

The Sacroiliac Joint: A Review of Anatomy, Biomechanics, Diagnosis, and Treatment Including Clinical and Biomechanical Studies (In Vitro and In Silico)

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Abstract

Sacroiliac joint (SIJ) is one of the most overlooked sources of LBP. The joint is responsible for the pain in 15–30% of people suffering from LBP. Fixation is increasingly recognized as a common surgical intervention for the treatment of chronic pain originating from sacroiliac joint (SIJ). Many studies have investigated the clinical outcomes and biomechanics of various SIJ surgical procedures. However, there is currently no agreement on the surgical indications for SIJ fusion or the best and most successful surgical technique for sacroiliac joint fixation and SIJ pain treatment.

Biomechanics of normal, and injured SIJs and biomechanical differences due to sex are well documented. Various studies have investigated the clinical outcomes of different surgical techniques and devices intended for treatment of the SIJ pain, and they have shown that these techniques are effective indeed. Several questions related to clinical and biomechanical effects of surgical parameters such as number, design/shape and positioning of implants, and unilateral versus bilateral placement remain unanswered. Biomechanical studies using *in vitro* and *in silico* techniques are crucial in addressing such unanswered questions. These are synthesized in the review.

Keywords

Sacroiliac joint · Fusion · Biomechanics · Surgery · Anatomy · Diagnosis · Treatment · Clinical · *In vitro* · *In silico*

et al. 2007; Frymoyer 1988). 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. LBP accounts for annual cost up to 60 billion dollars due to decreased productivity and income as well as medical expenses (Koenig et al. 2016; Rudolf 2012; Murray 2011).

The majority of LBP cases originate from the lumbar spine. One of the most overlooked sources of LBP is the sacroiliac joint (SIJ) due to its complex nature and the fact that the pain emanating from this region can mimic other hip and spine conditions (Weksler et al. 2007; Smith 1999). However, recent studies have reported a higher prevalence of the SIJ as a source for LBP, with some reports estimated that the SIJ is the actual source of pain in 15–30% of cases of LBP (Sachs and Capobianco 2012; Lingutla et al. 2016; Schwarzer et al. 1995). Increased physicians’ awareness of the prevalence of the SIJ as a source of LBP has given rise to an increased clinical suspicion of SIJ dysfunction as a pain generator and planning treatment accordingly.

Lumbar spine fusion, particularly L5–S1 segment, directly impacts the biomechanics of the SIJ by increasing both the motion and stress across the articular surface of the joint (Ivanov et al. 2009). 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 radio-frequency (RF) ablation. When patients continue to present chronic LBP characteristic with the SIJ, surgical procedures become a final resort.

Background

Low back pain (LBP) is the most common reason for primary care visits after common cold, with approximately 90% of adults being impacted by this condition at some point in their lives (Weksler

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 (Dietrichs 1991; Cohen 2005). The

SIJ lies between the sacrum and the ilium, spanning about 1–2 mm in width and held together by fibrous capsule (Fig. 1). The sacral side of the joint is covered with hyaline cartilage thicker than iliac cartilage, which appears more fibrocartilaginous (Foley and Buschbacher 2007).

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, and sacrotuberous, sacrospinous, and iliolumbar ligaments. The interosseous ligament, also known as the axial ligament, connects the sacrum and ilium at 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 the sacrum to the ischial tuberosity. The sacrospinous ligament's attachment is behind of the sacrotuberous ligament, and it connects the 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 (Fig. 2) (Ombregt 2013). The long dorsal sacroiliac ligament can stretch in periods of reduced lumbar lordosis, such as during pregnancy, which will be discussed further. Table 1 summarizes sacroiliac joint ligaments' locations and their functions.

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 (Miller et al. 1987; Solonen 1957; Albee 1909). 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 (Ombregt 2013). Table 2 summarizes sacroiliac joint muscles' actions and their effect on SIJ.

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 a 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 Fig. 3a, 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 (Snijders et al. 1993). 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 (Pel et al. 2008).

Pool-Goudzwaard et al. (2003) conducted a study on 12 human cadavers to assess the effect of the iliolumbar ligament (IL) on SIJ stability. Four cases were tested: (1) Intact IL, (2) random 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 the ventral side of the iliolumbar ligament is causing less SIJ stability

Fig. 1 Articular surfaces of the sacroiliac joint (Dall et al. 2015)

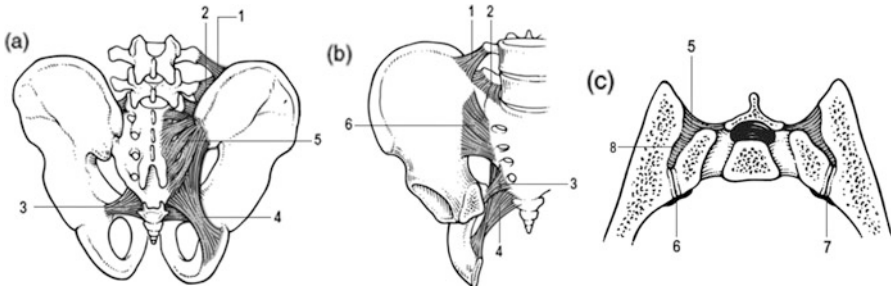
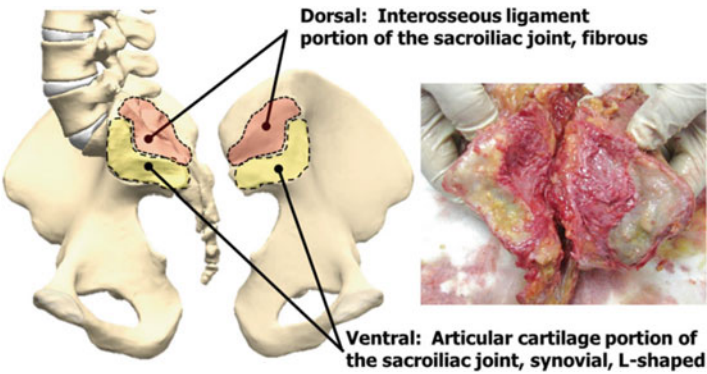


Fig. 2 (a) Posterior view; (b) anterior view; and (c) sacroiliac joint cut in transverse plane. (1, 2) Superior and inferior iliolumbar ligaments; (3) sacrospinous ligament; (4) sacrotuberous ligament; (5) posterior sacroiliac ligaments; (6) anterior sacroiliac ligaments; (7) sacroiliac joint; (8) interosseous ligament (Ombregt 2013)

Table 1 Sacroiliac joint ligaments' locations and their functions (Dall et al. 2015)

Ligament	Location	Primary restraint
Dorsal ligaments	PSIS to sacral tubercles	Sacral extension
Long ligament		
Short ligament		
Sacrotuberous	PSIS and sacrum to ischial tuberosity	Sacral flexion
Sacrospinous	Apex of sacrum to ischial spine	Sacral flexion
Ventral ligament	Crosses ventral and caudal aspect of SIJ	Sacral flexion
		Axial rotation
Interosseous	Between sacrum and ilium dorsal to SIJ	Sacral flexion
		Axial rotation
Iliolumbar	Transverse process of L5 to iliac tuberosity and crest	Lateral side bending
Ventral band		Ventral band
Dorsal band		Forward flexion
Sacroiliac part		Dorsal band

in the sagittal plane. Dorsal side and sacroiliac part of the IL does not have a significant role in providing SIJ stability (Pool-Goudzwaard et al. 2003). It is also stabilizing the lumbar vertebra on the sacrum (Yamamoto et al. 1990).

The posterior sacroiliac ligaments are contributed most to the SIJ mobility, while the anterior

sacroiliac ligament has little influence (Vrahas et al. 1995). 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), the sacrospinous ligament (SSL), and the long

Table 2 Sacroiliac joint muscles' actions and their effect on SIJ (Dall et al. 2015)

Muscle	Primary action	Effect on SIJ
Erector spinae <i>Iliocostalis lumborum</i> <i>Longissimus thoracis</i>	Bilateral: back extension Unilateral: side bending	Hydraulic amplifier effect
Multifidus	Back extension, side bending, and rotation	Imparts sacral flexion, force closure of SIJ with deep abdominals
Gluteus maximus	Hip extension, hip lateral rotation	Stabilizes SIJ
Piriformis	Hip lateral rotation	May alter SIJ motion via direct attachment to ventral aspect of sacrum
Biceps femoris	Hip extension, knee flexion	Long head: Imparts sacral extension via attachment to sacrotuberous ligament
Deep abdominals <i>Transversus abdominis</i>	Compression of abdominal cavity	Force closure of SIJ
Iliacus	Hip flexion (open chain) and tilts pelvis/sacrum ventrally (closed chain)	Synchronous tilting of the pelvis/sacrum ventrally (closed chain)
Pelvic floor	Support pelvic viscera	Imparts sacral extension

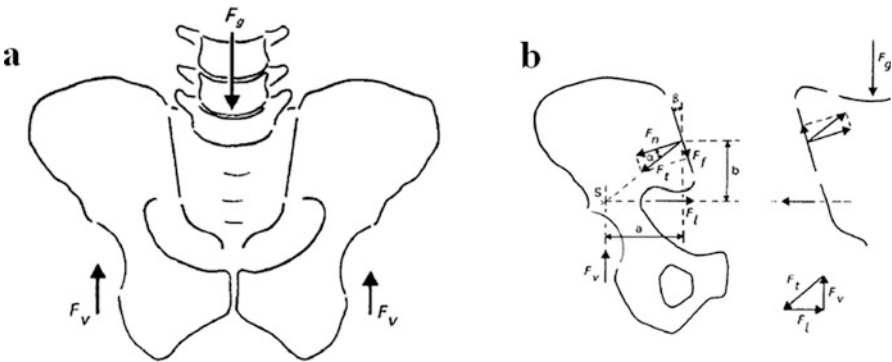


Fig. 3 (a) Pelvis free-body diagram due to gravity. Trunk weight (F_g) and hip joint forces (F_v). (b) Free-body diagram of self-bracing effect of the sacroiliac joint. SIJ

reaction force: normal and tangential (F_n and F_t), ligament or muscle force (F_l), and hip joint force (F_v) (Snijders et al. 1993)

dorsal ligament (LDL), respectively (Vleeming et al. 1992a; Sashin 1930). During pregnancy by increased laxity of SIJ ligaments, the pain is mostly experienced in LDL due to its counteraction to the counternutation (Eichenseer et al. 2011). Pain in this region is also common in men due to its location which is superficial and will put asymmetric stress on the SIJ. Flattening of lumbar lordosis brings about a decrease in SIJ nutation (Vleeming et al. 2012).

A cadaveric study was done by Wang et al. (Wang and Dumas 1998) 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° . 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 interosseous ligaments are the strongest ligaments which provide less motion in the joint's translation.

Dujardin et al. (2002) assessed the SIJ micro-motion under compression load applied to the ischial tuberosity. By sectioning SSL and STL, SIJ stability will decrease. Buyruk et al. (1995) using Doppler imaging of vibrations showed that left and right SIJ stiffnesses 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. (Rothkotter and Berner 1988) 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 the SIJ between the sacrum and ilium is working better than other loading directions.

Range of Motion

The sacrum can move with respect to the ilium in six degrees of freedom which is shown in Fig. 4. The intersection of the middle osteoligamentous column and the lumbosacral intervertebral disc is defined as the lumbosacral pivot point. Placing constructs posterior to this pivot point extending to the anterior of the point would provide rotational stability (McCord et al. 1992).

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 (Dietrichs 1991; Cohen 2005). The SIJ is unique in that it is rather stable, and motion of the joint is quite minimal (Foley and Buschbacher 2007). 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 (Vlaanderen et al. 2005; Jacob and Kissling 1995; Stureson et al. 1989, 2000a); they indicated that the SIJ rotation and translation in different planes do not exceed 2–3° and 2 mm, respectively (Foley and Buschbacher 2007; Zheng et al. 1997). 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° (Miller et al. 1987). 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 (Walker 1992; White and Panjabi 1990). 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. (1987). In this

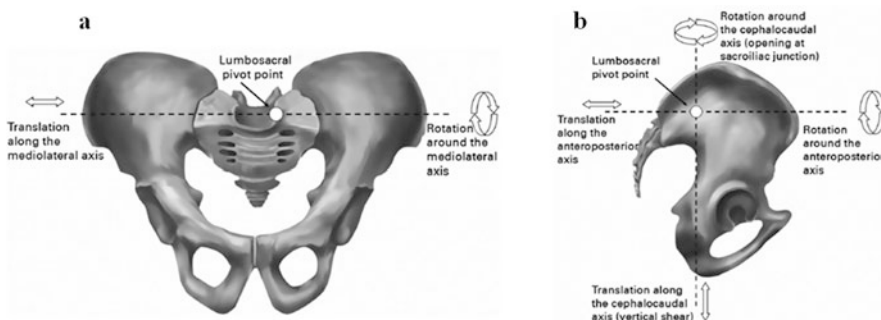


Fig. 4 Pelvis six degrees of movement and lumbosacral pivot point: (a) coronal plane, (b) sagittal plane (Berber et al. 2011)

study, rotations about all three axes were measured for one and both iliac fixed, with static test loads applied in superior, lateral, anterior, and posterior directions. According to their results, movements in all planes with one leg fixed ranged from 2 to 7.8 times greater than those measured with both legs fixed.

Another series of cadaveric studies by Vleeming et al. (1992a, b) 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. (1991) found that the maximum ROM for men and women was 1.2° and 2.8° , respectively. Another study by Stuesson et al. (1989) 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 three-dimensional motion analysis is not a useful tool for identifying painful SI joints in most patients (Stuesson et al. 1989). Jacob et al. (Jacob and Kissling 1995) 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.

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. 5 and 6). In the second decade of life,

women develop a groove in the iliac bone, the paraglenoid 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 (Vleeming et al. 2012).

According to a study by Ebraheim and Biyani (2003), 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 cm^2 (Miller et al. 1987; Ebraheim and Biyani 2003) with an upper limit of 18 cm^2 (Sashin 1930), this ligamentous area for males is approximately 22.3 cm^2 (Miller et al. 1987). 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 (Graves et al. 1990; Masi 1992).

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 (Tischauer et al. 1973; Bellamy et al. 1983). 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 (Vleeming et al. 2012). 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 (Vleeming et al. 2012; Stuesson et al. 2000a, b).

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 (Vleeming et al. 2012). While males typically have an average pubic angle of 50° – 82° , females have an average pubic angle of 90° (Bertino 2000). A possible reason for these

Structural Aspects	Female	Male
General structure	Light and thin	Heavy and thick
Pelvic brim (inlet)	Wide and more oval	Narrow and heart-shaped
Pubic arch	Greater than 90 angle	Less than 90 angle

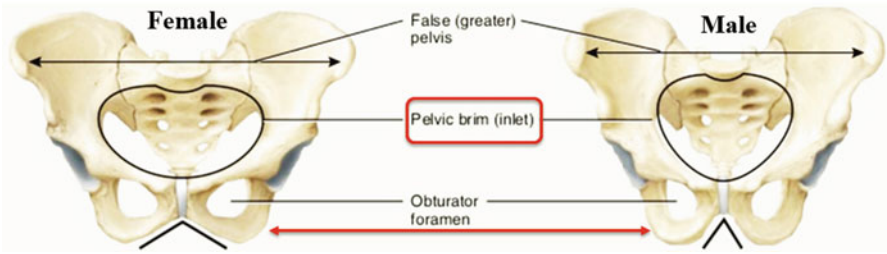


Fig. 5 Comparison of the female and male pelvic brim (inlet) (Tortora and Derrickson 2010)

Structural Aspect	Female	Male
Pelvic Outlet	Wider	Narrower

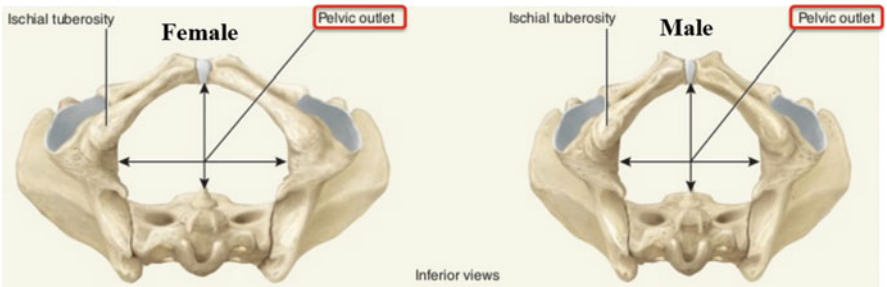


Fig. 6 Comparison of the female and male pelvic outlet (Tortora and Derrickson 2010)

differences can be attributed to the facilitation of parturition in females, which involves the influence of hormones such as relaxin (Dietrichs 1991; Cohen 2005; Ross 2000). Under the effect of relaxin, relative symphysiolysis appears to occur, and both of these factors loosen the SIJ fibrous apparatus, thus increasing mobility (Vleeming et al. 2012). 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 (Brooke 1924; Hisaw 1925; Chamberlain 1930; Borell and Fernstrom 1957). 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. (2001), 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 5 and 6 and Table 3 show the anatomical and biomechanical differences between male and female pelvis.

Table 3 A biomechanical comparison of the female and male SIJ

Biomechanical aspects	Female	Male
SIJ motions	More rotational	More translational
SIJ surface area	Lesser	Greater
Interosseous sacroiliac ligament	Larger	Smaller
Anterior sacroiliac ligaments	Smaller	Larger
Posterior sacroiliac ligaments	Smaller	Larger

Causes of SIJ Pain

The mechanism of SIJ injury has been viewed as a combination of axial loading and abrupt rotation (Dreyfuss et al. 1995). 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 (Cohen 2005). 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, and collisions during sports and car accidents. Abnormal loading due to lumbar spinal fusions, limb length discrepancy, or 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 (Ivanov

et al. 2009). When surgical arthrodesis causes degeneration of an adjacent segment, such as the SIJ, this profound adverse effect is known as adjacent segment disease (ASD) (Ivanov et al. 2009; Park et al. 2004; Ha et al. 2008; Hilibrand and Robbins 2004).

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 (Cohen 2005; Schuit et al. 1989; Winter and Pinto 1986; Golightly et al. 2007). Due to the length discrepancy, the mechanical alignment of the SI joints becomes increasingly imbalanced, resulting in an increased load distribution across both SI joints (Cohen 2005; Winter and Pinto 1986; Golightly et al. 2007).

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, spondyloarthropathies such as ankylosing spondylitis, inflammatory bowel disease (Cohen 2005), gait abnormalities (Herzog and Conway 1994), scoliosis (Schoenberger and Hellmich 1964), and excessive exercise (Marymount et al. 1986). Regardless of the cause, the association of pain with SIJ dysfunction is rather consistent.

Symptoms of SIJ dysfunction include pain in the lower back that sometimes radiates to the back of the thigh, and knee. Patients with LBP often experience pain when sitting, leaning forward, and with an increase in intra-abdominal pressure (DonTigny 1985). 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 4 summarizes the causes of intra-articular and extra-articular SIJ pain.

During pregnancy, many hormonal and biomechanical changes are occurring which contribute to ligaments laxity. One of the leading

Table 4 Causes of intra-articular and extra-articular SIJ pain (Holmes et al. 2015)

Intra-articular pain	Extra-articular pain
• Arthritis • Spondyloarthropathy • Malignancies • Trauma • Infection	• Ligamentous injury • Bone fractures • Malignancies • Myofascial pain • Enthesopathy • Trauma • Pregnancy

musculoskeletal changes is increasing the mass of uterus and breast which causes anterior displacement of the center of gravity. This effect heightens joint loads (e.g., 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 (Fitzgerald and Segal 2015).

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 (DonTigny 1985). While these pain characteristics are associated with SIJ dysfunction, they also are consistent with other hip or 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 (Cohen 2005). Other provocation tests for assessing SIJ pain include distraction/compression tests, the thigh thrust test, and the sacral thrust test (Table 5) (Laslett et al. 2005). 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 (Laslett 2006). 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 (Schwarzer et al. 1995; Cohen 2005). For this reason, other techniques have been suggested in conjunction with physical diagnostic tests to improve reliability.

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 (Cohen 2005). However, an exception is the high specificity of MRI in the setting of the seronegative spondyloarthropathies (90–100%) (Battafarano et al. 1993; Docherty et al. 1992; Murphey et al. 1991). 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 (Foley and Buschbacher 2007). 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 (Cohen 2005; Foley and Buschbacher 2007; Broadhurst and Bond 1998). After determining that the sacroiliac joint is the pain generator in patients with LBP, there are several treatment strategies for relieving SIJ pain.

Nonsurgical Management

The first step in the treatment of SIJ dysfunction involves nonsurgical management (NSM). Nonsurgical treatment options include physical therapy, steroid injections, radiofrequency (RF) ablation, and prolotherapy. For patients with leg length discrepancy (LLD), only utilizing shoe inserts can help eliminate LLD, consequentially equalizing and decreasing the load distribution across the joints over time (Cohen 2005; Kiapour et al. 2012). This conservative management strategy, however, is not a valid treatment option for

Table 5 A comparison of provocation tests

Provocation test	Patient position	Technique description
Gaenslen's test	Supine	With a 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 (Kokmeyer et al. 2002; Dreyfuss et al. 1996)
Distraction test	Supine	A vertical, posteriorly directed force is applied to both anterior superior iliac spines (ASIS) (Sashin 1930; Cook and Hegedus 2013; Laslett 2008; Laslett et al. 2003)
Compression test	On side	Pressure is applied to the upper part of the iliac crest, producing forward pressure on the sacrum (Magee 2008)
Thigh thrust test	Supine	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 (Vercellini 2011; Broadhurst and Bond 1998; Laslett 1997; Laslett and Williams 1998)
Sacral thrust test	Prone	With one hand placed directly on the sacrum and the other hand reinforcing it, an anteriorly directed pressure is applied over the sacrum (Vercellini 2011; Broadhurst and Bond 1998)

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 (Sasso et al. 2001; Cibulka and Delitta 1993; Osterbauer et al. 1993); however, there is currently a lack of prospectively controlled studies to back up these treatment strategies (Cohen 2005). Other stabilization plans have also been introduced, such as pelvic belts. These belts have shown to decrease sagittal rotation and consequently enhance pelvic stability, especially in pregnant women (Vleeming et al. 1992c; Damen et al. 2002). 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. (1996) 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. (1996) 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 (Cohen et al. 2008; Patel et al. 2012). However, similar to intra-articular injections, the reported success rates of RF denervation vary immensely. A retrospective study conducted by Ferrante et al. (2001) 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 (2007) 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.

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. A study of open fusion of the SIJ was conducted by Smith-Petersen and Rogers to determine the success of arthrodesis. 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 (Smith-Peterson and Rogers 1926).

While the success of open arthrodesis of the SIJ has been reported in numerous studies (Smith-Peterson and Rogers 1926; Wheeler 1912; Harris 1933; Ledonio et al. 2014a; Alaranta et al. 1990), several aspects of this procedure have also been deemed worthy of improvement. Smith et al. conducted a multicenter 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 operative time, greater blood loss, and 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 (Smith et al. 2013). 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 regard 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 (Ledonio et al. 2014a; Smith et al. 2013).

Minimally Invasive SIJ Fusion

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

One of the most commonly used outcome instruments for assessing variations in pain is the visual analog scale (VAS) (Damen et al. 2002). 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 (Wise and Dall 2008). 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 posttreatment outcomes (Gatchel 2006; Alaranta et al. 1990; Million et al. 1982).

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) (Gatchel 2006). 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 (Ware et al. 2002). The short form surveys allow for assessment of a patient's quality of life from the health care recipient's point of view (Gatchel 2006).

In conclusion, there is a wide range of treatment options for sacroiliitis, and most do improve with conservative, nonsurgical interventions. For those with refractory SI joint-mediated pain, minimally invasive SI Joint fusion has been found to be a safe and effective alternative.

Clinical Studies

Wise et al. (Wise and Dall 2008) performed percutaneous posterior minimally invasive SIJ fusion for 13 consecutive patients to assess the outcome of this technique within 24–35 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-Khayer et al. (2008). No one had combined MIS method and bone grafting for SIJ fusion before Al-khayar. Nine patients underwent surgery with 2 years follow-up, and it was shown that the VAS score fell from 8.1 Preoperation to 4.6 postoperation. This new technique provided a safe and successful fusion for SIJ pains. Hollow modular anchorage screw was also utilized by Khurana et al. (2009) for 15 patients during 9–39 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. (2013) 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 reduced 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 (Rudolf 2012; Smith et al. 2013; Lindsey et al. 2014). They have various unique features which make them different from 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 micro-motion and enhances bone ingrowth resulting in better fusion. Biomechanical studies showed that an 8 mm cannulated screw is three times weaker in shear and bending than a triangular implant (Fig. 7). In this fusion system, no grafts are placed in the sacroiliac joint, therefore all fusions are obtained by their porous coating (Wang et al. 2014).

During a minimally invasive SIJ fusion, the patient is administered general anesthesia and is placed in the prone position to use intraoperative fluoroscopy (Rudolf 2012; Sachs and Capobianco 2012; Smith et al. 2013). 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 (Cher et al. 2013). 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 malleated 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 (Rudolf 2012; Sachs and Capobianco 2012, 2013; Smith et al. 2013; Cher et al. 2013).

A prospective study by Duhon et al. (Cher et al. 2013) 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 6 months. According to the results, mean SI joint pain at baseline was about 76, while the 6-month follow-up pain score was approximately

Fig. 7 Triangular titanium implant with porous-coating – lateral approach (Wang et al. 2014)



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 (2013), except with a longer follow-up duration of 1 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. (Cher et al. 2013), 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 (2012) was performed to investigate the successful outcomes for minimally invasive arthrodesis after a 1-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 (2013) also conducted a retrospective 1-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 (Ha et al. 2008). Schroeder et al. (2013) 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 (Rudolf 2012; Ha et al. 2008). Unoki et al. (2015) 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 3) could enhance the incidence of SIJ pain. Another clinical study conducted by Shin et al. (2013) 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. (2016) 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. (Cher et al. 2013), 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 79.8–26.0 after 2 years, and the ODI decreased from 55.2 at baseline to 30.9 at 2 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 2 years (Duhon et al. 2016). A similar 2-year retrospective follow-up study of 45 subjects was conducted by Rudolf (2012), 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 (2014) 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 5 years, with a patient satisfaction rate of 82% after 1 year. 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 (Rudolf 2012; Sachs and Capobianco 2012, 2013; Wang et al. 2014; Cher et al. 2013; Cummings and Capobianco 2013; Duhon et al. 2016; Rudolf and Capobianco 2014). A comparison of the studies performed and the outcomes of MIS SIJ fusion is shown in Table 6.

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. (Koenig et al. 2016) analyzed the productivity benefits for patients with chronic SIJ dysfunction to compare worker function and economic outcomes between nonsurgical 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 among the groups was deemed to be not statistically significant with a value of approximately \$3128. When the metrics of working probability and expected change in earnings were combined, the annual increase in worker productivity between patients receiving MIS SIJ

Table 6 SIJ fusion with triangular implants outcome reports

Study	Patients included	Prior lumbar fusion	Follow-up duration	Pain score improvement	Patient satisfaction
Sachs and Capobianco (2012)	11 (10F/1M)	18%	12 months	70%	100%
Rudolf (2012)	50 (34F/16M)	44%	12 months	56%	82%
Rudolf (2013)	18 (12F/6M)	No prior fusion	24 months	80%	89%
	15 (11F/4M)	Prior lumbar fusion	24 months	73%	92%
	7 (3F/4M)	Prior lumbar pathology treated conservatively	24 months	63%	63%
Schroeder et al. (2013)	6 (6F/0M)	100%	10.25 months (4–15)	61%	100%
Gaetani et al. (2013)	12 (12F/0M)	8.3%	10 months (8–18)	4	100%
Cummings and Capobianco (2013)	18 (12F/6M)	61%	12 months	74%	95%
Sachs and Capobianco (2013)	40 (30F/10M)	30%	12 months	90%	100%
Duhon et al. (2013)	32 (21F/11M)	69%	6 months	67%	85%
Smith et al. (2013)	114 (82F/32M)	47.4%	24 months	79%	82%
Kim et al. (2013)	31 (24F/7M)	48%	12 months	N/A	87%
Ledonio et al. (2014a)	17 (11F/6M)	82%	12 months	78%	94%
Ledonio et al. (2014b)	22 (17F/5M)	64%	15 months (12–26)	54% (17%)	73%
Smith et al. (2013)	144 (102F/42M)	62%	12 months	68%	80%
Rudolf and Capobianco (2014)	17 (13F/4M)	47%	60 months	71%	82%
Vanaclocha-Vanaclocha et al. (2014)	24 (15F/9M)	8%	23 months (1–4.5 years)	43%	89%
Whang et al. (2015)	102 (75F/27M)	38%	6 months	63%	79%
Duhon et al. (2015)	172 (120F/52M)	44.2%	24 months	67%	78%
Polly et al. (2015)	102 (75F/27M)	38%	24 months	83%	73%
Sturesson et al. (2016)	52 (38F/14M)	N/A	6 months	55%	55%

fusion and those receiving nonsurgical management was estimated to be approximately \$6924.

SI-LOK is another MI SIJ fixation system which locates three hydroxyapatite-coated screws

across the sacroiliac joints laterally (Fig. 8). There are optional bone graft slots inside the screw which can be used to enhance fusion. Also, the optional lag screw thread allows applying



Fig. 8 SI-LOK sacroiliac joint fixation system – lateral approach (Wang et al. 2014)

compression force during placement (Wang et al. 2014). There is no biomechanical study on this screw yet, however, prospective 1-year outcomes of 32 patients were reported. VAS back pain improved from 55.8 ± 26.7 to 28.5 ± 21.6 ($P < 0.01$) and ODI improved from 55.6 ± 16.1 to 34.6 ± 19.4 at 1 year (Rappoport et al. 2017).

SImmetry is another cannulated titanium screw type SIJ fixation system which usually is used with two screws (one is antirotation screw) laterally across the SIJ (Fig. 9). There is no bone graft slot in this system, and the bone graft is placed across the articular part of the joint (Wang et al. 2014). This surgery technique is defined comprehensively in (Beaubien et al. 2015). One-year outcomes of 18 patients were reported as follows: VAS reduced from 81.7 (15.2) to 44.1 (22.9), and radiographic arthrodesis was identified on CT scan in 15 of 17 patients (88%) (Kube and Muir 2016).

SIFix is one of the posterior MI SIJ fixation systems and uses two-threaded cancellous bone to stabilize the joint. This method can be done bilaterally with a single midline incision (Fig. 10).

Beck et al. (2015) 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 (Fig. 11).

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.

In conclusion, the results of clinical studies showed that the minimally invasive approaches, compared to open surgical fusion, as minimally invasive techniques are accompanied by less tissue damage, blood loss, and duration of hospitalization. Furthermore, there are various techniques and different types of SIJ fusion implants for minimally invasive approaches. Since some clinical questions could not be answered through clinical studies, in vitro and in silico studies have been used to address these questions.

In Vitro and In Silico Studies

Soriano-Baron et al. (2015) 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 transarticular 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 transarticular approach, the superior and inferior implants were placed similar to

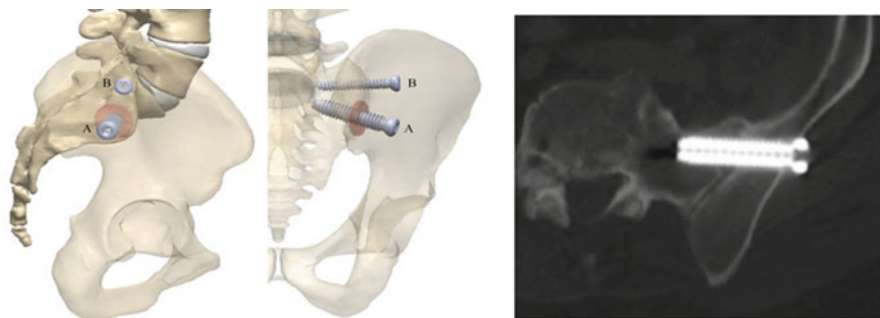


Fig. 9 Simmetry sacroiliac joint fusion system – lateral approach (Wang et al. 2014)

Fig. 10 SIFix sacroiliac joint fixation system – posterior approach (Mason et al. 2013)

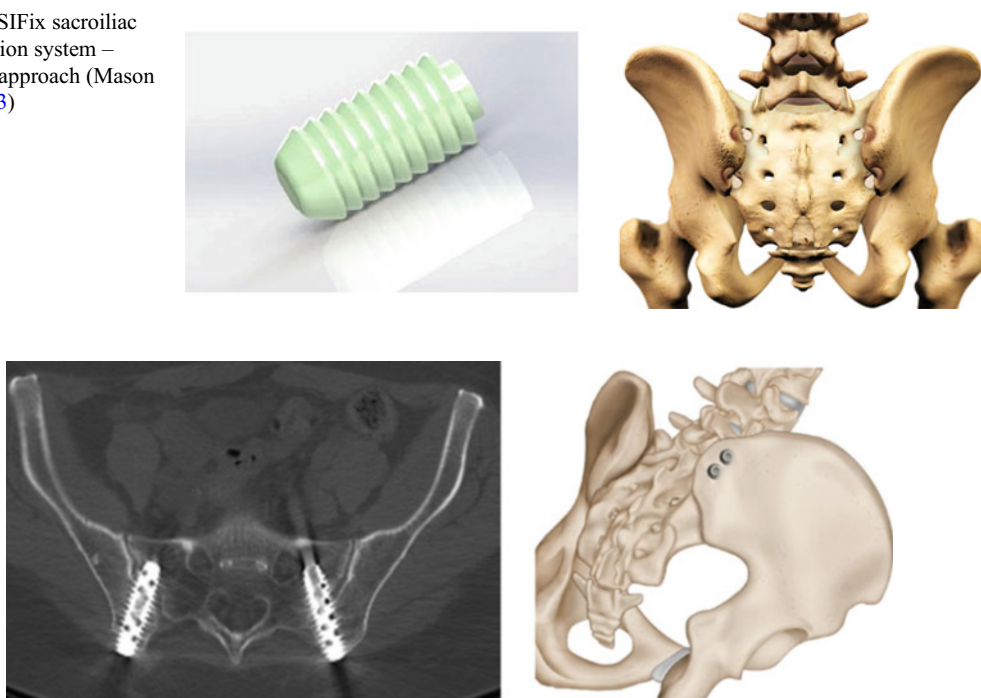


Fig. 11 RI-ALTO sacroiliac joint fusion system – posterior approach (Beck et al. 2015)

the posterior technique, and the middle implant was positioned toward the anterior third of the sacrum across the cartilaginous portion of the SI joint. The 7.5 Nm 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 (Soriano-Baron et al. 2015).

Hammer et al. (2013) 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 has opposite effect and causes an increase in the pelvic motion, and both are doing vertical load transfer

followed by sacrum translation. Moreover, in standing position, the ligaments strain is higher than in sitting position.

Eichenseer et al. (2011) also evaluated the correlation between ligaments stiffness and SIJ stress and motion. They showed that decreasing ligaments stiffness results in an increase in stress and motion at SIJ. Moreover, ISL has the highest strains under different spine motions which confirmed the finding of Hammer's study.

Mao et al. (2014) 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. (2015) 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. (2016) used finite element method to analyze SIJ biomechanics under RI-ALTO fusion implant which is a new sacroiliac fusion device. Thousand newton 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. Proximal insertion of the implant which was farther from the SIJ center of rotation was more efficient than distal insertion of the implant. Proximal 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 trajectories of placement which

were 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 the implant was inserted from the SIJ center of rotation, the more stability is provided.

Lindsey et al. (2018) 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 lengths of 55 and 75 mm; midline implant length of 45 mm; and inferior implant length of 45 mm for inline orientation and 50 mm for transarticular orientation. They showed that the transarticular 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. 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. (2012) 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 to 3 cm, the stresses increased accordingly.

Zhang et al. (2014) studied the biomechanical stability of four different SI screw fixations 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 to the finding by Bruna-Rosso.

Ivanov et al. (2009) 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 in 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. (2014) 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. (2017) 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. (2017) 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.

Joukar et al. (2017) studied the biomechanical differences between male and female SIJs using finite element analysis. They found out that female SIJ had higher mobility, stresses, loads, and pelvis ligament strains compared to the male SIJ which led to higher stress across the joint, especially on the sacrum under identical loading conditions. This could be a possible reason for higher incidence of SIJ pain and pelvic-stress fracture in females.

Joukar et al. (Joukar 2017) investigated the effect of unilateral and bilateral SIJ fusion and different placements of fully threaded screw and half threaded screw during standing upright (similar to RI-ALTO and SI-LOK implant systems), respectively, on the SIJ male and female models' range of motion and stresses. The fully-threaded and half-threaded screws were located posterior and lateral into the SI joint, respectively. Unilateral stabilization significantly reduced the fused SIJ range of motion along with reduction in contralateral (nonfused) SIJ motion during standing upright. Moreover, regardless of sex, lateral and posterior placements of the implants had similar performance on the SIJ stability. Both male and female models showed high reduction in stress and range of motion after treatment compared to the intact model, however, female model showed more stress and motion reductions after SIJ fusion due to higher stress and range of motion values in prior fusion compared to the male model. SIJ implants are more effective in females in terms of stability but may be more prone to higher rate of loosening/failure compared to males. The motion reduction at the SI joint after unilateral and bilateral fusions resulted in minimal changes at the adjacent lumbar levels for both male and female models. Although, the implant shape effects were minimal, the implant placements played a major role in stresses on the bone and implant. In both unilateral and bilateral fusions, SIJ stabilization was primarily due to the inferior and superior implants.

Joukar et al. (2019) developed a validated finite element (FE) model of lumbo-pelvic segment to investigate the biomechanical effects of fixation of the sacroiliac joint using triangular implants on the hip joint. Their model included the most critical anatomical features including connective tissue and articular cartilage across the hip joint. They performed an analysis with femurs fixed in double-leg-stance configuration and application of a 400 N compressive follower preload applied across the lumbo-sacral segment followed by a 10 Nm bending moment applied to the topmost level of the spine segment. Intact model was modified to include SIJ fixation and unilateral and bilateral joint instrumentations. The analyses demonstrated a decrease in range of motion of the SI joint in the instrumented model, compared to the intact. The bilateral fixation resulted in a greater reduction in motion compared to unilateral fixation. The contact stresses and load sharing did not significantly change in contralateral SI joint, following unilateral fixation.

The average hip contact stress and contact area changed less than 5% and 10% respectively in instrumented models relative to intact in most of anatomical motions. The data suggested a low risk of developing adjacent segment disease across the hip joint due to minimal changes in contact area and load sharing at the hip joint following instrumentation with the triangular implant compared to the intact. The changes in the lumbar spine segment were minimal as well.

In conclusion, *in vitro* studies were performed to address different unanswered questions in clinical studies such as implant failure, range of motion, and bone failure. Since *in vitro* studies were unable to record some biomechanical data like stresses across bones and implants, and ligament strains, *in silico* studies were used to overcome these limits of experimental tests.

Summary

SIJ is a complex joint sitting in between the sacrum and iliac bone on either side. The joint plays a vital role in transmitting upper body loads to lower extremities via the hip joints. The

wedging of the sacrum in between pelvic bones, irregular and rough surface of the joint itself, and tight banding due to ligaments and pelvic floor muscles (levator ani and coccygeus muscles) make the SIJ extremely stable. SIJ pain can be due to, but are not limited to, capsular and ligamentous tension, hypo- or hypermobility, extraneous compression or shearing forces, and a host of other factors. Other sources of pain are the surgical arthrodesis at one level causing degeneration of an adjacent segment, leg length discrepancy, and spondylo-arthropathies. There are anatomical differences between male and female pelvis, including SIJ characteristics. In females, ligaments become lax during pregnancy. These factors may make females more prone to low back pain. To restore quality of life and alleviate LBP due to SIJs, conservative and surgical treatments are available.

The first step in the treatment of SIJ dysfunction involves a thorough diagnostic workup followed by nonsurgical management. When nonsurgical management strategies fail, surgical management (open or minimal fusion) is considered. Several studies have investigated the clinical outcomes of surgical techniques for the sacroiliac joint. The studies have shown that minimally invasive techniques involve less tissue damage, blood loss, and duration of hospitalization, thus leading to superior clinical outcomes.

Despite the satisfactory data on clinical outcomes of SIJ fixation surgery, the data on biomechanics of SIJ in general and fixation techniques in particular are sparse. The existing literature suggests that at least two fixation devices spaced apart in their locations on either side of the pivot point of SIJ facilitate “solid” fixation/stabilization across the joint. Both unilateral and bilateral SIJ fusions reduce motion. However, if bilateral SIJ fusion is considered, it is essential to ensure that implant design and SIJ morphology permit such a procedure.

Both males and females showed high performance after SIJ fusion treatment, however, females showed more stress and motion reductions after SIJ fusion. Regardless of sex, lateral and posterior placements of the implants had similar performance on the SIJ stability. SIJ implants

are more effective in females in terms of stability but may be more prone to higher rate of loosening/failure compared to males. The optimum number of implants and implant placement location is two or three implants (depending on the bone quality and implant type) across S1 and S2 levels of the sacrum. Having more parallel and farther from SIJ-pivot-point implant placement results in higher stability of the joint. Using longer superior implant placed in S1 level (proximally) closer to the sacral midline leads to higher reduction in SIJ motion. It is better to place the implant in thicker cortical bone areas and a more dense bone region leading to better stability. Most importantly, SIJ fusion has no effect on the adjacent segments on either sides, spine or hip.

Finally, regarding the shapes of the implants, currently, there are two popular designs on the market: circular sections such as SImmetry, SI-LOK, and RI-ALTO; and triangular design such as iFuse. Further biomechanical studies and long-term clinical follow-ups are required to delineate the optimum design (e.g., implant shape) since the existing literature on biomechanics of circular SIJ devices (SImmetry and SI-LOK implant systems) is limited.

In conclusion, despite the existing literature, there are several unanswered questions related to the effect of surgical parameters on the clinical outcome of the SIJ fixation procedures. For example, the effects of different implant shapes on the biomechanical and long-term clinical outcomes of the sacroiliac joint are not fully understood. It is particularly crucial to understand the relationship between bone quality/density and effectiveness of the surgical technique from a biomechanics perspective and the long-term clinical outcomes. Such questions can be answered by looking at parameters such as load-sharing at the bone-implant interface, distribution of the load across the implant, failure mechanism of the bone/implant, and bone remodeling. The clinical studies, due to their inherent limitations, are unable to address such issues. Such knowledge will be crucial for improvement of existing techniques or development of more efficient instrumentation that would yield superior clinical outcomes for SIJ fixation.

Conclusion

The sacroiliac joint (SIJ) is one of the most overlooked sources of LBP. The joint is responsible for the pain in 15–30% of people suffering from LBP. Various studies have investigated the clinical outcomes of different surgical settings intended for treatment of the pain, and they have shown that these techniques are effective indeed. Several questions related to clinical and biomechanical effects of surgical parameters such as number and positioning of implants, unilateral versus bilateral placement, etc., remain unanswered. Biomechanical studies using in vitro and in silico techniques are crucial in addressing such unanswered questions. These were synthesized in the review.

Acknowledgments The work was supported in part by NSF Industry/University Cooperative Research Center at The University of California at San Francisco, CA, and The University of Toledo, Toledo, OH.

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Part III

Considerations and Guidelines for New Technologies