88
Superior cavity width	0.00	1.2	0.2	0.49	0.00	2.95	0.45	0.81	0.00	3.78	0.7	1.04	0.00	4.61	0.59	1.12
Superior cavity depth	0.00	0.27	0.05	0.11	0.00	2.51	0.31	0.59	0.00	4.37	0.6	1	0.00	4.06	0.57	1.11
Inferior cavity length	0.00	25.37	15.97	9.08	3.15	36.09	20.49	7.99	0.00	36.44	20.81	7.51	0.00	36.62	21.29	8.15
Inferior cavity width	0.00	4.87	2.4	1.74	0.14	7.51	2.64	1.24	0.00	6.27	2.78	1.33	0.00	5.01	2.56	0.97
Inferior cavity depth	0.00	5.22	2.7	2.04	0.29	7.34	3.03	1.82	0.00	8.94	2.78	1.62	0.00	6.69	2.9	1.7
Pubic tubercle extension	0.91	7.02	3.8	2.48	0.82	8.31	3.21	1.69	0.00	9.18	3.05	1.86	0.56	6.56	3.22	1.4

Table 25. Scar measurement data for known age groups within the TXSTDSC male sample (n = 45).*

Measurement variable	20 – 39 (n = 2)			40 – 59 (n = 6)			60 – 79 (n = 26)			80+ (n = 11)		
	Max (mm)	Mean (mm)	Std. dev	Max (mm)	Mean (mm)	Std. dev	Max (mm)	Mean (mm)	Std. dev	Max (mm)	Mean (mm)	Std. dev
Pit length – Single	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.45	1.21	2.97
Pitting length – Multi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.45	1.72	3.82
Pitting width	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.72	0.3	0.67
Pitting depth	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.34	0.21	0.48
Sulcus length	16.19	8.1	11.45	21.84	9.03	10.55	26.23	9.45	9.25	14.32	5.55	6.56
Sulcus width	2.21	1.11	1.56	3.82	1.56	1.75	4.58	1.56	1.51	5.26	1.31	1.88
Sulcus depth	0.48	0.24	0.34	1.47	0.57	0.65	1.4	0.49	0.49	3.54	0.69	1.12
Superior cavity length	0.00	0.00	0.00	8	1.47	3.61	7.65	0.86	2.27	11.27	1.75	3.59
Superior cavity width	0.00	0.00	0.00	1.84	0.26	0.63	1.66	0.15	0.41	1.9	0.42	0.75
Superior cavity depth	0.00	0.00	0.00	1.55	0.18	0.44	0.94	0.13	0.3	2.41	0.45	0.83
Inferior cavity length	29.47	14.74	20.84	25.11	12.92	9.33	32.18	14.38	10.12	32.14	15.8	9.36
Inferior cavity width	1.53	0.77	1.08	2.4	1.34	0.86	2.27	1.07	0.69	1.83	1.29	0.51
Inferior cavity depth	0.59	0.3	0.42	2.64	1.12	0.93	2.23	0.69	0.66	2.86	1.25	0.92
Pubic tubercle extension	5.63	4.2	2.04	5.35	4.19	0.98	6.07	4.02	1.34	7.52	4.14	1.88

**minimum values are absent as all values were 0.0 mm, except for pubic tubercle extension (20-39 = 2.75 mm; 40-59 = 2.68 mm; 60-79 = 1.68 mm; 80+ = 1.52 mm)*

Table 26. Chi-square and Phi results for each scar feature occurrence across known age-at-death groups for both full and single-sex TXSTDSC samples.

Pelvic Scar Feature	Full Sample (n = 214)			Females Only (n = 169)			Males Only (n = 45)		
	Chi-square value (χ2)	Strength of association (ϕ)	Test significance (*p*)	Chi-square value (χ2)	Strength of association (ϕ)	Test significance (*p*)	Chi-square value (χ2)	Strength of association (ϕ)	Test significance (*p*)
Dorsal pubic pitting	4.643	0.147	0.2	8.032	0.218	0.045	6.469	0.379	0.091
Preauricular sulcus	1.747	0.09	0.626	1.948	0.107	0.583	0.509	0.106	0.917
Superior interosseous cavity	1.942	0.095	0.585	2.559	0.123	0.465	1.218	0.165	0.749
Inferior interosseous cavity	7.187	0.183	0.066	6.37	0.194	0.095	2.031	0.212	0.566
Pubic tubercle extension	2.931	0.117	0.402	3.165	0.137	0.367	n/a*		

** Statistics not computed because of 100% pubic tubercle presence across all male age groups*

Table 27. Spearman's correlation results for scar feature measurements and age, height, and weight associations within the TXSTDSC full and single-sex samples.

Variable measurements (mm)	Age						Height						Weight					
	Full sample (n = 214)		Females (n = 169)		Males (n = 45)		Full sample (n = 212)		Females (n = 162)		Males (n = 50)		Full sample (n = 150)		Females (n = 100)		Males (n = 50)	
	Corr.	sig.	Corr.	sig.	Corr.	sig.	Corr.	sig.	Corr.	sig.	Corr.	sig.	Corr.	sig.	Corr.	sig.	Corr.	sig.
Pit length (single)	0.053	0.441	0.041	0.594	0.328	0.028	-0.043	0.533	0.063	0.425	0.112	0.44	0.003	0.972	0.101	0.315	-0.049	0.737
Pit length (multi)	0.056	0.416	0.045	0.558	0.328	0.028	-0.042	0.545	0.068	0.393	0.109	0.45	0.005	0.948	0.107	0.291	-0.049	0.737
Pit width	0.051	0.456	0.047	0.548	0.328	0.028	-0.045	0.518	0.072	0.365	0.124	0.389	0.001	0.993	0.102	0.313	-0.05	0.728
Pit depth	0.062	0.367	0.059	0.445	0.328	0.028	-0.058	0.402	0.048	0.546	0.122	0.399	-0.011	0.896	0.079	0.434	-0.05	0.728
Sulcus length	-0.117	0.087	-0.088	0.256	-0.117	0.443	-0.238	< 0.001	0.082	0.3	0.191	0.183	-0.2	0.014	-0.108	0.285	0.072	0.62
Sulcus width	-0.114	0.097	-0.117	0.13	-0.014	0.927	-0.332	< 0.001	-0.006	0.939	0.168	0.243	-0.111	0.178	0.144	0.154	0.026	0.859
Sulcus depth	-0.023	0.736	-0.003	0.974	0.002	0.991	-0.236	< 0.001	0.056	0.478	-0.005	0.974	-0.13	0.113	0.054	0.594	-0.019	0.894
Superior cavity length	0.086	0.21	0.094	0.225	0.143	0.347	-0.108	0.118	0.022	0.784	-0.198	0.168	-0.089	0.277	-0.036	0.724	-0.074	0.608
Superior cavity width	0.105	0.127	0.114	0.141	0.161	0.292	-0.112	0.105	-0.008	0.924	-0.179	0.214	-0.083	0.315	-0.048	0.634	-0.063	0.663
Superior cavity depth	0.121	0.076	0.13	0.092	0.17	0.264	-0.112	0.105	-0.01	0.902	-0.191	0.185	-0.093	0.26	-0.054	0.596	-0.084	0.56
Inferior cavity length	0.023	0.736	0.045	0.565	0.052	0.736	-0.118	0.087	0.019	0.808	0.117	0.418	-0.141	0.085	-0.118	0.241	-0.046	0.753
Inferior cavity width	-0.05	0.467	-0.021	0.782	-0.046	0.766	-0.337	< 0.001	-0.07	0.375	0.159	0.269	-0.185	0.023	-0.064	0.528	0.021	0.886
Inferior cavity depth	-0.032	0.643	-0.04	0.603	0.184	0.225	-0.282	< 0.001	0.021	0.79	0.056	0.701	-0.213	0.009	-0.068	0.502	-0.154	0.287
Pubic tubercle extension	0.025	0.721	0.029	0.705	-0.028	0.853	0.252	< 0.001	0.129	0.102	0.215	0.134	0.101	0.221	-0.063	0.533	0.198	0.167

Chapter 6: Discussion

The primary aim of this study was to evaluate the influence of biological factors on the development of pelvic scarring, focusing on three widely recognised scar features - dorsal pubic pitting, pubic tubercle extension, and preauricular sulcus formation - alongside the newly defined interosseous cavitation. Chapter 5 detailed the key findings in relation to the research questions and hypotheses underpinning this investigation. The present chapter aims to provide a comprehensive analysis of these results, integrating them with existing literature to enhance our understanding of pelvic scarring and its aetiological influences.

The chapter is structured into four main sections. First, it explores the relationship between biological sex and pelvic scar features, addressing research questions 1 and 2 and evaluating hypotheses 1 and 2. This section will consider how sex-specific morphological and biomechanical factors contribute to scar occurrence and severity across the pelvis. The discussion then shifts to the significant obstetric-related findings, providing a detailed interpretation of the data concerning research questions 3 to 5 and hypothesis 3. The third section considers the broader biological influences of age, height, and weight on scar development, aligning with the final research question and remaining hypotheses. This analysis will assess whether these factors independently or interactively affect the presentation of pelvic scarring. The chapter concludes with a critical reflection on the methodological and inferential strengths and limitations of this study. This final section will evaluate the robustness of the research process, acknowledging challenges encountered and suggesting avenues for future research to address identified gaps.

6.1. Biological Sex and Pelvic Scarring

The human pelvis has evolved to accommodate both bipedal locomotion and the biomechanical demands of childbirth, resulting in marked sexual dimorphism (Trevathan, 2017; Mitteroecker & Fischer, 2022). While the transition to bipedalism led to a shortened and broadened pelvic structure to support upright weight distribution, further adaptations in females allowed for a wider pelvic inlet and increased flexibility to facilitate parturition (Wall-Scheffler et al., 2020b). These adaptations introduced several anatomical landmarks that can be used to estimate biological sex (Lovell, 1989; Bytheway & Ross, 2010; White et al., 2012).

Given these adaptations, the female pelvis not only displays broader structural differences but also exhibits increased ligamentous flexibility to accommodate childbirth (Andersen, 1986; Waltenberger et al., 2022a). This increased flexibility predisposes the female pelvis to musculoskeletal stress, which some research indicates results in scarring at ligamentous and tendinous attachment sites (Maass, 2012), subsequently referred to as 'scars of excess motion' by Andersen (1986). These scar sites therefore provide an additional potential metric for estimating biological sex, particularly in forensic and archaeological contexts where traditional morphological methods may be limited by damage or preservation issues (Walker, 2005).

6.1.1. Non-metric Analysis

When examining the strength of association between individual scar feature presence and biological sex, this study identified the preauricular sulcus, inferior interosseous cavity, dorsal pubic pitting, and superior interosseous cavity as indicative of female biological sex, with the pubic tubercle extension demonstrating no significant sex association. These findings immediately support the cautious approach advocated by Maass & Friedling (2016) and Praxmarer et al. (2020) regarding the binary analysis of the pubic tubercle in particular. Notably, the two features with the strongest associations (preauricular sulcus and inferior interosseous cavity) were present in over 93% of females. However, the preauricular sulcus was also observed in 54.9% of males, and the inferior interosseous cavity in 80.4% of males, reinforcing the limitations of binary presence/absence analyses as highlighted by Andersen (1986), Novak et al. (2012), and Gohil et al. (2014).

A deeper interpretation of the preauricular sulcus results reveals an interesting contradiction to previous studies. Earlier research often concludes that the absence of a sulcus is more indicative of male sex than the presence is of female sex (Andersen, 1986; Novak et al., 2012; Karsten, 2018). For instance, Novak et al. (2012) found that while 63.4% of females exhibited a sulcus, the remaining 36.6% did not, demonstrating that presence alone could not accurately identify all females. Similarly, Karsten (2018) observed a sulcus in 89.96% of females but also in 37.12% of males, leading to the conclusion that while a missing sulcus strongly suggested a male individual, the presence of one was not sufficiently diagnostic. However, the findings of this study challenge that interpretation by demonstrating a stronger statistical association ($\phi = 0.451$) with sulcus presence than absence. This suggests that while the sulcus is not an absolute indicator, its presence may be more meaningful than previously assumed. The discrepancy may be attributable to differences in sample populations, data collection methods, or classification criteria. Ultimately, these results support the idea that while the absence of a sulcus remains a useful indicator of male sex, its presence should not be disregarded in sex estimation, particularly when assessed in conjunction with other non-metric traits.

Direct comparison of the interosseous cavity as a newly defined scar feature remains challenging. Running along the retroauricular border, this feature was present in 97.6% of females and 80.4% of males along the inferior border but was less common along the shorter superior border, occurring in 33.1% of females and 15.7% of males. Notably, the superior cavity follows an opposing trend to the inferior cavity: while the inferior cavity is more likely to be present in both sexes (though more frequently in females), the superior cavity is more likely to be absent in both sexes, with males exhibiting a greater absence rate.

The interosseous cavity lies closest to the interosseous groove, which has been linked to the attachment of the posterior sacroiliac ligament and has similarly demonstrated a higher prevalence in females. Early research by Işcan & Derrick (1984) identified a strong association between the interosseous groove and female sex, with presence recorded in the vast majority of females but rarely in males. However, Andersen (1986) and Gohil et al. (2014) later reported a weaker relationship, with Gohil et al. noting its presence in nearly one-third of males, demonstrating notable overlap between sexes. More recent studies, such as those by Mahadevappa & Shivalingaiah (2017), reaffirmed a stronger association, reporting groove absence in most males and presence in the majority of females, particularly when prominent. While not directly linked to the inferior cavity findings of this study, the presence of both superior and inferior cavities provides further evidence of osteological changes associated with the posterior sacroiliac ligament. However, as with other scar features, binary assessment alone is insufficient for reliable sex estimation.

The findings related to dorsal pubic pitting offer additional nuance. Only three males exhibited pitting compared to 41 (24.3%) females, resulting in a weak association ($\phi = 0.194$). This aligns with previous studies that assessed pitting as a binary trait, such as Andersen (1986), McArthur et al. (2016), and Praxmarer et al. (2020). While these studies consistently found that pitting is more frequently observed in females, they also demonstrated that its absence alone is not a reliable indicator of male sex. Ullrich (1975) was one of the first to identify dorsal pubic pitting as a sexually dimorphic trait, concluding that it was among the strongest skeletal indicators of sex. However, Andersen (1986) found pitting in only 51.3% to 56.7% of females, depending on parity status, while just 2.4% of males exhibited any evidence of pitting, and only in a mild form. This suggests that while pitting is highly specific to female sex, its absence does not reliably indicate that an individual is male.

McArthur et al. (2016) further reinforced this conclusion using CT scans of 359 living individuals, identifying pitting in 64.6% of females but in none of the 48 males. This represents the strongest binary differentiation between sexes in the literature, though it is notable that this study exclusively used radiographic analysis, which can introduce methodological differences from osteological studies. Praxmarer et al. (2020) similarly found pitting to be far more frequent in females, with 81% exhibiting some degree of pitting compared to just 24.3% in the present study. However, they also recorded at least minimal pitting in 24.3% of males, reinforcing the conclusion that its absence cannot be used as definitive evidence of male sex.

Interestingly, the occurrence of pubic tubercle extension showed no significant association with biological sex, aligning with Maass & Friedling (2016). This is because the occurrence of extension is present in 98.6% of the full sample, regardless of sex. Despite previous studies identifying dimorphic trends (e.g., Ullrich, 1975; Praxmarer et al., 2020), this study therefore reinforces the argument that pubic tubercle extension presence is not of value in biological sex estimation. This might reflect the anatomical variability of the pubic tubercle across populations or perhaps the influence of non-sex-related factors such physical activity or age (investigated further on), which could affect the extension of this feature.

Overall, these findings suggest that while individual scar features exhibit varying degrees of association with biological sex, none are entirely definitive when assessed in isolation. Even in those scar features presenting with a significant sex association, presence and absence percentages of scar features showed substantial overlap between males and females, resulting in reduced association strength. The maximum difference between male and female absence percentages for any single scar feature was 38.6%, underscoring the complexity of using individual features as sex indicators. This overlap is particularly evident in cases where high feature absence in males corresponds with high feature presence in females, and vice versa. This variability aligns with previous studies (Houghton, 1974; Andersen, 1986; Spring et al., 1989; Novak et al., 2012; Gohil et al., 2014; Maass & Friedling, 2016; McArthur et al., 2016; Karsten, 2018; Canty, 2020; Praxmarer et al., 2020), indicating that individual scar presence or absence alone does not provide a reliable indicator of biological sex.

As a result, this study further investigated the potential association between biological sex and the total number of scars present, revealing a stronger association and building upon previous findings by Gohil et al. (2014) and Andersen (1986). While direct comparison with these studies is challenging due to methodological differences, this study offers new insights into the potential for using scar feature counts as a biological sex estimation tool. The first key finding is that 47.7% of the sample presented with the median number of scar features (3), representing a near-equal distribution between males and females. This central clustering aligns with Andersen's (1986) observation that many individuals fall within an intermediate range where sex estimation becomes less reliable. However, this study further quantifies this uncertainty, demonstrating that a significant proportion of individuals would be classified as 'uncertain' using a proposed five-point biological sex estimation scale: 1 = very likely male; 2 = likely male; 3 = uncertain; 4 = likely female; 5 = very likely female. This underscores the necessity of exercising caution when interpreting mid-range feature counts, particularly in forensic contexts where certainty is paramount.

Moving away from the median point, this study identified a clear trend associating lower feature counts with male biological sex and higher feature counts with female biological sex. Notably, the extreme count groups (1 and 5 features) comprised only individuals of the associated biological sex, which represents a slight advancement over earlier studies (Andersen, 1986; Gohil et al., 2014). Andersen (1986) reported that 65.43% of males had no features present, alongside 7% of females. Conversely, Gohil et al. (2014) noted that 20.37% of females had all three scar features assessed, grouped with 7.4% of males, but provided no detail on the sex composition of those without any scarring. Thus, the exclusive sex-based composition of extreme groups in the present study not only supports but also enhances these earlier findings, suggesting a potential diagnostic utility for cases where a full pelvic scar assessment is feasible.

However, the high proportion of the sample falling into the 'uncertain' category (having three pelvic scar features) presents a limitation to the proposed estimation scale. This outcome implies that while the method could accurately categorise 47.1% of males and 44.4% of females as 'likely' or 'very likely' male or female, over half of the sample would remain ambiguous without further contextual information. When excluding the 'uncertain' group, the accuracy rates rise considerably to 82.8% for males and 87.2% for females, reflecting a robust potential for sex estimation in scenarios where ambiguity can be managed. This dichotomy highlights a critical consideration for practical applications: the proposed scale is most effective when a complete assessment of all relevant pelvic scarring sites is possible, and its reliability diminishes in cases of incomplete remains or poor preservation.

Nonetheless, further analysis of the 'uncertain' group could provide valuable insights. Given the anatomical and biomechanical factors influencing pelvic scarring, individuals within this median category may represent a more complex intersection of biological and environmental influences. In particular, developmental and hormonal factors such as pubertal timing, menstrual regularity, and adult hormonal disruptions may contribute to this complexity. Delayed puberty, for example, can prolong the androgynous state of the pelvis, potentially influencing scar presentation and reducing this in biological females (Fischer & Mitteroecker, 2017; Shi et al., 2022). Additionally, conditions such as polycystic ovary syndrome (PCOS) and external influences like chronic stress or hormonal contraceptive use could disrupt the typical cycle of connective tissue laxity and tension, leading to atypical female scar patterns (Berga et al., 2019; Fauser & Petraglia, 2020; Buck et al., 2024). By incorporating these factors into future models, it may be possible to refine the 'uncertain' category into more precise subgroups, enhancing the method's applicability in both forensic and archaeological contexts.

In practical terms, the non-metric findings of this study could contribute to a nuanced approach to biological sex estimation in forensic and archaeological contexts where a quick assessment is needed or metric analysis is not possible, or to complement existing methods. However, it is crucial to acknowledge the method's limitations, particularly its dependency on a full scarring assessment. In forensic cases where remains are incomplete or damaged, or in archaeological contexts with taphonomic challenges, the potential for misclassification may increase, necessitating cautious and contextually informed application of this technique.

6.1.2. Metric Analysis and Method Development

Through metric scar assessment, this study identified that all individual scar measurements correlated with biological sex, demonstrating a predominantly positive relationship where larger dimensions were more likely associated with being biologically female. This trend provides evidence of the heightened mechanical and hormonal influences on female pelvic musculoskeletal morphology across the life course, whereby these scar sites align directly with regions of acute ligament or tendon tension exacerbated by pelvic strain or structural movement. These findings concur with previous studies (Houghton, 1974; Andersen, 1986; Novak et al., 2012; Maass & Friedling, 2016; Mahadevappa & Shivalingaiah, 2017; Karsten, 2018; Canty, 2020; Praxmarer et al., 2020), further supporting the notion that pelvic scar morphology is influenced by female-specific anatomical and functional demands. The exception to this pattern was the pubic tubercle extension, where larger measurements were more frequently observed in biological males. This likely reflects distinct biomechanical stresses, particularly involving the inguinal ligament and the rectus abdominus and external oblique muscles.

The preauricular sulcus and inferior interosseous cavity exhibited the strongest associations with biological sex across all individual measurements. The preauricular sulcus demonstrated a strong correlation ($\tau b > 0.3$) for all three dimensions, making it the most sexually dimorphic feature. The inferior interosseous cavity followed closely, with width ($\tau b = 0.448$) and depth ($\tau b = 0.444$) displaying strong correlations, while length ($\tau b = 0.223$) showed a moderate association. These findings suggest that pelvic scar presentation is most sexually dimorphic at the sacroiliac joint, aligning with the observations of Houghton (1974). Both features are located around the auricular surface of the posterior pelvis and are subject to significant and regular mechanical stress at the sacroiliac joint in biological females (Maxwell, 1938; Micussi et al., 2015). The results of this study therefore support the theory of increased osteological response at the sites of sacroiliac ligament attachment - areas which play a critical role in stabilising the posterior pelvis (Waltenberger et al., 2022a).

The preauricular sulcus has long been associated with sexual dimorphism, particularly when evaluated using severity and dimensional assessments rather than binary presence or absence. Andersen (1986) introduced a detailed classification system based on sulcus depth and length, showing that while the feature may occur in both sexes, its morphology differs significantly. This observation was reinforced by Maass and Friedling (2016) and Praxmarer et al. (2020), both of whom used metric approaches to demonstrate that sulci in females tend to be markedly deeper and broader. Similarly, Novak et al. (2012) reported that the most pronounced sulci occurred exclusively in females - echoed by Canty (2020), who identified deeper, and more complex forms as strongly associated with female sex.

A comparable pattern was observed in the inferior interosseous cavity. While earlier research into the related interosseous groove (Işcan & Derrick, 1984) noted marked sexual dimorphism, subsequent work by Maass and Friedling (2016) refined this understanding by highlighting the significance of depth and width measurements. Their study showed that although shallow grooves were commonly present in both sexes, deeper and more clearly defined cavities were significantly more frequent in females. This finding was further supported by Mahadevappa and Shivalingaiah (2017), who concluded that the extent of groove development - rather than its mere presence - was the strongest indicator of biological sex.

To maximise the predictive utility of these features, individual dimensional values were combined to create a single volumetric variable for each scar site, effectively mitigating multicollinearity while incorporating all relevant measurements. This approach further strengthened correlations with biological sex, with preauricular sulcus volume achieving τb = 0.505 and inferior interosseous cavity volume reaching τb = 0.445, demonstrating an enhanced predictive relationship compared to individual dimensions alone. The overall classification accuracies for these features were 86.5% and 80.2%, respectively, confirming their significance in sex estimation. These results are comparable to the well-established Walker (2005) method of sex estimation using the sciatic notch, which typically achieves an accuracy between 80% and 89% (Walker, 2005; Bonczarowska et al., 2019; DesMarais et al., 2023). This finding is particularly significant as it positions the preauricular sulcus volume as a competitive metric for sex estimation, especially considering that existing sulcus-based methods report an average accuracy of 81.4% (Novak et al., 2012; Karsten, 2018; Inskip et al., 2019).

When comparing the predictive models, a notable disparity in accuracy emerged between the two scar features. While sex prediction accuracy for females remained consistently high (85–87.7%) across both models, accuracy for males dropped significantly from 73.9% using sulcus volume to just 56.3% with inferior cavity volume. This discrepancy suggests that the inferior interosseous cavity feature may exhibit greater variability in males, potentially reflecting inconsistent biomechanical or hormonal influences, unlike the more uniform patterns observed in females. This aligns with Maass & Friedling’s (2016) observation of the interosseous groove's inconsistent presentation in males, further emphasising the need for caution when using this feature as a sole metric for sex estimation.

Estimation accuracy improved significantly when both approximate volume variables were integrated into a combined regression model. This final model achieved a remarkable 97.1% accuracy, correctly identifying 98.8% of biological females and 91.7% of biological males. This performance exceeds that of the Phenice (1969) method of sex estimation, which originally reported 96% accuracy, though later studies have shown more variable outcomes ranging from 59% to 88.4% (Lovell, 1989; Maclaughlin & Bruce, 1990; Ubelaker & Volt, 2002). The integration of both variables into a single model suggests that the combined influence of these features better accounts for biological variability, particularly by offsetting the inaccuracies present in single-variable models.

The final model incorrectly classified just six individuals, resulting in a 2.9% error rate. These cases included four males misclassified as females and two females as males. Analysis of these outliers revealed no causal link to personal data, suggesting that idiosyncratic variation may explain these misclassifications. Notably, four cases fell near the central prediction line (25% - 75% prediction range), indicating ambiguity in sex classification. Two cases, one male and one female, approached a 90% likelihood of the opposite sex, reflecting the challenge of predicting sex in individuals with atypical pelvic morphology.

A key strength of this model is its demonstrated specificity, particularly regarding male sex classification. The significant increase in specificity suggests that measurement values responsible for misclassifications in the single-variable models were effectively counterbalanced in the final combined model. Importantly, no additional male outliers were excluded compared to earlier models, reinforcing the hypothesis that cross-variable inaccuracy offset, rather than case removal, contributed to the accuracy increase. Furthermore, with only 5.9% of the male sample absent of both final method variables, the minimal impact of male scar feature absence on method accuracy strengthens the robustness of this approach.

Overall, these findings suggest that while individual scar metrics offer valuable insights, their predictive power is significantly enhanced when utilised in a combined model, supporting a cumulative approach to pelvic scar analysis. This integrative metric strategy not only improves accuracy but also mitigates the limitations associated with individual scar feature variability, offering a particularly promising method for biological sex estimation in forensic and archaeological contexts.

6.1.3. Method Validation

The application of the final estimation method to the validation sample resulted in a slight reduction in overall estimation accuracy to 90.7%. While this represents a decrease from the initial model accuracy of 97.1%, it remains higher than many validation studies for widely used morphological sex estimation methods, demonstrating the robustness of the proposed method. This is particularly noteworthy given the challenges inherent in applying modern forensic methods to archaeological samples, where preservation, taphonomic processes, and historical variability can introduce additional complexities.

A notable finding of the validation study is the shift in accuracy trends between biological sexes. Unlike the initial sample, where female accuracy was higher, the validation sample demonstrated a higher accuracy for males (97.67%) than females (83.73%). This discrepancy may reflect differences between modern and archaeological populations, as skeletal morphology is influenced by lifestyle, activity levels, and health, which can change significantly over time (Duren et al., 2013; Larsen, 2015; Šerstņova et al., 2023). Historical populations often engaged in more physically demanding labour, exposing the pelvis and other joints to greater biomechanical stress (Roberts & Manchester, 2010; Larsen, 2015). Such stresses could lead to more pronounced or atypical scar feature presentation, potentially altering the predictive reliability of models developed on modern populations, where reduced skeletal robusticity and altered stress responses result from increasingly sedentary lifestyles (Albee, 2023). Additionally, improvements in nutrition and healthcare over time have influenced skeletal growth patterns, bone density, and the manifestation of age-related changes (Duren et al., 2013; Holick & Nieves, 2015; Larsen, 2015). These temporal and population-specific variations may impact pelvic scar presentation, affecting the consistency required for accurate sex estimation models.

The lower accuracy in female estimations within the validation sample may also be linked to specific feature presentations. Notably, a higher rate of preauricular sulcus absence was observed in females, accounting for five of the seven misclassified cases, despite this feature typically demonstrating a high degree of expression in modern samples (Houghton, 1974; Andersen, 1986; Karsten, 2018). This discrepancy may suggest historical variation in ligamentous attachment patterns or stress responses at the sacroiliac joint in particular. Given the biomechanical demands typically placed on the pelvis in labour-intensive lifestyles (Roberts & Manchester, 2010; Larsen, 2015), one might anticipate more advanced scarring in archaeological specimens. However, the reduced expression observed here highlights the potential complexity and non-linear nature of skeletal responses to stress.

However, the reduced scarring observed may alternatively reflect differences in pelvic morphology influenced by activity patterns, or other biological or environmental factors. For example, developmental and hormonal factors such as delayed or precocious puberty and conditions like polycystic ovary syndrome (PCOS) may influence pelvic scarring patterns by altering the typical cycle of connective tissue laxity and tension (Fischer & Mitteroecker, 2017; Fauser & Petraglia, 2020; Buck et al., 2024). Additionally, the impact of menstrual cycle regularity, or lack thereof, could affect scar presentation by altering the hormonal influence on pelvic connective tissues (Maxwell, 1938; Micussi et al., 2015; Chidi-Ogbolu & Baar, 2019). Individuals with disrupted cycles, whether due to hormonal conditions or poor diet may exhibit scar patterns that deviate from typical modern sex-specific presentations, highlighting the complexity of accurately interpreting pelvic scarring in forensic and archaeological contexts. Such influences offer a potential explanation for the variability in female classification accuracy, reinforcing the need to account for both biological and environmental factors in osteological analyses.

A particularly intriguing skeleton from the validation sample was recorded as female upon exhumation but displayed strongly male features according to multiple sex estimation methods, including Phenice (1969), Walker (2005), and the proposed method. This raises the possibility of interment or exhumation errors, where biological sex may have been misidentified based on the associated coffin plate rather than osteological evidence. Such discrepancies could lead to false negatives during analysis, highlighting a broader challenge in archaeological research. However, it is equally plausible that this case reflects natural idiosyncratic variation and phenotypic plasticity, demonstrating the complex spectrum of human morphology that occasionally defies standard phenotypic classification.

Nevertheless, the method maintained a high overall accuracy, demonstrating its adaptability and potential for broader application. This robustness is particularly valuable in osteological study, where skeletal remains from varying temporal and demographic backgrounds are frequently encountered.

6.1.4. Biological Sex and Pelvic Scarring Summary

Initial non-metric analysis identified associations between female biological sex and the presence of all scar features but pubic tubercle extension. However, when considered individually, none of these features provided sufficient accuracy for reliable sex estimation due to significant overlap between sexes. A cumulative approach showed greater promise, particularly by identifying that extreme scar counts (either very high or very low) were strongly indicative of biological sex. Despite this, a key limitation was the high proportion of 'uncertain' cases, where median feature counts did not allow for confident classification, highlighting the method’s dependency on complete scarring assessments.

Metric analysis strengthened findings, demonstrating statistically significant associations between all measured scar features and biological sex. The preauricular sulcus and inferior interosseous cavity emerged as the most robust indicators, showing high accuracy when their approximate cubic volumes were used as predictive metrics. When combined within a regression model, the estimation accuracy improved significantly, achieving 97.1% overall accuracy, with 98.8% accuracy for females and 91.7% for males. The validation phase showed only a slight reduction in accuracy to 90.7%, demonstrating robustness and adaptability of the method and reinforcing its potential as a versatile tool for reliable sex estimations in diverse forensic and archaeological contexts

6.2. Obstetric Events and Pelvic Scarring

The female pelvis has undergone substantial evolutionary modifications to accommodate the biomechanical and obstetric demands of childbirth. These adaptations are particularly evident in the expansion of the pelvic inlet, which has evolved to facilitate the passage of offspring with larger cranial dimensions (Mitteroecker & Fischer, 2022). However, as Mitteroecker and Fischer (2022) highlight, this evolutionary process is constrained by a delicate balance between obstetric adaptation and the preservation of efficient bipedal locomotion. Consequently, while the structural modifications of the pelvis support childbirth, they do not fully mitigate the mechanical and physiological stress imposed on the female musculoskeletal system during pregnancy and delivery.

Historically, many osteological studies have posited pelvic scarring as a direct and reliable biomarker of obstetric history, with specific scar features interpreted as reflections of the biomechanical stresses associated primarily with parturition. However, this interpretation has been increasingly challenged by a growing body of research, which highlights the complexity of pelvic scar formation and questions the assumption of a straightforward correlation between scarring and obstetric events (Holt, 1978; Kelley, 1979; Suchey et al., 1979; Andersen, 1986; Spring et al., 1989; Snodgrass & Galloway, 2003; Canty, 2020; Waltenberger et al., 2021; 2022b). Indeed, the presence of pelvic scars in nulligravid and nulliparous females, as well as in males, alongside the absence of scarring in some parous females, underscores the complexity and variability of these skeletal features. As debates surrounding the diagnostic value of pelvic scarring continue, it becomes evident that while such markers may offer insights into obstetric events, caution is required when interpreting their significance.

This discussion seeks to evaluate the current evidence on pelvic scarring within the context of obstetric events. By synthesising historical perspectives, contemporary research, and the findings presented in the previous subchapter, this analysis aims to contribute to a more nuanced interpretation of how gravidity and parity may influence pelvic morphology in forensic and archaeological contexts.

6.2.1. Non-Metric Analysis

Non-metric analysis of the full sample demonstrated significant associations between obstetric history and the presence of all scar features except pubic tubercle extension. The preauricular sulcus and superior interosseous cavity showed the strongest associations, particularly reinforcing earlier findings (Houghton, 1974; Ullrich, 1975; Kelley, 1979; Igarashi et al., 2019) that link stress at the sacroiliac joint during pregnancy and parturition to specific bony changes. Remaining significant results also support broader trends identified in prior research (Ullrich, 1975; Cox & Scott, 1992; McArthur et al., 2016; Waltenberger et al., 2022b), which document a progressive increase in pelvic scarring in response to obstetric events. In failing to demonstrate a statistically significant correlation with gravidity or parity, the pubic tubercle findings directly contradict the positive correlations previously observed by Cox & Scott (1992), while supporting findings from Snodgrass & Galloway (2003) and Waltenberger et al. (2022b).

Preauricular sulcus presence was most strongly associated with both gravidity (χ^2 = 29.777, ϕ = 0.368) and parity (χ^2 = 26.381, ϕ = 0.346) in the full sample. It was observed in 121 of 126 (96%) individuals with a history of pregnancy and in 116 of 121 (96.9%) individuals who had given birth, indicating a robust association between sulcus presence and obstetric history. The influence of pregnancy-related hormones - particularly relaxin - on ligamentous laxity and sacroiliac joint widening (Kumar & Magon, 2012; Dehghan et al., 2014; Mitteroecker & Fischer, 2022) provides a plausible biomechanical pathway for sulcus development. Relaxin has been shown to contribute specifically to the loosening of pelvic joints (Dehghan et al., 2014; Waltenberger et al., 2022a), which may drive the remodelling of cortical bone at this site.

However, simultaneous preauricular sulcus presence in 65 of 94 (69.1%) nulligravid and a similar 70 of 99 (70.7%) nulliparous individuals (including males) first complicates its interpretation. This high prevalence in non-gravid individuals aligns with earlier research (Houghton, 1974; Andersen, 1986; Karsten, 2018), suggesting that sulcus presence is not a definitive obstetric marker but rather an indicator of broader biomechanical stresses. The frequent occurrence of the sulcus in nulligravid individuals suggests that other stressors - such as habitual postural strain or general sacroiliac joint instability, which is more prevalent in females - are likely primary drivers (Gharib & Aglan, 2018). This is further reinforced by the reduced associations when males were excluded from the analysis.

In the female-only sample, the preauricular sulcus demonstrated weak associations with gravidity (χ^2 = 5.253, ϕ = 0.176), present in 37 of 43 (86%) nulligravid females, and parity (χ^2 = 3.954, ϕ = 0.153), present in 42 of 48 (87.5%) nulliparous females. These figures indicate substantial overlap in sulcus presence between females with and without positive obstetric history, aligning directly with past research. For example, Andersen (1986) found that ~75% of both parous and nulliparous females had a sulcus, with less than 6% presenting without one. Similarly, Cox & Scott (1992) observed that only 22.2% of nulliparous and 9.5% of parous females lacked a sulcus, reinforcing prevalence in females – although the negative obstetric female sample in this study was particularly small (n = 9), affecting reliability. More recent studies (Canty, 2020; Waltenberger et al., 2022b) nonetheless continue to support this, finding no significant differences in sulcus presence between obstetric groups. Furthermore, unlike what would be expected if obstetric history were the primary determinant, sulcus presence actually increased in non-obstetric females compared to the full sample.

This supports the concept of the sulcus as a 'scar of excess motion' (Andersen, 1986), wherein increased pelvic flexibility and ligamentous strain, common in females regardless of obstetric status, lead to its formation. This increased mobility is largely influenced by sex-specific biomechanics and hormonal factors, which facilitate ligamentous laxity and joint adaptability, ultimately leading to bony remodelling at the sacroiliac joint. This finding is particularly relevant given that the preauricular sulcus was one of the two key sites for sex estimation identified in the first part of this study. Thus, its high frequency in females, regardless of obstetric history, aligns with its established use in morphological sex estimation, echoing that the sulcus is strongly linked to the structural and functional differences of the female pelvis.

The superior interosseous cavity demonstrated a significant, though weaker, association with obstetric history than the preauricular sulcus in the full sample. It was associated with both gravidity ($\chi^2 = 16.037$, $\phi = 0.27$) and parity ($\chi^2 = 14.587$, $\phi = 0.257$), appearing in 50 of 126 gravid individuals (39.7%) and 48 of 121 parous individuals (39.7%). It was also observed in 14 of 94 nulligravid individuals (14.9%) and 16 of 99 nulliparous individuals (16.2%), suggesting that while obstetric history plays a role in its development, additional biomechanical or anatomical factors may also contribute. Unlike the preauricular sulcus, the association between the superior interosseous cavity and obstetric history remained moderate even after males were excluded from the analysis, with continued significance for both gravidity ($\chi^2 = 9.579$, $\phi = 0.238$) and parity ($\chi^2 = 8.207$, $\phi = 0.22$). The cavity was present in only 6 of 43 (14.0%) nulligravid females and 8 of 48 (16.7%) nulliparous females. In contrast to the sulcus - where non-obstetric expression increased when analysing females alone - the superior interosseous cavity displayed consistent expression rates across both the full and female-only samples. This pattern suggests that superior cavitation is less influenced by broader sexually dimorphic mechanisms, supporting earlier interpretations (see Section 6.1).

Moreover, while the preauricular sulcus exhibited the strongest association with obstetric history in the full sample, the superior interosseous cavity showed a stronger association in the female-only subsample. This reversal in association strength implies that the superior cavity may serve as a more specific indicator of obstetric history within biological females. Whereas sulcus formation is more likely modulated by broader sex-related biomechanical factors, the superior interosseous cavity appears more directly responsive to obstetric-related mechanical stress. Its consistent expression pattern from full to female-only groups supports the interpretation that increased biomechanical strain along the posterosuperior sacroiliac margin during pregnancy, exacerbated by foetal growth and postural changes, contributes to its development (Talbot & Maclennan, 2016; Gharib & Aglan, 2018).

Although the superior interosseous cavity demonstrated a moderate but significant association with obstetric history, its presence alone does not necessarily imply an exclusive causal relationship. Given its anatomical proximity to the traditional interosseous groove, and the fact that both are associated with the posterior sacroiliac ligament, it is important to contextualise these findings alongside earlier research. Kelley (1979) and Andersen (1986), for example, found no significant relationship between obstetric events and the post-auricular interosseous groove. Kelley (1979) reported that while nulligravid females were less likely to exhibit grooving (67.3% absence), similar proportions of the gravid sample were distributed across all groove categories (31.9%–36.2%), thereby refuting a direct obstetric association. Andersen (1986) similarly failed to identify a correlation, excluding detailed results from their discussion.

However, it remains plausible that while changes across the broader interosseous groove may not reflect obstetric history, the superior-most region - corresponding to the superior interosseous cavity - may be subject to more localised and directional strain. Anatomically, the superior cavity lies along the upper margin of the auricular surface of the ilium, at the inferior edge of the superior demiface, where the posterior sacroiliac ligament inserts. This position places it at a key interface for the transmission of downward mechanical forces during pregnancy, particularly as pelvic load increases in the later stages of gestation. Therefore, unlike the broader interosseous groove or the inferior cavity, the superior cavity is anatomically positioned and proportioned in a way that makes it more likely to exhibit a consistent response to tensile stress. This may explain why the superior interosseous cavity occurrence demonstrates a moderate but significant association with obstetric history, despite earlier studies showing no such relationship across the interosseous groove more generally. Nevertheless, the moderate strength of association and potential for additional, yet undetermined influential factors, underscores the need for cautious interpretation.

The inferior interosseous cavity and dorsal pubic pitting occurrence both demonstrated statistically significant associations with obstetric events in the full sample. The inferior interosseous cavity was associated with gravidity ($\chi^2 = 11.29$, $\phi = 0.227$) and parity ($\chi^2 = 10.014$, $\phi = 0.213$), while dorsal pubic pitting was similarly associated with gravidity ($\chi^2 = 8.99$, $\phi = 0.202$) and parity ($\chi^2 = 8.889$, $\phi = 0.201$). However, when examining the female-only sample, these associations weakened substantially, with the inferior interosseous cavity and dorsal pubic pitting losing statistical significance entirely. While this study could not establish an association between biological sex and dorsal pubic pitting - given its limited occurrence across the sample - the findings do support a sexually dimorphic presentation of the inferior interosseous cavity. Its notable sex-based distribution reinforces its potential utility as a key indicator in the proposed method for sex estimation outlined in this research.

The results concerning dorsal pubic pitting align with long-standing concerns regarding its validity as an obstetric indicator. While early studies (Stewart, 1970; Holt, 1978) initially hypothesised a direct correlation between dorsal pitting and parturition, subsequent research consistently challenged this assumption. The presence of pitting in nulliparous females (Kelley, 1979; Suchey et al., 1979;

Andersen, 1986) and its absence in some parous individuals suggest that it is not an exclusive marker of reproductive history. For example, Kelley (1979) found dorsal pitting in 44% of parous females, but also 33.4% of nulliparous females, meanwhile, Suchey et al. (1979) demonstrated that over 73% of nulligravid females exhibited pitting. More recent studies (Cox & Scott, 1992; McArthur et al., 2016; Waltenberger et al., 2022b) reinforce that while dorsal pitting may be more frequent in individuals with obstetric history, its high prevalence in nulligravid females and lack of diagnostic specificity undermine its reliability at the individual level. This study further supports these findings, as dorsal pitting failed to maintain statistical significance when males were excluded, reinforcing the unlikelihood of obstetric origins. The inconsistency of pitting across reproductive groups suggests that its formation is influenced by broader biomechanical or hormonal factors.

Compared to the superior interosseous cavity results, the findings regarding the inferior interosseous cavity align more closely with previous research on the interosseous groove (e.g., Kelley, 1979; Andersen, 1986). This further supports the hypothesis that superior ligament strain may be a more relevant factor in obstetric-induced sacroiliac joint remodelling and reinforces the conclusion that while obstetric events may contribute to posterior sacroiliac-related scar development, their effects are highly localised, restricting macroscopic cortical bone changes to the area of superior attachment only.

6.2.2. Metric Analysis

Statistically significant full-sample relationships were noted between all scar feature measurements and obstetric history ($p < 0.05$), reinforcing a general trend of increased scar dimensions in obstetric-positive individuals. However, as observed in the non-metric analysis, the strength of these relationships varied considerably across features, with some displaying moderate-to-strong correlations, while others exhibited only weak associations. The preauricular sulcus presented the strongest associations with obstetric history, followed by the inferior interosseous cavity, particularly in width and depth. The remaining scar features: superior interosseous cavitation, dorsal pubic pitting, and pubic tubercle extension, displayed weak-to-moderate correlations with obstetric history, with the latter uniquely demonstrating an inverse trend by decreasing in size in association with obstetric event occurrence.

The preauricular sulcus exhibited the strongest full-sample metric relationships, with all three dimensions demonstrating strong correlations. Sulcus length displayed the highest association, correlating with gravidity ($\tau b = 0.399$, $p < 0.001$) and parity ($\tau b = 0.387$, $p < 0.001$), reinforcing a pattern of longitudinal sulcus expansion in response to pregnancy and childbirth. Sulcus width ($\tau b = 0.382$, $p < 0.001$ for gravidity; $\tau b = 0.37$, $p < 0.001$ for parity) and depth ($\tau b = 0.329$, $p < 0.001$ for gravidity; $\tau b =$

0.315, $p < 0.001$ for parity) followed a similar trend, initially suggesting obstetric influence on sulcus remodelling. However, as in the non-metric analysis, the sulcus remained highly prevalent in non-obstetric individuals, complicating interpretation. This was further reinforced when the removal of the male sample once again resulted in a significant weakening of sulcus correlations, with sulcus width and depth losing significance entirely. Sulcus length remained statistically significant, albeit with reduced correlation strengths ($\tau b = 0.168$, $p = 0.008$ for both gravidity and parity), highlighting that biological sex remains the dominant factor influencing sulcus expression. The continued significance of length, in particular, may reflect a minor influence of downward strain, given its alignment with the vertical axis of the sulcus, though the relatively weak correlation suggests this force plays only a limited role.

The inferior interosseous cavity exhibited similarly strong metric relationships with obstetric history, particularly in width and depth. While cavity length demonstrated a weak correlation ($\tau b = 0.136$, $p = 0.014$ for gravidity; $\tau b = 0.147$, $p = 0.008$ for parity), both cavity width and depth displayed stronger associations. Width increased from negative to positive obstetric groups ($\tau b = 0.328$, $p < 0.001$ for gravidity; $\tau b = 0.335$, $p < 0.001$ for parity), while depth also expanded ($\tau b = 0.324$, $p < 0.001$ for gravidity; $\tau b = 0.331$, $p < 0.001$ for parity). These results suggest that pregnancy and childbirth contribute to notable remodelling at this site, particularly affecting width and depth. However, in contrast to its strong full-sample correlations, the inferior interosseous cavity lost all statistical significance in the female-only dataset. These results reinforce that while the inferior cavity is responsive to biomechanical strain, it does not exhibit consistent remodelling specific to obstetric events.

The superior interosseous cavity initially displayed moderate statistical associations with obstetric history, although notably lower than those observed for the sulcus or inferior cavity. Among its three measurements, depth exhibited a moderate relationship with obstetric events ($\tau b = 0.258$, $p < 0.001$ for gravidity; $\tau b = 0.251$, $p < 0.001$ for parity), followed closely in strength by length ($\tau b = 0.256$, $p < 0.001$ for gravidity; $\tau b = 0.253$, $p < 0.001$ for parity) and then width ($\tau b = 0.248$, $p < 0.001$ for gravidity; $\tau b = 0.237$, $p < 0.001$ for parity). However, unlike the preauricular sulcus and inferior cavity, the superior interosseous cavity retained statistical significance across all dimensions within the female-only sample. Superior cavity depth retained the strongest individual association ($\tau b = 0.226$ for gravidity; $\tau b = 0.216$ for parity), slightly exceeding that of length ($\tau b = 0.192$ and 0.191, respectively) and width ($\tau b = 0.198$ and 0.184, respectively). Notably, these results surpassed those of any other female-only metric variables.

These findings expand upon the non-metric results by demonstrating that obstetric strain influences not only the presence of the superior cavity, but also the degree of its expansion. Within the female-only sample, correlation strengths between superior cavity measurements and obstetric events were consistently higher than those observed with biological sex, reinforcing the conclusion that obstetric history exerts a more direct influence on superior cavity development and severity than dimorphism. The retention of statistical significance across all three dimensions suggests a relatively uniform distribution of mechanical loading across the surface of the cavity. However, the marginally stronger association with depth is consistent with the influence of downward-directed strain on this scar site, given its orientation and exposure to gravitational loading during pregnancy, promoting deeper cortical remodelling. The superior interosseous cavity therefore emerges not only as the most reliable metric indicator of obstetric history in females, but also as a feature that reflects a biomechanically plausible and directionally consistent response to gestational strain.

The remaining scar features exhibited statistically significant but weak correlations with obstetric history. Dorsal pubic pitting showed marginal associations, with correlation strengths around $\tau b = 0.2$, while pubic tubercle extension was the only feature to display an inverse trend, decreasing from negative to positive obstetric groups ($\tau b = -0.161$, $p = 0.004$ for gravidity; $\tau b = -0.134$, $p < 0.001$ for parity). Restricting the analysis to females resulted in the loss of statistical significance for both scar features across all measurements. These trends are consistent with the non-metric findings, which similarly demonstrated that dorsal pubic pitting and pubic tubercle extension were not reliable predictors of obstetric history once sex was controlled for.

6.2.3. Individual Obstetric Event Correlations

Despite frequent discussions of both gravidity and parity in previous studies, few have examined these events independently. Many analyses have been constrained by sample limitations, particularly in archaeological contexts, where available records often only document the number of offspring or lack obstetric data altogether, necessitating life-history assumptions (e.g., Stewart, 1970; Houghton, 1974; Ullrich, 1975). In cases where obstetric records were accessible, researchers have often focused solely on parity. For instance, Andersen (1986), Cox & Scott (1992), Snodgrass & Galloway (2003), and McArthur (2016) analysed only the number of births, overlooking potential skeletal changes associated with pregnancy itself. Others, such as Kelley (1979) and Suchey et al. (1979) seemed to use the terms interchangeably, conflating their osteological effects – for example, Kelley refers to the number of pregnancies (gravidity count) but refers to nulligravid as nulliparous individuals. More recently, Igarashi et al. (2019) combined total pregnancies and births into a single variable, making it difficult to assess whether pregnancy-related or childbirth-related factors were driving observed skeletal changes. Notably, Waltenberger et al. (2022b) provided rare distinction between the two variables but ultimately reported only parity-related results, citing high similarity between pregnancy and birth outcomes. This methodological pattern highlights a persistent gap in research, where the independent effects of gravidity and parity remain underexplored.

Findings from the present study demonstrate that while maximum scar feature dimensions remain unchanged across all measured variables, some mean values exhibit slight increases from gravid to parous groups. The largest recorded mean increase from gravid to parous is observed in the inferior interosseous cavity, with a 0.23 mm length expansion. However, among scar features with a confirmed obstetric association, the changes are minimal. Maximum sulcus length remains fixed at 52.52 mm, with a marginal mean increase from 25.29 mm to 25.35 mm. Mean superior interosseous cavity width increases slightly from 3.12 mm to 3.19 mm, depth from 2.87 mm to 2.93 mm, and length from 5.41 mm to 5.53 mm.

Although small in magnitude, these mean increases suggest that pregnancy initiates remodelling in this region, while childbirth serves as a reinforcing rather than a primary modifying factor, supporting the interpretation of cumulative microstructural change rather than discrete traumatic modification. The greater impact of pregnancy on pelvic remodelling is likely attributable to its prolonged biomechanical and hormonal stresses. Independent of birth outcome, pregnancy exposes the pelvis to sustained hormonal fluctuations, particularly elevated relaxin and oestrogen levels, which promote ligamentous laxity and increased joint mobility. These effects, compounded by foetal weight gain and associated pelvic pressure, initiate bone remodelling at key stress points, contributing to the gradual expansion of scar features. In contrast, while childbirth represents an intense mechanical event, its acute nature may limit its long-term structural impact compared to the protracted physiological demands of pregnancy.

Differentiating between these obstetric factors offers a deeper understanding of how reproductive history influences pelvic morphology. Given the stability of maximum values, gravidity data may provide the most reliable basis for analysis, as it captures the most significant morphological changes. This is particularly relevant considering that many previous studies have focused on parity. However, these results highlight the continued challenge in distinguishing between natural and caesarean births in skeletal remains, as parity has only a limited effect within the broader impact of gravidity on scar site development.

6.2.4. Obstetric Events and Pelvic Scarring Summary

Ultimately, these results reinforce the importance of interpreting pelvic scars within a broader biomechanical and anatomical framework, considering the interplay between sex-based morphology, and pregnancy-related adaptation. The progressive reduction in statistical significance between the full and female-only analyses highlights the dominant influence of biological sex over obstetric events in the development of many pelvic scar features. Dorsal pubic pitting, pubic tubercle extension, and inferior interosseous cavitation lost significance in the female-only dataset, refuting obstetric strain as a primary driver. While largely influenced by biological sex, preauricular sulcus severity appears to be minimally affected by obstetric events, suggesting that sacroiliac joint loading during pregnancy may amplify its expression rather than dictate its initial occurrence. Interosseous cavity analysis refined interpretations of ligamentous strain during pregnancy and birth. Inferior interosseous cavitation correlated with obstetric history in the full sample but lost predictive utility in the female-only dataset, reinforcing sex-based skeletal variation as its primary determinant. In contrast, the superior interosseous cavity showed a stronger relationship with obstetric strain, with correlations exceeding those with biological sex in the female-only dataset.

These findings align with broader research on pregnancy-induced sacroiliac joint strain, particularly in the third trimester, when ligament laxity and joint widening peak (Garagiola et al., 1989; Maass, 2012). This instability can result in microtrauma and localized remodelling (Ritchie, 2003), potentially explaining the superior interosseous cavity's correlation with obstetric history. The persistence of sacroiliac malalignment after the first pregnancy and birth may maintain ligament tension (Williams, 1995), reinforcing its role in remodelling. As part of the sacroiliac joint, the superior interosseous cavity may serve as an osteological marker of these mechanical adaptations, supporting its moderate but consistent obstetric association.

Furthermore, the stability of maximum scar feature dimensions across obstetric groups suggests that pregnancy establishes the morphological limits of these features, while childbirth serves as a secondary factor that reinforces rather than fundamentally alters them. Given this pattern, gravidity data may provide the most reliable basis for skeletal assessment, as it captures the most significant morphological changes.

6.3. Additional Biological Variables and Pelvic Scarring

While the influence of sex and obstetric history on pelvic scarring has been more extensively examined, additional biological factors such as age, height, and weight have also been proposed as potential contributors to scar development and persistence. Ageing is associated with skeletal remodelling, hormonal changes, and alterations in biomechanical loading, all of which may impact scar formation. Many osteological studies have explored the relationship between age and pelvic scarring (Stewart, 1970; Kelley, 1979; Suchey et al., 1979; Andersen, 1986; Spring et al., 1989; Cox & Scott, 1992; Snodgrass & Galloway, 2003; Maass & Friedling, 2016; Karsten, 2018; Praxmarer et al., 2020; Waltenberger et al., 2021; 2022a), with some identifying clear age-related trends in certain scar features, while others find no significant associations.

Relationships between pelvic scarring and height or weight remain less well understood. Taller individuals typically exhibit larger pelves with longer iliac blades and increased pelvic inlet dimensions (Holland et al., 1982; Tague, 2000; Fischer & Mitteroecker, 2015), leading to hypotheses that height might influence scar severity due to increased ligamentous tension at attachment sites. Similarly, higher body mass has been suggested as a contributor to scar formation due to increased mechanical loading and sustained musculoskeletal strain (Holt, 1978; Karlsson et al., 2005). However, fewer studies have systematically investigated height and weight effects on pelvic scarring (Snodgrass & Galloway, 2003; Canty, 2020; Praxmarer et al., 2020; Waltenberger et al., 2021; 2022b), resulting in inconsistent conclusions.

This discussion examines the influence of additional biological variables on the occurrence and presentation of pelvic scar features, assessing whether age, height, and weight function as independent determinants of scarring or whether their effects are mediated by broader biological and mechanical processes. By integrating these findings with existing literature, this subchapter evaluates their significance within forensic and anthropological contexts.

6.3.1. Age and Pelvic Scarring

Dorsal pubic pitting exhibited an age-related trend within the full sample, with occurrence peaking in the 60–79 age group (25.7%) before declining to 16.7% in the 80+ group. This trend is largely driven by the female sample, where 33.7% of individuals aged 60–79 exhibited pitting, followed by a marked reduction to 16.2% in the 80+ group - a comparable rate to that in the 20–39 group. In contrast, male pitting occurrence was minimal, with only two instances, in the 80+ male group only, replicating observations by Andersen (1986). Nonetheless, a weak positive correlation was identified between age and pitting severity in biological males, aligning with Waltenberger et al. (2022a). However, given that this trend is based on only two individuals, its broader applicability remains uncertain, but it confirms that scarring can occur in the absence of reproductive events.

The female dorsal pitting findings initially align with the age-related patterns observed in studies by Praxmarer et al. (2020) and Waltenberger et al. (2022a), which report an increase in scarring with advancing female age. Although, the decline in pitting among the oldest females supports earlier claims by Stewart (1970) and Kelley (1979) that scarring may become less visible due to advanced age-related skeletal deterioration. Kelley (1979) noted that scarring in parous females peaked during the childbearing years and began declining from the fifth decade onwards, a trend similarly reflected in Andersen’s (1986) work. However, the findings from this research suggest a more prolonged period of continued scarring, extending beyond the typical reproductive years. This aligns with the idea that postmenopausal remodelling continues to influence scarring, potentially delaying the decline in visibility observed in other studies. This study demonstrates a statistically significant association between pitting presence and female age ($\chi^2 = 8.032$, $p = 0.045$). However, while categorical occurrence suggests a moderate age effect, metric analysis of pit severity (size and depth) does not reveal a corresponding increase. Thus, despite an age-related rise in overall pitting occurrence in females (with a drop-off in advanced age), continuous age variables do not significantly correlate with pit length, width, or depth, suggesting that while pitting becomes generally more common with age, individual pits do not necessarily enlarge or deepen. This reinforces the importance of distinguishing between occurrence-based trends and actual scar expansion.

The preauricular sulcus was highly prevalent across the full sample, with a maximum difference of 8.6% across age groups. A marginal decline was observed in the oldest individuals, with occurrence reducing from 86.2% in the 60–79 group to 79.2% in the 80+ group. Similar patterns of sulcus presentation have been reported in many previous studies (Spring et al., 1989; Cox & Scott, 1992; Novak, 2012; Maass & Friedling, 2016; Karsten, 2018; Igarashi et al., 2019; Canty, 2020; Waltenberger et al., 2021). This relative stability suggests that the sulcus is a long-term skeletal feature, with only minor late-life reduction. However, single-sex analysis highlights clear dimorphism. Female occurrence again remained high in all age groups, with a 93.5% occurrence rate across the full female sample, though there was a marginal decline in the 80+ category (89.2%). In contrast, male occurrence was significantly lower overall (54.9%), with no clear relationship with age. These findings support prior studies (Snodgrass & Galloway, 2003; Canty, 2020) that classify the sulcus as primarily sexually dimorphic rather than age-dependent. Metric analyses further reinforce the minimal influence of chronological age. Full group sulcus length peaked at 54.06 mm in the 60–79 group before decreasing slightly to 52.52 mm in the 80+ group. Width and depth followed a similar trajectory, with small increases in older groups, but no statistically significant correlations in either the full sample or single-sex analyses. This confirms that, while sulcus dimensions may fluctuate slightly, age does not strongly dictate its development or progression.

A comparable pattern was observed for the superior interosseous cavity, where full sample occurrence peaked at 33.0% in the 60–79 group before reducing to 29.2% in the 80+ group. Female occurrence followed the same trend, peaking at 38.6% (60–79) before declining to 29.7% (80+). The male sample displayed lower overall frequencies (ranging from 0–27.3%), with no clear association. Metric data supports these observations, showing that maximum superior cavity length increased to 29.24 mm in the 60–79 group but declined to 22.66 mm in the 80+ group - however, as with the sulcus, statistical analysis did not reveal significant correlations.

The decline in dorsal pubic pitting, preauricular sulcus, and superior interosseous cavity presence in females over 80 suggests that these scars may become obliterated with advanced age. This reduction is likely influenced by reduced biomechanical strain and metabolic changes that drive age-related skeletal deterioration, including shifts in bone remodelling, decreased osteoblastic activity, and increased porosity. Given the strong link between oestrogen loss, osteoporosis, and altered bone turnover, post-menopausal metabolic shifts are a key contributing factor. However, rather than active resorption of scar features, it is more plausible that the skeletal response to mechanical stress at scar sites diminishes, preventing the maintenance of existing lesions. Osteoporotic bone, being structurally weaker and remodelled differently due to reduced vascularisation and impaired osteoblastic activity (Rodriguez et al., 2019; Umur et al., 2024), may be more susceptible to scar loss rather than continued lesion persistence or formation. Notably, within this sample, several individuals exhibited osteoporotic changes, as expected given the age demographic, further supporting the idea that compromised bone quality accelerates the reduction of scar prominence over time.

A decline in biomechanical strain with age may further explain the reduction across all three sites. Dorsal pubic pitting, preauricular sulcus formation, and superior interosseous cavity development all reflect bony responses to mechanical loading. As individuals age, declining mobility and reduced physical activity lessen habitual mechanical strain, diminishing bony responses at tendon or ligament attachment sites. Since bone remodels in response to sustained musculoskeletal strain (Lang, 2011; Pataky et al., 2021), a lack of continued loading may result in reduced scar prominence. This effect is particularly pronounced in postmenopausal females, as oestrogen loss reduces mechanosensitivity (Lang, 2011), limiting the ability of bone to respond to strain. The accompanying pelvic floor laxity and ligamentous changes (Moalli et al., 2004) may further reduce mechanical tension at attachment sites, potentially accelerating scar decline in older females. By contrast, males experience a slower decline in mechanosensitivity, with testosterone continuing to support bone density and adaptive remodelling for longer (Lang, 2011). This prolonged hormonal influence may explain the delayed but still observable presence of dorsal pubic pitting in elderly males.

The inferior interosseous cavity followed a different trajectory from the superior cavity, maintaining a high prevalence across all female age groups, exceeding 97% occurrence from the age of 40 upwards (83.3% in the 20-39 group). In males, occurrence was slightly lower but showed a slight increase with age – to 90.9% occurrence rate in the 80+ group. However, neither full nor single-sex samples presented significantly in terms of statistical correlations. The metric data further reinforces this conclusion. While a slight increase in cavity width and depth were observed with age in both sexes, the variation was insignificant. In the female sample, inferior cavity depth ranged from a mean of 5.7 mm in the youngest cohort to 6.1 mm in the 80+ group, while male values ranged by just 0.4 mm. Although, the higher occurrence in females across all age groups, coupled with its lower but increasing presence in males, suggests some dimorphic influence – supporting earlier sex-related results.

Meanwhile, the pubic tubercle exhibited no significant age-related variation, maintaining occurrence rates exceeding 96% in females and 100% in males across all age groups. Metric analysis showed only minor fluctuations, with maximum tubercle extension increasing slightly to 9.18mm in the 60–79 full-sample group before decreasing to 7.52 mm in the 80+ category. However, no significant correlations were identified.

6.3.2. Height and Pelvic Scarring

The influence of height on pelvic scarring has received limited attention previously, yet its potential biomechanical implications warrant consideration. Taller individuals typically exhibit larger pelves (Holland et al., 1982; Tague, 2000; Fischer & Mitteroecker, 2015), potentially leading to greater tension at ligament and tendon attachment sites, and subsequently increased scarring. However, the present findings contradict this assumption. Instead, within the full study sample, height was negatively correlated with sulcus length, width, and depth ($\rho = -0.236$ to -0.332, $p < 0.001$) as well as inferior interosseous cavity width ($\rho = -0.337$, $p < 0.001$) and depth ($\rho = -0.282$, $p < 0.001$), suggesting that shorter individuals exhibit more pronounced scarring in these regions. The sulcus results align with Praxmarer et al. (2020), who observed similar trends in sulcus severity, although height was estimated in their dataset.

However, no significant height effects were observed in the sex-specific analyses, indicating that the full-sample correlations likely reflect the broader dimorphic trends identified in this research, rather than height acting as an independent variable. If height were a direct determinant of scarring, significant correlations would be expected within at least one sex group, yet this was not observed. Given that females tend to be shorter than males and exhibit greater scarring at several pelvic sites, the height-related relationships in the full sample likely stem from broader sex-based variation rather than stature itself influencing scar formation. These findings contradict earlier hypotheses that shorter females might exhibit more pronounced scarring due to obstetric stress. Cox (1989) and Maass (2012) suggested that shorter females with smaller pelves might experience increased mechanical strain during childbirth, leading to greater scarring at pelvic attachment sites. However, if height were directly linked to pelvic scarring through obstetric mechanisms, a stronger correlation would be expected in the female-only sample.

Pubic tubercle extension was the only additional scar feature to present significantly, in exhibiting a weak positive correlation with height in the full sample ($\rho = 0.252$, $p < 0.001$). This aligns with findings from Waltenberger et al. (2021) and supports the idea that tubercle development is at least partially linked to skeletal size, as taller individuals generally have larger bony structures. Unlike other scar features, the pubic tubercle functions as a proliferative rather than lytic feature, and its extension may reflect generalised skeletal growth patterns rather than localised stress responses. However, this association was also absent within single-sex groups.

6.3.3. Weight and Pelvic Scarring

The relationship between weight and pelvic scarring is complex, as body mass comprises multiple components - muscle, fat, and bone density - each of which may exert distinct effects on skeletal adaptation and presentation. Previous research has hypothesised that higher body weight might contribute to greater pelvic scarring due to increased intra-abdominal pressure and sustained mechanical strain at soft tissue attachment sites (Holt, 1978; Karlsson et al., 2005; Winter et al., 2020). However, the findings of this study do not support this hypothesis. Instead, weak negative correlations were found between weight and sulcus length ($\rho = -0.2$, $p = 0.014$), inferior interosseous cavity width ($\rho = -0.185$, $p = 0.023$), and inferior interosseous cavity depth ($\rho = -0.213$, $p = 0.009$), suggesting that individuals with lower body mass exhibit more pronounced presentation at these sites.

However, much like in the assessment of height association, an absence of significant weight effects in the sex-specific analyses further underscores the lack of independent influence of body mass. Instead, as with height, the full-sample negative correlations appear to reflect broader sex differences rather than true weight effects. Given that females generally have lower body mass than males and also exhibit greater overall scar presence, the observed weight trends reaffirm sulcus and inferior cavity variation as a by-product of sexual dimorphism. The findings of this study also contradict the weight-pitting hypothesis proposed by Maass & Friedling (2016), which suggested that higher body mass might contribute to dorsal pubic pitting due to increased mechanical stress at the pubic symphysis, with the present study finding no such relationship. This study thereby reinforces previous research by Waltenberger et al. (2022b), which also failed to identify significant weight-pitting associations.

Nonetheless, a key consideration in interpreting these findings is that weight in this study was based on total body weight rather than specific measures of fat mass or muscle composition. This distinction is important, as fat distribution plays a key role in mechanical loading and bone metabolism (Orwoll et al., 2006; Horstman et al., 2012). Adipose tissue contributes to peripheral oestrogen production (Horstman et al., 2012; Pataky et al., 2021), which could influence scar persistence or modification through hormonal pathways rather than direct mechanical effects. However, our results reflect general body mass rather than adipose-specific effects, meaning that the observed correlations likely reflect overall skeletal loading rather than hormonally mediated bone changes related to fat mass. Future research incorporating fat distribution metrics, such as waist circumference or body fat percentage, could therefore provide greater insight into whether fat tissue influences pelvic scarring through endocrine pathways rather than mechanical stress alone.

6.3.4. Age, Height, Weight, and Pelvic Scarring Summary

These findings reinforce the dominant role of sexual dimorphism in pelvic scarring, highlighting its interaction with skeletal ageing and biomechanical adaptation. While age demonstrated some association with dorsal pubic pitting in females, height and weight effects were largely secondary and failed to show independent significance within sex-specific analyses.

Overall, the data suggests limited association between age and scar presence, with most skeletal features showing no significant correlation or only weak, site-specific trends. Dorsal pubic pitting in females followed a non-linear pattern, peaking in the 60–79 age group before declining in those aged 80+, suggesting a cumulative effect of mechanical strain followed by later skeletal deterioration. However, the absence of significant metric correlations for pit size or depth indicates that while pitting became more frequent with age, individual lesions did not necessarily enlarge or persist. In males, dorsal pitting was rare and only observed in the oldest group, with a weak correlation with age that should be interpreted cautiously due to the small sample size. The preauricular sulcus and superior interosseous cavity remained largely stable across age groups, with only minor late-life reductions. The inferior interosseous cavity and pubic tubercle showed no significant variation with age, further reinforcing that these features are not age dependent. While osteoporosis and declining mechanosensitivity, may contribute to scar reduction in older females, the overall lack of strong correlations suggests that age alone is not a primary determinant of scarring. Instead, the findings confirm that sex-based strain plays a more dominant role.

Height and weight showed weak but inconsistent trends, with shorter and lower-weight individuals exhibiting more pronounced scarring in the full sample. However, these relationships disappeared in sex-specific analyses, suggesting that sexual dimorphism, rather than stature or body mass, is the primary determinant. This is particularly evident in the preauricular sulcus and inferior interosseous cavity, the most sexually dimorphic scar sites included in the final proposed sex estimation method. Ultimately, these results confirm that pelvic scarring reflects underlying dimorphic skeletal patterns, with age, height, and weight exerting only limited influence on scar formation and persistence.

6.4. Research Strengths and Limitations

6.4.1. Strengths

One of the key strengths of this research is its comprehensive scope, which investigates pelvic scarring across multiple sites while accounting for a diverse range of biological variables. By incorporating factors such as sex, obstetric history, age, height, and weight, the study provides a thorough analysis of their impact on pelvic scar patterns. This multivariable approach allows for a detailed understanding of not only how each factor independently influences scar development, but also their potential interactions. The emphasis on the complete obstetric history and its impact on scarring is particularly significant, as this study includes the analysis of individual obstetric events that may contribute to scar formation. By exploring the relationship between pregnancy or childbirth and pelvic scarring, this research adds valuable knowledge not only to archaeology and forensics, as well as obstetrics and gynaecology.

The study makes a substantial contribution to both anthropological and clinical knowledge. From an anthropological perspective, it enhances the understanding of pelvic morphology, biomechanics, and scar patterns in relation to demographic variables. Clinically, the findings can inform medical practitioners about the potential impacts of demographic and anthropometric factors on pelvic health, aiding in the development of treatments and preventive strategies. Translating these findings into practical applications can facilitate collaboration with practitioners in these fields, ensuring the results are both applicable and actionable.

The study employs an innovative methodological approach by integrating modern and archaeological samples where necessary for validation purposes. This integration not only provides a historical context but also confirms findings across different temporal periods. While this approach presents certain limitations, such as differences in preservation and demographic composition between samples, it enriches the study by offering comparative insights that inform both contemporary and historical understandings of pelvic scar patterns. The high intra-observer reliability further underscores the methodological rigour, ensuring consistency and reliability in measurements and observations.

Finally, the ethical diligence demonstrated in this study is noteworthy. Obtaining ethical approval and addressing potential concerns related to the use of human skeletal remains underscore the commitment to ethical research practices. This ensures that the research is conducted with respect and sensitivity towards the individuals included in the study. In line with best practice for the treatment of curated human remains, this study adheres to established ethical guidelines, including those outlined by the British Association for Biological Anthropology and Osteoarchaeology (BABAO), the Advisory Panel on the Archaeology of Burials in England (APABE), and the Department for Digital, Culture, Media and Sport (DCMS) Guidance for the Care of Human Remains in Museums (2005). These frameworks reinforce the importance of treating human remains with dignity, maintaining appropriate stewardship, and ensuring that their study contributes to respectful and ethically sound scientific inquiry.

6.4.2. Limitations

The data primarily originates from a body donation program, with information either self-reported at pre-registration or provided post-mortem by next of kin. Despite efforts to ensure accuracy, the reliability of reported data may be subject to inherent biases and potential inaccuracies. Given the nature of such programs, the sample composition is skewed towards older individuals, with a notable concentration in the 60-79 age range. This age bias reflects the typical demographics of donors and may limit the applicability of study findings to younger populations or those with different age distributions. Additionally, the geographic restrictions imposed by the need to obtain bodies shortly after death limit the sample representativeness concerning geographical diversity and urban-rural differences. Sample limitations are further pronounced concerning ancestral diversity, with the sample predominantly comprising individuals of white American descent – reflecting the ancestral variation within the TXSTDSC. This homogeneity may restrict the generalisability of findings, highlighting a gap in understanding potential pelvic scar variation across different ancestral groups. Future research should therefore aim to include more diverse populations to provide a broader understanding of pelvic scar patterns across different groups.

Furthermore, a sex bias is evident in the original skeletal sample utilised, with a larger proportion of females than males. This imbalance primarily results from data collection requirements for the obstetric element of this research and could unfortunately not be later resolved due to logistical constraints related to international travel. Efforts were made to mitigate this bias by ensuring an equal distribution of males and females in the validation sample, and the results of the secondary analysis proved that the method remained accurate despite the original sample sex bias. There was additional obstetric history bias towards females who have experienced pregnancy, which must be acknowledged. This may skew the interpretation of scar occurrence and severity in relation to obstetric factors. However, it was unavoidable as this again represented the obstetric variation within the full TXSTDSC sample as available for analysis.

Anthropometric measurement availability posed additional limitations, as not all donor records included comprehensive height and weight data. With this in mind, efforts were made to include a diverse range of anthropometric data. However, variations in data completeness for each individual remain a limitation that could affect the accuracy or precision of correlations between pelvic biological factor variation and scar occurrence. Additionally, weight data was limited to total body weight, without differentiation between fat, muscle mass, or overall body composition, which may have influenced observed trends. Further testing of height and weight associations with pelvic scarring would therefore be beneficial to increase confidence in the conclusions drawn pertaining to these biological variables.

Finally, the study faced methodological constraints due to the absence of inter-observer testing. Time and logistical constraints precluded conducting inter-observer studies, although intra-observer testing demonstrated high consistency and reliability. Nevertheless, implementing inter-observer testing in future research will be crucial for verifying the reliability of the method across different observers and settings.

Chapter 9: Conclusions & Future Work

Building on longstanding debates concerning scar aetiology, this thesis presents a novel, methodologically rigorous investigation into potential associations with biological sex, obstetric history, chronological age, height, and body mass. Through the integration of both macromorphological and metric analyses - applied consistently across multiple scar sites - this study has sought to address key limitations in previous research, advancing the analytical precision and interpretive utility of pelvic scarring.

A primary finding of this research is the extent to which pelvic scarring reflects dimorphic variation, and its potential for estimating biological sex from skeletal remains. The study initially explored a non-metric scar presentation - testing the hypothesis that individuals exhibiting pelvic scar features (individual or accumulatively) would be more likely to be biologically female. Initial analysis identified associations between female sex and the presence of all scar features except pubic tubercle extension. However, when considered individually, none of these features offered sufficient accuracy for reliable sex estimation due to notable overlap between sexes. An accumulative approach showed more promise, revealing that higher counts of scar features were more commonly observed in females, and that those presenting with either a low (one to two) or high (four to five) number of scar features could be assigned sex with a relatively high degree of confidence. However, 47.7% of individuals fell into the mid-range category (three scar features), in which sex estimation could not be reliably inferred. Moreover, the method would require complete preservation of key scar sites across the pubic and auricular regions, which may limit its applicability in cases involving fragmentary remains. As such, while the accumulative method provides valuable insights into dimorphic scar expression, its limited resolution in equivocal cases restricts its use as a standalone sex estimation tool.

To address these limitations, the study developed and tested a novel metric approach, hypothesising that metric assessment of individual scar features would enhance estimation accuracy and overcome the binary constraints of presence-based methods. Quantitative analyses revealed that biological females tended to present not only with a greater number of scar features, but also with significantly larger metric values - particularly in the preauricular sulcus and the inferior interosseous cavity. These two features, located at the posterior pelvis, demonstrated the strongest dimorphism – indicating that the broader and more flexible female pelvis, adapted to accommodate reproductive function, appears more vulnerable to the cumulative biomechanical loading that drives scar formation in these areas.

When the approximate cubic volumes of the preauricular sulcus and inferior interosseous cavity were assessed in combination, the results produced a highly accurate sex estimation model, supporting the second hypothesis of the study. During method development, this approach achieved the highest accuracy of any published method to date, with a slight decrease noted during the validation phase, yet still maintaining high reliability. This supports the view that pelvic scarring, particularly around the auricular surface, can serve as a powerful proxy for underlying sexual dimorphism when evaluated metrically. Importantly, this method focuses on a limited number of discrete features that are often preserved even in incomplete remains, and while it requires a sound knowledge of pelvic morphology, only basic osteological tools are needed. As such, it offers a practical, field-appropriate alternative to multi-site macroscopic techniques, which may be infeasible in contexts of poor preservation. The inclusion of an estimation graph allows for rapid visual interpretation of results, while a logistic regression equation is available to refine estimation where values fall close to the central prediction threshold. However, while more extensive scarring was more frequently observed in female individuals, a small number of males in the sample also presented with large scar volumes. This highlights the importance of considering additional contributing factors, to ensure such cases are not simply dismissed as anomalous without thorough investigation.

In addition to the influence of biological sex, this study also investigated the complex and historically contested relationship between obstetric events and pelvic scarring. This addressed the third aim of the research, which sought to determine whether scar features could serve as osteological indicators of gravidity or parity. Initial analyses revealed significant associations between obstetric history and several scar features, most notably within the preauricular sulcus and the interosseous cavity. However, these associations were notably stronger in the mixed-sex sample and weakened substantially when analyses were restricted to females, suggesting that many observed relationships were at least partially driven by broader dimorphic patterns rather than obstetric events alone.

Subsequent analysis clarified these dynamics further. For example, the preauricular sulcus - long associated with obstetric function - was shown to be primarily dimorphic in nature, with expression significantly heightened in females regardless of confirmed obstetric history. A similar trend was observed with the inferior interosseous cavity. In contrast, the superior interosseous cavity retained statistically significant associations with obstetric history across all measured dimensions in the female-only sample. Furthermore, correlations between superior cavity dimensions and gravidity or parity exceeded those observed with biological sex, demonstrating a more direct and consistent link to obstetric strain. These results support the interpretation that the superior cavity reflects microstructural remodelling of the posterosuperior sacroiliac joint, likely driven by the cumulative biomechanical and hormonal stresses of pregnancy.

Nonetheless, while these patterns offer support for obstetric influence - partially confirming the third hypothesis - the overall predictive value of pelvic scarring for reconstructing detailed obstetric history remains limited. Most scar features could not reliably differentiate between gravid/parous and nulligravid/nulliparous females, and associations were frequently confounded by underlying sex-based morphological variation. These results underscore the importance of caution when interpreting pelvic scarring as direct evidence of obstetric events, particularly in archaeological or forensic contexts where supporting documentation may be absent.

Even so, the identification of the superior interosseous cavity as a feature closely linked to obstetric strain represents a meaningful contribution to the field. It highlights the potential of evaluating localised biomechanical responses to life history events and suggests that, with further investigation, this feature may support more refined reconstructions of pelvic function and reproductive biomechanics. Moreover, these findings hold relevance beyond osteological analysis. In clinical contexts, a deeper understanding of how obstetric events influence pelvic morphology, particularly at the sacroiliac joint, could inform postnatal rehabilitation, pain management strategies, and orthopaedic assessment. Identifying regions of the pelvis vulnerable to stress-induced remodelling offers insight not only into skeletal plasticity, but also into the long-term biomechanical consequences of reproductive function on pelvic health.

Finally, this research further examined the potential influence of additional biological factors (specifically age, height, and weight) on pelvic scar expression. This addressed the fourth aim of the study, which sought to assess the extent to which these variables might contribute to scar development or severity, either independently or in conjunction with biological sex. While several statistically significant associations were initially identified, these were limited in scope, weakened under closer scrutiny, and frequently failed to retain interpretive value when considered alongside broader patterns of skeletal variation.

Of all scar features examined, dorsal pubic pitting was the only one to exhibit any statistical association with age. In the female sample, a weak relationship was identified with pitting occurrence, though this was not supported by metric data and likely reflects scoring variability or random distribution rather than a meaningful biological pattern. In the male sample, a moderate correlation was observed with pitting severity, but this was driven entirely by just two known-age individuals, limiting its generalisability. Moreover, the overall rarity of dorsal pubic pitting, particularly in known-age individuals, compromised the robustness of any conclusions. These findings underscore the interpretive limitations of infrequent features and the importance of cautious evaluation when statistical patterns emerge from small subsets of data.

For height and weight, all observed associations were confined to metric data and limited to just two features: the preauricular sulcus and inferior interosseous cavity. Weak negative correlations were noted across the full sample, suggesting a potential inverse relationship between body size and scar severity. However, these associations disappeared entirely when analysed within single-sex samples, indicating a reflection of underlying sexual dimorphism in stature and mass, rather than the independent influence of height or weight on scar development.

Combined, these findings confirm hypotheses 4 and 5: age, height, and weight do not exert a consistent or meaningful influence on pelvic scar formation. These variables therefore need not be considered essential when interpreting pelvic scarring for the purpose of biological sex estimation. However, the possibility remains that other biological or biomechanical factors, such as body fat percentage, waist-to-hip ratio, hormonal profiles, skeletal robustness, or habitual physical activity, may shape scar expression over time. Although such factors fell outside the scope of the present study, future longitudinal or cross-sectional research involving living individuals may provide valuable insight into the broader physiological processes underpinning scar development.

Ultimately, this thesis has demonstrated that posterior pelvic scarring - particularly when assessed metrically - can offer valuable insight into biological sex and, to a lesser extent, obstetric history. By focusing on discrete, often well-preserved anatomical landmarks, this study presents a novel approach to sex estimation that combines methodological precision with field applicability. The resulting model offers a statistically validated, anatomically grounded tool for use in skeletal analysis. More broadly, this research highlights the interpretive potential of posterior pelvic scarring within the construction of the biological profile and underscores the importance of evaluating these features through an integrated biomechanical and osteological framework.

Despite the limitations inherent in sample composition and preservation, this research has made a significant contribution to current understanding of pelvic scar formation. By identifying the strongest indicators of biological sex and clarifying the limited role of obstetric history and other biological variables, it meaningfully refines existing approaches to biological profile estimation. In doing so, this study contributes both conceptual clarity and practical advancement to the fields of forensic anthropology and bioarchaeology. It highlights the need to incorporate biological, biomechanical, and developmental perspectives when interpreting skeletal variation, and lays the groundwork for more nuanced reconstructions of the human skeleton. Future work - drawing on broader population samples, inter-observer validation, and multidisciplinary approaches - will be critical in refining these insights. With access to advanced technologies, such as high-resolution 3D scanning, surface texture analysis, geometric morphometrics, and machine learning, the present method could be further expanded to support more precise, scalable, and standardised interpretations of pelvic scarring. While this study was deliberately grounded in accessible, field-appropriate techniques, the integration of such tools offers an ambitious and promising path forward, both for refining osteological methods and for contributing to broader innovations in forensic and archaeological science

References

Albee, M. E. (2023) ‘Take a load off: skeletal implications of sedentism in the feet of modern body donors’, *Evolution, Medicine, & Public Health*, 11(1), pp. 485–501. Available at: https://doi.org/10.1093/emph/eoad041

Andersen, B. C. (1986) *Parturition Scarring a Consequence of Flexible Pelvis Architecture*. Doctoral Dissertation. Simon Fraser University.

Angel, J. L. (1969) ‘The bases of paleodemography’, *American Journal of Physical Anthropology*, 30(3), pp. 427–437. Available at: https://doi.org/10.1002/AJPA.1330300314

Ashton-Miller, J. A., & DeLancey, J. O. L. (2007) ‘Functional anatomy of the female pelvic floor’, *Annals of the New York Academy of Sciences*, 1101, pp. 266–296. Available at: https://doi.org/10.1196/annals.1389.034

Ashton-Miller, J. A., & DeLancey, J. O. L. (2009) ‘On the biomechanics of vaginal birth and common sequelae’, *Annual Review of Biomedical Engineering*, 11, pp. 163–176. Available at: https://doi.org/10.1146/annurev-bioeng-061008-124823

Berga, S. L., Genazzani, A. R., Naftolin, F., & Petraglia, F. (2019) *Menstrual Cycle Related Disorders, Volume* 7. New York: Springer.

Bergfelder, T., & Herrmann, B. (1980) ‘Estimating Fertility on the Basis of Birth-traumatic Changes in the Pubic Bone’, *Journal of Human Evolution*, 9, pp. 611–613. Available at: https://doi.org/10.1016/0047-2484(80)90091-3

Bonczarowska, J. H., Bonicelli, A., Papadomanolakis, A., & Kranioti, E. F. (2019) ‘The posterior portion of the ilium as a sex indicator: A validation study’, *Forensic Science International*, 294, pp. 216.e1-216.e6. Available at: https://doi.org/10.1016/j.forsciint.2018.10.031

Box, G. E. P., & Tidwell, P. W. (1962) ‘Transformation of the Independent Variables’, *Technometrics*, 4(4), pp. 531–550. Available at: https://doi.org/10.2307/1266288

Brothwell, D., & Zakrzewski, S. R. (2004) ‘Metric and non-metric studies of archaeological human bone’, in M. Brickley & J. I. McKinley (eds), *Guidelines to the Standards for Recording Human Remains* Institute of Field Archaeologists; British Association for Biological Anthropology and Osteoarchaeology. pp. 27–33.

Buck, E., McNally, L., Vadakekut, E. S., & Jenkins, S. M. (2024) *Menstrual Suppression.* Treasure Island: StatPearls Publishing.

Burger, H. G., Dudley, E. C., Robertson, D. M., & Dennerstein, L. (2002) 'Hormonal Changes in the Menopause Transition', in A. R. Means (ed.), *Recent Progress in Hormone Research*, 57. The Endocrine Society Press. pp. 257–275.

Bytheway, J. A., & Ross, A. H. (2010) 'A geometric morphometric approach to sex determination of the human adult os coxa', *Journal of Forensic Sciences*, 55(4), pp. 859–864. Available at: https://doi.org/10.1111/j.1556-4029.2010.01374.x

Cable, J. K., & Grider, M. H. (2023). *Physiology, Progesterone*. Treasure Island: StatPearls Publishing.

Calais-Germain, B. (2003) *The Female Pelvis Anatomy & Exercises*. Seattle: Eastland Press.

Calguneri, M., Bird, H. A., & Wright, V. (1982) 'Changes in joint laxity occurring during pregnancy', *Annals of the Rheumatic Diseases*, 41(2), pp. 126–128. Available at: https://doi.org/10.1136/ard.41.2.126

Canty, S. E. (2020) *The preauricular sulcus in relation to sexual dimorphism, pregnancy and parturition in humans.* Doctoral Dissertation. Liverpool John Moores University.

Cauley, J. A. (2015) 'Estrogen and bone health in men and women', *In Steroids,* 99(A), pp. 11–15. Elsevier Inc. Available at: https://doi.org/10.1016/j.steroids.2014.12.010

Chidi-Ogbolu, N., & Baar, K. (2019) 'Effect of estrogen on musculoskeletal performance and injury risk', *Frontiers in Physiology*, 15(9). Available at: https://doi.org/10.3389/fphys.2018.01834

Christensen, A. M., Passalacqua, N. V., & Bartelink, E. J. (2014) *Forensic Anthropology: Current Methods and Practice*. Oxford: Elsevier Academic Press.

Coldron, Y., Stokes, M. J., Newham, D. J., & Cook, K. (2008) 'Postpartum characteristics of rectus abdominis on ultrasound imaging', *Manual Therapy*, 13(2), pp. 112–121. Available at: https://doi.org/10.1016/J.MATH.2006.10.001

Coleman, W. H. (1969) 'Sex Differences in the Growth of the Human Bony Pelvis', *American Journal of Physical Anthropology*, 31(2), pp. 125–151. Available at: https://doi.org/10.1002/ajpa.1330310202

Cox, M. J. (1989). *An Evaluation of the Significance of "Scars of Parturition" in the Christ Church Spitalfields Sample*. Doctoral Dissertation. University College London.

Cox, M., & Mays, S. (2000) *Human Osteology in Archaeology and Forensic Science*. 1st edn. Greenwich: Greenwich Medical Media Ltd.

Cox, M., & Scott, A. (1992) 'Evaluation of the obstetric significance of some pelvic characters in an 18th century British sample of known parity status', *American Journal of Physical Anthropology*, 89(4), pp. 431–440. Available at: https://doi.org/10.1002/AJPA.1330890404

Cronbach, L. J. (1951) 'Coefficient Alpha and the Internal Structure of Tests', *Psychometrika*, 16(3), pp. 297-334. Available at: https://doi.org/10.1007/BF02310555

Cronk, B. C. (2020) *How to Use SPSS®: A Step-By-Step Guide to Analysis and Interpretation.* 11th edn. New York: Routledge.

Cunningham, C., Scheuer, L., & Black, S. (2016) *Developmental Juvenile Osteology.* 2nd edn. Oxford: Elsevier Science.

Dar, G., & Hershkovitz, I. (2006) 'Sacroiliac joint bridging: Simple and reliable criteria for sexing the skeleton', *Journal of Forensic Sciences*, 51(3), pp. 480–483. Available at: https://doi.org/10.1111/j.1556-4029.2006.00119.x

Davivongs, V. (1963) 'The Pelvic Girdle of the Australian Aborigine; Sex Differences and Sex Determination', *American Journal of Physical Anthropology*, 21(4), pp. 443–455. Available at: https://doi.org/10.1002/ajpa.1330210403

Dehghan, F., Haerian, B. S., Muniandy, S., Yusof, A., Dragoo, J. L., & Salleh, N. (2014) 'The effect of relaxin on the musculoskeletal system', *Scandinavian Journal of Medicine & Science in Sports*, 24(4), pp. 220–229. Available at: https://doi.org/10.1111/SMS.12149

DesMarais, A., Obertova, Z., & Franklin, D. (2023) 'The influence of age on greater sciatic notch morphology: testing the Walker method in an Australian population', *International Journal of Legal Medicine*, 138(1), pp. 239–247. Available at: https://doi.org/10.1007/s00414-023-02988-1

Dimitrov, D. M. (2002) 'Reliability: Arguments for multiple perspectives and potential problems with generalization across studies', *Educational and Psychological Measurement*, 62(5), pp. 783–801. Available at: https://doi.org/10.1177/001316402236878

Duren, D. L., Seselj, M., Froehle, A. W., Nahhas, R. W., & Sherwood, R. J. (2013) ‘Skeletal growth and the changing genetic landscape during childhood and adulthood’, A*merican Journal of Physical Anthropology*, *150*(1), 48–57. Available at: https://10.1002/ajpa.22183

Eggington, J. (2020) ‘Diet, skeletal stress and socioeconomic status in post-medieval Britain (1700-1850)’, *The Post Hole*, 56. Available at: https://www.theposthole.org/read/article/463

FACTS. (2022). *Whole Body Donations*. Available at:
https://doi.org/https://www.txst.edu/anthropology/facts/donations/Body.html (Accessed: 28 October 2022)

Fauser, B. C., & Petraglia, F. (2020) *Female Reproductive Dysfunction*. Cham: Springer International Publishing.

Ferin, M., Jewelewicz, R., & Warren, M. (1993) *The Menstrual Cycle Physiology, Reproductive Disorders, and Infertility*. Oxford: Oxford University Press.

Ferretti, J. L., Cointry, G. R., Capozza, R. F., & Frost, H. M. (2003) ‘Bone mass, bone strength, muscle/bone interactions, osteopenias and osteoporoses’, *Mechanisms of Ageing and Development*, 124(3), pp. 269–279. Available at: https://doi.org/10.1016/s0047-6374(02)00194-x

Fiani, B., Sekhon, M., Doan, T., Bowers, B., Covarrubias, C., Barthelmass, M., De Stefano, F., & Kondilis, A. (2021) ‘Sacroiliac Joint and Pelvic Dysfunction Due to Symphysiolysis in Postpartum Women’, *Cureus*, 13(10). Available at: https://doi.org/10.7759/cureus.18619

Field, A. P. (2009) *Discovering statistics using SPSS (and sex and drugs and rock “n” roll)*. London: SAGE Publications.

Filler, M. G., & DiGabriele, J. A. (2012) *A Quantitative Approach to Commercial Damages*. Hoboken: John Wiley & Sons, Inc.

Fischer, B., Grunstra, N. D. S., Zaffarini, E., & Mitteroecker, P. (2021) ‘Sex differences in the pelvis did not evolve de novo in modern humans’, *Nature Ecology and Evolution*, 5(5), pp. 625–630. Available at: https://doi.org/10.1038/s41559-021-01425-z

Fischer, B., & Mitteroecker, P. (2015) ‘Covariation between human pelvis shape, stature, and head size alleviates the obstetric dilemma’, *PNAS*, 112(18), pp. 5655–5660. Available at: https://doi.org/10.5061/dryad.2d728

Fischer, B., & Mitteroecker, P. (2017) ‘Allometry and Sexual Dimorphism in the Human Pelvis.’, *Anatomical Record*, 300(4), pp, 698–705. Available at: https://doi.org/10.1002/ar.23549

Fraser, J. E. (1958) *Anatomy of the Human Skeleton*. 5th edn. J, & A. Churchill.

Garagiola, D. M., Tarver, R. D., Gibson, L., Rogers, R. E., & Wass, J. L. (1989) ‘Anatomic Changes in the Pelvis After Uncomplicated Vaginal Delivery: A CT Study on 14 Women’, *American Journal of Roentgenology*, 153(6), pp. 1239–1241. Available at: https://doi.org/10.2214/ajr.153.6.1239

Gharib, M. N. EL, & Aglan, A. D. (2018) ‘Changes in Skeletal System during Pregnancy’, *Interventions in Gynaecology and Women’s Healthcare*, 2(1). Available at: https://doi.org/10.32474/IGWHC.2018.02.000127

Gilleard, W. L., & Brown, J. M. M. (1996) ‘Structure and Function of the Abdominal Muscles in Primigravid Subjects During Pregnancy and the Immediate Postbirth Period’, *Physical Therapy*, 76(7), pp. 750–762. Available at: https://doi.org/10.1093/PTJ/76.7.750

Gocha, T. P., Mavroudas, S. R., & Wescott, D. J. (2022) ‘The Texas State Donated Skeletal Collection at the Forensic Anthropology Center at Texas State’, *Forensic Sciences*, 2(1), pp. 7–19. Available at: https://doi.org/10.3390/FORENSICSCI2010002

Gohil, D., Dangar, K., Rathod, S., Jethwa, K., & Singal, G. (2014) ‘A study of morphological features of ilium for sex determination in Gujarat state’, *Journal of Research in Medical and Dental Science*, 2(4), pp. 75-78. Available at: https://doi.org/10.5455/jrmds.20142415

Greer, W. J., Richter, H. E., Bartolucci, A. A., & Burgio, K. L. (2008) ‘Obesity and pelvic floor disorders: A systematic review’, *Obstetrics & Gynecology,* 112(2), pp. 341–349. Available at: https://doi.org/10.1097/AOG.0b013e31817cfdde

Guggenbuhl, P. (2009) ‘Osteoporosis in males and females: Is there really a difference?’, *Joint Bone Spine*, 76(6), pp. 595–601. Available at: https://doi.org/10.1016/j.jbspin.2009.10.001

Hammes, S. R., & Levin, E. R. (2019) ‘Impact of estrogens in males and androgens in females’, *Journal of Clinical Investigation*, 129(5), pp. 1818–1826. Available at: https://doi.org/10.1172/JCI125755

Holland, E. L., Cran, G. W., Elwood, J. H., Pinkerton, J. H. M., & Thompson, W. (1982) ‘Associations between pelvic anatomy, height and year of birth of men and women in Belfast’, *Annals of Human Biology*, 9(2), pp. 113–120. Available at: https://doi.org/10.1080/03014468200005581.

Holt, C. A. (1978) ‘A re-examination of parturition scars on the human female pelvis’, *American Journal of Physical Anthropology*, 49(1), pp. 91–94. Available at: https://doi.org/10.1002/AJPA.1330490114

Horstman, A. M., Dillon, E. L., Urban, R. J., & Sheffield-Moore, M. (2012) ‘The role of androgens and estrogens on healthy aging and longevity’, *Journals of Gerontology: Series A*, 67(11), pp. 1140–1152. Available at: https://doi.org/10.1093/gerona/gls068

Hoshi, H. (1961) ‘On the Preauricular Groove in the Japanese Pelvis with Special Reference to the Sex Difference’, *Okajimas Folia Anatomica Japonica*, 37(3), pp. 259–269. Available at: https://doi.org/10.2535/ofaj1936.37.3_259

Houghton, P. (1974) ‘The Relationship of the Pre-auricular Groove of the Ilium to Pregnancy’, *American Journal of Physical Anthropology*, 41, pp. 381–390. Available at: https://doi.org/https://doi.org/10.1002/ajpa.1330410305

Houghton, P. (1975) ‘The bony imprint of pregnancy’, *Bulletin of the New York Academy of Medicine*, 51(5), pp. 655-661. Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1749523/

Igarashi, Y., Shimizu, K., Mizutaka, S., & Kagawa, K. (2019) ‘Pregnancy parturition scars in the preauricular area and the association with the total number of pregnancies and parturitions’, *American Journal of Physical Anthropology*, 171(2). Available at: https://doi.org/10.1002/ajpa.23961

Inskip, S., Scheib, C. L., Wohns, A. W., Ge, X., Kivisild, T., & Robb, J. (2019) ‘Evaluating macroscopic sex estimation methods using genetically sexed archaeological material: The medieval skeletal collection from St John’s Divinity School, Cambridge’, *American Journal of Physical Anthropology*, 168(2), pp. 340–351. Available at: https://doi.org/10.1002/ajpa.23753

Işcan, Y. M., & Derrick, K. (1984) ‘Determination of Sex from the Sacroiliac Joint: A Visual Assessment Technique’, *Florida Scientist*, 47(2), pp. 94–98. Available at: http://www.jstor.org/stable/24319808

Ives, G., Johns, S. E., & Deter, C. (2024) ‘Sexual dimorphism of pelvic scarring: A new method of adult biological sex estimation’, *Journal of Forensic Sciences*, 69(6), pp. 1959-1971. Available at: https://doi.org/10.1111/1556-4029.15587

Ives, G., Johns, S. E., & Deter, C. (2024) ‘Pelvic Scarring: A Result of Gravidity and Parity, or Simply Evidence of Biological Potential?’, *Journal of Archives of Biology & Life Sciences*, 1(2). Available at: https://doi.org/10.33140/ABLS

Karlsson, M. K., Ahlborg, H. G., & Karlsson, C. (2005) ‘Female reproductive history and the skeleton - A review’, *BJOG: An International Journal of Obstetrics and Gynaecology*, 112(7), pp. 851–856. Available at: https://doi.org/10.1111/j.1471-0528.2005.00571.x

Karsten, J. K. (2018) ‘A test of the preauricular sulcus as an indicator of sex’, *American Journal of Physical Anthropology*, 165(3), pp. 604–608. Available at: https://doi.org/10.1002/ajpa.23372

Kelley, M. A. (1979) ‘Parturition and pelvic changes’, *American Journal of Physical Anthropology*, 51(4), pp. 541–545. Available at: https://doi.org/10.1002/AJPA.1330510405

Kiapour, A., Joukar, A., Elgafy, H., Erbulut, D. U., Agarwal, A. K., & Goel, V. K. (2020) ‘Biomechanics of the sacroiliac joint: Anatomy, function, biomechanics, sexual dimorphism, and causes of pain’, *International Journal of Spine Surgery*, 14, pp. 3–13. Available at: https://doi.org/10.14444/6077

Klales, A. R. (2020) ‘Sex estimation using pelvis morphology’ in A. R. Klales (ed.) *Sex Estimation of the Human Skeleton: History, Methods, and Emerging Techniques.* London: Elsevier Academic Press, pp.75-94.

Kumar, P., & Magon, N. (2012) ‘Hormones in pregnancy’, *Nigerian Medical Journal: Journal of the Nigeria Medical Association*, 53(4), pp. 179-183. Available at: https://doi.org/10.4103/0300-1652.107549

Kuzmar, I. (2021) ‘Hormones and Labour - Role of Progesterone, Oestrogen and Other Hormones in Pregnancy’, *Maternal and Pediatric Nutrition*, 6(4). Available at: https://doi.org/10.35248/2472-1182.21.6.140

Lambert, D. M., Marceau, S., & Forse, A. (2005) ‘Intra-abdominal Pressure in the Morbidly Obese’, *Obesity Surgery*, 15, pp. 1225–1232. Available at: https://doi.org/10.1381/096089205774512546.

Lang, T. F. (2011) ‘The Bone-Muscle Relationship in Men and Women’, *Journal of Osteoporosis*, 2011, pp. 1–4. Available at: https://doi.org/10.4061/2011/702735

Larsen, C. S. (2015) *Bioarchaeology: Interpreting Behavior from the Human Skeleton*. 2nd edn. Cambridge: Cambridge University Press.

Leong, A. (2006) ‘Sexual dimorphism of the pelvic architecture: A struggling response to destructive and parsimonious forces by natural & mate selection’, *McGill Journal of Medicine*, 9(1), pp. 61–66. Available at: https://doi.org/10.26443/mjm.v9i1.602

Lierse, W., Frohmüller, H., Stelzner, F., & Stegner, H. (2012) *Applied Anatomy of the Pelvis.* 2nd edn. Heidelberg: Springer.

Longcope, C., & Johnston, C. C. (1988) 'Androgen and Estrogen Dynamics in Pre-and Postmenopausal Women: A Comparison Between Smokers and Nonsmokers', *Journal of Clinical Endocrinology and Metabolism*, 67(2), pp. 379-383. Available at: https://doi.org/10.1210/jcem-67-2-379.

Lovell, N. C. (1989) 'Test of Phenice's Technique for Determining Sex from the Os Pubis', *American Journal of Physical Anthropology*, 79, pp. 117–120. Available at: https://doi.org/https://doi.org/10.1002/ajpa.1330790112

Maass, P. (2012) *The Bony Pelvis: Scars of Parturition and Factors Influencing their* Manifestation. Master's Dissertation. University of Cape Town.

Maass, P., & Friedling, L. J. (2016) 'Scars of Parturition? Influences Beyond Parity', *International Journal of Osteoarchaeology*, 26(1), pp. 121–131. Available at: https://doi.org/10.1002/OA.2402

MacEvilly, M., & Buggy, D. (1996) 'Back pain and pregnancy: a review', *Pain*, 64(3), pp. 405–414. Available at: https://doi.org/10.1016/0304-3959(95)00184-0

Maclaughlin, S. M., & Bruce, M. F. (1990) 'The Accuracy of Sex Identification in European Skeletal Remains Using the Phenice Characters', *Journal of Forensic Science*, 35(6), pp. 1384–1392. Available at: https://doi.org/https://10.1520/JFS12974J

Mahadevappa, R. G., & Shivalingaiah, N. (2017) 'Sex determination by post auricular sulcus in South Karnataka', *Indian Journal of Forensic and Community Medicine*, 4(3), pp. 176–180. Available at: https://doi.org/10.18231/2394-6776.2017.0038

Marsh, C., & Elliot, J. (2008) *Single Variables. In Exploring Data: An Introduction to Data Analysis for Social Scientists.* 2nd edn. Cambridge: Polity Press.

McArthur, T. A., Meyer, I., Jackson, B., Pitt, M. J., & Larrison, M. C. (2016) 'Parturition pit: the bony imprint of vaginal birth', *Skeletal Radiology*, 45(9), pp. 1263–1267. Available at: https://doi.org/10.1007/S00256-016-2418-3

McFadden, C. (2020) 'Parturition markers and skeletal sex estimation' in A. R. Klales (ed.) *Sex Estimation of the Human Skeleton: History, Methods, and Emerging Techniques.* London: Elsevier Academic Press, pp. 131–146.

Menard, S. (2010). *Logistic Regression: From Introductory to Advanced Concepts and Applications*. California: Sage Publications.

Mengert, W. F. (1936) ‘Mechanics of uterine support and position’, *American Journal of Obstetrics and Gynaecology*, 31(5), pp. 775-782. Available at: https://doi.org/10.1016/S0002-9378(36)91068-2

Micussi, T. M., FreiTas, P. R., Angelo, H. P., Soares, M. E., LeMos, M. T., & Maranhão, M. T. (2015) ‘Is there a difference in the electromyographic activity of the pelvic floor muscles across the phases of the menstrual cycle?’, *Journal of Physical Therapy Science*, 27, pp. 2233–2237. Available at: https://doi.org/https://10.1589/jpts.27.2233

Mihm, M., Gangooly, S., & Muttukrishna, S. (2011) ‘The normal menstrual cycle in women’, *Animal Reproduction Science*, 124(3), pp. 229–236. Available at: https://doi.org/10.1016/j.anireprosci.2010.08.030

Mitteroecker, P., & Fischer, B. (2022) ‘Evolution of the human birth canal’, *American Journal of Obstetrics and Gynecology*, 230(3), pp. 841–855. Available at: https://doi.org/10.1016/j.ajog.2022.09.010

Moalli, P. A., Talarico, L. C., Sung, V. W., Klingensmith, W. L., Shand, S. H., Meyn, L. A., & Watkins, S. C. (2004) ‘Impact of menopause on collagen subtypes in the arcus tendinous fasciae pelvis’, *American Journal of Obstetrics and Gynecology*, 190(3), pp. 620–627. Available at: https://doi.org/10.1016/j.ajog.2003.08.040

Molleson, T., Cox, M., Waldron, A. H., & Whittaker, D. K. (1993) ‘*The Spitalfields Project, Volume 2: The Middling Sort*’, Council for British Archaeology, 86. Available at: https://doi.org/10.5284/1081778

Morgan, G. A., Leech, N. L., Gloeckner, G. W., & Barrett, K. C. (2011) *IBM SPSS for Introductory Statistics Use and Interpretation.* 4th edn. New York: Routledge.

Morino, S., Ishihara, M., Umezaki, F., Hatanaka, H., Yamashita, M., & Aoyama, T. (2019) ‘Pelvic alignment changes during the perinatal period’, *PLoS ONE*, 14(10). Available at: https://doi.org/10.1371/journal.pone.0223776

Netter, F. H. (2017) *Atlas of Human Anatomy E-Book*. 7th edn. Philadelphia: Elsevier Health Sciences.

Novak, L., Schultz, J. J., & McIntyre, M. (2012) ‘Determining Sex of the Posterior Ilium from the Robert J. Terry and William M. Bass Collections’, *Journal of Forensic Sciences*, 57(5), pp. 1155–1160. Available at: https://doi.org/10.1111/j.1556-4029.2012.02122.x

Olsen, L. (2023). *Learning From the Dead*. Texas Observer. Available at: https://www.texasobserver.org/body-ranch-postcard-texas-state-forensic-anthropology (Accessed: 3 June 2023)

Opala-Berdzik, A., & Dăbrowski, S. (2009) ‘Physiotherapy in diastasis of the rectus muscles of abdomen in women during pregnancy and postpartum’, *Physiotherapy*, 17(4), pp. 67–70. Available at: https://doi.org/10.2478/v10109-010-0039-2

Ott, S. M. (2008) ‘Reproductive Hormones and Skeletal Health in Young Women’, *The Journal of Clinical Endocrinology & Metabolism*, 93(4), pp. 1175–1177. Available at: https://doi.org/10.1210/JC.2008-0379

Pany-Kucera, D., Spannagl-Steiner, M., Argeny, S., Maurer-Gesek, B., Weninger, W. J., & Rebay-Salisbury, K. (2019) ‘Sacral preauricular extensions, notches, and corresponding iliac changes: New terms and the proposal of a recording system’, *International Journal of Osteoarchaeology*, 29(6), pp. 1013–1021. Available at: https://doi.org/10.1002/oa.2814

Pany-Kucera, D., Spannagl-Steiner, M., Desideri, J., & Rebay-Salisbury, K. (2021) ‘Indicators of motherhood? Sacral preauricular extensions and notches in identified skeletal collections’, *International Journal of Osteoarchaeology*, 32(1), pp. 1–11. Available at: https://doi.org/10.1002/OA.3044

Pedhazur, E. J. (1997) *Multiple Regression in Behavioral Research: An Explanation and Prediction.* 3rd edn. Belmont: Wadsworth Publishing Co Inc.

Praxmarer, E. M., Tutkuviene, J., & Kirchengast, S. (2020) ‘Metric and morphological analysis of pelvic scars in a historical sample from Lithuania: Associations with sex, age, body size and pelvic dimensions’, *International Journal of Osteoarchaeology*, 30(5), pp. 629–641. Available at: https://doi.org/10.1002/oa.2887

Ramalingam, K., & Monga, A. (2015) ‘Obesity and pelvic floor dysfunction’, *Best Practice and Research: Clinical Obstetrics and Gynaecology*, 29(4), pp. 541–547. Available at: https://doi.org/10.1016/j.bpobgyn.2015.02.002

Rebay-Salisbury, K., Pany-Kucera, D., Spannagl-Steiner, M., Kanz, F., Galeta, P., Teschler-Nicola, M., & Salisbury, R. B. (2018) ‘Motherhood at Early Bronze Age Unterhautzenthal, Lower Austria’, *Archaeologica Austriaca*, 102, pp. 71–134. Available at: https://doi.org/10.2307/26668581

Reed, B. G., & Carr, B. R. (2018) *The Normal Menstrual Cycle and the Control of Ovulation*. Endotext [Internet]. Available at: https://www.ncbi.nlm.nih.gov/books/NBK279054 (Accessed: 4 Jan 2023).

Riggs, B. L., Wahner, H. W., Dunn, W. L., Mazess, R. B., Offord, K. B., & Melton, L. J. (1981) 'Differential changes in bone mineral density of the appendicular and axial skeleton with aging: relationship to spinal osteoporosis', *Journal of Clinical Investigation*, 67(2), pp. 328–335. Available at: https://doi.org/10.1172/JCI110039

Ritchie, J. R. (2003) 'Orthopedic Considerations During Pregnancy', *Clinical Obstetrics and Gynecology*, 46(2), pp. 456–466. Available at: https://doi.org/10.1097/00003081-200306000-00024

Roberts, C., & Manchester, K. (2010) *The Archaeology of Disease*. 3rd edn. Stroud: The History Press.

Rodriguez, A. J., Scott, D., & Ebeling, P. R. (2019) 'Exploring the links between common diseases of ageing—Osteoporosis, sarcopenia and vascular calcification', Clinical Reviews in Bone and Mineral Metabolism, 17(1), pp. 1–23. Available at: https://doi.org/10.1007/s12018-018-9251-2

Rostaminia, G., Peck, J. D., Van Delft, K., Thakar, R., Sultan, A., & Shobeiri, S. A. (2016) 'New Measures for Predicting Birth-Related Pelvic Floor Trauma', *Female Pelvic Medicine and Reconstructive Surgery*, 22(5), pp. 292–296. Available at: https://doi.org/10.1097/SPV.0000000000000282

Russo, C. R., Lauretani, F., Bandinelli, S., Bartali, B., Di Iorio, A., Volpato, S., Guralnik, J. M., Harris, T., & Ferrucci, L. (2003) 'Aging bone in men and women: Beyond changes in bone mineral density', *Osteoporosis International*, 14(7), pp. 531–538. Available at: https://doi.org/10.1007/s00198-002-1322-y

Scheuer, L., & Black, S. (2004) *The Juvenile Skeleton*. 1st edn. London: Elsevier Academic Press.

Schwartz, Jeffrey. H. (2007) *Skeleton Keys*. 2nd edn. Oxford: Oxford University Press.

Seidman, A., Brossy, K., Faulkner, A., & Taylor, J. (2019) 'Case Report Traumatic Pelvic Ring Injury following Childbirth with Complete Pubic Symphysis Diastasis', *Case Reports in Orthopedics*, article number 1785167. Available at: https://doi.org/10.1155/2019/1785167

Šerstņova, K., Edelmers, E., Zolovs, M., & Pilmane, M (2023) 'Comparison of Bone Quality in Middle Ages and Late Modern Period Human Skeletons from Latvia', *Heritage*, 6(7), pp. 5329-5346. Available at: https://doi.org/10.3390/heritage6070281

Sharma, R. D. (2017) ‘Tests of significance for the ordinal level of variables.’, In R. D. Sharma (ed.) *Elements of Statistics: A Hands-on Primer*. 1st edn. Cambridge: Cambridge Scholars Publishing. pp. 144–157.

Shek, K. L., & Dietz, H. P. (2019) ‘Vaginal Birth and Pelvic Floor Trauma’, *Current Obstetrics and Gynecology Reports*, 8(2), pp. 15–25. Available at: https://doi.org/10.1007/s13669-019-0256-8

Shi, L., Jiang, Z., & Zhang, L. (2022) ‘Childhood obesity and central precocious puberty’, *Frontiers in Endocrinology*, 13. Available at: https://doi.org/10.3389/fendo.2022.1056871

Snodgrass, J. J., & Galloway, A. (2003) ‘Utility of dorsal pits and pubic tubercle height in parity assessment’, *Journal of Forensic Sciences*, 48(6), pp. 1226–1230. Available at: https://doi.org/10.1520/JFS2003027

Spring, D. B., Lovejoy, C. O., Bender, G. N., & Duerr, M. (1989) ‘The radiographic preauricular groove: Its non-relationship to past parity’, *American Journal of Physical Anthropology*, 79(2), pp. 247–252. Available at: https://doi.org/10.1002/AJPA.1330790212

Stevens, J. P. (2002) *Applied multivariate statistics for the social sciences*. 4th edn. New Jersey: Lawrence Erlbaum Associates Publishers.

Stewart, T. D. (1970). *Personal identification in mass disasters*. Washington: National Museum of Natural History, Smithsonian Institution, pp. 127-136. Available at: https://doi.org/10.5479/sil.30678.39088001440254

Suchey, J. M., Wiseley, D. V., Green, R. F., & Noguchi, T. T. (1979) ‘Analysis of dorsal pitting in the Os pubis in an extensive sample of modern American females’, *American Journal of Physical Anthropology*, 51(4), pp. 517–539. Available at: https://doi.org/10.1002/AJPA.1330510404

Suresh, L., & Radfar, L. (2004) ‘Pregnancy and lactation’, *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontics*, 97(6), pp. 672–682. Available at: https://doi.org/10.1016/j.tripleo.2004.02.002

Tabachnick, B. G., & Fidell, L. S. (2014) *Using Multivariate Statistics*. 6th edn. Harlow: Pearson Education.

Tague, R. G. (2000) ‘Do Big Females Have Big Pelves?’, *American Journal of Physical Anthropology*, 112, pp. 377–393. Available at: https://doi.org/10.1002/1096-8644(200007)112:3<377::AID-AJPA8>3.0.CO;2-O

Talbot, L., & Maclennan, K. (2016) ‘Physiology of pregnancy’, *Anaesthesia & Intensive Care Medicine*, 17(7), pp. 341–345. Available at: https://doi.org/10.1016/J.MPAIC.2016.04.010

Theodorsen, N. M., Strand, L. I., & Bø, K. (2019) ‘Effect of pelvic floor and transversus abdominis muscle contraction on inter-rectus distance in postpartum women: a cross-sectional experimental study’, *Physiotherapy*, 105(3), pp. 315–320. https://doi.org/10.1016/J.PHYSIO.2018.08.009

Tim, S., & Mazur-Bialy, A. I. (2021) ‘The Most Common Functional Disorders and Factors Affecting Female Pelvic Floor’ *Life*, 11(12), article number 1397. https://doi.org/10.3390/life11121397

Ubelaker, D. H., & Volt, C. G. (2002) ‘A Test of the Phenice Method for the Estimation of Sex’, *Journal of Forensic Sciences*, 47(1), pp. 19–24. Available at: https://doi.org/10.1520/JFS15200J

Ulfelder, H. (1956) ‘The mechanism of pelvic support in women: Deductions from a study of the comparative anatomy and physiology of the structures involved’, *American Journal of Obstetrics and Gynecology*, 72(4), pp. 856–864. Available at: https://doi.org/10.1016/0002-9378(56)90177-6

Ullrich, H. (1975) ‘Estimation of fertility by means of pregnancy and childbirth alterations at the pubis, the ilium, and the sacrum’, *Ossa*, 2(1), pp. 23–39.

Umur, E., Bulut, S. B., Yiğit, P., Bayrak, E., Arkan, Y., Arslan, F., Baysoy, E., Kaleli-Can, G., & Ayan, B. (2024) ‘Exploring the role of hormones and cytokines in osteoporosis development’, *Biomedicines, 12*(8), article number 1830. Available at: https://doi.org/10.3390/biomedicines12081830

Veljovic, F., Straus, S., Karabdic, I., & Masic, I. (2019) ‘Spinal Column and Abdominal Muscles Loading in Pregnant Women Dependent on Working Postures’, *Acta Informatica Medica*, 27(1), pp. 54–57. Available at: https://doi.org/10.5455/AIM.2019.27.54-57

Verbruggen, S. W., & Nowlan, N. C. (2017) ‘Ontogeny of the Human Pelvis’, *Anatomical Record*, 300(4), 643–652. Available at: https://doi.org/10.1002/ar.23541

Verma, J. P., & Abdel-Salam, A. G. (2019). *Testing Statistical Assumptions in Research*. Hoboken: John Wiley & Sons, Inc.

Verma, R., Krishan, K., Rani, D., Kumar, A., Sharma, V., Shrestha, R., & Kanchan, T. (2020) ‘Estimation of sex in forensic examinations using logistic regression and likelihood ratios’, *Forensic Science International*, 2(165), article number 100118. Available at: https://doi.org/10.1016/j.fsir.2020.100118

Vina, J., Sastre, J., Pallardo, F. V, Gambini, J., & Borras, C. (2006) ‘Role of mitochondrial oxidative stress to explain the different longevity between genders’, *Free Rad Research*, 40(12), pp. 1359–1365. Available at: https://doi.org/10.1080/10715760600952851

Walker, J. M. (1992) ‘The Sacroiliac Joint: A Critical Review’, *Physical Therapy*, 72(12), pp. 903–916. Available at: https://doi.org/ 10.1093/ptj/72.12.903

Walker, P. L. (2005) ‘Greater sciatic notch morphology: Sex, age, and population differences’, *American Journal of Physical Anthropology*, 127(4), pp. 385–391. Available at: https://doi.org/10.1002/ajpa.10422

Wall-Scheffler, C. M., Kurki, H. K., & Auerbach, B. M. (2020) ‘Developmental Biology of the Pelvis’, In C. M. Wall-Scheffler, H. K. Kurki and B. M. Auerbach (ed.) *The Evolutionary Biology of the Human Pelvis*. Cambridge: Cambridge University Press, pp. 99-110.

Waltenberger, L., Pany-Kucera, D., Rebay-Salisbury, K., & Mitteroecker, P. (2021) ‘The association of parturition scars and pelvic shape: A geometric morphometric study’, *American Journal of Physical Anthropology*, 174(3), pp. 519–531. Available at: https://doi.org/10.1002/AJPA.24196

Waltenberger, L., Rebay-Salisbury, K., & Mitteroecker, P. (2022a) ‘Age dependent changes in pelvic shape during adulthood’, *Anthropologischer Anzeiger*, 79(2), pp. 143–156. Available at: https://doi.org/10.1127/anthranz/2021/1463

Waltenberger, L., Rebay-Salisbury, K., & Mitteroecker, P. (2022b) ‘Are parturition scars truly signs of birth? The estimation of parity in a well-documented modern sample’, *International Journal of Osteoarchaeology*, 32(3), pp. 619–629. Available at: https://doi.org/10.1002/OA.3090

Wescott, D. J. (2015) ‘Sexual Dimorphism in Auricular Surface Projection and Postauricular Sulcus Morphology’, *Journal of Forensic Sciences*, 60(3), pp. 679–685. Available at: https://doi.org/10.1111/1556-4029.12737

Wesnes, S. L., & Seim, E. (2020) ‘Birthweight and urinary incontinence after childbirth: a systematic review and meta-analysis’, *European Journal of Obstetrics and Gynecology and Reproductive Biology*, 8(12). Available at: https://doi.org/10.1016/j.eurox.2020.100115

White, T. D., Black, M. T., & Folkens, P. A. (2012). *Human Osteology*. 3rd edn. California: Elsevier Academic Press.

Williams, P. L. (1995) *Gray's anatomy: The anatomical basis of medicine and surgery*. 38th edn. London: Churchill Livingstone.

Wilson, J. R., & Lorenz, K. A. (2015) *Modeling Binary Correlated Responses Using SAS, SPSS and R*. 1st edn. New York: Springer.

Winter, E. M., Ireland, A., Butterfield, N. C., Haffner-Luntzer, M., Horcajada, M. N., Veldhuis-Vlug, A. G., Oei, L., Colaianni, G., & Bonnet, N. (2020) 'Pregnancy and lactation, a challenge for the skeleton', *Endocrine Connections*, 9(6), pp. 143–157. Available at: https://doi.org/10.1530/EC-20-0055

Young, J. (1940) 'Relaxation of the Pelvic Joints in Pregnancy: Pelvic Arthropathy of Pregnancy', *Journal of Obstetrics & Gynaecology of the British Empire*, 47(5), pp. 493–524. Available at: https://doi.org/10.1111/j.1471-0528.1940.tb08842.x

Zeller, R. A. (2005) 'Measurement Error, Issues and Solutions', Encyclopedia of Social Measurement, 2, pp. 665-676. Available at: https://doi.org/10.1016/B0-12-369398-5/00109-2

Zhu, J., Si, J., Zhao, L., & Liu, W. (2023) 'Association between infant birthweight and pelvic floor muscle strength: a population-based cohort study', *BMC Pregnancy and Childbirth*, 23(1). Available at: https://doi.org/10.1186/s12884-023-05511-x

Appendix A: Excluded Female Samples (TXSTDSC)

Donor No.

2009.004/009/011 – Damaged symphyses (bilateral)

2010.003 – Unavailable (not curated)

2012.001 – Fusion across dorsal pubic surfaces (bilateral)

2012.048 – Ilia missing (bilateral) (no auricular surfaces)

2013.009 – Damaged symphyses (bilateral)

2013.040 – Unavailable

2013.041 – Missing symphyses (bilateral)

2014.023 – Missing entire pelvis

2014.031 – Unavailable (not curated)

2014.035 – Damaged symphysis (other missing)

2014.041 – Missing entire pelvis

2014.064 – Pelvis completely fused (sacrum included)

2014.067 – Damaged symphyses (bilateral)

2015.032 – Surgical fusion of sacrum and ilia (bilateral)

2015.054 – Unavailable (not curated)

2017.011 – Damage to auricular surfaces (bilateral)

2017.018/056/070/071 – Unavailable (not curated)

2017.073 – Missing entire pelvis

2017.075/076/077 – Unavailable (not curated)

2018.001/015/016/022/035/042/050/059/062/066/068/071 – Unavailable (not curated)

2019.003 – Missing entire pelvis

2019.005/006/016/018/019 – Unavailable (not curated)

2019.029 – Cremains

2019.031/045/048/053/054/056/057/058/059 – Unavailable (not curated)

2019.061/063/065/069/071/072/073/074/076 – Unavailable (not curated)

2020.002/005/011/017/018/022/025/026/031/041/042/053 – Unavailable (not curated)

2021.003/004/006/007/010/011 – Unavailable (not curated)

2021.020 < - Unavailable (not curated)