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Biomechanical Evaluation of Supplemental Percutaneous Lumbo-Sacro-iliac Screws For Spino-pelvic Fixation Following Total Sacrectomy

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Abstract

Study Design—This is a cadaveric biomechanical study evaluating the biomechanical properties of a novel spino-pelvic fixation technique with percutaneous lumbo-sacro-iliac (LSI) screws in an unstable total sacrectomy model.

Objective—To compare standard posterior dual rod spino-pelvic fixation alone with dual rod fixation supplemented with LSI screw fixation.

Summary of Background Data—Primary or metastatic tumors of the sacrum requiring a total sacrectomy can result in spino-pelvic instability if inadequate fixation is achieved. Many fixation techniques have been proposed to address this instability. However, to date, an optimal fixation technique has not been established.

Methods—Ten fresh-frozen cadaveric spino-pelvic specimens were randomized according to bone mineral density (BMD) to either posterior rod fixation (control group) or posterior rod fixation with supplemental LSI screws (LSI group). Following fixation, a total sacrectomy of each specimen was performed. Specimens were then potted and axially loaded in a caudal direction. Stiffness, yield load, energy absorbed at yield load, ultimate load, and energy absorbed at ultimate load were computed. A student's t-test was used for statistical analysis with significance set at $p < 0.05$.

Results—The average age and BMD were not significantly different between the control and LSI groups (age, $p = 0.255$; BMD, $p = 0.810$). After normalizing for BMD, there were no significant differences detected for any of the biomechanical parameters measured between the two fixation techniques: stiffness ($p = 0.857$), yield load ($p = 0.219$), energy at yield load ($p = 0.293$), ultimate load

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($p=0.407$), and energy at ultimate load ($p=0.773$). However, both fixation techniques were able to withstand physiological loads.

Conclusions—Our study did not demonstrate any biomechanical advantage for supplemental LSI screw fixation in our axial loading model. However, given the theoretical advantage of this percutaneous technique, further studies are warranted that take into account forward bending and sagittal stability.

Introduction

The sacrum provides a critical link between the weight bearing axis of the spine and the appendicular portions of the skeleton. Primary or metastatic tumors requiring total sacrectomy can result in spino-pelvic instability. Following en bloc total sacrectomy, spino-pelvic reconstruction of the lumbar spine and pelvis is required to restore the normal transmission of force from the axial spine to the pelvis and lower weight-bearing limbs.

There have been many proposed methods of spino-pelvic fixation following total sacrectomy including the modified Galveston reconstruction and its variations with single or dual iliac screw fixation, triangular frame reconstruction, sacral rod reconstruction, bilateral fibular flap reconstruction, and four-rod reconstruction.¹⁻⁷ The most common surgical stabilization techniques involve posteriorly based spino-pelvic constructs with pedicle and iliac screw fixation using titanium rods. However, this technique lacks adequate anterior spinal column structural support at the lumbo-pelvic junction, leading to increased stress on the posterior implants.

Since forces are normally transmitted obliquely from the lumbar spine in the midline to the sacro-iliac joints laterally, traditional posteriorly-based spino-pelvic fixation lacks true load-sharing properties due to a lack of anterior column support after total sacrectomy. Supplemental anterior column support has been proposed using trans-sacral fixation with or without large structural grafts and bulky implants; however, these strategies are technically challenging and require longer surgical time.

In traumatic injuries of the sacrum and pelvis, percutaneous sacro-iliac (SI) screws have become commonplace because they have comparable stability with less soft tissue damage, less blood loss, and fewer complications compared with more traditional open approaches.⁸⁻¹³ Lumbo-sacro-iliac (LSI) screws are a novel extension of the traditional percutaneous SI screws. These screws are inserted in a more cephalad direction compared to traditional SI screws, ending in the L5 vertebral body rather than the S1 body. In spino-pelvic reconstruction after total sacrectomy, the addition of LSI screws to the posteriorly based techniques would theoretically provide increased stability to the anterior spinal column without requiring extra dissection or significantly prolonging operative time. The LSI screws can be safely inserted from the outer ilium into the L5 vertebral body using fluoroscopic or navigated guidance in a percutaneous manner.

This is the first cadaveric study to assess the biomechanical efficacy of the standard posterior spino-pelvic fixation supplemented with novel LSI screw fixation in an unstable total sacrectomy model.

Materials & Methods

Ten specimens including the entire lumbar spine and pelvis were selected. The cadavers were dissected of all soft tissues with care taken to preserve the lumbo-sacral, ilio-lumbar and sacro-iliac ligaments, and the disco-ligamentous structures of the spine. Specimens with any skeletal pathology or significant degenerative changes were excluded from our study.

The specimens were randomly assigned to one of two bone mineral density (BMD)-matched groups. The control group (n=5) received standard posterior spino-pelvic fixation with titanium alloy (Ti-6Al-4V) rods (5.5 mm diameter), pedicle screw (6.5 mm × 40 mm) fixation from L3-L5 and bilateral dual iliac screw (7.5 mm × 70 mm) fixation with lateral offset connectors (Armada Spinal System, NuVasive, Inc., San Diego, CA). The group receiving LSI screws (n=5) received the same posterior instrumentation supplemented with bilateral lumbo-sacro-iliac screw fixation using 6.5 mm × 120 mm fully-threaded, cannulated screws (Depuy Synthes, Raynham, MA). A crosslink was placed at the L5-iliac screw junction in all specimens. After posterior spino-pelvic instrumentation of both groups was completed, a total sacrectomy was performed by creating osteotomies at the L5-S1 interval and along bilateral sacral foramina and ala. The LSI screws were then placed after total sacrectomy was performed.

Technique for LSI Screw Insertion

The starting point for the LSI screw was approximately 2 cm superior to the superior point of the greater sciatic notch and 2 cm anterior to the posterior superior iliac spine. The trajectory was towards the L5 vertebral body, stopping short of the anterior cortex of the L5 vertebral body to prevent vascular injuries. (Figures 1) A 2.8 mm partially threaded guidewire was used with a powered drill to create the aforementioned path under direct visualization and fluoroscopic guidance. The screw length was then measured using a precalibrated measuring tool that accompanied the guidewire. A 6.5 mm fully threaded cannulated screw with the appropriate length was then placed over the guidewire, which was subsequently removed.

Each specimen was then potted in Plaster of Paris up to the superior margin of the acetabulum and oriented such that the pubic symphysis and anterior superior iliac spine were coplanar in the coronal plane. The L1 and L2 vertebral levels were potted in a PVC-Plaster of Paris construct and fixed with transverse metal screws. The potted specimens were then mounted to an MTS loading system (MTS Systems Corp., Eden Prairie, MN) with a uniaxial load cell fixed below the specimen.

All specimens were subjected to axial compressive loading in a caudad direction. Nondestructive cyclical loading between 10 and 100 N was first performed at 0.2 Hz for 10 cycles, followed by load-to-failure at 10 mm/min. Stiffness, yield load, energy absorbed at yield load, ultimate load, and energy absorbed at ultimate load were measured. Stiffness was determined by calculating the slope of the linear portion of the load-elongation curve immediately following the initial toe region. The yield load was determined by taking the force on the load-elongation curve at the point just prior to a decrease in slope that was sustained for more than 1mm of displacement. Ultimate load was determined as the highest

registered force just prior to catastrophic failure (a drop in force of 5%) or impingement at the lumbar-pelvic interface. The energy absorbed at the yield and ultimate loads were calculated by computing the area under the load-elongation curve at the yield and ultimate loads respectively.

All of the aforementioned variables underwent a BMD-correction by dividing the raw value by the ratio of the specimen's BMD over the average BMD of all 10 specimens (i.e. raw value/(BMD_{specimen}/BMD_{average}). The variables were compared between the two groups using two-tailed unpaired t-tests with statistical significance set at $p < 0.05$.

Results

The average age for the LSI group was 57.0 ± 9.5 years (range: 44-67) and the average BMD was 0.826 ± 0.198 g/cm² (range: 0.604-1.036 g/cm²). For the control group, the average age was 47.6 ± 14.3 years (range: 26-62 years) and the average BMD was 0.851 ± 0.091 g/cm² (range: 0.711-0.937 g/cm²). These averages were not significantly different (age, $p=0.255$; BMD, $p=0.810$). (Table 1)

After normalizing for BMD, there were no significant differences detected between any of the biomechanical parameters measured between the two fixation techniques. The group with the supplemental LSI fixation displayed lower values for stiffness (164.3 ± 40.6 N/mm vs. 171.5 ± 75.8 N/mm, $p=0.857$), yield load (483.2 ± 307.5 N vs. 758.3 ± 344.2 N, $p=0.219$), energy at yield load (1036.1 ± 1075.1 N·mm vs. 1936.3 ± 1420.2 N·mm, $p=0.293$), ultimate load (1987.7 ± 418.3 N vs. 2238.3 ± 484.3 N, $p=0.407$), and energy at ultimate load (35260.7 ± 16330.0 N·mm vs. 37912.8 ± 11310.1 N·mm, $p=0.773$) compared to the control group, though none of these differences were statistically significant. (Table 2) All of the specimens failed at the bone-iliac screw interface.

Discussion

To date, only a handful of cadaveric biomechanical studies have examined spino-pelvic reconstruction techniques in a total sacrectomy model. This study was the first to investigate the efficacy of a novel technique using supplemental LSI screws in a total sacrectomy model. Our results did not show a statistically significant difference between the two groups for all of the biomechanical parameters measured.

Since the introduction of posterior instrumentation, posteriorly based fixation has been commonly performed in spino-pelvic reconstruction. However, fixation failure has been well-documented clinically, including reports of breakage or loosening of hardware.¹⁴⁻¹⁷ Murakami et al. performed a finite element study looking at two posteriorly based techniques: modified Galveston reconstruction and triangular frame reconstruction.³ With modified Galveston reconstruction, excessive stress was concentrated on the spinal rods at the L5-iliac screw junction. Similarly, there was increased stress at the interface between the sacral rod and iliac bone with triangular frame reconstruction. Due to these findings, they cautioned against early mobilization for fear of instrumentation failure.

Consequently, various reconstruction techniques have been introduced in an attempt to optimize fixation. Cheng et al. performed a cadaveric biomechanical study looking at the stability of four different reconstruction techniques: sacral rod reconstruction, bilateral fibular flap reconstruction, four-rod reconstruction, and improved compound reconstruction, which was a combination of sacral rod reconstruction, bilateral fibular flap reconstruction, and four-rod reconstruction.¹⁸ After nondestructive axial compression testing, the four-rod reconstruction specimen displayed the greatest displacement of L5 compared to the other techniques. Interestingly, four-rod reconstruction was the only group that did not have any anterior spinal column support. Thus, anterior support was recommended in this biomechanical study. However, the authors stated that providing anterior spinal column support at the spino-pelvic junction may be technically challenging, potentially leading to longer surgical time and further patient morbidity.

LSI screws as investigated in the current study have a theoretical advantage because they provide anterior spinal column fixation at the spino-pelvic junction without significantly prolonging surgical time and dissection since they can be placed in a percutaneous fashion. Our hypothesis before starting the study was that supplementation with LSI screws would increase stability relative to standard posterior spino-pelvic reconstruction fixation, but our data revealed that the addition of LSI screws did not provide greater stability than the standard posterior construct alone in our axial compression model. It is entirely possible that the benefits of anterior column support documented previously in the literature¹⁹ may be better demonstrated in a model that takes into account bending in the sagittal plane.

These results can be further explained by the trajectory of the LSI screws which were not in line with the axis of the compressive load, and thus may have functioned as a stress riser at the posterior-pelvis-screw interface. Since axial compression was the only loading modality performed, it is unknown whether or not these screws impacted spino-pelvic stability during flexion, extension, lateral bending, and axial rotation of the specimens. Our model did not assess translation or deformation in these planes and thus may not have accurately represented true physiological forces. Furthermore, our model did not address pelvic ring instability created by our total sacrectomy since our pelvis was fixed in Plaster of Paris up to the acetabulum. Perhaps, a more relevant total sacrectomy model would allow for flexion, extension, and lateral bending, and recreate the pelvic ring instability caused by the total sacrectomy.

Interestingly, based on our raw values (i.e., values not corrected for BMD), the average yield and ultimate load for both fixation groups exceeded 500 N and 2000 N, respectively. According to Nachemson and Elfstrom, the typical load on the lumbar spine ranges from 500 N to 2000 N based on daily activities.²⁰ Five hundred Newtons corresponds to erect standing, whereas 2000 N mimics light manual work. Hence, based on this data, posterior spino-pelvic reconstruction with pedicle and dual iliac screws connected by rods can potentially provide enough stability to withstand normal and low impact physiologic load. Though it is unclear whether the addition of LSI screws will provide any additional clinical or biomechanical benefit. As mentioned previously, normal physiologic loading involves multiplanar loading so it is difficult to make a conclusion based on the values obtained in this investigation.

Additionally, cadaveric in vitro studies like this have inherent limitations compared to in vivo studies, as they do not take into account bone healing and soft tissue reinforcement. Also, it is worth noting that the average T-score among all specimens may not be representative of the typical patient needing spino-pelvic reconstruction.

Contrary to the study of Murakami et al., in which a similar technique without LSI screws was examined in a modified Galveston reconstruction, the mode of failure in our specimens occurred at the iliac screw-bone interface. This was in contrast to that study's report of excessive strain on the rods at the L5-iliac junction. However, both their study and our findings illustrated that most of the stress is concentrated along the posterior-caudad aspect of the fixation constructs, presumably from an anteriorly-directed moment in the sagittal plane.

The aforementioned limitations of this study warrant further biomechanical studies before any definitive conclusion about the use of LSI screws can be recommended. Although our sample size was the largest of all cadaveric biomechanical studies looking at spino-pelvic reconstruction, it was either too small to detect any significant differences between the test groups, or possible that no difference exists under these loading parameters.

Conclusion

Although LSI screws can provide anterior spinal column fixation at the spino-pelvic junction with minimal dissection, our data suggest that supplementation with LSI screws does not improve rigidity in axial compression compared to the standard posterior spino-pelvic fixation alone.

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Fig. 1. Photographs and fluoroscopy depicting the entry point and cephalad orientation of the LSI screws and posterior spino-pelvic reconstruction with bilateral pedicle and dual iliac screws connected by rods. **(a)** Posterior and **(b)** posterolateral photographs of LSI screw and posterior fixation; **(c)** lateral and **(d)** posterior fluoroscopic views of the LSI screw and posterior fixation construct.

Table 1

Group characteristics, displayed as means $\pm$ standard deviation. Significance set at p-value < 0.05 .

	+LSI	Control	P-value
Age	57.0 $\pm$ 9.5	47.6 $\pm$ 14.3	0.255
BMD	0.826 $\pm$ 0.198	0.851 $\pm$ 0.091	0.810

Table 2

Biomechanical parameters measured during load-to-failure testing, normalized for BMD, displayed as means $\pm$ standard deviation

	+LSI	Control	P-value
Stiffness (N/mm)	164.3 $\pm$ 40.6	171.5 $\pm$ 75.8	0.857
Yield Load (N)	483.2 $\pm$ 307.5	758.3 $\pm$ 344.2	0.219
Energy at Yield (N*mm)	1036.1 $\pm$ 1075.1	1936.3 $\pm$ 1420.2	0.293
Ultimate Load (N)	1987.7 $\pm$ 418.3	2238.3 $\pm$ 484.3	0.407
Energy at Ultimate (N*mm)	35260.7 $\pm$ 16330.0	37912.8 $\pm$ 11310.1	0.773