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Biomechanical contributions of upper cervical ligamentous structures in Type II odontoid fractures

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ABSTRACT

Fractures of the odontoid present frequently in spinal trauma, and Type II odontoid fractures, occurring at the junction of the odontoid process and C2 vertebrae, represent the bulk of all traumatic odontoid fractures. It is currently unclear what soft-tissue stabilizers contribute to upper cervical motion in the setting of a Type II odontoid fracture, and evaluation of how concomitant injury contributes to cervical stability may inform surgical decision-making as well as allow for the creation of future, accurate, biomechanical models of the upper cervical spine. The objective of the current study was to determine the contribution of soft-tissue stabilizers in the upper cervical spine following a Type II odontoid fracture. Eight cadaveric C0-C2 specimens were evaluated using a robotic testing system with motion tracking. The unilateral facet capsule (UFC) and anterior longitudinal ligament (ALL) were serially resected to determine their biomechanical role following odontoid fracture. Range of motion (ROM) and moment at the end of intact specimen replay were the primary outcomes. We determined that fracture of the odontoid significantly increases motion and decreases resistance to intact motion for flexion–extension (FE), axial rotation (AR), and lateral bending (LB). Injury to the UFC increased AR by 3.2° and FE by 3.2°. ALL resection did not significantly increase ROM or decrease end-point moment. The UFC was determined to contribute to 19% of intact flexion resistance and 24% of intact AR resistance. Overall, we determined that Type II fracture of the odontoid is a significant biomechanical destabilizer and that concurrent injury to the UFC further increases upper cervical ROM and decreases resistance to motion in a cadaveric model of traumatic Type II odontoid fractures.

1. Introduction

Cervical spine trauma represents 5.4% of all trauma in the United States, becoming increasingly burdensome to society (Passias et al., 2018). Fractures at the C2 level represent the most frequently observed cervical fracture (Passias et al., 2018; Smith et al., 2010), with 59% of C2 fractures occurring at the odontoid process (Greene et al., 1997). One-year mortality has been found to be as high as 26–37% in patients over 65 years old who sustain an odontoid fracture (Venkatesan et al., 2014; White et al., 2010), and further research is needed to optimize the treatment and management of these patients.

The most frequently used classification was defined by Anderson and D'Alonzo (1974), with Type II odontoid fractures occurring at the junction of the odontoid process with the vertebral body of C2. Type II odontoid fractures represent the majority of odontoid fractures seen across all age groups (Chapman et al., 2013; Pal et al., 2011).

There is considerable debate on how to best manage Type II odontoid fractures (Chapman et al., 2013; Grabel et al., 2018). Acute operative intervention has been associated with greater short-term risks during the perioperative period (Woods et al., 2014). However, previous studies have cited more favorable long-term outcomes with operative management of odontoid fractures in the elderly compared to non-operative management (Pearson et al., 2016; Scheyerer et al., 2013; Vaccaro et al., 2013). Displaced fractures, seen on computed tomography (CT) or flexion-extension radiographs, are often treated operatively given their increased rate of symptomatic nonunion and decreased stability with non-operative management (Jubert et al., 2013). Sasso (2001), in his review of C2 fracture management, indicated that due to the complexity of the occipitoatlantoaxial joint, odontoid fractures should be considered in the context of bony and ligamentous injury in determining surgical decision making. Given the

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higher short-term risk of operative management, there is a need to better understand the mechanical contributions to stability of surrounding ligamentous structures to help guide clinical decision-making and create future biomechanical models of the upper cervical spine.

Biomechanical evaluation using cadaveric modeling of Type II odontoid fractures will inform sub-categorization of Type II odontoid fractures by associated ligamentous injury. Currently, there is limited biomechanical data available involving Type II odontoid fractures for delineation of the relative contributions of bony and ligamentous structures to mechanical stability (McCabe et al., 2012). Evaluation of how individual soft-tissue structures in the upper cervical spine contribute to cervical stability may help to inform surgical decision-making. The purpose of the present study was to measure motion changes in a human cadaveric model of Type II odontoid fractures, and to quantify the contribution of ligamentous structures in the upper cervical spine. We hypothesized that the facet capsules are important for resistance to motion in axial rotation and that the anterior longitudinal ligament resists flexion-extension motion leading to destabilization of the C0–C2 joint following odontoid fracture.

2. Materials and methods

The Committee for Oversight of Research and Clinical Training Involving Decedents at our institution approved this study (CORID #694). Nine fresh frozen human cadaveric specimens of skull base to C2 were obtained (mean 56.2 ± 5.1 years old, 3 female and 5 male). Specimens were maintained at −20 °C until testing. Prior to preparation, specimens were placed in 4 °C cold room for 12 h to adequately thaw. Specimens were evaluated with plain radiographs and visual inspection to identify any underlying abnormalities. Dissection of subcutaneous tissue and muscle was performed with careful preservation of ligamentous attachments and joint structures. Hydration with 0.9% saline was performed prior to initial testing and between tests to prevent desiccation of specimen tissue throughout preparation and testing. Specimens were mounted to a testing station using polyaxial, titanium cervical pedicle/lateral mass screws (3.5 mm width, 14–18 mm length, DePuy Spine, Raynham, MA) with a custom fixation system (Fig. 1). Three pedicle screws were placed into the occiput/skull base to accommodate attachment to the robot manipulator arm. Three pedicle screws were inserted into C2 (two placed in standard intrapedicle location and one in the anterior inferior body). One pedicle screw was placed into the anterior arch of C1 for the purpose of motion tracking of that segment (Bell et al., 2018).

A six-axis serial linkage robotic manipulator (Staubli RX90; Staubli, Duncan, SC) was controlled using a hybrid-controlled algorithm, as previously described, to apply a pure moment to a set moment target (Bell et al., 2013; Gilbertson and Kang, 2000; Tian and Gilbertson, 2004). Loads were recorded using an on-board six-axis load cell (UFS Model 90M38A-150, JR3 Inc., Woodland, CA) located between the robotic end effector and the occipital fixture. Motion of each segment was tracked, using three markers in a triangular formation on a post directly attached to each spinal segment, and a five-camera infrared motion tracking system (VICON 460; VICON, Oxford, United Kingdom) recording at 40 Hz. The vertebral coordinate system for C1 and C2 was defined as the tip of the transverse processes bilaterally and the middle of the anterior arch or vertebral body anteriorly.

An Anderson-D'Alonzo Type II odontoid fracture was created at the base of the odontoid process by inserting a 2 mm drill bit lateral to the anterior longitudinal ligament (ALL), creating multiple bicortical drill paths, and completing the transverse fracture line using a 0.5 cm osteotome to minimize surrounding soft-tissue injury. Fracture was confirmed through direct visualization and manual manipulation. Specimens were randomly assigned to either initial unilateral facet capsule (UFC) removal or ALL transection. Soft tissue injury was completed by subsequent ALL or UFC transection, whichever was not performed previously (Table 1). All soft-tissue transections were performed at the C1-C2 junction to represent soft-tissue injury at the level of the fracture.

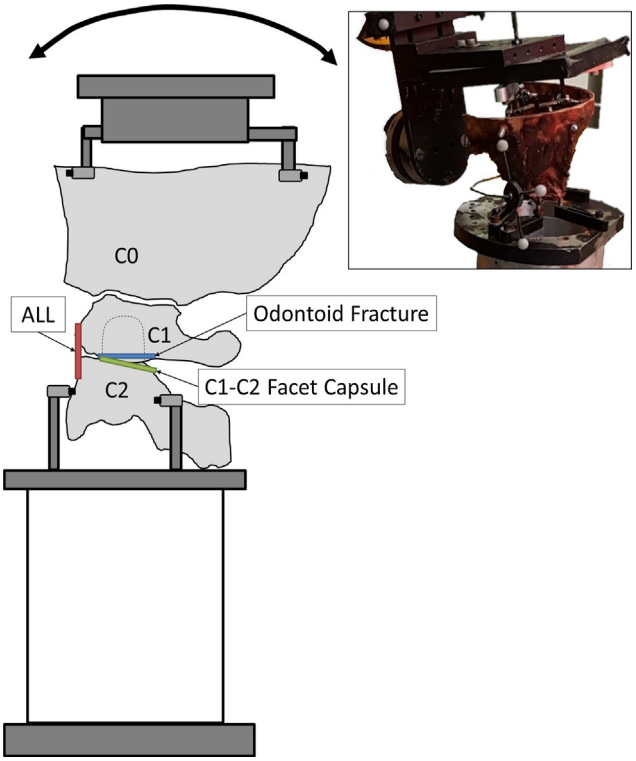

Fig. 1. Experimental system and custom specimen mounting using multiple polyaxial pedicle screws. Lines demonstrate experimental steps: Odontoid fracture site – blue, C1-C2 facet capsule – green, and anterior longitudinal ligament (ALL) transection – red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Specimens were tested under 10 N of vertical preload to maintain joint congruency. All specimens were subjected to quasi-static motion at approximately 10 s/degree to a pure moment target of 1.5 Nm for flexion–extension (FE) and lateral bending (LB), and to 0.75 Nm for axial rotation (AR) (Puttlitz et al., 2004; Wilke et al., 1998). For each motion, specimens underwent three cycles to reduce tissue memory effects. Subsequently, one cycle "replaying" the exact recorded motion path of the intact specimen was performed for each—FE, LB, and AR. The moment at maximal intact specimen motion (end point moment) was recorded to quantify the moment contribution of each structure during physiologic motions as previously described (Hartman et al., 2016).

VICON motion tracking was analyzed at end-point of each motion—FE, AR, and LB—at the end of the third cycle of motion. The position of each marker within space, at the maximum and minimum of each motion, was transformed to the vertebral coordinate system to determine vertebral movement. Motion at the C1-C2 joint in the anterior-posterior (AP) direction during physiologic motions was measured to estimate the clinical instability seen on flexion-extension radiographs. Clinically, odontoid displacement >4 mm has been associated with 88% rate of odontoid non-union with non-operative management (Apuzzo et al., 1978) and surgery is indicated in patients with >4 mm of AP odontoid translation (Iyer et al., 2018).

Table 1
Experimental testing protocol and data acquired for each state of the specimen.

Specimen State	Loading Conditions	Data Acquired
Intact	Flexion-extension (FE), Lateral bending (LB), Axial rotation (AR)	Kinematics of intact C0-C2 (a)
Odontoid Fracture	FE, LB, AR Replay (a)	In situ force seen by odontoid and attachments
Transection #1	FE, LB,	In situ force in ALL or UFC
Anterior longitudinal ligament (ALL) - OR - C1/C2 unilateral facet capsule (UFC)	AR Replay (a)	
Transection #2	FE, LB,	In situ force in ALL or UFC
UFC - OR - ALL	AR Replay (a)	

Within each group, normality was assessed using the Shapiro-Wilk test and paired t-tests/Wilcoxon signed rank were employed accordingly with significance set at $p < 0.05$. Statistical tests were performed on the change in rotation and moment values from one state to the next, defined as the delta value. Inter-group statistical comparisons assumed equal mean/median delta rotation between the two groups and were used to compare the change with UFC or ALL transection to determine if the specimen delta values could be analyzed together due to the law of linear superposition. Intra-group comparisons compared delta values of each state to zero to assess the contribution of the cut structure to overall joint kinematics in each direction—FE, LB, and AR. All values are presented as mean (95% confidence interval) unless otherwise noted.

3. Results

Prior to initial testing, one specimen was found to have significant osteophyte formation at the left C1-C2 facet joint and asymmetry of the C2 vertebral body and was excluded from testing. All other specimens were found to be free of obvious bony pathology and eight specimens completed testing through all motions.

3.1. Inter-group analysis

Inter-group comparison showed no difference in combined injury if ALL or UFC were resected first, except for the flexion-extension state for the specimen kinematics ($p = 0.02$). This allowed for combined analysis of all specimens' delta values for the odontoid fracture, UFC, and ALL interventions except in flexion-extension, which was analyzed as two separate groups.

3.2. Occiput-C2 rotational motion

Baseline range of motion (ROM) for the C0-C2 joint was measured at the robotic end-effector. Average ROM for FE was 47.4° [range 36.8° to 58.9°], LB 12.6° [range 6.3° to 16.8°], and AR 65.8° [range 53.5° to 78.0°].

Fracture of the odontoid significantly increased motion in all directions (Fig. 2a); FE by 8.6° (5.0°–12.2°, $p = 0.003$), LB by 4.4° (2.9°–5.8°, $p = 0.001$), and AR by 5.5° (0.51°–10.5°, $p = 0.03$). Despite the intra-group comparison showing differences in motion after odontoid fracture, both groups analyzed separately reached significance for increased motion following odontoid fracture compared to the intact state. Transection of the ALL did not

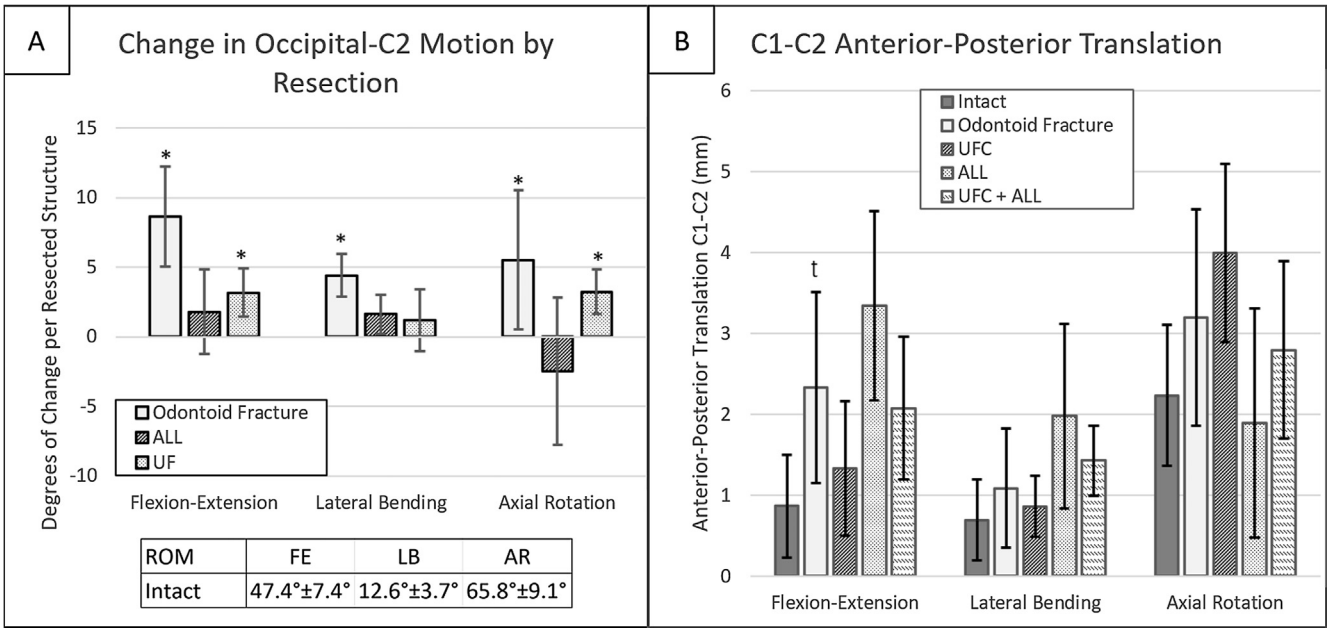

Fig. 2. Range of motion data for (A) change in Occiput-C2 motion for FE, AR, and LB by resection state and (B) anterior-posterior translation of C1 on C2 during primary motions normalized to the intact state of each specimen. (Mean ± 95% confidence interval). Abbreviations: UFC (unilateral facet capsule), ALL (anterior longitudinal ligament). t – $p < 0.05$ significant difference compared to intact state. * - $p < 0.05$ significant difference compared to zero degree change.

significantly increase motion in any direction, but LB trended towards a significant increase (p = 0.07). UFC injury significantly increased motion in AR by 3.2° (1.7°–4.8°, p = 0.007) and in FE by 3.2° (1.4°–4.9°. p = 0.01), but did not significantly affect LB.

3.3. C1-C2 motion

Motion at the C1-C2 joint in the anterior-posterior (AP) direction during physiologic motions (FE, AR, and LB) was measured to estimate the clinical instability seen on flexion radiographs used to assess clinical instability (Fig. 2b). AP motion at the C1-C2 level was 0.9 mm (0.3 mm–1.5 mm) in the intact specimen and increased significant with odontoid fracture to 2.3 mm (1.1 mm-3.5 mm, p = 0.006). Further resection of the ALL and UFC did not increase anterior motion of C1 on C2 during flexion. Anterior motion of the C1-C2 joint did not change significantly with AR or LB with odontoid fracture or subsequent soft-tissue resection.

3.3.1. End point moment

The resistance to rotation, as measured compared with the intact specimen, decreased at each stage of resection (Fig. 3a). Following fracture of the odontoid, the end point moment decreased by 37% (17.2–56.7%, p < 0.01) in flexion, 45% (33.3–56.6%, p < 0.01) in extension, and 71% (62.4–81.5%, p < 0.01) in LB compared with intact specimen loading mechanics. The odontoid represented the primary stabilizer in each of these motions (Fig. 3b). During intact replay, following odontoid fracture the moment at intact end-motion reduced by 31% (18.0–45.0%, p < 0.01) in AR, making the odontoid the secondary stabilizer. Resection of the UFC was significant for decreased moment in flexion, 19.0%

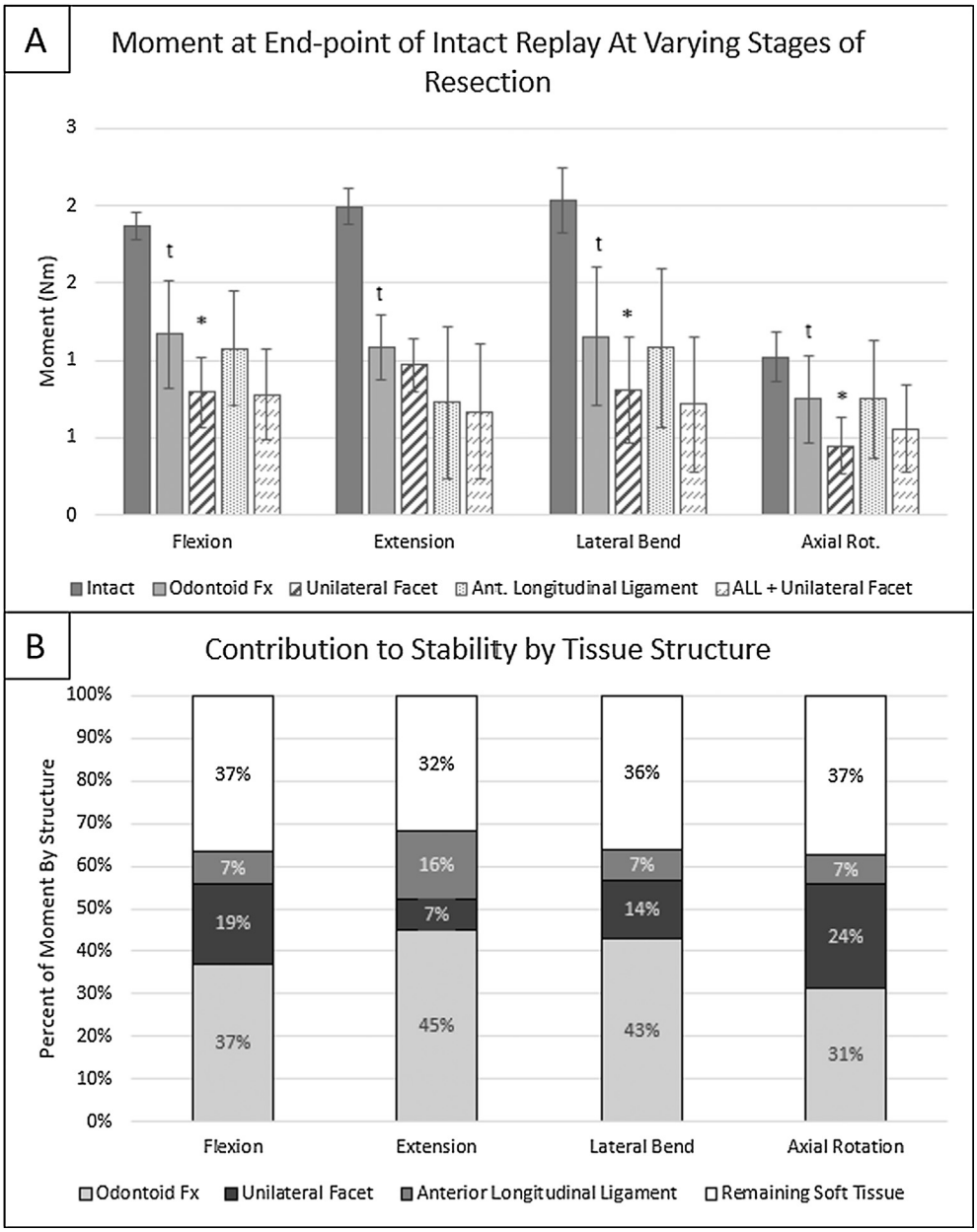

Fig. 3. Decrease in end-point moment measured during intact motion replay. (A) Mean motion at intact replay ± 95% confidence interval. Abbreviations: ALL (anterior longitudinal ligament). (B) Relative contribution of each tested upper cervical spine structure to resistance of motion during flexion, extension, lateral bending, and axial rotation. t – p < 0.05 significant difference compared to intact state. * - p < 0.05 difference compared to odontoid fracture state.

(6.9–31.1%, $p < 0.01$), and AR, 24.3% (8.9–39.6%, $p = 0.03$). No other soft tissue resection decreased the end point moment of the specimen in a statistically significant manner.

4. Discussion

Fractures of the odontoid process represent a frequent traumatic occurrence for which treatment options remain controversial in the surgical literature, especially for the elderly (Chapman et al., 2013). This study aimed to determine the contributions of supporting ligamentous and capsular tissue towards overall stability in the atlantoaxial spine in a simulated Type II odontoid fracture model. We demonstrated significant increases in ROM and end point moment decreased significantly after UFC injury for both AR and FE. Further analysis showed that the UFC contributes 19% of flexion and 24% of AR end point moment in normal motion.

Clinical decision-making regarding the treatment of odontoid fractures in the elderly can be difficult. The Anderson and D'Alonzo system, while useful in stratifying patients based upon the location of the fracture line, speaks little to the associated ligamentous injuries that contribute to instability. Operative versus non-operative management of Type II odontoid fractures is a moving target, with a steady increase in the proportion treated operatively over the last 20 years (Smith et al., 2008). Improved long-term mortality outcomes have been observed with operative management, however short-term morbidity remains higher in the operative management group (Smith et al., 2008; Woods et al., 2014).

The key supporting ligamentous structures to C1-C2 articulation are the ALL, facet capsules, the alar ligaments, and the posterior longitudinal ligament as it transitions to the tectorial membrane. Prior biomechanical studies in the upper cervical spine have focused on failure of the C0-C2 cervical segments in FE (Nightingale et al., 2007) and AR (Goel et al., 1990) as it relates to traffic safety and biomechanical modeling. Total odontoidectomy was shown to increased FE ROM by 40% (Puttlitz et al., 2004), but the individual contributions of the surrounding ligamentous structures in physiologic motions are largely unclear. McCabe et al. (2012) previously studied the biomechanical role of upper cervical ligaments in AR and anterior translation only, and showed that the C1-C2 facet capsules and ALL do contribute to a significant increase in AR of the upper spine following Type II odontoid fracture, but were unable to quantify restraint provided by these structures during other physiologic motions. Similarly, our study demonstrates that the facet capsules, even with unilateral injury, increase atlantoaxial AR. This study shows that there is increased FE, and we were able to quantify the resistance to motion provided by the ALL and the UFC in the upper cervical spine complex, which will provide mechanical data for future biomechanical modeling of the upper cervical spine. C1-C2 AP translation, used to assess the risk of symptomatic non-union clinically, did not show a significant change with further soft tissue injury after odontoid fracture. This conclusion may support the potential for attempted non-operative management of Type II odontoid fractures that do not have significant soft-tissue compromise or retropulsion of the odontoid fragment.

Several limitations of this study have been identified. The use of human cadaveric specimens is limited by the quality of specimens obtained. Specimens were visually inspected and freeze-thaw cycles were minimized to decreased tissue damage and desiccation, but intrinsic damage to the specimens could not be ruled out. The testing protocol developed for this study utilized mounting the specimens at the skull base and at C2. By rigidly fixing the body of C2, we hoped to observe motion only at the C1-2 and occiput-C1 articulations. This was performed to eliminate the contributions of motion from the caudal cervical vertebrae; however, this is not entirely representative of cervical spine motion *in vivo*. Simulated fracture of the odontoid process and injury to targeted ligaments was performed in the most minimally invasive and easily reproducible manner possible. In doing this, however, these injuries may not represent identical models of the *in vivo* trauma where sharper fracture lines and more ligamentous and soft tissue shredding may be present.

Bracing using a rigid cervical collar is a typical non-operative management for Type II odontoid fractures, future work may be needed to evaluate if bracing alone adequately replicates the biomechanical losses seen with osseous and soft tissue damage in the upper cervical spine. Future mechanical studies are needed to assess the success of various operative interventions such as anterior retrograde fixation, posterior retrograde fixation, and C1-C2 fusion in regaining stability in Type II odontoid fracture models with various ligamentous injuries. Clinical studies using imaging findings of ligamentous injury are also needed to validate the findings of our study.

This study aimed to identify the alteration in the mechanical environment of the upper cervical spine in the setting of a Type II odontoid fracture with concomitant ligamentous injuries to guide clinical decision-making. Our findings suggest that UFC rupture following a Type II odontoid fracture greatly influences the motion and mechanical stability of the occipitoatlantoaxial complex. The odontoid fracture itself creates the greatest change in stability in all motions. We demonstrated that soft tissue injury concurrently with odontoid fracture led to significant increases in range of motion and decrease in end point moment after UFC injury for both AR and FE. Further analysis showed that the UFC contributes 19% of flexion and 24% of AR end point moment in normal motion. Studies have cited magnetic resonance imaging (MRI) as having a high sensitivity and specificity for identifying ligamentous injuries in the cervical spine (Vaccaro et al., 2001). Clinically, this may guide surgeons towards surgical intervention if UFC ligamentous injuries are present on imaging studies.

In conclusion, the present biomechanical study demonstrates that fracture of the odontoid process significantly destabilizes the upper cervical spine, but subsequent injury to the ALL does not significantly increased range of motion or resistance to motion. Additionally, the facet capsule acts as an important secondary stabilizer, which may be of clinical importance for surgical decision-making.

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Conflict of interest

No authors have any conflicts of interest to disclose.

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