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Idiopathic Pelvic Girdle Pain as it Relates to the Sacroiliac Joint

Form and Force Closure of the Sacroiliac Joints

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Abstract

The principles of form and force closure were introduced to describe the complex mechanism of sacroiliac joint (SIJ) stability. Form closure refers to a theoretical stable state of a joint with close fitting articular surfaces, where no extra forces are needed to maintain the stable state of the system during loading and unloading situations. If the sacrum would fit in the pelvis with perfect form closure, no lateral compressional forces would be needed to maintain stability. However, such a construction would make mobility practically impossible. Force closure is the theoretical state where lateral force and friction resulting in joint compression, are required for the joint to withstand a vertical load. Structures that contribute to SIJ stability via “form closure” include (1) the configuration of the interfacing joint surfaces, along with dorsocranial “wedging” of the sacrum into the ilia; (2) the corresponding ridges and grooves of the articular surfaces of the SIJs and resultant high coefficient of friction; and (3) the integrity of the binding ligaments, which are among the strongest in the body. Shearing forces absorbed in the SIJ occur because of a combination of person-specific anatomical features. This results in unique form and force closure situations that provide effective and tailored joint accommodation that balance both friction and compression in the joint. Force closure occurs because of altered joint reaction force via taut ligaments, fascia, muscles, and the ground reaction force they are reacting to at the moment. In the ideal state, force closure creates a perpendicular compressive reaction force to the SIJ to adapt and overcome the forces of gravity. In order for force closure to be effective, sacral nutation must occur and is considered to be anticipatory for joint loading. Sacral nutation results in tensing all of the dorsal SIJ ligaments (interosseous, dorsal sacroiliac) with the exception of one, the long dorsal ligament (LDL). This prepares the pelvis to absorb and increase in load. As a result, the posterior ilium are pressed together causing an increase in SIJ compression. This review will discuss the importance of understanding form and force closure principles because they are related to understanding the relationship of anatomy and function of the SIJ.

Introduction

The mechanisms for load and shear force transmission across the pelvic girdle are complex because they involve the trunk above and the lower extremities below. The intricacies of movement involving bone, cartilage, ligaments, muscle, and fascia provide further complexity, which can be difficult for a healthcare provider to assess and apply when caring for a patient with posterior pelvic girdle pain.

Human posture requires forces that oppose gravity in order to maintain the upright posture. The mass of the upper limbs, trunk, and head is transferred to the pelvis via a vertical trajectory. When the mass is transferred, an increase in compression type forces of the lumbopelvic region are required to maintain stability. As a result, the need for joint stability across the bony pelvis is at the expense of joint mobility.[1-5]

The sacroiliac joint (SIJ) and pubic symphysis provide the primary bony and ligamentous support for the pelvis. Regarded as a closed ring of variable stiffness[6-10], biomechanical analysis of the pelvis shows the major area of load transfer to the SIJ runs through the cortical shell of the ilia, down the shafts of the femur and tibia, to the feet. Reverse load transfer occurs as a result of ground reaction forces transmitting from the lower extremities up through the pelvis and spine. These forces are critical in providing joint stability during pelvic load transfer[11]. An asymmetry or dysfunction in load transmission can lead to compensatory muscle activation to stabilize the pelvis. In turn, pain may develop and it can be difficult to identify a culprit because intra-articular and

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periarticular structures may all be involved. Inadequate pelvic joint stability has been described to be clinically associated with specific disorders about the pelvic girdle including lumbopelvic pain,[12] groin,[13] and hamstring pain.[14,15]

Understanding force transmission across the bony structure of the SIJ and the responsive force of the ligaments and muscle surrounding and intrinsic to the SIJ is imperative for the healthcare provider caring for patients with posterior pelvic girdle pain.

The purpose of this narrative review is to provide a selective synopsis of the literature as it pertains to understanding the mechanism of form and force closure of the sacroiliac joint and the clinical implications in evaluating and treating patients with posterior pelvic girdle pain that includes the SIJ.

Why Not a Solid Pelvic Ring?

In contrast to ball and socket joints, the SIJ is relatively flat. This configuration is curious given that flat articular surfaces are poorly equipped to resist shear forces. As a result, questions arise including (1) "Why is the pelvis not a solid ring"; (2) "How do humans specifically adapt to resist shear force across the SIJ"; and (3) "What mechanisms exist for when these specific adaptations are not sufficient?"

The human SIJ is required to transfer large forces that a flat joint, like the SIJ, is, theoretically well suited to handle.[16,17] Another mechanism for effective load transfer would be a solid bony connection between the ilium and sacrum. For humans, this is not functional because the human SIJ accommodates critical roles including economize gait, accommodate shock and shear absorption, and accommodate specific and unique needs of pregnancy and childbirth. Further, an important function of the SIJ is to offload stress. A solid bony ring would be more susceptible to fracture as the result of the force and stress the SIJ is typically subjected to in everyday activities.[18]

Which Specific Adaptations Are Available to Resist Shear in the SIJs?

The cartilage adaptions that occur in utero are unique to the SIJs. Undulations in the cartilage are greater on the ilium vs the sacral side of the SIJ. Researchers originally misinterpreted that the undulations represented degenerative arthrosis.[19,20] These undulations are more prominent in men as compared to women resulting in greater stiffness across the SIJ in men.[6,7] Several authors have speculated that purposes for these sex differences include the need to accommodate pregnancy and childbirth. [6,7] Further, these cartilage differences may accommodate the sex-related location of the center of gravity in relationship to the SIJ.[6,7,21] Females have thicker sacral cartilage, which further contributes the less prominent undulations. [22] Vleeming and colleagues proposed that cartilage thickness and undulations that developed over time were in response to the need to functionally adapt to forces initially noted during the first year(s) of life crawling and later in walking.[6,7] Increase in body weight and growth during puberty further promote the adaptive changes across the SIJ resulting in a coarse texture of the cartilage and a "wedge and propeller-like form" of the joint surfaces.[6,7]

Coronal (frontal) sections of intact SIJs from embalmed specimens show the presence of cartilage-covered bony extensions protruding into the joint from both the sacral and iliac surfaces (Figure 1). These bony protrusions are not irregular but are a part of complementary ridges and grooves. Joint samples taken from normal SIJs, with both coarse texture and complementary ridges and grooves, are characterized by high-friction coefficients[7] and therefore reflect adaptation to humans who are bipedal. This contributes to a high coefficient of friction that in turn, enhances the stability of the SIJ against shear force.[6] This mechanism allows for the need for less muscle and ligament force contribution required to accept the weight of the upper body.

Vleeming and colleagues described the bony architecture of the sacrum to be "keystone-like" and thereby, contributes to the stability within the pelvic ring.[6,7] The sacrum's surfaces are wider cranially and anteriorly as compared to the caudal and posterior respective bony surfaces. This orientation allows the sacrum to become "wedged" into the ilia within the pelvic ring in the axial and coronal planes. This suggests the SIJ evolved from a relatively flat joint to become a more stable joint based on these bony configurations (Figure 2).

The principles of form and force closure were introduced to describe the important role of friction in the SIJ. [6,7] Form closure is theoretically a stable setting for the SIJ with joint surfaces that fit closely and where no extra forces are needed to respond to load in order to maintain SIJ stability. Form closure that provides SIJ stability is related to the following structures: wedging of the sacrum between the ilium, ridges, and grooves of the articular surfaces between the ilium and sacrum (Figure 2) that result in a high coefficient of friction,[6,7,16,17] and the dense ligaments of the SIJ. The intrinsic ligaments for the SIJ are among the strongest in the body.[25]

What Mechanisms Exist for When These Specific Adaptations Are Not Sufficient?

Perfect form closure would be similar to the fit of interlocking toy blocks or pieces of a puzzle. If the sacrum lateral surfaces fit perfectly congruent between the two ilium, additional external forces would not be required to maintain joint stability. Such a construct would not allow for the joint mobility required for ambulation, activities of daily living, and accommodations for

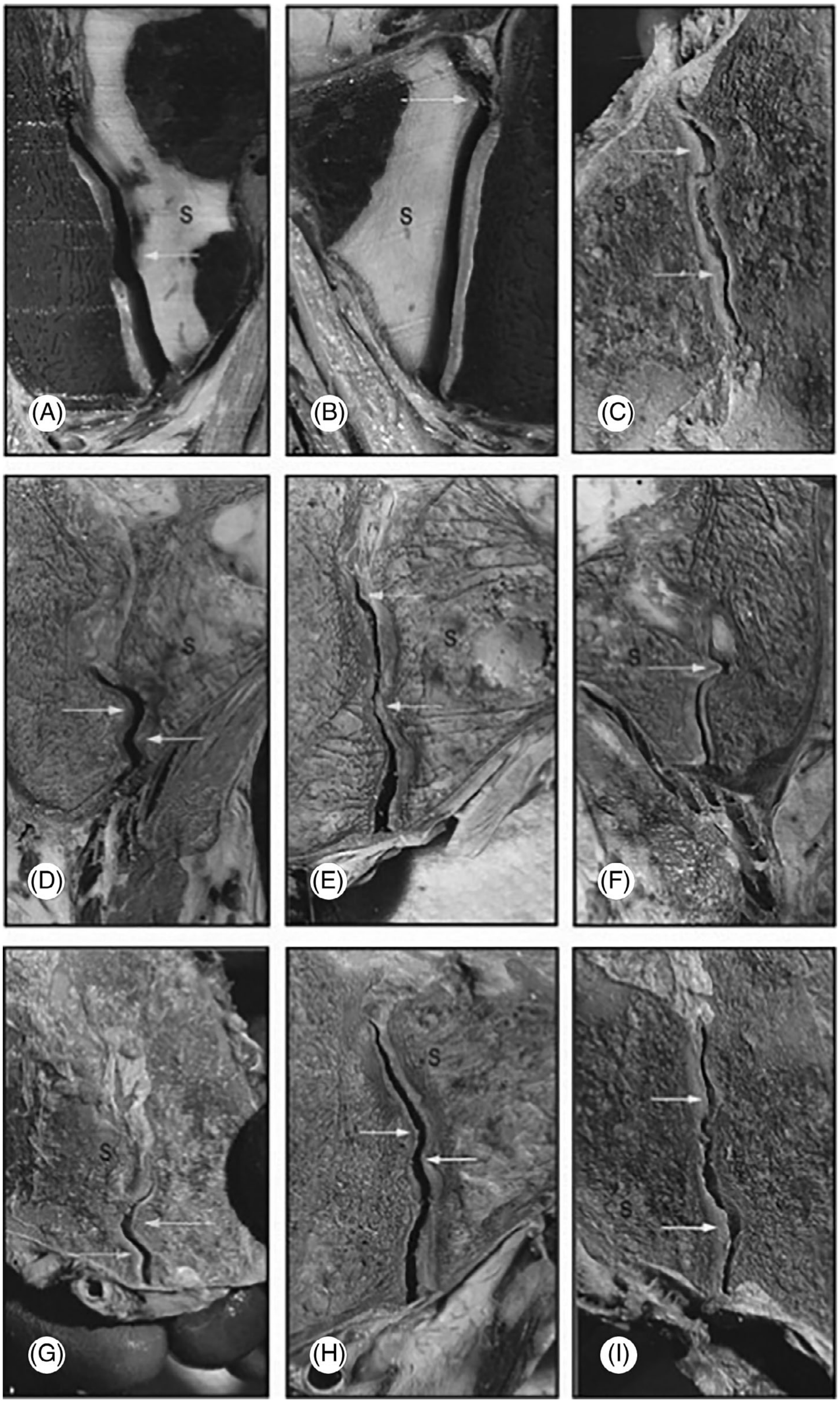

Figure 1. Frontal sections of the sacroiliac joint (SIJ) of embalmed male specimen. S indicates the sacral side of the SIJ. (A) and (B) concern a 12-year-old boy; (C)–(I) concern a specimen older than 60 years. Arrows are directed at complementary ridges and depressions. They are covered by intact cartilage, as was confirmed by opening the joints afterward. (With permission from the Vleeming collection.)[23]

pregnancy and childbirth. Instead, form closure is not perfect, and in some cases, the joint cannot withstand vertical shear forces and loads. When form closure alone is insufficient, *force closure* is required to stabilize the joint. With force closure, (leading to joint compression) both a lateral force and friction are needed to withstand vertical load. The SIJ absorbs shear load by a combination of the bone and cartilage specific anatomic features

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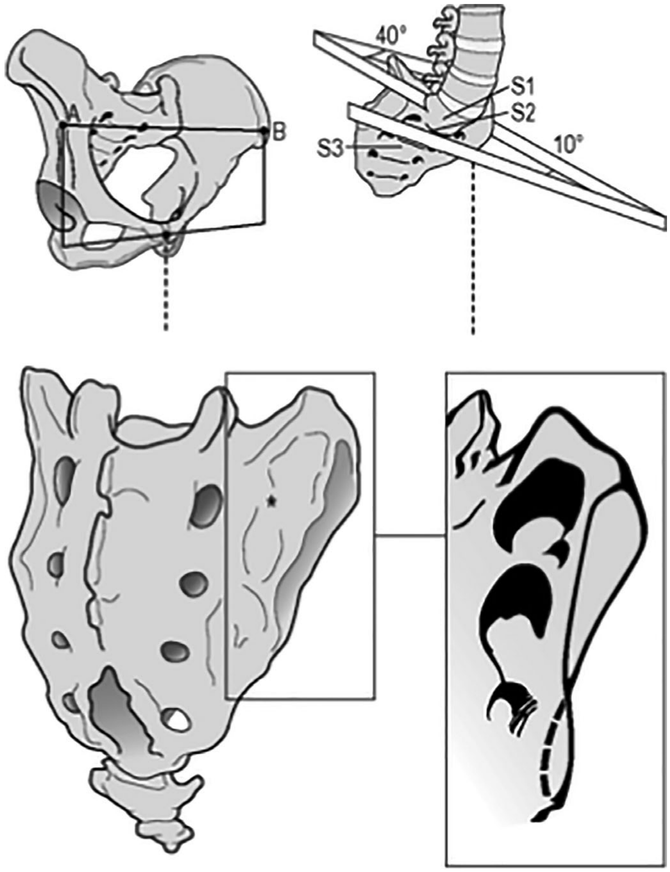

Figure 2. (Top left) Pelvis in erect posture. (Top right) View of the sacrum from ventrolateral side, showing the different angles between left and right sacral articular surface. (Bottom left) Dorsolateral view of the sacrum. The * indicates a cavity in the sacrum in which an iliac tubercle fits and called the "axial" SIJ joint. (Bottom right) Sacral articular surface at the right side. The different angles reflect the propeller-like shape of an adult sacroiliac joint. With permission from the Vleeming collection.[24]

providing form closure and the compression generated by muscles and ligaments provide force closure. Force closure is the effect of altered joint reaction forces generated by tension in ligaments, fasciae, and muscles and ground reaction forces.[6,7,16,17,25] Together, form and force closure are able to accommodate specific load and shear to ultimately provide joint stability.

Force closure ideally generates a perpendicular reaction force to the SIJ to overcome the forces of gravity. This shear prevention system is coined the self-bracing mechanism of the joints.[6,7,16,17,25] When a larger lever is applied and/or neuromotor control of bony movement accommodation becomes less, leading to increased stiffness across the SIJs resulting in accommodations during movement requiring increased force closured to provide stability.[26] Appropriate and accurate neuromotor control is necessary for this mechanism of stability to work.

In self-bracing of the pelvis, nutation of the sacrum is crucial. Sacral nutation is a small rotation of the sacral promontory in an anteroinferior direction and can be seen as an anticipation for joint loading (Figure 3). Therefore, nutation is a movement that is necessary to prepare the pelvis for an increase in load during standing or the swing phase of gait. By creating distance between the bony attachments, nutation tightens most of the SIJ ligaments including the interosseous, short dorsal sacroiliac, sacrotuberous, and sacrospinous ligaments. The consequence of the resulting ligamentous tautness is the drawing together of the posterior iliac bones. This increases compression of the SIJ and forces is closed. This myofascial-ligamentous force closure creates efficient transfer of load that could not be sustained by sacrum and ilium bony anatomy alone.[6,7,16,17,27]

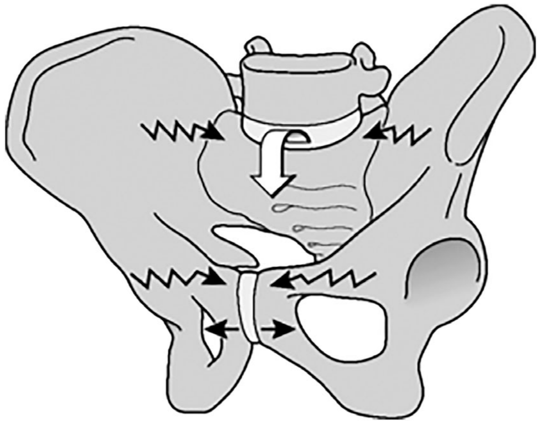

Figure 3. Nutation in the sacroiliac joint. The iliac bones are pulled to each other due to ligament tension (among others) and compress the sacroiliac joints (upper black arrows). It can be expected that especially the upper (anterior) part of the pubic symphysis is compressed. Reproduced with permission from Vleeming.[12]

Form and Force Closure of the SIJ Defined

The SIJ is able to resist shear force because of specific bony and cartilage anatomical components and form and force closure that allows for specific SIJ accommodation. Together, these structural and movement mechanisms provide a way for the SIJ to then balance the friction and compression in the joint. As the sacrum and ilium move in opposite planes during nutation and counternutation and the muscles around the SIJ contract, the tension increases in the ligaments of the SIJ. In this situation where the SIJ is force closed, friction in the SIJ increases[7] and thereby enhances the self-bracing mechanism of the SIJ.[6,7,16,17,25] This force closure increases the SIJ stiffness, which enhances the control of the shear forces and ultimately leads to SIJ stability.

Ligaments and muscles of the trunk including the deep abdominal muscles provide regional contributions to force closure of the SIJ.[28] The combination of regional trunk structures with the structures inherent to the SIJs allow for controlled transmission of shear forces between the ilium and sacrum. As a result, load can then be effectively transferred across the trunk, pelvis, and lower extremities.[16,17] The complexity of this mechanism of load transmission brings to light the importance of neuromotor control to provide efficient and effective

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force closure that is required to counteract gravitation forces during usual posture and movement forces.[29-34] Resting muscle tone and fascial tension coordinated with appropriate force closure are required to provide compression of the SIJs for energy efficient performance of movement and posture.[35-37]

The Principal Muscles of SIJ Force Closure

There are many muscles associated with SIJ force closure including rectus femoris, sartorius, iliacus, gluteus maximus, and hamstrings. These muscles are oriented to have the appropriate lever arms to affect SIJ motion. However, open or closed kinematic movements determine the effectiveness of these muscles to help provide sufficient self-bracing of the SIJ.[27] An alteration in this mechanism can lead to strain on the SIJ. For example, increased ipsilateral pull through the erector spinae, multifidus, quadratus lumborum, and/or the hamstrings can increase shear and force through the SIJ promoting side-to-side asymmetry.[27] Several studies have demonstrated that the stiffness of the SIJ increases with minimal muscle activity further supporting the concept that load transfer from the spine to the lower extremities occurs when muscle contraction both compresses and prevents shearing of the SIJs.[32,34]

Other muscles of the abdomen and pelvis affect the stiffness of the spine and SIJ.[30,34-37] Examples of these muscles include the transversus abdominis (TrA), pelvic floor muscles, and diaphragm. Studies in healthy asymptomatic people have found that appropriate spine stability is noted even with just modest coactivation of paraspinal and abdominal muscles occurs.[38,39] Deeper positioned muscles including the TrA, internal oblique (IO), multifidus, diaphragm, and pelvic floor muscles have been found to perform an anticipatory stabilizing role as noted by their predictable activation just prior to gross movements.[40,41] These deeper muscles are close to the center of rotation of the spine and SIJs and exert higher compressive forces as compared to more superficial muscles.[18] This group of muscles has a greater biomechanical advantage to provide trunk and SIJ stability.[27] Theoretically, because these deeper muscles are so influential on trunk and SIJ stability, altered motor control in these muscles may especially contribute to lumbopelvic pain.

A Biomechanical Model for Force Closing the Pelvic Joints in the Transverse Plane

Several studies have focused on the influence of the contraction muscles including IO and TrA muscles and their influence in providing force closure of the bony pelvic ring.[42-45] The importance of this muscle activity was demonstrated in a study of patients with SIJ and pelvic girdle pain that were found to have decreased IO and TrA muscle activation and reduced erector spinae and multifidi strength.[45] The authors concluded that the aberrant compensatory pattern of muscle activation led to reduced bracing on the SIJ and ultimately, pain.

The biomechanical effect of pelvic stabilization by the anterior abdominal muscles and the importance of the pelvic thoracolumbar fascia are demonstrated in a pelvic model adapted from Snijders et al[46] (Figure 4). This model illustrates the unique effects of the TrA and IO. Further, muscles that flex the hip (iliacus, sartorius, and rectus femoris) are shown to contribute to adding force across the bony pelvis and ultimately have an impact on SIJ stability (Figure 4: Fo). The position of the leg in relationship to the hip joint determines the degree of this contribution. A small gapping force to the

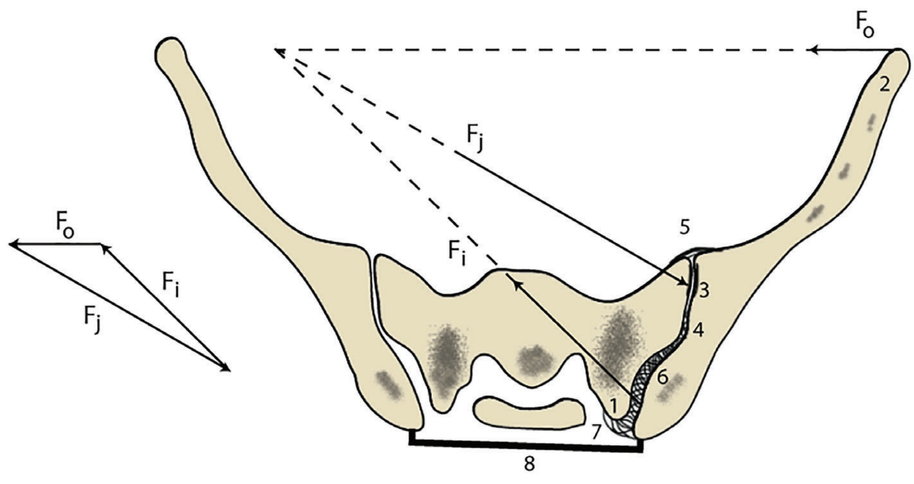

Figure 4. Cross-section of the SIJ on level of S2. A small anterior compressive force is applied from the anterior superior iliac spines, mimicking the transverse and internal oblique muscles (Fo), producing tension dorsally both to the SIJ ligaments and the composite tissues of the thoracolumbar fascia (Fi); a larger reaction force ensues (Fj). Lateral tuberculum sacrum (1), ventral part of the ilium (2), auricular part of the SIJ (3), dorsal SIJ ligaments (4, 6), anterior SIJ ligaments (5), long dorsal ligament (LDL) (7), a composite of thoracolumbar fascia with aponeurosis and especially multifidi muscles visualized as a "clamp."[8] Modified from Snijders et al 1995.

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interosseous, dorsal SIJ ligaments and composite of posterior pelvic muscle and fascia is produced by the lever arm of the anterior muscles (Figure 4: Fo). This combination results in a large joint reaction force (Figure 4Fj). The model also demonstrates that altered anterior abdominal muscle function (Figure 4: Fo), with or without posterior pelvic muscle weakness, can reduce pelvic stability.[45] For example, if the iliacus is activated within an open kinematic chain without effective bracing of the pelvis, anterior rotation of the ipsilateral ilium in the sagittal plane may occur. This movement initiates counternutation of the SIJ, which, in turn, leads to reduced tension in the SIJ ligaments. The degree of reduction in tension is related to the integrity of the long dorsal ligament (LDL) and the anterior portion of the interosseous ligament.[47] This mechanism magnifies the small anterior abdominal force in this biomechanical model (Figure 4) and has been compared to the mechanism of a nutcracker.[46]

Tension in the anterior muscles compresses the anterior SIJ, which would be expected to open posteriorly unless the force was countered from posterior structures. This posterior force has been described as a "clamp" brace comprised of muscle and fascia that overlie the lower dorsal and caudal spine and the SIJ.[48] The thoracolumbar fascia (TLF) contributes to this mechanism. This fascia becomes thicker and better able to resist force in the lower segments including L5, S1, and S2.[49] The erector spinae aponeurosis overlies the multifidus and sacrospinal parts of the erector spinae muscles. This composite of tissue is immediately anterior to the TLF. Further contributions to increase the stiffness of this composite of muscle and fascia is the superficial blending of the lumbar multifidi to the aponeurosis on the dorsal side of the sacrum. The superficial and deep layers of the TLF and the erector spinae aponeurosis all fuse at the level of the posterior superior iliac spine. In turn, this tissue composite fuses to the ilium and blends caudally into the sacrotuberous ligament.[50] When both the erector spinae and multifidus muscles contract, (Figure 5) the muscle and fascia composite layers effectively push and pull leading to an increase in the tension across these blended layers of fascia.

Biomechanical studies have shown that the TrA and oblique abdominal muscles pull the anterior portion of the anterior superior iliac spine (ASIS) toward each other, which results in increased pressure in the SIJ and pubic symphysis. In turn, this contributes to increased force closure of the pelvis in upright posture.[51] The active straight leg test is a physical examination test that assesses, in part, this mechanism. While in the supine position the patient reports the ability to actively raise each leg in a straightened position and then self-reports a grade of 0 (normal ability) to grade 5 (unable to lift the leg). The examiner then applies anterior compression to the ASIS to assist with the self-bracing mechanism of the pelvis and, in most cases, the patient will report an improved ability to lift the leg.[8,51]

Further translation of assessment of this force closure to patient care is noted in a study of patients with severe pelvic girdle pain in whom interdisciplinary rehabilitative care had failed and who were unable to walk. They reported pain relief and improved ability to ambulate following the placement of a temporary of external fixator frame typically used only for pelvic trauma patients[52] (Figure 6). Compression applied to the frame simulates the contraction of the TrA and IO to enhance force closure. Because the lever arms are long, the amount of anterior compression force needed to stabilize the pelvis is small. When the external fixator frame was tightened,

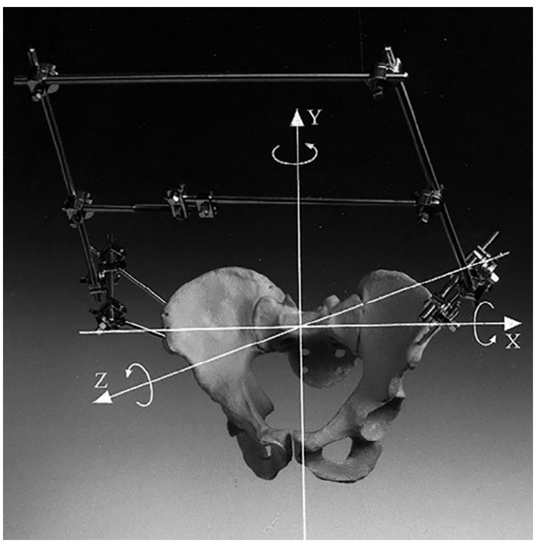

Figure 5. An axial plane computed tomography scan of a male pelvis approximately at the level of PSIS. The sacroiliac joint is indicated by the two opposing black arrows. The body of the multifidus muscles is seen between the two ilia. The posterior lamina of the fascia covering the multifidus is indicated by the double curved line. This portion of the posterior wall of the thoracolumbar fascia is composed of the fused aponeuroses of the erector spinae. The strength of this structure strongly affects Fi and hence the compressive force on Fj.

Figure 6. Frame consisting of two steel rods inserted at the anterior superior iliac spine and connected to a double crossbar anteriorly. With permission from the Vleeming collection.

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the ilium symmetrically rotated posteriorly in a sagittal frame .5° around the x-axis and .9° around the axis of the screw thereby causing nutation of the SIJ.[52] In this situation, compression of the frame forces the sacrum into a more stable anterior position. When tension is increased in the frame, the motion of the SIJ around the helical axis is reduced by 60%-75%. Patients who reported reduced pain with the external fixator were offered an SIJ fusion utilizing the Smith-Peterson technique. Patients who chose surgery continued to use the fixator in the immediate postoperative time period while initiating rehabilitation.[52,53] Long-term outcomes have not been reported on this small group of patients and therefore the long-term effect and adaptions that occur regionally around a fused SIJ are unknown.

If the deep abdominal muscles and the hip flexors are not able to appropriately activate and provide bracing to the pelvis, a counternutation of the SIJ occurs. Counternutation is more common in the unloaded pelvis such as when a person is lying supine. Several studies have confirmed that counternutation is common in patients with pelvic girdle pain.[54–57]

Conclusion

Virtually all movement begins with stabilization of the pelvis. Because the SIJ is a relatively flat joint oriented in the vertical plane, it encounters tremendous vertical forces. Form closure is not sufficient to overcome the shear force, so in order to stabilize the pelvis, the muscles contract and ligaments tighten to force close the pelvis. Any conditions that impair or delay these force closure mechanisms may lead to instability and pelvic girdle pain including the SIJ.

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Disclosure

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