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Sacroiliac Joint Fusion in Nulliparous and Parous Females and Males

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SACROILIAC JOINT FUSION IN NULLIPAROUS AND PAROUS FEMALES AND MALES

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Abstract

Previous research shows that sacroiliac (SI) joint fusion is age and sex dependent. Older individuals—specifically starting in the fifth or sixth decade of life—are more likely to develop SI fusion. Females have a lower frequency of SI joint fusion than males, perhaps due to pregnancy or parturition. This study examines the relationship between SI joint fusion with both sex and parity status in females. The issue is whether the prevalence of SI fusion in nulliparous females is more similar to that of males or parous females. The sample consists of 46 nulliparous females, 119 parous females, and 158 males from the William M. Bass Donated Skeletal Collection. Ages of the individuals ranged from 50-89 years. Sex, age, and parity status were self-reported. Results show that the frequency of SI joint fusion is significantly different among males (13.29%), nulliparous females (6.52%), and parous females (0.84%). Pairwise comparison of the three groups for SI joint fusion shows that parous females and males are significantly different, but parous females and nulliparous females and nulliparous females and males are nonsignificantly different. Nulliparous females are intermediate in frequency of SI joint fusion between males and parous females which suggests that pregnancy or parturition is involved in lower frequencies of SI joint fusion in parous females. The relationship between surgical implants and fusion of the lumbar vertebrae on SI joint fusion was tested in males and neither showed a significant relationship. The relationship between age and SI joint fusion was tested in males; the age category 60-69 had a significantly lower frequency of fusion than the other age categories which is likely an anomaly of this sample. Results of the study show that SI joint fusion is not more likely to occur on either the right or left side of the pelvis, nor is fusion more likely to be unilateral or bilateral. In conclusion, the birth of one or more children is associated with reduced likelihood of SI joint fusion. This study offers suggestions for why nulliparous

females have a frequency of SI joint fusion that is intermediate between males and parous females.

Chapter 1. Introduction

The adult human pelvis consists of two ilia, a sacrum, and coccygeal vertebrae that are connected by four joints: two sacroiliac (SI) joints, the interpubic joint, and the sacral-coccygeal joint. The coccyx articulates with the sacrum and has been known to fuse to the sacrum in both males and females (Alderink, 1991; Tague, 2011). A primary function of the pelvis is to distribute weight from the trunk and upper limbs to the lower limbs (Alderink 1991). The pelvic joints provide stability and flexibility for the pelvic girdle so that it is less susceptible to breaks or fractures. The following research for this thesis primarily focuses on the SI joints. The SI joints represent the contact between the ilia and sacrum. First, second, and third sacral vertebrae (S1, S2, and S3, respectively) typically articulate with the ilium (Vleeming et al. 2012). SI joints in females do not typically include all of the S3 vertebra. A primary function of the SI joints is to transmit loads between the spine and lower limbs. The SI joints also provide flexibility in the pelvis (Vleeming et al. 2012).

SI joint fusion can be difficult to study in living patients due to its position, which is inaccessible unless through the use of radiographs or CT scans (MacDonald and Hunt 1952). Fusion of the SI joints has been noted in archaeological samples (Waldron and Rogers, 1990; Fornaciari et al., 2007). Age and sex are associated with SI joint fusion (Waldron and Rogers 1990). Older individuals are more likely to develop SI joint fusion than younger individuals. SI joint fusion is sexually dimorphic, with males exhibiting higher frequencies of fusion than females (Waldron and Rogers, 1990; Dar and Hershkovitz, 2006). Waldron and Rogers (1990) had a ratio of 3:1, with males exhibiting a higher frequency of SI joint fusion than females. Dar and Hershkovitz (2006) studied two samples to determine if SI joint fusion could be used to sex male skeletons in a forensics context. Their results showed that males have a higher frequency of

SI joint fusion than females in both samples (12.27% of males and 1.83% of females in a skeletonized sample in the Hamann-Todd Collection; 34.2% of males and 4.6% of females in a live sample). Lower frequencies of SI joint fusion in females is attributed to parturition (Stewart 1984).

The purpose of this research is to test if nulliparous females have a higher frequency of SI joint fusion than parous females. Nulliparous females are females with no recorded live births, whereas parous females are females with one or more recorded live births. I hypothesize that parturition inhibits SI joint fusion. Therefore, nulliparous females would have a higher rate of SI joint fusion than parous females and the same rate of SI joint fusion as males.

CHAPTER 2. BACKGROUND

2.1. Relationship of Age and Sex to Sacroiliac (SI) Joint Fusion

The two variables that are most commonly associated with SI joint fusion are age and sex (Waldron and Rogers, 1990; Dar et al., 2005; Dar and Hershkovitz, 2006; Dar et al., 2007). SI joint fusion most often occurs in older individuals. Older males are more likely to develop fusion than younger males. For instance, Dar and Hershkovitz (2006) studied the sexually dimorphic nature of SI joint fusion to determine if fusion would be useful for sexing individuals in a forensics context, and found that SI joint fusion was present in 8.3% of males and 0.05% of females less than 60 years of age, whereas SI joint fusion was present in 23.6% of males and 6% of females greater than 60 years of age. In females, SI joint fusion most commonly develops after the completion of the reproductive process. That is, postmenopausal females are more likely to develop fusion in the SI joint than premenopausal females (Waldron and Rogers 1990; Dar and Hershkovitz, 2006). SI joint fusion later in life could be partly attributed to the development of the sacrum, whose inclination varies with age. The sacrum is more vertically oriented during adolescence but shifts towards a horizontal orientation during adulthood. The horizontal orientation of the sacrum does not stabilize until after the age of thirty (Peleg et al., 2007; Passalacqua, 2009). The sacrum is one of the last bones in the human body to finish fusion, with the sacral vertebrae fusing during the third decade of life (Peleg et al. 2007). The late fusion of the sacral vertebrae could be a factor in delaying potential fusion of the SI joint region.

The second factor associated with SI joint fusion is sex. SI joint fusion experiences high rates of sexual dimorphism. Males experience fusion more often than females. In a study by Dar and Hershkovitz (2006), the marked sexual dimorphism of the presence of SI joint fusion was examined as a variable for determining the sex of an individual. Samples of males and females were taken from two places: the Hamman-Todd Human Osteological Collection of the Cleveland Museum of Natural History and from CT scans of patients who came for abdominal or pelvic exams at the Radiology Department, Carmel Medical Center, Haifa, Israel. The authors studied 2,845 individuals from the Hamann-Todd Collection and 81 individuals from the CT scans. The authors concluded that in the Hamann-Todd Collection, 12.27% of males had SI joint fusion whereas only 1.83% of females had SI joint fusion. The sample taken from the CT scans resulted in 34.2% of males with SI joint fusion and 4.6% of females with SI joint fusion. The researchers concluded that the presence of bony spurs on the ilium and partial or full bridging of the SI joint are indicative of a male skeleton. Determination of SI joint fusion requires little experience on the part of the researcher. More importantly, the researchers claim that SI joint fusion (or sacroiliac joint bridging (SIB) as termed in their study) is not dependent on ancestry. This means that the application of SI joint fusion as a sexing criterion is useful independent of geography or ancestry. The authors did not provide an interpretation for the approximately threefold difference in prevalence of SI joint fusion between the Hamann-Todd and CT samples (Dar and Hershkovitz 2006).

Another example of the sexually dimorphic nature of SI joint fusion is highlighted in a study by Waldron and Rogers (1990). Their research was a bioarchaeological study conducted in a cemetery in London based on individuals who were interred during the eighteenth and nineteenth centuries. An estimated 1,000 individuals were buried in this cemetery and 968 of those individuals were recovered during excavation. None of the individuals included in this study was younger than 45 years of age. From the 968 burials recovered, 387 individuals with information such as sex and age legible from headstones were used for the purposes of the study.

From the 387 individuals recovered, 41 individuals (10.6%) had SI joint fusion. Of these 41 individuals, 30 (73.2%) were male while the other 11 (26.8%) were female (Waldron and Rogers 1990).

2.2. Parturition and Bipedalism

Parturition potentially prevents SI joint fusion in females (Stewart 1984). The female pelvis must retain its joint mobility to give birth to large-brained infants. Human evolution has been affected by increasing brain size and bipedalism. However, these two traits did not occur at the same time in human evolution with adaptations towards bipedalism happening before adaptations for encephalization. Human birth can be a difficult process due to the large head as well as the broad, rigid shoulders of the fetus relative to the maternal pelvis (Trevathan, 1988; Rosenberg and Trevathan, 2002). Birth did not likely become difficult until after the pelvis evolved towards more efficient bipedal locomotion (Tague and Lovejoy, 1986; Trevathan, 1987). Difficulty in childbirth is not only an evolutionary issue but also a contemporary one. Maternal and offspring mortality is still prevalent in contemporary populations with obstructed labor being one of the four main causes of maternal death, with the delivery process contributing one third of offspring mortality (Wells et al. 2012).

Encephalization and bipedalism have different anatomical requirements on the pelvis that result in a complex birthing process. Encephalization requires that the female pelvis have an expanded birth canal whereas habitual bipedalism necessitates a narrow pelvis. As a result, the human female pelvis is anteroposteriorly oval at the midplane (Tague and Lovejoy, 1986; Trevathan, 1987). Bipedalism also requires that the pelvis supports more than half of the weight of the entire body. Thus, the bony anatomy of the human pelvis cannot be overly flexible. Bipedalism also results in a shorter and broader ilium and ischium. The SI joint region is larger in bipedal mammals in order to provide more stability and support (Trevathan 1987). However, these are not the only changes that contribute to a more complex birthing process in human females.

The distance between the acetabulum and the sacroiliac joint is shortened which narrows the sagittal dimension of the pelvis. The human sacrum and pubic symphysis are positioned opposite each other (Trevathan 1987). The relationship between the sacrum and pubic symphysis is different in nonhuman primates. The apex of the sacrum does not stretch far into the birth canal of monkeys, which means that the fetal head does not have to pass the sacrum and pubic symphysis at the same time. Thus, passage of the fetus can be fairly easy. For great apes, the fetus passes the sacrum and pubic symphysis at the same time. However, the relatively large birth canal of apes compared to the fetal head allows for easy births. The sacrum is the dorsal wall of the human pelvis which considerably decreases the anterior-posterior diameters of the human birth canal (Rosenberg 1992). Thus, the position of the sacrum and pubic symphysis—especially the sacrum—contributes to a smaller pelvic inlet. The human pelvic inlet is widest at the transverse dimension while the pelvic outlet is widest at the sagittal dimension (Trevathan 1987). These anatomical features mean that the long axis of the fetal head enters the birth canal in the transverse plane of the mother's pelvis and passes by the sacrum and pubic symphysis simultaneously. However, in order to exit the maternal pelvis the fetal head must rotate 45 to 90 degrees. To begin descent into the birth canal at a transverse plane and exit at 45 to 90 degrees, the fetus must rotate its head, neck, and shoulders (Trevathan 1987).

Fetal rotations are typically divided into two stages: internal rotation and external rotation. Internal rotation happens when the fetal head turns so that the anteroposterior diameter of the fetal head is aligned with the anteroposterior diameter of the mother's pelvis while the shoulders maintain a transverse position. External rotation occurs after the fetal head has emerged from the birth canal and the shoulders rotate internally. The purpose of these rotations is to ensure that the longer fetal dimensions align with the longer maternal pelvic dimensions as the fetus travels down the birth canal. In other words, the widest dimensions of the fetus must rotate to meet the widest dimensions of the mother’s pelvis. The various rotations that the fetus endures are included in a process termed the cardinal movements of labor. Birth is often a long and arduous process for both mother and infant and requires a third party such as a midwife to aid during the birthing process (Trevathan, 1987; Rosenberg, 1992; Trevathan and Rosenberg 2000; Rosenberg and Trevathan, 2002). Fusion of the SI joint would preclude the mobility of this joint during labor, thereby creating less pelvic space for the fetus to maneuver. An unfused SI joint can become mobile enough that the diameter of the pelvic outlet can increase by 1.5-2.0 cm (Cicek et al. 2015).

Stewart (1984) attributes the sexual dimorphism of SI joint fusion to mobility of the pelvis, where males are better adapted for strength and females for parturition. The location of SI joint fusion in males typically occurs close to the superior aspect of the joint and, therefore, situates the joint fusion in the line of weight transmission between the axial skeleton and the lower limb. In females, the fusion is located close to the anteroinferior aspect of the SI joint. Stewart claims that the location of fusion reveals the functional organization of the human bony pelvis. For males it is locomotion; for females it is a combination of locomotion and parturition.

The male pelvis has not evolved to accommodate reproductive pressures. The primary adaptation for the male pelvis has been for upright walking. SI joint fusion decreases mobility of the joints and instead stabilizes the pelvis. Since males have evolved under pressures of strength and stability, SI joint fusion would not be disadvantageous. SI joint fusion would be disadvantageous for females (Stewart 1984). Efficient bipedal locomotion and large neonates have conflicting anatomical needs (Trevathan 1987). The SI joint must be flexible to allow for the passage of a fetus through the maternal pelvis. A fused SI joint would eliminate flexibility and make childbirth potentially more dangerous for both mother and fetus. Therefore, the requirements of parturition on the pelvis are significant and could inhibit SI joint fusion in females.

2.3. Hormones and SI Joint Fusion

Pregnancy related hormones, such as estrogen, progesterone, and relaxin, could also affect SI joint fusion. Estrogen is present in both non-pregnant and pregnant females. High levels of estrogen are produced at ovulation and towards the end of pregnancy. Estrogen levels are highest in the third trimester. Progesterone is a hormone that is also produced in both non-pregnant and pregnant females. In ovulating females, the hormone ranges from 3 to 20 mg per day and then increases around ovulation. In the second trimester, progesterone levels rise to 75 mg per day. By the third trimester, progesterone levels increase to 250 mg per day but drop significantly before delivery. Both estrogen and progesterone are produced at high levels by the placenta. However, estrogen sharply increases shortly before delivery whereas progesterone levels decrease. Estrogen partly functions to decrease maternal pain sensitivity and progesterone partly functions to inhibit uterine contractions (Trevathan, 1987; Peck et al., 2002). Estrogen and progesterone also function to stimulate the luteinizing hormone surge for ovulation (Christensen et al. 2012). The hormone relaxin partially functions to ready the endometrium for the fetus as well as to maintain the strength of endometrial connective tissue in the first trimester (Goldsmith and Weiss 2009), and it also causes cervical ripening in the third trimester before delivery (Wood

1994). Levels of relaxin in the first trimester reach approximately 0.56 to 1.06 ng/ml but increase right before delivery (Goldsmith and Weiss 2009). Estrogen, progesterone, and relaxin are also associated with increased joint laxity during pregnancy (Calguneri et al., 1982; Joseph, 1988; Maclennon, 1991; Damen et al., 2001; Cohen, 2005; Talbot and Maclennon, 2016; Mahato, 2016).

Joints must first be primed by estrogen before relaxin can take effect (Tague 1988). For perimenopausal females, estrogen—specifically estradiol—levels decrease in the months prior to the final menstrual period (Pinkerton and Stovall 2010) and progesterone drops to almost undetectable levels (Santoro and Randolph 2011). Relaxin levels in premenopausal females are approximately 109.441 ± 134.365 pq/ml. In menopausal females, relaxin levels decrease to approximately 56.800 ± 57.097 pq/ml (Ardiansyah et al. 2015).

Both males and females experience some degree of joint laxity. After puberty, females experience higher rates of generalized joint laxity than males. Male joint laxity decreases during their twenties while female joint laxity continues into their forties (Larsson et al. 1987). Laxity is especially pronounced during pregnancy and has shown to increase from the first to third trimester (Marnach et al. 2003). Hormones such as relaxin, progesterone, and estrogen have been attributed to cause relaxation of the joints during pregnancy and during labor (Calguneri et al., 1982; Joseph, 1988; Maclennon, 1991; Damen et al., 2001; Cohen, 2005; Talbot and Maclennon, 2016; Mahato, 2016).

The period of laxity during pregnancy affects the pubic symphysis as well as the SI joints (Hagen, 1974; Calguneri et al., 1982; Larsson et al., 1987; Damen et al., 2001). All three pelvic joints undergo relaxation so that the pelvic inlet and outlet can widen enough for a large-brained neonate to pass through the birth canal. An important occurrence to note is that relaxation of the pelvic ligaments occurs throughout the period of pregnancy and not simply at the onset of labor, which means that the sacroiliac ligaments experience prolonged periods of laxity. Although the pubic symphysis undergoes more widening during birth than the sacroiliac joints, gases are still noted in both the pubic joint and sacroiliac joints after birth of the neonate (Garagiola et al., 1989; Becker et al., 2010; Mahato, 2016). The presence of gas in the SI joint suggests that it is a mobile joint (Takata et al. 2016) that undergoes an increase in widening, thickening, softening, and vascularization during pregnancy (Camiel and Aaron 1956). Joint laxity reaches its peak during the second pregnancy and plateaus in subsequent pregnancies (Calguneri et al. 1982).

Estrogen can also have an osteoclastic function during pregnancy. Tague (1988) suggests that estrogen potentially stimulates osteoclastic activity at ligamentous sites in the pelvis, which results in resorption of the bone. Resorption of the pubic bones has been noted in response to pregnancy in both humans and non-human mammals. Resorption at the pubic symphysis could serve two related purposes: to keep the joint from fusing and, thus, to maintain its flexibility for childbirth. The pubic symphysis is especially sensitive to estrogen and is exposed to high levels of the hormone during pregnancy (Tague 1988).

2.4. Joint Diseases

SI joint fusion can also be associated with joint pathologies such as diffuse idiopathic skeletal hyperostosis (DISH), osteoarthritis of the spine, and ankylosing spondylitis (AS). SI joint fusion could be a result of an acquired pathology such as osteoarthritic changes in relatively immobile joints, instead of a factor included in the aging process. Age and degeneration of the joints could promote SI joint fusion in an individual, especially if that individual suffered an injury. An injury to a joint would potentially cause degeneration of the cartilage and an amorphous debris to fill the eroding joint space. The superficial cartilage would not receive the nutrition it needs and would be more susceptible to degeneration. The SI joint is not considered a true diarthrodial joint because it has components of both a diarthrosis and synarthrosis. Thus, the SI joint is considered an amphiarthrodial joint. This means that it is not a freely mobile joint. Since movement is restricted, the SI joint could potentially develop more pronounced degenerative symptoms such as fusion (MacDonald and Hunt, 1952; Vleeming et al., 2012).

Waldron and Rogers (1990) conducted research pertaining to the relationship between joint disease and SI joint fusion. The authors examined a sample of 387 skeletons of known age and sex from the cemetery at Christ Church in East London. The cemetery was in use from A.D. 1729 to 1859. Waldron and Rogers noted that there was a propensity of some individuals in the sample to undergo calcification of cartilage and that SI joint fusion could be involved in the bone forming process. The authors created scores based on six criteria of bone formation: calcification of costal cartilages, thyroid cartilage, cricoid cartilage, or xiphoid; one or more enthesophytes; and one or more spinal osteophytes. The bone forming scores ranged from 0 to 6, based on how many of these criteria an individual did or did not possess. Bone forming scores were high in individuals with SI joint fusion, and also with those individuals with both SI joint fusion and DISH. There was a positive correlation between SI joint fusion and DISH, with 26.8% of the 41 individuals with SI joint fusion in the sample also having DISH.

Another study by Dar et al. (2007) found a positive correlation between SI joint fusion and DISH. In their article, DISH is defined as the fusion of four adjacent vertebrae. The researchers posit that DISH could potentially represent a vulnerable osseous state instead of a specific disease. Some individuals could respond to stressful stimuli with exaggerated bone growth, whereas other individuals could respond with moderate bone growth. Individuals with both DISH and SI joint fusion exhibit high frequencies of entheseal reactions at other sites in the body. The demographics of both DISH and SI joint fusion are also similar, as opposed to the demographics of AS. The authors define AS as a type of spondyloarthropathy that is characterized by erosive joint disease as well as bone remodeling and formation. Both DISH and SI joint fusion are more common in older males, whereas AS is more common in adolescents and young adults less than 45 years of age. To further explore the relationship between DISH and SI joint fusion, Dar et al. used a study by Weinfeld et al. (1997) to compare the statistics between DISH and SI joint fusion. In the sample used by Weinfeld et al., 25% of males over 50 years had DISH and 20.1% of males over 50 years had SI joint fusion. In males older than 70 years of age, the frequencies of DISH increased to more than 30% and 28.8% for SI joint fusion. The sex ratio also showed that males experienced DISH and SI joint fusion more often than females, with a ratio of 3:1 for DISH and a ratio of 6.7:1 for SI joint fusion. The statistics support a prevalence of DISH in males as opposed to females.

As stated previously, Dar et al. (2007) defined DISH as the fusion of four adjacent vertebrae. However, the authors claimed that their definition was arbitrary. The researchers instead proposed a flexible definition of DISH which would encompass less severe forms of DISH. The researchers did not specify how flexible the definition should be, but implied that less severe forms of DISH would include fusion of fewer than four adjacent vertebrae. If the criteria for DISH were less strict and more individuals were diagnosed with the pathology than before, then there could potentially be a stronger association between DISH and SI joint fusion.

Dar et al. (2007) deemed the association between SI joint fusion and AS to be weak. AS is not as sexually dimorphic as DISH or SI joint fusion, although males are more affected by the pathology than females. The sample in Dar and colleagues' (2007) study showed that males have a higher prevalence rate than females by a ratio of 2.6:1 for AS and 6.7:1 for SI joint fusion.

2.5. SI Joint Fusion in the Literature

SI joint fusion cannot be attributed solely to pathology. Though there is a relationship between DISH and SI joint fusion, etiology has not been determined (Waldron and Rogers 1990). SI joint fusion could occur concurrently, yet independently, of DISH. A study including known nulliparous females in its sample is important in determining the etiology of SI joint fusion, its relationship to the pelvis, and its relationship to other pathologies such as DISH.

Important variables, such as known parity status, are difficult to obtain. In the past, researchers have estimated parity status based on a set of criteria presented by the specific museum where they were conducting their research. T. Wingate Todd at the Cleveland Museum of Natural History conducted examinations of over 400 female cadavers and assigned the parity status of each individual. Todd based his findings on factors such as the presence of a hymen, the presence or absence of perineal tears, scars from a caesarean section, the presence of the female fourchette, and striations on the abdomen. Parity status for these individuals would then be determined based on the physical characteristics presented by the cadaver (Kelley 1979).

Childbirth often leaves physical evidence in the tissue. Trevathan (1987) posits that the bony anatomy of the pelvis is most dangerous for the fetus, while most of the difficulty for the mother lies in the soft tissues, where tearing is possible. Parity status is impossible to accurately determine from a female skeleton without prior knowledge such as medical records or information given by the family. Most skeletal collections do not have access to information concerning parity status of individuals.

Age and sex in the archaeological record are two variables that can make SI joint fusion difficult to detect. SI joint fusion occurs more frequently in individuals older than 45-50 years of age, so a past community with a life span below 50 years of age would not demonstrate high frequencies of SI joint fusion (Stewart 1984). Sex presents another problem in the archaeological record. Skeletal samples can be too damaged or ambiguous to accurately determine sex. In some instances there are other markers such as headstones or gendered grave goods that help an archaeologist determine the sex of a skeleton. However, if no such markers are available, then sex determination can prove difficult when dealing with archaeological samples. Thus, the demographics of SI joint fusion can be difficult to determine in the archaeological record (Dar and Hershkovitz 2006).

For the current study, the hypothesis is that nulliparous females will be more similar to males than parous females in frequency of SI joint fusion. The testable null hypothesis is that nulliparous females, parous females, and males do not differ in prevalence of SI joint fusion. The objective of this study is to test the relationship between sex and parity on prevalence of SI joint fusion, so the sample was evaluated for other variables that could reasonably be associated with SI joint fusion. The variables included age at death, surgical implantation near the pelvis, and fusion of lumbar vertebrae. The null hypothesis is that there is no association between these variables and the prevalence of SI joint fusion. However, if there is a positive association between SI joint fusion, surgical implants, and lumbar fusion, then those individuals with surgical implants and lumbar fusion would be removed from the study sample. Finally, directional asymmetry (i.e., right side versus left side) in SI joint fusion was tested. The null hypothesis is that there is no directional asymmetry in SI joint fusion.

CHAPTER 3. MATERIALS AND METHODS

3.1. Materials

The human skeletal remains for this research come from the William M. Bass Donated Skeletal Collection housed at the University of Tennessee, Knoxville. The Bass Collection consists of contemporary males and females who were donated after death. Parity information has been collected from donors since the 1990s. The number of children was self-reported by females prior to death. Donors fill out forms provided by the Forensic Anthropology Center. Options for ancestry are listed as White, Black, Hispanic, or Other on the forms. Information on sex, age at death, ancestry, and parity status was provided for this study by Dr. Dawnie Steadman, the Director of the Forensic Anthropology Center at the University of Tennessee.

For this research, I focused on the variables age, sex, and number of children. With the exception of one African American female and one White/American Indian female, all other individuals in the sample were White. Males consisted of primarily White individuals with one individual listed as White/Jewish. The sample consisted of 46 nulliparous females, 119 parous females, and 158 males, for a total of 323 individuals between 50-89 years of age (Table 3.1).

Table 3.1. Age categories for nulliparous females, parous females, and males

Age Category	**Nulliparous Females**	**Parous Females**	**Males**	**Total**
50-59	17	31	47	95
60-69	14	34	43	91
70-79	8	32	40	80
80-89	7	22	28	57
Total	46	119	158	323

In this sample, 35.42% of females in the 50-59 age category were nulliparous; 29.17% of females in the 60-69 age category were nulliparous; 20% of females in the 70-79 age category were nulliparous; and 24.14% of females in the 80-89 age category were nulliparous. The sample was structured based on age and number of children. Individuals younger than 50 years of age or older than 89 years of age were not included in the sample. I excluded individuals younger than 50 because I wanted females who were likely postmenopausal and who had likely completed their reproduction. Age categories were divided into ten years: 50-59, 60-69, 70-79, 80-89. Parity status was divided into four categories: nulliparous, primiparous (one live birth), parous II (two live births), and parous III+ (three or more live births). Number of children was not recorded for males.

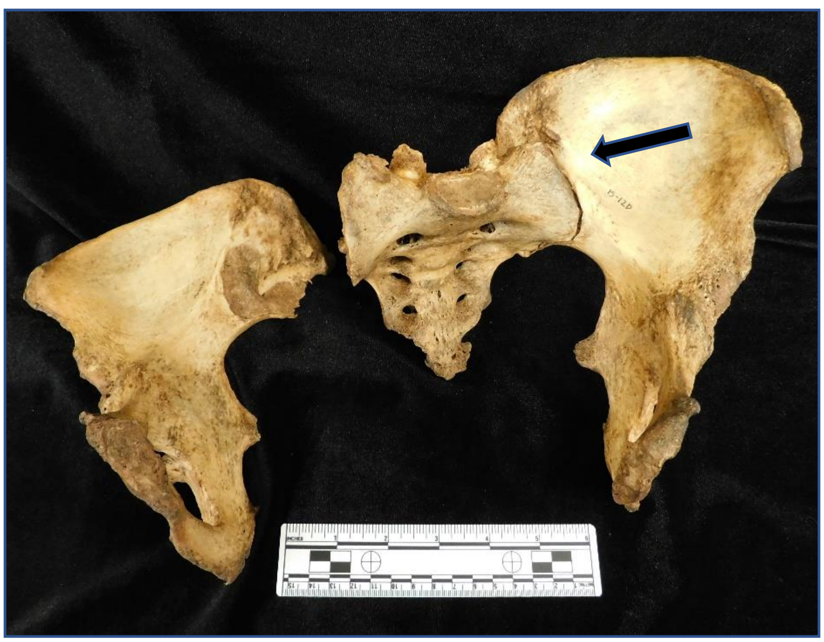

Figure 3.1. Unilateral sacroiliac joint fusion of a female pelvis (specimen number 15-12D)

Figure 3.2. Bilateral sacroiliac joint fusion of a male pelvis (specimen number 47-11D)

The following skeletal elements were observed: the ilia, sacrum, lumbar vertebrae, and femur. The pelvis and vertebrae were observed for fusion and evidence of surgery. Due to the proximity of the lumbar vertebrae to the SI joint, observation of fusion of the lumbar vertebrae was recorded. Presence or absence of surgical implantations was also recorded, including a metal brace in the lumbar and/or sacral vertebrae, hip replacements, and a metal brace in the proximal end of the femur. Data for these variables were recorded for all individuals in the study. Figure 3.1 shows a female pelvis with unilateral SI joint fusion. Figure 3.2 shows a male pelvis with bilateral SI joint fusion.

3.2. Methods

SAS and SPSS were used to conduct the statistical analyses, which included chi square, Fisher's exact test, and the binomial test. Two-tailed tests of significance were used. Fisher's exact test was used when some contingency table cells had less than five individuals. The level of significant probability was set at ≤ 0.05. Presence or absence of fusion of the left and right SI joint was recorded in a dichotomous manner for males and females. Stewart (1984) observed a difference between males and females in location of SI joint fusion. In this study, only presence or absence of SI joint fusion was recorded. The objective of this research is to examine if sexual differences of SI joint fusion are related to parturition. SI joint fusion, no matter the extent, would preclude joint mobility during parturition.

CHAPTER 4. RESULTS

4.1. Summary Statistics

The mean age of females in this study was 67.45 years and of males 67.09 years. Nulliparous females had a mean age of 65.63 years. Parous females had a mean age of 68.17 years (Table 3.1). The mean number of children among parous females was 1.79. Number of children ranged from 0-7 children in the sample. Only one parous female had SI joint fusion so the parity categories (primiparous, parous II, and parous III+) were combined for analyses. The results in Table 4.1 show 13.92% of males, 6.52% of nulliparous females, and 0.84% of parous females with SI joint fusion. Of the 165 females, four individuals experienced SI joint fusion (2.42%). Three of the females with fusion were nulliparous and one was multiparous. The only parous female with SI joint fusion had a parity status of two births and was fused on the left joint.

Table 4.1. Frequency of sacroiliac (SI) joint fusion among males and females for each parity category

Parity Status	**Absolute Number**	**Number with SI Joint Fusion**	**Frequency of SI Joint Fusion**
Males	158	22	13.92%
Nulliparous Females	46	3	6.52%
Parous Females	119	1	0.84%

4.2. Age and SI Joint Fusion

Males were tested as a control to see if the prevalence of SI joint fusion is associated with age. A chi-square test was run to compare the following age groups: 50-59, 60-69, 70-79, and 80-89. The chi-square test for age groups showed statistical significance (P<0.0298) and, therefore, the null hypothesis that SI joint fusion is not related to age at death is rejected for males. The following pairwise comparisons were run: 50-59 years and 60-69 years (P<0.0604); 50-59 years and 70-79 years ($P<0.2841$); 50-59 years and 80-89 years ($P<1.000$); 60-69 years and 70-79 years ($P<0.0028$); 60-69 years and 80-89 years ($P<0.0752$); and, 70-79 years and 80-89 years ($P<0.3677$). The pairwise comparisons were used to determine which age category was significantly different from the others. However, the only age group that was statistically different from the others was the age group 60-69 (2.33%; $P<0.0028$). This result is likely an anomaly of the sample since it is unlikely that the frequency of SI joint fusion would decrease as individuals age from 50-59 to 60-69. Therefore, all individuals between 50 and 89 years of age will be used in succeeding analyses.

Table 4.2. Frequency of sacroiliac (SI) joint fusion in age categories for males

Age Category	**Absolute Number**	**Number with SI Joint Fusion**	**Frequency of SI Joint Fusion**
50-59	47	7	14.89%
60-69	43	1	2.33%
70-79	40	10	25.00%
80-89	28	4	14.29%

4.3. Surgery, Lumbar Fusion, and SI Joint Fusion

Among the 165 females, 14 individuals had surgical implants (8.48%) and 15 individuals had fusion of one or more lumbar vertebrae (9.09%). Among the 158 males, eight individuals had surgical implants (5.06%) and 17 individuals had fusion of one or more lumbar vertebrae (10.76%). Males were used to test the null hypothesis that SI joint fusion is not related to surgical implants or lumbar fusion. Results showed that neither surgical implants nor lumbar fusion is significantly associated with SI joint fusion (Fisher's exact test, $P<0.1667$ and $P<0.7091$, respectively). Thus, analyses for the remainder of this study will come from the entire sample of individuals.

4.4. Sacroiliac (SI) Joint Fusion among Nulliparous Females, Parous Females and Males

Nulliparous females, parous females, and males were compared with one another using Fisher's exact test to test the null hypothesis that the three groups do not differ in prevalence of SI joint fusion. The three groups showed a significant difference (Table 4.1; P<0.0004). To determine which group(s) is different than the others in prevalence of SI joint fusion, all pairwise comparisons of groups were analyzed. Parous females and males showed a significant difference in prevalence of SI joint fusion (P<0.0001). Parous females and nulliparous females showed no significant difference (P<0.0662). Nulliparous females and males showed no significant difference (P<0.2113).

4.5. Asymmetry and Symmetry of SI Joint Fusion

Table 4.3. Number of sacroiliac (SI) joint fusion on the right SI joint and the left SI joint in nulliparous females, parous females, and males

Parity Status	**Right SI Joint Fusion**	**Left SI Joint Fusion**	**Both**	**Total**
Nulliparous Females	0	2	1	3
Parous Females	0	1	0	1
Males	5	7	10	22
Total	**5**	**10**	**11**	**26**

Of the four females with SI joint fusion, three (75%) had fusion of the left SI joint and one (25%) had fusion of the right and left SI joints (Table 4.3). Males had 22 individuals with SI joint fusion, with 5 (22.72%) having fusion of the right SI joint, 7 (31.82%) having fusion of the left SI joint, and 10 (45.45%) having fusion of both right and left SI joints. A binomial test was run for males to test the null hypothesis that there is no difference in the likelihood of fusion in the right or left SI joint. Asymmetrical fusion of either the right SI joint or left SI joint showed a probability of P=0.774. Symmetrical fusion of both the right and left SI joint compared to asymmetrical fusion of either the right or left showed a probability of P=0.832. Therefore, the null hypothesis failed to be rejected. Thus, neither asymmetric nor symmetric SI joint fusion is more likely to occur.

CHAPTER 5. DISCUSSION AND CONCLUSION

The results reject the null hypothesis that the prevalence of SI joint fusion is the same among nulliparous females, parous females, and males. Males have a significantly higher prevalence rate of SI joint fusion than parous females, but nulliparous females are not significantly different from either males or parous females and are thus intermediate between the two groups. Therefore, SI joint fusion is not more likely to occur in nulliparous females than parous females. Such results could mean that the mechanics of childbirth might not play a role in the inhibition of fusion. Pregnancy may be more influential than the act of birth itself in the presence or absence of SI joint fusion. The cause for the intermediate frequency in SI joint fusion in nulliparous females is probably multifactorial and cannot be attributed to one facet of pregnancy. Specifically, physiological and hormonal components such as joint laxity and bone resorption as a result of pregnancy could reduce the opportunity for the SI joint to experience any fusion in parous females. Thus, the absence of increased joint laxity and bone resorption due to pregnancy could contribute to the vulnerability of nulliparous females to SI joint fusion.

5.1. Joint Laxity

Joint laxity could play a role in the intermediate frequencies of SI joint fusion in nulliparous females. Females experience increased levels of estrogen, progesterone, and relaxin in pregnancy. Although these three hormones have multiple functions (such as strengthening the endometrium in the first trimester and inhibiting early contractions), one such function is to increase joint laxity during childbirth (Trevathan, 1987; Peck et al,. 2002; Goldsmith and Weiss, 2009). Although both estrogen and relaxin increase significantly before delivery (Trevathan 1987), all three hormones are present throughout the pregnancy (Calguneri et al., 1982; Joseph, 1988; Maclennon, 1991; Damen et al., 2001; Cohen, 2005; Talbot and Maclennon, 2016; Mahato, 2016). What's more, relaxin cannot act on ligaments unless those ligaments have already been primed with estrogen (Tague 1988). Therefore, the process of pregnancy, and not just the mechanical act of parturition, is important for increased levels of joint laxity.

Multiparous females are more likely to experience hyperlaxity at the SI joints due to the repeated increase in laxity of the sacroiliac ligament during pregnancy (Damen et al. 2001). Pelvic ligaments typically return to their normal shape three to five months after the birth of the neonate (Calguneri et al. 1982), so the possibility exists that the repeated laxity and increased movement of the SI joints could potentially inhibit SI joint fusion later in life. This could especially be true for multiparous females whose last child was born later in life. Since joint laxity occurs throughout the period of pregnancy, a female could experience an increase in ligamentous movement even if she did not carry to term. Although a nulliparous female could have given birth to a stillborn, other nulliparous females could have either miscarried early in pregnancy or never been pregnant. As such, a nulliparous female might not experience the same amount of joint laxity as a parous female who carried to term more than once. Furthermore, since pelvic joints do not return to their normal shape until 3 to 5 months after birth of the neonate (Calguneri et al. 1982), this would suggest that parous females maintain longer periods of laxity than nulliparous females, even if a nulliparous female was pregnant and miscarried. However, information concerning pregnancy in nulliparous females was not available for this research.

5.2. Bone Resorption

Another potential explanation for the intermediate frequency of SI joint fusion in nulliparous females is bone resorption in relation to pregnancy. Most studies in the literature have focused on resorption or pitting in the pubis. Tague (1988) examined resorption of the pubic symphysis in nonhuman mammals. He concluded that resorption of the pubic bones could be obstetrically advantageous because resorption would potentially delay fusion of the pubic joint thereby allowing the pelvis to remain flexible during birth. As previously mentioned, relaxation and movement of the pubic symphysis and SI joints are important during birth. Tague (1988) suggests that estrogen could stimulate osteoclastic activity at ligamentous sites in the pelvis. Since estrogen levels increase during pregnancy, bone resorption could be exacerbated at ligamentous sites such as the pubic symphysis and SI joints.

Suchey et al. (1979) examined the degree of pitting in female pubic bones in relation to three variables: the number of full term pregnancies, the amount of time since the last pregnancy, and age at death. The authors found that, while there is a correlation with the number of pregnancies and interval since last birth, age was the most important variable in relation to pubic pitting. Nulliparous females younger than 30 years of age are less likely to have pubic pitting than nulliparous females older than 30 years of age. The authors conclude that the degree of resorption in the pubic bones increases with both age and parity status.

Spring et al. (1989) examined the relationship between deep, scooped-out grooves in the preauricular sulcus and parity status. Part of the SI joint capsule ligament attaches to the preauricular area. The authors found no statistical relationship between the depth of the grooves and number of full term births. However, the presence of grooves is sexually dimorphic with females showing a higher prevalence of resorption than males. The authors conclude that pits in the preauricular groove cannot predict parity status but are more common in females than males.

However, Tague (1990) found a positive correlation between age, parity status, and degree of pubic bone resorption adjacent to the pubic symphysis in *Macaca mulatta* (rhesus monkey). While the pubic bones experience resorption in *M. mulatta*, the preauricular area does not experience the same degree of resorption. However, both the preauricular area and pubic bone experience resorption in the human. Thus, the author concludes that there are probably differing etiologies for bone resorption adjacent to the pubic symphysis and in the preauricular area. Pregnancy associated hormones may not be the sole or primary cause of bone resorption in the preauricular area.

The results from these studies suggest that an association between pregnancy and bone resorption, specifically in the pubis, exists. The pubic bones are potentially more sensitive to hormones such as estrogen (Tague, 1988, 1990) than is the preauricular area and, therefore, the SI joints. However, the intermediate frequency of SI joint fusion in nulliparous females compared to parous females and males could suggest that estrogen plays a role in bone resorption at the SI joints. Females without children probably did not experience the same levels of estrogen that occur during pregnancy as parous females who carried to term. Lower levels of estrogen could contribute to the increased potential of SI joint fusion later in life since the osteoclastic activity associated with estrogen could have been compromised.

Furthermore, the human pelvis carries and distributes half of the weight of the human body due to obligate bipedal locomotion. The pelvic joints, specifically the SI joints, carry and distribute all of the weight that falls onto the pelvis (Alderink, 1991; Vleeming et al., 2012). Carrying weight over the span of years can make the pelvis vulnerable to pathologies such as osteophytes and fusion. Since the absence of fusion is obstetrically beneficial for the pelvic joints of human females, hormones that encourage osteoclast activity at pelvic joints—such as estrogen—could partially function to prohibit bone growth caused by the repeated minor traumas of bipedal locomotion.

The results of this research are similar to the results of Dar and Hershkovitz (2006) and Waldron and Rogers (1990). In this study, males had a higher prevalence of SI joint fusion than females, with 13.92% of males and 2.42% of females (combined sample of nulliparous and parous females) displaying SI joint fusion. Thus, SI joint fusion is sexually dimorphic in this sample. The skeletal sample from the Hamann-Todd collection used in the study by Dar and Hershkovitz (2006) showed that 12.27% of males and 1.83% of females showed SI joint fusion. In the sample of CT scans also used by Dar and Hershkovitz (2006), 34.2% of males and 4.6% of females displayed SI joint fusion. Dar and Harshkovitz (2006), Waldron and Rogers (1990), and this research show high rates of sexual dimorphism between males and females in SI joint fusion. However, there is a difference in percentages among the sample from this research, the Hamann-Todd collection, and the CT-scan sample. The difference for SI joint fusion in this study shows that males are 5.8 times higher than females. The difference for SI joint fusion in the study by Dar and Herskovitz (2006) shows that males are 6.7 times higher than females in the Hamann-Todd collection and 7.4 times higher than females in the sample of CT-scans. The percent of SI joint fusion in both males and females is higher in the CT scan sample than in the other two samples. As those individuals with CT-scans came to the hospital due to abdominal and pelvic issues, those individuals showing abdominal or pelvic symptoms also have a higher frequency of SI joint fusion. A fruitful follow-up study would be to examine if individuals suffering from abdominal and/or pelvic symptoms are also more likely to develop SI joint fusion.

The results in this study suggest that SI joint fusion in males is not associated with advancing age. However, it is not possible to ascertain the age at which SI joint fusion occurs in this sample. The objective of this research was to study completed reproductive history and its relationship to SI joint fusion. Thus, individuals 50 years of age and older were examined. A fruitful follow-up study would be of individuals who are younger than 50 years of age.

A question in this research is why males experience SI joint fusion. Dar et al. (2007) suggest that there could be an association between SI joint fusion and DISH. However, results of this study found a nonsignificant association between SI joint fusion and fusion of the lumbar vertebrae in males. Other variables that could contribute to SI joint fusion in males could be body mass or types of activities.

5.3. Future Research and Conclusion

A caveat to this research is whether a female was truly nulliparous or parous. The possibility exists that one or more nulliparous females in this sample were pregnant at least once. The possibility also exists that a female who suffered a stillbirth would mark herself as having no children. Adoption could be another confounding factor. A female could have given birth to a child, put that child up for adoption, and reported herself as having no children. Conversely, a female could have adopted and reported the number of her adopted children but was, by definition, nulliparous. Another variable that was not available for this study is whether or not a female underwent surgical intervention (i.e., a cesarean-section) during labor. However, these factors are unknowable for this study. Another factor that could affect SI joint fusion in females is osteoporosis, which could also partially inhibit fusion in females. Future research could examine the relationship between osteoporosis, parity status, and SI joint fusion in postmenopausal females.

In conclusion, the etiology of SI fusion is unknown. However, this study suggests that the intermediate position of nulliparous females in frequency of SI joint fusion between the frequencies of males and parous females could be due in part to the process of pregnancy. Parous females experience increased levels of estrogen and relaxin that allow the ligaments in the pelvis to become relaxed, thus allowing pelvic joints to experience increased movement during pregnancy. Such movement is necessary for the birthing of a large-brained neonate. However, the nulliparous females in this sample probably did not experience the same levels of estrogen and relaxin as parous females and, therefore, the SI joints of nulliparous females were more vulnerable to fusion than the SI joints of parous females. Bone resorption in the pubic bones and preauricular area has been noted during pregnancy. The absence of an increase in hormones related to joint laxity and absence of accelerated bone resorption due to full-term pregnancy could make the SI joint region of nulliparous females more vulnerable to fusion.

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