A Thesis

entitled

Gender Specific Sacroiliac Joint Biomechanics: A Finite Element Study

by

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Submitted to the Graduate Faculty as partial fulfillment of the requirements for the

Master of Science Degree in

Bioengineering

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August 2017
An Abstract of
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Sacroiliac joint (SIJ) pain has been recognized as a main source of pain in 13% to 30% of patients with low back pain. Although it is not clear how the pain is created, it is believed that alteration in the normal joint motion can contribute to development of sacroiliac pain. Thus understanding the kinematics and load sharing across the joint can help to understand the mechanisms for generation of SIJ pain. Despite various biomechanical studies on biomechanics of SIJ, there is no literature on biomechanical differences between male and female SIJs. Due to limitation of in vivo and in vitro studies in quantifying load-sharing and stress distribution patterns in the joint, finite element analysis is a useful tool to assess these biomechanical parameters.

The validated finite element models of a male and female lumbar spine-pelvis were utilized to simulate anatomical flexion, extension, lateral bending, and axial rotation motions. The range of motion, stress distribution, load sharing across the SIJ and pelvis ligaments strain for intact, instrumented, and post-partum female model were computed and compared between male and female models.
This study found that the female sacroiliac joint had relatively higher range of motion, stresses, and loads than male model at both sides of the joint. Unilateral stabilization significantly reduced the fixed and contralateral SI joint range of motion. Moreover, laterally placement of the implant and presence of threads on the implant provided higher control on the SIJ motion. The motion reduction at the SI joint after unilateral and bilateral fusions resulted in minimal change in motion at the adjacent lumbar levels for both male and female models. The implant shape characteristics and their placements played a major role in stresses on the bone and implant. In both unilateral and bilateral fusions, SIJ stabilization was primarily provided by the inferior and superior implants. The simulated post-partum period female pelvis showed that post-partum effect along with ligament laxity increased SIJ motion and stresses markedly.

Female SIJ had higher mobility, stresses, and loads compared to male SIJ leading to higher chances of feeling pain across the joint. This could be a possible reason for higher incidence of low back pain in females.
To Mom and Dad,

who always picked me up on time

and encouraged me to go on every adventure,

especially this one
Acknowledgements

First and foremost, I would like to acknowledge my fellow lab mates and graduate students. Without the companionship and good natured fun of the students in the ECORE lab, the drudgery of debugging finite element code would quickly lose its appeal. A special thanks goes out to Ardalan, Sushil, Anoli, Ali, Rodney, Marcel, Manoj, Amey and Sara for their help in completing my research.

Most importantly, I would like to thank my advisor Dr. Goel. Under his care and guidance I have unlocked my true potential. By giving me impossible tasks and deadlines he taught me that nothing is impossible. Throughout the course of my master’s education, I have learned more than I ever expected and gained a broad exposure to the field of biomechanics. I am eternally grateful for his mentorship.

I would also like to acknowledge Dr. Agarwal for teaching me about spinal anatomy, surgery, and clinically relevant implant ideas.
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List of Abbreviations

ASL............................Anterior Sacroiliac Ligament
CT ..............................Computed Tomography
FE...............................Finite Element
FEA .............................Finite Element Analysis
ISL.............................Interosseous Sacroiliac Ligament
L1 ...............................First Lumbar Vertebra
L2 ...............................Second Lumbar Vertebra
L3 ...............................Third Lumbar Vertebra
L4 ...............................Fourth Lumbar Vertebra
L5 ...............................Fifth Lumbar Vertebra
LB ..............................Left Lateral Bending
LBP .............................Low Back Pain
LPSL ............................Long Posterior Sacroiliac Ligament
LR ..............................Left Axial Rotation
RB ..............................Right Lateral Bending
ROM ...........................Range of Motion
RR ..............................Right Axial Rotation
S1 ...............................First Vertebra of the Sacrum
SIJ .............................Sacroiliac Joint
SPSL ............................Short Posterior Sacroiliac Ligament
SSL.............................Sacrospinous Ligament
STL .............................Sacrotuberous Ligament
List of Symbols

N.................................Newton
N*m............................Newton Meter
mm .............................Milimeter
MPa.............................Mega Pascal
° ..............................Degree
Chapter 1

Introduction

Low back pain (LBP) is one of the most common reasons for primary care visits after the common cold, with approximately 90% of adults being impacted by this condition at some time in their lives [1, 2]. Apart from hindering the quality of life of those affected by LBP, if left untreated or improperly diagnosed, LBP may profoundly impact affected patients’ work productivity and therefore can have a significant burden on the economy of the society. One of the most overlooked sources of LBP is the sacroiliac joint (SIJ) due to its complex nature and the fact the pain emanating from this region can mimic other hip and spine conditions [1, 3]. However, recent studies have reported a higher prevalence of the SIJ as a source for LBP, leading physicians to place greater focus on the treatment and consideration of SIJ dysfunction as a pain generator [4].

The SIJ, the largest axial joint in the body, is the articulation of the spine with the pelvis that allows for the transfer of loads to the pelvis and lower extremities [5, 6]. The SIJ lies between the sacrum and the ilium, spanning about 1-2 mm in width and held together by a fibrous capsule [7].

Sexual dimorphism exists in the pelvis with the male pelvis being larger, a distinction that decreases in the later years of childhood. While sacral base articular facet for the fifth lumbar vertebra sits more than a third of the width of the sacral base in males, it occupies
less than a third in females. Compared to the male sacrum, the female sacrum is wider, more uneven, less curved, and tilted in the coronal plane. Males tend to have a relatively long and narrow pelvis, with a longer and more conical pelvic cavity than those of females. In the second decade of life, women develop a groove in the iliac bone, the paraglenoidal sulcus, which usually does not occur in men. Such gender-related differences in the development of the SIJ can lead to a higher rate of SIJ misalignment in young women [8].

Furthermore, females and older subjects have been shown to be associated with higher prevalence of LBP and SIJ pain. This higher rate of pain in females can be explained by several factors: 1) pregnancy, menstruation, or osteoporosis, and 2) divergent growth patterns between genders in adolescence since the peak of the prevalence of low back pain happens earlier in girls than in boys due to puberty [9].

The SIJ is unique in that it is rather stable and motion of the joint is quite minimal [7]. The exact range of motion (ROM) of the SIJ is hard to measure and has been debated and studied extensively, with varying results. There are different methods to measure the SIJ motion such as roentgen stereophotogrammetric, radiostereometric, ultrasound, and Doppler [10-13]. These methods have indicated that the SIJ rotation and translation in different planes were not exceeding 2-3 degrees and 2mm, respectively [7, 14].

Although there are various studies which measured the ROM of SIJ, there is only one cadaver study conducted by Brunner et al. [15] which compared the range of motion of male and female SIJ. The study found that the maximum ROM for men and women was 1.2° and 2.8°, respectively, although the authors did not measure and compare the stress and load sharing across the joint between male and female SIJ.
When non-surgical method strategies fail to reduce the pain and discomfort of patients with suspected SIJ dysfunction, surgical measures become an option, beginning with open arthrodesis, or fusion of the SIJ. While the success of open arthrodesis of the SIJ has been reported in numerous studies [16-19], several aspects of this procedure have also been deemed worthy of improvement. Smith et al. conducted a multi-center comparison between open and minimally invasive SIJ fusion procedures using triangular titanium implants to compare the clinical outcomes. According to their results, open surgical fusion required longer operating room time, significantly greater estimated blood loss, and reasonably longer hospital stays [20].

To date, numerous studies have been conducted to investigate the effectiveness of minimally invasive SIJ fusion techniques. Most of the clinical studies have been done using the triangular implants and reported the satisfaction rate of patients after SIJ surgery. A few biomechanical studies have been performed to examine the SIJ fusion. Lindsey et al. [21] found that SIJ motion reduction by fusion resulted in reduced adjacent lumbar segment motion. In another study, Soriano-Baron et al. [22] showed that placement of three implants in posterior and trans-articular approaches significantly reduced the ROM in all motions. In another study done by Lindsey et al. [23], they evaluated and compared the biomechanical impact of unilateral and bilateral triangular implant placement across the SI joint. They found that the unilateral and bilateral SIJ fusion resulted in significant motion reduction across SIJ. In the previous studies [22-24], due to difficulty in measuring two leg stance SIJ range of motion, they performed the experiment in the one-leg stance condition and sectioned the pubic symphysis ligaments without applying a follower load. Moreover, a study on the effect of different placements
of the sacroiliac joint implants has not presented itself in the literature. These drawbacks would lead to a less realistic measurement of sacroiliac joint motions which were resolved in our numerical simulation.

To our knowledge, there have been no other biomechanical studies which have shed light on biomechanical differences between male and female SIJs. Cadaveric studies are technically demanding due to little motions at SIJ. Also, quantifying stresses across the joint is not feasible in _in vitro_ and _in vivo_ analyses. Therefore, finite element analysis is a helpful tool to assess the range of motion in the SIJ and stresses across the joint. The first goal of this thesis was to develop and validate two detailed computational models of a ligamentous human spine-pelvis-femur for a male and female subject. The objective of this study was to quantify the range of motion and load distribution at the SIJ using gender specific finite element model of the sacroiliac joint to better understand the biomechanical differences in SIJ between genders regarding their mobility and the possible pain locations.

After validation, this study aimed to fill a gap in the literature as it focused mainly on one particular types of implants and limited biomechanical parameters. Our next objective was gender specific biomechanical analysis of SIJ fusion under three types of sacroiliac joint implants which were different in placement and shape. In the last part of the thesis, we examined the effect of post-partum period on the female SIJ which was not studied previously in the literature.
Chapter 2

Anatomy and Literature Review

2.1. Background

Low back pain (LBP) is the most common reason for primary care visits after the common cold, with approximately 90% of adults being impacted by this condition at some point in their lives [1, 2]. Apart from hindering the quality of life of those affected by LBP, if left untreated or improperly diagnosed, LBP may also profoundly impact affected patients’ work productivity and therefore economic success. When undertreated or improperly relieved, LBP can result in an annual cost up to approximately $60 billion dollars due to decreased productivity and income as well as medical expenses [25-27]. The obvious problems that accompany LBP have caused prompt diagnosis and treatment to become a paramount focus in the medical field.

One of the most overlooked sources of LBP is the sacroiliac joint (SIJ) due to its complex nature and the fact the pain emanating from this region can mimic other hip and spine conditions [1,3]. However, recent studies have reported a higher prevalence of the SIJ as a source for LBP, leading physicians to place greater focus on the treatment and consideration of SIJ dysfunction as a pain generator [4]. While the majority of LBP is
perceived to originate from the lumbar spine, more recent studies have estimated that the SIJ is the actual source of pain in 15-30% of cases of LBP [28,29]. Increased awareness of the prevalence of the SIJ as a source of LBP has given rise to a greater exhibition of clinical suspicion while planning treatment, especially when considering surgical arthrodesis as a last resort.

Arthrodesis, or surgical fusion, of the lumbar or lumbosacral region, directly impacts the biomechanics of the SIJ by increasing both the motion and stress across the articular surface of the joint [30]. As a significant source of LBP, focus on the SIJ is presently quite high. Current nonsurgical treatment and pain management strategies include physical therapy, SI joint injections, and radiofrequency (RF) ablation. When patients continue to present chronic LBP characteristic with the SIJ, surgical procedures become a final resort.

2.2. Anatomy

The SIJ, the largest axial joint in the body, is the articulation of the spine with the pelvis that allows for the transfer of loads to the pelvis and lower extremities [5,6]. The SIJ lies between the sacrum and the ilium, spanning about 1-2 mm in width and held together by fibrous capsule (Figure 2-1). The sacral side of the joint is covered with hyaline cartilage thicker than iliac cartilage, which appears more fibrocartilaginous [7].
2.2.1. Ligaments

Several ligaments support and limit the movement and mobility of the SIJ. These ligaments include the interosseous sacroiliac ligament, the posterior and anterior ligaments, sacrotuberous, sacrospinous and iliolumbar ligaments. The interosseous ligament, also known as the axial ligament, connects the sacrum and ilium at the S1 and S2 levels. The posterior sacroiliac ligament is quite strong and consists of multiple bundles which pass from the lateral crest of the sacrum to the posterior superior iliac spine and the posterior end of the iliac crest. The anterior sacroiliac ligament is a thin ligament that is weaker than the posterior ligament and runs over the joint obliquely from sacrum to ilium. The sacrotuberous ligament is located at the inferior-posterior part of the pelvis and runs from sacrum to the ischial tuberosity. The sacrospinous ligament’s attachment is behind of the sacrotuberous ligament, and it connects outer edge of the sacrum and coccyx to the Ischia of the ilium. The iliolumbar originates from the tip of the fifth lumbar vertebral body to the iliac crest (Figure 2-2) [32]. The long dorsal sacroiliac
ligament can stretch in periods of reduced lumbar lordosis, such as during pregnancy, which will be discussed further. Table 2.1 summarizes sacroiliac joint ligaments locations and their functions.

Figure 2-2: (a) Posterior view, (b) anterior view and (c) sacroiliac joint cut in transverse plane. 1, 2, superior and inferior iliolumbar ligaments; 3, sacrospinous ligament; 4, sacrotuberous ligament; 5, posterior sacroiliac ligaments; 6, anterior sacroiliac ligaments; 7, sacroiliac joint; 8, interosseous ligament [32].

Table 2.1: Sacroiliac joint ligaments locations and their functions [31]
2.2.2. Muscles

While no muscles are designed to act on the SIJ to produce active movements, the joint is still surrounded by some of the largest and most powerful muscles of the body. These muscles include the erector spinae, psoas, quadratus lumborum, piriformis, abdominal obliques, gluteal and hamstrings. While they do not act directly on the SIJ, the muscles that cross the joint act on the hip or the lumbar spine [33-35]. Movements of the SIJ are indirectly produced by gravity and muscles acting on the trunk and lower limbs rather than active movements of the sacrum [32]. Table 2.2 summarizes sacroiliac joint muscles actions and their effect on SIJ.

Table 2.2: Sacroiliac joint muscles actions and their effect on SIJ [31]
### 2.3. Age-Related Changes

Beginning at puberty, the SIJ undergoes age-related changes as the iliac surface became rougher and coated with fibrous plaques in some areas. During the third and fourth decades of life, these age-related changes accelerate and are accompanied by surface irregularities, crevice formation, and the clumping of chondrocytes [6]. Degenerative changes occur for the iliac surface about 10-20 years before those affecting the sacral side. In the sixth decade, the capsule becomes increasingly collagenous and fibrous ankyloses occurs, causing motion at the joint to become significantly restricted [6,36]. Finally, by the eighth decade of life, erosions and plaque formation become unavoidable [36]. As the joint space decreases with age and becomes filled with debris, it becomes stiffer and less efficient at absorbing and transmitting loads [7,37].

### 2.4. Function and Biomechanics
The flat shape of SIJ along with its ligaments helps it to transfer large bending moments and compression loads. However, it is weak against shear loads; it is counteracted by compression of SIJ which is generated by a self-bracing mechanism. The self-bracing mechanism consists of loading mode of pelvis and forces produced by muscles and ligaments which are normal to the joint surface. The loading mode of the pelvis due to gravity and the free body diagram of the self-bracing mechanism which involves normal and tangential forces of the joint surface, hip joint force, and muscle or ligament force are shown in Figure 2-3 a and b, respectively. The friction coefficient of SIJ surfaces without grooves and ridges was measured as 0.4. This resistance can be increased by grooves and ridges and wedge angle β to prevent sliding of SIJ surfaces due to shear [38]. It was shown that M. transversus abdominis and the pelvic floor muscles are playing a major rule in SIJ stability by enlarging the SIJ compression load to resist shear loads [39].

Figure 2-3: a) Pelvis free body diagram due to gravity. Trunk weight (Fg) and hip joint forces (Fv). b) Free body diagram of self-bracing effect of sacroiliac joint. SIJ reaction force: normal and tangential (Fn and Ff), ligament or muscle force (Fl) and hip joint force (Fv) [38]
Goudzward et al. [40] did a study on 12 human cadavers to see the effect of the iliolumbar ligament (IL) on SIJ stability. Four cases were tested: 1. Intact IL, 2. randomly dissection of IL, 3. further dissection of IL, and 4. cut IL. The moment-rotation relationships were assessed by applying various moments to SIJ and measuring the rotation in the sagittal plane. The sacrum and iliac bones were fixed and the moment was applied by a traction device to generate a tension in the string. Eight light reflecting markers were utilized to calculate the rotation. Dissection of that the ventral side of the iliolumbar ligament is causing less SIJ stability in the sagittal plane. Dorsal side and sacroiliac part of the IL does not have significant role in providing SIJ stability [40]. It is also stabilizing the lumbar vertebra on the sacrum [41].

The posterior sacroiliac ligaments are contributed most to the SIJ mobility, while the anterior sacroiliac ligament has little influence [42]. The motion of ilium respect to sacrum is called nutation which is anterior sacral tilt and counternutation which is posterior sacral tilt. Resisting the nutation and counternutation of the joint is done by the sacrotuberous ligament (STL) and sacrospinous ligament (SSL), and long dorsal ligament (LDL), respectively [43, 44]. During pregnancy by increased laxity of SIJ ligaments, the pain is mostly experienced in LDL due to its counteraction to the counternutation [45]. Pain in this region is also common in men due to its location which is superficial will put asymmetric stress on the SIJ. Flattening of lumbar lordosis brings about a decrease in SIJ nutation [8].

A cadaveric study was done by Wang et al. [46] to calculate the SIJ motion and influence of anterior and posterior ligaments on the SIJ stability. Four female cadaver specimens were tested by applying five different eccentric compressive loads
(combination of compression, bending moment, and forward shear due to inclination angle) to the sacrum. The main motions of the sacrum were lateral rotation and nutation rotation which were less than 1.2 degrees. The lateral rotation is restricted by transverse portions of anterior and posterior ligaments. Also, the nutation rotation is prevented by the top portion of anterior and lower portion of posterior ligaments (i.e. Shear resisting couple), and dissection of these two ligaments has a significant influence on the joint stability. It was shown that intersosseous ligaments are the strongest ligaments which provide less motion in the joint’s translation.

Dujardin et al. [47] assessed the SIJ micromotion under compression load applied to the ischial tuberosity. By sectioning SSL and STL, SIJ stability will decrease. Buyruk et al. [48] using Doppler imaging of vibrations showed that left and right SIJ stiffness are different in various conditions which means there is asymmetry in the SIJ stiffness resulting in low back pain and pelvic pain. Rothkotter et al. [49] indicated that the SIJ ligamentous structure failed at 3368 N under transverse loading with displacement range from 5.5 to 6.6 mm. They found that under dorsocranial loading, the self-bracing mechanism of SIJ between sacrum and ilium is working better than other loading directions.

2.5. Range of Motion

The sacrum can move with respect to the ilium in six degrees of freedom which is shown in Figure 2-4. The intersection of the middle osteoligamentous column and the lumbosacral intervertebral disc is defined as the lumbosacral pivot point. Placing constructs posterioriorly of this pivot point extending anterior of the point would provide rotational stability [50].
Figure 2-4: Pelvis six degrees of movement and lumbosacral pivot point, a) coronal plane, b) sagittal plane [51]

While the primary function of the SIJ is to absorb and transmit forces from the spine to the pelvis, it is also responsible for facilitating parturition and limiting x-axis rotation [5,6]. The SIJ is unique in that it is rather stable and motion of the joint is quite minimal [7]. The exact range of motion (ROM) of the SIJ has been debated and studied extensively, with varying results. There are different methods to measure the SIJ motion such as roentgen stereophotogrammetric, radiostereometric, ultrasound, and Doppler [10-13], they indicated that the SIJ rotation and translation in different planes do not exceed 2-3 degrees and 2mm, respectively [7, 14]. The joint’s ROM is greatest in flexion-extension with a value of approximately 3°. Axial rotation of the SIJ is about 1.5°, and lateral bending provides the least ROM with approximately 0.8° [33]. As the characteristics of the SIJ change with aging, these values can increase or decrease depending on the circumstance.
Many studies have been conducted concerning the biomechanics of the SIJ, and the results can be summarized quite simply: the SIJ rotates about all three axes, and these incredibly small movements are very difficult to measure [52,53]. In an attempt to understand the load-displacement behavior of single and paired SI joints, a study involving eight elderly cadavers was conducted by Miller et al. [33]. In this study, rotations about all three axes were measured for one and both ilia fixed, with static test loads applied in the superior, lateral, anterior and posterior directions. According to their results, movements in all planes with one leg fixed ranged from between 2 to 7.8 times greater than those measured with both legs fixed.

Another series of cadaveric studies by Vleeming et al. [43, 54] was conducted to investigate the biomechanics of the SIJ, reporting that the ROM for flexion and extension rarely exceeded 2°, with an upper limit of 4° during sagittal rotation. To compare male and female SIJ ROM, a cadaver study by Brunner et al. [15] found that the maximum ROM for men and women was 1.2° and 2.8°, respectively. Another study by Sturesson et al. [13] involved measuring SIJ movements in 25 patients diagnosed with SIJ pain. According to their results, all movements were incredibly small, with translations never exceeding 1.6 mm and an upper rotational limit of 3°. This study also found that no differences in ROM existed between symptomatic and asymptomatic SI joints, which led the authors to conclude that 3-dimensional motion analysis is not a useful tool for identifying painful SI joints in most patients [13]. Jacob et al. [55] reported mobility of SIJ of 15 healthy people using a three-dimensional stereophotogrammetric method. The average total rotation and translation were 1.7 and 0.7 mm, respectively.
2.6. Sexual Dimorphism

Sexual dimorphism exists in the pelvis with the male pelvis being larger, a distinction that decreases in the later years of childhood. While the sacral base articular facet for the fifth lumbar vertebra occupies more than a third of the width of the sacral base, it occupies less than a third in females. Compared to the male sacrum, the female sacrum is wider, more uneven, less curved, and more backward tilted. Males tend to have a relatively long and narrow pelvis, with a longer and more conical pelvic cavity than those of females (Figs. 3 and 4). In the second decade of life, women develop a groove in the iliac bone, the paraglenoidal sulcus, which usually does not occur for men. Such gender-related differences in the development of the SIJ can lead to a higher rate of SIJ misalignment in young women [8].

According to a study by Ebraheim and Biyani [56], the SIJ surface area is relatively greater in adult males than females, which consequentially allows males to withstand greater biomechanical loading. While the average auricular surface area for females has been reported to range from 10.7 to 14.2 cm² [33,56] with an upper limit of 18 cm² [57], this ligamentous area for males is approximately 22.3 cm² [33]. Another reason that males can withstand greater biomechanical loading can be attributed to the fact that males possess significantly higher lumbar isometric strength, almost twice as strong as those of females, thus requiring more significant load transfers through the SI joints [58,59].

Another significant influence on the development of particular SIJ form is the center of gravity, which has been reported to exist in different positions for males and females. Compared to men, who have a more ventral center of gravity, the center of gravity in
females commonly passes in front of or through the SIJ [60,61]. This difference implies that men would have a greater lever arm than women, accounting for the higher loads on the joints and stronger SI joints in males [8]. This characteristic also may explain why males have more restricted mobility, as the average movement for men is approximately 40% less than that of women [8,62,63].

The increased mobility of the SIJ in women can be attributed to individual anatomical correlations. Two features that allow for higher mobility in women are the less pronounced curvature of the SIJ surfaces and a greater pubic angle compared to those of males [8]. While males typically have an average pubic angle of 50-82°, females have an average pubic angle of 90° [64]. A possible reason for these differences can be attributed to the facilitation of parturition in females, which involves the influence of hormones such as relaxin [5,6,65]. Under the effect of relaxin, relative symphysiolysis appears to occur, and both of these factors loosen the SIJ fibrous apparatus, thus increasing mobility [8]. While these unique aspects of the SIJ provide females with the necessary ability to give birth, they also may predispose females to a greater risk of experiencing pelvic pain [66-69]. One factor that plays a major role in determining the severity of this predisposition involves the laxity of the female SI joints during pregnancy. According to a study by Damen et al. [70], females who experience asymmetric laxity of the SI joints during pregnancy are three times more likely to develop moderate to severe pelvic girdle pain (PGP) than females who experience symmetric laxity. As the particular form of the SIJ differs immensely between males and females, it becomes rather clear that women are more likely to develop PGP, and are therefore at greater risk of experiencing LBP.
Figures 2-5 and 2-6 and table 2.3 show the anatomical and biomechanical differences between male and female pelvis.

Figure 2-5: Comparison of the female and male pelvic brim (inlet) [71].

Figure 2-6: Comparison of the female and male pelvic outlet [71].

Table 2.3: A Biomechanical Comparison of the Female and Male SIJ.

<table>
<thead>
<tr>
<th>Biomechanical Aspects</th>
<th>Female</th>
<th>Male</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIJ Motions</td>
<td>More Rotational</td>
<td>More Translational</td>
</tr>
<tr>
<td>SIJ Surface Area</td>
<td>Lesser</td>
<td>Greater</td>
</tr>
<tr>
<td>Interosseous Sacroiliac</td>
<td>Larger</td>
<td>Smaller</td>
</tr>
<tr>
<td>Ligament</td>
<td>Smaller</td>
<td>Larger</td>
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<tr>
<td>--------------------------------</td>
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<td>--------</td>
</tr>
<tr>
<td>Anterior Sacroiliac Ligaments</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Posterior Sacroiliac Ligaments</td>
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</tbody>
</table>

2.7. Causes of SIJ Pain

The mechanism of SIJ injury has been viewed as a combination of axial loading and abrupt rotation [72]. From an anatomical perspective, pathologic changes specific to different SI joint structures can result in SIJ pain. These changes include, but are not limited to, capsular and ligamentous tension, hypomobility or hypermobility, extraneous compression or shearing forces, microfractures or macrofractures, soft tissue injury, and inflammation [6]. Also, numerous other factors can predispose a person to a gradual development of SIJ pain.

As the primary function of the SIJ is to transfer loads between the spine and lower extremities effectively, simple daily activities such as walking and lifting objects can also cause stress and wear on the joint over time. However, dysfunction and pain of the joint often are not solely due to these activities. Many other causes of SIJ pain exist and impact the joint in combination with daily load bearing and aging. Some of the most common sources of SIJ pain include injuries sustained from falling directly on the buttocks, collisions during sports and car accidents. Prior medical procedures may also play a role in SIJ pain and dysfunction.

As mentioned, many studies have reported that prior lumbar fusion can directly increase angular motion and stress across the patient’s SIJ, and the magnitude of both of
these parameters is strongly correlated to the specific lumbar levels fused as well as the number of segments fused [30]. When surgical arthrodesis causes degeneration of an adjacent segment, such as the SIJ, this profound adverse effect is known adjacent segment disease (ASD) [30,73-75].

Other causes of SIJ pain and dysfunction have also been studied extensively, one of which involves limb length discrepancy (LLD). While it has commonly been accepted that LLD is related to LBP, the exact mechanism of this relation is unknown. However, several authors have reported the correlation between LLD and LBP to be strongly related to SIJ dysfunction [6,76-78]. Due to the length discrepancy, the mechanical alignment of the SI joints become increasingly imbalanced, resulting in an increased load distribution across both SI joints [6,77,78].

Apart from injuries, prior lumbar fusion, and LLD, several other factors can also cause the gradual development of SIJ pain. Additional sources of increased stress and pain across the SI joints include joint infection, spondylo-arthritis such as ankylosing spondylitis [6], gait abnormalities [79], scoliosis [80], and excessive exercise [81]. A complete list of intra-articular and extra-articular SIJ pain sources is presented in Table 7. Regardless of the precise cause, the associated pain mechanisms for SIJ dysfunction are rather consistent.

Symptoms of SIJ dysfunction include pain in the lower back, buttock, back of the thigh, and knee. Patients with LBP often experience pain when sitting, leaning forward, and with an increase in intra-abdominal pressure [82]. While these pain characteristics are associated with SIJ dysfunction, they also are consistent with other hip and spine conditions, making accurate diagnosis and confirmation of the SIJ as the pain source a
rather difficult task. Table 2.4 summarizes the causes of intra-articular and extra-articular SIJ pain.

Table 2.4: Causes of intra-articular and extra-articular SIJ pain [83].

<table>
<thead>
<tr>
<th>INTRA-ARTICULAR PAIN</th>
<th>EXTRA-ARTICULAR PAIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Arthritis</td>
<td>• Ligamentous injury</td>
</tr>
<tr>
<td>• Spondyloarthropathy</td>
<td>• Bone fractures</td>
</tr>
<tr>
<td>• Malignancies</td>
<td>• Malignancies</td>
</tr>
<tr>
<td>• Trauma</td>
<td>• Myofascial pain</td>
</tr>
<tr>
<td>• Infection</td>
<td>• Enthesopathy</td>
</tr>
<tr>
<td>• Cystic Disease</td>
<td>• Trauma</td>
</tr>
<tr>
<td></td>
<td>• Pregnancy</td>
</tr>
</tbody>
</table>

2.8. Pregnancy

During pregnancy, many hormonal and biomechanical alterations are happening which contribute to ligaments laxity and compressing or loosening joints. One of the leading musculoskeletal changes is increasing the mass of uterus and breast which causes anterior displacement of the center of mass. This effect heightens joint loads (ex. Increased hip joint anterior torque by eight times) and is aggravated by the laxity of other ligaments and other joints which may contribute to pain and risk of injury [84].
Figure 2-7: Posture changing in pregnancy due to displaced center of mass, a) Normal posture, b) anteriorly displaced center of mass increases anterior torque at the hip, c) Restoring sagittal stability by increasing lumbar lordosis and to move the center of mass back to the original place [84].

Another significant musculoskeletal change occurs in spinal posture. Lateral expiation of ribs by 10-15 cm, cervical kyphosis, extreme thoracic kyphosis, and enhanced lumbar lordosis are the changes in spinal posture leading to impaired spine stability and pain during pregnancy. The sagittal stability of spine is met by lumbar paraspinal muscles leading to increasing lumbar lordosis. The paraspinal muscle also counteracts the anterior torque caused by displacement of the center of mass. This muscular contribution required to maintain spine stability enlarges force and lever arm across the joint (ex. Enhanced facet joint shear stress by 60%) and contributes to increased stretch in posterior muscle, tensioning of anterior muscles, and anterior and posterior longitudinal ligaments laxity in spine [84].
In the pelvic region, several changes happen. This anterior displacement of the center of mass is influencing pelvis posture which leads to increased anterior pelvic tilt [84]. A study by Yamaguchi et al. [85] was conducted to show the difference in pelvic alignment among never-pregnant, pregnant, and postpartum women. The anterior width of the pelvis in postpartum women is wider than never-pregnant women due to loosening of the pubic symphysis. Due to SIJ asymmetric laxity and pelvic tilt during pregnancy, pelvic asymmetry of pregnant and postpartum women was larger than never-pregnant women. Because pelvic laxity may continue during postpartum, hence, postpartum women may have pelvic asymmetry and pelvic laxity.

During delivery, the pubic symphysis and sacroiliac joints which are inherently stable are widening and leading to increased motion at SIJ. The pubic symphysis increases from 3-5 mm to 5-8 mm during pregnancy. This joint laxity contributes to increasing the risk of injury, and they return to their normal condition after 4-12 weeks postpartum. Many studies have investigated the changes in bone mineral content during pregnancy, but there are inconsistencies between their findings. Other changes also occur in lower limbs and gait during pregnancy, but it is beyond the scope of this chapter [84].

Studies have shown that the pelvic belt helps pregnant women to reduce SIJ motion by altering the laxity of the ligaments [8, 86, 87]. It is shown that the amount of tension of the pelvic belt is not as important as pelvic belt position [86], it is better to be placed superior to the greater trochanter and inferior to the SIJ to put pressure on the inferior-posterior side of sacrum [8, 86].

2.9. Diagnosis of SIJ Dysfunction
Symptoms of SIJ dysfunction include pain in the lower back, buttock, back of the thigh, and knee. Patients with LBP often experience pain when sitting, leaning forward, and with an increase in intra-abdominal pressure [82]. While these pain characteristics are associated with SIJ dysfunction, they also are consistent with other hip and spine conditions, making accurate diagnosis and confirmation of the SIJ as the pain source a rather difficult task.

Due to the complexity of diagnosing the SIJ as the pain source, numerous physical examination tests have been utilized, many of which incorporate distraction of the sacroiliac joints. Two of the most commonly performed tests are the Gaenslen’s test and Patrick’s test, also known as the FABER test [6]. Other provocation tests for assessing SIJ pain include distraction/compression tests, the thigh thrust test, and the sacral thrust test (Table 2.5) [88]. It is commonly accepted that if three or more of these tests are deemed positive, then they can be considered reliable for diagnosing the SIJ as the source of pain [89]. Despite the various physical diagnostic tests available, many clinical studies have shown rather inconsistent findings in the success of identifying the pain source to be SIJ dysfunction [6,29]. For this reason, other techniques have been suggested in conjunction with physical diagnostic tests to improve reliability.

Table 2.5. A Comparison of Provocation Tests

<table>
<thead>
<tr>
<th>Provocation Test</th>
<th>Patient Position</th>
<th>Technique Description</th>
</tr>
</thead>
</table>

24
<table>
<thead>
<tr>
<th>Test</th>
<th>Position</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaenslen’s Test</td>
<td>Supine</td>
<td>With symptomatic leg resting on the edge of a table and the nonsymptomatic hip and knee flexed, a force is applied to the symptomatic leg while a counterforce is simultaneously applied to the flexed leg, producing pelvic torque [90,91].</td>
</tr>
<tr>
<td>Distraction Test</td>
<td>Supine</td>
<td>A vertical, posteriorly directed force is applied to both anterior superior iliac spines (ASIS) [57, 92-94].</td>
</tr>
<tr>
<td>Compression Test</td>
<td>On Side</td>
<td>Pressure is applied to the upper part of the iliac crest, producing forward pressure on the sacrum [95].</td>
</tr>
<tr>
<td>Thigh Thrust Test</td>
<td>Supine</td>
<td>The hip is flexed to 90° to stretch posterior structures. With one hand fixated below the sacrum, the other applies downward axial pressure along the femur, which is used as a lever to push the ilium posteriorly [96-99].</td>
</tr>
<tr>
<td>Sacral Thrust Test</td>
<td>Prone</td>
<td>With one hand placed directly on the sacrum and the other hand reinforcing it, an anteriorly directed pressure is applied over the sacrum [96,97].</td>
</tr>
</tbody>
</table>

Two techniques that are implemented in addition to physical examinations include radiological studies and diagnostic blocks, or intra-articular injections. Radiological imaging tests, however, have proven to be rather insufficient, yielding reports of low sensitivities and poor correlations with diagnostic injections and symptoms [6]. Diagnostic blocks, on the other hand, are often considered to be one of the most reliable methods for diagnosing SIJ pain. These blocks, which are typically fluoroscopically guided, are used to determine if the patient experiences a significant reduction in pain.
while the anesthetic is active [7]. A controversial aspect of diagnostic blocks is that no actual “gold standard” exists for this technique, though it is commonly accepted that a successful injection helps the diagnosis of SIJ dysfunction [6,7,97]. After determining that the sacroiliac joint is the pain generator in patients with LBP, there are several treatment strategies for relieving SIJ pain.

2.10. Non-Surgical Management

The first step in the treatment of SIJ dysfunction involves non-surgical management (NSM). Non-surgical treatment options primarily include physical therapy, steroid injections, radiofrequency (RF) ablation, and prolotherapy. For patients with LLD, only utilizing shoe inserts can help eliminate the length discrepancy, consequentially equalizing and decreasing the load distribution across the joints over time [6,10]. This conservative management strategy, however, is not a valid treatment option for patients with causes of SIJ pain irrelevant to LLD. For such patients, other measures must be taken.

For patients with SIJ pain not related to LLD, physical therapy and chiropractic manipulation are typically advocated for NSM strategies. Several studies of physical therapy and chiropractic manipulation programs have reported promising long-term results, achieving reductions in pain and disability, as well as enhanced mobility [101-103]; however, there is currently a lack of prospective controlled studies to back up these treatment strategies [6]. Other stabilization plans have also been introduced, such as pelvic belts. These belts have shown to decrease sagittal rotation and consequentially enhance pelvic stability, especially in pregnant women [104,105]. In addition to
therapeutic measures, intra-articular injections have also been advocated for SIJ pain relief.

Studies regarding the effectiveness of corticosteroid injections have been conducted to quantify the magnitude of pain reduction in patients with varying reported results. A controlled study by Maugars et al. [106] reported that after a 6-month follow-up, the subjects experienced a mean pain reduction of 33%. While this is one of the lowest pain reduction rates that have been reported, it should be noted that the sample size was rather small with ten subjects. In contrast, another study conducted by Bollow et al. [107] consisted of a mean follow-up duration of 10 months and reported a statistically significant pain reduction in 92.5% of the subjects. With a larger sample size of 66 subjects, such a high pain reduction rate in the majority of subjects indicates that there is effectiveness in administering intra-articular corticosteroid injections for many patients despite the different reported results. For those who do not find significant reductions in pain from intra-articular injections, alternative treatment measures must be considered.

Radiofrequency (RF) denervation procedures are utilized as another treatment strategy with a goal of providing intermediate-term pain relief. Several studies have proven that lateral branch RF denervation strategies may improve the pain, disability, and quality of life for patients suffering from chronic SIJ pain [108,109]. However, similar to intra-articular injections, the reported success rates of RF denervation vary immensely. A retrospective study conducted by Ferrante et al. [110] involved the targeting of the intra-articular nerves via a bipolar leapfrog RF technique, and a success rate of 36.4% was reported at follow-up of 6 months. In contrast, a prospective, observational study conducted by Burnham and Yasui [111] focusing on the targeting of the L5-S3 nerves via
the same RF procedure reported a success rate of 89% after 12 months. With such inconsistent reported success rates, perhaps larger studies are required to confirm the effectiveness of RF denervation. Nevertheless, the disparity of success reports raises greater clinical suspicion regarding the reliability of such procedures.

2.11. Open SIJ Fusion

When NSM strategies fail to reduce the pain and discomfort of patients with suspected SIJ dysfunction, surgical measures become an option, beginning with open arthrodesis, or fusion of the SIJ. An end-study of open fusion of the SIJ was conducted by Smith-Petersen and Rogers to determine the success of several arthrodesis cases. According to their results, in approximately 96% of cases, the patients were able to return to their previous work, though it should also be noted that the average time required to go back to regular activities was approximately four and a half months [16].

While the success of open arthrodesis of the SIJ has been reported in numerous studies [16-19-114], several aspects of this procedure have also been deemed worthy of improvement. Smith et al. conducted a multi-center comparison between open and minimally invasive SIJ fusion procedures using triangular titanium implants to compare the clinical outcomes. According to their results, open surgical fusion required longer operating room time, significantly greater estimated blood loss, and reasonably longer hospital stays. Apart from having less advantageous operative measures, open arthrodesis of the SIJ also showed less superior SIJ pain rating changes over the duration of 12 and 24 months [20]. According to their study, the mean change in VAS pain score at 24 months was approximately -2.0 and -5.6 for open surgical fusion and minimally invasive
fusion, respectively, demonstrating the advantage of minimally invasive surgery in regards to pain recovery ratings. Results of the study also further confirm the superiority of minimally invasive approaches compared to open surgical fusion, as minimally invasive techniques are accompanied by less tissue damage, blood loss, and duration of hospitalization [19, 20].

2.12. Minimally Invasive SIJ Fusion

To date, numerous studies have been conducted to investigate the effectiveness of minimally invasive SIJ fusion techniques. Amongst the various studies, several of the parameters measured included pain scores, disability indices, quality of life, patient satisfaction, and economical outcomes.

One of the simplest and most commonly used outcome instruments for assessing variations in pain is the visual analog scale (VAS) [86]. The VAS is obtained by marking on the patient a 100-mm line along which the patient indicates the intensity of the pain they are experiencing [112]. The scoring of the VAS typically ranges from 0 to 100, though it can also be expressed between 0 and 10. Due to its high degree of reliability, validity, and responsiveness, the VAS is a widely utilized instrument for gauging pre- to post-treatment outcomes [113-115].

Another commonly used measure of pain and disability is the Oswestry Low Back Pain Disability Index (ODI), which is a self-rating questionnaire that measures a patient’s degree of functional impairment. Advantageous aspects that make the ODI a popular outcome instrument include the ease of administration and the short amount of time
needed to complete and evaluate. Another commonly used questionnaire that measures health-related quality of life is the Medical Outcomes Short Form-36 Health-Status Survey (SF-36), which is comprised of eight separate scales, along with a standardized mental component scale (MCS) and physical component scale (PCS) [113]. While the SF-36 consists of 36 questions, a shorter, yet still valid version known as the SF-12 has been adapted to have only 12 questions [116]. The short form surveys allow for assessment of a patient’s quality of life from the health care recipient’s point of view [113].

2.12.1. Clinical Studies

Wise et al. [117] performed percutaneous posterior minimally invasive SIJ fusion for 13 consecutive patients to assess the outcome of this technique within 24 to 35 months follow-up. It was shown that the total fusion rate was 89% and there was a significant improvement in pain scores. After Wise, a new percutaneous lateral SIJ arthrodesis technique using a Hollow Modular Anchorage screw was introduced by Al-khayar et al. [118]. No one had not combined MIS method and bone grafting for SIJ fusion before Al-khayar. Nine patients underwent surgery with two years follow-up, and it was shown that the VAS score fell from 8.1 Pre-operation to 4.6 post-operation. This new technique provided a safe and successful fusion for SIJ pains. Hollow modular anchorage screw was also utilized by Khurana et al. [119] for 15 patients during 9 to 39 months follow-up. They observed good results regarding pain score improvement and concluded that this method is a suitable surgery process for SIJ fusion. Mason et al. [120] did a study using
this fixation system for 55 patients within 12-84 months follow-up. This fusion resulted in reduced VAS score from 8.1 to 4.5 and improved pain.

As one key focus of the medical field is the improvement of surgical procedures and the discovery of novel treatment approaches, various studies have been performed to further confirm the important trend toward less invasive arthrodesis procedures.

Among the different techniques for minimally invasive SIJ fusion, perhaps the most popular fusion system involves triangular titanium implants with a porous titanium plasma spray coating. The shape, coating, and interference fit of these implants allow for initial stabilization or mechanical fixation, and then effective stabilization of the joint is eventually achieved from long-term biological fixation [20,24,26]. They have various unique features which make them different than traditional cages and screws. Due to their design, an interference fit was provided to allow them the proper fixation. Their triangular profile reduces implant rotation significantly, and their porous surface minimizes the implant micromotion and enhances bone ingrowth resulting in better fusion. Biomechanical studies showed that 8mm cannulated screw is three times weaker in shear and bending than a triangular implant (Figure 2-8). In this fusion system, no grafts are placed in the sacroiliac joint; therefore all fusions are obtained by their porous coating [121].

During a minimally invasive SIJ fusion, the patient is administered general anesthesia and is placed in the prone position to use intraoperative fluoroscopy [4,20,26]. A 3 cm lateral incision is then made in the buttock region, and the gluteal fascia is penetrated and dissected to reach the outer table of the ilium. A Steinmann pin is then passed through the ilium across the SI joint to the middle of the sacrum and lateral to the neural foramen.
A soft tissue protector is inserted over the pin, and a drill is utilized to create a pathway and decorticate the bone. Upon removal of the drill, a triangular broach is malleted across the joint to prepare the triangular channel for the first implant. Finally, using a pin guidance system, the implants can be placed, which is followed by irrigation of the incision and closure of the tissue layers [4,20,26,122,123].

Figure 2-8: Triangular titanium implant with porous coating-Lateral approach [121]

A prospective study by Duhon et al. [122] was conducted to determine the safety and effectiveness of MIS fusion with a follow-up duration of 6 months. In this study, the safety cohort consisted of 94 subjects while the effectiveness cohort consisted of 32 subjects, 26 of which were available for postoperative follow-up at six months. According to the results, mean SI joint pain at baseline was about 76, while the 6-month follow-up pain score was approximately 29.3, indicating an improvement of about 49 points. Furthermore, the mean ODI at baseline was about 55.3 and decreased to approximately 38.9 points, showing an improvement of about 15.8 points. To determine the 6-month outcome of quality of life, this study incorporated Short Form-36 (SF-36)
PCS and MCS questionnaires. The results from this study revealed that the SF-36 PCS and SF-36 MCS improved by about 6.7 and 5.8 points, respectively. Finally, patient satisfaction was assessed and recorded to be approximately 85%, a rather high rate of satisfaction.

A similar study was conducted by Cummings and Capobianco [124], except with a longer follow-up duration of one year involving 18 subjects. Similarly, the parameters measured were pain score, disability index for back functionality, quality of life via Short Form-12 questionnaires, and patient satisfaction. Upon a 12-month follow-up, the results of this study revealed an improvement in VAS pain score of about 6.6 points, ODI improvement of -37.5 points, and SF-12 PCS and SF-12 MCS improvements of 11.19 and 20.37 points, respectively. Similar to the study by Duhon et al. [84], patient satisfaction was again rather high with a value of 95% satisfaction and 89% of patients claiming that they would undergo the same surgery again.

A study by Sachs and Capobianco [4] was performed to investigate the successful outcomes for minimally invasive arthrodesis after a one-year follow-up duration for the first 11 consecutive patients who underwent MIS SIJ fusion using triangular porous plasma coated titanium implants by a single surgeon. At baseline, the mean pain score was approximately 7.9, which decreased to about 2.3 after 12 months. This improvement in mean pain score of about 6.2 points from baseline was considered clinically and statistically significant, and patient satisfaction was immensely high with 100% of subjects claiming that they would again undergo the same surgery.

Sachs and Capobianco [123] also conducted a retrospective one-year outcome analysis of MIS SIJ fusion in 40 patients. The parameters measured in this study
primarily involved pain score changes and patient satisfaction; postoperative complications were also taken into consideration. The pain scores in this study were measured on a numerical rating scale (NRS) from 0 to 10, with 10 indicating the highest amount of pain. At baseline, the mean pain score was approximately 8.7, while at follow-up of 12 months, the average pain score decreased to about 0.9, indicating an improvement of approximately 7.8 points. According to the results, patient satisfaction was highest in this study with a value of 100% of the subjects declaring that they would undergo the same surgery again.

It is shown that lumbosacral fusion is contributed to 75% of SIJ degeneration [125]. Schroeder et al. [126] performed a clinical study on six patients who had SIJ fusion besides long fusions ending in sacrum with the 10.25 months average follow-up. SIJ fixation improved the results of all scores like Leg VAS score, Back VAS score, SRS 22, and also ODI score from 22.2 to 10.5. They indicated that the SIJ fixation in patients with long fusions results in back pain reduction. The SIJ fusion was achieved by using titanium triangular implants within the follow-up which led to minimized rotation and micromotion due to osteogenic interference fit used in this study and not having implant loosening and breakage. Long fusions to the sacrum are providing increased motion and force at the SIJ resulting in an increase in SIJ pain [26, 125]. Unoki et al. [127] reported a retrospective study to determine the effect of multiple segment fusion on the incidence of SIJ pain for 262 patients. It was indicated that multiple segment fusion (at least three) could enhance the incidence of SIJ pain. Another clinical study conducted by Shin et al. [128] indicated that greater pelvic tilt and insufficient restored lumbar lordosis by far play a role in generating SIJ pain after PLIF surgery.
While the effectiveness and safety of minimally invasive fusion of the SIJ have been reported to be significant over the duration of 6 and 12 months, studies of longer follow-up durations have been conducted to confirm the long-term success of these implants. A study by Duhon et al. [129] was carried out to determine the long-term results over a 2-year follow-up duration from a prospective multicenter clinical trial. Similar to the 6-month study by Duhon et al. [122], this analysis also measured parameters of SIJ pain rating, ODI, Short Form-36 PCS and MCS, and patient satisfaction. According to their results, SIJ pain decreased from a baseline value of 79.8 to 26.0 after two years, and the ODI decreased from 55.2 at baseline to 30.9 at two years. Furthermore, SF-36 PCS and MCS improved by approximately 8.9 and 10.1 points, respectively, and 88.5% of subjects reported decreased pain at follow-up of two years [129]. A similar two-year retrospective follow-up study of 45 subjects was conducted by Rudolf [26], which reported a mean pain score improvement of approximately 5.9 points and an 82% patient satisfaction rate.

To further investigate and confirm the previous findings of the effectiveness and safety of minimally invasive fusion procedures, Rudolf and Capobianco [130] conducted a 5-year clinical and radiographic outcome study of 17 patients treated with MIS SIJ fusion for degenerative sacroiliitis and sacroiliac joint disruptions. The parameters measured in this study include pain on a visual analog scale (VAS) from 0 to 10, mean ODI score, and patient satisfaction. The results of this study revealed an improvement in VAS pain score from 8.3 at baseline to 2.4 after five years, with a patient satisfaction rate after one year of 82%. While a preoperative mean ODI score was not reported, the reported mean ODI score at the 5-year follow-up was approximately 21.5.
Regardless of the duration of follow-up time and the parameters measured, the numerous studies of the outcomes of MIS SI joint fusion reveal that fusion of the SIJ via minimally invasive approaches with triangular titanium implants can be considered a safe and efficient option for treatment of SIJ pain [4,26,121,122,123,124,129,130]. A comparison of the studies performed and the outcomes of MIS SIJ fusion are shown in Table 2.6.

Table 2.6. SIJ fusion with triangular implants outcome reports

<table>
<thead>
<tr>
<th>Study</th>
<th>Patients Included</th>
<th>Prior Lumbar Fusion</th>
<th>Follow-up Duration</th>
<th>Pain Score Improvement</th>
<th>Patient Satisfaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sachs †, 2012</td>
<td>11(10F/1M)</td>
<td>18%</td>
<td>12 Months</td>
<td>70%</td>
<td>100%</td>
</tr>
<tr>
<td>Rudolf 26, 2012</td>
<td>50 (34F/16M)</td>
<td>44%</td>
<td>12 Months</td>
<td>56%</td>
<td>82%</td>
</tr>
<tr>
<td>Rudolf 131, 2013</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18 (12F/6M)</td>
<td>No Prior Fusion</td>
<td>24 Months</td>
<td>80%</td>
<td>89%</td>
<td></td>
</tr>
<tr>
<td>15 (11F/4M)</td>
<td>Prior Lumbar Fusion</td>
<td>24 Months</td>
<td>73%</td>
<td>92%</td>
<td></td>
</tr>
<tr>
<td>7 (3F/4M)</td>
<td>Prior Lumbar Pathology Treated Conservatively</td>
<td>24 Months</td>
<td>63%</td>
<td>63%</td>
<td></td>
</tr>
<tr>
<td>Schroeder 126, 2013</td>
<td>6 (6F/0M)</td>
<td>100%</td>
<td>10.25 Months (4-15)</td>
<td>61%</td>
<td>100%</td>
</tr>
<tr>
<td>Gaetani 132, 2013</td>
<td>12 (12F/0M)</td>
<td>8.3%</td>
<td>10 Months (8-18)</td>
<td>4</td>
<td>100%</td>
</tr>
<tr>
<td>Cummings 124, 2013</td>
<td>18 (12F/6M)</td>
<td>61%</td>
<td>12 Months</td>
<td>74%</td>
<td>95%</td>
</tr>
<tr>
<td>Name</td>
<td>Year</td>
<td>Sample Size</td>
<td>Follow-Up</td>
<td>Pain Relief 6 Months</td>
<td>Pain Relief 12 Months</td>
</tr>
<tr>
<td>-----------------------</td>
<td>------</td>
<td>-------------</td>
<td>-----------</td>
<td>----------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>Sachs</td>
<td>2013</td>
<td>40 (30F/10M)</td>
<td>30%</td>
<td>90%</td>
<td>100%</td>
</tr>
<tr>
<td>Duhon</td>
<td>2013</td>
<td>32 (21F/11M)</td>
<td>69%</td>
<td>67%</td>
<td>85%</td>
</tr>
<tr>
<td>Graham-Smith</td>
<td>2013</td>
<td>114 (82F/32M)</td>
<td>47.4%</td>
<td>79%</td>
<td>82%</td>
</tr>
<tr>
<td>Kim</td>
<td>2013</td>
<td>31 (24F/7M)</td>
<td>48%</td>
<td>90%</td>
<td></td>
</tr>
<tr>
<td>Ledonio</td>
<td>2014</td>
<td>17 (11F/6M)</td>
<td>82%</td>
<td>78%</td>
<td>94%</td>
</tr>
<tr>
<td>Ledonio</td>
<td>2014</td>
<td>22 (17F/5M)</td>
<td>64%</td>
<td>54% (12-26)</td>
<td>73%</td>
</tr>
<tr>
<td>Sachs</td>
<td>2014</td>
<td>144 (102F/42M)</td>
<td>62%</td>
<td>68%</td>
<td>80%</td>
</tr>
<tr>
<td>Rudolf</td>
<td>2014</td>
<td>17 (13F/4M)</td>
<td>47%</td>
<td>71%</td>
<td>82%</td>
</tr>
<tr>
<td>Vanaclocha</td>
<td>2014</td>
<td>24 (15F/9M)</td>
<td>8%</td>
<td>43%</td>
<td>89%</td>
</tr>
<tr>
<td>Whang</td>
<td>2015</td>
<td>102 (75F/27M)</td>
<td>38%</td>
<td>63%</td>
<td>79%</td>
</tr>
<tr>
<td>Duhon</td>
<td>2015</td>
<td>172 (120F/52M)</td>
<td>44.2%</td>
<td>67%</td>
<td>78%</td>
</tr>
<tr>
<td>Polly</td>
<td>2015</td>
<td>102 (75F/27M)</td>
<td>38%</td>
<td>83%</td>
<td>73%</td>
</tr>
<tr>
<td>Sturesson</td>
<td>2016</td>
<td>52 (38F/14M)</td>
<td>N/A</td>
<td>55%</td>
<td>55%</td>
</tr>
</tbody>
</table>

While pain scores, disability indices, and quality of life questionnaires have served as important measures for determining the long-term effects of SI joint fusion procedures,
other studies have been conducted to investigate the success of such operations from a unique perspective involving work productivity and economic concerns.

One study conducted by Saavoss et al. [25] analyzed the productivity benefits for patients with chronic SIJ dysfunction to compare worker function and economic outcomes between non-surgical management and MIS SIJ fusion. The importance of this study was to determine the impact of arthrodesis on worker productivity, a relationship which has not been previously examined. According to their results, patients who underwent MIS SIJ fusion were expected to have an increase in the probability of working for 16% compared to patients who received nonsurgical management, and the expected difference in earnings amongst the groups was deemed to be not statistically significant with a value of approximately $3,128. When the metrics of working probability and expected change in earnings were combined, the annual increase in worker productivity between patients receiving MIS SIJ fusion and those receiving nonsurgical management was estimated to be approximately $6,924.

SI-LOK is another MI SIJ fixation system which locates three hydroxyapatite-coated screws across the sacroiliac joints laterally (Figure 2-9). There are an optional bone graft slots inside the screw which can be used to enhance fusion. Also, the optional lag screw thread allows applying compression force during placement [121]. There is no biomechanical study on this screw yet.
SImmetry is another cannulated titanium screw type SIJ fixation system which usually is used with two screws (one is anti-rotation screw) laterally across the SIJ (Figure 2-10). There is no bone graft slot in this system, and the bone graft is placed across the articular part of the joint [121]. This surgery technique is defined comprehensively in [143]. Zyga company is performing a study with one-year follow-up.
SIFix is one of the posterior MI SIJ fixation systems which use two threaded cancellous bone to stabilize the joint. This method can be done bilaterally with a single midline incision (Figure 2-11).

Beck et al. [144] conducted posterior fusion surgery utilizing RI-ALTO implants for 20 patients during 17-45 months follow-up. The fusion rate and satisfaction ratings were 97% and 76%, respectively. It was shown that this method is safe and effective in SIJ fusion and reduces surgical morbidity due to posterior approach (Figure 2-12).

From significantly successful reports of surgical outcomes, patient satisfaction, recovery rate, and implant survivorship, minimally invasive procedures have now become the predominant focus for treating patients with chronic SIJ pain.
2.12.2. In Vitro and In Silico Studies

Soriano-Baron et al. [135] conducted a cadaver study to investigate the effect of placement of sacroiliac joint fusion implants which were triangular implants. Nine human cadaveric specimens from L4-pelvis were used to perform the range of motion testing for one leg stance under three conditions: intact, cut pubic symphysis to allow the right and left SI joints to move freely, and treated. The treated condition was performed using two different approaches for SIJ fusion implant placement which were posterior and trans-articular techniques. In the posterior procedure, the three implants were placed inline in the inlet view, and parallel in the outlet and lateral views. In the trans-articular approach, the superior and inferior implants were placed similar to the posterior technique, and the middle implant was positioned toward the anterior third of the sacrum across the cartilaginous portion of SI joint. The 7.5 N.m pure moment was applied to simulate the flexion, extension, lateral bendings, and axial rotations under one-leg stance condition.
They showed that placement of three implants in both approaches significantly reduced the ROM in all motions. Interestingly, there was no significant difference between these two techniques regarding motion reduction [22].

Hammer et al. [145] using finite element analysis showed that SIJ cartilage and ligaments are playing a significant role in pelvic stability. By increasing in SIJ cartilage and ISL, IL, ASL, and PSL stiffness would decrease the pelvic motion with highest strains at ISL, and pubic ligaments have the least effect on the pelvic motion. These ligaments are contributed to transferring loads horizontally at the acetabulum and ilium. In contrast, increasing stiffness of SS and ST have opposite effect increasing the pelvic motion, and they are doing vertical load transfer followed by sacrum translation. Moreover, in standing position, the ligaments strain is higher than sitting position.

Eichenseer et al. [45] also evaluated the correlation between ligaments stiffness and SIJ stress and motion. They showed that by decreasing ligaments stiffness, stress, and motion at SIJ would increase. Moreover, ISL has the highest strains under different spine motions which confirmed the finding of Hammer’s study.

Mao et al. [146] investigated the effect of lumbar lordosis alteration on sacrum angular displacement after lumbosacral fusion. Decreasing and increasing lumbar lordosis result in increased sacrum angular motion. In addition, fusion at L4-S1 level is providing higher sacrum angular displacement compared to L3-L5 level. Therefore, it can be the reason why SIJ degeneration incidence is higher in fusions at S1 rather than L5.

Lindsey et al. [21] assessed the range of motion of SIJ and the adjacent lumbar spinal motion segments after SIJ fusion using triangular implants via finite element analysis. They evaluated the ROM of their model which was L3- Pelvis under 10 Nm moment to
simulate flexion, extension, lateral bendings and, axial rotation. They showed that SIJ fusion using three triangular implants provided a significant reduction in SIJ motion in all six motions. Moreover, SIJ motion reduction by fusion resulted in least increase in adjacent lumbar segment motion.

Bruna-Rosso et al. [147] used finite element method to analyze SIJ biomechanics under RI-ALTO fusion implant which is a new sacroiliac fusion device. 1000 N compression load was applied to the pelvis to simulate the experimental test. They evaluated the effect of number of implants (one and two implants) and their placement at SIJ. Proximally insertion of the implant which was farther from SIJ center of rotation was more efficient than distally insertion of the implant. Proximally insertion of one implant even had better performance than using two implants in terms of motion reduction. There is no significant difference in providing stability between two trajectory of placement which was medial and oblique for using one implant instrumentation, although medial placement provided higher stability compared to oblique in two implant instrumentation. Overall, the more parallel and farther from SIJ center of rotation implant inserted, the more stability is provided.

Lindsey et al. [148] performed another finite element study on SIJ fusion with triangular implants to assess the biomechanical effects of length, orientation, and number of implants under all six spine motions. The variables were: one, two, and three implants, superior implant length of 55 mm and 75 mm, midline implant length of 45 mm, and inferior implant length of 45 mm for inline orientation and 50 mm for trans-articular orientation. They showed that the trans-articular orientation provided better fixation compared to inline orientation due to crossing more the cartilaginous portion of SIJ,
although Soriano-Barron revealed that there was no significant difference between these two approaches. Using longer superior implant led to more reduced SIJ motion under different spine motions. In addition, placing two implants close together is less stable than two implants far from each other. In overall, placing implants in the thicker cortical bone areas and a more dense bone region is providing more stability.

A finite element analysis was conducted by Kiapour et al. [149] to quantify the changes in load distribution through the SIJ as a result of LLD. In this study, the peak stresses and contact loads across the SIJ were measured for leg length discrepancies of 1, 2, and 3 cm. The results showed that the peak loads and stresses of both legs were always higher than that of the intact model, with a greater magnitude consistently occurring on the longer leg side. Furthermore, as the length discrepancies increased from 1 cm to 3 cm, the stresses increased accordingly.

Zhang et al. [150] studied the biomechanical stability of four different SI screw fixation under two types of SI dislocation using finite element method. They placed implants at SIJ in four different configurations: Single screw in S1, single screw in S2, two screws in S1, and one screw in S1 and another one in S2. Then biomechanical analysis of implanted pelvis was done under inferior translation, flexion, and lateral bending. In type B dislocation, except LPS and SPS ligaments, all ligaments are damaged, and in type C, all ligaments are damaged. The weakest placement configuration was the single screw in S2 in both injury types due to placement farther from S1 end plate which confirmed the study of Bruna-Rosso. Two screws at S1 and S2 were the strongest placement compared to placing two screws closely in S1 in both dislocation types which is in contrast of finding by Bruna-Rosso.
Ivanov et al. [30] evaluated sacrum angular motion and stress across SIJ after lumbar fusion. Fusion was performed at different levels of L4-L5, L5-S1, and L4-S1. They showed that lumbar fusion would result in an increase of SIJ motion and stress across SIJ. L4-S1 level fusion provided the greatest SIJ motion and stress across SIJ compared to fusions at other levels.

Another study conducted by Lindsey et al. [24] investigated the outcomes of minimally invasive SIJ fusion from an in vitro biomechanical approach, comparing the initial and cycled properties. Because the goal of fusion is a reduction in joint motion, the effectiveness of the implants was measured by joint motion properties in flexion-extension, lateral bending, and axial rotation. The results of this study revealed a significant decrease in flexion-extension range of motion (ROM), and an insignificantly altered lateral bending and axial rotation in the treated specimen compared to the intact condition. Although deemed statistically insignificant, lateral bending and axial rotation were decreased in the majority of subjects, indicating that the implants effectively reduced joint motion in most of the specimens.

A recent study performed by Lindsey et al. [151] assessed experimentally how various implants placement variables such as orientation, caudal implant length, and number of the implants impact sacroiliac joint range of motion after treatment. It was shown that the implant placement is limited by anatomy and placement of 3 implants using trans-articular orientation penetrated to sacral midline provided the highest stability. In their recent study [23], they evaluated and compared the biomechanical impact of unilateral and bilateral triangular implant placement across the SI joint. They
found that the unilateral and bilateral SIJ fusion lead significant motion reduction across SIJ.

Lee et al. [152] investigated the biomechanics of intact and treated pelvis via FE and experimental analysis. The spine-pelvis-femur FE model included ligaments and muscles as truss elements. It was demonstrated that posterior iliosacral screw fixation provided higher stability and lower risk of implant failure compared to sacral bar fixation and a locking compression plate fixation.

Another study of the outcomes of MIS SIJ fusion unique from the previously conducted research involved the analysis of implant survivorship over a four-year duration [153]. While most of the prior studies on MIS fusion procedures incorporated pain and disability scores, quality of life questionnaires, and patient satisfaction, little research has been reported on the frequency of implant revision for MIS SIJ fusion surgeries. Furthermore, this study sought to determine whether a correlation existed between gender or age and the requirement for implant revision. According to their results, approximately 96.46% of subjects did not require implant revision after four years, and a revision rate correlation amongst sexes was not confirmed. Age, however, did appear to play a role in the requirement for implant revision, as the revision rate was lower for subjects older than 65. Furthermore, the cause for implant revision was investigated, and the results reported that the most common reasons for revision were symptomatic malposition (SM) with a rate of 38.4%, and symptom recurrence (SR) with a rate of 47.6%. It should be noted that over time, the 1-year revision rates improved with a rate of 9.7% in 2009 and 1.4% in 2014. Because of this trend, this study’s reported
revision rate of approximately 3.55% could be assumed to overestimate the actual four-year revision rate.
Chapter 3

Materials and Methods

A detailed FEM of the lumbo-pelvic model was built to assess the biomechanics of SIJ fixation and to evaluate the impact of instrumentation parameters.

3.1. Male Model- Finite Element Model of the Lumbar Spine and Pelvis

The previously developed and validated finite element lumbar spine model [21, 30] was used for the male model. The 3-dimensional (3D) pelvic geometry was generated using a 1 mm slice of computer tomography (CT) of a 55 year old male pelvis without any abnormalities, degeneration or deformation of the pelvis. The 3D reconstruction of spinopelvic models were done using MIMICS software (Materialise, Leuven, Belgium). After 3D reconstruction of bones and spinal discs, they were taken to the Geomagic Studio software (Raindrop Geomagic Inc., USA) to reduce noises, remove spikes, smooth surfaces, and create patches and grids to be prepared for meshing. Hypermesh software (Altair Engineering, Inc., USA) was used to mesh the pelvis. The model development process is summarized in the figure 3-1.
Lumbar spine and pelvic bones were modeled as trabecular cores surrounded by a cortical layer with a thickness of 1 mm [30, 147]. The linear hexahedral element type was utilized for cortical and cancellous bones of vertebrae well as for spinal discs. The element types of cortical and cancellous bones of the pelvis were defined as tetrahedral elements. The truss elements were employed for ligamentous tissues including for the sacroiliac joint and spine ligaments. 144,360 elements were generated for the male model.

3.2. Female Model- Finite Element Model of the Lumbar Spine and Pelvis

Computer tomography (CT) images of a 55 years old female’s spine and pelvis without any abnormalities, degeneration or deformation, were used to reconstruct the
female spinopelvic model. MIMICS software (Materialise, Leuven, Belgium) was utilized to build the 3D geometry of the bones and then spine discs were made by filling the space between each two vertebrae of CT images. Next, smoothing was carried out by Geomagic Studio software (Raindrop Geomagic Inc., USA) to be prepared for meshing. The spine discs were meshed using IAFEMESH software (University of Iowa, IA) and Hypermesh software (Altair Engineering, Inc., USA) was used to mesh the vertebrae and pelvis. Figure 3-2 shows the FE of male and female spine-pelvis-femur models.

Figure 3-2: a) FE model of male spine-pelvis-femur, b) FE model of female spine-pelvis-femur

1 mm thickness of cortical bone was made for vertebrae and pelvis cortical bones surrounding the cancellous bone. The linear hexahedral element type was utilized for
cortical bone of each vertebrae and spinal discs. Tetrahedral elements were assigned to the cancellous bone of both the vertebrae and the pelvis as well as the cortical bone of the pelvis. The truss elements were employed for ligamentous tissues including the sacroiliac joint and spine ligaments. The SIJ ligaments were anterior sacroiliac ligament (ASL), interosseous ligament (ISL), long posterior sacroiliac ligament (LPSL), short posterior sacroiliac ligament (SPSL), sacrospinous ligament (SSL), and sacrotuberous ligament (STL). A detailed view of the pelvis ligaments is shown in the figure 3-3. The model as a whole contained 463,735 elements for the female model.

![Figure 3-3: Anterior and posterior views of the pelvis finite element model. Ligaments are demonstrated in red. (interosseous ligament is not visible in this view) a) Anterior view, anterior sacroiliac ligament (ASL), b) Posterior view, long posterior sacroiliac ligament (LPSL), short posterior sacroiliac ligament (SPSL), sacrospinous ligament (SSL), and sacrotuberous ligament (STL).](image)

### 3.3. Material Properties
The material properties extracted from previous studies [21, 154] for cortical and cancellous bones, annulus, nucleus, ligaments, and joints were summarized in table 3.1, 3.2, 3.3, and 3.4. The same material properties were used for both male and female spinopelvic models. The sacroiliac joints, spine facets, articular cartilages, and pubic symphysis were modelled as non-linear soft contact. The contact between the femurs and the pelvis was defined as coupling. The cartilagous area of the sacrum and ilium are illustrated in figure 3-4.

![Figure 3-4: a) Sacral articular surface, b) ilium articular surface](image)

<table>
<thead>
<tr>
<th>Component</th>
<th>Material Properties</th>
<th>Constitutive Relation</th>
<th>Element Type</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertebral cortical bone</td>
<td>$E = 12000 , GPa$</td>
<td>Isotropic, elastic</td>
<td>8 Nodes brick element</td>
<td>Lindsey et al.</td>
</tr>
<tr>
<td></td>
<td>$v = 0.3$</td>
<td></td>
<td>(C3D8)</td>
<td></td>
</tr>
<tr>
<td>Component</td>
<td>Material Properties</td>
<td>Constitutive Relation</td>
<td>Element Type</td>
<td>Reference</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>---------------------</td>
<td>-----------------------</td>
<td>----------------------------------------</td>
<td>--------------------</td>
</tr>
</tbody>
</table>
| Ground substance of annulus fibrosis (male model) | $C_{10} = 0.3448$  
$D_1 = 0.3$ | Hyperelastic, neo-Hookean | Rebar | Lindsey et al. |
| Ground substance of annulus fibrosis (female model) | $C_{10} = 0.035$  
$K_1 = 0.296$  
$K_2 = 65$ | Hyperelastic anisotropic (HGO) | 8 Nodes brick element (C3D8) | Shahraki et al. |
<table>
<thead>
<tr>
<th>Component</th>
<th>Material Properties</th>
<th>Constitutive Relation</th>
<th>Element Type</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td><strong>Nucleus Pulposus</strong></td>
<td>$E = 1\ GPa$</td>
<td>Isotropic, elastic</td>
<td>8 Nodes brick element (C3D8)</td>
<td>Lindsey et al.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Material Properties</th>
<th>Constitutive Relation</th>
<th>Element Type</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior Longitudinal</td>
<td>7.8 (&lt;12%), 20 (&gt;12%)</td>
<td>Non-linear Hypoelastic</td>
<td>Truss element (T3D2)</td>
<td>Lindsey et al.</td>
</tr>
<tr>
<td>Posterior Longitudinal</td>
<td>10 (&lt;11%), 20 (&gt;11%)</td>
<td>Non-linear Hypoelastic</td>
<td>Truss element (T3D2)</td>
<td>Lindsey et al.</td>
</tr>
<tr>
<td>Ligamentum Flavum</td>
<td>15 (&lt;6.2%), 19.5 (&gt;6.2%)</td>
<td>Non-linear Hypoelastic</td>
<td>Truss element (T3D2)</td>
<td>Lindsey et al.</td>
</tr>
<tr>
<td>Intertransverse</td>
<td>10 (&lt;18%), 58.7 (&gt;18%)</td>
<td>Non-linear Hypoelastic</td>
<td>Truss element (T3D2)</td>
<td>Lindsey et al.</td>
</tr>
<tr>
<td>Interspinous</td>
<td>10 (&lt;14%), 11.6 (&gt;14%)</td>
<td>Non-linear Hypoelastic</td>
<td>Truss element (T3D2)</td>
<td>Lindsey et al.</td>
</tr>
<tr>
<td>Supraspinous</td>
<td>8 (&lt;20%), 15 (&gt;20%)</td>
<td>Non-linear Hypoelastic</td>
<td>Truss element (T3D2)</td>
<td>Lindsey et al.</td>
</tr>
<tr>
<td>Capsular</td>
<td>7.5 (&lt;25%), 32.9 (&gt;25%)</td>
<td>Non-linear Hypoelastic</td>
<td>Truss element (T3D2)</td>
<td>Lindsey et al.</td>
</tr>
<tr>
<td>Anterior SIJ</td>
<td>125(5%), 325(&gt;10%), 316(&gt;15%)</td>
<td>Non-linear Hypoelastic</td>
<td>Truss element (T3D2)</td>
<td>Lindsey et al.</td>
</tr>
<tr>
<td>Short posterior</td>
<td>43(5%), 113(&gt;10%)</td>
<td>Non-linear</td>
<td>Truss element</td>
<td>Lindsey et al.</td>
</tr>
<tr>
<td>Component</td>
<td>Material Properties</td>
<td>Constitutive Relation</td>
<td>Element Type</td>
<td>Reference</td>
</tr>
<tr>
<td>----------------------</td>
<td>---------------------</td>
<td>-----------------------</td>
<td>----------------</td>
<td>----------------</td>
</tr>
<tr>
<td><strong>SI</strong></td>
<td>110(&gt;15%)</td>
<td>Hypoelastic</td>
<td>(T3D2)</td>
<td></td>
</tr>
<tr>
<td><strong>Long posterior</strong></td>
<td>150(5%), 391(&gt;10%), 381(&gt;15%)</td>
<td>Non-linear Hypoelastic</td>
<td>Truss element (T3D2)</td>
<td>Lindsey et al.</td>
</tr>
<tr>
<td><strong>SI</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Intraosseus</strong></td>
<td>40(5%), 105(&gt;10%), 102(&gt;15%)</td>
<td>Non-linear Hypoelastic</td>
<td>Truss element (T3D2)</td>
<td>Lindsey et al.</td>
</tr>
<tr>
<td><strong>Sacrospinous</strong></td>
<td>304(5%), 792(&gt;10%), 771(&gt;15%)</td>
<td>Non-linear Hypoelastic</td>
<td>Truss element (T3D2)</td>
<td>Lindsey et al.</td>
</tr>
<tr>
<td><strong>Sacrotuberous</strong></td>
<td>326(5%), 848(&gt;10%), 826(&gt;15%)</td>
<td>Non-linear Hypoelastic</td>
<td>Truss element (T3D2)</td>
<td>Lindsey et al.</td>
</tr>
</tbody>
</table>

**Table 3.4: Joints properties**

3.4. **Mesh Convergence Study**
A mesh convergence analysis was performed on the female model to identify the appropriate mesh seed size which would result in accurate predictions of biomechanical parameters by the FE model. The mesh convergence analysis was done on the segregated L4-L5 motion segment of the female model. An initial seed size was assigned and the model was subjected to 7.5Nm bending moment; the range of motion was measured in all anatomical planes. The mesh was refined, the analysis was repeated and the results were compared with the model that had coarser mesh. The mesh refined was repeated until the difference in range of motion in all planes was below 4%. The mesh convergence was achieved following four iterations. The simulation was ran using ABAQUS 6.14 software (Abaqus, Inc., Providence, RI, USA).

3.5. Finite Element Model Validation

The validation study was performed by simulation of previous cadaver studies on an intact spine and sacroiliac joint with the same loading and boundary condition. Range of motion values of spine levels and sacroiliac joints were compared with the results which were reported in literature.

The female lumbar spine was validated with Panjabi et al [155]. The boundary condition was simulated as both hip joints were fixed. A 7.5 Nm moment was applied to the L1 top endplate to represent spinal motions in different anatomical planes in addition to a 100 N follower load tangential to each functional spinal units.

To validate the sacroiliac joints range of motion for intact male and female models, a cadaver study done by Lindsey et al. [24] was simulated. This experiment was carried out
for intact L5 to pelvis of the male and female specimens using triangular implants under single leg stance condition. A 7.5 Nm pure moment load was applied to the top endplate of L1 in spine six motions. In this test, the left leg was fixed and the right leg was free to move. After simulating the experiment loading and boundary conditions for the male and female models separately, the range of motion of the left and right sacroiliac joints were calculated for each model to be compared with the test data. The motion at the SIJ was calculated using the angular displacements at the sacrum minus those at the ilium for both right and left joints.

3.6. SIJ Instrumentation Modelling

After testing the intact condition, some portions of the interosseous ligaments were removed as an injury made at the left side of the joint. For the treated condition, SIJ implants were placed across the left joint. Three different types of implants were utilized for the unilateral SIJ fusion which are shown in the figure 3-5.

The First implant which was triangular implant had a 7 mm diameter for the inside cylinder and 10 mm of height for the triangle. In this technique, 3 implants were placed laterally into the left SI joint, inline in the inlet view, parallel in the outlet view, and parallel in the sagittal view. Briefly, the cranial implant was placed parallel to the S1 endplate and above the S1 neuroforamen. The middle (second) and caudal (third) implants were inserted parallel to the cranial implant (Figure 3-6). The material properties of the implants were Ti6Al4V (E=113 GPa, ν = 0.3) [21]. The implants lengths were: superior, 55 mm; middle, 45; inferior, 50 mm.
Figure 3-5: Three types of sacroiliac joint fusion implants used in the FE simulation. Implant 1: Triangular implant; implant 2: fully threaded screw; implant 3: half threaded screw

The second implant was a fully threaded screw with a diameter of 10 mm. In this technique, 3 implants were positioned posteriorly into the left SI joint. The cranial
implant was inserted from posterior superior iliac spine to the sacrum at 15 degrees lateral to medial. The middle (second) and caudal (third) implants were located parallel to the cranial implant (Figure 3-7). The material properties of the implants were Ti6Al4V (E=113 GPa, ν = 0.3) [21]. The implants lengths were: superior, 55 mm; middle, 55; inferior, 45 mm.

The third implant was a half threaded screw with a diameter of 10 mm. This approach also followed the same placement as implant 1. 3 implants were inserted laterally into the left SI joint and parallel to one another (Figure 3-8). The material properties of the implants were Ti6Al4V (E=113 GPa, ν = 0.3) [21]. The implants lengths were: superior, 55 mm; middle, 45; inferior, 50 mm.

Figure 3-6: Trajectory of lateral placement of implant 1 into the pelvis. a) Posterior view, b) Lateral view
Figure 3-7: Trajectory of posterior placement of implant 2 into the pelvis. a) Posterior view, b) Lateral view

Figure 3-8: Trajectory of lateral placement of implant 3 into the pelvis. a) Posterior view, b) Lateral view
To study the bilateral SIJ fusion, both right and left SI joints were fused by having 3 implants inserted at each joint (3 implants across the right side; 3 implants across the left side) (Figure 3-9, 3-10, and 3-11).

Figure 3-9: Bilateral placement of implant 1 into the pelvis.

Figure 3-10: Bilateral placement of implant 2 into the pelvis.
The effect of implant number for all three types of implants was investigated. Typically, three implants are placed across each joint. For this study either 1 or 2 implants were placed. All six potential instrumented combinations were simulated.

Implants were totally fixed at the pelvis bone and tie constraints were used to represent the contact between the bone and implants.

3.7. Simulation of Post-partum Period

To simulate the effect of post-partum period, the intact female model geometry was modified to mimic the anatomical and physiological changes of the pelvis after delivery. Two changes were made in the pelvis to create a post-partum female model. First, the pubic symphysis gap was increased from 3 mm to 10 mm. To increase the gap, two opposite displacement boundary conditions were applied to both sides of the pubic region to generate a 10 mm pubic gap. Second, the ligaments laxity across the pelvis was made to simulate the physiological changes happening to the pelvis ligaments after delivery.
Initially, a model with healthy ligaments was simulated and the load-displacement curve of each ligament was shifted to simulate 5% and 10% of ligament laxity. The never-pregnant and post-partum FE models are shown in the figure 3-12.

Figure 3-12: a) never-pregnant FE model with 3 mm pubic gap (intact female model), b) post-partum FE model with 10 mm pubic gap

3.8. Loading and Boundary Conditions

Following the preparation of the intact and instrumented male and female lumbo-pelvic segments, a set of simulations were performed by applying anatomical equivalent load to lumbar spine on the double legged stance configurations. To constrain the model, acetabulum was fixed in all degrees of freedom in both models to prevent relative displacement of the legs (Figure 3-13). In all models, a 400 N compressive follower load was applied through wire elements which followed the curvature of the lumbo-pelvic segment. The follower load was defined to simulate the effect of muscle forces and
weight of the upper trunk. Another 400 N compressive force was applied to the sacral base as a concentrated force to mimic the effect of body weight and muscle forces on the pelvis and femur. A 10 Nm bending moment was then applied at the superior surface of the L1 vertebrae to simulate the physiological flexion, extension, lateral bending, and axial rotation (Figure 3-14) [21, 30].

Figure 3-13: Spine-pelvis-femur FE with constrained area

Figure 3-14: Loading and boundary condition simulated in the FE analysis
3.9. Data Analysis

3.9.1. Spine and SIJs Range of Motion Analysis

The range of motion between each level of vertebral bodies was computed using the angular displacement of the upper vertebral body minus the counterparts at the lower vertebral body. The angular displacements were calculated as a motion relative to a coupled reference point in the middle of each vertebral body. During flexion and extension, only the angular displacement within the sagittal plane was considered. For bending, motion in the frontal plane was recorded. For rotation, motion was recorded within the transverse plane. The motion at SIJ was calculated using the angular displacements at the sacrum minus those at the ilium for right and left joints. For the instrumented models of the male and the female, the sacroiliac joints and spinal range of motion were calculated and then compared to the intact condition to study the biomechanical differences of genders. In addition, the SIJ range of motion of the post-partum female model was compared with the intact female model.

3.9.2. SIJ and Implants Stress Analysis

The maximum von Mises stresses across the SIJ for each of the models were analyzed. For each model, the articular surfaces of the sacrum and ilium on each side were intersected to record the maximum stress. The maximum von Mises stresses data for each motion as well as the contours of stresses were shown for each implant. Moreover, the maximum von Mises stress across the SIJ for the post-partum female model was compared with the intact female model.
3.9.3. Pelvis Ligaments Strain Analysis

The average of the maximum principal strain was calculated for all six ligaments of the pelvis in the intact male and female models, and the post-partum female model. For each motion, the average strain of different ligaments was compared to each other for both genders.

3.9.4. SIJ Load Sharing Analysis

The normal and shear loads were calculated across the each side of the SI joint. Each normal and shear load on both the right and left sacrum and ilium were called out. The normal and shear loads for both sides of each sacrum and ilium were then averaged separately. This data was recorded for the intact male and female models and post-partum female model.
Chapter 4

Results

4.1. Overview

This chapter covers the results of the FE analysis beginning with ROM validation results for spine and SIJ for both genders, followed by the ROM, stress, strain, and load sharing summarized data for each intact and treated group.

4.2. Finite Element Analysis Validation

In order to validate the FE models of male and female spine and SIJ, range of motion results of the in vitro experiments for intact conditions were compared to those derived from the FE models.

The male spine FE model was previously validated against experimental data. Figure 4-1 shows the validation results for the female spine (L1-L5) FE model. The FE ROM values obtained during the different loading conditions of 7.5 N.m pure moment to simulate flexion, extension, left bending, right bending, left rotation, and right rotation with a 100 N preload are compared with study done by Panjabi et al. [155]. The FE output lies within standard deviations for all loading modes.
Figure 4-1: Validation results for the intact female lumbar spine at 7.5 N.m moment with 100 N preload

The validation graph for the male and female intact SIJ FE models is illustrated in Figure 4-2. The SIJ ROM values were obtained for both SIJ sides by applying 7.5 pure moment to L5-Plevis model under one-leg stance condition.
Figure 4-2: Validation results for the intact female and male sacroiliac joints (right and left sides) at 7.5 N.m moment under one-leg stance condition.

These data were compared to in vitro study performed by Lindsey et al. [24] for both genders. FE model predictions in all physiological loading fell within standard deviations of the experimental data. We can conclude that the male and female spinopelvic models behave close to experiments under different physiological motions.

4.3. Intact SI Joint Biomechanics

In this section, only the data for the intact male and female models are discussed. This section is broken up into four parts: range of motion, stress across the SIJ, SIJ ligaments strain, and load sharing across the SI joint.

4.3.1. Range of Motion

Male and female spine (L1-S1) ROM data at 10 N.m are shown for each of the loading conditions (flexion, extension, left bending, right bending, left axial rotation, right axial rotation with a 400 N preload) in Figure 4-3 and 4-4.
Figure 4-3: Intact female lumbar spine ROM at 10 N.m moment with 400 N follower load under two-leg stance condition

Lumbar Spine ROM-Intact Male Model (L1-S1)

![Graph showing lumbar spine ROM for an intact male model with different movements and their respective ROM values.]

Figure 4-4: Intact male lumbar spine ROM at 10 N.m moment with 400 N follower load under two-leg stance condition

Flexion, extension, left and right lateral bending and rotation motions at both left and right SIJs in the female and male models were calculated (Figures 4-5 and 4-6). The ROM of SIJ was the greatest in extension (1.36 deg left SIJ, 1.33 deg right SIJ) in the female model followed by flexion (0.50 deg left SIJ, 0.50 deg right SIJ), right rotation (0.44 deg left SIJ, 0.44 deg right SIJ), right bending (0.30 deg left SIJ, 0.35 deg right SIJ), left rotation (0.29 deg left SIJ, 0.33 deg right SIJ), and left bending (0.24 deg left SIJ, 0.30 deg right SIJ). In the male model, the maximum ROM of SIJ occurred in left rotation (0.54 deg left SIJ, 0.58 deg right SIJ) followed by right rotation (0.45 left SIJ, 0.48 right SIJ), extension (0.37 left SIJ, 0.36 right SIJ), flexion (0.28 deg left SIJ, 0.27 deg right SIJ), left bending (0.11 deg left SIJ, 0.12 deg right SIJ), and right bending (0.12 deg left SIJ, 0.10 deg right SIJ). It was found that in flexion-extension (F-E) movements,
SIJ had the highest motion in female (1.86 deg), however, male model had highest motion in axial rotation (1.07 deg). The smallest motion occurred in lateral bending in both female and male models (0.55 deg vs. 0.24 deg). According to the predicted motion data the female model experienced 86% higher mobility in flexion, 264% in extension, 143% in left bending, and 228% in right bending compared to the same motions in the male model. In left rotation and right rotation, the range of motion of male model was 78% and 9% higher than female model, respectively.

**Intact Right SIJ ROM-Female vs Male**

![Graph showing comparison of right SIJ ROM for female and male models](image1)

Figure 4-5: Comparison of male and female intact right SIJ ROM at 10 N.m moment with 400 N follower load under two-leg stance condition

**Intact Left SIJ ROM-Female vs Male**

![Graph showing comparison of left SIJ ROM for female and male models](image2)
4.3.2. Stress across SI Joint

The peak stress values were also measured and compared between the models. The peak stress values at the female and male SIJs are shown in figure 4-7. The maximum stress in the female model occurred in left rotation, followed by flexion, right rotation, right bending, left bending, and extension. In the male model, the greatest maximum stress happened during left rotation, followed by left bending, extension, flexion, right bending, and right rotation.

As shown by the data given in figure 4-7, the maximum stresses at the female sacroiliac joint were higher by 27% in flexion, 28% in right bending, 49% in left bending, 45% in right rotation, and 20% in left rotation compared to those of the male model.
Figure 4-8 shows the comparison of maximum stress values on sacrum and ilium for female and male models. Sacrum had higher stresses compared to ilium in both models. Stress at female sacrum and ilium were higher up to 49%, and 29% compared to the male model.

![Comparison of maximum stresses on the sacrum and ilium for intact female vs intact male](image)

**4.3.3. Pelvis Ligaments Strains**

Figure 4-9 and 4-10 show the results of the SIJ ligament strain for female and male models, respectively. The ASL was strained the same during all motions. The LPSL experienced greatest tension during extension and had no strain under the other motions. The SPSL was strained maximum during extension, but had comparable values under the other loads. The ISL underwent the largest tensile strains during all motions. The SSL and STL ligaments are both most strained during flexion, experienced similar values under other loads, and had no strain during extension.
Figure 4-9: Average strains of female pelvis ligaments for 10 N.m moment including 400 N preload. ASL is anterior sacroiliac ligament; ISL, interosseous sacroiliac ligament; LPSL, long posterior sacroiliac ligament; SPSL, short posterior sacroiliac ligament; SSL, sacrospinous ligament; STL, sacrotuberous ligament.

In the female model, ASL, LPSL, SPSL and STL underwent larger strains compared to the male model ligaments, but SSL had similar value for both genders, and ISL had higher strains in the male model.
Figure 4-10: Average strains of male pelvis ligaments for 10 N.m moment including 400 N preload. ASL is anterior sacroiliac ligament; ISL, interosseous sacroiliac ligament; LPSL, long posterior sacroiliac ligament; SPSL, short posterior sacroiliac ligament; SSL, sacrospinous ligament; STL, sacrotuberous ligament.

4.3.4. Load Sharing across SI Joint

The load sharing across the SIJs are shown in Table 4.1 and 4.2 for the female and male models, respectively. Reported load values represent the SIJ loads, which were defined as average force on the sacrum and ilium of each side, on the side with the greater magnitude.

Table 4.1: Load sharing across the female SIJ including total load, shear load, and normal load.

<table>
<thead>
<tr>
<th>Motion</th>
<th>Gender</th>
<th>Total Load (N)</th>
<th>Shear Load (N)</th>
<th>Normal Load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion</td>
<td>Female</td>
<td>262</td>
<td>242</td>
<td>97</td>
</tr>
<tr>
<td>Extension</td>
<td>Female</td>
<td>170</td>
<td>150</td>
<td>80</td>
</tr>
<tr>
<td>RB</td>
<td>Female</td>
<td>308</td>
<td>281</td>
<td>126</td>
</tr>
<tr>
<td>LB</td>
<td>Female</td>
<td>250</td>
<td>221</td>
<td>102</td>
</tr>
<tr>
<td>RR</td>
<td>Female</td>
<td>254</td>
<td>205</td>
<td>142</td>
</tr>
<tr>
<td>LR</td>
<td>Female</td>
<td>226</td>
<td>214</td>
<td>71</td>
</tr>
</tbody>
</table>

Female SIJs experienced higher loads across SIJ compared to the male SIJs under the same load. In both male and female models, the shear loads were higher than normal forces acting on the SIJ surfaces.
Table 4.2: Load sharing across the male SIJ including total load, shear load, and normal load.

<table>
<thead>
<tr>
<th>Motion</th>
<th>Gender</th>
<th>Total Load (N)</th>
<th>Shear Load (N)</th>
<th>Normal Load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion</td>
<td>Male</td>
<td>192</td>
<td>190</td>
<td>16</td>
</tr>
<tr>
<td>Extension</td>
<td>Male</td>
<td>161</td>
<td>142</td>
<td>31</td>
</tr>
<tr>
<td>RB</td>
<td>Male</td>
<td>157</td>
<td>113</td>
<td>104</td>
</tr>
<tr>
<td>LB</td>
<td>Male</td>
<td>223</td>
<td>221</td>
<td>18</td>
</tr>
<tr>
<td>RR</td>
<td>Male</td>
<td>206</td>
<td>201</td>
<td>27</td>
</tr>
<tr>
<td>LR</td>
<td>Male</td>
<td>155</td>
<td>153</td>
<td>12</td>
</tr>
</tbody>
</table>

4.4. Instrumented SI Joint Biomechanics

In this section, the data for instrumented male and female models are discussed. This section is divided into three parts: unilateral SIJ fusion, bilateral SIJ fusion, and different number of implants placement. Then each part is subdivided into three portions: range of motion, stress across the SIJ, and stress on the implant.

4.4.1. Unilateral SIJ Fusion

4.4.1.1. Range of Motion

The amount of motion reduction for the male and female models after getting instrumented by all three types of implants and inserting 3 implants at 10 N.m with 400 N preload are shown for each of loading conditions (Table 4.3 and 4.4). In both models, all three fusion devices reduced the ROM of the fixed SIJ significantly.

Table 4.3: Motion reduction percentage across female SIJ after unilateral fusion

<table>
<thead>
<tr>
<th>Motion</th>
<th>Gender</th>
<th>Motion Reduction @ Fused SIJ/Contralateral SIJ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Implant 1</td>
</tr>
<tr>
<td>Extension</td>
<td>Female</td>
<td>95%</td>
</tr>
</tbody>
</table>
In the female model, all three fusion devices produced highest and lowest motion reduction across the fixed SIJ during flexion-extension and axial rotation, respectively. Maximum motion reduction in all loading cases occurred in the model instrumented with the implant 3. However, Implant 1 produced lowest motion reduction in the female model.

In the male model, the greatest motion reduction happened during the flexion-extension motions. Under axial rotation, the implant 2 had the least motion reduction; however, implant 1 provided least motion reduction within flexion-extension and lateral bending.

Table 4.4: Motion reduction percentage across male SIJ after unilateral fusion

<table>
<thead>
<tr>
<th>Motion</th>
<th>Gender</th>
<th>Motion Reduction @ Fused SIJ/Contralateral SIJ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Implant 1</td>
</tr>
<tr>
<td>Extension</td>
<td>Male</td>
<td>94%</td>
</tr>
<tr>
<td>Flexion</td>
<td>Male</td>
<td>91%</td>
</tr>
<tr>
<td>RB</td>
<td>Male</td>
<td>85%</td>
</tr>
<tr>
<td>LB</td>
<td>Male</td>
<td>82%</td>
</tr>
<tr>
<td>RR</td>
<td>Male</td>
<td>87%</td>
</tr>
<tr>
<td>LR</td>
<td>Male</td>
<td>90%</td>
</tr>
</tbody>
</table>

In the male model, implant 3 provided highest stability during lateral bending and axial rotation motions, however, under flexion-extension loading condition, implant 2
demonstrated lowest ROM at the fixed SIJ. In the female model, implant 3 and implant 1 had highest and lowest motion reduction, respectively. Unilateral SI fusion also decreased the contralateral ROM significantly. In the male model, implant 1 and implant 3 resulted in higher motion reduction at the contralateral joint. For the contralateral SI joint of female model, the greatest motion reduction was performed by implant 1.

After unilateral SIJ fusion, ROM of L1-S1 was determined and reported (Table 4.5). Under all loading cases, L1-S1 ROM for the male and female models after unilateral SIJ fusion using all three types of implants changed less than 1%.

Table 4.5: Percentage change at L1-S1 ROM after unilateral fusion for male and female models

<table>
<thead>
<tr>
<th>Motion</th>
<th>Extension</th>
<th>Flexion</th>
<th>RB</th>
<th>LB</th>
<th>RR</th>
<th>LR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Implant 1</td>
<td>Implant 2</td>
<td>Implant 3</td>
<td>Implant 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female/Male</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
</tr>
</tbody>
</table>

4.4.1.2. Stress across SI Joint

The stresses across the SI joint after unilateral fusion were computed and compared with those of the intact SIJ for both genders (Figure 4-11 and 4-12). Stresses across the SI bone were reduced after unilateral SIJ fusion. The implant 2 had maximum and implant 1 had minimum stresses across the SIJ for both genders. In the male model, after fusion,
implant 1 had highest stress reduction compared to two other implant types. However, implant 2 experienced lowest stress reduction across the joint for all motions.

**Figure 4-11:** Comparison of maximum stresses across the SIJ for male model after unilateral fusion for all three types of SIJ implants

In the female model, similar to male model, greatest and lowest stress reduction occurred in implant 1 and implant 2, respectively.
Figure 4-12: Comparison of maximum stresses across the SIJ for female model after unilateral fusion for all three types of SIJ implants

These data showed that instrumented female model SI bone underwent higher stresses compared to the male model SI bone similar to the intact models. Minimum stresses across the bone happened during extension motions.

4.4.1.3. Stress on the implants

Maximum stresses on the superior, middle, and inferior implants were shown for both genders in the table 4.6 and 4.7. In both genders, maximum stresses occurred on the implant 3 for all loading cases. During flexion, right bending, and left rotation, implant 2 experienced lowest stresses, however, in the other motions, implant 1 provided lowest stresses. In all loading cases of implant 2, implants inserted into the female model had higher stresses compared with those of male model. For implant 1 and implant 3, female model implants provided greater stresses than the male model under flexion, right bending, and left rotation.

Table 4.6: Maximum von Mises stresses on the implants for the male model under different motions

<table>
<thead>
<tr>
<th>Motion</th>
<th>Gender</th>
<th>Maximum von Mises Stress on SIJ implants (MPa)</th>
<th>Superior/Middle/Inferior Implants</th>
<th>Superior/Middle/Inferior Implants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Superior/Middle/Inferior Implants</td>
<td>Implant 1</td>
<td>Implant 2</td>
</tr>
<tr>
<td>Flexion</td>
<td>Male</td>
<td>70</td>
<td>33</td>
<td>92</td>
</tr>
<tr>
<td>Extension</td>
<td>Male</td>
<td>30</td>
<td>19</td>
<td>49</td>
</tr>
<tr>
<td>RB</td>
<td>Male</td>
<td>38</td>
<td>25</td>
<td>73</td>
</tr>
<tr>
<td>LB</td>
<td>Male</td>
<td>56</td>
<td>26</td>
<td>63</td>
</tr>
</tbody>
</table>
The maximum stresses locations were located on the portion of implants which was between sacrum and ilium. Figure 4-13, 4-14, and 4-15 show examples of stress distributions on the implants in the male model. In both genders, for all three types of implants, inferior implant and middle implant underwent highest stresses and lowest stresses, respectively. Minimum stresses across the bone happened during extension motions.

Table 4.7: Maximum von Mises stresses on the implants for the female model under different motions

<table>
<thead>
<tr>
<th>Motion</th>
<th>Gender</th>
<th>Maximum von Mises Stress on SIJ implants (MPa)</th>
<th>Superior/Middle/Inferior Implants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Implant 1</td>
<td>Implant 2</td>
</tr>
<tr>
<td>Flexion</td>
<td>Female</td>
<td>77</td>
<td>57</td>
</tr>
<tr>
<td>Extension</td>
<td>Female</td>
<td>27</td>
<td>15</td>
</tr>
<tr>
<td>RB</td>
<td>Female</td>
<td>50</td>
<td>26</td>
</tr>
<tr>
<td>LB</td>
<td>Female</td>
<td>39</td>
<td>26</td>
</tr>
<tr>
<td>RR</td>
<td>Female</td>
<td>38</td>
<td>13</td>
</tr>
<tr>
<td>LR</td>
<td>Female</td>
<td>54</td>
<td>44</td>
</tr>
</tbody>
</table>
Figure 4-13: Stress distribution on the implant 1 for the male model

Figure 4-14: Stress distribution on the implant 2 for the male model
4.4.2. Bilateral SIJ Fusion

4.4.2.1. Range of Motion

The amount of motion reduction for male and female models after getting instrumented by all three types of implants and inserting 6 implants at 10 N.m with 400 N preload are shown for each of loading conditions (Table 4.8 and 4.9). In the male model, all three fusion devices reduced the ROM of both sides of SIJ significantly. The greatest motion reduction happened during the flexion-extension motions. Under all loading cases, the implant 1 had the least motion reduction.

Table 4.8: Motion reduction percentage across female SIJ after bilateral fusion

<table>
<thead>
<tr>
<th>Motion</th>
<th>Gender</th>
<th>Motion Reduction @ Left SIJ/Right SIJ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Implant 1</td>
</tr>
</tbody>
</table>

Figure 4-15: Stress distribution on the implant 3 for the male model
In the female model, maximum motion reduction in flexion-extension occurred in the model instrumented with implant 2, but for the other motion, implant 3 provided highest motion reduction. Implant 2 produced lowest motion reduction in lateral bending and axial rotation in the female model.

In the male model, implant 3 provided highest stability during lateral bending and axial rotation motions, however, under flexion-extension loading condition, implant 2 demonstrated lowest ROM across both SIJs. Range of motion of the SI joints were reduced more compared to the unilateral SIJ fusion.

Table 4.9: Motion reduction percentage across male SIJ after bilateral fusion

<table>
<thead>
<tr>
<th>Motion</th>
<th>Gender</th>
<th>Motion Reduction @ Left SIJ/Right SIJ</th>
<th>Implant 1</th>
<th>Implant 2</th>
<th>Implant 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion</td>
<td>Male</td>
<td></td>
<td>96%</td>
<td>93%</td>
<td>99%</td>
</tr>
<tr>
<td>Extension</td>
<td>Male</td>
<td></td>
<td>94%</td>
<td>88%</td>
<td>98%</td>
</tr>
<tr>
<td>RB</td>
<td>Male</td>
<td></td>
<td>90%</td>
<td>87%</td>
<td>94%</td>
</tr>
<tr>
<td>LB</td>
<td>Male</td>
<td></td>
<td>90%</td>
<td>90%</td>
<td>93%</td>
</tr>
<tr>
<td>RR</td>
<td>Male</td>
<td></td>
<td>91%</td>
<td>90%</td>
<td>92%</td>
</tr>
<tr>
<td>LR</td>
<td>Male</td>
<td></td>
<td>93%</td>
<td>92%</td>
<td>93%</td>
</tr>
</tbody>
</table>
After bilateral SIJ fusion, ROM of L1-S1 was calculated and compared with those of the intact SIJ for both genders. Under all loading cases, L1-S1 ROM for the male and female models after bilateral SIJ fusion using all three types of implants changed less than 1% compared to the L1-S1 ROM of intact model (Table 4.10).

Table 4.10: Percentage change at L1-S1 ROM after bilateral fusion for male and female models

<table>
<thead>
<tr>
<th>Motion</th>
<th>Percentage Change @ L1-S1 ROM</th>
<th>Female/Male</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Implant 1</td>
<td>Implant 2</td>
</tr>
<tr>
<td>Extension</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Flexion</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>RB</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>LB</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>RR</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>LR</td>
<td>1%</td>
<td>1%</td>
</tr>
</tbody>
</table>

4.4.2.2. Stress across SI Joint

The stresses across the SI joint after bilateral fusion were computed and compared with those of the intact SIJ for both genders (Figure 4-16 and 4-17). Stresses across the SI bone were reduced after bilateral SIJ fusion. The implant 1 had minimum stresses across the SIJ for both genders.
In the male model, after bilateral fusion, implant 2 experienced lowest stress reduction across the joint for all motions. In the female model, implant 3 showed lowest stress reduction across the joint. Minimum stresses across the bone happened during extension motions.

Figure 4-16: Comparison of maximum stresses across the SIJ for male model after bilateral fusion for all three types of SIJ implants

Figure 4-17: Comparison of maximum stresses across the SIJ for female model after bilateral fusion for all three types of SIJ implants
4.4.2.3. Stress on the implants

In both genders, maximum and minimum stresses occurred on the implant 3 and implant 1 for all loading cases, respectively. In all loading cases of implant 2, implants inserted into the female model had higher stresses compared with those of male model. Tables 4.11, 4.12, and 4.13 show peak stress values on the implant 1, implant 2, and implant 3 for the female model, respectively.

Table 4.11: Peak stress values on the implant 1 in the female SIJ after bilateral fusion

<table>
<thead>
<tr>
<th>Motion</th>
<th>Gender</th>
<th>Implant</th>
<th>Superior L</th>
<th>Superior R</th>
<th>Middle L</th>
<th>Middle R</th>
<th>Inferior L</th>
<th>Inferior R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion</td>
<td>Female</td>
<td>Implant 1</td>
<td>35</td>
<td>34</td>
<td>29</td>
<td>34</td>
<td>46</td>
<td>40</td>
</tr>
<tr>
<td>Extension</td>
<td>Female</td>
<td>Implant 1</td>
<td>6</td>
<td>9</td>
<td>10</td>
<td>7</td>
<td>13</td>
<td>10</td>
</tr>
<tr>
<td>RB</td>
<td>Female</td>
<td>Implant 1</td>
<td>12</td>
<td>25</td>
<td>11</td>
<td>22</td>
<td>17</td>
<td>27</td>
</tr>
<tr>
<td>LB</td>
<td>Female</td>
<td>Implant 1</td>
<td>25</td>
<td>14</td>
<td>21</td>
<td>13</td>
<td>28</td>
<td>16</td>
</tr>
<tr>
<td>RR</td>
<td>Female</td>
<td>Implant 1</td>
<td>21</td>
<td>23</td>
<td>8</td>
<td>28</td>
<td>12</td>
<td>29</td>
</tr>
<tr>
<td>LR</td>
<td>Female</td>
<td>Implant 1</td>
<td>22</td>
<td>23</td>
<td>26</td>
<td>12</td>
<td>32</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 4.12: Peak stress values on the implant 2 in the female SIJ after bilateral fusion

<table>
<thead>
<tr>
<th>Motion</th>
<th>Gender</th>
<th>Implant</th>
<th>Superior L</th>
<th>Superior R</th>
<th>Middle L</th>
<th>Middle R</th>
<th>Inferior L</th>
<th>Inferior R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion</td>
<td>Female</td>
<td>Implant 2</td>
<td>52</td>
<td>55</td>
<td>44</td>
<td>53</td>
<td>84</td>
<td>49</td>
</tr>
<tr>
<td>Extension</td>
<td>Female</td>
<td>Implant 2</td>
<td>14.5</td>
<td>27</td>
<td>18</td>
<td>28</td>
<td>37</td>
<td>35</td>
</tr>
<tr>
<td>RB</td>
<td>Female</td>
<td>Implant 2</td>
<td>18</td>
<td>52</td>
<td>16</td>
<td>53</td>
<td>44</td>
<td>51</td>
</tr>
<tr>
<td>LB</td>
<td>Female</td>
<td>Implant 2</td>
<td>38</td>
<td>27</td>
<td>46</td>
<td>28</td>
<td>76</td>
<td>32</td>
</tr>
<tr>
<td>RR</td>
<td>Female</td>
<td>Implant 2</td>
<td>32</td>
<td>48</td>
<td>30</td>
<td>50</td>
<td>60</td>
<td>59</td>
</tr>
<tr>
<td>LR</td>
<td>Female</td>
<td>Implant 2</td>
<td>36</td>
<td>36</td>
<td>33</td>
<td>30</td>
<td>60</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 4.13: Peak stress values on the implant 3 in the female SIJ after bilateral fusion
For all types of implants, female model implants provided lower stresses than the male model under all loading cases. In both genders, for all three types of implants, inferior implants and middle implants underwent highest stresses and lowest stresses, respectively. Minimum stresses across the bone happened during extension motions. Tables 4.14, 4.15, and 4.16 showed peak stress values on the implant 1, implant 2, and implant 3 for the male model, respectively.

For both genders, during each side rotation and bending, the maximum stresses occurred mostly on the implants on the side which motion happened.

### Table 4.14: Peak stress values on the implant 1 in the male SIJ after bilateral fusion

<table>
<thead>
<tr>
<th>Motion</th>
<th>Gender</th>
<th>Implant</th>
<th>Superior</th>
<th>Middle</th>
<th>Inferior</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>L</td>
<td>R</td>
<td>L</td>
</tr>
<tr>
<td>Flexion</td>
<td>Male</td>
<td>Implant 1</td>
<td>41</td>
<td>67</td>
<td>31</td>
</tr>
<tr>
<td>Extension</td>
<td>Male</td>
<td>Implant 1</td>
<td>30</td>
<td>37</td>
<td>22</td>
</tr>
<tr>
<td>RB</td>
<td>Male</td>
<td>Implant 1</td>
<td>28</td>
<td>43</td>
<td>24</td>
</tr>
<tr>
<td>LB</td>
<td>Male</td>
<td>Implant 1</td>
<td>42</td>
<td>38</td>
<td>29</td>
</tr>
<tr>
<td>RR</td>
<td>Male</td>
<td>Implant 1</td>
<td>23</td>
<td>60</td>
<td>21</td>
</tr>
<tr>
<td>LR</td>
<td>Male</td>
<td>Implant 1</td>
<td>48</td>
<td>30</td>
<td>37</td>
</tr>
</tbody>
</table>

### Table 4.15: Peak stress values on the implant 2 in the male SIJ after bilateral fusion

<table>
<thead>
<tr>
<th>Motion</th>
<th>Gender</th>
<th>Implant</th>
<th>Superior</th>
<th>Middle</th>
<th>Inferior</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>L</td>
<td>R</td>
<td>L</td>
</tr>
<tr>
<td>Flexion</td>
<td>Male</td>
<td>Implant 2</td>
<td>33</td>
<td>63</td>
<td>41</td>
</tr>
</tbody>
</table>
### Table 4.16: Peak stress values on the implant 3 in the male SIJ after bilateral fusion

<table>
<thead>
<tr>
<th>Motion</th>
<th>Gender</th>
<th>Implant</th>
<th>Superior</th>
<th>Middle</th>
<th>Inferior</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>L</td>
<td>R</td>
<td>L</td>
</tr>
<tr>
<td>Flexion</td>
<td>Male</td>
<td>Implant 3</td>
<td>122</td>
<td>61</td>
<td>71</td>
</tr>
<tr>
<td>Extension</td>
<td>Male</td>
<td>Implant 3</td>
<td>88</td>
<td>36</td>
<td>46</td>
</tr>
<tr>
<td>RB</td>
<td>Male</td>
<td>Implant 3</td>
<td>82</td>
<td>55</td>
<td>54</td>
</tr>
<tr>
<td>LB</td>
<td>Male</td>
<td>Implant 3</td>
<td>111</td>
<td>36</td>
<td>60</td>
</tr>
<tr>
<td>RR</td>
<td>Male</td>
<td>Implant 3</td>
<td>56</td>
<td>62</td>
<td>20</td>
</tr>
<tr>
<td>LR</td>
<td>Male</td>
<td>Implant 3</td>
<td>134</td>
<td>30</td>
<td>21</td>
</tr>
</tbody>
</table>

#### 4.4.3. Effect of Number of Implants

#### 4.4.3.1. Range of Motion

For both genders, among these six different implant placement, the superior-inferior implant placement had the greatest motion reduction across the fused and contralateral SJs for all three types of implants. In the male model, the two implant models with superior and inferior implants for implant 1, implant 2, and implant 3 resulted in increased percent motions of 1-5%, 1-5%, and 1-3% compared with the 3 implant model, in all loading cases, respectively. In the female model, the two implant models with superior and inferior implants for implant 1, implant 2, and implant 3 led increased percent motions of 1-5%, 1-3%, and 1-5% compared with the 3 implant model, in all loading cases, respectively (Tables 4.17, 4.18, and 4.19).
Table 4.17: Motion reduction percentage across female SIJ after various unilateral fusion placements of implant 1

<table>
<thead>
<tr>
<th>Motion Female</th>
<th>Motion Reduction @ Fused SIJ/Contralateral SIJ using Implant 1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 (S, -, I)</td>
</tr>
<tr>
<td>Extension</td>
<td></td>
</tr>
<tr>
<td></td>
<td>94%</td>
</tr>
<tr>
<td></td>
<td>64%</td>
</tr>
<tr>
<td>Flexion</td>
<td>84%</td>
</tr>
<tr>
<td>LB</td>
<td>86%</td>
</tr>
<tr>
<td>RB</td>
<td>90%</td>
</tr>
<tr>
<td>LR</td>
<td>76%</td>
</tr>
<tr>
<td>RR</td>
<td>83%</td>
</tr>
</tbody>
</table>

Table 4.18: Motion reduction percentage across female SIJ after various unilateral fusion placements of implant 2

<table>
<thead>
<tr>
<th>Motion Female</th>
<th>Motion Reduction @ Fused SIJ/Contralateral SIJ using Implant 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 (S, -, I)</td>
</tr>
<tr>
<td>Extension</td>
<td></td>
</tr>
<tr>
<td></td>
<td>96%</td>
</tr>
<tr>
<td></td>
<td>69%</td>
</tr>
<tr>
<td>Flexion</td>
<td>90%</td>
</tr>
<tr>
<td>LB</td>
<td>87%</td>
</tr>
<tr>
<td>RB</td>
<td>91%</td>
</tr>
<tr>
<td>LR</td>
<td>81%</td>
</tr>
<tr>
<td>RR</td>
<td>87%</td>
</tr>
</tbody>
</table>

Table 4.19: Motion reduction percentage across female SIJ after various unilateral fusion placements of implant 3

<table>
<thead>
<tr>
<th>Motion Female</th>
<th>Motion Reduction @ Fused SIJ/Contralateral SIJ using Implant 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 (S, -, I)</td>
</tr>
<tr>
<td>Extension</td>
<td></td>
</tr>
<tr>
<td></td>
<td>98%</td>
</tr>
<tr>
<td></td>
<td>77%</td>
</tr>
<tr>
<td>Flexion</td>
<td>94%</td>
</tr>
<tr>
<td>LB</td>
<td>96%</td>
</tr>
<tr>
<td>RB</td>
<td>97%</td>
</tr>
<tr>
<td>LR</td>
<td>84%</td>
</tr>
</tbody>
</table>
In the male model, two implant models configuration with super-inferior implants for implant 2 and implant 3 resulted in lower/similar motions when compared with the 3 implant configuration of implant 1, in flexion-extension and lateral bending, respectively. For single implant models, the percent motion increases ranged from 78 to 133%, 29 to 53%, and 61 to 115%, in flexion-extension, lateral bending, and axial rotation, respectively (Tables 4.20, 4.21, and 4.22).

In the female model, two implant models configuration with super-inferior implants for implant 3 resulted in lower motions compared with the 3 implant configuration of implant 1 and implant 2, in flexion-extension, lateral bending, and lateral bending.

Table 4.20: Motion reduction percentage across male SIJ after various unilateral fusion placements of implant 1

<table>
<thead>
<tr>
<th>Motion Male</th>
<th>Motion Reduction @ Fused SIJ/Contralateral SIJ using Implant 1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 (S,(\cdot),I)</td>
</tr>
<tr>
<td>Extension</td>
<td>93%</td>
</tr>
<tr>
<td>Flexion</td>
<td>90%</td>
</tr>
<tr>
<td>LB</td>
<td>78%</td>
</tr>
<tr>
<td>RB</td>
<td>81%</td>
</tr>
<tr>
<td>LR</td>
<td>86%</td>
</tr>
<tr>
<td>RR</td>
<td>82%</td>
</tr>
</tbody>
</table>

Table 4.21: Motion reduction percentage across male SIJ after various unilateral fusion placements of implant 2

<table>
<thead>
<tr>
<th>Motion</th>
<th>Motion Reduction @ Fused SIJ/Contralateral SIJ using Implant 2</th>
</tr>
</thead>
</table>

91
Table 4.22: Motion reduction percentage across male SIJ after various unilateral fusion placements of implant 3

<table>
<thead>
<tr>
<th>Motion</th>
<th>Male</th>
<th>Extension</th>
<th>2 (S,-,I)</th>
<th>2 (S,M,-)</th>
<th>2 (-,M,I)</th>
<th>1 (S,-,)</th>
<th>1 (-,M,-)</th>
<th>1 (-,-,I)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>96%</td>
<td>45%</td>
<td>85%</td>
<td>36%</td>
<td>91%</td>
<td>42%</td>
<td>57%</td>
<td>19%</td>
</tr>
<tr>
<td></td>
<td>94%</td>
<td>21%</td>
<td>79%</td>
<td>12%</td>
<td>86%</td>
<td>19%</td>
<td>50%</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>88%</td>
<td>33%</td>
<td>73%</td>
<td>24%</td>
<td>73%</td>
<td>28%</td>
<td>57%</td>
<td>22%</td>
</tr>
<tr>
<td></td>
<td>89%</td>
<td>31%</td>
<td>76%</td>
<td>23%</td>
<td>76%</td>
<td>26%</td>
<td>63%</td>
<td>21%</td>
</tr>
<tr>
<td></td>
<td>82%</td>
<td>59%</td>
<td>77%</td>
<td>55%</td>
<td>83%</td>
<td>59%</td>
<td>63%</td>
<td>45%</td>
</tr>
<tr>
<td></td>
<td>80%</td>
<td>55%</td>
<td>76%</td>
<td>51%</td>
<td>81%</td>
<td>54%</td>
<td>67%</td>
<td>45%</td>
</tr>
</tbody>
</table>

4.4.3.2. Stress on the Implants

Addition of the third implant reduced the maximum stress values on the implants. For both genders, among these six different implant placements, the superior-inferior implant placement had the lowest stresses on the implant for all three types of implants (Tables 4.23, 4.24, and 4.25).

Table 4.23: Peak von Mises stress on the implant 1 for male and female SIJs after various unilateral fusion placements

<table>
<thead>
<tr>
<th>Motion</th>
<th>Maximum von Mises Stress on SIJ for implant 1 (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Female/Male</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

92
<table>
<thead>
<tr>
<th>Motion</th>
<th>Maximum von Mises Stress on SIJ for implant 2 (MPa)</th>
<th>Female/Male</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 (S,-,I)</td>
<td>2 (S,M,-)</td>
</tr>
<tr>
<td>Flexion</td>
<td>139</td>
<td>110</td>
</tr>
<tr>
<td>Extension</td>
<td>37</td>
<td>58</td>
</tr>
<tr>
<td>RB</td>
<td>104</td>
<td>89</td>
</tr>
<tr>
<td>LB</td>
<td>64</td>
<td>74</td>
</tr>
<tr>
<td>RR</td>
<td>59</td>
<td>43</td>
</tr>
<tr>
<td>LR</td>
<td>91</td>
<td>119</td>
</tr>
</tbody>
</table>

Table 4.24: Peak von Mises stress on the implant 2 for male and female SIJs after various unilateral fusion placements

<table>
<thead>
<tr>
<th>Motion</th>
<th>Maximum von Mises Stress on SIJ for implant 3 (MPa)</th>
<th>Female/Male</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 (S,-,I)</td>
<td>2 (S,M,-)</td>
</tr>
<tr>
<td>Flexion</td>
<td>157</td>
<td>92</td>
</tr>
<tr>
<td>Extension</td>
<td>75</td>
<td>70</td>
</tr>
<tr>
<td>RB</td>
<td>116</td>
<td>59</td>
</tr>
<tr>
<td>LB</td>
<td>117</td>
<td>99</td>
</tr>
<tr>
<td>RR</td>
<td>123</td>
<td>103</td>
</tr>
<tr>
<td>LR</td>
<td>109</td>
<td>66</td>
</tr>
</tbody>
</table>

Table 4.25: Peak von Mises stress on the implant 3 for male and female SIJs after various unilateral fusion placements
4.5. Effect of Post-partum Period on SIJ

In this section, the data for female model with the effect of postpartum period are discussed. This section is broken up into three parts: range of motion, stress across the SIJ, SIJ ligaments strain, and load sharing across the SI joint.

4.5.1 Range of Motion

Flexion, extension, left and right lateral bending and rotation motions at both left and right SIJs in the post-partum period female model with no laxity, 5% laxity, and 10% laxity were calculated (Figure 4-18 and 4-19). The ROM of SIJ increased by increasing the ligament laxity. The highest change occurred in extension, followed by flexion, left rotation, right bending, left bending, and right rotation. In the model without laxity compared to the pre-partum model, axial rotation had the highest increase in the motion followed by flexion; lateral bendings were similar; and extension decreased. In the models with laxity compared to the pre-partum model, flexion-extension had the greatest increased motion followed by axial rotation, and lateral bending.
Figure 4-18: Comparison of postpartum model left SIJ ROM at 10 N.m moment with 400 N follower load under two-leg stance condition for different amounts of ligament laxities

![Graph showing SIJ ROM for different ligament laxities](image)

Figure 4-19: Comparison of postpartum model right SIJ ROM at 10 N.m moment with 400 N follower load under two-leg stance condition for different amounts of ligament laxities

![Graph showing SIJ ROM for different ligament laxities](image)

### 4.5.2. Stress across SI Joint

Figures 4-20, 4-21, and 4-22 show the maximum stress on the sacrum and ilium for the post-partum female model with different amounts of ligament laxity. By increasing the ligament laxity, the stresses across the SIJ decreased in all loading cases.

![Graph showing von Mises stress for different ligament laxities](image)
Figure 4-20: Comparison of maximum stresses across the SIJ for the post-partum female model with different amount of ligament laxity

Figure 4-21: Comparison of maximum stresses on the sacrum and ilium for the post-partum female model with no ligament laxity

Figure 4-22: Comparison of maximum stresses on the sacrum and ilium for the post-partum female model with 5% ligament laxity
Figure 4-23: Comparison of maximum stresses on the sacrum and ilium for the post-partum female model with 10% ligament laxity

Sacrum underwent higher stresses compared to the ilium in all laxity modes. In extension motion, SIJ experienced lowest amount of stresses.

4.5.3. Pelvis Ligaments Strains

Figures 4-24, 4-25, and 4-26 show the average strains of the post-partum female model ligaments strain with different amounts of ligament laxity. By increasing the ligament laxity, the ligaments strain increased in all loading cases. The ASL was strained most during flexion. The LPSL experienced greatest tension during extension and had no strain under the other motions. The SPSL was strained maximum during extension, but had comparable values under the other loads. The ISL underwent the largest tensile strains during all motions. Addition of ligament laxity caused ISL to stretch most in extension. The SSL and STL ligaments are both most strained during flexion, experienced similar values under other loads, and had no strain during extension.
Figure 4-24: Average strains of the post-partum female model ligaments strain with no ligament laxity for 10 N.m moment including 400 N preload. ASL is anterior sacroiliac ligament; ISL, interosseous sacroiliac ligament; LPSL, long posterior sacroiliac ligament; SPSL, short posterior sacroiliac ligament; SSL, sacrospinous ligament; STL, sacrotuberous ligament.

Figure 4-25: Average strains of the post-partum female model ligaments strain with 5% ligament laxity for 10 N.m moment including 400 N preload. ASL is anterior sacroiliac ligament; ISL, interosseous sacroiliac ligament; LPSL, long posterior sacroiliac ligament; SPSL, short posterior sacroiliac ligament; SSL, sacrospinous ligament; STL, sacrotuberous ligament.
Figure 4-26: Average strains of the post-partum female model ligaments strain with 10% ligament laxity for 10 N.m moment including 400 N preload. ASL is anterior sacroiliac ligament; ISL, interosseous sacroiliac ligament; LPSL, long posterior sacroiliac ligament; SPSL, short posterior sacroiliac ligament; SSL, sacrospinous ligament; STL, sacrotuberous ligament.

4.5.4. Load Sharing across SI Joint

The load sharing across the SIJs are shown in tables 4.26, 4.27, and 4.28. Reported load values represent the SIJ load, which were defined as average force on the sacrum and ilium of each side, on the side with the greater magnitude. The model with laxer ligaments experienced higher loads across SIJ compared to the other models under the same load. In all models, the shear loads were higher than normal forces acting on the SIJ surfaces.

Table 4.26: Load sharing across the post-partum female model SIJ with no ligament laxity including total load, shear load, and normal load.
<table>
<thead>
<tr>
<th>Motion</th>
<th>Ligament Laxity</th>
<th>Total Load (N)</th>
<th>Shear Load (N)</th>
<th>Normal Load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion</td>
<td>No laxity</td>
<td>217</td>
<td>216</td>
<td>12</td>
</tr>
<tr>
<td>Extension</td>
<td>No laxity</td>
<td>115</td>
<td>115</td>
<td>16</td>
</tr>
<tr>
<td>RB</td>
<td>No laxity</td>
<td>251</td>
<td>248</td>
<td>37</td>
</tr>
<tr>
<td>LB</td>
<td>No laxity</td>
<td>225</td>
<td>221</td>
<td>42</td>
</tr>
<tr>
<td>RR</td>
<td>No laxity</td>
<td>172</td>
<td>162</td>
<td>57</td>
</tr>
<tr>
<td>LR</td>
<td>No laxity</td>
<td>196</td>
<td>193</td>
<td>26</td>
</tr>
</tbody>
</table>

Table 4.27: Load sharing across the post-partum female model SIJ with 5% ligament laxity including total load, shear load, and normal load.

<table>
<thead>
<tr>
<th>Motion</th>
<th>Ligament Laxity</th>
<th>Total Load (N)</th>
<th>Shear Load (N)</th>
<th>Normal Load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion</td>
<td>5% laxity</td>
<td>240</td>
<td>190</td>
<td>16</td>
</tr>
<tr>
<td>Extension</td>
<td>5% laxity</td>
<td>141</td>
<td>142</td>
<td>31</td>
</tr>
<tr>
<td>RB</td>
<td>5% laxity</td>
<td>292</td>
<td>113</td>
<td>104</td>
</tr>
<tr>
<td>LB</td>
<td>5% laxity</td>
<td>236</td>
<td>225</td>
<td>48</td>
</tr>
<tr>
<td>RR</td>
<td>5% laxity</td>
<td>233</td>
<td>200</td>
<td>118</td>
</tr>
<tr>
<td>LR</td>
<td>5% laxity</td>
<td>203</td>
<td>201</td>
<td>22</td>
</tr>
</tbody>
</table>

Table 4.28: Load sharing across the post-partum female model SIJ with 10% ligament laxity including total load, shear load, and normal load.
Chapter 5

Discussion and Conclusions

5.1. Overview

This chapter contains a thorough discussion of the results of this study, beginning validation results for the FE models and proceeding to results of the FE models. This chapter provided quantitative information about the kinematics, stress, load sharing across the sacroiliac joint, and pelvis ligament strains of a male and female lumbo-pelvic segments under simulated physiological loadings. The conclusions and limitations of this study are also described.

5.2. Finite Element Model Validations

The 3D male and female spine-pelvis-femur FE models were validated with loading in flexion, extension, lateral bending and axial rotations. For lumbar spine ROM validation, pure moment loading along with preload under two leg stance condition were used to obtain these physiological rotations. The male model was previously validated,
and the female model had a good agreement within one standard deviation of the experimental data.

Intact SIJ ROM validations for both genders were performed by subjecting the FE model to the pure moment loading without preload while standing on one leg. The FE model responses for the right and left SIJs were recorded. The SIJ rotations in intact models predicted by the FE model were compared with the experiments in the literature. Therefore, based on the validation results, our male and female spinopelvic-femur models are good predictors of the ROM for the lumbar spine segments and sacroiliac joint.

5.3. Finite Element Analysis Range of Motion

The SIJ is a unique joint as it is a stable segment with a small amount of motion across the joint [4]. Accurate measurement of the SIJ is rather challenging and has been debated and studied extensively, with varying results [4, 11, 12, 13, 14, 15, 33, 43, 54, 62, 63]. Understanding the mechanics of the SIJ is crucial for identification of the mechanism for the pain.

Although there are many studies which quantified the ROM, the literature on the biomechanical differences between male and female SIJ is rare with only one study comparing the range of motion differences of SIJ between genders [15]. However, they did not provide load sharing and stress data across the SI joint. It is also shown that pelvic gender differences become recognizable as early as the fourth month [156]. According to Schunke et al. [156], males develop a more stable sacroiliac joint with lower mobility.
which is primary due to adaption to tolerate major forces. In both genders, SIJ mobility is reduced from birth to puberty but increases in adult females until a peak at 25 years old, while in males, joint mobility continues as low, especially in old men [66]. Such findings highlight the importance of investigating into biomechanical differences of gender specific SIJ to understand the relationship between biomechanics of the joint and development of joint related disorders. Therefore, we aimed to use validated finite element models of male and female lumbo-pelvic segment to quantify biomechanical parameters for male and female sacroiliac joints.

In various studies, Sturesson et al. [13, 62, 63] utilized in-vivo techniques determined the SIJ mobility around the sagittal axis in patients with PGP and showed that men have the average 40% less mobility than women. In the previous studies, due to difficulty in measuring two leg stance SIJ range of motion, they experimented in the one-leg stance condition and sectioned the pubic symphysis ligaments without having follower load. These drawbacks would lead to a less realistic measurement of sacroiliac joint motions which was resolved in our numerical simulation.

Our data showed that sacroiliac joint had higher mobility in the females compared to males which were in agreement with the literature. In both male and female models, the motion was minimum in lateral bending. The major difference in the SIJ motions between the male and female models occurred during extension which female model had significantly higher motion than the male model. The increased mobility in the female model SIJ can be attributed to a less pronounced curvature of the SIJ surfaces, a larger gap (2 mm) at SIJ and a greater pubic angle (111°) compared to the male model which had 1 mm gap at SIJ and pubic angle of 76° [7, 64].
Unilateral stabilization significantly reduced the fixed and contralateral SI joint range of motion in all loading cases, however, the motion reduction at the fixed SIJ was higher than the contralateral SIJ. Previous studies also have proven that unilateral stabilization of the SI joint considerably reduces the SI joint range of motion [22, 24]. In the previous FE and cadaver studies, they did not perform a gender-specific study and also in in-vitro studies, their experimental setups were on one-leg stance condition, without follower load, and sectioned pubic symphysis. The use of follower load and preserved pubic would be more physiologic, and double-leg stance increases stability of the model.

As previously noted in the material and methods, the implant 1 and implant 3 were inserted laterally across the SIJ while the implant 2 were inserted posteriorly. Implant 3 which was inserted laterally and had sharp threads provided the highest stability for the male and female models across the SIJ. Implant 1 was also a lateral approach implant with no thread had the lowest stability. By comparing the two lateral approach implants, implant 1 and implant 3, it can be seen that threads played a major role in reducing motion across the SIJ. It is difficult to pick one of these approaches as the best surgery approach in terms of motion reduction, because implant 2 which was inserted posteriorly was superior to the implant 1 and inferior to the implant 3 in motion reduction. Therefore, we can conclude that presence of threads on the implant can be attributed to the increase of the stability. Moreover, laterally placement of the screw (with threads) provides higher control on the SIJ motion. This data confirmed the results of Bruna-Rosso et al. [150] by showing that instrumentation using the medial orientation (more angled respect to the sagittal axis of rotation) provides better stabilization than the one with oblique orientation (more parallel to the sagittal axis of rotation). However, posterior approaches suggest
easier access to fixation of the SI joint without major surgical morbidity compared to the lateral approach which is more invasive. It just requires little dissection with low damage risk to the neural and vascular structures, and muscles.

The motion reduction at the SI joint after unilateral fusion resulted in minimal change in motion at the adjacent lumbar levels for both male and female models. The change in adjacent segment lumbar motion after unilateral SIJ fusion in this study (< 1%) was considerably lower than those reported in the adjacent lumbar segment after lumbar fusion. Cadaver studies have reported an increase of 20% to 127% for the adjacent segment motion after lumbar/lumbosacral fusion [157, 158]. While insertion of implants significantly reduced SI joint range of motion, the overall adjacent lumbar segment motion was insignificant.

Bilateral stabilization significantly reduced the both fixed and contralateral SI joint range of motion in all loading conditions. Since the unilateral fusion also reduced the contralateral joint motion, hence, this more motion reduction across the contralateral joint suggests that depending on how much damaged the contralateral joint is, fusion across the contralateral joint might be required. There are only two papers published on the bilateral sacroiliac joint fusion and the effect of this fusion on the SIJ biomechanics. The first study done by Shutz et al. [159] reported poor results on bilateral fusion but in the second study performed by Dall et al. [160], the outcomes were greatly improved when compared to the first study. They showed that a bilateral sacroiliac joint fusion can be achieved safely, with low complications, reduced pain scores, and promising patient satisfaction rates.
We showed that the reduction in motion at the SI joint after bilateral fusion led to little change in motion at the adjacent lumbar levels for both male and female models.

Our data demonstrated that insertion of 3 implants resulted in higher motion reduction than any combination of two implants, and single implant placements. Therefore, reducing the number of placed number caused an increase in SIJ ROM. Previous studies have shown that the use of two SI screws provides higher stability compared with a single SI screw [161-164]. We investigated the SIJ motion reduction as a function of number of implants: 1 implant and 2 implants with various placements. In clinical studies, 3 implants are being used in 91% of cases and the rest with 2 or 4 implants in rest of the cases [141]. Our results showed that no matter what type of implant was used, two implant models configurations with super-inferior implants were more stable than other combinations of single and dual implants. In addition, in the male model, placement of two numbers of implant 3 with super-inferior configuration was more stable than the three implants configuration of implant 1, and implant 2 in axial rotation and lateral bending.

Moreover, in the female model, placement of two numbers of implant 3 with super-inferior configuration was more stable than the three implants configuration of implant 1, and implant 2 in all loading cases.

Therefore, insertion of only two screws of implant 3 provided higher stability compared to two other implants in any configuration for both genders.

In the last section of this study, the effect of post-partum period on the female pelvis biomechanics was investigated. The simulated post-pregnancy pelvis showed that post-partum effect along with ligament laxity increases SIJ motion markedly.
During postpartum period, the pubic symphysis and sacroiliac joints, which are inherently stable, are widening and leading to increased motion at SIJ. The pubic symphysis increases from 3-5 mm to 5-10 mm during pregnancy. This joint laxity contributes to increasing the risk of injury, and they return to their normal condition after 4-12 weeks postpartum. Our data showed that by enhancing the pubic gap to 10mm, the anterior width of the pelvis and the gap at SIJ increase. These anatomical changes along with ligament laxity from moderate (5%) to severe (10%) led to greater SIJ motion compared to non-pregnant pelvis model. A possible reason for these differences can be attributed to the facilitation of parturition in females, which involves the influence of hormones such as relaxin [3,27,65].

Yamaguchi et al. [85] conducted a study to show the difference in pelvic alignment among never-pregnant, pregnant, and postpartum women. The anterior width of the pelvis in postpartum women was wider than never-pregnant women due to loosening of the pubic symphysis which could be seen in our post-partum female model. It is well documented that the laxity of the joint increases during pregnancy [70,165-167]. Under the influence of relaxin relative symphysisiolysis appears to occur, and both of these factors loosen the SIJ fibrous apparatus, thus increasing mobility [7]. Ligament laxity had the greatest change in range of motion on the flexion-extension motion of the post-partum especially extension. Therefore, performing tasks which needs spine flexion-extension might cause pain in SIJ region for females during post-partum period. While these unique aspects of the SIJ provide females with the necessary ability to give birth, they also may predispose females to a greater risk of experiencing pelvic pain. This ligament laxity plays an important role in determining the severity of this predisposition.
Studies have shown that the pelvic belt helps pregnant women to reduce SIJ motion by altering the laxity of the ligaments [8, 87, 105].

As the particular form of the SIJ differs immensely between males and females, it becomes rather clear that women are more likely to develop pelvic girdle pain, and are therefore at greater risk of experiencing LBP.

5.4. Finite Element Analysis Stress

According to a study by Ebraheim and Biyani [67], the SIJ surface area is relatively greater in adult males than females, which consequentially allows males to withstand greater biomechanical loading due to distribution of the load on a larger surface. In our female model, auricular surface area for females was 18 cm$^2$, this ligamentous area for the male model was approximately 22.3 cm$^2$, which were in the range with clinical data [38]. This smaller joint surface area in female SIJ can result in higher local stresses across the joint as can be seen from the data obtained in this study. The stress values for the female model, which had less surface area compared to male, were higher than the male model. This higher stresses implied that females are at higher risk of pelvic injury. The maximum stress values in the female model were 49% higher than male model. Our results showed that higher motion at SIJ would result in higher stresses across the joint under different motions especially on sacrum which had experienced higher stresses compared to the ilium in both genders. The higher stresses can translate to higher risk of sacral stress fracture in both genders. Furthermore, the stress concentration area across the joint was located more in anterior part of the SIJ. Dar et al [168] reported that SIJ
fusion of the females usually happen at the most anterior point of the joint. This evidence pointed out that stress concentration may occur in the anterior part of the SIJ due to load transfer to the pelvis caused by body weight and motion.

Overall, stress fracture injuries consist of approximately 15–20 % of patients visiting sports medicine clinics [169, 170] and pelvic stress fractures include 1.3–5.6 % of all stress fractures in athletes [171].

In both genders, sacrum experienced higher stress compared to the ilium which can be because of the reason that sacrum is the keystone arch of the pelvis and transfer loads from spine to the legs. Moreover, female sacrum was more stressed under different loadings compared to the male sacrum. Previous studies showed that there are some anatomical disadvantages in females that raise their risk of developing stress fractures. In women, for their size, having wider pelvic breadths negatively change loading strains. Angular tilt on the hips and knees are altered due to wider pelvis leading to increase the stress on these bones, tibia and foot. This anatomical difference can be related to the higher distribution of stress fractures in the pelvis and hip observed in females [171]. The other reasons for the gender disparity are women’ lower bone density, lower muscle strength, and shorter legs compared to males [172].

As literatures reported that females have a much higher incidence of pelvic fracture compared with males in similar activities [171, 172]. Wentz et al. [172] showed that the incidence of stress fractures was 9.2 % in female military individuals, 3 % in male military individuals, 9.7 % in female athletes, and 6.5 % in male athletes. Sacral stress fractures were 50 times more common among females than males [173].
After unilateral stabilization of the joint, SIJ devices reduced the amount of stresses occurred across the SI joint. In both genders, implant 2 and implant 1 demonstrated greatest and lowest stresses across the SIJ, respectively. The high stress across the bone induced by implant 2 compared to implant 1 can be explained by presence of threads or different placement of implant 2. Implant 3 caused higher stresses compared to the implant 1 due to having threads, however, there was no thread on the implant 1 and it had flat surfaces which led to lower stresses across the joint. Although implant 3 also had sharper threads compared to the implant 2, it produced lower stresses compared to the implant 2. This lower stresses can be because of the posterior placement of the implant 2 on the bone stresses. Therefore, these evidences can indicate that the implant shape characteristics and their placement play a major role in stresses values on the bone.

Similar to stresses on the intact models, instrumented SIJ bone of female model experienced higher stresses compared to the male model.

Implant 3 underwent high stresses compared to two other implants due to stress concentration on the sharp threats of this implant. However, implant 1 with no thread experienced lowest stresses. It indicated the direct effect of thread on the stress values on the device. Our data showed that extension is the safest motion which would lead lowest stresses on the bone and implant.

The maximum stresses locations were located on the portion of implants which was out of the bones between sacrum and ilium. This happened because in this region there is no interface between bone and implant to share the stresses.

Similar to the unilateral fusion, bilateral fusion of the joint resulted in reduced the stresses across the joint. In the male and female models, implant 2 and implant 3
produced highest stress values on the bone, respectively. This can be explained by presence of the threads on these two types of the implants. In both unilateral and bilateral fusions, this analysis of stress reported on the implants revealed that SIJ stabilization was primarily provided by the inferior and superior implants which were the farthest from the sacrum rotation center.

The three implants instrumentations showed significant improvement of the stress reduction as compared to equivalent configurations with two implants and single implant. The addition of implant helped the instrumentations to share stresses on more implants. Superior-Inferior configuration provided lowest stresses on the implant due to less mechanical contribution of middle implant into the stabilization of the joint.

The relationship between SIJ ligament laxity during pregnancy and pelvic pain has been reported in the previous literature on peri- and postpartum pregnancy related pain. Increasing ligament laxity during postpartum pregnancy resulted in high stresses across the SIJs, suggesting that the ligaments function both in preserving joint stability and in force transfer from to the lower extremities.

5.5. Finite Element Analysis Load Sharing

Understanding the load distribution across SIJ is also important in the diagnosis of SIJ malfunction. Under all loading cases, shear loads subjected to the SIJ were greater than compression forces. Pel et al. [174] showed that in the balanced standing posture model with all muscles, ligaments, and 500 N of trunk weight, shear SIJ force was much higher than compression force. The SIJ compression force was represented as the force
applied perpendicular to the SIJ surface. SIJ shear force determined in the model demonstrated the combination of real joint friction and friction due to interdigitation of bones in the SI joint space. Due to the frictionless contact between the articular surfaces, the real joint friction forces may be very small. The majority of the shear force was the result of normal contact pressures due to the bony interdigitation in the SI joint space. Our data showed that the female SIJ underwent higher loads compared to the male SIJ. Male SIJ could withstand greater biomechanical loadings due to distribution of the load on a larger surface.

During postpartum pregnancy, the model with laxer ligaments experienced higher loads across SIJ compared to the other models under the same loading. We concluded that ligament laxity during postpartum period can increase the load and stress at the SIJ. These observations can help the physicians to advice their patients regarding what movements to avoid.

5.6. Finite Element Analysis Ligaments Strain

Obtaining more quantitative information may be essential to recognize SIJ dysfunction in both genders due to the lack of quantitative relationship between the physiological spine motion and the biomechanical factors such as ligament strain that may be associated with pains in the sacroiliac joint. In the current study, we illustrated that depending on the spine motion, the ligament strains varied. The ASL, IPSL, STL, SSL, and ISL underwent tension to constrain the SIJ during flexion. LPSL is one of the posterior ligaments which only functions during extension. SSL and STL seem to have no
function in extension, however, SSL serves as a main constraint in other motions. As previous study showed that by sectioning sacrospinous and sacrotuberous ligaments, SIJ stability will decrease [47]. The posterior sacroiliac ligaments was contributed most to the SIJ mobility, while the anterior sacroiliac ligament had little influence [41]. Resisting the nutation and counternutation of the joint were done by ISL, STL, SSL, and LPSL [43, 44]. The major role in stabilizing the SIJ was performed by ISL which was one of the strongest ligaments in the body. Interestingly, ASL, LPSL, SPSL and STL underwent higher strains in the female model and ISL stretched more in the male model. These high strains on certain ligaments in the female and male models can be explained by these anatomical differences which females have smaller ASL, LPSL, and SPSL and males have smaller ISL compared to each other [8]. Although in our models, ligaments had same properties in both models, but depending on the gender, the strain exerted to ligaments were different in each gender.

As noted previously, it is well documented that laxity of the joint increases during postpartum period due to hormonal changes. As the laxity increased in the postpartum period, the minimal changes in strains happened in SPSL except in extension. During postpartum period by increased laxity of SIJ ligaments, the pain is mostly experienced in LPSL due to its counteraction to the counternutation [45]. We showed that the greatest change in ROM happened during extension motion, hence, the ligaments which were more stretched than the initial condition (intact female model) caused pain across the joint. During extension, the LPSL had highest strain change compared to the intact model which confirmed previous studies. Damen et al. [70] proposed that asymmetric SIJ ligament laxity have a threefold greater risk of pelvic pain into the postpartum period.
than subjects with symmetric laxity. Although we did not address asymmetric laxity, our results suggested that even symmetric laxity led to SIJ hypermobility to cause high stresses across the joint. This ligament laxity did not provide sufficient tension to preserve the joint in its optimal position, particularly during movement. This increase in motion and ligament strains can lead to tears within ligament fibers which will reduce the stability of the joint and increase the load across the articular cartilage surfaces of the joint.

5.7. Limitations

There were several limitations to this study. Firstly, we used same material properties of bone and ligaments for the female model and male model due to lack of experimental data. Secondly, the lack of muscle forces which greatly affected the results. Marres et al. [176] showed that gender differences in muscle geometry would play an important role in biomechanical models. These differences were mainly present in the physiological cross sectional area (PCSA) of the erector spinae, external and internal obliques, psoas major and quadratus lumborum. This suggests that considering gender differences in predicting trunk muscle forces is of great importance in biomechanical models. As shown previously, bone stress injuries were correlated to low muscle strength [177]. Having poor muscle strength increases the risk of bone stress injury. Thirdly, as stated previously, female pelvis undergoes some anatomical changes by aging. Our female model was a 55 years old specimen and could not predict biomechanical parameters of a
young female. Lastly, coupling as the contact between the femurs and the pelvis does not simulate the cartilage of the hip joint properly.

5.8. Conclusions

In conclusion, to the best of our knowledge, this study performed the first FE analyses of male and female SIJ to investigate their ROM, load sharing, pelvis ligaments, and stresses across the joint. This study found that the female sacroiliac joint had relatively higher range of motion than male model at both sides of the SI joint. Also, the female SIJ experienced higher stresses across the joint especially on the sacrum compared to males which implied that females are at a higher risk of stress fracture injury.

The major role in stabilizing the SIJ was performed by ISL which is one of the strongest ligaments in the body. ASL, LPSL, SPSL and STL underwent higher strains in the female model and ISL stretched more in the male model.

Under all loading cases, shear loads subjected to the SIJ were greater than compression forces. The female SIJ underwent higher loads compared to the male SIJ. Male SIJ can withstand greater biomechanical loadings due to distribution of the load on a larger surface.

These biomechanical loadings have an impact on the loads transferred to the pelvis and cause changes in biomechanics of male and females. Due to the anatomical differences and effect of pregnancy such as alterations in ligament stiffness, lead to biomechanical asymmetries and subjecting high stress on the SIJs, women are more
susceptible to develop pelvic girdle pain, and are therefore at greater risk of experiencing low back pain.

Unilateral stabilization significantly reduced the fixed and contralateral SI joint range of motion in all loading cases. However, the motion reduction at the fixed SIJ was higher than the contralateral SIJ. Moreover, presence of threads on the implant can be attributed to the increase of the stability. In addition, laterally placement of the screw (with threads) provided higher control on the SIJ motion.

The motion reduction at the SI joint after unilateral and bilateral fusions resulted in minimal change in motion at the adjacent lumbar levels for both male and female models. Bilateral stabilization also significantly reduced the both fixed and contralateral SI joint range of motion in all loading conditions. Since the unilateral fusion also reduced the contralateral joint, hence, if it is necessary, fusion across the contralateral joint is required.

After unilateral and bilateral stabilization of the joint, SIJ devices reduced the amount of stresses occurred across the SI joint. The implant shape characteristics and their placement played a major role in stresses on the bone and implant.

In both unilateral and bilateral fusions, this analysis of stress reported on the implants and ROM revealed that SIJ stabilization was primarily provided by the inferior and superior implants which were the farthest from the sacrum rotation center. Moreover, the addition of implant helped the instrumentations to share stresses on more implants. Superior-Inferior configuration provided lowest stresses on the implant due to less mechanical contribution of middle implant into the stabilization of the joint. Insertion of
only two screws of implant 3 which was inserted laterally provided higher stability compared to two other implants in any configuration for both genders.

The simulated post-pregnancy pelvis showed that post-partum effect along with ligament laxity increased SJJ motion markedly. Ligament laxity had the greatest change in range of motion on the flexion-extension motion of the post-partum especially extension. Increasing ligament laxity during postpartum pregnancy resulted in high stresses and loads across the SJJ s, suggesting that the ligaments function both in preserving joint stability and in force transfer from to the lower extremities.

In the postpartum model, greatest change in ROM happened during extension motion, hence, the ligaments which were more stretched than the initial condition (intact female model) are causing pain across the joint. During extension, the LPSL had highest strain change compared to the intact model.

We utilized load and stress parameters as factors to assess the biomechanics of the intact and postpartum SJJ, but that does not necessarily mean the direct correlation between loading and pain at the SJJ. In spite of that, higher stresses and loads across the SJJ would most probably increase the chance of having a painful SJJ.
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