Soft Tissue Injury in Cervical Spine Is a Risk Factor for Intersegmental Instability: A Finite Element Analysis

Norihiro Nishida[1], Sudharshan Tripathi[2], Muzammil Mumtaz[2], Amey Kelkar[2], Yogesh Kumaran[2], Takashi Sakai[1], Vijay K. Goel[2]

■ OBJECTIVE: **Soft tissue cervical spine injury (CSI) has the possibility of causing cervical segmental instability, which can lead to spinal cord injury. There is a lack of certainty in assessing whether soft tissue CSI is unstable or not. This biomechanical study aimed to investigate the risk factors of soft tissue CSI.**

■ METHODS: **A 3-dimensional finite element model of the ligamentous cervical spine (C2-C7) was created from medical images. Three soft tissue injury models were simulated at C4-C5: 1) posterior ligament complex (PLC) injury, 2) intervertebral disk (ID) with anterior longitudinal ligament injury (IDI), and 3) anterior longitudinal ligament, PLC, and ID injury (API) model. Pure moment with compressive follower load was applied, and the range of motion, annular stress, nucleus stress, and facet forces were analyzed.**

■ RESULTS: **For the IDI and API models, the range of motion increased at the injury level in extension (by 101%) and left/right axial rotations (>30%) compared with the intact model. The IDI and API models showed an increase of >50% in annular and nucleus stresses at the injury level in extension and left/right rotations compared with the intact model. The PLC injury showed similar stresses as the intact model except for flexion. The facet contact forces of IDI and API models increased more than 100% compared with other models in all motions.**

■ CONCLUSIONS: **In CSI, all soft tissues have a key role in stabilizing cervical spine, but ID is the most important component of all.**

INTRODUCTION

Cervical spine injury (CSI) includes injuries to soft tissues, such as the intervertebral disk and ligaments, along with vertebral fractures. Soft tissue CSIs have the possibility of causing cervical segmental instability, which can lead to spinal cord injury.[1] The incidence rate of CSI is high in the elderly population and causes severe economic burden, as well as significant impact on quality of life.[2,3] The most recent documented estimate of the annual incidence of CSIs is approximately 54 cases per 1 million people in the United States, which equals about 17,900 new CSI cases each year. According to the National Spinal Cord Injury Statistical Center, most of these injuries are caused by car accidents (38%), falls (30%), violent injuries (14%), sports and other recreational activities (9%), medical errors (5%), and various other factors (4%).[4] Certain percentages of people with CSI are rehospitalized 1 or more times during any given year

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

Abbreviations and Acronyms
ALL: Anterior longitudinal ligament
API: Anterior longitudinal ligament, posterior ligament complex, and intervertebral disk injury
CL: Capsular ligament
CSI: Cervical spine injury
CT: Computed tomography
FE: Finite element
ID: Intervertebral disk
IDI: Intervertebral disk with anterior longitudinal ligament injury
ISL: Interspinous ligament
LF: Ligamentum flavum
PLC: Posterior ligament complex
PLCI: Posterior ligament complex injury
PLL: Posterior longitudinal ligament
ROM: Range of motion
SSL: Supraspinous ligament

From the [1]Department of Orthopedic Surgery, Yamaguchi University Graduate School of Medicine, Ube City, Yamaguchi Prefecture, Japan; [2]Engineering Center for Orthopaedic Research Excellence (E-CORE), Departments of Bioengineering and Orthopaedics, The University of Toledo, Toledo, Ohio, USA

*To whom correspondence should be addressed: Norihiro Nishida, M.D.
[E-mail: nishida3@yamaguchi-u.ac.jp]*

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following initial injury.[5] CSIs significantly impact the world's economy due to their often chronic and life-threatening nature, creating a global health care burden.[6] Thus CSI has a significant impact on life and society. Early treatment of CSIs is essential,[7,8] but unfortunately, the occurrence of misdiagnosed cases is high.[9] If there are vertebral fractures associated with the CSIs, the correct diagnosis rate is higher and the chances of misdiagnosis are low.[10,11] However, a soft tissue CSI without an associated vertebral fracture can sometimes be difficult to diagnose.[12,13] In addition, there is a lack of certainty in assessing whether soft tissue CSI is unstable or not and it is difficult to predict the prescribed timing for the removal of the cervical collar worn by patients after suffering from soft tissue CSIs.

We hypothesized that by creating a cervical spine model with soft tissue CSIs, we can analyze the biomechanics of different CSI models under flexion/extension, lateral bending, and axial rotation motion. These results could help clinicians approximate the extent of instability caused by different soft tissue CSIs.

This study used a C2-C7 three-dimensional finite element (FE) cervical spine model to examine how stress and mobility in the cervical spine changed for different types of soft tissue CSIs.

MATERIAL AND METHODS

Model Development

A previously validated FE model of the cervical spine (C2-C7) was used in this study.[14] In summary, the FE model was created on the basis of the computed tomography (CT) images of a healthy adult subject. The relevant approvals were obtained for the use of these images at the corresponding author's facility. The 3-dimensional reconstruction of cervical spine geometry was carried out using the image segmentation software MIMICS v 15.0 (Materialise, Leuven, Belgium). The reconstructed geometry of hard and soft tissues was meshed with the hexahedral elements using IA-FEMesh software (University of Iowa, Iowa, USA). The meshed vertebrae/disks were exported to ABAQUS software (Dassault Systèmes, Simulia Inc., Providence, Rhode Island, USA). The facet joints in the model were represented using surface-surface sliding contact, whereas the Luschka joints in the lower cervical intervertebral disk (ID) were modeled using GAPUNI elements.[15,16] The anterior longitudinal ligament (ALL), posterior longitudinal ligament (PLL), interspinous ligament (ISL), supraspinous ligament (SSL), capsular ligament (CL), and ligamentum flavum (LF) 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 ±25 degrees (Figure 1).[17] The material properties for all the structures in the FE model were taken from the literature and summarized in Table 1.[16,18-22] 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 by author's previously published work.[14,15]

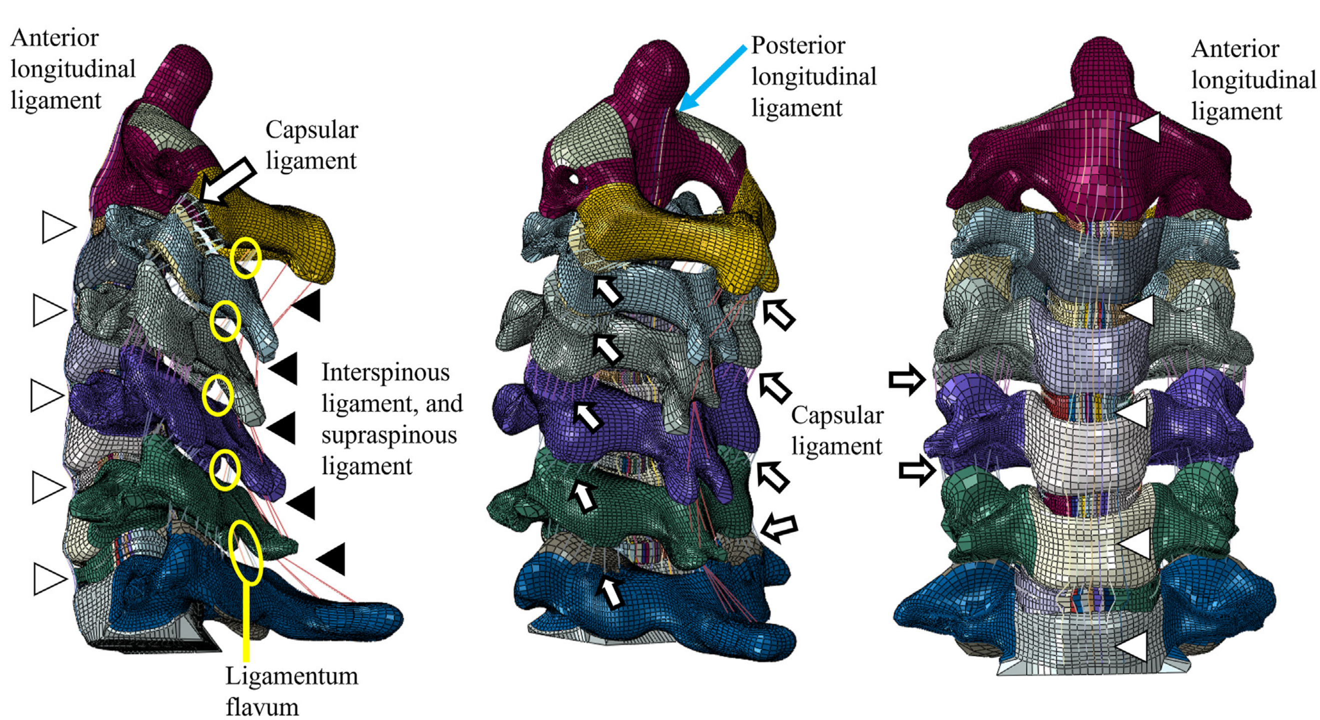

Figure 1. The intact (C2-C7) FE model. The anterior longitudinal ligament (ALL) *(white arrow)*, posterior longitudinal ligament (PLL) *(blue direction arrow)*, interspinous ligament (ISL), supraspinous ligament (SSL) *(black arrow)*, capsular ligament (CL) *(direction arrow)*, and ligamentum flavum (LF) *(yellow circle)* were modeled.

Table 1. Material Properties Assigned to Finite Element Model[16,18-22]

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			
Vertebrae-posterior	E = 3500 MPa	Isotropic, elastic	C3D10	—
	v = 0.25			
Intervertebral disk				
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	T3D3	5.4
	v = 0.3			
Capsular ligament	7.0 (<30%), 30 (>12%)	Nonlinear, hypoelastic	T3D4	46.6
	v = 0.3			
Ligamentum flavum	5.0 (<25%), 10.0 (>25%)	Nonlinear, hypoelastic	T3D5	50.1
	v = 0.3			
Interspinous ligament	4.0 (20%-40%), 8.0 (>40%)	Nonlinear, hypoelastic	T3D6	13.1
	v = 0.3			
Facet joints				
Apophyseal joints	Nonlinear soft contact, GAPPUNI elements	—	—	—

Simulation of Soft Tissue Cervical Spine Injuries

For the posterior ligament complex (PLC) injury model (PLCI), the intact model's ISL, SSL, CL, and LF at C4-C5 level were resected (Figure 2A). In the ID injury model (IDI), ALL and the ventral half at the center of the ID were resected (see Figure 2A). A frictionless contact interface was added between the caudal and cranial parts of the injured ID (see Figure 2B). For creating the anterior-posterior injury model (API), the IDI model was used as baseline and additionally the PLC was also resected.

Loads and Boundary Conditions

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

Data Analyses

The ROM, annular stresses, intradiskal (nucleus) stresses, and facet contact forces were calculated for PLCI, IDI, and API models. The maximum von mises stress was noted for the annular and nucleus stresses. The data for facet forces were averaged for the left/right facets for calculating the facet joint force. The percentage change (%) was calculated using the following equation:

$$\text{Percentage change } (\%) = \frac{\text{Injury Model Data} - \text{Intact Model Data}}{\text{Intact Model Data}} \cdot 100$$

RESULTS

Range of Motion

In extension, IDI and API models' ROM increased by 101% at the injury level (C4-C5) compared with the intact model. In flexion,

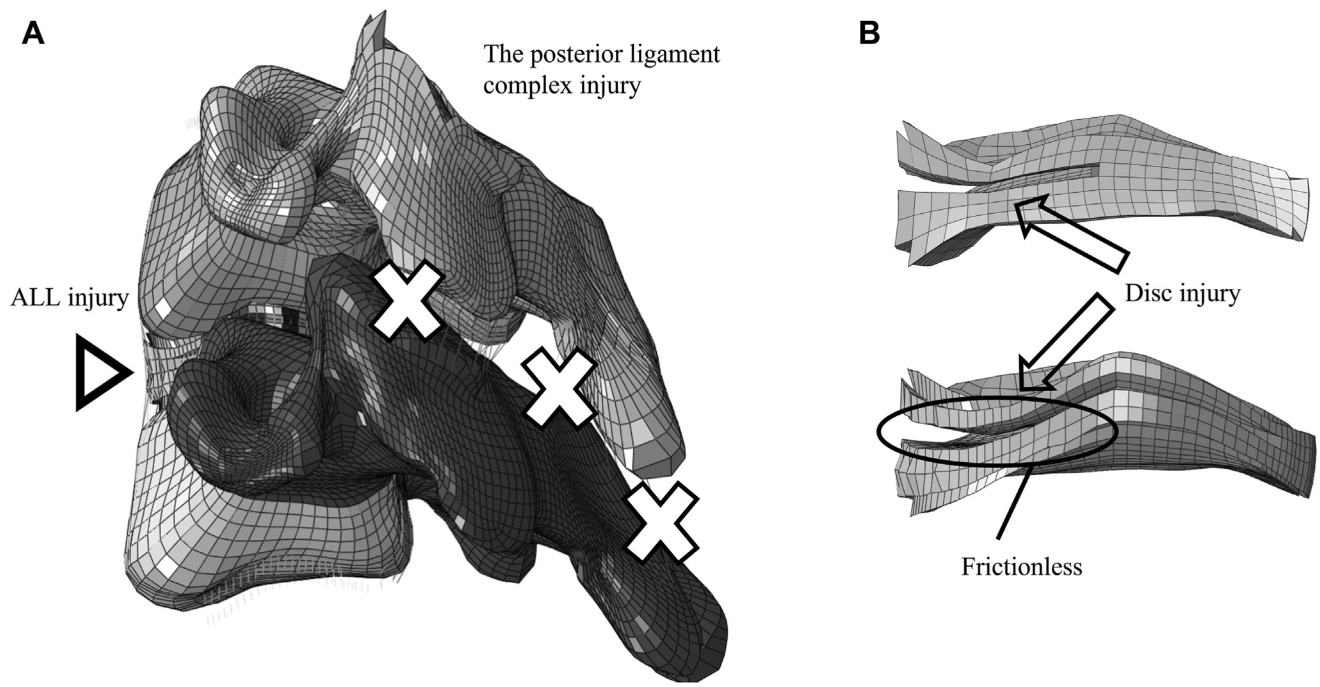

Figure 2. (**A**) Anterior longitudinal ligament and the intervertebral disc injury model *(white arrow).* The posterior ligament complex injury (x-mark). (**B**) Intervertebral disk injury.

PLCI and API models' ROM increased by 6% and 7%, respectively, at the injury level compared with the intact model. In left and right bending, PLCI, IDI, and API models' ROM increased slightly, respectively, at the injury level compared with the intact model. In left rotation, IDI and API models' ROM increased by 31% and 33%, respectively, at the injury level compared with the intact model. In right rotation, PLCI, IDI, and API models' ROM increased by 7%, 31%, and 51%, respectively, at the injury level compared with the intact model (Figure 3).

Annular Stress

In extension, the annular stress at the injury level for IDI and API models' decreased by 8% compared with the intact model. In flexion, the annulus stress at the injury level for PLCI and API models increased by 4% and 7%, respectively, compared with the intact model. In left and right bending, the annular stress at the injury level for IDI and API models decreased slightly compared with the intact model. In left rotation, the annulus stress at injury level for PLCI, IDI, and API models increased by 22%, 195%, and 205%, respectively, compared with the intact model. In right rotation, the C4-C5 annulus stress at injury model for IDI and API models increased by 52% and 96%, respectively, compared with the intact model (Figure 4).

Nucleus Stresses

In extension, the nucleus stress at the injury level for IDI and API models increased by 107% compared with the intact model. In flexion, the nucleus stress at the injury level for IDI and API models increased by 35% and 45%, respectively, compared with the intact model. In left bending, the injury level nucleus stress for IDI and API models increased by 77% and 78%, respectively, compared with the intact model. In right bending, the injury level nucleus stress of IDI and API models increased by 28% and 31% compared with the intact model. In left rotation, the C4-C5 nucleus stress for IDI and API models increased by 115% and 118%, respectively, compared with the intact model. In right rotation, the C4-C5 nucleus stress for IDI and API models increased by 110% and 149%, respectively, compared with the intact model. The PLCI models showed a small increase in the nucleus stress at injury level in flexion and right bending while the stresses were like the intact model in other cases (Figure 5).

Facet Contact Forces

In extension, the facet contact forces at the injury level for IDI and API models increased by 103%, respectively, compared with the intact model. In rotation, the C4-C5 facet contact forces for IDI and API models increased by 129% and 140%, respectively, compared with the intact model (Figure 6).

DISCUSSION

In soft tissue CSI, early surgical interventions are critical for a favorable neurologic recovery of CSI patients.[23,24] However, this assumes that the patient has been reliably diagnosed and a concrete treatment plan has been established. Regarding clinical

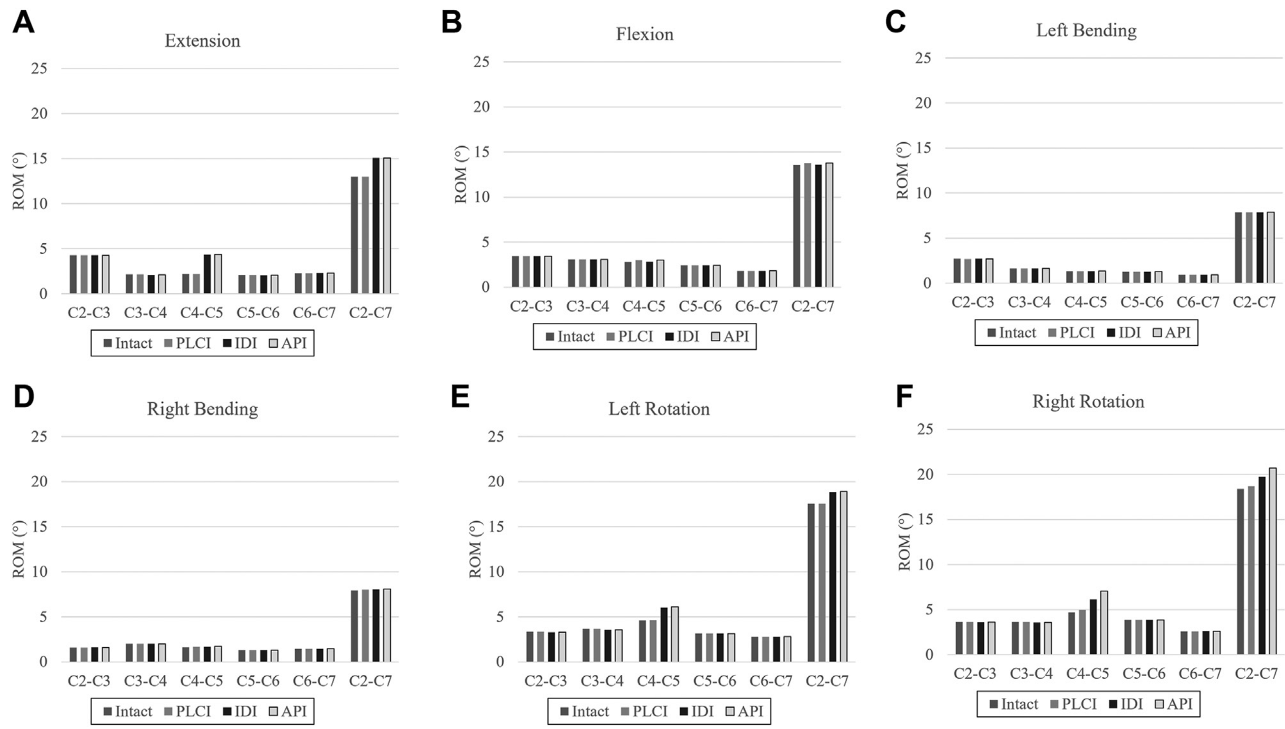

Figure 3. Range of motion. (**A**) Extension, (**B**) flexion, (**C**) left bending, (**D**) right bending, (**E**) left rotation, and (**F**) right rotation. The vertical axis is an angle (degree). The horizontal axis is each intervertebral level.

diagnosis, Nkusi et al[25] reported some causes of delayed diagnosis of soft tissue CSI due to the poor sensitivity of plain radiographs and CT scans for soft tissues. Conversely, magnetic resonance imaging has excellent sensitivity for diagnosis of soft tissue injuries (100%).[11,13,26] The use of magnetic resonance imaging has gradually increased the rate of soft tissue CSI diagnosis. In addition, dynamic evaluation with flexion/extension radiographs stresses the ligamentous structures and can be used for soft tissue CSI diagnosis.[27] However, these examinations are often limited as patients with soft tissue CSIs have neck pain and therefore are unable to produce the adequate ROM required for injury diagnosis.[28]

The importance of the ID and ligaments injuries of the spine has been discussed in the literature. The PLC, which includes the LF, facet joint/capsule, ISL, and SSL is considered a critical predictor of spinal stability and PLC injury causes segmental instability, which can be observed on dynamic imaging.[12,29,30] Clinically, within the spine injury classification, scoring is also made according to soft tissue damage.[31,32] The subaxial cervical spine injury classification (SLIC) system and severity score is a system for cervical spine trauma that helps guide treatment and predicts prognosis including morphology of vertebral fracture and neurologic status.[32] As a parameter of soft tissue injury of SLIC, the diskoligamentous complex comprises the ID, ALL, PLL, LF, CL, ISL, and SSL. The intact score of the diskoligamentous complex is 0, whereas the disk space widening or facet dislocation such as IDI and API model represents a max score 2. Though not a cervical classification, classification of thoracolumbar burst fractures uses the Thoracolumbar Injury Classification System (TLICS) score to determine treatment including morphology of the vertebral fracture, PLC injury, and neurologic status.[31] The intact score of the PLC is 0, whereas suspected injury of the PLC has a score of 2 and injury to the PLC has a score of 3. In this study, PLC injury also caused the increase of ROM, annular stress, and nucleus stress in flexion and rotations. Erbulut et al[33] created a detailed PLC injury FE model and analyzed the ROM changes. They reported that the ISL resected model exhibited a gradual increase in motion of about 30% compared with the intact model in flexion. LF and PLL resected models demonstrated a marginal ROM increase compared with the intact model. In our results, the magnitude of change in ROM due to PLC injury was smaller compared with Erbulut`s report, but a similar trend was observed.[33] Yoganandan characterized the geometry and mechanical properties of the cervical ligaments such as the ALL, PLL, joint capsules, LF, and ISL from human cadavers. They concluded that PLC injury should be fully considered when analyzing soft tissue CSI.[34] The PLC injury results of this study showed ROM increase in flexion and right rotations. Regarding annular stresses and nuclear

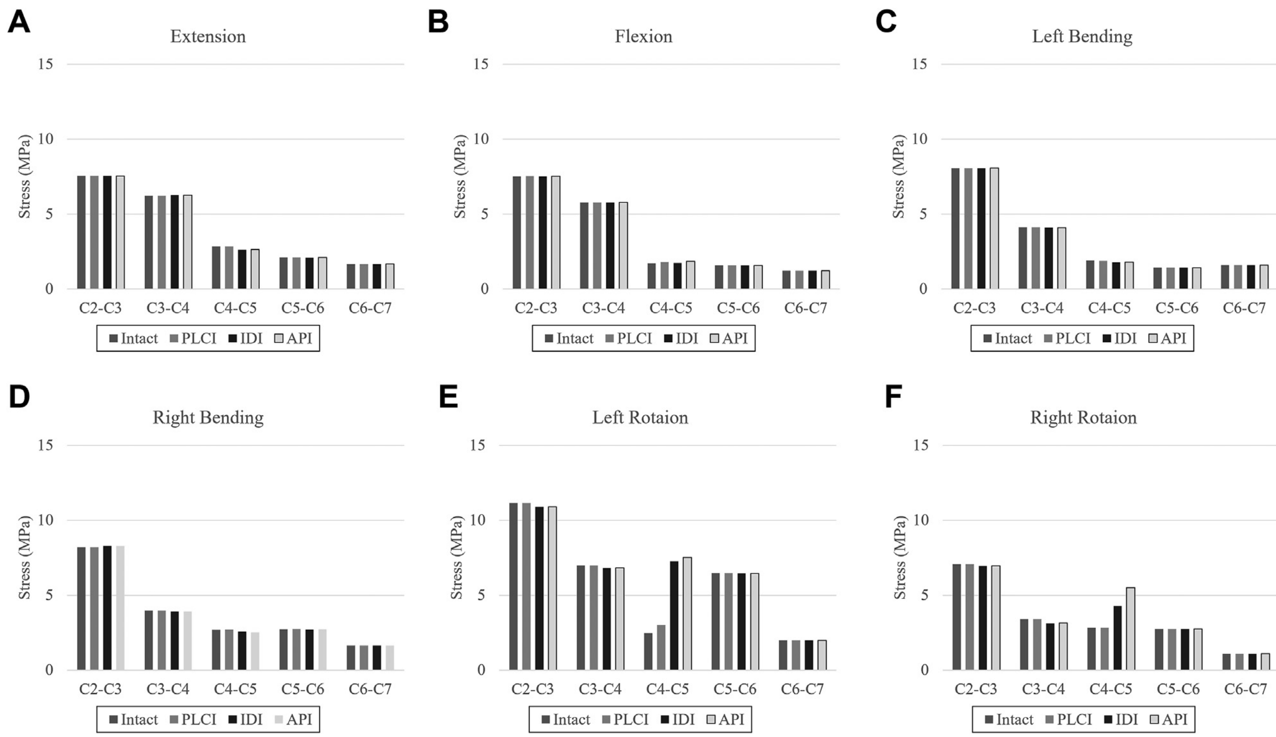

Figure 4. Annulus pressure. (**A**) Extension, (**B**) flexion, (**C**) left bending, (**D**) right bending, (**E**) left rotation, and (**F**) right rotation. The vertical axis is stress (Mega Pascal; MPa). The horizontal axis is each intervertebral level.

stresses, the PLC injury affected flexion and both rotations compared with the intact model. Clinically, surgical stabilization is required for PLC injury. However, consideration of patient-specific characteristics is necessary when identifying a suitable surgical strategy (anterior-only or posterior-only).[35]

Maeda et al[36] reported that the damage to ALL and ID were significantly associated with initial cervical segmental instability as judged by flexion-extension radiographs. Samartzis et al[37] performed a cadaveric study to investigate various stages of a distractive-extension injury and reported a 5 times increase in ROM compared with the intact model after resection of ALL and ID. The results of our study also showed a large increase in ROM in extension and axial rotation. Regarding annular stresses, the IDI model showed an increase in annular stress in both rotations compared with other models. Regarding nuclear stresses, the IDI model showed higher stresses in all motions compared with other models. When accompanied by ID injury, damage to the support mechanism of the annulus fibrosus for the cervical spine leads to increased stress on the nucleus. The facet contact forces of the IDI model were higher in all motions compared with intact and PLCI. This analysis's small effect on flexion may be due to the 1-layer mesh representing the damage in the FE model, which had a small gap. However, the results of the analysis were consistent with those reported in previous papers.[12,36,38] Further stabilization in extension and axial rotation may be required if surgical procedure (anterior-only, posterior-only, or combined approach) is performed.

There are some reports on the effect of soft tissue injury combining the ID and PLCs on cervical spine stability.[29,39] Samartzis et al[37] reported a 20% increased ROM and significantly increased posterior translation compared with the intact model after serial sectioning of ALL, ID, the facet capsule, and the PLL in extension. Beauséjour et al[40] created ID and PLC CSI FE models and reported that PLC rupture increased the ROM at the injured level by 77.2% compared with their intact model. ID rupture also caused an increase in ROM at the injured level of 120.4%. They mentioned that ID injury and PLC injury both significantly increased the risk for instability at the injury level; however, they could not conclude which injury produced the most risk for instability.[40] In our study, ID injury with PLC injury increased ROM compared with the other CSI models and affected flexion, extension, and both rotations. Regarding annular stresses, the API model had higher stresses in both rotations compared with other models. The nucleus stresses of the API model were also higher in flexion and both rotations compared with other models. The facet contact forces of the API model were higher in all motions compared with other models. Furthermore, in an ID injury combined with PLC injury, the facet joints could move freely in all motions, which increased the forces on the annulus fibrosus

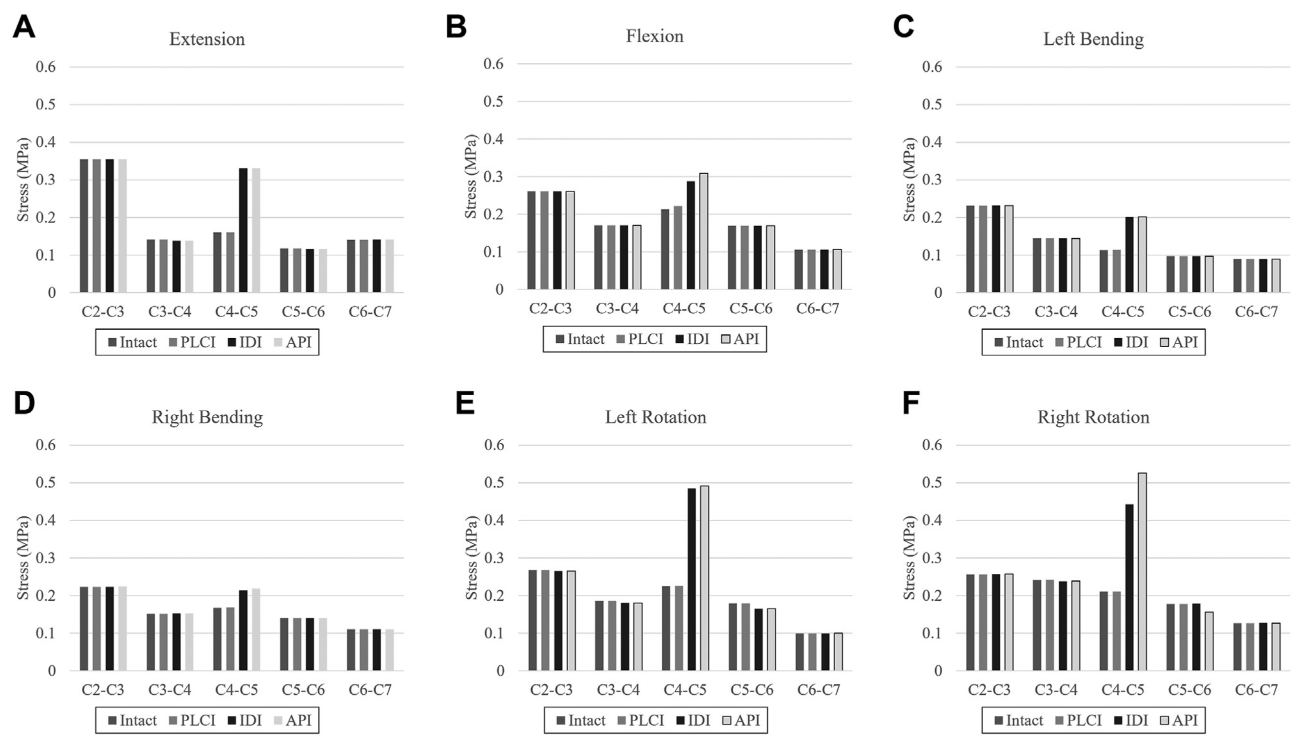

Figure 5. Nucleus stresses. (A) Extension, (B) flexion, (C) left bending, (D) right bending, (E) left rotation, and (F) right rotation. The vertical axis is stress (MPa). The horizontal axis is each intervertebral level.

and nucleus. This finding was in line with previous reports of the importance of each tissue,[29,39] and the direction of increased ROM was found to depend on the damaged tissue. The results of this analysis suggest that ID injury may have a large degree of rotational instability. When ID injury is diagnosed, conservative treatment may require careful follow-up and all motion stabilization may be necessary if surgical procedure (anterior-only, posterior-only, or combined approach) is performed.

The current study has several limitations. Soft tissue CSI is more common in the elderly, but this model was constructed from CT scans of a young adult and did not consider age-related deformities and degenerative changes in the material properties of the ID. The mechanical behavior of the ligaments also changes with age,[41] but that has not been examined in our study. We also did not examine the effects of unilateral ligament injury. This study also does not include paraspinal muscles, though their

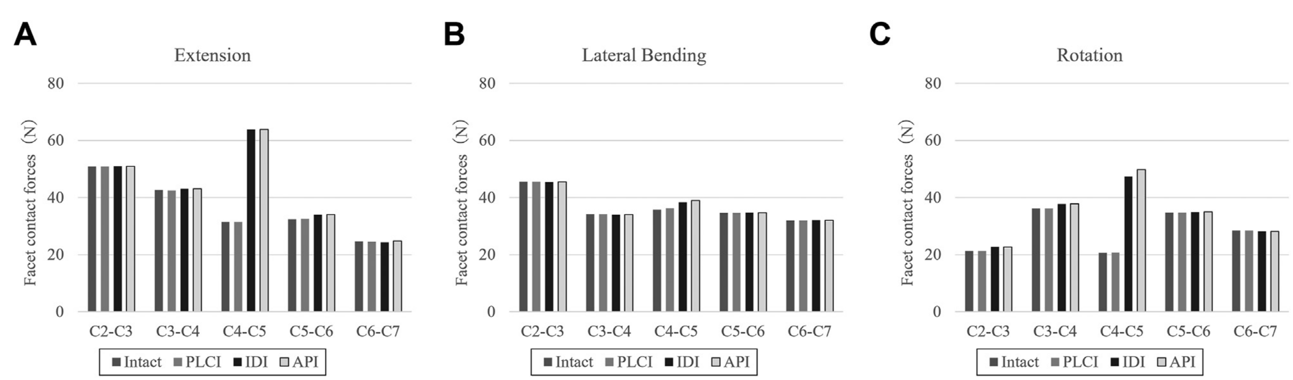

Figure 6. Facet contact forces. (A) Extension, (B) lateral bending, (C) axial rotation. Vertical axis is force (N). Horizontal axis is each intervertebral level.

effect was simulated by compressive follower load. Despite these limitations, our study provides valuable insights into different soft tissue CSI injuries. In the future, the soft tissue CSI in conjunction with hard tissue injury may be simulated to investigate the severe cervical spine injuries that patients experience during trauma/whiplash.

CONCLUSIONS

This study investigated the biomechanical changes and instability after soft tissue CSI using FE analysis. In soft tissue CSI, instability was exacerbated by PLC injury, especially when combined with ID injury. When diagnosing a patient with a suspected neck injury, a thorough evaluation of the soft tissue injury is necessary.

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:** Contributed to supervision and editing of manuscript. **Vijay K. Goel:** Supervisior.

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