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Posted Date: 8 April 2026

doi: 10.20944/preprints202604.0525.v1

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Article

# Biomechanical Evaluation of Sacral Load Redistribution Following Unilateral and Bilateral Sacroiliac Joint Disruption: A Three-Dimensional Finite Element Comparison of Three Fixation Strategies

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## Abstract

**Background:** Sacroiliac joint (SIJ) disruption alters posterior pelvic ring stability and may result in abnormal sacral stress redistribution. The biomechanical effects of different fixation strategies on sacral load transfer remain controversial. This study aimed to compare sacral stress patterns under unilateral and bilateral SIJ instability using three fixation techniques in a three-dimensional finite element model. **Methods:** A three-dimensional lumbosacral–pelvic finite element model was reconstructed from computed tomography data of a healthy adult and validated against previously published pelvic biomechanical data. SIJ instability was simulated by reducing the friction coefficient to represent ligamentous failure. Three fixation constructs were analyzed: anterior plate with posterior screw fixation, spinopelvic fixation, and hybrid fixation. A 750 N axial compressive load was applied to simulate static standing conditions; dynamic loading scenarios such as walking or sitting were not included. Peak sacral von Mises stress and stress amplification factors were calculated and compared with the intact model. **Results:** Anterior plate combined with posterior screw fixation produced the highest sacral stress amplification (SAF = 3.46 under unilateral instability; peak stress 265.40 MPa), exceeding three times the intact value, particularly under unilateral left instability (SAF = 3.46). Spinopelvic fixation significantly reduced peak sacral stress (125.66 MPa under bilateral instability; SAF = 1.64) but remained above physiological levels. Hybrid fixation demonstrated sacral stress values closest to the intact condition (81.64 MPa; SAF = 1.06), with minimal amplification and near-symmetrical load distribution. **Conclusions:** Fixation strategy significantly influences sacral load redistribution following SIJ disruption. Hybrid fixation most effectively restored near-physiological sacral stress patterns, whereas anterior plate with posterior screw fixation resulted in excessive stress concentration. Hybrid stabilization may provide a biomechanically balanced approach for unstable posterior pelvic injuries.

**Keywords:** sacroiliac joint; pelvic ring instability; spinopelvic fixation; hybrid fixation; finite element analysis; sacral stress redistribution; posterior pelvic ring biomechanics

## Introduction

The sacroiliac joint (SIJ) plays a fundamental role in load transmission between the axial skeleton and the lower extremities. As a keystone structure of the posterior pelvic ring, the SIJ contributes significantly to vertical load transfer, rotational stability, and energy dissipation during standing and gait. Disruption of the sacroiliac complex—whether due to high-energy trauma, vertical shear injuries, or ligamentous failure—alters physiological load pathways and results in abnormal stress

redistribution across the sacrum and pelvic ring (1,2). Biomechanically, even subtle instability of the posterior ring may compromise spinopelvic balance and increase the risk of fixation failure if not adequately addressed (3,4).

The structural behavior of the pelvis has been described as a closed ring system in which stability depends on both anterior and posterior elements (5). Posterior sacroiliac ligamentous integrity is considered the primary determinant of vertical stability, whereas the pubic symphysis contributes to rotational control (6). Experimental cadaveric investigations have demonstrated that posterior ring disruption produces asymmetric stress concentration in the sacrum and significant micromotion at the SIJ interface (7,8). Such instability often necessitates surgical fixation to restore load continuity and prevent progressive deformity.

Various fixation strategies have been proposed to stabilize sacroiliac joint disruptions. Iliosacral screw fixation remains one of the most commonly employed techniques, offering minimally invasive stabilization (9). However, concerns regarding screw loosening, stress concentration at the sacral ala, and inadequate resistance to vertical shear forces have been reported, particularly in osteoporotic bone (10,11). Anterior plating combined with posterior screw fixation has been introduced to improve rotational stability in cases with concomitant symphyseal disruption, yet biomechanical superiority remains debated (12).

Spinopelvic fixation, involving pedicle screws anchored in the lumbar spine and iliac screws connected via rods, has emerged as a rigid bridging construct capable of restoring vertical stability in highly unstable pelvic injuries (13). Recent finite element and cadaveric studies have demonstrated increased construct stiffness with spinopelvic systems compared to isolated iliosacral screws (14,15). However, excessive rigidity may alter physiological load sharing and potentially induce stress shielding or implant-related complications (16,17). Therefore, the balance between construct stiffness and physiological load transmission remains a critical biomechanical consideration.

Finite element (FE) modeling has become an essential tool for evaluating pelvic biomechanics and fixation strategies under controlled loading conditions (6,18). Several recent investigators have utilized FE models to analyze sacroiliac fixation constructs, reporting differences in stress patterns across the sacrum and implants depending on fixation topology (14,15,19). Nevertheless, comparative analyses simultaneously evaluating anterior plating, spinopelvic fixation, and hybrid constructs under identical injury simulations remain limited. In particular, no prior study has simultaneously compared all three fixation constructs under both unilateral and bilateral instability conditions simulated through contact-based friction modification, which more closely replicates ligamentous failure than geometric joint removal.

From a biomechanical perspective, ligamentous failure primarily alters shear resistance and joint contact mechanics rather than causing immediate gross geometric discontinuity (3). Changes in frictional resistance at the SIJ interface significantly influence stress transfer patterns across the posterior ring (20). Consequently, computational models simulating instability through modified contact parameters may provide a more physiologically representative approach than simple element removal strategies.

Despite the increasing clinical utilization of combined fixation strategies, the optimal method for restoring physiological sacral load transfer following unilateral and bilateral SIJ disruption remains controversial. Specifically, it remains unclear whether rigid spinopelvic constructs reduce sacral stress more effectively than anterior plating with posterior screw fixation, or whether hybrid stabilization provides a more balanced biomechanical environment by redistributing load without excessive rigidity.

Therefore, the aim of the present study was to perform a three-dimensional finite element analysis to compare sacral stress distribution under unilateral and bilateral sacroiliac joint disruption across three fixation strategies. We hypothesized that hybrid fixation would demonstrate a sacral stress pattern closer to the intact model while avoiding excessive stress concentration observed in isolated anterior–posterior fixation constructs.

## Materials and Methods

### *Finite Element Model Development*

A three-dimensional anatomically validated finite element (FE) model of the lumbosacral spine and pelvis was developed to investigate sacral load redistribution following sacroiliac joint (SIJ) disruption. The geometry was reconstructed from high-resolution computed tomography (CT) data obtained from the Visible Human Project (National Library of Medicine, Bethesda, MD, USA), a publicly available anatomical dataset. As all data were obtained from an open-access repository, institutional ethical approval and informed consent were not required. The model included the L4 and L5 vertebrae, intervertebral discs, sacrum, and bilateral pelvic bones (ilium, ischium, and pubis).

All geometric processing, implant positioning, and assembly operations were performed using SpaceClaim (ANSYS Inc., Canonsburg, PA, USA). Numerical simulations were conducted in ANSYS Workbench R14.

To simulate different clinical conditions, four primary configurations were constructed:

- **Model 0 (Reference Model):** Intact pelvis without implants. Injury scenarios (unilateral and bilateral SIJ disruption) were also simulated in this model.
- **Model 1 (Anterior Plate + Posterior Screw Fixation):** Symphyseal plating combined with trans-iliac screw stabilization across the SIJ.
- **Model 2 (Spinopelvic Fixation):** Pedicle screws placed in L4–L5 connected to bilateral iliac screws using rod constructs.
- **Model 3 (Hybrid Fixation):** Combination of anterior plating and spinopelvic posterior stabilization.

All implant geometries were designed according to commonly used clinical dimensions reported in biomechanical studies. Anterior symphyseal plate was modeled as a 6-hole reconstruction plate (thickness: 3.5 mm), consistent with standard anterior pelvic ring fixation. Posterior iliosacral screws were modeled as solid cylinders (diameter: 7.3 mm; length: 80 mm). Spinopelvic constructs included L4–L5 pedicle screws (diameter: 6.5 mm; length: 45 mm) connected to bilateral iliac screws (diameter: 7.5 mm; length: 80 mm) via titanium rods (diameter: 5.5 mm). These dimensions are consistent with implant specifications reported in previously published finite element studies of pelvic ring fixation.

### *Material Properties*

All bony structures were modeled as homogeneous, isotropic, and linearly elastic materials, consistent with established pelvic FE modeling approaches bone exhibits anisotropic behavior, linear elastic assumptions are widely accepted for comparative fixation analysis under physiological loading ranges.

Material properties were assigned as follows:

- Cortical bone: Elastic modulus = 17,000 MPa; Poisson's ratio = 0.30. Trabecular bone: Elastic modulus = 700 MPa; Poisson's ratio = 0.25. These values are consistent with previously validated pelvic finite element models
- Intervertebral disc: Elastic modulus = 4.2 MPa; Poisson's ratio = 0.45(4,6)
- Pubic symphysis cartilage: Elastic modulus = 5.0 MPa; Poisson's ratio = 0.45
- Titanium alloy implants (Ti-6Al-4V): Elastic modulus = 111,000 MPa; Poisson's ratio = 0.30

Material parameters were derived from previously validated finite element studies of sacropelvic and lumbopelvic fixation.(4,6)

### *Model Validation:*

The intact finite element model was validated by comparing predicted sacral von Mises stress and pelvic displacement patterns against previously published experimental and computational data. Under 750 N axial loading, the intact model produced a peak sacral stress of 76.67 MPa, which is consistent with values reported in validated pelvic finite element studies under comparable loading

conditions ripathi et al., 2024; Lee et al., 2017). Qualitative stress distribution patterns across the sacrum and posterior pelvic ring were also consistent with established biomechanical literature. Although direct cadaveric validation was not performed in the present study, the use of previously reported material properties and boundary conditions from validated models provides an acceptable basis for comparative fixation analysis, as widely acknowledged in computational pelvic biomechanics (6,18).

#### *Mesh Generation and Convergence*

Due to the complex geometry of the pelvis and implant interfaces, ten-node quadratic tetrahedral elements (SOLID187) were used throughout the model. This element type provides superior accuracy for irregular anatomical structures and curved surfaces.

Mesh refinement was applied in regions of expected stress concentration, including:

- Sacral ala
- Implant-bone interfaces
- Screw entry points
- Sacroiliac joint surfaces

A mesh convergence study was conducted using three global element sizes (1.8 mm, 1.2 mm, and 0.8 mm). The variation in peak sacral von Mises stress between the medium and fine mesh densities was less than 3%. Therefore, the medium-density mesh was selected for final simulations to balance computational efficiency and numerical accuracy.

#### **Contact Definitions and Injury Simulation**

Bone-implant interfaces were defined as fully bonded contacts, assuming complete osseointegration and absence of micromotion at the screw-bone interface.

Sacroiliac joint contact behavior was modeled using surface-to-surface frictional contact algorithms.

- **Intact side:** Friction coefficient ( $\mu$ ) = 0.3, representing physiological cartilage resistance.
- **Injured side:** Friction coefficient was reduced to  $\mu = 0.05$  to simulate ligamentous failure and loss of shear resistance at the SIJ interface.

This contact-based instability simulation approach preserves articular congruity while selectively altering mechanical resistance, thereby avoiding artificial geometric discontinuity associated with element removal strategies. Although ligament stiffness reduction represents an alternative simulation approach, friction modification has been employed in prior pelvic FE studies to represent joint surface laxity under pathological conditions. This approach allows simulation of instability without artificial geometric separation, thereby preserving joint congruency while altering mechanical resistance.

To prevent rigid body motion and improve convergence stability:

- “Adjust to Touch” contact correction was applied
- Pinball region optimization was used
- Weak spring stabilization was activated for non-implanted unstable models

#### *Boundary and Loading Conditions*

To simulate physiological standing posture:

- Both acetabular surfaces were fully constrained in all translational and rotational degrees of freedom.

- A vertical compressive load of 750 N was applied to the superior surface of the L4 vertebral body along the axial (Z) direction.

The magnitude of 750 N corresponds to the estimated upper body weight of a 75 kg adult under static standing conditions.

No additional bending or torsional moments were applied in this study to isolate axial load transfer characteristics (Figures 1 and 2).

#### *Outcome Measures*

Primary outcome parameter:

- Maximum von Mises stress within the sacrum (MPa)

Secondary outcome parameters:

- Bilateral SIJ contact stress distribution
- Stress asymmetry between left and right SIJ
- Comparative stress ratio relative to intact condition

Sacral stress redistribution was compared across:

- Unilateral left injury
- Unilateral right injury
- Bilateral injury

### Results

Under 750 N axial compression, distinct load redistribution patterns were observed across fixation constructs and injury configurations. Quantitative comparisons were performed using raw sacral von Mises stress values and derived biomechanical indices including stress amplification factor, asymmetry ratio, bilateral load deviation, and normalized stress transfer coefficient.

**Table 1. Peak Sacral von Mises Stress (MPa).**

Model	Intact	Left Injury	Right Injury	Bilateral Injury
<b>Model 0</b>	76.67	75.81	88.12	88.62
<b>Model 1</b>	—	265.40	223.89	235.66
<b>Model 2</b>	—	109.25	106.79	125.66
<b>Model 3</b>	—	79.25	103.86	81.64

The intact model demonstrated a peak sacral stress of 76.67 MPa, confirming symmetrical and physiologically distributed load transfer across the posterior ring. In the absence of fixation (Model 0), unilateral instability caused asymmetric stress elevation, particularly under right-sided injury, where peak stress increased by approximately 15% relative to intact conditions. The asymmetric stress response observed between left and right unilateral injury scenarios in Model 0 (75.81 MPa vs. 88.12 MPa, respectively) may reflect geometric asymmetry inherent to the CT-reconstructed pelvic model, as minor morphological differences between the left and right hemipelvis are well recognized in the literature. This finding underscores the importance of side-specific biomechanical assessment in posterior pelvic ring injuries. Bilateral instability further amplified sacral stress, reflecting compromised posterior ring integrity and increased dependence on sacral load-bearing.

Model 1 (anterior plate + posterior screw fixation) generated the highest stress magnitudes among all constructs. Peak sacral stress exceeded 265 MPa in unilateral injury conditions, representing more than a threefold increase relative to intact levels. This marked amplification suggests that the construct channels axial load directly through the sacral ala rather than redistributing it along a broader load-sharing pathway. Such stress concentration may predispose to sacral insufficiency fractures, screw loosening, or hardware fatigue, particularly in osteoporotic bone.

Spinopelvic fixation (Model 2) significantly reduced sacral stress compared to Model 1, maintaining peak values within the 100–125 MPa range. Although stress remained elevated compared to intact conditions, the reduction indicates effective vertical load bridging through the lumbopelvic construct. Hybrid fixation (Model 3) demonstrated stress magnitudes closest to physiological levels, particularly in bilateral injury, where peak stress (81.64 MPa) nearly approximated intact values. This suggests superior load redistribution without excessive rigidity.

**Table 2. Stress Amplification Factor (SAF).**

$$\text{SAF} = \sigma_{\text{model}} / \sigma_{\text{intact}}$$

Model	Left Injury	Right Injury	Bilateral Injury
<b>Model 1</b>	3.46	2.92	3.07
<b>Model 2</b>	1.42	1.39	1.64
<b>Model 3</b>	1.03	1.35	1.06

Stress amplification analysis further clarifies construct behavior. Model 1 amplified sacral stress by up to 346%, indicating a non-physiological load transfer mechanism. Such excessive amplification implies that the construct increases local stiffness without adequately compensating for posterior ligamentous deficiency.

Spinopelvic fixation limited stress amplification to approximately 40–60%, demonstrating effective vertical load bypass through the spinal rods. However, bilateral injury still produced elevated SAF values (1.64), suggesting that complete restoration of physiological load transfer was not achieved.

Figure 1 illustrates the peak sacral von Mises stress values under bilateral sacroiliac joint instability across the three fixation constructs. The anterior plate combined with posterior screw fixation (Model 1) generated the highest stress concentration within the sacrum (235.66 MPa), representing a substantial deviation from physiological load distribution. This marked elevation suggests that the construct channels axial load directly through the sacral ala without sufficient redistribution along the posterior ring. Such concentrated stress patterns may increase the risk of sacral insufficiency fractures, screw loosening, and implant fatigue, particularly in osteoporotic bone.

Spinopelvic fixation (Model 2) significantly reduced sacral stress (125.66 MPa), indicating effective vertical load bridging through the lumbopelvic rod system. However, stress levels remained notably elevated compared to the intact baseline, suggesting that while rigidity improves stability, it does not fully restore physiological load-sharing mechanisms.

Hybrid fixation (Model 3) demonstrated the lowest peak sacral stress (81.64 MPa), closely approximating intact conditions. This finding indicates that the combined anterior and posterior stabilization provides controlled stiffness while preserving near-physiological load transmission. From a biomechanical standpoint, the hybrid construct appears to achieve an optimal balance between structural rigidity and physiological load redistribution.

Hybrid fixation achieved amplification values close to unity, particularly in bilateral instability (SAF = 1.06). This indicates that the combined construct neither excessively stiffens nor under-supports the sacrum, but instead approximates intact biomechanical conditions. From a mechanobiological perspective, maintaining SAF near 1 may be advantageous for bone remodeling and implant longevity.

**Table 3. Left–Right Asymmetry Ratio (AR).**

$$\text{AR} = |\sigma_{\text{left}} - \sigma_{\text{right}}| / ((\sigma_{\text{left}} + \sigma_{\text{right}})/2)$$

Model	Left Injury	Right Injury	Bilateral Injury
<b>Model 0</b>	0.06	0.26	0.11

<b>Model 1</b>	0.28	0.09	0.15
<b>Model 2</b>	0.09	0.00	0.12
<b>Model 3</b>	0.38	0.27	0.09

Unilateral injury in the non-fixated model generated significant asymmetry (AR up to 0.26), confirming disrupted posterior ring load equilibrium. Model 1 failed to adequately restore symmetry, particularly under left-sided injury (AR = 0.28), suggesting uneven load transmission through the sacral interface.

Spinopelvic fixation demonstrated superior symmetry control, especially in right injury (AR  $\approx$  0), indicating balanced bilateral load sharing. Hybrid fixation exhibited some asymmetry under unilateral injury; however, in bilateral instability the AR decreased to 0.09, approaching intact symmetry. This suggests that hybrid constructs are particularly effective in globally unstable configurations where symmetrical load redistribution is critical.

**Table 4. Bilateral Stress Deviation from Intact (%).**

Model	Bilateral Injury (%)
<b>Model 0</b>	+15.6
<b>Model 1</b>	+207
<b>Model 2</b>	+64
<b>Model 3</b>	+6.5

Bilateral instability without fixation increased sacral stress modestly (+15.6%), reflecting physiological compensation mechanisms. However, anterior plating produced extreme deviation exceeding +200%, indicating pathological stress concentration. Spinopelvic fixation reduced deviation substantially but remained above physiological thresholds. Hybrid fixation limited deviation to +6.5%, effectively restoring intact load transfer characteristics. This minimal deviation suggests that hybrid stabilization maintains biomechanical homeostasis under axial loading.

Figure 2 presents the stress amplification factor (SAF), defined as the ratio of peak sacral stress in each fixation model relative to the intact configuration. Model 1 exhibited a stress amplification exceeding threefold (SAF = 3.07), highlighting a pronounced deviation from natural biomechanical behavior. This excessive amplification indicates that the construct increases local sacral stiffness without effectively compensating for posterior ligamentous insufficiency, thereby transferring excessive axial load to a confined region.

Spinopelvic fixation (Model 2) reduced amplification to approximately 1.64, demonstrating improved biomechanical moderation. The reduction reflects partial offloading of the sacrum through the spinal instrumentation; however, residual amplification suggests incomplete restoration of physiological load pathways.

Hybrid fixation (Model 3) achieved an SAF of 1.06, nearly equivalent to intact biomechanics. This near-unity value indicates that the hybrid construct neither over-stiffens nor under-supports the sacrum, thereby preserving load-sharing characteristics similar to the natural posterior pelvic ring. Mechanobiologically, maintaining stress levels close to physiological thresholds may be advantageous for bone remodeling and long-term implant survival.

**Table 5. Mean Sacral Stress Across Injury States (MPa).**

Model	Mean Stress
<b>Model 1</b>	241.65
<b>Model 2</b>	113.90
<b>Model 3</b>	88.25

Averaged across injury configurations, Model 1 maintained persistently elevated stress levels. Spinopelvic fixation halved mean stress relative to Model 1. Hybrid fixation demonstrated the lowest overall stress burden, reinforcing its biomechanical advantage across multiple instability scenarios.

Figure 3 demonstrates the percentage reduction in peak sacral stress achieved by each construct relative to the anterior plate and posterior screw configuration (Model 1). Spinopelvic fixation achieved a 46.6% reduction in sacral stress, confirming its superior ability to redistribute axial forces compared to isolated anterior-posterior fixation. The rod system effectively transfers a portion of vertical load to the lumbar spine, thereby alleviating sacral stress concentration.

From a clinical perspective, such magnitude of stress reduction may translate into decreased implant failure rates and improved mechanical longevity, particularly in highly unstable bilateral injuries. Overall, the graphical analysis confirms that hybrid fixation demonstrates the most favorable biomechanical performance under axial loading conditions.

**Table 6. Relative Stress Reduction Compared to Model 1 (%).**

Comparison	Bilateral Injury (%)
<b>Model 2 vs Model 1</b>	46.6
<b>Model 3 vs Model 1</b>	65.4

Hybrid fixation reduced sacral stress by more than 65% relative to anterior plating. This magnitude of reduction is biomechanically substantial and may translate into decreased risk of sacral overload and implant fatigue.

## Discussion

The present finite element analysis demonstrated that fixation strategy plays a decisive role in sacral stress redistribution following unilateral and bilateral sacroiliac joint (SIJ) disruption. The principal finding of this study is that hybrid fixation restored sacral stress magnitudes and symmetry patterns closest to the intact physiological condition, whereas anterior plate combined with posterior screw fixation resulted in marked stress amplification and concentration within the sacral ala.

The sacroiliac joint is a key load transfer structure between the spine and the lower extremities. Its biomechanical stability depends on both osseous congruity (form closure) and ligamentous compression forces (force closure), as demonstrated in more recent biomechanical investigations analyzing SIJ load transfer and pelvic ring stability (21,22). Posterior ligamentous structures are critical in resisting vertical shear forces and maintaining symmetrical load distribution (21). Experimental cadaveric and computational studies have confirmed that posterior ring disruption significantly increases sacral motion and alters stiffness of the pelvic ring (23,24). Our non-fixed instability simulations reproduced this behavior, with unilateral injury generating asymmetric stress patterns and bilateral disruption leading to global sacral stress elevation.

Among the evaluated constructs, anterior plating combined with posterior screw fixation produced the highest sacral stress values, exceeding intact levels by more than threefold in certain

scenarios. Contemporary biomechanical studies have reported that isolated iliosacral screw fixation may demonstrate limited resistance to vertical shear forces in unstable injuries (25,26). Furthermore, recent finite element analyses have shown that screw trajectory, length, and fixation topology significantly influence stress concentration within the sacral ala and adjacent bone (14,19). The excessive stress amplification observed in Model 1 likely reflects the biomechanical consequence of creating a rigid anterior-posterior construct that increases local sacral stiffness without providing a parallel vertical load bypass pathway. In this configuration, axial forces transmitted from the lumbar spine are concentrated at the sacral ala — the primary screw insertion zone — rather than being distributed broadly across the posterior ring. This load channeling mechanism is consistent with stress concentration phenomena reported in isolated iliosacral screw constructs under vertical shear loading (25,26).

Spinopelvic fixation significantly reduced sacral stress compared to anterior plating. Modern lumbopelvic fixation techniques provide enhanced vertical stability and improved posterior ring stiffness (13,27). Biomechanical analyses comparing S2-alar-iliac and iliac screw constructs have demonstrated improved construct rigidity and reduced sacral micromotion (14,15). Our findings are consistent with these studies, as spinopelvic fixation reduced stress amplification and improved symmetry. However, stress levels remained elevated compared to intact conditions, suggesting that increased construct rigidity may alter physiological load-sharing behavior.

The concept of optimal stiffness has been increasingly emphasized in contemporary spinal and pelvic biomechanics (16,28). Excessive rigidity may modify physiological load transmission and potentially induce stress shielding phenomena or adjacent segment mechanical overload (28). While spinopelvic constructs provide superior vertical stabilization, complete load bypass of the sacrum may not replicate natural pelvic load transfer. Our stress amplification analysis indicates that although spinopelvic fixation mitigates overload, it does not fully normalize sacral stress patterns.

Hybrid fixation demonstrated the most favorable biomechanical profile. By combining anterior stabilization with posterior spinopelvic support, this construct appeared to balance rigidity and physiological load redistribution. Mechanistically, the anterior plate component provides rotational stability and controls symphyseal diastasis, while the posterior spinopelvic rods create a vertical load bypass pathway from the lumbar spine to the iliac wings, effectively offloading the sacrum. The combination of these two mechanisms allows controlled force distribution without excessive constraint at any single anatomical region. This dual-pathway load sharing likely explains why hybrid fixation achieved sacral stress values closest to intact conditions, as neither the anterior nor posterior component alone bears the full axial load. Under bilateral instability, sacral stress magnitudes approached intact levels, and normalization indices approximated unity. Recent biomechanical modeling studies have emphasized the importance of controlled stiffness and balanced load-sharing in maintaining implant longevity and minimizing stress concentration (18). Hybrid fixation demonstrated the most favorable overall biomechanical profile, achieving the greatest stress reduction while maintaining sacral stress levels closest to intact physiological conditions. Our results align with these principles, suggesting that hybrid constructs may optimize load transfer while avoiding excessive constraint.

From a clinical perspective, several practical considerations must be acknowledged when interpreting these biomechanical findings. Hybrid fixation, while demonstrating superior stress distribution, involves a more extensive surgical procedure combining both anterior plating and posterior spinopelvic instrumentation. This translates into longer operative time, increased implant costs, greater surgical exposure, and potentially higher perioperative morbidity compared to isolated anterior or posterior fixation. Therefore, hybrid stabilization may be most appropriate in cases of highly unstable bilateral sacroiliac disruptions where restoration of spinopelvic balance is critical, rather than as a universal approach for all posterior pelvic ring injuries. Patient selection, bone quality, surgeon experience, and injury pattern should guide construct choice in clinical practice.

An important methodological strength of this study is the injury simulation approach using modified friction coefficients rather than artificial joint separation. Contemporary computational

investigations have increasingly focused on contact-based modeling of ligamentous failure rather than element removal, highlighting the role of joint friction and contact mechanics in SIJ stability (21,30). By reducing friction coefficients to simulate ligamentous insufficiency, our model preserved anatomical congruity while altering mechanical resistance, providing a physiologically representative instability simulation.

Clinically, the findings suggest that while anterior plate combined with posterior screw fixation may provide structural stabilization, it may also generate unfavorable sacral stress concentrations under axial loading. Spinopelvic fixation improves vertical load redistribution but may introduce excessive rigidity. Hybrid fixation appears to provide a biomechanically balanced alternative, preserving load-sharing characteristics closer to intact physiology. Given that sacral insufficiency fractures and implant-related complications remain concerns in unstable pelvic injuries (26,27), constructs that minimize stress amplification may offer mechanical advantages.

Several limitations must be acknowledged. The model assumed homogeneous, isotropic material properties despite the anisotropic nature of bone. Only axial loading was applied; combined loading conditions may influence construct performance. Muscle forces were not incorporated, which may affect in vivo load distribution. The instability simulation was performed through friction coefficient reduction rather than explicit ligament removal or stiffness modification; while this approach preserves joint congruity, it may not fully replicate the complex three-dimensional mechanical behavior of ligamentous failure. Nevertheless, finite element modeling remains a validated and widely accepted method for comparative biomechanical evaluation of pelvic fixation constructs (6,18).

In summary, fixation topology directly influences sacral stress redistribution following SIJ disruption. Hybrid fixation most closely restored physiological load transmission, whereas anterior plate combined with posterior screw fixation resulted in substantial stress amplification. Spinopelvic fixation provided intermediate performance. These findings contribute to ongoing biomechanical optimization of posterior pelvic ring stabilization strategies.

## Conclusion

This finite element study demonstrated that fixation strategy significantly influences sacral load redistribution following unilateral and bilateral sacroiliac joint disruption. Anterior plate combined with posterior screw fixation resulted in marked sacral stress amplification and concentration, indicating limited physiological load-sharing capacity under axial loading. Spinopelvic fixation effectively reduced peak sacral stress through vertical load bridging; however, stress levels remained elevated compared to intact conditions, reflecting increased construct rigidity.

Hybrid fixation provided the most favorable biomechanical performance, restoring sacral stress magnitudes and symmetry patterns closest to the physiological baseline. By balancing stability and controlled load transfer, the hybrid construct achieved near-normal stress amplification values and minimized deviation from intact biomechanics.

These findings suggest that construct topology plays a critical role in maintaining physiological sacral load distribution after sacroiliac instability. Hybrid stabilization may offer a biomechanical advantage in restoring near-physiological load transmission while avoiding excessive stress concentration associated with isolated anterior-posterior fixation strategies.

These biomechanical findings support the selective use of hybrid stabilization in highly unstable posterior pelvic ring injuries, particularly bilateral sacroiliac disruptions, where restoration of physiological load symmetry is a primary surgical objective. Future clinical and cadaveric studies are warranted to validate these computational findings in vivo.

**Author Contributions:** Conceptualization, B.A.; Methodology, B.A, M.C, N.Y; Software, N.Y, M,C; Validation, B.A, M.C, N.Y; Formal Analysis, N.Y, M,C.; Investigation, B.A, M.C, N.Y.; Resources, A.B.; Data Curation, N.Y, M,C.; Writing – Original Draft Preparation, B.A.; Writing – Review and Editing, B.A.; Visualization, B.A, N.Y, M,C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Ethical review and approval were waived for this study, as it is based solely on computational finite element analysis using a three-dimensional model reconstructed from anonymized computed tomography data of a healthy adult volunteer, in accordance with the Declaration of Helsinki. No human subjects were recruited or directly involved in this study.

**Informed Consent Statement:** Patient consent was waived due to the computational and non-interventional nature of the study.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author. The finite element model and simulation outputs are not publicly available due to ongoing research.

**Conflicts of Interest:** The author declares no conflicts of interest.

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