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Fixation Strength of Modified Iliac Screw Trajectory Compared to Traditional Iliac and S2 Alar-Iliac Trajectories: A Cadaveric Study

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■ OBJECTIVE: **Traditional iliac (TI) screws require extensive dissection, involve offset-connectors, and have prominent screw heads that may cause patient discomfort. S2 alar-iliac (S2AI) screws require less dissection, do not need offset connectors, and are less prominent. However, the biomechanical consequences of S2AI screws crossing the alar-iliac joint is unknown. The present study investigates the fixation strength of a modified iliac (MI) screw, which has a more medial entry point and reduced screw prominence, but does not cross the alar-iliac joint.**

■ METHODS: **Eighteen sacropelvic spines were divided into 3 groups (n = 6): TI, S2AI, and MI. Each specimen was fixed unilaterally with S1 pedicle screws and pelvic fixation according to its group. Screws were loaded at ±10 Nm at 3Hz for 1000 cycles. Motion of each screw and rod strain above and below the S1 screw was measured.**

■ RESULTS: **Toggle of the S1 screw was lowest for the TI group, followed by the MI and S2AI groups, but there were no significant differences (*P* = 0.421). Toggle of the iliac screw relative to the pelvis was also lowest for the TI group, followed by the MI group, and was greatest for the S2AI group, without significant differences (*P* = 0.179). Rod strain was similar across all groups.**

■ CONCLUSIONS: **No statistically significant differences were found between the TI, S2AI, and MI techniques with regard to screw toggle or rod strain. Advantages of the MI screw include its lower profile and a medialized starting point eliminating the need for offset-connectors.**

INTRODUCTION

Concepts for spinopelvic fixation have evolved dramatically over recent decades.[1-4] The insertion of independently placed traditional iliac screws (TI) at the posterior superior iliac spine (PSIS) for lumbopelvic fixation results in increased pullout strength compared to Galveston rods, as well as increased fusion rates.[5-7] Despite these fusion rates, concerns regarding TI include a compromised vascularity as well as integrity of the muscle and skin layers caused by extensive dissection required due to rod connectors and prominent screw heads leading to wound breakdown.[8,9] Therefore, the S2 alar-iliac (S2AI) technique has gained popularity because of its perceived decreased tissue dissection, lesser prominence of the implant, and the advantage of not having to use a connector between the screw head and rod.[8,10-13]

A modified iliac screw trajectory (MI) with a more medial entry point and reduced screw prominence (**Figure 1**) has been described to address the perceived shortcomings of the TI.[14-16] Although there are anatomical considerations and a few case series published utilizing this technique,[15,17,18] there is only 1 finite element study evaluating the biomechanical properties of the MI.[19]

Key words
- Alar-iliac joint
- Dynamic loading
- Modified iliac screws
- S2 alar-iliac screws
- Toggle forces
- Traditional iliac screws

Abbreviations and Acronyms
BMD: Bone mineral density
Co-Cr: Cobalt-chromium
DEXA: Dual-energy X-ray absorptiometry
LED: Light-emitting diode
MI: Modified iliac screw
PSIS: Posterior superior iliac spine
S2AI: S2 alar-iliac screw
TAV: Titanium-aluminum-vanadium
TI: Traditional iliac screw
UHMWPE: Ultra-high-molecular-weight polyethylene

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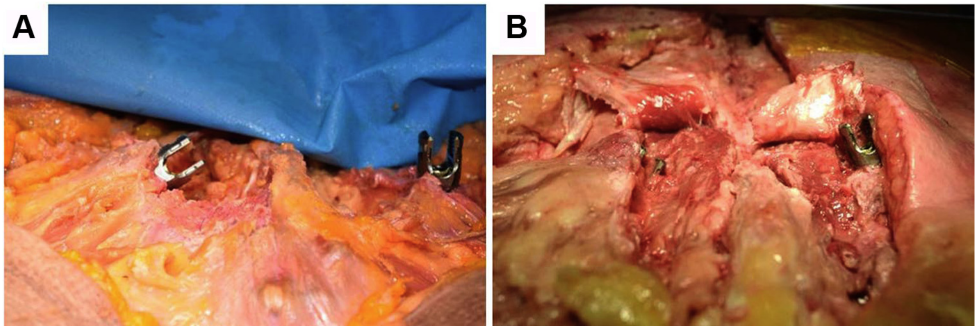

Figure 1. (**A**) Example of medial insertion point of modified iliac screw (*left*) versus traditional iliac screw (*right*). (**B**) Example of reduced screw prominence of modified iliac screw (*left*) versus traditional iliac screw (*right*).

With no biomechanical evidence supporting a favorable technique, it is unclear as to which pelvic fixation techniques provide the most favorable outcomes.[20-22]

The aim of this cadaveric study was to compare the abilities of TI, S2AI, and MI screws to resist toggle forces during dynamic loading, and to investigate differences in strain on the posterior rod above and below the sacral pedicle screw between constructs during this simulated physiologic loading.

METHODS

Specimen Preparation

Eighteen fresh-frozen human cadaveric sacropelvic spines were utilized in this study. The medical history of each donor was examined to exclude trauma, malignancy, or metabolic disease that might otherwise compromise the biomechanical properties of the spine. Specimens were radiographed in both the anteroposterior and lateral planes to ensure the absence of fractures, deformities, or any metastatic disease. Each specimen also had a dual-energy X-ray absorptiometry (DEXA) scan performed to quantify bone mineral density (BMD) using a water-bath protocol. Paravertebral musculature was carefully denuded, avoiding disruption of spinal ligaments and joints. A 0.9% solution of saline was used throughout testing to preserve the viscoelastic properties of the specimens. All specimens were stored in double plastic bags at −20°C until testing was performed.

Surgical Constructs

Specimens were divided into 3 groups of n = 6 each: TI screws, S2AI screws, and MI screws. Each group included specimens with similar average BMD. Screws were inserted unilaterally for each specimen. All iliac and sacroiliac screws (CREO, Globus Medical, Inc., Audubon, PA) were 8.5 mm in diameter, and screw length was determined based on the individual anatomy of each specimen. Screws were also inserted unilaterally into the S1 pedicles of each specimen. All sacral screws were 6.5 mm in diameter, and screw length was determined based on the individual anatomy of each specimen.

Axial radiographs showing the insertion point and trajectory of each technique are included in **Figure 2**. S2AI screws were inserted following the trajectory described by O'Brien et al.,[23] with a starting point approximately 1 mm inferior and 1 mm lateral to the S1 dorsal foramen, and the screw angled toward the anterior inferior iliac spine just above the sciatic notch in the craniocaudal plane.[23] Traditional iliac screws were inserted with a starting point at the superior prominence of the PSIS and angled toward the anterior inferior iliac spine.[7,24]

Portions of the PSIS were removed in order for the TI screws to be recessed such that they could be connected with a cross-connector to the posterior rod without requiring bending of the rod or the connector. The entry point of the MI screw differed from that of the TI, and was located along the medial border of the PSIS lateral to the rudimentary S1/S2 joint.[18] This allows the screw head to be better aligned with the pedicle screws without the adjunctive need for a slotted connector or offset-connector. Using fluoroscopy, the obturator outlet view was used to confirm correct screw positioning. The intended screw path was developed using a blunt probe in a general trajectory towards the anterior superior iliac spine, using true lateral radiographs to confirm. Appropriate-length iliac screws were then inserted.

Dynamic Testing

Following screw insertion, specimens were dynamically tested using an MTS Bionix 858 servo hydraulic testing machine (MTS Systems Corporation, Eden Prairie, MN). Pedicle screws were inserted into an ultra-high-molecular-weight polyethylene (UHMWPE) block that was attached to the actuator of the testing machine. A UHMWPE test block was used to reduce possible loosening of these screws, which were used to simulate rod attachment to the L5 pedicle. The specimen was aligned on the machine to allow for unilateral placement of a pre-contoured 5.5 mm-diameter titanium-aluminum-vanadium (TAV) rod spanning from the screw inserted in the test block to the distal-most screw of the construct (**Figure 3**). The TAV rod was attached with a cross-connector to a pre-contoured cobalt-chromium (CoCr) rod that was only fixed to the test block, and not to the specimen. The

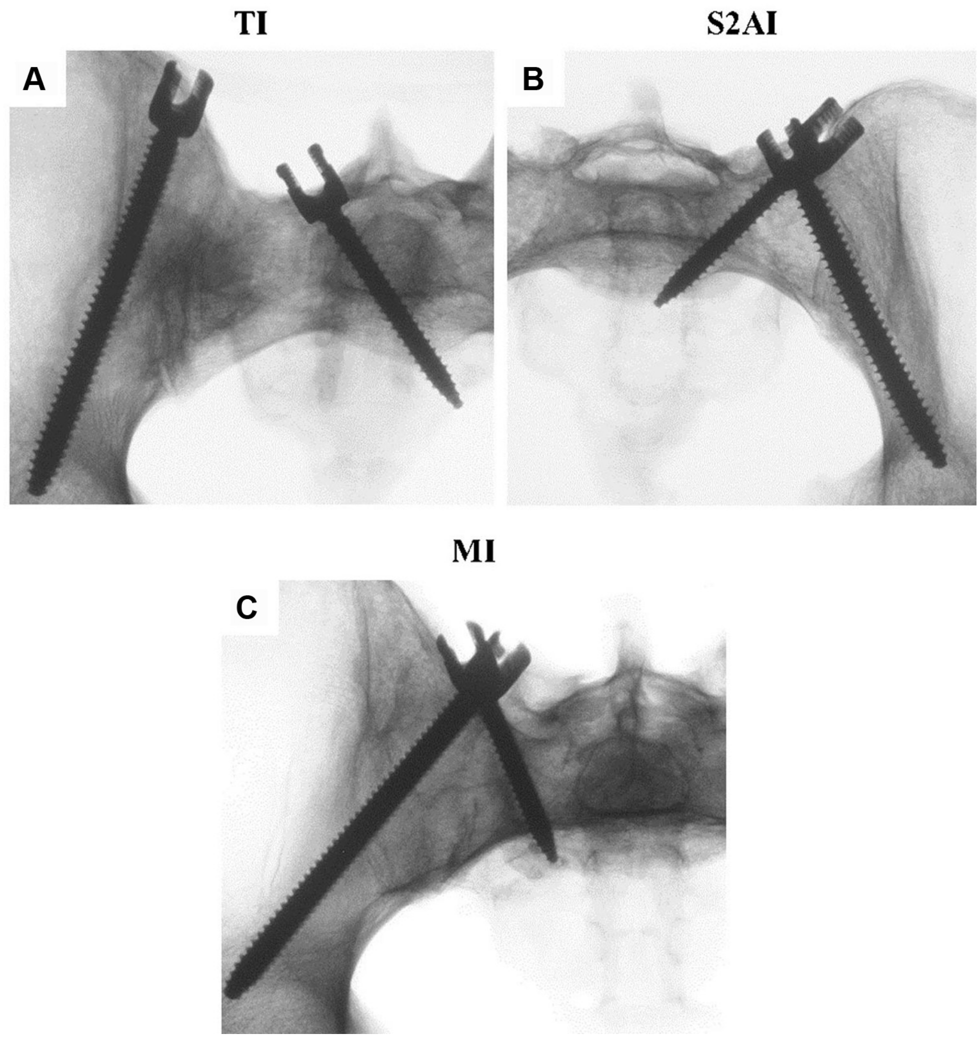

Figure 2. Example axial radiographs showing insertion point and trajectory of (**A**) TI screw, (**B**) S2AI screw, and (**C**) MI screw. MI screw insertion is significantly more medial than that of TI screw, but the trajectory does not cross the SI joint like the S2AI screw.

CoCr rod was used to increase the stiffness of the construct to ensure that the applied load toggled the screws and did not simply bend the TAV rod. Once the specimen was aligned and the pelvis was rigidly fixed in all planes of translation and rotation, the lever arm was measured from the center of the actuator head to the distal-most screw. Using this lever arm, the required axial load was determined such that a load control protocol of ±10 Nm could be applied.[25] Specimens were loaded sinusoidally for 50,000 cycles at a frequency of 3 Hz.

Screw Toggling

Screw loosening of the sacral and iliac screws were measured with motion analysis software (Optotrak Certus Northern Digital Inc., Waterloo, Canada). Light-emitting diode (LED) markers were locked in the screw heads of the sacral and iliac screws to track each screw's motion using the Optotrak Certus motion analysis system. LED markers were also fixed to the sacrum and the pelvis. This system superimposes the coordinate systems of 2 adjacent rigid bodies to determine the relative translation and Eulerian rotations in each of the 3 planes, showing an accuracy of 0.1 mm and a resolution of 0.01 mm. The translation of each screw in the plane of loading, with respect to the bone in which it was inserted, was tracked for evidence of screw toggling. Relative motion of the sacral and iliac screws, within the sacrum and pelvis respectively, was captured for the duration of dynamic loading. Motion of the S2AI screw was measured relative to both the sacrum and the pelvis. The average toggle over the last 1000 cycles of loading was used for data analysis.

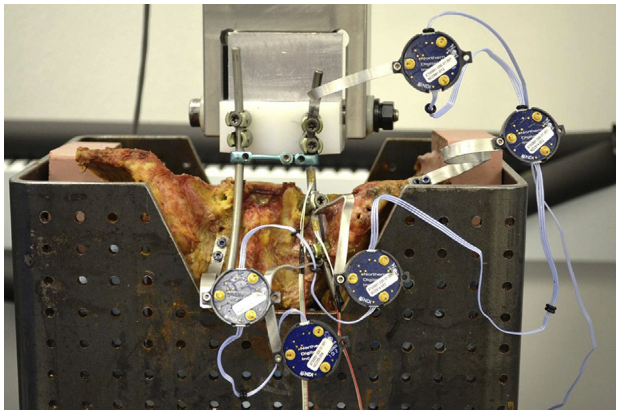

Figure 3. Example test setup for dynamic toggling of the S1 and iliac screws.

Rod Strain

Uniaxial surface strain gauges (KFH-03-350-C1-11L3M3R, Omega Engineering, Inc., Stamford, CT) were affixed to the rods to measure surface strain during dynamic loading. Strain data were acquired by using a multi-channel signal-conditioning amplifier (Model 5100B, Vishay Precision Group, Raleigh, NC) interfaced with a personal computer. For each specimen, fresh surface strain gauges were positioned on the posterior rod both above and below the sacral screw. Rods were first cleaned and prepared for the strain gauge by a sequential cleaning process, as recommended by the strain gauge manufacturer. Following rod prep, a polyurethane glue adhesive was used to secure the strain gauge to the rod. The gauges recorded both tension and compression of surface of the rod throughout the duration of testing. Output was reported as total strain — the difference in strain recorded between maximum tension and maximum compression. The average total strain over the last 1000 cycles of loading was used for data analysis.

Statistical Analysis

Statistical analysis was performed with SPSS v20.0.0 software (IBM Corp., Armonk, NY). A 1-way analysis of variance with Bonferroni post hoc analysis was performed to assess the differences in screw loosening and rod-strain between groups. Significance was defined as $P < 0.05$.

RESULTS

Specimen Information

Comparisons of average BMD, iliac screw length, and sacral screw length are depicted in Table 1. There were no significant differences between groups in BMD ($P = 0.765$), sacral screw length ($P = 0.797$), or pelvic screw length ($P = 0.071$). While TI and MI had the same mean pelvic screw length (105.8 mm), mean S2AI pelvic screw length (92.5 mm) was more than 10 mm shorter.

Table 1. BMD and Screw Length Comparisons

Screw Type	BMD (T-Score)	Sacral Screw Length (mm)	Pelvic Screw Length (mm)
TI	−0.9 ± 1.6	55.8 ± 4.9	105.8 ± 9.2
S2AI	−0.8 ± 2.2	54.2 ± 4.9	92.5 ± 11.3
MI	−0.2 ± 1.6	55.8 ± 4.9	105.8 ± 11.1
P value	0.765	0.797	0.071

Screw Toggle

Toggle of the sacral screw followed the following trend: S2AI > MI > TI (Figure 4). The sacral screw in the S2AI group toggled 0.35 mm ± 0.34 mm, while the MI and TI sacral screws toggled by 0.30 mm ± 0.25 mm and 0.25 mm ± 0.08 mm, respectively. Toggle of the pelvic screw relative to the pelvis followed the following trend: S2AI > TI > MI. The pelvic screw in the S2AI group toggled 0.43 mm ± 0.11 mm relative to the pelvis, while the MI and TI sacral screws toggled by 0.22 mm ± 0.05 mm and 0.23 mm ± 0.23 mm, respectively. The pelvic screw in the S2AI group also toggled 0.53 ± 0.55 mm relative to the sacrum. Neither the TI nor MI groups had pelvic screw toggle relative to the sacrum since the pelvic screws in those groups were not anchored in the sacrum. There were no statistically significant differences in toggle of either the sacral screw ($P = 0.797$) or the pelvic screw relative to the pelvis ($P = 0.052$) between groups.

Rod Strain

Total rod strain above the S1 screw followed the following trend: MI > TI > S2AI (Figure 5). Rod strain above S1 in the MI group was 655 μm/mm ± 319 μm/mm, while rod strain above S1 for the TI and S2AI groups was 625 μm/mm ± 302μm/mm and 454 μm/mm ± 343μm/mm, respectively. Total rod strain below the S1 screw followed the following trend: S2AI > TI > MI. Rod strain below S1 in the S2AI group was 191 μm/mm ± 229μm/mm, while rod strain above S1 for the TI and MI groups was 114

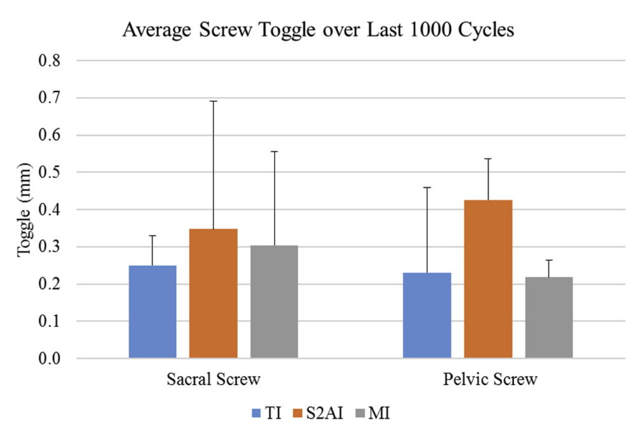

Figure 4. Average toggle of the sacral screw relative to the sacrum, and pelvic screw relative to the pelvis over the last 1000 cycles of loading.

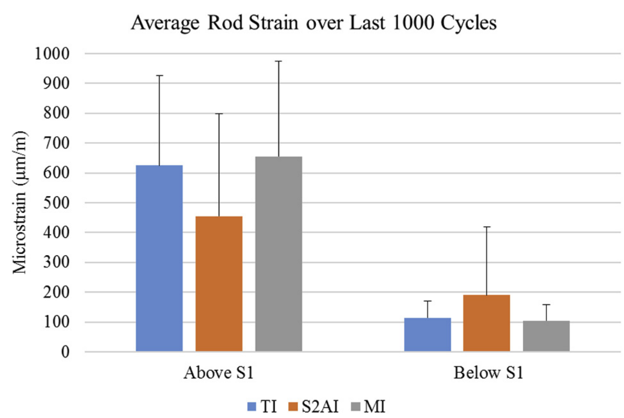

Figure 5. Average rod strain above and below the S1 screw over the last 1000 cycles of loading.

μm/mm ± 57μm/mm and 104 μm/mm ± 53 μm/mm, respectively. There were no statistically significant differences in total rod strain either above ($P = 0.522$) or below ($P = 0.519$) the S1 screw between groups.

DISCUSSION

Lumbopelvic fixation has been commonly used for a spectrum of spinal surgeries including fixation for deformity correction, lumbosacral trauma, and spinal metastatic disease.[11,21,26,27] Anchoring spinal constructs to the pelvis has been shown to reduce implant failure and promote arthrodesis at the lumbosacral junction by extending cantilever forces through an extended level arm to the ileum.[28,29] TI screws have been correlated with expanded dissection and hardware prominence resulting in wound complications along with an additional construct failure point.[8,30,31] The S2AI screw has gained prominence as an alternative, which has been associated with less morbidity, but revealed higher failure rates compared to the traditional iliac screw.[22] While both TI and S2AI screws are commonly used in lumbopelvic fixation, biomechanical comparisons have failed to prove that either is significantly better biomechanically.[23,30,32]

To overcome the complications associated with TI and S2AI screws, MI screws address the limitations of those techniques.[15,16,19] From a clinical standpoint, the insertion technique of MI screws avoids dissection to expose the PSIS subperiosteally, and therefore preserves the integrity of the gluteus maximus. Moreover, an extensive osteotomy at the PSIS to provide a less prominent screw head can be avoided. The MI technique reduces screw head prominence, and prevents the need for removal of the cortical bone of PSIS and use of offset connectors.[15,18] This avoids extensive surgical dissection, and therefore may help decrease wound-healing complications. Furthermore, the short- and long-term effects of violating the articular cartilage of the SI joint via S2AI screws are still unknown.[8] This is especially important when considering the need for temporary fixation to achieve reduction and stabilization of fracture dislocations involving the lumbosacral region.

In this study, the researchers implemented a new biomechanical model of the lumbopelvic junction to compare the MI technique with established pelvic fixation techniques. This biomechanical evaluation of the modified iliac screw reveals comparable screw toggle comparing all 3 fixation techniques after 50,000 cycles. The presumption of less toggle using an S2AI screw, which transverses 3 cortices, giving strong purchase in both the ilium and sacrum could not be supported by the authors' results, with S2AI screws presenting more toggle than TI and MI screws, relative to both the sacrum and the ilium.[8,33] Accordingly, a quadruple cortical S2AI screw did not show any advantage compared to the traditional iliac screw with an offset connector.[23]

A fundamental principle of lumbopelvic fixation is to achieve a fixation endpoint anterior to the pivot point.[34] As the stiffness in flexion improves further from this pivot point, the length of the iliac screw and the resulting lever arm through the middle of the L5—S1 disc may affect toggling and the resulting screw loosening.[34] As described by Schildhauer et al., the TI screw allows screw length up to 140 mm compared with an average of only 90 mm using S2AI screws.[8,24,35,36] Recent biomechanical studies comparing these techniques used iliac screws that were 90 mm long or less, and therefore did not test the most clinically relevant iliac screw length.[23,30] Despite using a longer iliac screw in both the MI and TI groups, no significant effect on screw toggling was observed in this study. This confirms the findings of Zheng et al., who compared short (70 mm) with long (138 mm) TS, pointing out a higher pullout strength using a long screw, but similar mechanical stability with no significant difference under physiologic torsional and compressive loading conditions.[37] Moreover, Burns et al. could not point out any significant differences for torsional stiffness in extension, flexion, left-, or right-bending between S2AI (80 mm) and iliac screw (80 mm) constructs.[30]

The use of TI screws commonly creates an offset between the TI and the S1 screw that requires the use of offset connectors to facilitate rod placement. Another assumed advantage of the MI screw is the avoidance of offset connectors, which have been clinically associated with higher instrumentation failure rates, more wound-healing complications, and increased need for revision surgery.[8,13,20-22,31] High offset failure of up to 12% has been reported in clinical studies of this technique.[9,22,38] This may be attributed to an increased lever arm using offset connectors, which may increase load levels and toggle moment at the TI screw.[39] Whereas Sohn et al. found the highest-peak von Mises stresses in flexion located at the offset connectors in TS,[19] the use of an offset connector did not have any impact on screw toggling in the present study.

While similar rod strain was found above and below the S1 screw with the use of Iliac fixation (TI and MI), the S2AI screw resulted in an increased rod strain below the S1 screw. This increased rod strain below S1 fixation using an S2AI screw may explain the clinically encountered higher instrumentation failure rate of S2AI screws in comparison to TI screws (35% vs. 12%) due to screw head dislocation, rod breakages, or deformation in S2AI.[22] Accordingly to this study's finding of increased rod strain below S1 fixation using S2AI screws, Sohn et al. found the most distractive demonstrating highest-peak von Mises stresses with S2AI fixation while it was compressing in the MI group.[19] As postulated by Desrocher-Perrault et al., different lever arms resulting from the different insertion points of these 3 techniques may increase rod strain in S2AI below the S1 screws due to the shortest distance between the S2AI insertion point and the S1 screw.[40]

The current study has several limitations inherent to an in vitro biomechanical spine study. Although the specimens used in this study were carefully denuded to preserve their posterior and anterior ligamentous complexes, all of the major muscles were removed from the spine. Therefore, it does not replicate the in vivo condition in which a variety of muscular interactions create forces across the motion segments of the spine.[41] Moreover, this study relies on a relatively small sample size, and is limited by inherent cadaveric bone quality. However, previous studies have utilized a similar number of specimens.[23,30] Furthermore, we recognize that this study only describes the biomechanical properties of initial fixation using various iliac fixation methods. Important considerations regarding fatigue, pullout profile, SI pain, and long-term loosening have to be considered when selecting a method of lumbopelvic fixation. Moreover, this model does not consider L5—S1 interbody support, which would be expected to enhance stability across the lumbosacral region.[42] Further biomechanical and clinical testing is necessary to compare the MI trajectory to more common TI and S2AI trajectories.

CONCLUSIONS

This study found no statistically significant differences between the TI, S2AI, and MI techniques in fixation to the pelvis with regard to construct toggle or rod strain. Advantages of the MI screw include its lower profile, potentially leading to fewer wound complications. Further, inline connections are not required, eliminating a potential source of modular failure. Based on the findings of this study, with no clear biomechanical advantage of any pelvic fixation technique, the choice of fixation should be guided by surgeon preference and experience with the techniques. Prospectively randomized controlled trials are needed to better determine which construct has the best clinical outcomes.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Alexander Von Glinski: Conceptualization, Methodology, Investigation, Writing — original draft, Formal analysis. **Clifford Pierre:** Methodology, Investigation, Writing — original draft, Formal analysis. **Sven Frieler:** Writing — original draft, Formal analysis. **Jonathan M. Mahoney:** Conceptualization, Methodology, Investigation, Writing — original draft, Formal analysis. **Jonathan A. Harris:** Conceptualization, Methodology, Investigation, Writing — original draft, Formal analysis. **Dhara B. Amin:** Conceptualization, Methodology, Investigation, Writing — original draft, Formal analysis. **May Allall:** Conceptualization, Methodology, Investigation, Writing — original draft, Formal analysis. **Brandon S. Bucklen:** Conceptualization, Methodology, Investigation, Writing — original draft, Supervision, Project administration. **Thomas A. Schildhauer:** Conceptualization, Methodology, Writing — original draft, Formal analysis, Writing — review & editing, Validation. **Rod J. Oskouian:** Conceptualization, Methodology, Investigation, Writing — original draft, Formal analysis, Writing — review & editing, Supervision, Project administration, Validation. **Jens R. Chapman:** Conceptualization, Methodology, Investigation, Writing — original draft, Formal analysis, Writing — review & editing, Supervision, Project administration, Validation.

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