The Effect of Anterior-Only, Posterior-Only, and Combined Anterior Posterior Fixation for Cervical Spine Injury with Soft Tissue Injury: A Finite Element Analysis

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■ OBJECTIVE: **This finite element analysis aimed to investigate the effects of surgical procedures for cervical spine injury.**

■ METHODS: **A three-dimensional finite element model of the cervical spine (C2-C7) was created from computed tomography. This model contained vertebrae, intervertebral discs, anterior longitudinal ligament, and posterior ligament complex. To create the cervical spine injury model, posterior ligament complex and anterior longitudinal ligament at C3-C4 were resected and the center of the intervertebral disc was resected. We created posterior-only fixation (PF), anterior-only fixation (AF), and combined anterior-posterior fixation (APF) models. A pure moment with a compressive follower load was applied, and range of motion, annular/nucleus stress, instrument stress, and facet forces were analyzed.**

■ RESULTS: **In all motion except for flexion, range of motion of PF, AF, and APF models decreased by 80%—95%, 85%—93%, and 97%—99% compared with the intact model. C3-C4 annulus stress of PF, AF, and APF models decreased by 28%—72%, 96%—100%, and 99%—100% compared with the intact model. Facet contact forces of PF, AF, and APF models decreased by 77%—79%, 97%—99%, and 77%—86% at C3-C4 compared with the intact model. Screw stress in the PF model was higher than in the APF model, and plate stress in the AF model was lower than in the APF model, but bone graft stress in the AF model was higher than in the APF model.**

■ CONCLUSIONS: **Cervical stabilization was preserved by the APF model. Regarding range of motion, the PF model had an advantage compared with the AF model except for flexion. An understanding of biomechanics provides useful information for the clinician.**

INTRODUCTION

Cervical spine injury (CSI) without major vertebral fractures is common among middle-aged adults.[1] These CSIs include injury to soft tissues, such as on the intervertebral disc (ID) and ligaments, which may lead to segmental instability.[2] Spinal cord injury resulting from cervical segmental instability of CSI leads to respiratory, digestive, circulatory, and musculoskeletal diseases that can be life threatening.[3] Emergent adequate surgical fixation treatment of CSIs for cervical segmental instability is essential for the restoration of mechanical stability and prevention of further neurological deterioration.[4,5] Fixation for the unstable cervical spine can be achieved by posterior-alone (cervical pedicle screw/lateral mass screw [LMS] fixation), anterior-alone (anterior fixation with plate), and combined anterior-posterior stabilization.[6] Combined anterior-posterior approach stabilization provides the strongest fixation, but is the most invasive and requires

Key words
- Cervical injury without vertebral fracture
- Cervical spine injury
- CSI
- Finite element method
- Segmental instability
- Soft tissue injury

Abbreviations and Acronyms
3D: Three-dimensional
AF: Anterior-only fixation
APF: Anterior-posterior fixation
CSI: Cervical spine injury
FE: Finite element
ID: Intervertebral disc
LMS: Lateral mass screw
PF: Posterior-only fixation
ROM: Range of motion

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repositioning during the operation. This procedure also has a significantly longer operative time compared with the posterior-alone and anterior-alone approaches.[6] The posterior approach allows for direct reduction and stability. However, it is considered inadequate in anterior column instability because of the possibility of additional soft tissue damage due to its invasive nature.[7,8] The anterior approach is better at preserving cervical lordosis compared with the posterior approach, which is associated with a positive long-term outcome.[9] However, the anterior approach may fail to address the injured the posterior ligament complex because the anterior bone graft and plate are reliant on stabilization.[10] To our knowledge, there are no studies that have analyzed the mechanics of these 3 approaches for the same CSI. We hypothesized that creating a CSI model and 3 surgical procedure models, applying multiple motions, and analyzing which movements strain the cervical spine and instruments may assist clinicians in selecting the appropriate treatment for unstable CSI. This study used the C2-C7 three-

Table 1. Material Properties Assigned to the Finite Element Model[9-14]

Component	Material Properties	Constitute Relation	Element Type	Area (mm^2)
Bone				
Vertebral cortical bone	E = 10,000 MPa	Isotropic, elastic	C3D8	—
	v = 0.3			
Vertebral cancellous bone	E = 450 MPa	Isotropic, elastic	C3D8	—
	v = 0.25			
Posterior vertebrae	E = 3500 MPa	Isotropic, elastic	C3D10	—
	v = 0.25			
Artificial bone	E = 10,000 MPa	Isotropic, elastic	C3D8	—
	v = 0.3			
Intervertebral disc				
Ground substance of annulus fibrosis	C10 = 0.7	Hyperelastic, Mooney-Rivlin	C3D8	—
	C01 = 0.2			
Nucleus pulposus	C10 = 0.12	Incompressible hyperelastic, Mooney-Rivlin	C3D8	—
	C01 = 0.03			
	D1 = 0			
Ligaments				
Anterior longitudinal ligament	15.0 (<12%), 30.0 (>12%)	Nonlinear, hypoelastic	T3D2	6.1
	v = 0.3			
Posterior longitudinal ligament	10.0 (<12%), 20.0 (>12%)	Nonlinear, hypoelastic	T3D2	5.4
	v = 0.3			
Capsular ligament	7.0 (<30%), 30 (>12%)	Nonlinear, hypoelastic	T3D2	46.6
	v = 0.3			
Ligamentum flavum	5.0 (<25%), 10.0 (>25%)	Nonlinear, hypoelastic	T3D2	50.1
	v = 0.3			
Interspinous ligament	4.0 (20%—40%), 8.0 (>40%)	Nonlinear, hypoelastic	T3D2	13.1
	v = 0.3			
Facet joints				
Apophyseal joints	Nonlinear soft contact, GAPUNI elements	—	—	—
Lateral mass screw				
Ti alloy	E = 110,000 MPa	Isotropic, elastic	C3D4	—
	v = 0.3			

E, Young's modulus; v, Poisson's ratio; Ti, titanium.

dimensional (3D) finite element (FE) cervical spine model to examine how stress and mobility in the cervical spine changed for different surgical procedures in CSI.

MATERIALS AND METHODS

Model Development

A validated FE model of the cervical spine (C2-C7) was used in this study.[11] The FE model was created based on computed tomography images of a healthy adult subject. The ethics committee approved using these images at the Center for Clinical Research at author Vijay K.Goel's facility. The 3D reconstruction of the cervical spine geometry (vertebrae as well as IDs) was carried out using MIMICS version 15.0 (Materialise, Leuven, Belgium) image segmentation software. The reconstructed geometry of hard and soft tissues was meshed with the hexahedral elements using IA-FEMesh software from the University of Iowa (Iowa City, Iowa, USA). The meshed vertebrae/discs were exported to Abaqus (Dassault Systèmes Simulia Corp., Providence, Rhode Island, USA) software. The facet joints in the model were represented using surface-surface sliding contact, whereas the Luschka joints in the lower cervical IDs were modeled using GAPUNI elements.[12,13] The anterior longitudinal ligament, posterior longitudinal ligament, interspinous ligament, supraspinous ligament, capsular ligament, and ligamentum flavum were modeled as truss elements and added to the model. The IDs were composed of annulus fibrosus (50%) and nucleus pulposus (50%). The annulus consisted of ground substance along with embedded fibers oriented at $\pm 25°$.[14] The material properties for all the structures were taken from the literature and are summarized in Table 1.[13,15-20] The intact C2-C7 cervical spine model was validated by comparing the range of motion (ROM), intervertebral nucleus stress, and facet contact force data against published in vitro cadaveric testing data as reported previously by the authors' group.[11,12]

Simulation of CSI without Associated Vertebral Fracture

Instability increases were highest in flexion/extension distraction for most injury types.[21] As there is no possibility to fix extension surgically, the flexion model was assumed. The base model used for the cervical validation had C2-C7 lordosis with an angle of $-5°$. The cervical spine sagittal parameters were iteratively modified to develop the flexion/distraction cervical alignment model leading to a C2-C7 angle of 10° (Figure 1A). To create the CSI model, in the intact model, the interspinous ligament, supraspinous ligament, capsular ligament, and ligamentum flavum at the C3-C4 level were resected, and the anterior longitudinal ligament and the ventral at the center of the ID were resected (Figure 1B and C). A sliding contact with zero friction was defined between the cranial and caudal surface of the resected disc.

Development of Posterior-Only Fixation Model

For the posterior-only fixation (PF) model, the instrumentation comprised 3.5-mm-diameter and 16-mm-length C3 and C4 LMSs. A 3.5-mm rod was connected to the head of the LMS. The LMSs and rods were assigned titanium alloy material properties.[22] The interaction between the screw and bone and the screw head and rod was simulated via TIE constraint in Abaqus software to simulate the rigid connection between these components (Figure 2A).[23]

Development of Anterior-Only Fixation Model

The surgical technique for the anterior-only fixation (AF) model was simulated by removing the anterior portion of the annulus and the complete nucleus at the operated level (C3-C4). In the AF model, the cranial endplate of C3 and caudal endplate of C4 were also trimmed. Assuming that the bones were taken from the ilium, a rectangular bone graft was placed in the trimmed space. The bone graft was connected to the decompressed area of the vertebral body using the TIE constraint in Abaqus software.[24] After bone graft placement, a titanium plate was rigidly fixed to screws from C3 to C4 to provide additional stability to the fixation model. Along the ends of the anterior plate, 2 titanium screws were placed inside both C3 and C4 vertebral bodies. Screws of 13 mm length with a mean diameter of 3.5 mm were rigidly fixed using the TIE constraint in Abaqus software (Figure 2B).

Development of Combined Anterior-Posterior Fixation Model

The instrumentation of both the AF model and the PF model were added in the cervical spine model to create the anterior-posterior fixation (APF) model (Figure 2C).

Loads and Boundary Conditions

A pure moment of 1.5 N-m was applied to the C2 odontoid process to simulate 6 motions of flexion/extension, lateral (left and right) bending, and axial (left and right) rotations. The inferior endplate of the C7 vertebra was fixed. The model was subjected to the compressive follower load of 100 N to represent the weight of the head/cranium and cervical muscle contractions.

Data Analyses

ROM, annular stresses, intradiscal (nucleus) stresses, facet contact forces, and stresses of instrumentation and bone graft were calculated for the PF, AF, and APF models. The maximum von Mises stresses were noted for annular stresses, nucleus stresses, and instrumentation and bone graft. The data for facet forces were averaged for the left/right facets for calculating the facet joint force. In the CSI model, C3-C4 had complete instability and could not be analyzed. The rate of change (%) was calculated for these values using the following equation:

$$\text{Percentage change (\%)} = \frac{\text{the value of PF/AF/APF models data} - \text{the value of intact model data}}{\text{the value of intact model}} \star 100$$

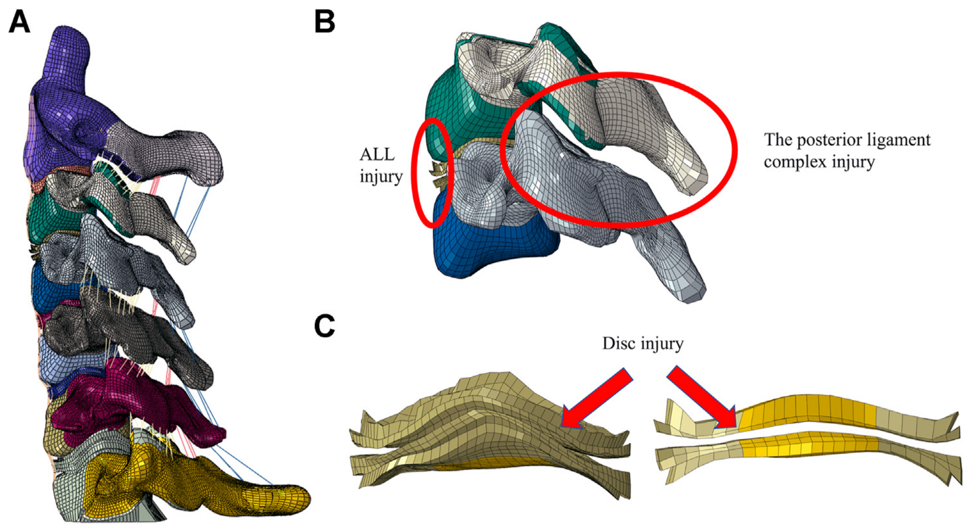

Figure 1. Cervical spine injury (C2-C7) finite element model. The anterior longitudinal ligament, posterior longitudinal ligament, interspinous ligament, supraspinous ligament, capsular ligament, and ligamentum flavum were modeled. The interspinous ligament, supraspinous ligament, capsular ligament, and ligamentum flavum at C3-C4 level were resected to create the cervical spine injury model (**A**), and the anterior longitudinal ligament and the ventral at the center of the intervertebral disc were resected (**B** and **C**). ALL, anterior longitudinal ligament.

RESULTS

Range of Motion

In extension, ROM of the PF, AF, and APF models decreased by 95%, 90%, and 97%, respectively, at C3-C4 and 22%, 20%, and 22% at C2-C7 compared with the intact model. In flexion, ROM of the PF, AF, and APF models decreased by 7% at C2-C3 and decreased by 81%, 94%, and 98%, respectively, at C3-C4 and 23%, 26%, and 27% at C2-C7 compared with the intact model. In left bending, ROM of the PF, AF, and APF models decreased by 86%, 85%, and 97%, respectively, at C3-C4 and 19%, 17%, and 21% at C2-C7 compared with the intact model. In right bending, ROM of the PF, AF, and APF models decreased by 89%, 85%, and 97%, respectively, at C3-C4 and 27%, 23%, and 29% at C2-C7 compared

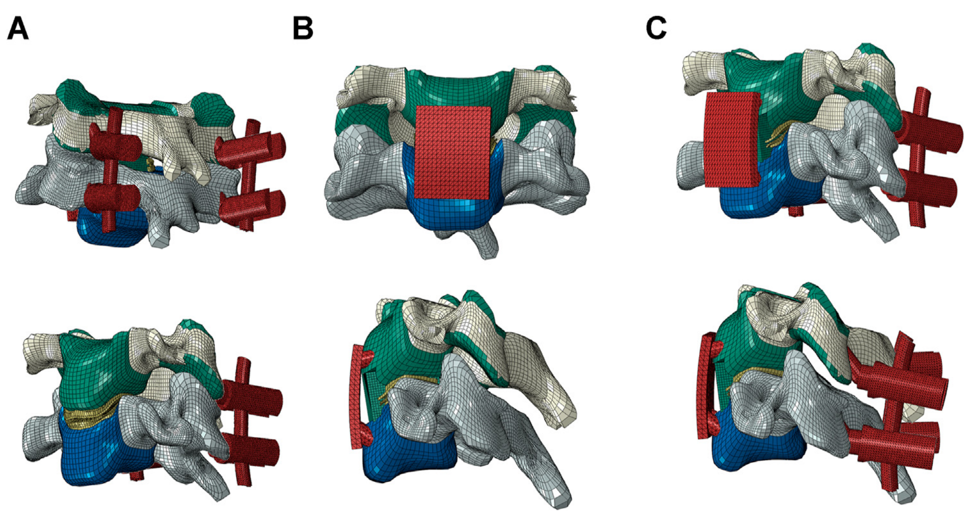

Figure 2. (**A**) Posterior-only fixation model. (**B**) Anterior-only fixation model. (**C**) Combined anterior-posterior fixation model.

with the intact model. In left rotation, ROM of the PF, AF, and APF models decreased by 97%, 93%, and 99%, respectively, at C3-C4 and 23%, 22%, and 23% at C2-C7 compared with the intact model. In left rotation, ROM of the PF, AF, and APF models decreased by 95%, 92%, and 99%, respectively, at C3-C4 and 22%, 21%, and 23% at C2-C7 compared with the intact model. (Figure 3).

Annular Stress

In extension, the C3-C4 annulus stress of the PF, AF, and APF models decreased by 72%, 98%, and 100%, respectively, compared with the intact model. The C2-C3 annulus stress of the PF, AF, and APF models increased by 2%, 9%, and 5%, respectively, compared with the intact model. In flexion, the C3-C4 annulus stress of the PF, AF, and APF models decreased by 28%, 100%, and 100%, respectively, compared with the intact model. The C2-C3 annulus stress of the PF, AF, and APF models increased by 19%, 20%, and 19%, respectively, compared with the intact model. In left bending, the C3-C4 annulus stress of the PF, AF, and APF models decreased by 48%, 100%, and 100%, respectively, compared with the intact model. The C2-C3 annulus stress of the PF, AF, and APF models increased by 2%, 9%, and 5%, respectively, compared with the intact model. In right bending, the C3-C4 annulus stress of the PF, AF, and APF models decreased by 50%, 96%, and 99%, respectively, compared with the intact model. In left rotation, the C3-C4 annulus stress of PF, AF, and APF models decreased by 25%, 99%, and 100%, respectively, compared with the intact model. In right rotation, the C3-C4 annulus stress of the PF, AF, and APF models decreased by 3%, 99%, and 99%, respectively, compared with the intact model (Figure 4).

Nucleus Stresses

In the AF and APF models, the nucleus could not be measured because it was resected. In extension, the C3-C4 annulus stress of the PF model decreased by 72% compared with the intact model. In flexion, the C3-C4 annulus stress of the PF model decreased by 14% compared with the intact model. In left bending, the C3-C4 annulus stress of the PF model decreased by 10% compared with the intact model. In right bending, the C3-C4 annulus stress of the PF model decreased by 43% compared with the intact model. In left rotation, the C3-C4 annulus stress of the PF model decreased by 56% compared with the intact model. In right rotation, the C3-C4 annulus stress of the PF model decreased by 62% compared with the intact model (Figure 5).

Facet Contact Forces

In extension, facet contact forces of the PF, AF and APF models decreased by 79%, 97%, and 86%, respectively, at C3-C4 compared with the intact model. Facet contact forces of the PF and

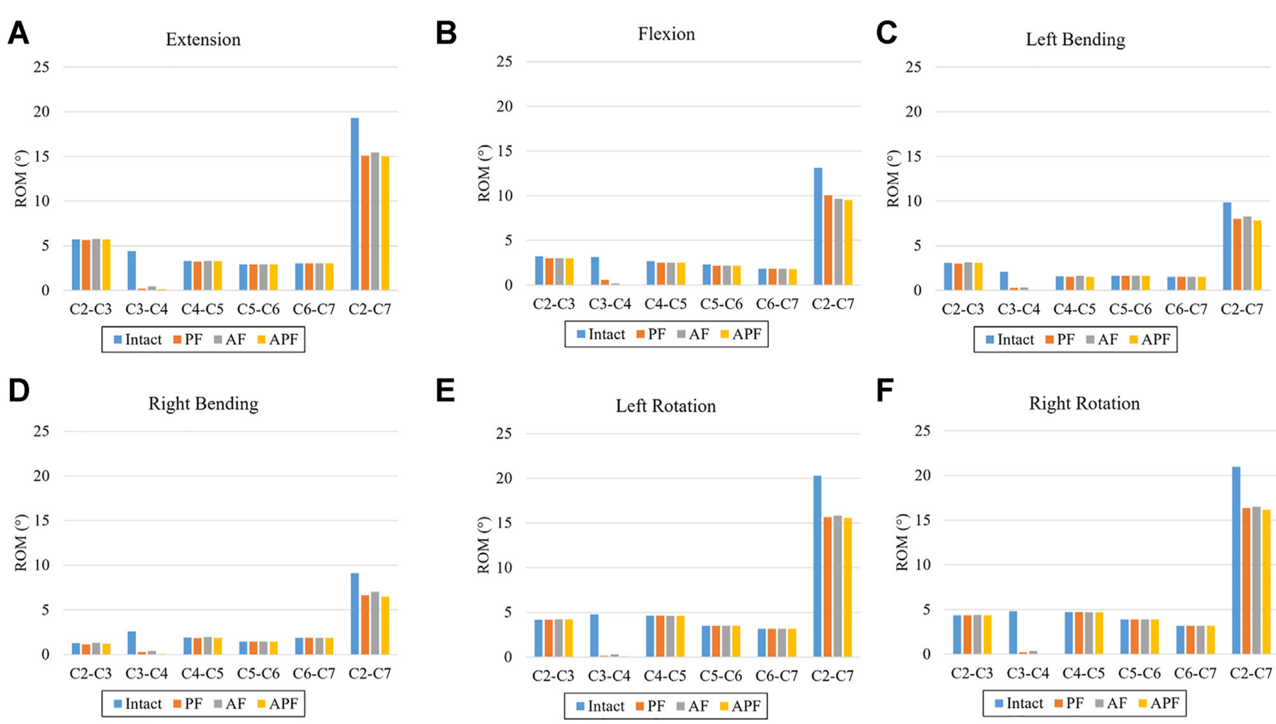

Figure 3. Range of motion. (**A**) Extension, (**B**) flexion, (**C**) left bending, (**D**) right bending, (**E**) left rotation, and (**F**) right rotation. The vertical axis is the angle (°), and the horizontal axis is each intervertebral level. ROM, range of motion; PF, posterior-only fixation; AF, anterior-only fixation; APF, anterior-posterior fixation.

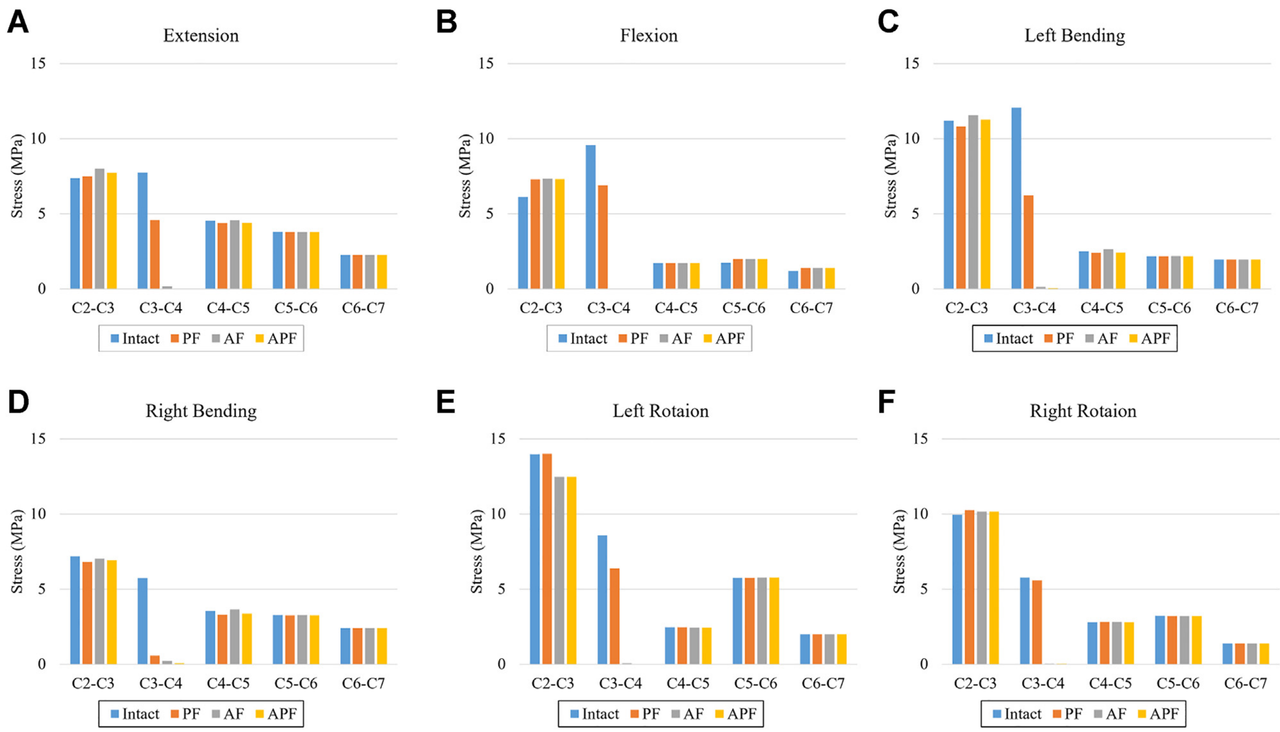

Figure 4. Annulus pressure. (**A**) Extension, (**B**) flexion, (**C**) left bending, (**D**) right bending, (**E**) left rotation, and (**F**) right rotation. The vertical axis is stress (MPa), and the horizontal axis is each intervertebral level. PF, posterior-only fixation; AF, anterior-only fixation; APF, anterior-posterior fixation.

APF models increased by 11% and 5%, respectively at C2-C3, and facet contact forces of the AF models decreased by 5% compared with the intact model. Facet contact forces of the PF and APF models increased by 29% and 10%, respectively, at C4-C5, and facet contact forces of the AF model decreased by 29% compared with the intact model. In lateral bending, facet contact forces of the PF, AF, and APF models decreased by 72%, 98%, and 77%, respectively, at C3-C4 compared with the intact model. Facet contact forces of the PF and AF models decreased by 1% and 3%, respectively, compared with the intact model. In axial rotation, facet contact forces of the PF, AF, and APF models decreased by 77%, 99%, and 85%, respectively, at C3-C4 compared with the intact model. Facet contact forces of the PF, AF, and APF models decreased by 10%, 29%, and 22%, respectively, at C2-C3 compared with the intact model. Facet contact forces of the PF, AF, and APF models increased by 77%, 4%, and 31%, respectively, at C4-C5 compared with the intact model (Figure 6).

Stress of Instruments and Bone Graft

Maximum von Mises stress values on the LMSs and rods under PF and APF models and the plate and bone graft under AP and APF models were recorded (Tables 2 and 3). Screw stress in the PF model was higher than in the APF model, and plate stress in the AF was lower than in the APF model, but the bone graft stress in the AF model was higher than in APF model.

DISCUSSION

This analysis aimed to perform 3 fixation procedures on an FE model of cervical instability caused by injury of soft tissues and examine the effects on the cervical spine, bone graft, and instrumentation for surgical procedures. Use of combined anterior and posterior stabilizations has been suggested for 3-column subaxial CSIs with respect to stabilization and reduction.[6,25,26] There have been some reports about CSI model analyses. Liu et al.[27] created a 3D FE ankylosing spondylitis cervical spine fracture model and AF, PF, and APF models with multiple lengths of fixation. The APF model had the strongest stabilization, and the rate of motion change of 1-level APF was decreased 100% compared with the fracture model. In our study, ROM of the APF model was most rigidly stabilized and agreed with these clinical and experimental results. However, clinical operative time and bleeding volume were higher than in AF and PF approaches.[6] Surgeons must consider AF and PF depending on the patient's situation (e.g., performance status, medical history, age).

PF is considered superior to AF in achieving reduction.[28] In the case of unilateral facet dislocation with injury to posterior structures, PF is sufficient, whereas in bilateral facet dislocation, extensive and equal involvement of APF is required for stabilization.[7] As the incidence of traumatic and disc herniation with CSI is relatively high, anterior decompression and reconstruction seems to be a reasonable and safe treatment

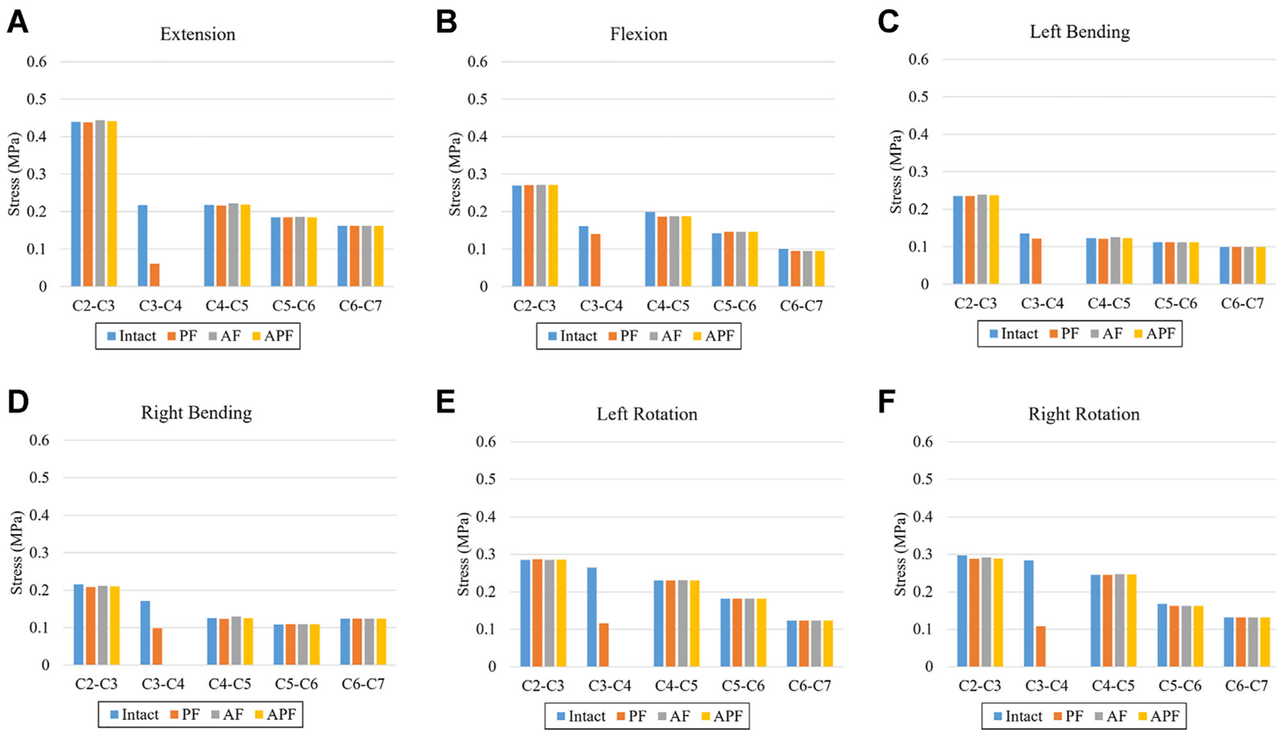

Figure 5. Nucleus stresses. (**A**) Extension, (**B**) flexion, (**C**) left bending, (**D**) right bending, (**E**) left rotation, and (**F**) right rotation. The vertical axis is stress (MPa), and the horizontal axis is each intervertebral level. PF, posterior-only fixation; AF, anterior-only fixation; APF, anterior-posterior fixation.

option.[29] Bozkus et al.[30] conducted PF, AF, and APF techniques for an intact cadaveric spine C4-T1 and reported stabilization of PF was higher than AF in flexion/extension, bending, and rotation. However, they did not analyze ligament injury. In our PF model, flexion ROM stability and annulus stress were inferior to the AP and APF models, but superior to the AP model in other motions. Duan et al.[31] created a 3D FE C2-C7 cervical model and analyzed a C4-C6 posterior fixation model for stabilization and effect on adjacent segment level in the intact model without any injury on ligaments using LMSs. Their study showed that the fixation level ROM of the posterior LMS model decreased from 7° to 2°, and ROM of adjust segmental level increased by 8° to 13° compared

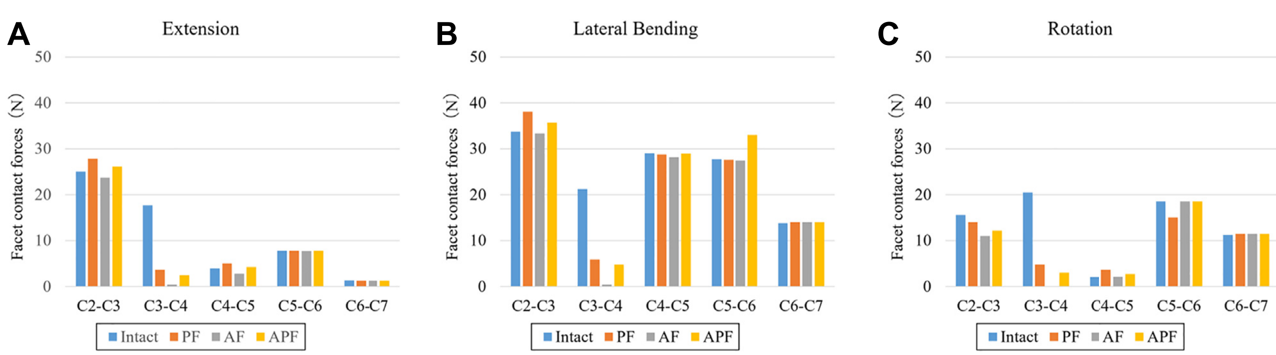

Figure 6. Facet contact forces. (**A**) Extension, (**B**) lateral bending, and (**C**) axial rotation. The vertical axis is force (N), and the horizontal axis is each intervertebral level. PF, posterior-only fixation; AF, anterior-only fixation; APF, anterior-posterior fixation.

Table 2. Maximum von Mises Stress Values on Lateral Mass Screw and Rods Under Posterior and Anterior-Posterior Approach

Motion	Maximum von Mises Stress on Screws Under Posterior Approach (MPa)	Maximum von Mises Stress on Screws Under Anterior-Posterior Approach (MPa)	Maximum von Mises Stress on Rods Under Posterior Approach (MPa)	Maximum von Mises Stress on Rods Under Anterior-Posterior Approach (MPa)
Extension	200	126	165	74
Flexion	307	42	93	16
Left bending	400	41	280	58
Right bending	372	178	173	107
Left rotation	287	88	128	39
Right rotation	334	110	220	57

with the intact model. In this study, the PF model stabilized the complete soft tissue injured model. However, the ROM of the adjacent segmental level did not increase as in the previous report; on the other hand, annular stresses of C2-C3 were increased in flexion and extension. This difference in ROM may be due to the length of fixation and requires further analysis.

Clinically, similar positive outcomes have been reported for the AF approach for 3-column injuries compared with the PF or APF approach.[32,33] However, the stabilization of the AF approach is questioned in highly unstable major posterior injuries.[34] There were reports that 8%–13% of mechanical failure with AF occurred in facet subluxation/dislocation.[10,32,34] Additionally, patients with facet fractures have a higher risk of fixation failure in the AF approach.[34] Pitzen et al.[35] analyzed in a cadaveric study of AF with an interbody bone graft and stepwise transection of the posterior ligaments and facets whether AF was insufficient in providing stabilization. In a 3D FE analysis, Jin et al.[36] created a C2-T1 injury model with a unilateral facet joint fracture, an anterior-only plate fixation model, and a combined anterior-posterior model. They reported that in flexion and both rotations, ROM of the anterior-only plate fixation model was lower by >10% compared with the combined anterior-posterior model. Plate stresses of the anterior-only plate fixation model were more than twice as high as the combined anterior-posterior model. Oberkircher et al.[37] performed 1-level AF on 15 fresh-frozen cervical spines (C3-T1) by dissecting the entire posterior and anterior ligament complex between C4 and C5. The study showed that facet joints with ligament resection led to load failure in AF on average occurring at 175 N. Fractured bilateral facet joints lead to load failure of AF at an average of 73 N. In our study, the AF model is relatively stable similar to the PF and APF models. However in flexion, the stabilization of ROM was lower than in the PF model. In the facet force analysis of the AF model, there was almost no contact force at the injured level C3-C4; therefore, posterior stability function was not expected. The bone graft stresses of the AF model were higher than the APF model, while the stress in the plate of the AF model was lower than in the APF model. In the AF model, the initial fixation may depend on material properties of the bone graft. If the material property of the bone graft is low or bone union is delayed, this may lead to inadequate screw stabilization, which can then lead to AF failure. Because our model did not assume facet fracture, PF and APF were necessary for the posterior fracture to fix firmly.

The current study has several limitations. Alignment and disc height are one limitation; CSI is more common in elderly patients, but this model was constructed from computed tomography scans of a younger patient that did not consider deformities. Also, the study did not examine what happens if vertebral body fracture and facet injury occur on one side or part of the body. The cage with screws and bone graft may provide stronger fixation. The mineral

Table 3. Maximum von Mises Stress Values on Plate and Bone Graft Under Anterior and Anterior-Posterior Approach

Motion	Maximum von Mises Stress on Plate Under Anterior Approach (MPa)	Maximum von Mises Stress on Plate Under Combined Anterior-Posterior Approach (MPa)	Maximum von Mises Stress on Graft Bone Under Anterior Approach (MPa)	Maximum von Mises Stress on Graft Bone Under Combined Anterior-posterior Approach (MPa)
Extension	7	21	57	11
Flexion	4	15	43	13
Left bending	7	31	57	10
Right bending	10	36	63	15
Left rotation	9	24	46	8
Right rotation	5	31	40	9

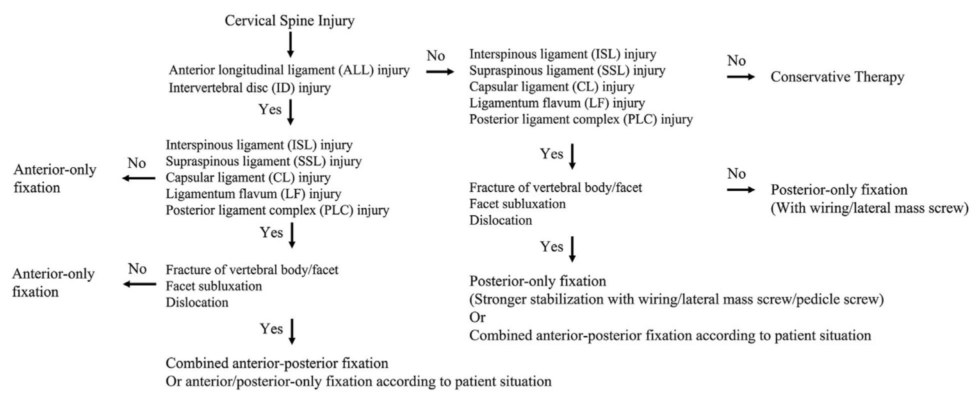

Figure 7. Cervical spine injury treatment algorithm based on study data.

density of bone graft and screw slip were not considered. In the PF model, the posterior interspinous cable and pedicle screw may provide stabilization, though clinically speaking there is a risk of vertebral artery injury when inserting pedicle screws.[38] The surgeries were simulated on the same base model. Thus, statistical analysis could not be performed. Our study showed general outcomes for different surgical procedures. Further clinical studies may be required to confirm these findings.

CONCLUSIONS

As previous reports stated, cervical stabilization was best preserved by the APF model compared with the PF and AF models for CSI.[6] The PF model had an advantage compared with the AF model except in flexion. In addition, the stress on the bone graft was higher in the AP model compared with the APF model. An understanding of the biomechanics involved in the procedures used to treat CSI provides useful information to guide the clinician in developing a surgical plan. Also, depending on the patient's condition and the hospital system, we propose a flow diagram for treatment of CSI (Figure 7).

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Norihiro Nishida: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft. **Sudharshan Tripathi:** Methodology, Formal analysis, Data curation. **Muzammil Mumtaz:** Methodology, Validation, Writing – review & editing. **Amey Kelkar:** Methodology, Writing – review & editing. **Yogesh Kumaran:** Writing – review & editing. **Takashi Sakai:** Supervision. **Vijay K. Goel:** Supervision.

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