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Contribution of ligaments to intersegmental stability following type II odontoid fracture

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Introduction

Epidemiology

Cervical spine fractures pose an increasing burden to society despite accounting for merely 3-5% of all traumatic injury cases [10,14]. C2 fractures comprise 7,8% of all spinal fracture cases [8] and represent a predominant type within cervical spine fractures.

Odontoid fractures form a notable subset of C2 fractures, with Anderson and D'Alonzo type II [1] being the most common odontoid fractures (OFII). Granted their clinical significance and relatively frequent occurrence, controversies continue about whether conservative or surgical treatments are preferable, particularly concerning the geriatric population [23,20,17,6,11,7].

Biomechanical studies on OFII

One pivotal aspect of managing OFII involves assessing the stability of the injured craniovertebral junction (CVJ). In the absence of fractures, ligament integrity primarily influences stability. Consequently, a massive body of research has delved into the role of specific ligaments, such as the alar ligament (AL), the vertical portion of the cruciate ligament (CV), transverse ligament (TL), apical ligament (APL), capsular ligaments (CL) and anterior longitudinal ligament (ALL), in stabilizing the intact CVJ [2,15,16]. Yet, no more than a handful of studies have explored this issue within the context of a fractured CVJ.

The first cadaveric biomechanical assessment of the CVJ destabilized by OFII was conducted by Crawford et al. [3]. The primary objective of this study was to assess a fixation method in multiple injury scenarios, including TL-AL-APL tearing, OFII, and odontoidectomy. With regards to OFII, a key finding highlighted that odontoidectomy led to the most significant instability. Furthermore, OFII alone resulted in a considerable increase in the range of motion in C1-C2 compared to what the TL-AL-APL rupture induced.

McCabe et al. [9] pioneered the study of ligament function following OFII, particularly to quantify their capacity to maintain CVJ stability. The central emphasis was placed on elucidating the biomechanical contribution of ALL and C1-C2 CL after OFII. The study involved in vitro ROM measurements in both intact and injured specimens. Key findings suggested that each ligament independently provided stabilization under axial rotation but resisted translations in an “all-or-nothing” manner. Instead of flexion-extension, axial rotation was proposed as a diagnostic technique for identifying CVJ instability.

In a similar manner to McCabe et al. 's work, Tisherman et al. [21] conducted a cadaveric empirical study. Their leading findings indicate that CL did contribute to stability to some extent in the presence of OFII. However, their report revealed that ligaments did not possess a significant capacity to restrict motion following OFII; hence, the fracture stood out as the dominant source of instability.

Objective of the present study

A review of the cited biomechanical studies highlights the need for increased focus on AL, CV, and TL, which are traditionally considered critical stabilizers of the C0-C2 unit **[13,18,22]**. Instead, CL and ALL have been examined in the context of OFII in the existing literature – a logical approach if one posits that AL, CV, and TL cease to function after OFII. Regardless, this assumption lacks confirmation. Moreover, OFII with a concurrent injury to AL, CV, or TL appears more probable than for any other CVJ ligament, given their anatomical proximity to the fracture site. Surprisingly, to the authors' knowledge, no study has explored the separate and combined contributions of AL, CV, and TL to stability post-OFII

The integrity of the three odontoid ligaments, individually or in combination, could play a crucial role in OFII management. Hence, using the finite element method, we aimed to investigate how AL, CV, and TL affect the stability of Anderson-D'Alonzo type II odontoid fractures.

Biomechanical terminology in intersegmental stability

A widely used metric in assessing spinal instability is range of motion (ROM), which refers to the extent of rotation a joint can undergo measured in degrees **(Figure 1)**. The ROM comprises the neutral zone (NZ) and the elastic zone (EZ). NZ refers to the central segment of the rotation-moment curve where the joint shows high flexibility due to the laxity of connective tissues. In contrast, EZ is characterized by a relatively high stiffness and essentially linear mechanical behavior, extending from the end of NZ to the corresponding end of ROM. Both quantities are expressed in degrees. Neutral zone compliance (NZC) and elastic zone compliance (EZC) characterize the associated zone's flexibility – essentially representing the slope of the rotation-moment curve. Specifically, EZC is defined as the slope of the linear portion of the EZ.

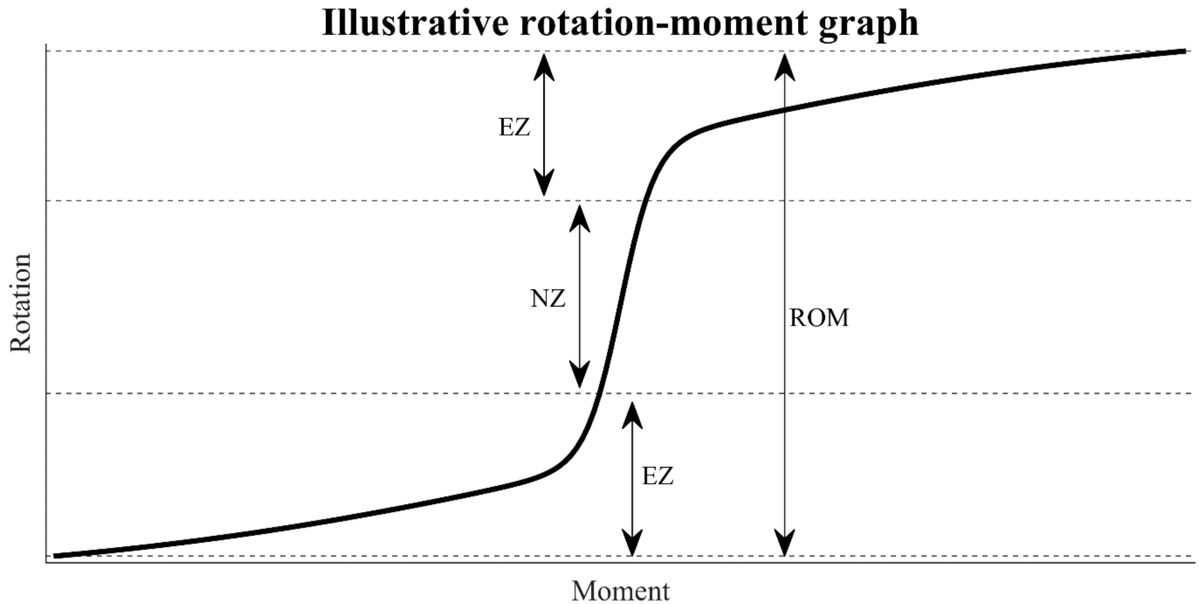

Figure 1. Rotation-moment graph of a functional spinal unit.

Materials and Methods

Computational model

A validated finite element model of the human cervical spine [4] was developed, employing ANSYS 21.1 software package (ANSYS Inc., USA) for performing large displacement static simulations. The model **(Figure 2)** consists of the cranium, the seven cervical vertebrae, intervertebral disks, and ligaments. The patient-specific model originates from CT scans of a 21-year-old male free of craniocervical pathology or injury. The resolution of the scans is 0.504 mm x 0.504 mm x 1.25 mm along the sagittal, frontal, and longitudinal axes, respectively.

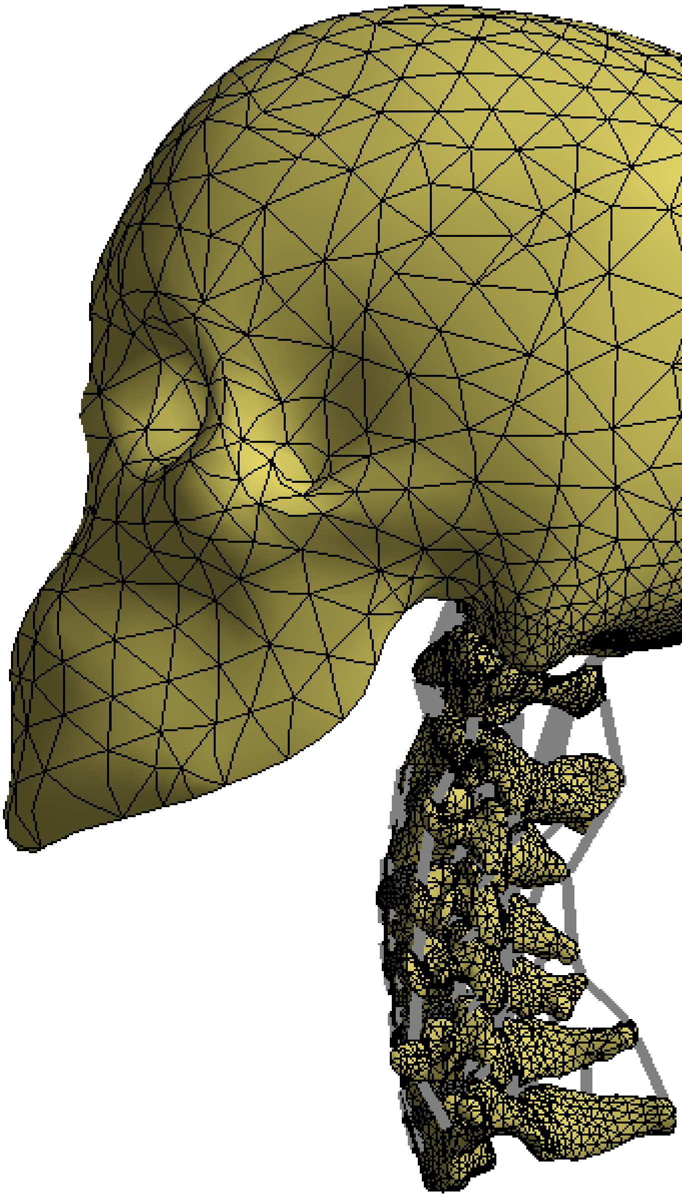

Figure 2. Lateral view of the validated finite element model

Injury conditions, coding scheme

Figure 3 illustrates the three ligaments under investigation. Two states of the ligaments were defined: intact or bilaterally torn. Nine unique conditions of the cervical spine were analyzed, including undamaged, and fractured states with all possible combinations of bilateral ruptures in the ligaments mentioned above (Table 1). Each of the nine conditions involved subjecting the finite element model to flexion, extension, lateral bending to the right, and axial rotation to the right. Consequently, this resulted in a total of 36 simulations.

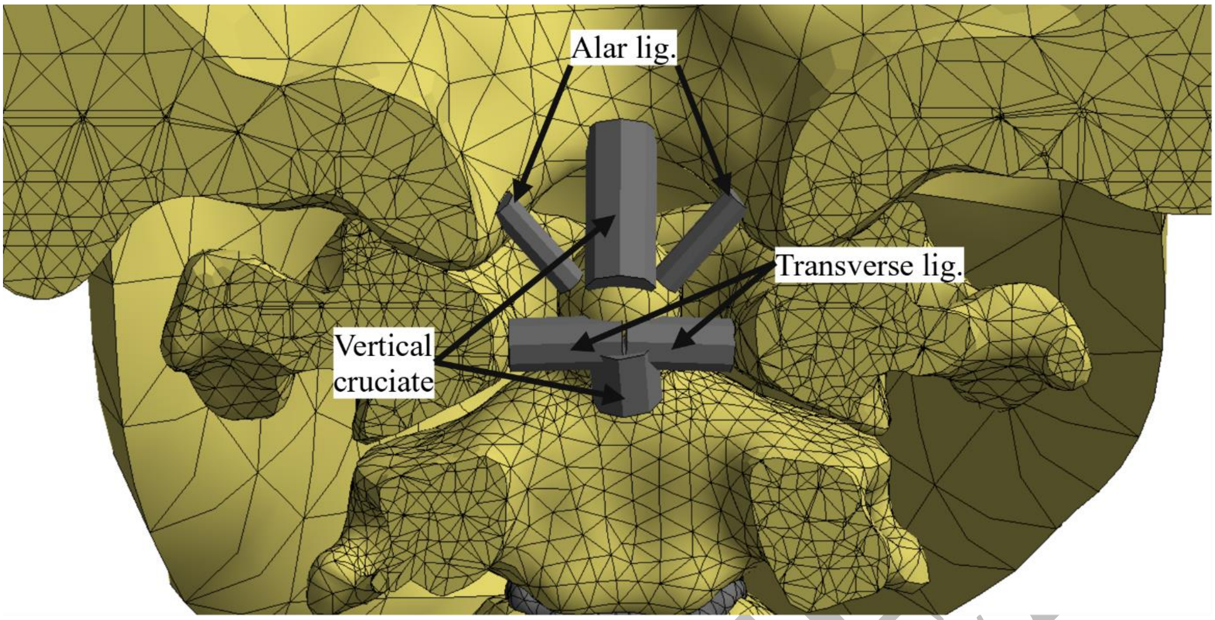

Figure 3. Coronal cross-section. Odontoid ligaments are shown only.

State	Code name
intact	0-00-00-00
C2 fractured	F-00-00-00
C2 fractured, AL ruptured	F-AL-00-00
C2 fractured, CV ruptured	F-00-CV-00
C2 fractured, TL ruptured	F-00-00-TL
C2 fractured, AL and CV ruptured	F-AL-CV-00
C2 fractured, AL and TL ruptured	F-AL-00-TL
C2 fractured, CV and TL ruptured	F-00-CV-TL
C2 fractured, AL, CV, and TL ruptured	F-AL-CV-TL

Table 1. Investigated states of the cervical spine and their corresponding code names

A coding scheme was implemented to ensure the unique identification of each state and simulation. Figure 4. illustrates the logic of this system using an example. Consider the codename "F-AL-CV-00-F", which indicates a simulation involving the fractured C2, torn AL and CV, and intact TL subjected to flexion. However, by omitting "-F", resulting in "F-AL-CV-00", the codename specifically denotes the injured state itself **(Table 1)** — this flexibility in utilizing the coding scheme allowed for versatile usage.

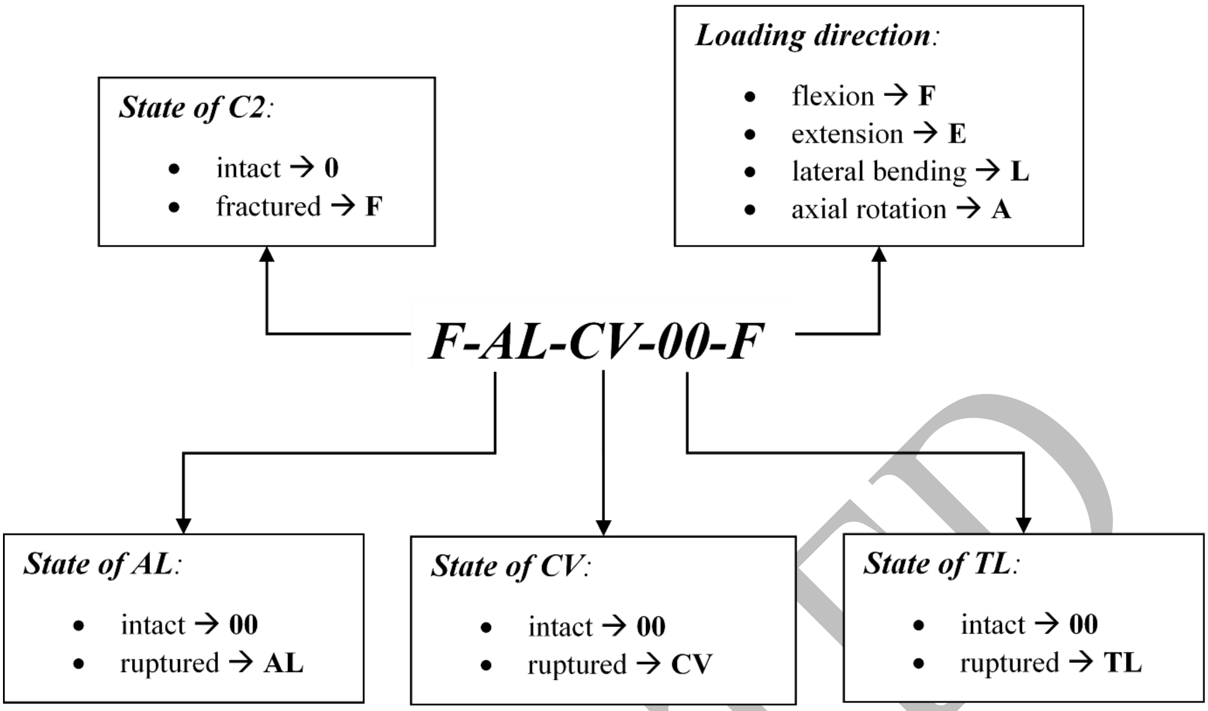

Figure 4. Coding scheme

Simulation setup, boundary conditions

The reference configuration corresponded to the upright position of the head, maintaining a normal lordosis **(Figure 2)**. As for the injured states, the reference configuration included the fracture surface and lacked the appropriate ligaments. Thus, the fracture surface was generated manually by modifying the geometric model before simulations, positioned perpendicular to the axis of the odontoid process **(Figure 5)**. On the other hand, ligament injury was addressed by suppressing the appropriate ligaments. Additionally, the fractured dens was excluded from the reference configuration to prevent a singular stiffness matrix due to the absence of connective elements in the specific state of the F-AL-CV-TL.

The model was fixed at the inferior surface of the C7 vertebral body while prescribed rotations were imposed at the top of the cranium. Two of the three components of the prescribed rotations were set to zero to achieve numerical stability and ensure the desired head motion. Furthermore, translations were not specified.

Moreover, modeling ligament laxity involved setting a fictive coefficient of thermal expansion and applying a fictive thermal load to the tension-only bar elements representing the ligaments. For more in-depth information, see Danka et al. [4]. The complete loading process, therefore, encompasses the application of the fictive thermal load to induce ligament laxity, followed by the prescribed rotations to achieve the desired head motions.

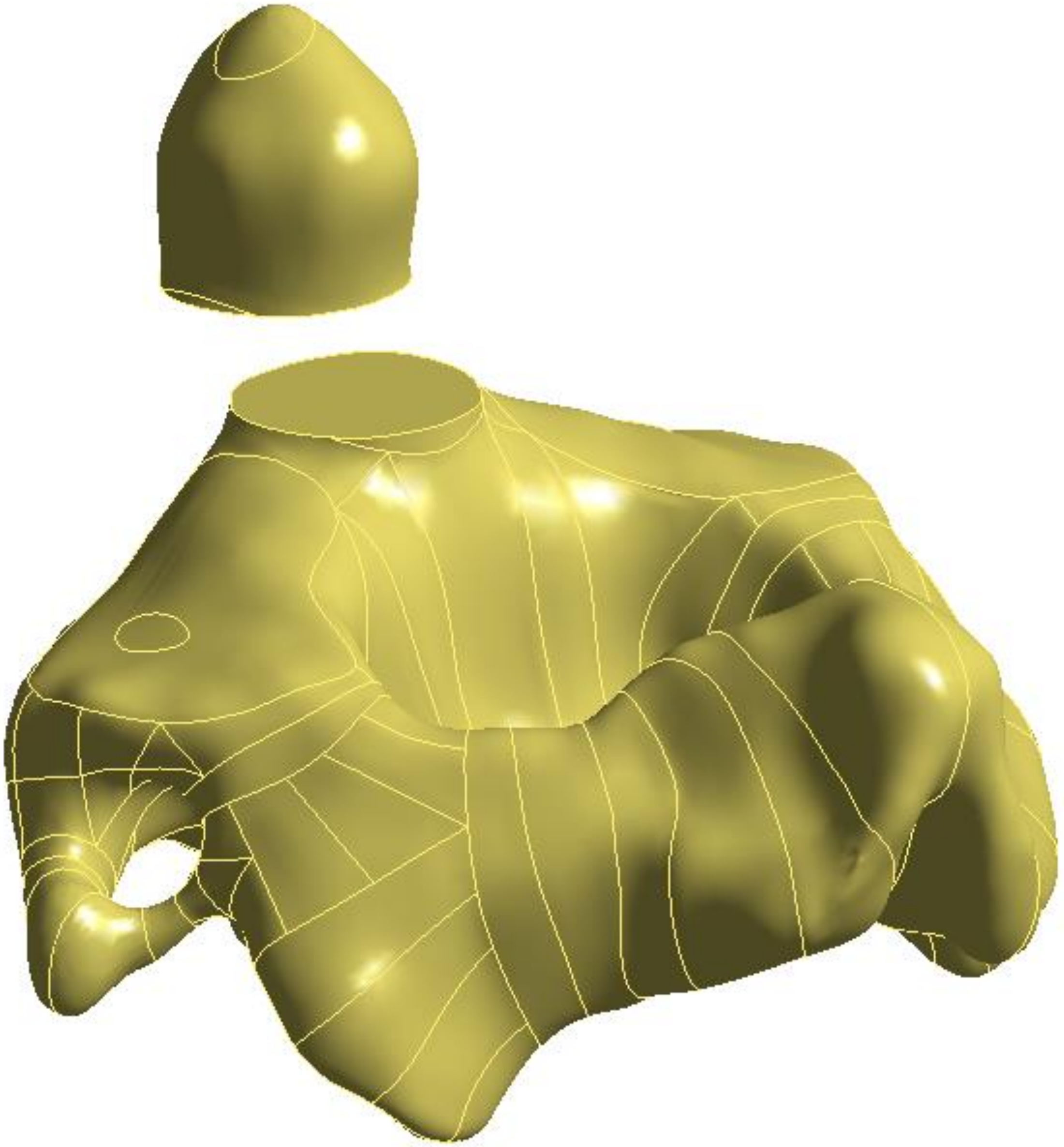

Figure 5. Exploded view of C2: manually created OFII fracture surface

The model incorporates several frictionless contacts. The associated articular facets were set to permit contact. Moreover, when OFII was present in the model, the two fracture surfaces were defined as contact surfaces. In the case of the extension, additional contacts were also configured between the posterior arch of C1, the posterior side of the foramen magnum, and the superior side of the C2 arch.

Rotation-moment relationship

Primary angulations of C0-C1 and C1-C2 resulting from prescribed rotations were retrieved from the 36 simulations. The moment was defined as the reaction moment component acting parallel to the corresponding nonzero prescribed rotation. The relative rotation of spinal segments was obtained using ANSYS's Remote Point feature.

As mentioned earlier, lateral bending and axial rotation simulations were exclusively carried out in one direction. A point reflection was performed on the results with respect to the origin to generate the complete rotation-moment diagram. Thus, the finite element model was assumed to be perfectly symmetric to the median sagittal plane.

Results

One specific simulation, denoted as F-00-CV-TL-L, posed significant numerical challenges, leading to a negligible magnitude of the moment. Thus, F-00-CV-TL-L was excluded from the corresponding charts.

Flexion-extension

Examining the flexion of the C0-C1 unit (Figure 6), there is no noticeable change in the intersegmental motions. The NZ and the EZC remained unaltered, regardless of either OFII or concurrent ligament tear. However, during extension, pronounced differences became apparent across multiple injury states. Specifically, the EZC of F-00-00-00 and F-AL-00-00 are similar and higher than in 0-00-00-00. Moreover, further comparable enlargement is evident in F-00-00-TL and F-AL-00-TL. Finally, EZC developed further to virtually the same extent in the case of F-00-CV-00, F-AL-CV-00, F-00-CV-TL, and F-AL-CV-TL.

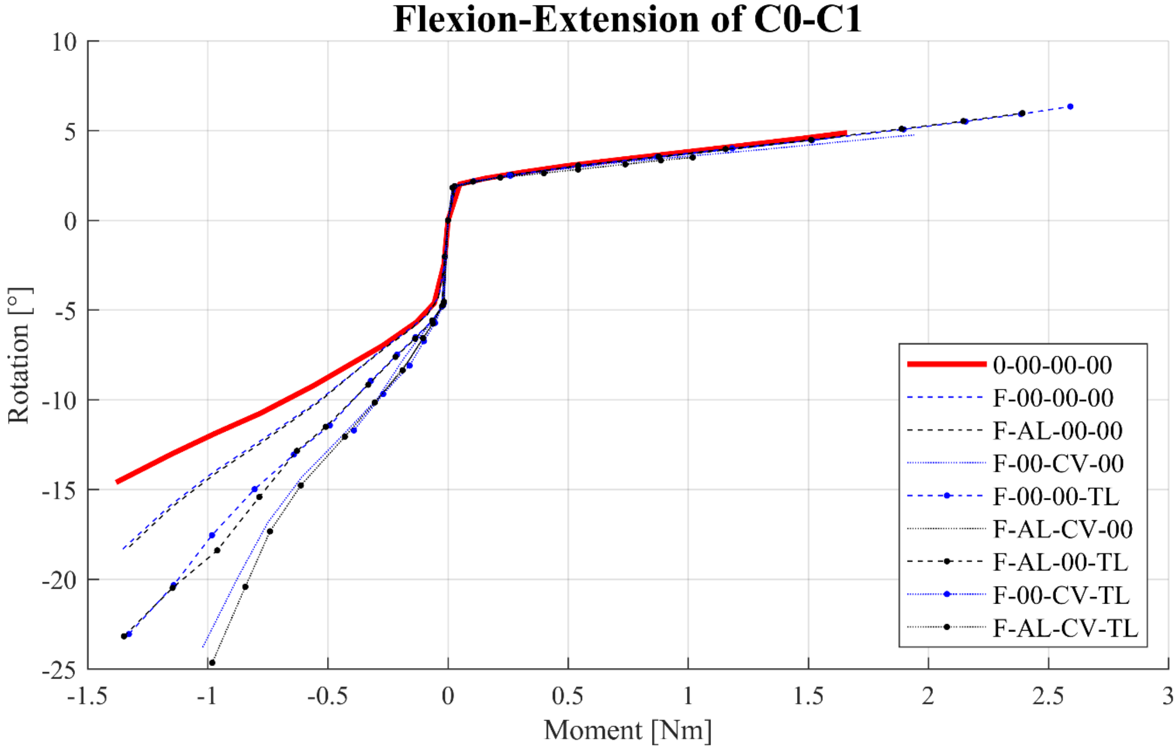

Figure 6. Rotation-moment diagram of C0-C1 spinal unit subjected to flexion-extension

The case of C1-C2 subjected to flexion-extension (Figure 7) is somewhat different. There is a distinct growth in the magnitude of the NZ under all injured conditions. The curves show minimal variation on the extension side regarding EZC. On the other hand, compliance is higher in all injury states compared to the intact case. Furthermore, a more extensive transition zone is observed in the EZ near the NZ. On the flexion side, a slight softening behavior is seen, indicated by the increasing slope of the curves. This contrasts with the intact state where the EZ demonstrates a linear behavior. The curves of F-00-00-00 and F-AL-00-00, F-00-00-TL and F-AL-00-TL, and F-00-CV-TL and F-AL-CV-TL closely align. Notably, F-AL-CV-TL manifested in the largest EZC.

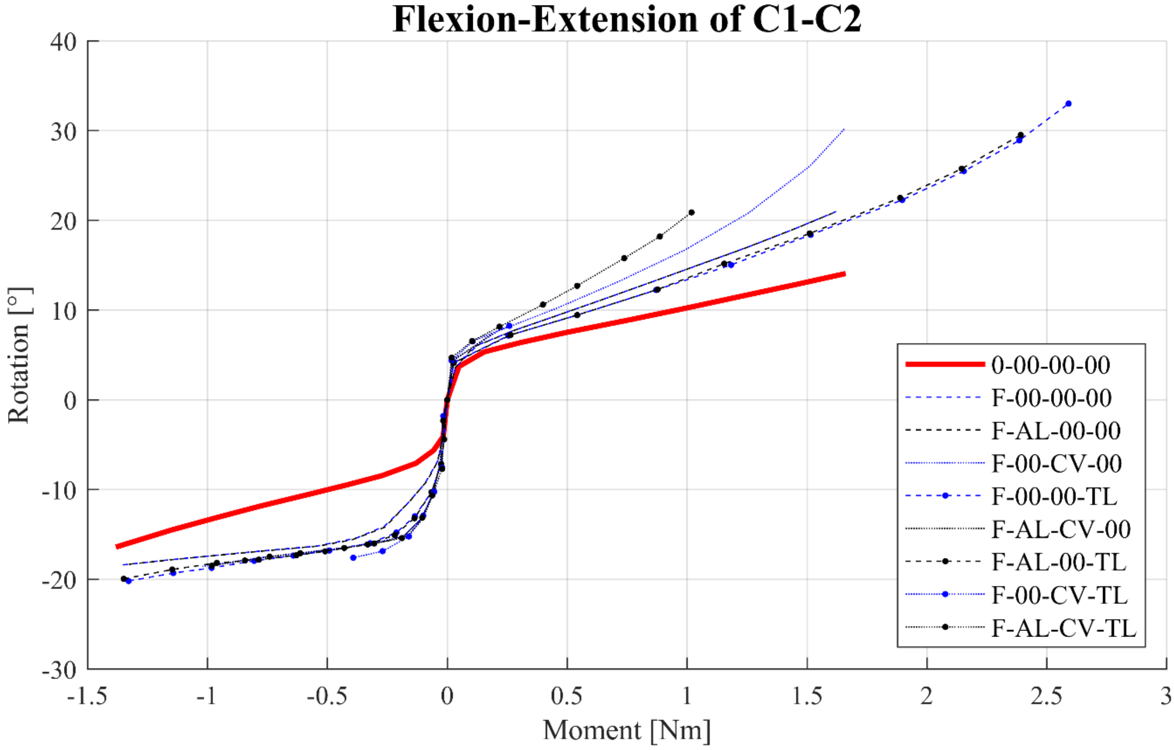

Figure 7. Rotation-moment diagram of C1-C2 spinal unit subjected to flexion-extension

Lateral bending

Undergoing lateral bending (Figure 8), the increment in the NZ of C0-C1 is moderate. Instead, the NZC is considerably higher in all injury scenarios. A clear trend indicates that the NZC rises as more ligaments rupture. However, the variance in each injury case is slight. Notably, the curve representing F-AL-CV-TL displays the highest compliance.

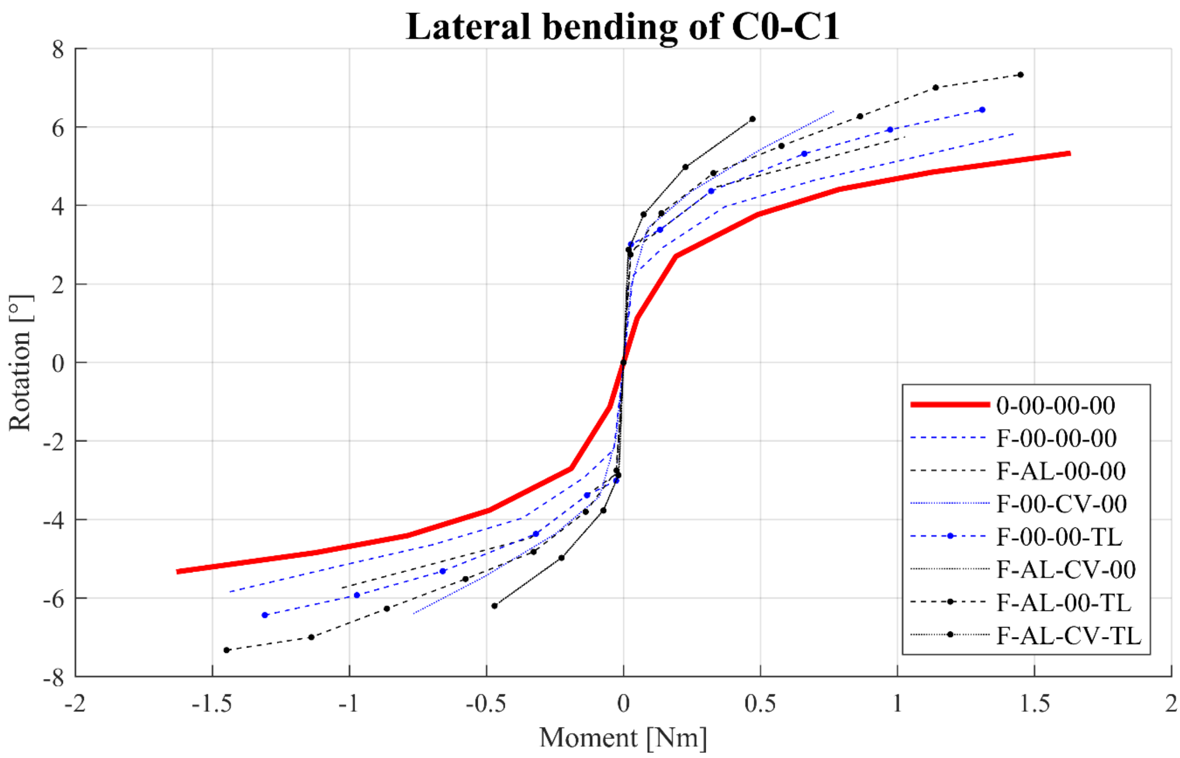

Figure 8. Rotation-moment diagram of C0-C1 spinal unit subjected to lateral bending

In the case of lateral bending of C1-C2 (Figure 9), the change in NZ and NZC is less prominent than in the C0-C1 unit. The influence of CV is predominant, as seen in the practically coincident curves of F-00-CV-00, F-AL-CV-00, and F-AL-CV-TL. For AL, the curves F-00-00-00 and F-AL-00-00 are also nearly identical. Up to a moment magnitude of approximately 0.8 Nm, F-00-00-TL and F-AL-00-TL remained mostly coincident, after which a marked change in compliance of F-AL-00-TL is evident.

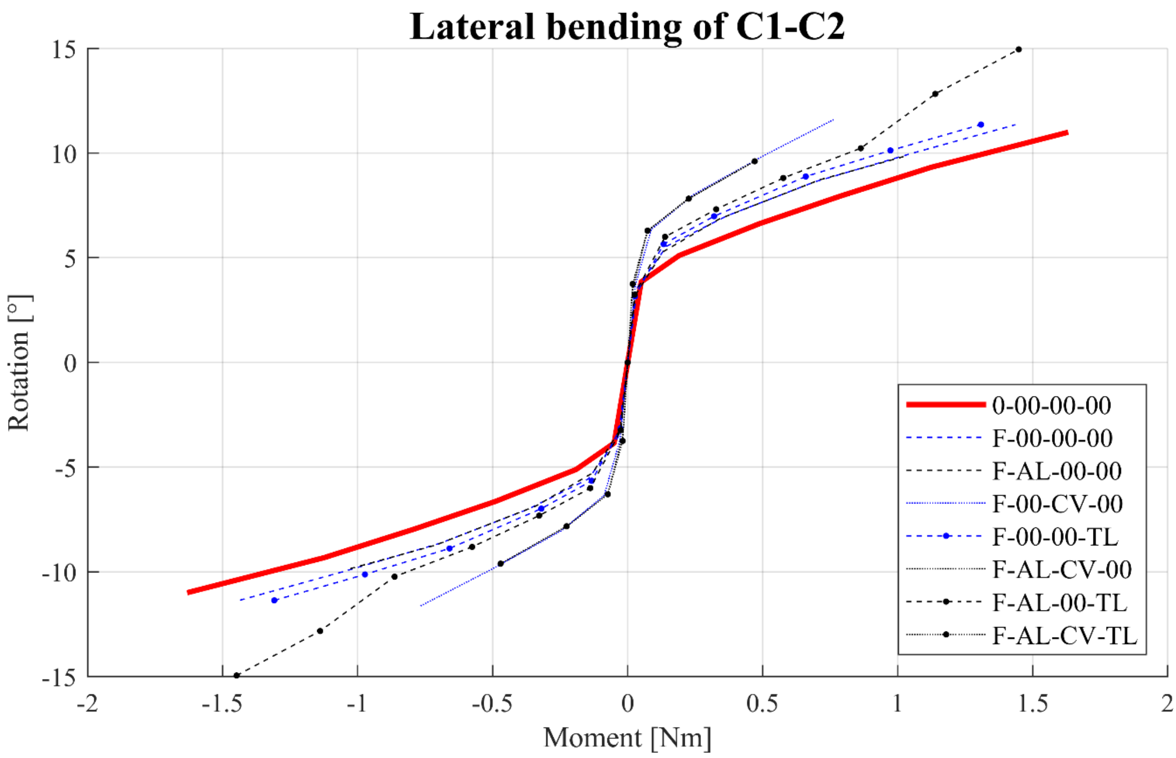

Figure 9. Rotation-moment diagram of C1-C2 spinal unit subjected to lateral bending

Axial rotation

In the context of axial rotation of both spinal units (Figure 10 and Figure 11), the NZ experienced a stark rise in all injury cases. All injured conditions led to a nearly identical increase in EZC. Curves associated with either CV or TL rupture demonstrate the most significant additional growth in NZ. Apart from F-00-00-00 and F-AL-00-00, curves involving the torn AL show no deviation from their counterparts involving the intact AL.

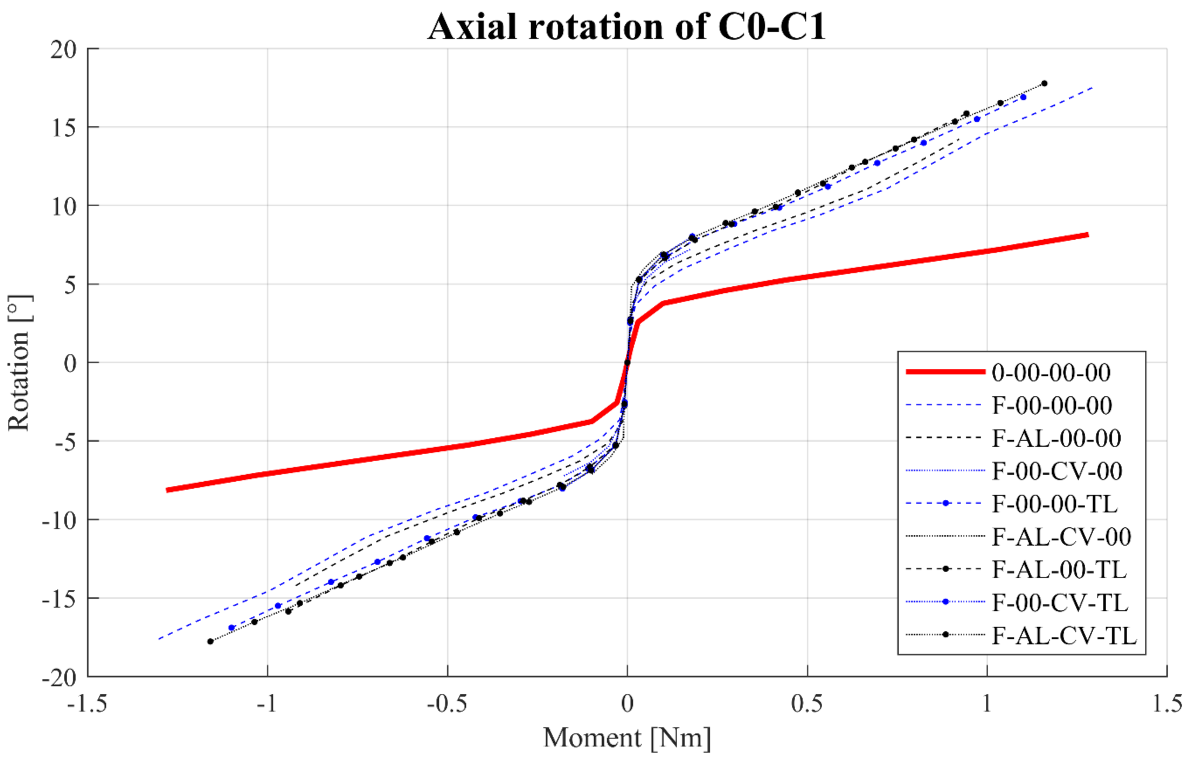

Figure 10. Rotation-moment diagram of C0-C1 spinal unit subjected to axial rotation

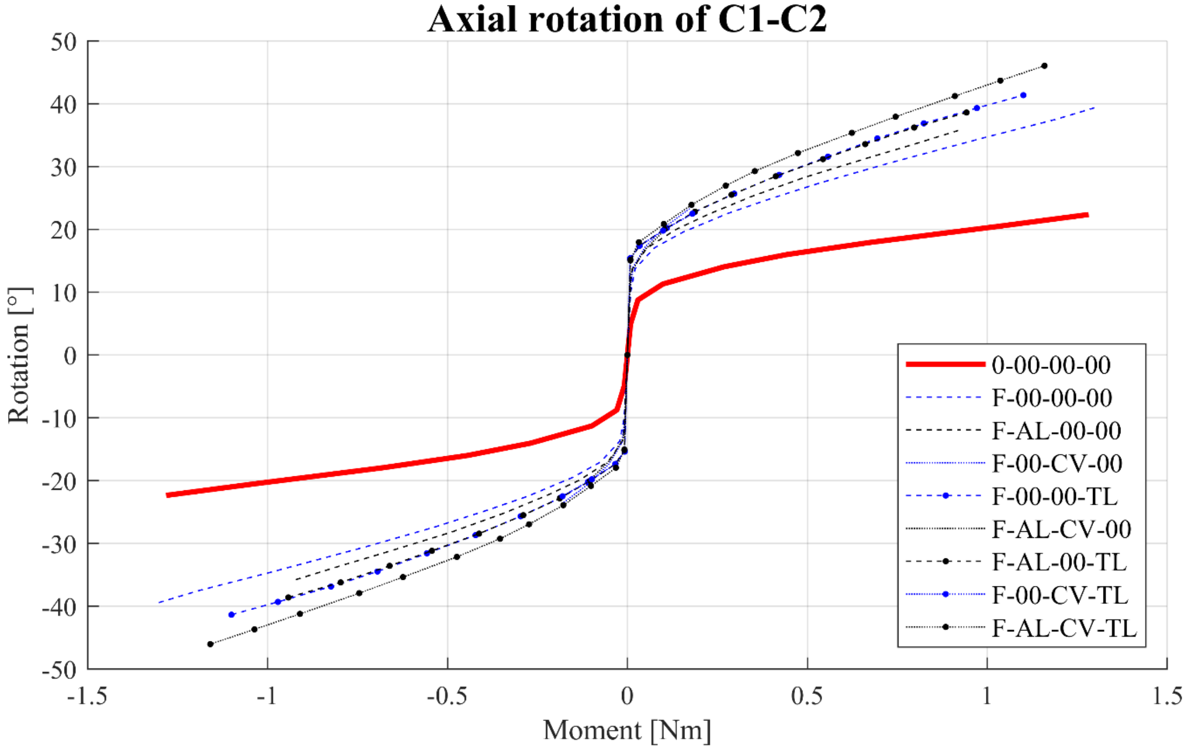

Figure 11. Rotation-moment diagram of C1-C2 spinal unit subjected to axial rotation

Discussion

A validated C0-C7 ligamentous finite element model was used to explore the intersegmental motions of CVJ following OFII under a variety of loading conditions. The independent variables comprised OFII fracture, AL, CV, and TL rupture, while the rotation-moment responses served as the dependent quantities.

As anticipated, F-00-00-00 demonstrated the most stable behavior among the injured conditions. In contrast, F-AL-CV-TL indicated the highest degree of instability across all loading cases and spinal units regarding all introduced metrics. However, a detailed examination of the rotation-moment curves reveals nuances.

Role of the dens fracture

According to our results, OFII alone did not necessarily generate substantial instability, contrary to prior findings [3,21]. For instance, during the flexion-extension of both spinal units (Figure 6 and Figure 7), OFII led to significant instability solely in the extension of C1-C2.

In addition, the way OFII induced instability differed across numerous loading conditions and spinal segments. In the extension of C1-C2, OFII resulted in a substantial transition zone between NZ and the linear segment of EZ. In the lateral bending of C0-C1, OFII resulted in a stark NZC growth but only slightly increased in NZ. In the axial rotation of both segments, OFII alone caused a predominant rise in all biomechanical metrics, while ligament disintegration had a modest influence on stability.

Role of the ligaments

The contribution of AL in offering post-OFII restraint was generally minimal, particularly absent during flexion-extension. In lateral bending of C0-C1 (Figure 8) and axial rotation (Figure 10 and Figure 11), AL disruption produced a marginal growth in NZ. Still, AL provided mild restraint in axial rotation when both CV and TL remained intact.

The most crucial restraint upon OFII in flexion-extension was CV. The torn CV solely resulted in the most substantial expansion in ROM and EZC. In lateral bending, the significance of CV was pronounced. Nevertheless, in axial rotation, the role of CV was notable but roughly equivalent to that of TL.

TL had the most substantial restraining capacity in axial rotation alongside CV, as evidenced by the minor difference in curves involving the ruptured TL. Under other circumstances, TL played a noticeable role in stabilization.

Building upon the observations above, ligaments offered some independent restraint, yet certain interdependencies were evident. Both CV and TL were needed for stability in axial rotation, which contrasts McCabe et al.'s findings [9] that ligaments independently provide stability under rotational motions.

However, the extent of additional restraint ligaments provided was negligible from a practical, neurosurgical standpoint. This finding aligns with recent recommendations [12,19] suggesting that ligament lesions should not be considered essential factors in managing OFII.

Strengths and limitations

The chief strength of the present study lies in using a complete cervical spine model in contrast to the common practice of employing a separate C0-C2 model. Moreover, this work stands out for its exploration of a more extensive array of injury cases compared to the relatively limited scenarios covered in prior studies. From a computational perspective, the model's predictive power was enhanced by adopting frictionless contacts at the articular facets and elsewhere instead of traditional joints (e.g., ball joints). This approach facilitated the reproduction of complex motion patterns due to various loading scenarios and injury states. To capture ligament laxity, a critical component in the biomechanics of the spine, tension-only bar elements (LINK180) were utilized.

Nevertheless, our study has limitations. The principal was that a single patient-specific computational model was applied instead of a dozen. The lack of multiple patient-specific model simulations introduced uncertainties since the dependency of the intersegmental motions on the natural variance in anatomical details across individuals remains to be determined, limiting the broader applicability of the present study's findings. Furthermore, unilateral ligament rupture was not examined despite being possibly much more probable than bilateral rupture. Since our results were primarily analyzed qualitatively, obscurity remained to some extent. A complete quantitative analysis is preferable. Still, the need for more consensus on NZ and NZC calculation methods [5] presents a significant hindrance.

Conclusions

As the prevalence of Anderson and D'Alonzo type II odontoid fractures (OFII) poses a growing societal burden, proper management remains a subject of ongoing debate, even with extensive research. We found a scarcity of studies examining the biomechanics of OFII, specifically the stabilizing role of the three odontoid ligaments: the alar ligament, the vertical cruciate, and the transverse ligament.

Using a validated C0-C7 finite element model of the cervical spine, the intersegmental angulations of the C0-C1 and C1-C2 units were produced in flexion-extension, lateral bending, and axial rotation. Our results underscore the overarching significance of OFII as the primary source of instability, especially in axial rotation, in contrast to flexion-extension and lateral bending. Out of the three odontoid ligaments, the vertical cruciate and the transverse ligament proved to be the main restrainers of the craniovertebral junction after OFII. However, frequently, both ligaments were needed to offer stability. In light of the results, ligaments, while influential, provide modest to no restraint after OFII.

Authors' contribution

A. The preparation of the research program: D. Danka, I. Bojtár
B. The execution of the research: D. Danka
C. The statistical analysis: -
D. The interpretation of the data: D. Danka, I. Bojtár
E. Preparation of the manuscript: D. Danka, I. Bojtár
F. Obtain financing: -

Declaration of conflicting interest

All authors declare no competing interests.

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