Biomechanics of a laterally placed sacroiliac joint fusion device supplemental to S2 alar-iliac fixation in a long-segment adult spinal deformity construct: a cadaveric study of stability and strain distribution

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OBJECTIVE S2 alar-iliac (S2AI) screw fixation effectively enhances stability in long-segment constructs. Although S2AI fixation provides a single transarticular sacroiliac joint fixation (SIJF) point, additional fixation points may provide greater stability and attenuate screw and rod strain. The objectives of this study were to evaluate changes in stability and pedicle screw and rod strain with extended distal S2AI fixation and with supplemental bilateral integration of two sacroiliac joint fusion devices implanted using a traditional minimally invasive surgical approach.

METHODS Eight L1–pelvis human cadaveric specimens underwent pure moment (7.5 Nm) and compression (400 N) tests under 4 conditions: 1) intact (pure moment loading only); 2) L2–S1 pedicle screw and rod with L5–S1 interbody fusion; 3) added S2AI screws; and 4) added bilateral laterally placed SIJF. Range of motion (ROM), rod strain, and screw-bending moment (S1 and S2AI) were analyzed.

RESULTS Compared with S1 fixation, S2AI fixation significantly reduced L5–S1 ROM in right lateral bending by 50% (0.11°, $p = 0.049$) and in compression by 39% (0.22°, $p = 0.003$). Compared with fixation ending at S1, extending fixation with S2AI significantly decreased sacroiliac joint ROM by 52% (0.28°, $p = 0.02$) in flexion, by 65% (0.48°, $p = 0.04$) in extension, by 59% (0.76°, $p = 0.02$) in combined flexion-extension, and by 36% (0.09°, $p = 0.02$) in left axial rotation. The addition of S2AI screws reduced S1 screw-bending moment during flexion (0.106 Nm [43%], $p = 0.046$). With S2AI fixation, posterior L5–S1 primary rod strain increased by 124% (159 μ E, $p = 0.002$) in flexion, by 149% (285 μ E, $p = 0.02$) in left axial rotation, and by 99% (254 μ E, $p = 0.04$) in right axial rotation. Compared with S2AI fixation, the addition of SIJF reduced L5–S1 strain during right axial rotation by 6% (28 μ E, $p = 0.04$) and increased L5–S1 strain in extension by 6% (28 μ E, $p = 0.02$).

CONCLUSIONS Long-segment constructs ending with S2AI screws created a more stable construct than those ending with S1 screws, reducing lumbosacral and sacroiliac joint motion and S1 screw-bending moment in flexion. These benefits, however, were paired with increased rod strain at the lumbosacral junction. The addition of SIJF to constructs ending at S2AI did not significantly change SI joint ROM or S1 screw bending and reduced S2AI screw bending in compression. SIJF further decreased L5–S1 rod strain in axial rotation and increased it in extension.

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KEYWORDS iFuse; iliac fixation; minimally invasive surgery; rod strain; sacroiliac joint; sacropelvic fixation; S2AI; sacral

ADULT spinal deformity correction surgery is a widely researched area in spine surgery because of the unique clinical and biomechanical challenges associated with these procedures. The estimated incidence of pseudarthrosis is 24% in patients with long fusions that

end caudally at the sacrum.¹ A solid foundation able to resist the robust moment and load present at the lumbosacral junction may help prevent mechanical failure at the base of the construct.² Despite the reported mechanical benefits of extending distal fixation to the ilium, including shield-

ABBREVIATIONS ALIF = anterior lumbar interbody fusion; MIS = minimally invasive surgery; PSR = pedicle screw and rod; ROM = range of motion; SIJF = sacroiliac joint fixation; S2AI = S2 alar-iliac.

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TABLE 1. Cadaveric specimen information

Specimen No.	Sex/Age (yrs)*	L4 BMD (g/cm ²)†	Cause of Death
1	F/62	0.521	Drug overdose (polysubstance)
2	M/60	0.871	Heart failure
3	F/60	0.729	Progressive multisystem atrophy
4	M/61	0.768	Unknown
5	F/64	0.890	Stroke (CVA)
6	F/64	0.687	Pickwickian syndrome
7	F/61	0.545	Stroke (CVA)
8	F/52	0.641	Unknown

BMD = bone mineral density; CVA = cerebrovascular accident.

* The overall mean $\pm$ SD age was 60.5 ± 3.5 years.

† The overall mean $\pm$ SD BMD was 0.707 ± 0.13 g/cm², determined with dual-energy x-ray absorptiometry.

ing the sacral screw from mechanical stress and achieving stability similar to that of constructs with anterior column support,^{3–7} this fixation is still associated with a relatively high rate of failure. Increased rod strain in the lumbosacral region^{5,8} and mechanical complication rates as high as 35% have been reported⁹ for distal fixation to the ilium.

Sacropelvic fixation with S2 alar-iliac (S2AI) screw placement has been widely used because it requires less extensive dissection, has decreased skin prominence, and does not require offset rod connectors. Biomechanically, S2AI fixation has been reported to provide stability similar to that of a traditional iliac screw.^{10–14} Although S2AI screws uniquely cross the articular cartilage of the sacroiliac joint, the full biomechanical ramifications are not well known.¹⁵

Sacroiliac joint fixation (SIJF) with minimally invasive surgery (MIS) for laterally placed triangular titanium implants and multiple fixation points has been used clinically for patients with chronic back pain.^{16–21} Previous in vitro biomechanical studies demonstrated that 3 triangular titanium implants placed across the sacroiliac joint significantly reduced range of motion (ROM) compared with that in the intact joint.^{22–24} Multiple biomechanical studies have demonstrated that using 1 sacroiliac joint screw results in less stability than that achieved with the placement of 2 screws across the joint.^{25–28} The general hypothesis—that increased number of fixation points across the sacroiliac joint improves stability—is corroborated by these studies; however, data are scarce about this effect in long-segment constructs used to address adult spinal deformity.

Because of the transarticular nature of the S2AI screw and the large and irregular surface of the sacroiliac joint, it is hypothesized that rotational motion of the joint can occur about the long axis of the screw. A previous biomechanical study reported that S2AI fixation demonstrated minimal change in sacroiliac joint motion compared with the intact condition.²⁹ Therefore, adding multiple points of sacroiliac fixation through an MIS approach may provide additional stability and serve to attenuate screw and rod strain. The objectives of the current study were to evaluate changes in stability and pedicle screw and rod (PSR) strain with extension of long-segment lumbosacral fixation (with L5–S1 anterior lumbar interbody fusion [ALIF]) from S1

TABLE 2. Testing order of the intact and 3 instrumented conditions

Order	Instrumentation	Anterior Support	Abbreviation
1	Intact	None	Intact
2	L2–S1 PSR	L5–S1 ALIF	S1
3	L2–S2AI PSR	L5–S1 ALIF	S2AI
4	L2–S2AI + SIJF PSR	L5–S1 ALIF	SIJF

to S2AI and with supplemental integration of bilateral stand-alone SIJF devices implanted through a traditional lateral MIS approach.

Methods

Eight fresh-frozen human cadaveric L1–pelvis specimens were selected for this study: 6 females and 2 males, with a mean $\pm$ SD age of 60.5 ± 3.5 years. Review of medical records and plain film radiographs and direct manual inspection were performed to ensure that no obvious pathology or sacroiliac abnormality may have affected the results. Dual-energy x-ray absorptiometry scans were performed on the L4 vertebra of each specimen to assess bone mineral density (g/cm²) (Table 1).

Specimens were stored at -20°C until test day, then thawed in normal saline at 21°C . Muscles and soft tissues were cleaned while all ligaments, joint capsules, and intervertebral discs were kept intact. The ischium was bilaterally reinforced with household wood screws, placed in a rectangular metal mold, and embedded using fast-curing resin (Smooth-Cast, Smooth-On, Inc.) to permit attachment to the base of the testing apparatus. The top vertebra (L1) was also reinforced with household screws and embedded in the same resin in a cylindrical pot for test frame attachment and loading.

Instrumentation

The 4 test conditions are listed in Table 2 and illustrated radiographically in Fig. 1. All specimens were first tested in the intact “S1” condition. The S1 test condition included the following instrumentation. Polyaxial pedicle screws (6.0×45 mm, Stryker Corp.) were inserted from L2 to S1 under fluoroscopic guidance. Wide anterior annulotomy, followed by full discectomy, was performed at L5–S1, and an ALIF titanium implant (NuVasive, Inc.) was placed with three 5.0×25 -mm screws (1 into L5, 2 into S1). Interbody spacers were sized to contact the surfaces of both endplates without changing alignment ($6 \times 38 \times 28$ mm) with varying lordosis (15° – 20°). Two 5.5-mm diameter titanium rods were contoured bilaterally to fit screw heads from L2 to S1 and to minimize the need for reduction.

After specimens were tested in the S1 condition, S2AI screws were placed bilaterally using fluoroscopy (8.5×80 mm, Stryker Corp.) and connected to the rods; then, each specimen was retested (“S2AI” condition). For the last test condition (“SIJF”), each specimen underwent additional SIJF (iFuse-3D Implant System, SI-BONE, Inc.) through a lateral approach with rods still attached. Two additional SIJF devices were implanted across the sacroiliac joint

FIG. 1. Radiographic views of the 3 instrumented spine conditions that were tested. ALIF with S1 fixation (A), ALIF with S2AI fixation (B), and lateral (C) and posterior (D) ALIF with S2AI screws and additional SIJF.

through an MIS approach. Implant length varied according to the anatomy of each specimen. Fluoroscopic guidance was used to ensure correct positioning. Procedures for implanting the SIJF device were performed according to the manufacturer's recommendations.

Surgical Technique

Two SIJF devices were implanted across each sacroiliac joint. The first was implanted at the superior aspect of the joint at the S1 level, and the second just inferior to it at the S1 neuroforamen level. The entry points were lateral on the pelvis. The trajectory was started with a pin and prepared using a set of probes, a drill bit, and a broach under fluoroscopic guidance using a ruler to monitor depth. The outlet, inlet, and lateral views were the main radiographic views used to guide this procedure. The SIJF devices crossed the sacroiliac joint, with the cranial implant resting just superior to the S1 foramen and lateral to the S1 pedicle screw; the caudal implant was placed lateral to the S1 foramen and superior to the S2AI screw.

Biomechanical Tests

Test specimens were fixed caudally to the testing frame

table to permit unconstrained relative medial-lateral translation between the ilia, and they were fixed cranially to the end effector of a robotically controlled testing frame with 6 degrees of freedom (Fig. 2).³⁰ To assess ROM stability, rod strain, and sacral screw-bending moment, specimens were subjected to dynamic, nondestructive pure moment flexibility tests at 7.5 Nm with a mean global rotation rate of 1.5°/sec. In each case, 3 cycles of nonconstraining pure moment were applied in flexion, extension, right and left lateral bending, and right and left axial rotation, followed by 3 cycles of vertical gravitational compression forces to 400 N (intact spine condition excluded), with data from the last cycle used for analysis.

Angular Motion Tracking

Angular ROM was determined with 3D optical tracking using an Optotrak 3020 active marker system (Northern Digital, Inc.). This system stereophotogrammetrically measured the 3D positions of infrared-emitting markers attached to each vertebra in a noncollinear arrangement. Custom software was used to convert the marker coordinates to angles about each of the anatomical axes.³¹

FIG. 2. Test specimen in the robotic testing frame with 6 degrees of freedom. **A:** Anterior view of a specimen with optical marker arrays. **B:** Lateral view with SIJF (white arrows) in place. **C:** Posterior view of a specimen with L5–S1 rosette strain gauges (white arrow) in place on the right posterior rod. The S1–2 strain gauge is covered with gauze. Figure is available in color online only.

Screw-Bending Moment and Rod Strain Monitoring

Before insertion into the bone, each right-side screw intended for the L5, S1, and S2AI levels was instrumented with 4 circumferentially placed uniaxial strain gauges (C2A-06-015LW-120). A loading calibration procedure was performed on each screw to establish strain versus screw-bending moment relationships.³² The posterior rod intended for the right side of each specimen was instrumented with stacked rosette strain gauges (C2A-06-G1350-120) at the midlevel between L5–S1 and S1–S2AI, with the gauges facing posteriorly. The rod gauges were attached after rod contouring and were not calibrated to externally applied loads. Strain gauge placement at L5–S1 is visible in Fig. 2.

Statistical Analysis

Statistical comparisons of mean ROM, screw-bending moment, and rod strain among the 4 conditions were performed using GraphPad Prism statistics software (version 7, GraphPad Software, Inc.). Comparisons involving 3 or more conditions were performed using 1-way repeated-measures analysis of variance, followed by Holm–Šidák post hoc comparisons (as needed), with the assumption of no sphericity and use of an alpha level of $p = 0.05$. Comparisons between measurements involving only 2 instrumented conditions (i.e., S2AI screw-bending moment in the S2AI and SIJF conditions, S1–2 rod strain) were performed using paired t-tests.

Results

Range of Motion

L2–S1 ROM

Compared with the intact condition, all 3 instrumented conditions resulted in significantly decreased L2–S1 ROM in all directions of bending (Table 3, $p < 0.001$). No

significant differences in L2–S1 ROM were observed between instrumented conditions in any direction of motion ($p \geq 0.09$).

L5–S1 ROM

Compared with the intact condition, all 3 instrumented conditions resulted in significantly decreased L5–S1 ROM in all directions of bending ($p \leq 0.01$). Compared with S1 fixation, S2AI fixation significantly reduced L5–S1 ROM in right lateral bending and compression by 50% (0.11° , $p = 0.049$) and 39% (0.22° , $p = 0.003$), respectively.

Sacroiliac Joint ROM

Compared with the intact condition, PSR fixation ending at S1 did not significantly change sacroiliac joint ROM in any direction of loading ($p \geq 0.20$). Compared with the intact condition, the S2AI and SIJF conditions significantly decreased ROM in extension by 61% (0.40° , $p = 0.04$) and by 68% (0.45° , $p = 0.04$), respectively, as well as in combined flexion-extension by 56% (0.67° , $p = 0.03$) and by 65% (0.77° , $p = 0.03$), respectively. Compared with PSR, which ended at S1, extension of distal fixation under the S2AI condition significantly decreased sacroiliac joint ROM by 52% (0.28° , $p = 0.02$) in flexion, by 65% (0.48° , $p = 0.04$) in extension, by 59% (0.76° , $p = 0.02$) in combined flexion-extension, and by 36% (0.09° , $p = 0.02$) in left axial rotation.

Screw-Bending Moment

L5 Screw-Bending Moment

Mean $\pm$ SD screw-bending moments at L5, S1, and S2AI are summarized in Fig. 3. The addition of S2AI screws reduced mean L5 screw-bending moment in all directions of loading (except extension) by 37%. However, reduction was statistically significant during only right lateral bending (0.104 Nm [49%], $p = 0.04$).

TABLE 3. ROM at L2–S1, L5–S1, and sacroiliac joint under the intact and 3 instrumented conditions

Location & Test Parameter	ROM (°)			
	Intact	S1	S2AI	SIJF
L2–S1				
Flexion	18.73 ± 6.13	1.29 ± 0.67*	1.13 ± 0.42*	1.32 ± 0.67*
Extension	–12.22 ± 3.22	–1.75 ± 1.29*	–1.59 ± 0.67*	–1.77 ± 0.90*
Total flexion-extension	30.94 ± 8.02	3.05 ± 1.94*	2.72 ± 1.07*	3.09 ± 1.51*
Lat bending				
Lt	–17.78 ± 4.54	–1.19 ± 0.58*	–1.15 ± 0.58*	–1.26 ± 0.74*
Rt	14.78 ± 3.86	1.12 ± 0.45*	1.08 ± 0.43*	1.15 ± 0.60*
Total	32.55 ± 8.00	2.31 ± 1.03*	2.22 ± 1.01*	2.41 ± 1.33*
AR				
Lt	8.55 ± 2.99	2.30 ± 1.18*	2.23 ± 0.99*	2.39 ± 1.12*
Rt	–8.04 ± 2.88	–2.48 ± 1.50*	–2.35 ± 1.07*	–2.43 ± 1.26*
Total	16.59 ± 5.83	4.77 ± 2.67*	4.58 ± 2.06*	4.81 ± 2.37*
Compression		1.04 ± 0.40	0.97 ± 0.41	0.89 ± 0.43
L5–S1				
Flexion	5.18 ± 2.59	0.48 ± 0.41*	0.12 ± 0.09*	0.18 ± 0.13*
Extension	–3.84 ± 1.53	–0.71 ± 0.85*	–0.14 ± 0.12*	–0.22 ± 0.17*
Total flexion-extension	9.02 ± 3.32	1.19 ± 1.25*	0.26 ± 0.17*	0.41 ± 0.29*
Lat bending				
Lt	–3.18 ± 1.26	–0.29 ± 0.28*	–0.09 ± 0.05*	–0.12 ± 0.07*
Rt	2.62 ± 1.08	0.22 ± 0.15*	0.11 ± 0.06*†	0.13 ± 0.08*†
Total	5.80 ± 2.27	0.51 ± 0.40*	0.20 ± 0.11*	0.25 ± 0.14*
AR				
Lt	1.56 ± 0.62	0.38 ± 0.36*	0.22 ± 0.14*	0.28 ± 0.22*
Rt	–1.39 ± 0.49	–0.43 ± 0.35*	–0.25 ± 0.14*	–0.29 ± 0.22*
Total AR	2.95 ± 1.08	0.82 ± 0.69*	0.47 ± 0.26*	0.57 ± 0.44*
Compression		0.56 ± 0.31	0.34 ± 0.33†	0.23 ± 0.21†
Sacroiliac joint‡				
Flexion	0.54 ± 0.36	0.54 ± 0.31	0.26 ± 0.17†	0.21 ± 0.13†
Extension	–0.66 ± 0.38	–0.74 ± 0.51	–0.26 ± 0.15*†	–0.21 ± 0.17*†
Total flexion-extension	1.19 ± 0.70	1.28 ± 0.78	0.52 ± 0.32*†	0.42 ± 0.29*†
Lat bending				
Lt	–0.15 ± 0.12	–0.14 ± 0.08	–0.07 ± 0.04	–0.03 ± 0.01
Rt	0.13 ± 0.13	0.13 ± 0.07	0.07 ± 0.04	0.03 ± 0.02†
Total	0.28 ± 0.25	0.27 ± 0.15	0.14 ± 0.08	0.06 ± 0.03†
AR				
Lt	0.24 ± 0.11	0.25 ± 0.06	0.16 ± 0.07†	0.14 ± 0.07
Rt	–0.25 ± 0.10	–0.24 ± 0.09	–0.17 ± 0.05	–0.15 ± 0.06
Total	0.49 ± 0.21	0.48 ± 0.14	0.32 ± 0.11	0.29 ± 0.12
Compression		0.67 ± 0.44	0.69 ± 0.41	0.49 ± 0.29

AR = axial rotation.

Values are shown as mean ± SD.

* p < 0.05 compared with the intact condition.

† p < 0.05 compared with the S1 condition.

‡ Mean values of the left and right joints of each specimen were used in the analysis.

FIG. 3. Screw-bending moment at L5 (A), S1 (B), and S2AI (C) during flexion (FL), extension (EX), left lateral bending (LLB), right lateral bending (RLB), left axial rotation (LAR), right axial rotation (RAR), and compression (COM). Mean values are shown with SD (error bars).

FIG. 4. Posterior (primary) rod strain at L5–S1 (**A**) and S1–S2AI (**B**) during FL, EX, LLB, RLB, LAR, RAR, and COM. Mean values are shown with SD (error bars). See Fig. 3 for definitions of abbreviations.

S1 Screw-Bending Moment

The addition of S2AI screws reduced S1 screw-bending moment during flexion (43% [0.106 Nm], $p = 0.046$). The subsequent addition of SIJF did not change S1 screw-bending moment compared with S2AI alone ($p > 0.14$).

S2AI Screw-Bending Moment

In combination with S2AI fixation, SIJF reduced mean S2AI screw-bending moment in all directions of load by 19%. The only statistically significant difference was found in compression (0.24 Nm [45%], $p = 0.02$).

Primary Principal Rod Strain

L5–S1 Rod Strain

Mean $\pm$ SD primary rod strains at L5–S1 and S1–S2AI (derived from the respective rosette strain gauge data) are summarized in Fig. 4. With S2AI fixation, posterior L5–S1 primary rod strain increased significantly by 124% (159 μE , $p = 0.002$) in flexion, by 149% (285 μE , $p = 0.02$) in left axial rotation, and by 99% (254 μE , $p = 0.04$) in right axial rotation. Compared with the S2AI condition, the SIJF condition slightly reduced L5–S1 strain during right axial rotation by 6% (28 μE , $p = 0.04$) but significantly increased rod strain in extension by 6% (28 μE , $p = 0.02$).

S1–S2AI Rod Strain

Regarding primary rod strain at S1–S2AI, the addition of SIJF to the S2AI condition did not significantly increase S1–S2AI rod strain ($p \geq 0.08$).

Discussion

Multisegment fusion of the lumbar spine can result in large cantilever moment and consequently mechanical stress at the sacroiliac joint.³³ Lumbopelvic fixation represents a solid foundation for long-segment constructs going toward the sacrum that are aimed at resisting high stress.³⁴ S2AI fixation results in a single linear transarticular axis of fixation across the sacroiliac joint that may allow joint rotation. Cunningham et al.²⁹ reported that, although S2AI fixation decreased lumbosacral motion in several directions, sacroiliac joint motion was not significantly reduced compared with that of the intact condition. In the current study, we sought to evaluate spinal and sacroiliac joint motion, rod strain, and screw-bending moment in the lumbopelvic region with extension of a long-segment posterior PSR construct to the pelvis using S2AI fixation and with 2 additional points of lateral SIJF.

Our technique for SIJF was described previously for stand-alone SIJF in patients with chronic back pain who

experienced satisfactory results compared with conservative management.^{17–20} Lumbopelvic fixation using S2AI screws was supplemented with 2 additional triangular titanium-coated sacroiliac joint implants placed bilaterally under fluoroscopic guidance.

The addition of S2AI screws to a long-segment construct ending at S1 stabilized the lumbosacral junction; however, no additional statistically significant differences in ROM were observed after SIJF. The addition of S2AI to a construct ending at S1 generally decreased motion significantly at the sacroiliac joint in multiple directions. The addition of SIJF to S2AI provided subsequent small increases in stability that were not significant under bending loads. Adding SIJF to S2AI reduced sacroiliac joint motion by 29% (0.20°) during compression; however, this reduction was also not significant.

The influence of posterior fusion to the sacrum alone on sacroiliac joint motion remains unclear, with different outcomes reported. In the current study, fusion to the sacrum did not significantly alter sacroiliac joint motion compared with that under the intact condition. In a recent *in vitro* study, Baria et al.³⁵ reported that vertical translations of the sacroiliac joint increased during flexion-extension by 67% with L4–5 instrumentation and by 77% with L4–S1 instrumentation. Because we did not quantify sacroiliac joint translational movements in the current study, it is difficult to compare rotational displacement with translational displacement.

Regarding strain, the introduction of S2AI screw to constructs initially ending at S1 increased primary rod strain at the lumbosacral (L5–S1) junction in most loading directions. SIJF slightly increased S1–2 primary rod strain by as much as 117 μ E in all directions of motion compared with S2AI. In terms of the screw-bending moment, extension of the L2–S1 construct to S2AI fixation provided a mild protective effect on L5 screw bending, and it provided a greater protective effect on S1 screw-bending loads in several directions. However, statistically significant differences were found in only a few directions of loading, likely because of high variability in data. When SIJF was added to S2AI, it did not significantly affect L5 and S1 screw-bending loads. A small but significant protective effect of SIJF on the S2AI screw-bending moment was observed during compression.

The protective effect of sacropelvic fixation on the S1 screw-bending moment observed in the current study was similar to that reported in previous studies.^{4,5} Hlubek et al.³⁶ also demonstrated an increase in lumbosacral junction rod strain with the addition of iliac bolts in a similar long-segment construct. Other previous clinical studies have reported comparable observations.³⁴ In a cadaveric study using L2–S1 constructs, Fleischer et al.⁴ demonstrated that the addition of iliac screws mitigated S1 screw-bending moment in sagittal plane motion and axial torsion. Similarly, Sutterlin et al.⁵ reported a reduction in *in vitro* S1 screw-bending moment with constructs ending distally in S2AI in comparison with that found with PSR alone distally ending at S1.

Casaroli et al.³⁷ used a finite element model to analyze the effects of sacropelvic fixation with 3 triangular titanium devices in comparison with those of PSR ending at S1 and iliac screws and S2AI screws as the basis for lumbo-

pelvic fusion from L4 to the pelvis. They reported that all 3 forms of sacropelvic fixation reduced S1 screw stress in comparison with PSR alone. Although simulation without SIJF alleviated rod stress significantly or markedly, iliac screws increased stress (to twice that of PSR ending at S1), whereas S2AI stress was similar to that of constructs ending at S1. In contrast, our current study results demonstrated that, with S2AI fixation, reduced S1 screw-bending moment was paired with significantly increased rod strain at L5–S1. The differences between these 2 studies, including PSR fixation only up to L4 without L5–S1 interbody fusion as used in the Casaroli et al. model, may account for these differences in observation.

Panico et al.³⁸ used a T10–pelvis finite element model to analyze constructs with SIJF triangular devices coupled with S2AI screws in patients requiring T10–S1 thoracolumbar fusion. They reported a similar percentage of reduction in sacroiliac joint ROM with the addition of S2AI screws compared with that of constructs ending at S1, as well as additional smaller reductions of 15% to 25% with the addition of triangular implants placed in either a sacral alar-iliac trajectory or a lateral trajectory. They also reported significant decreases in S1 screw stress with the addition of S2AI screws and no further change after the addition of SIJF. However, as in the Casaroli et al.³⁷ study, Panico et al.³⁸ reported no protective effect of sacropelvic S2AI fixation on rod strain. Our findings in the current study of increased L5–S1 rod strain with S2AI fixation contrast these earlier findings. The use of different study methods (i.e., *in vitro* study vs finite element model) or different construct lengths (i.e., L2 vs T10 as the upper level), or both, may account for some or all of these differences.

In a previous study that used an *in vitro* testing protocol identical to that of the current study, our laboratory reported ROM, rod strain, and screw-bending moment for an identically instrumented cadaver model; however, instead of the SIJF condition, one posteriorly placed SIJF device was investigated as an adjunct to S2AI screw fixation.³⁹ The continuity between our past study and our current study renders the data sets from each as the best possible matched data for comparison.

Overall, the results of these two studies were quite similar and comparable, with some notable observations. Regarding screw-bending moment, the resultant moment distribution with 2 laterally placed SIJF devices at each sacroiliac joint appeared to differ from that achieved with 1 posteriorly placed device. With lateral SIJF, the mean S2AI screw moment was 26% lower in flexion, extension, and left-right axial rotation; the mean S1 screw moment was 64% higher in 4 of 7 directions of loading; and the mean L5 screw moment was 36% lower in all directions of loading except extension. In terms of ROM comparisons between the two studies, the mean global L2–S1 ROM increased 22% in all directions of loading; the mean L5–S1 increased 17% in 5 of 6 directions of loading, and the mean sacroiliac joint ROM was reduced by 21% in all directions of loading with the addition of lateral SIJF (2 implants per joint) in comparison with posterior fixation (1 implant per joint). The mean posterior L5–S1 rod strain was also 24% higher with lateral SIJF in 5 of 7 directions of loading than in the previous study.

FIG. 5. Comparison of outcomes between 1 posteriorly placed SIJF³⁹ and 2 laterally placed SIJF devices supplemental to S2AI fixation. **A:** L2–S1 ROM. **B:** L5–S1 ROM. **C:** Sacroiliac (SI) joint ROM. **D:** L5 screw-bending moment. **E:** S1 screw-bending moment. **F:** S2AI screw-bending moment. **G:** S1–S2 rod strain. **H:** L5–S1 rod strain. Mean values are shown with SD (error bars). See Fig. 3 for definitions of abbreviations.

The rationale for these differences is not clear. It is plausible that increased stabilization of the sacroiliac joint, with additional fixation in the lateral case, served to slightly shield the S2AI screw, thereby transferring construct support more to the S1 screw and ROM more to the L5–S1 and upper vertebral joint levels. However, the overall mag-

nitude of these changes was not large (maximum 0.211 Nm in screw bending, -122μ E rod strain at L5–S1, and 0.54° ROM at the sacroiliac joint), and other confounding factors may have influenced the results. Overall, there were no substantial biomechanical differences between 1 posteri-

only placed and 2 laterally placed SIJF devices in terms of motion or strain (Fig. 5). Surgical approach selection should take into consideration other factors, including the level of comfort of the surgeon with the approach. Nevertheless, additional clinical and biomechanical studies that directly compare these 2 techniques should be considered.

Limitations

This study is not without limitations. As with any other biomechanical cadaveric study, the testing paradigm evaluated only immediate stability and strain distributions that can affect longer-term mechanical failure in the clinical scenario. Evaluation of cyclic loading was beyond the scope of this research and is problematic in vitro because of tissue degradation, which prevents simulation of the long-term in vivo loading environment before the occurrence of any instrumentation failure. Additional limitations include the absence of paraspinal and trunk muscle activity, which plays a role in stabilizing the sacroiliac joint,⁴⁰ and the absence of a targeted disease. Our analysis of primary rod strain was localized and may not reflect overall strain distribution. Lastly, we evaluated only one sacropelvic fixation technique, and other techniques may produce different results. We performed ALIF at L5–S1; other L5–S1 interbody configurations (e.g., transforaminal lumbar interbody fusion) or those without interbody fusion may yield different results.

Conclusions

Unlike S1 fixation, long-segment constructs ending distally with S2AI screw fixation tended to create a more stable construct with a significant reduction in lumbosacral motion and mean S1 screw-bending moment in flexion. These benefits, however, were paired with increased rod strain at the lumbosacral junction. Supplementing S2AI fixation with laterally placed triangular titanium sacroiliac joint implants in a long-segment construct did not significantly reduce SI joint motion or S1 screw bending over that obtained with fixation ending at S2AI. SIJF demonstrated reduced S2AI screw bending in compression and reduced L5–S1 rod strain in axial rotation, but with increased strain in extension, in comparison with that found with constructs ending at S2AI alone.

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