Biomechanics of unilateral and bilateral sacroiliac joint stabilization: laboratory investigation

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OBJECTIVE Bilateral symptoms have been reported in 8%–35% of patients with sacroiliac (SI) joint dysfunction. Stabilization of a single SI joint may significantly alter the stresses on the contralateral SI joint. If the contralateral SI joint stresses are significantly increased, degeneration may occur; alternatively, if the stresses are significantly reduced, bilateral stabilization may be unnecessary for patients with bilateral symptoms. The biomechanical effects of 1) unilateral stabilization on the contralateral SI joint and 2) bilateral stabilization on both SI joints are currently unknown. The objectives of this study were to characterize bilateral SI joint range of motion (ROM) and evaluate and compare the biomechanical effects of unilateral and bilateral implant placement for SI joint fusion.

METHODS A lumbopelvic model (L5–pelvis) was used to test the ROM of both SI joints in 8 cadavers. A single-leg stance setup was used to load the lumbar spine and measure the ROM of each SI joint in flexion-extension, lateral bending, and axial rotation. Both joints were tested 1) while intact, 2) after unilateral stabilization, and 3) after bilateral stabilization. Stabilization consisted of lateral transiliac placement of 3 triangular titanium plasma-sprayed (TPS) implants.

RESULTS Intact testing showed that during single-leg stance the contralateral SI joint had less ROM in flexion-extension (27%), lateral bending (32%), and axial rotation (69%) than the loaded joint. Unilateral stabilization resulted in significant reduction of flexion-extension ROM (46%) on the treated side; no significant ROM changes were observed for the nontreated side. Bilateral stabilization resulted in significant reduction of flexion-extension ROM of the primary (45%) and secondary (75%) SI joints.

CONCLUSIONS This study demonstrated that during single-leg loading the ROMs for the stance (loaded) and swing (unloaded) SI joints are significantly different. Unilateral stabilization for SI joint dysfunction significantly reduces the ROM of the treated side, but does not significantly reduce the ROM of the nontreated contralateral SI joint. Bilateral stabilization is necessary to significantly reduce the ROM for both SI joints.

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KEY WORDS sacroiliac joint disruption; degenerative sacroilitis; fusion; biomechanics; minimally invasive surgery; sacral

The sacroiliac (SI) joints represent 2 of the 3 joints of the pelvic ring. This ring is relatively stiff, yet it maintains some flexibility due to the motion, even though small, of the SI joints and pubic symphysis. Due to this ring structure, a change in stability (i.e., fracture) has been noted to correlate to a change in stability elsewhere in the pelvis.30

The SI joint is a common source of low-back pain and is involved in 15%–30% of patients diagnosed with chronic low-back pain.3,16,23,24 SI joint–related pain can be incapacitating, as evidenced by high Oswestry Disability Index (ODI) scores,12,31 and has a burden of disease similar to that of other spinal conditions (e.g., spinal stenosis, degenerative spondylolisthesis) that are treated surgically.4

The prevalence of SI joint degeneration increases with age,8 and the condition is more common in patients with a previous lumbar fusion.10 SI joint dysfunction can be related to various pathologies (e.g., inflammatory arthropathy, postpartum strain, and trauma), and patients may present with either unilateral or bilateral symptoms.
Recent SI joint fusion studies have reported that a majority of patients receive unilateral treatment, although bilateral (same-day or staged) SI joint surgery has been reported in 8%–35% of patients receiving surgical treatment.6,22,27,33 The 2-year results from a randomized trial demonstrated that both unilateral and bilateral treatment using triangular titanium plasma-sprayed (TPS) implants resulted in significant reductions in visual analog scale scores for SI joint pain and ODI scores for the treated joint.21

As a result of the ring-like nature of the pelvis, stabilization of a single SI joint could significantly affect the motion of the unstabilized SI joint. In the intact condition, the biomechanical stresses at the left and right SI joints are similar.11 As a result of stabilizing a single SI joint, the stresses and range of motion (ROM) of the contralateral SI joint could be either increased or decreased in relation to the intact conditions. If the contralateral SI joint stresses are significantly increased, degeneration may occur; fusion of the lumbar motion segments has been reported to increase the biomechanical stresses at the adjacent levels, likely leading to adjacent-segment disease.19 Alternatively, if the stresses are significantly reduced, bilateral surgery may be unnecessary for patients with bilateral symptoms. Kiapour et al.11 demonstrated that altering pelvic biomechanics by creating and increasing leg length discrepancies resulted in altered stresses for both the ipsilateral and contralateral SI joints. Previous investigations have demonstrated that stabilization of a unilateral SI joint results in reduced ROM of that joint,14,25 while the ROM in the lumbar spine is minimally increased.13 Whether unilateral SI joint stabilization increases or decreases the ROM of the contralateral SI joint is currently unknown. Lastly, if the contralateral SI joint motion is reduced, whether unilateral fixation may be sufficient for a patient with bilateral symptoms remains to be investigated.

The ex vivo biomechanics of the pelvis have been investigated using single-leg stance,15,20 bilateral stance,5,18,32 and most recently alternate leg loading.1,26 One major difference between these models is the unique requirements for the experimental fixturing to apply physiological loading (e.g., bilateral stance should allow for motion through the pelvic ring, which single-leg stance inherently does). The use of a single-leg stance model allows for investigation of the ROM of both the stance and swing SI joints; alternate leg loading can be experimentally simulated by loading the left and right sides in single-leg stance. Typically, these models have generated bending moments by applying axial compression at a known distance from the center of rotation and measured the motion at the pubic symphysis. To simulate the motions of daily living, an alternative approach is to apply pure moments to the specimen in the 3 anatomical planes (sagittal, coronal, and transverse).14,25 Each of these methods has been used to investigate different biomechanical parameters (e.g., pubic symphysis motion and SI joint motion) with relative appropriateness. The motions of the nonloaded joints during single-leg stance remain an area of investigation.

In this study, we sought to explore the motion of the intact SI joint during single-leg stance in both the stance (loaded) and swing (unloaded) phases and compare this with the motion of SI joints that have been stabilized unilaterally and bilaterally. We hypothesized that 1) the mean intact ROM of the unloaded (swing) side would be lower than that of the loaded (stance) side and 2) implanted specimens would have lower mean SI joint ROM on both the primary and secondary sides than the intact specimen.

**Methods**

**Specimen Preparation**

Eight cadaveric specimens (L5–pelvis) were prepared by stripping the soft tissue, while preserving the joint capsule and pubic symphysis. The left and right ischia were embedded with the pelvis oriented in an upright position.14,25

**Test Procedure**

Specimens were tested in the following conditions: intact, unilateral stabilization, and bilateral stabilization. For each condition, loading was applied using a single-leg stance model for both the left and right SI joints.14,25 Pure moment loading was used to apply a 7.5 N-m moment to the superior endplate of L-5 in flexion-extension (nutation/counternutation), left and right bending, and left and right rotation.14,25 Loading was applied via a servohydraulic test frame (858 Mini Bionix II; MTS) through a custom fixture for pure moment loading.7

**Motion Analysis**

Optoelectronic markers were placed on each side of the sacrum and on each iliac wing. The marker motions were captured by an optoelectronic system (Optotrak 3020; Northern Digital, Inc.). The accuracy of the Optotrak 3020 optical active-marker system has been reported to have a bias of 0.05° and 0.03 mm, with repeatability limits of 0.67° and 0.29 mm.17 The motion in flexion and the motion in extension were measured and combined; likewise, left and right bending and left and right rotation were combined to result in lateral bending ROM and axial rotation ROM, respectively. Motions were captured for both SI joints during both left and right single-leg stances.

**Treatment**

Treatment consisted of placement of 3 triangular TPS implants (iFuse Implant System; SI-BONE, Inc.) using a lateral transiliac procedure. Briefly, this treatment uses a simple pin, drill, broach, and implant technique under fluoroscopic guidance.9 Using this technique, the cranial implant was placed caudal to thealar line (iliac cortical density), above the S-1 neuroforamen, and parallel to the S-1 endplate. The middle implant was placed with the entry point ventral to the anterior sacral cortical body line with a trajectory toward the anterior third of the sacral body. The caudal implant was placed roughly parallel to the cranial implant in the inlet and outlet views and positioned between the S-1 and S-2 neuroforamina.

**Data Analysis**

The intact data were analyzed using paired t-tests between the left and right SI joints for both the stance (load-
ed) and swing (unloaded) conditions in flexion-extension, axial rotation, and lateral bending. The data for the treated conditions were analyzed using a repeated-measures ANOVA with post hoc comparisons using the method of Holm (R version 3.2.1). Data for each SI joint were compared between the 3 conditions (intact, unilateral, and bilateral) for each of the loading conditions; p values less than 0.05 were considered statistically significant.

**Results**

Eight cadaveric specimens (age range 28–57 years, 6 female and 2 male) were tested (Table 1).

Analysis of the intact motion data demonstrated no statistically significant differences between the left and right SI joints during the stance phase when loaded in flexion-extension (p = 0.2), axial rotation (p = 0.7), and lateral bending (p = 0.2); likewise, no significant differences were observed in the SI joints during the swing phase when loaded in flexion-extension (p = 0.3), axial rotation (p = 0.3), and lateral bending (p = 0.2) (Table 2). Due to the lack of significance between the left and right joint motions during the stance and swing phases, respectively, the left and right SI joint motions were pooled into stance and swing groupings for intact comparisons, respectively. The intact SI joints during the swing phase had 27% (p < 0.0001), 32% (p < 0.001), and 69% (p < 0.01) less ROM than the intact SI joints during the stance phase in flexion-extension, axial rotation, and lateral bending, respectively (Table 3).

Unilateral SI joint stabilization during the stance phase resulted in a significant reduction in the flexion-extension ROM of the fixated (primary) SI joint of 46% (p = 0.03); no significant differences were observed in axial rotation (p = 0.29) or lateral bending (p > 0.99) of the primary SI joint during the stance phase (Fig. 1). Unilateral stabilization resulted in no significant differences in any motion of the nonstabilized (secondary) SI joint during loading stance (Fig. 2) or swing (Fig. 3) phases of the SI joints (p > 0.07).

Bilateral SI joint stabilization resulted in a significant reduction of 75% in flexion-extension motion of the secondary SI joint during the stance phase (p = 0.049); no significant differences were observed in axial rotation (p > 0.99) or lateral bending (p = 0.37) of the secondary SI joint during the stance phase (Fig. 2). The reduction in motion of the primary SI joint during the stance phase was maintained in flexion-extension (45%, p = 0.0022) when

### Table 1. Specimen demographics and treatment parameters

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Age (yrs), Sex</th>
<th>Primary Implant Side</th>
<th>Implant Lengths* (superior, middle, inferior)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>52, F</td>
<td>Lt</td>
<td>60, 50, 50, 60, 50, 45</td>
</tr>
<tr>
<td>B</td>
<td>52, F</td>
<td>Lt</td>
<td>55, 60, 40, 60, 50, 35</td>
</tr>
<tr>
<td>C</td>
<td>28, F</td>
<td>Lt</td>
<td>55, 50, 40, 60, 55, 40</td>
</tr>
<tr>
<td>D</td>
<td>52, M</td>
<td>Lt</td>
<td>50, 45, 40, 40, 50, 55</td>
</tr>
<tr>
<td>E</td>
<td>57, F</td>
<td>Rt</td>
<td>65, 50, 45, 55, 35</td>
</tr>
<tr>
<td>F</td>
<td>49, F</td>
<td>Rt</td>
<td>50, 45, 50, 60, 50, 40</td>
</tr>
<tr>
<td>G</td>
<td>48, F</td>
<td>Rt</td>
<td>60, 60, 60, 55, 50, 45</td>
</tr>
<tr>
<td>H</td>
<td>36, M</td>
<td>Rt</td>
<td>55, 40, 40, 60, 60, 60</td>
</tr>
</tbody>
</table>

* Measurements are in millimeters.

### Table 2. Intact SI joint ROM for the left and right joints during loading for single-leg stance of the left and right joints

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Flexion-Extension ROM (°)</th>
<th>Axial Rotation ROM (°)</th>
<th>Lateral Bending ROM (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stance Phase</td>
<td>Swing Phase</td>
<td>Stance Phase</td>
</tr>
<tr>
<td>A</td>
<td>3.309</td>
<td>1.788</td>
<td>0.747</td>
</tr>
<tr>
<td>B</td>
<td>4.441</td>
<td>4.059</td>
<td>3.532</td>
</tr>
<tr>
<td>C</td>
<td>1.096</td>
<td>1.452</td>
<td>0.883</td>
</tr>
<tr>
<td>D</td>
<td>1.255</td>
<td>0.993</td>
<td>0.443</td>
</tr>
<tr>
<td>E</td>
<td>6.675</td>
<td>5.362</td>
<td>4.843</td>
</tr>
<tr>
<td>F</td>
<td>2.473</td>
<td>2.825</td>
<td>1.691</td>
</tr>
<tr>
<td>G</td>
<td>2.424</td>
<td>1.923</td>
<td>1.69</td>
</tr>
<tr>
<td>H</td>
<td>1.056</td>
<td>1.226</td>
<td>0.957</td>
</tr>
<tr>
<td>Mean</td>
<td>2.841</td>
<td>2.454</td>
<td>1.848</td>
</tr>
<tr>
<td>SD</td>
<td>1.947</td>
<td>1.537</td>
<td>1.548</td>
</tr>
</tbody>
</table>

**p value** (p = 0.2) (p = 0.3) (p = 0.7) (p = 0.3) (p = 0.2) (p = 0.2)

**Boldface type indicates statistical significance.**

### Table 3. Results of analysis of pooled data (left and right) for intact SI joints

<table>
<thead>
<tr>
<th>Flexion-Extension ROM (°)</th>
<th>Axial Rotation ROM (°)</th>
<th>Lateral Bending ROM (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stance Phase</td>
<td>Swing Phase</td>
<td>Stance Phase</td>
</tr>
<tr>
<td>Mean</td>
<td>2.647</td>
<td>1.940</td>
</tr>
<tr>
<td>SD</td>
<td>1.706</td>
<td>1.626</td>
</tr>
</tbody>
</table>

**p value** <0.0001 0.0002 0.0011

Boldface type indicates statistical significance.
compared with the intact condition (Fig. 1); no additional motion reduction was observed in axial rotation or lateral bending when compared with the unilateral condition ($p \geq 0.24$) (Fig. 1). During the swing phase, there was no significant difference between the mean motions in flexion-extension, axial rotation, and lateral bending for the intact, unilaterally stabilized, and bilaterally stabilized primary joints ($p \geq 0.06$) (Fig. 4).

**Discussion**

The current study analyzed the intact motion of the SI joint during both the stance phase and swing phase of single-leg stance. It also demonstrated that the nonloaded (swing phase) SI joint had 27% less flexion-extension ROM than the loaded SI joint. Sturesson et al.\[^{28}\] reported that hyperextension of the left and right legs resulted, respectively, in $0.4^\circ$ (18%) and $0.6^\circ$ (27%) less sagittal plane motion in the contralateral SI joint. In addition to the SI joints, the pelvic ring contains the pubic symphysis, which allows for additional motion between the left and right pubis. The mobility at the pubic symphysis allows for some (but incomplete) transmission of load to the contralateral SI joint. The mobility of the pubic symphysis appears to be the primary reason that stabilization of a single SI joint does not significantly reduce the motion of the contralateral SI joint.

**FIG. 1.** Primary SI joint ROM in stance (loaded) phase. Single-leg stance was simulated by fixing the ischium on the primary side during loading of the lumbar spine. Data shown as mean ± SD. Deg = degrees. *$p < 0.05$. Figure is available in color online only.

**FIG. 2.** Secondary SI joint ROM in stance (loaded) phase. Single-leg stance was simulated by fixing the ischium on the secondary side during loading of the lumbar spine. Data shown as mean ± SD. *$p < 0.05$. Figure is available in color online only.
Unilateral stabilization significantly reduced the primary SI joint ROM in flexion-extension, but did not significantly alter (i.e., increase or decrease) the motion of the secondary, untreated joint. Previous studies have demonstrated that unilateral stabilization of the SI joint significantly reduces the SI joint ROM of the treated joint.\textsuperscript{14,25} Soriano-Baron et al.\textsuperscript{25} compared 2 laterally oriented stabilization techniques and reported significant decreases in flexion-extension, lateral bending, and axial rotation ROM. In that study, the pubic symphysis was sectioned to allow for a paired statistical analysis between the 2 treatment techniques. The current study preserved the pubic symphysis as part of the intact pelvic ring, which is more physiological. As noted for the intact comparison, the pubic symphysis appears to transfer load through the pelvic ring from the primary SI joint to the secondary SI joint. This load transfer may explain the statistical differences between the current study and the previously reported results in lateral bending and axial rotation. These results demonstrate that unilateral stabilization did not increase the ROM of the untreated joint, suggesting that adjacent-segment disease of the untreated SI joint due to increased biomechanical stresses is unlikely. In addition, unilateral stabilization did not significantly reduce the untreated SI

**FIG. 3.** Secondary SI joint ROM in swing (unloaded) phase. Single-leg stance was simulated by fixing the ischium on the primary side during loading of the lumbar spine. No significant differences were observed. Data shown as mean ± SD. Figure is available in color online only.

**FIG. 4.** Primary SI joint ROM in swing (unloaded) phase. Single-leg stance was simulated by fixing the ischium on the secondary side during loading of the lumbar spine. No significant differences were observed. Data shown as mean ± SD. Figure is available in color online only.
joint ROM, suggesting that unilateral stabilization would not be biomechanically sufficient for patients presenting with bilateral symptoms.

Bilateral stabilization significantly reduced the secondary SI joint ROM in flexion-extension. In line with unilateral treatment, stabilization of the secondary SI joint maintained the reduced ROM of the treated joint, and did not lead to any further reduction in motion at the primarily treated SI joint. The additional stabilization of the secondary SI joint provided by bilateral fixation suggests that treatment for a symptomatic SI joint requires treatment of the symptomatic side.

For patients with bilateral symptoms, bilateral surgery can be performed in a single surgical session (i.e., as “same-day” or “simultaneous” surgery) or in a staged manner (i.e., 2 procedures separated by a length of time allowing for recovery from the initial surgery). Duhon et al. reported that 21% of patients undergoing bilateral SI joint fusion had surgery for both joints on the same day.6 Simultaneous bilateral surgery is commonly performed for hip and knee replacements.2,29 Comparison of unilateral and bilateral total knee arthroplasty procedures has shown that bilateral procedures are associated with increased complications, reoperation, total length of hospital stay, and more intensive rehabilitation.29 Comparison of simultaneous and staged hip replacement bilateral surgeries has demonstrated that simultaneous surgeries are as safe as or safer than 2-stage interventions.2 The practical consideration with simultaneous SI joint fusion is the recommendation for protected weight bearing on both sides, which at times may necessitate using a wheelchair during postoperative recovery. For some patients, using a wheelchair may be suboptimal due to risk of muscle and bone loss from immobility and general patient inconvenience. Comparative data on long-term clinical results of staged and simultaneous SI joint surgeries are not currently available, and further investigation is warranted.

The current study used an ex vivo single-leg stance model to investigate the biomechanical ROM of the SI joints. This model has some limitations. Although this model mimicked physiological loading using 3 loading directions, these may not encompass all loading combinations that could be encountered after surgery. In addition, the present model did not simulate biological fixation of the implants (i.e., bone ingrowth or ongrowth to the implants) and as such, the findings are only indicative of the time of initial implant placement. Lastly, the amount of stabilization (i.e., reduction in SI joint ROM) required at the time of surgery to result in a positive clinical outcome is not known. The stabilization is only the initial step in treating SI joint dysfunction. Fusion is a biological process that takes many months and ultimately leads to reduction of both joint motion and SI-mediated pain. The amount of initial ROM reduction after placement of implants that will result in the greatest likelihood of solid fusion is unknown. As in other anatomical areas (spine), some load sharing between the implants and bones after initial stabilization may result in a greater chance of solid arthrodesis than complete initial joint immobilization. As such, the application of these results to the clinical setting must be made with caution.

Conclusions
This study demonstrated that in the intact condition, single-leg stance results in less ROM for the nonloaded SI joint in the swing phase than for the loaded SI joint in the stance phase (i.e., stresses on an SI joint are highest when that joint is loaded). This study also demonstrated that unilateral stabilization of the SI joint significantly reduces the treated SI joint ROM, but not the untreated SI joint ROM. Lastly, this study demonstrated that bilateral stabilization of both SI joints maintains the unilateral reduction of the initially treated (primary) SI joint ROM, while also significantly reducing the secondarily treated SI joint ROM. As such, for a patient with bilateral SI joint symptoms, unilateral SI joint stabilization does not appear to be biomechanically sufficient to treat bilateral SI joint dysfunction.

References
Disclosures
This study was funded by SI-BONE, Inc. Mr. Lindsey and Dr. Yerby are employees of SI-BONE, Inc. Dr. Kondrashov is a paid consultant of and conducts clinical research for SI-BONE, Inc. Dr. Gundanna is a paid consultant of SI-BONE, Inc. Dr. Kondrashov also reports a consultant relationship with Spineart and receipt of support from AOSpine for non–study-related research or clinical effort.

Author Contributions
Conception and design: Lindsey, Gundanna, Leasure, Yerby, Kondrashov. Acquisition of data: Lindsey, Parrish, Leasure, Kondrashov. Analysis and interpretation of data: Lindsey, Gundanna, Yerby. Drafting the article: Lindsey. Critically revising the article: all authors. Approved the final version of the manuscript on behalf of all authors: Lindsey. Statistical analysis: Lindsey.

Supplemental Information
Previous Presentations
Portions of this work were presented at the 9th Interdisciplinary World Congress on Low Back and Pelvic Girdle Pain, October 31–November 3, 2016, in Singapore.

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