

# Biomechanical Comparison of Three Internal Fixation Techniques for Subaxial Cervical Spine Fractures in Ankylosing Spondylitis: A Finite Element Analysis

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## Research Article

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# Abstract

To compare the biomechanical performance of anterior long-segment fixation, posterior long-segment fixation, and combined anterior-posterior fixation for subaxial cervical spine fractures in ankylosing spondylitis (ASCF) using finite element analysis, providing quantitative evidence for clinical decision-making. A C2-T1 finite element model was constructed from CT data of a typical ASCF patient (male, 56 years). The fracture line crossed the C5-C6 disc space and obliquely involved C6. Three constructs were developed: anterior C4-C7 plate, posterior C4-C7 pedicle screw-rod, and combined (anterior C5-C6 short plate+posterior C4-C7 screw-rod). A 50 N axial preload was applied to C2, followed by a 2.0 N·m pure moment to simulate six physiological motions. Overall maximum displacement, von Mises stress in bone and implants, and equivalent strain were compared among the three constructs. Anterior fixation showed the smallest displacement, highest stiffness, and lowest implant stress under all conditions. Posterior fixation had the largest displacement, while combined fixation was intermediate. Under flexion, peak screw stress in posterior fixation (256.98 MPa) was much higher than in anterior (59.82 MPa) and combined (138.70 MPa) fixation, indicating the highest failure risk. Combined fixation consistently exhibited the highest equivalent strain, suggesting greater bone microdamage potential. For all three constructs, stress/strain concentrations localized at the adjacent lower vertebra (T1). Anterior long-segment fixation provides superior immediate stability and implant safety. Posterior fixation carries a high failure risk under flexion. Combined fixation offers balanced mechanics for complex fractures but warrants caution regarding bone microdamage. Clinical choice must integrate stability, safety, surgical morbidity, and long-term osseointegration.

## Introduction

Ankylosing spondylitis (AS) is a chronic autoimmune disorder primarily characterized by inflammation of the axial skeleton. Its pathological hallmark is progressive ossification of ligaments, the annulus fibrosus, and intervertebral discs, culminating in segmental spinal fusion and the classic "bamboo spine" appearance <sup>1</sup>. As the disease advances, the biomechanical properties of the spine fundamentally change. The normal cervical spine dissipates stress through the viscoelastic deformation of discs and ligaments; conversely, the ankylosed cervical spine transforms into a long, rigid lever arm with markedly diminished capacity for shock absorption. Concurrently, chronic inflammation and disuse often lead to severe osteoporosis and significantly reduced bone quality <sup>2</sup>. This paradoxical state of "rigidity combined with fragility" predisposes AS patients to unstable three-column fractures following minor trauma, such as a low-energy fall <sup>3,4</sup>.

The subaxial cervical spine (C3-C7), particularly the junction between the more mobile cervical region and the relatively rigid thoracic spine, represents one of the most frequent sites for spinal fractures in AS patients. This condition is clinically termed an ankylosing spondylitis subaxial cervical fracture (ASCF) <sup>5</sup>. ASCFs are predominantly extension-type injuries traversing the intervertebral disc space, presenting as a "pseudoarthrosis" that disrupts all three spinal columns. These fractures are highly unstable and often

complicated by spinal cord injury or epidural hematoma, carrying significant morbidity and mortality rates <sup>6,7</sup>.

Currently, surgical intervention is the cornerstone of ASCF management, aiming for neural decompression, restoration of spinal alignment, and immediate stability <sup>8</sup>. However, the optimal surgical approach remains controversial. Anterior surgery allows for direct decompression of ventral neural elements and restoration of anterior column support. However, patients with AS frequently have concomitant osteoporosis, compromising screw purchase; moreover, long-segment anterior plate fixation (four or more fixed segments are considered long-segment fixation) may increase hardware failure risk due to an extended lever arm <sup>9</sup>. Posterior long-segment pedicle screw fixation provides robust biomechanical stability but may inadequately decompress ventral pathology and involves extensive soft tissue dissection, leading to greater surgical morbidity <sup>2,10</sup>. Combined anterior-posterior fixation theoretically offers the advantages of both approaches, providing 360° stability but at the cost of increased operative time, blood loss, and complication rates <sup>2,11</sup>. Therefore, balancing immediate construct stability, implant safety, surgical trauma, and long-term outcomes remains a significant challenge in spinal surgery.

Finite element analysis (FEA), a powerful numerical simulation technique allowing for precise parameter control and high reproducibility, has increasingly been applied to the biomechanical study of AS. However, prior investigations have largely focused on single techniques or thoracolumbar segments. Comparative biomechanical studies of different internal fixation strategies specifically for ASCF are scarce and have yielded inconsistent conclusions <sup>8-16</sup>. This study employs a validated, high-fidelity three-dimensional FEA model of ASCF to systematically compare the biomechanical responses of anterior long-segment fixation, posterior long-segment fixation, and combined anterior-posterior fixation under physiological loading. By providing quantitative data on immediate construct stability, implant failure risk, and the potential for adjacent vertebral body re-fracture, this study aims to inform evidence-based surgical decision-making.

## Materials and Methods

### 1.1 Patient Selection Criteria

Inclusion Criteria: ☐ Age 18-80 years; ☐ Meeting diagnostic criteria for AS; ☐ Radiographically confirmed cervical ankylosis with a subaxial fracture; ☐ Fracture amenable to reduction and fusion with anterior, posterior, or combined approach fixation.

Exclusion Criteria: ☐ Prior cervical spine surgery; ☐ Multiple cervical spine fractures; ☐ Pathological fracture; ☐ Incomplete imaging data.

### 1.2 Patient Demographics

Among five ASCF patients treated at Luohe Central Hospital between July 2024 and December 2024, one typical case meeting the criteria was selected as the modeling basis. The patient has a 20-year history of ankylosing spondylitis (AS) and has also suffered from trauma. Imaging revealed a "bamboo spine" appearance with widespread ligamentous ossification. The fracture line traversed the C5-C6 disc space and obliquely involved the C6 vertebral body, consistent with an unstable three-column injury.

1.3 Construction of the ASCF 3D Finite Element Model and Experimental Grouping

The model's geometry was derived from the patient's CT data to ensure anatomical fidelity. Helical CT (64-slice) scans from the superior endplate of C1 to T2 were exported in DICOM format. Mimics 21.0 software was used to segment the C2-T1 vertebral models, which were exported as STL files. Geomagic Wrap 2017 was employed for surfaceization, denoising, and reconstruction of the fracture line, distinguishing between cortical and cancellous bone, and finally exporting as STP files. Three internal fixation models were constructed in SolidWorks 2023: (1) Anterior fixation system: A four-level C4-C7 plate; (2) Posterior fixation system: A four-level C4-C7 pedicle screw-rod system; (3) Combined fixation system: An anterior short-segment C5-C6 plate combined with a posterior C4-C7 screw-rod system. These implant models were assembled with the cervical fracture model, ensuring accurate screw placement into the pedicles or vertebral bodies (Figure 1). The models were exported in x\_t format to the static structural module of Ansys Workbench 2024 R2.

Boundary Conditions: The inferior surface of the T1 vertebra was fully constrained. A 50 N axial compressive load was applied to the superior surface of the C2 vertebra to simulate head weight, followed by a 2.0 N·m pure moment to simulate six physiological motions: flexion, extension, left lateral bending, right lateral bending, left axial rotation, and right axial rotation. Material properties and contact conditions were assigned according to prior literature<sup>6,16-17</sup> (Table 1). Mesh convergence was verified by testing different mesh densities for the three fixation models; results varied by less than 5% between successive refinements<sup>18</sup>. Model validation was performed by comparing the range of motion and stress distribution trends with published cervical spine biomechanical data. Subsequent results were recorded using the higher-precision 0.3 mm mesh density.

Table 1. Material Properties

|                   | Young modulus (MPa) | Poisson ratio |
|-------------------|---------------------|---------------|
| Cortical bone     | 8040                | 0.3           |
| Cancellous bone   | 34                  | 0.25          |
| Screw             | 110000              | 0.3           |
| Ossified ligament | 8040                | 0.3           |

Figure 1. Lateral views of the three ASCF fixation constructs with schematic representation of loading (flexion condition).

1.4 Outcome Measures

- ☒ Overall Maximum Displacement (mm): Smaller values indicate superior construct stability.
- ☒ Equivalent (von Mises) Stress in the Internal Fixation System (MPa): Higher values indicate increased risk of implant failure/fracture.
- ☒ Equivalent (von Mises) Stress and Equivalent Strain in the Vertebral Body: Higher values indicate greater risk of osseous structural damage.

1.5 Statistical Analysis

This study involved a comparative simulation analysis based on a single representative patient model. The outcomes for the three fixation techniques under different loading conditions are reported descriptively; no inferential statistical tests were performed.

Results

2.1 Comparison of Maximum Cervical Spine Displacement

Across the six loading conditions, overall displacement for all three models was highest during flexion, lowest during extension, and similar for the remaining four motions. Anterior fixation consistently demonstrated the smallest displacement under all six conditions, indicating the greatest overall construct stiffness. Posterior fixation showed the largest displacement (lowest stiffness), while combined fixation yielded intermediate values. Under lateral bending and rotation, the displacement in the combined group ranged from 0.172 to 0.195 mm, differing from the anterior group by less than 0.03 mm (Table 2).

Table 2. Maximum Overall Displacement (mm) for Different Fixation Models

| Loading Condition | Anterior Fixation | Posterior Fixation | Combined Fixation |
|-------------------|-------------------|--------------------|-------------------|
| Flexion           | 0.280             | 0.378              | 0.312             |
| Extension         | 0.051             | 0.063              | 0.057             |
| Left Bending      | 0.179             | 0.230              | 0.195             |
| Right Bending     | 0.160             | 0.214              | 0.177             |
| Left Rotation     | 0.154             | 0.209              | 0.172             |
| Right Rotation    | 0.173             | 0.226              | 0.190             |

2.2 Comparison of Equivalent Stress in the Internal Fixation Systems

Equivalent stress in all three fixation systems was highest under flexion and lowest under extension. Under all loading conditions, the anterior fixation system experienced the lowest stress, indicating the minimal risk of hardware failure; stress concentration was observed at the interface between the inferior screws and the plate (Figure 2J). The posterior fixation system exhibited significantly higher equivalent stresses than the other two groups, with notably high levels under flexion, suggesting the highest failure risk; stress peaks concentrated at the rod-screw junction (Figure 2K). The combined fixation system demonstrated stress levels generally higher than the anterior but notably lower than the posterior system. Its stress distribution was more dispersed, with the peak stress shifting from the posterior rod-screw junction to the central region of the anterior short plate (Figure 2L) (Table 3).

**Table 3. Maximum Equivalent Stress (MPa) in Different Internal Fixation Systems**

| Loading Condition | Anterior Fixation | Posterior Fixation | Combined Fixation |
|-------------------|-------------------|--------------------|-------------------|
| Flexion           | 59.816            | 256.980            | 138.700           |
| Extension         | 9.435             | 14.707             | 17.270            |
| Left Bending      | 41.764            | 104.140            | 80.201            |
| Right Bending     | 37.399            | 160.060            | 78.596            |
| Left Rotation     | 47.877            | 95.824             | 58.787            |
| Right Rotation    | 46.289            | 168.320            | 98.271            |

Figure 2. Representative results under flexion loading. Anterior fixation showed minimal overall displacement (A), posterior fixation maximal (B), and combined fixation intermediate (C). Maximum vertebral equivalent stress (D-F) and equivalent strain (G-I) were consistently located in the adjacent lower vertebra (T1). Stress in the anterior fixation system concentrated at the inferior screw-plate interface (J). In the posterior fixation system, stress concentrated at the rod-screw junction (K); after adding the anterior short-segment fixation (Combined), the peak stress shifted to the middle of the anterior short plate (L).

2.3 Comparison of Vertebral Body Equivalent Stress and Equivalent Strain

The combined approach yielded the highest bone strain values under most motion directions, notably exceeding those for anterior and posterior fixation during flexion (9.031E-03 mm/mm) and right rotation (7.178E-03 mm/mm). Posterior fixation produced the lowest bone strain, suggesting it may minimize bone micro-deformation. Anterior fixation resulted in intermediate strain levels. Regarding bone stress, anterior and posterior fixations exhibited similar levels, generally surpassing those of combined fixation under most loading conditions (e.g., flexion: anterior 22.788 MPa, posterior 23.134 MPa, combined

17.758 MPa). The combined approach frequently demonstrated lower peak bone stress (e.g., right bending: 11.74 MPa; right rotation: 16.256 MPa), indicating more uniform load dispersion. Across all three fixation methods, the concentration of both stress and strain in the vertebral body occurred at the lower adjacent vertebra (T1) distal to the fixation construct (Table 4, Figure 2).

**Table 4. Maximum Vertebral Body Equivalent Stress (MPa) / Equivalent Strain (mm/mm)**

| Loading Condition |                 | Anterior Fixation | Posterior Fixation | Combined Fixation |
|-------------------|-----------------|-------------------|--------------------|-------------------|
| Flexion           | Max. Eq. Stress | 22.788            | 23.134             | 17.758            |
|                   | Max. Eq. Strain | 6.714E-03         | 3.626E-03          | 9.031E-03         |
| Extension         | Max. Eq. Stress | 9.378             | 9.467              | 9.383             |
|                   | Max. Eq. Strain | 1.601E-03         | 1.383E-03          | 1.640E-03         |
| Left Bending      | Max. Eq. Stress | 22.434            | 23.16              | 23.015            |
|                   | Max. Eq. Strain | 4.306E-03         | 3.365E-03          | 6.798E-03         |
| Right Bending     | Max. Eq. Stress | 14.407            | 17.544             | 11.744            |
|                   | Max. Eq. Strain | 4.267E-03         | 2.380E-03          | 4.472E-03         |
| Left Rotation     | Max. Eq. Stress | 16.233            | 17.800             | 18.116            |
|                   | Max. Eq. Strain | 4.463E-03         | 2.506E-03          | 5.042E-03         |
| Right Rotation    | Max. Eq. Stress | 18.376            | 17.425             | 16.256            |
|                   | Max. Eq. Strain | 4.351E-03         | 2.439E-03          | 7.178E-03         |

## Discussion

### 3.1 Biomechanical Characteristics of ASCF and the Rationale for Surgery

The biomechanical environment of the cervical spine in patients with AS undergoes substantial alteration during disease progression. While the normal cervical spine dissipates stress via viscoelastic deformation of discs and ligaments, the ankylosed spine becomes a rigid, long-segment lever with compromised shock absorption. Coupled with osteoporosis-induced reduction in bone quality, even minor trauma can precipitate an unstable three-column fracture at stress concentration sites. ASCF fractures typically traverse the disc space across all three columns, creating a "pseudoarthrosis." These often involve spinal cord injury, and conservative management yields significantly higher mortality rates compared to surgical intervention<sup>7</sup>. Consequently, surgical treatment aimed at neural decompression, sequence restoration, and immediate stabilization is unequivocally necessary.

This study quantitatively compared the biomechanical behavior of three internal fixation techniques using FEA, aiming to address a gap left by previous single-technique investigations and provide theoretical support for clinical decisions. It is crucial to note that FEA biomechanical research on ASCF

is still nascent. Prior studies have either focused on a single technique or the thoracolumbar spine<sup>8-15</sup>; systematic comparisons of three mainstream surgical techniques specific to the subaxial cervical region remain scarce.

### **3.2 Analysis of Immediate Construct Stability**

Immediate stability reflects the construct's ability to resist deformation under physiological loads. Our FEA demonstrated a consistent trend for overall maximum displacement across six physiological motions: Posterior fixation > Combined fixation > Anterior fixation. The anterior long-segment plate provided the smallest displacement under all conditions (0.280 mm in flexion), indicating the highest overall construct stiffness. This aligns with the mechanical principle of anterior reconstruction of the primary weight-bearing axis<sup>20</sup>. Anterior fixation enhances anterior column load-bearing capacity through an integrated plate-screw-vertebra structure; the long-segment construct prolongs the lever arm and disperses load transmission pathways<sup>10</sup>. Under flexion load, the anterior plate lies on the tension side of the spine, directly counteracting tensile stress and generating a compression effect at the fracture site.

Posterior fixation produced the largest overall displacement (0.378 mm in flexion), suggesting a higher degree of construct deformation under physiological loads. While potentially beneficial for stress dispersion, this characteristic may compromise absolute stability at the fracture site. Combined fixation resulted in intermediate displacement (0.312 mm in flexion). Notably, its displacement under lateral bending and rotation differed from the anterior construct by less than 0.03 mm, suggesting that combined fixation retains the anti-flexion advantage of anterior constructs while supplementing shear and rotational resistance via the posterior instrumentation, thus providing balanced multidirectional stability.

### **3.3 Assessment of Hardware Failure Risk**

Peak stress within the internal fixation system is a critical indicator for predicting fatigue fracture and mechanical failure. In this study, equivalent stress peaked under flexion for all three systems, following the overall pattern: Posterior fixation > Combined fixation > Anterior fixation. Posterior fixation exhibited extremely high stress under flexion (256.98 MPa), a level associated with elevated fatigue failure risk. The mechanism likely involves ossification of the posterior ligamentous complex in AS patients, which eliminates its elastic buffering function. When an anterior column fracture defect exists, the majority of the flexion load is consequently borne by the posterior screw-rod system, leading to abnormal stress concentration<sup>20</sup>.

Although combined fixation still showed considerable stress under flexion (138.70 MPa), the anterior short-segment plate partially shares the anterior column load, creating a "stress-shunting" effect. This shifts the peak stress location from the posterior rod-screw junction to the anterior plate, thereby reducing the fracture risk associated with isolated posterior fixation. Anterior fixation demonstrated the lowest stress under all conditions (59.816 MPa in flexion). Even under rotation, where its stress increased (left rotation: 47.877 MPa; right rotation: 46.289 MPa), the values remained significantly lower

than those for posterior fixation (left: 95.824 MPa; right: 168.320 MPa). This indicates that while anterior long-segment plates have relative weakness in resisting rotation, their overall failure risk is the lowest. It is crucial to emphasize that regardless of the approach, postoperative restriction of cervical flexion is mandatory to mitigate the risk of fatigue fracture or screw cut-out.

### **3.4 Assessing Adjacent Vertebral Re-fracture Risk Across Fixation Techniques**

Osteoporosis in AS patients is an independent risk factor for postoperative adjacent segment re-fracture<sup>2</sup>. In our study, the peak stress and strain in the vertebral body for all three fixation constructs localized at the inferior adjacent vertebra (T1). This is an inevitable consequence of the "long lever arm" mechanics of the ankylosed cervical spine, as the rigid spine cannot buffer external forces through segmental bending, transmitting loads directly down to the lower vertebrae<sup>21,22</sup>.

Regarding bone strain, the combined fixation was highest across all six loading conditions. While this suggests a highly rigid overall construct, it may increase the risk of osseous micro-damage accumulation due to stress shielding. Posterior fixation consistently produced the lowest bone strain, potentially because its greater global deformation allows the construct to absorb some of the loading energy<sup>10</sup>, with anterior fixation yielding intermediate values. In terms of bone stress, anterior and posterior fixations generally demonstrated higher values compared to the combined approach under most loading conditions. Conversely, the combined approach frequently exhibited lower peak bone stress, indicating more uniform load distribution and reduced focal stress concentration. However, none of the three constructs can completely eliminate stress/strain concentration at the adjacent vertebra. Clinical decisions must therefore balance immediate stability against the risk of long-term adjacent segment pathology. For combined fixation, despite its favorable bone stress dispersion, the high strain characteristics warrant vigilance regarding potential long-term adjacent vertebral re-fracture risk.

### **3.5 Clinical Implications of Findings**

Synthesizing our biomechanical data with prior clinical outcome comparisons<sup>2</sup>, the choice of fixation technique mandates an individualized approach. Anterior long-segment fixation offers biomechanical advantages of greatest overall stiffness and lowest implant stress, corresponding clinically to shorter operative times, less blood loss, and lower complication rates. For ASCF patients where adequate anterior exposure is feasible, fracture-dislocation can be anatomically reduced, and posterior decompression is unnecessary, anterior long-segment fixation should be the preferred strategy. This technique allows direct ventral spinal cord decompression, restores anterior column support, and achieves fracture stability via long-segment compression.

However, ASCF patients often have severe cervical kyphosis. The subaxial cervical spine is also anatomically constrained by the manubrium and mandible. When anterior exposure for long-segment fixation (e.g., at the C7-T1 junction) is inadequate or fixation is not feasible, a posterior or combined approach must be considered. Posterior long-segment fixation is unconstrained by segment length, allows extensive exposure of the ankylosed spine, and can enhance stability by extending the fusion

mass. It is particularly suited for cases complicated by severe kyphosis, difficult anterior access, or requiring posterior spinal canal decompression<sup>2,10</sup>. Nevertheless, our biomechanical findings show that isolated posterior fixation carries a markedly elevated risk of screw failure under flexion loads. Surgeons opting for this approach should carefully assess this risk and enforce strict postoperative bracing.

Combined anterior-posterior fixation merges the benefits of anterior reduction/decompression with posterior long-segment stabilization, providing balanced multidirectional biomechanical stability and more dispersed stress compared to isolated posterior fixation. It is indicated for complex fractures requiring both approaches due to gross instability, severe osteoporosis, or when a single approach fails to achieve adequate decompression and rigid fixation. However, combined fixation significantly increases operative time, blood loss, and complication risk<sup>2</sup>. Furthermore, our study suggests it confers the highest adjacent vertebral bone strain, which may potentiate long-term re-fracture risk. Therefore, indications for combined fixation should be rigorously applied, and it should not be routine. In practice, it might be reserved for cases where significant posterior column instability persists after adequate anterior long-segment fixation or when anterior screw purchase is severely compromised by profound osteoporosis.

### **3.6 Distinction from Prior FEA Studies and Incremental Contributions**

Compared with the prior finite element analysis (FEA) studies by Robinson et al.<sup>10</sup>, Chen et al.<sup>11</sup>, and Liu et al.<sup>20</sup>, our work provides several novel insights. First, we employed clinically relevant long-segment anterior and posterior constructs, whereas Liu et al. used short-segment fixation<sup>20</sup>; long-segment constructs fundamentally alter load transfer and implant stress distribution<sup>2,5</sup>. Second, our fracture line accurately reproduces the transdiscal pattern with oblique vertebral body involvement<sup>5</sup>, better reflecting the actual morphology of ASCF. Third, we introduced an asymmetric combined fixation configuration, revealing a unique peak stress shift from the rod–screw junction to the anterior plate—a comparison not performed in the study by Robinson et al.<sup>10</sup>, who did not contrast anterior fixation with combined fixation. Fourth, we systematically analyzed bone equivalent strain, demonstrating that combined fixation yields the highest strain, which may serve as a critical predictor of adjacent vertebral re-fracture in osteoporotic AS bone. Finally, our findings are directly linked to clinical outcome data from the same patient cohort, establishing a biomechanical–clinical correlation that was absent from prior pure simulation studies.

### **3.7 Limitations**

This study has several limitations. First, the FEA model was based on a single representative patient. While this allows good variable control, material properties were simplified as homogeneous and linearly elastic, failing to capture the non-linear, anisotropic nature of real bone or patient-specific bone mineral density distributions. Second, the static analysis cannot simulate physiological bone healing, dynamic muscle loading, or long-term implant fatigue effects in vivo. Third, subgroup analyses stratifying by fracture type, osteoporosis severity, or implant parameters were not performed. Future research should

validate our findings using dynamic FEA models incorporating patient-specific bone density data, and through multi-center, large-scale prospective clinical studies with long-term follow-up for adjacent segment re-fracture and implant failure rates.

## Conclusion

Anterior long-segment fixation provides superior immediate construct stability and greater implant safety profile, making it suitable for ASCF patients where adequate anterior exposure and fixation are achievable. Posterior long-segment fixation carries a substantially elevated risk of implant failure due to high screw stresses under flexion loads, necessitating strict postoperative immobilization; its advantages are freedom from exposure constraints and enhanced stability via extended fixation, fitting cases with difficult anterior access or requiring posterior decompression. Combined anterior-posterior fixation offers balanced mechanical properties, appropriate for complex fractures, severe osteoporosis, or instability unattainable with a single approach; however, the attendant risk of long-term adjacent vertebral re-fracture due to elevated bone strain mandates caution. Clinical decision-making must integrate biomechanical stability, implant safety, surgical morbidity, and individual patient anatomy.

## Declarations

## Competing interests

All the authors declare no competing interests. The funding sources had no role in study design, data collection, analysis, interpretation, or manuscript preparation.

## Consent for publication

Not applicable. The manuscript contains no individual person's data in any form (no clinical photographs, no facial images, no personal identifiers). All figures are finite element model reconstructions and stress contour plots that cannot be used to identify the patient.

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## Author Contribution

S.G. and X.L. contributed equally to this work. S.G., X.L. and Y.L. conceived and designed the study, performed the statistical analysis, drafted the manuscript, and critically revised it for important intellectual content. W.X., C.L., and H.W. participated in the implementation of the study and data acquisition. All authors reviewed and approved the final manuscript.

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## Data Availability

The CT imaging data used to construct the finite element model are not publicly available due to patient privacy protection and institutional policy. The finite element model (Ansys Workbench project files) and the raw output data presented in this study are available from the corresponding author upon reasonable request, subject to approval of the relevant ethics committee.

## Ethics declarations

This study was approved by the Ethics Committee of Luohe Central Hospital (approval No. LH-KY-2023-002-132). The need for informed consent was waived by the committee because the finite element model was constructed using retrospectively collected, anonymized computed tomography data that did not interfere with patient treatment or reveal personal identities. All procedures followed the ethical standards of the responsible committee and the 1964 Helsinki declaration and its later amendments.

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## Figures

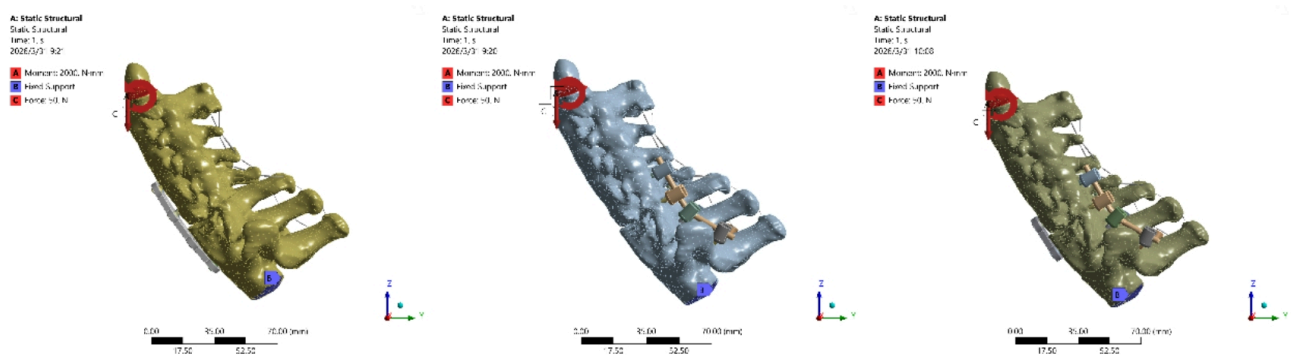


**Figure 1**

Lateral views of the three ASCF fixation constructs with schematic representation of loading (flexion condition).

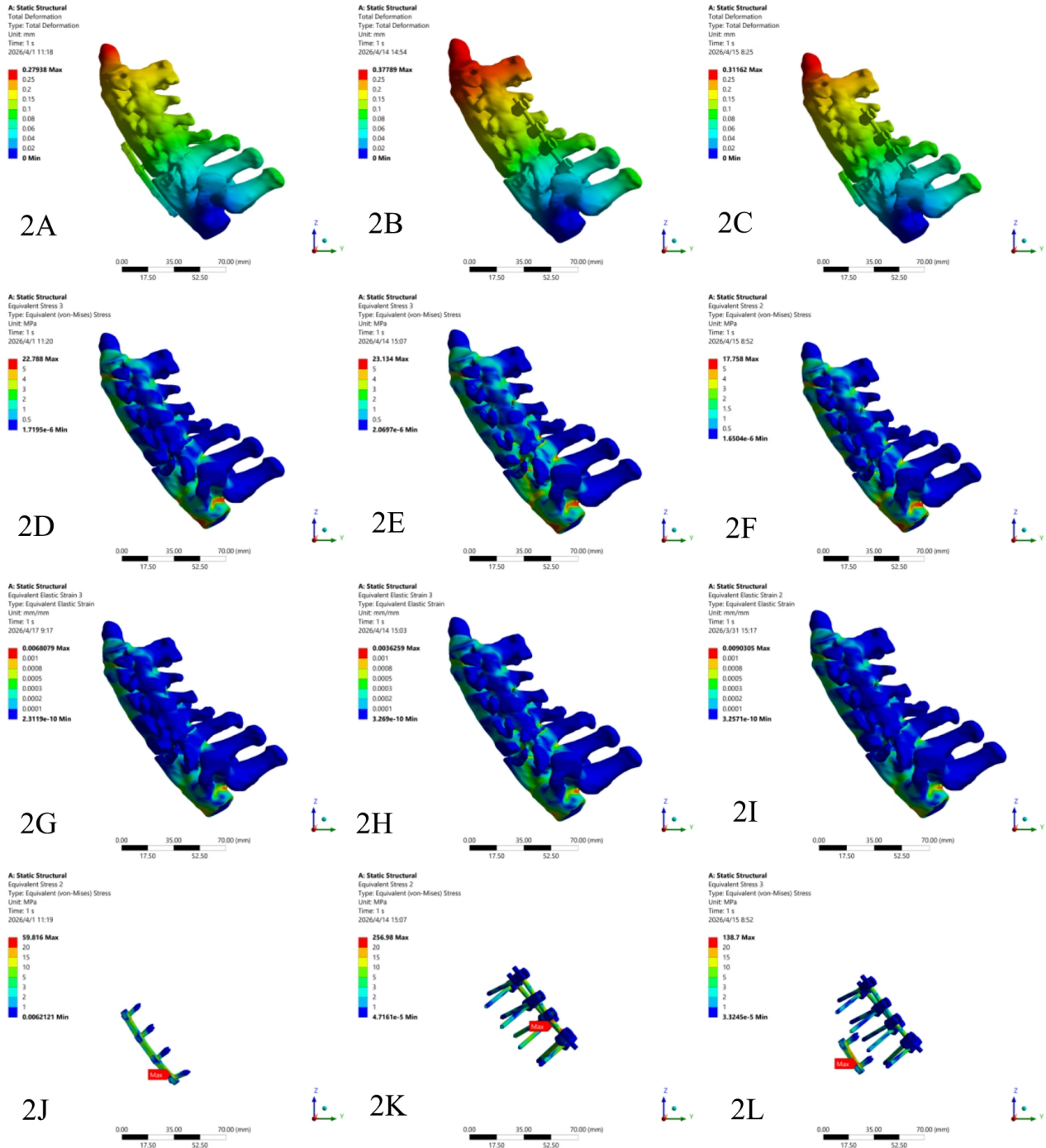


**Figure 2**

Representative results under flexion loading. Anterior fixation showed minimal overall displacement (A), posterior fixation maximal (B), and combined fixation intermediate (C). Maximum vertebral equivalent stress (D-F) and equivalent strain (G-I) were consistently located in the adjacent lower vertebra (T1). Stress in the anterior fixation system concentrated at the inferior screw-plate interface (J). In the

posterior fixation system, stress concentrated at the rod-screw junction (K); after adding the anterior short-segment fixation (Combined), the peak stress shifted to the middle of the anterior short plate (L).