Neck Injury Risk in Out-of-Position Rear Impact Scenarios Using a Reference Geometry-Based Head Repositioning

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ABSTRACT

Rear-end vehicle collisions may lead to whiplash-associated disorders (WADs), comprising a variety of neck and head pain responses. Specifically, increased axial head rotation has been associated with the risk of injuries during rear impacts, while specific tissues, including the capsular ligaments, have been implicated in pain response. Given the limited experimental data for out-of-position rear impact scenarios, computational human body models (HBMs) can inform the potential for tissue-level injury. Previous studies have considered external boundary conditions to reposition the head axially but were limited in reproducing a biofidelic movement. The objectives of this study were to implement a novel head repositioning method to achieve targeted axial rotations and evaluate the tissue-level response for a rear impact condition. The repositioning method used reference geometries to rotate the head to three target positions, showing good correspondence to reported interverbal rotations. Under a 7g rear impact scenario, the head-turned models were compared with the neutral position and demonstrated increases in the maximum capsular ligament distractions. Increased head rotation was associated with increased ligament distractions. The locations with critical ligament distractions shifted to the lower cervical spine (below C3) and lateral portion of the capsular ligaments for the head-turned position cases. The proposed repositioning method introduced in this study enabled the model to achieve steady head rotations with realistic cervical spine movements, increasing the biofidelity of out-of-position rear impact simulations.

INTRODUCTION

Rear-end vehicle collisions can lead to whiplash-associated disorders (WADs), which are generally non-fatal but cause a variety of prolonged neck and head pain responses (Haldorsen et al., 2003). Among possible sources of pain response, the distraction of facet joint ligaments has been widely investigated and can exceed sub-catastrophic failure thresholds for different rear impact severities (Cronin, 2014; Pearson et al., 2004). Head position has been reported to affect the risk of WADs during vehicle crashes (Jakobsson, 2004), with axial rotation accounting for the most frequent non-neutral position during travel time (Reed et al., 2020). In-car pilot studies observed that drivers spent 13.0% of the time outside the neutral head position with average peak

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angles of 35.7° (SD 14.2°) and 42.5° (SD 18.0°) for left and right cervical axial rotation (Shugg et al., 2011). These non-neutral positions generate complex spine rotations during rear impact scenarios, potentially resulting in multiplanar cervical spine injuries (Panjabi et al., 2006).

Considering the limited experiments for non-neutral position rear impact scenarios, numerical human body models (HBMs) can inform the potential for tissue-level response and injury risk. Although human neck rotations are achieved using muscle activation, reproducing axial rotation in a finite element model is a complex task. Due to insufficient data for defining realistic activation levels for the muscles, several authors have considered alternative head repositioning methods, such as external rotation boundary conditions. Storvik and Stemper (2011) simulated the head-turning of a cervical spine model by applying an axial rotation between the C1 and C2 vertebrae. Results showed an increase in ligament strain for the head-rotated models under rear impact conditions, but the method generated unrealistic intervertebral rotations. Alternatively, Shateri and Cronin (2015) modelled an out-of-position impact by prescribing an axial head rotation around the occipital condyle, improving the cervical spine motion representation. The study confirmed the increase in ligament distractions for non-neutral position impacts but did not consider the contribution of musculature and other neck soft tissues. In addition, imposing a rotation for a specific model part constrains its movement, affecting the head kinematics during the impact scenario. Therefore, numerical studies have been limited in achieving a static head and neck non-neutral position with biofidelic intervertebral movements for a detailed HBM.

The head and neck model used in this study was extracted from version 6.0 of the Global Human Body Models Consortium (GHBMC) detailed occupant model (M50-O), representing an average-stature (50th percentile) male with a detailed neck model (Barker & Cronin, 2021). The head-forward model, created to analyze crash-induced injuries, had its gross kinematics and tissue-level responses validated in multiple frontal, lateral, rear (Barker & Cronin, 2021), and oblique (Barker & Cronin, 2022) impact conditions. The objectives of the current study were to implement a novel head repositioning method using reference geometry to achieve biofidelic target head rotations and simulate out-of-position rear impact scenarios to assess tissue-level response and the potential for neck injury.

METHODS

Implementation of a Novel Head Repositioning Method

A new iterative method for repositioning the head in axial rotation was developed to simulate out-of-position rear impacts, so the model was required to stabilize and achieve equilibrium in a target head-rotated position. In addition, it was desirable to retain stresses and strains occurring in the model due to the head rotation as it was hypothesized that pre-stretch of tissues could contribute to injury. Based on these requirements, a repositioning method using reference geometries was proposed to pre-stretch the neck soft tissues (passive muscle, adipose tissue, and skin) and achieve an equilibrium position that would generate a target head rotation.

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The repositioning method was divided into two stages: prescribing an axial head rotation to define reference nodal positions and pre-stretching the soft tissues to reposition the head. In Stage 1, an axial rotation was prescribed to the skull to achieve a head rotation greater than the target and obtain the nodal positions of the soft tissues. In Stage 2, the model was initialized from a neutral position with the previously calculated reference nodal positions, causing the head and neck model to axially rotate and achieve equilibrium while generating deformations in the soft tissues. To ensure a smooth movement in this stage, two auxiliary configurations were defined for the initial 100 ms. A skull rotation was prescribed to enable the head to converge to the target position, and damping was applied to the model to reduce oscillations during repositioning. The soft tissues interacted with other neck parts, such as vertebrae and ligaments, that did not have their stresses initialized so the model would reach an equilibrium between the neutral position and the prescribed rotation. The method was iterative as several axial head rotations needed to be prescribed in Stage 1 to obtain the desired axial rotation in Stage 2. Figure 1 illustrates the two stages of the reference geometry-based head repositioning.

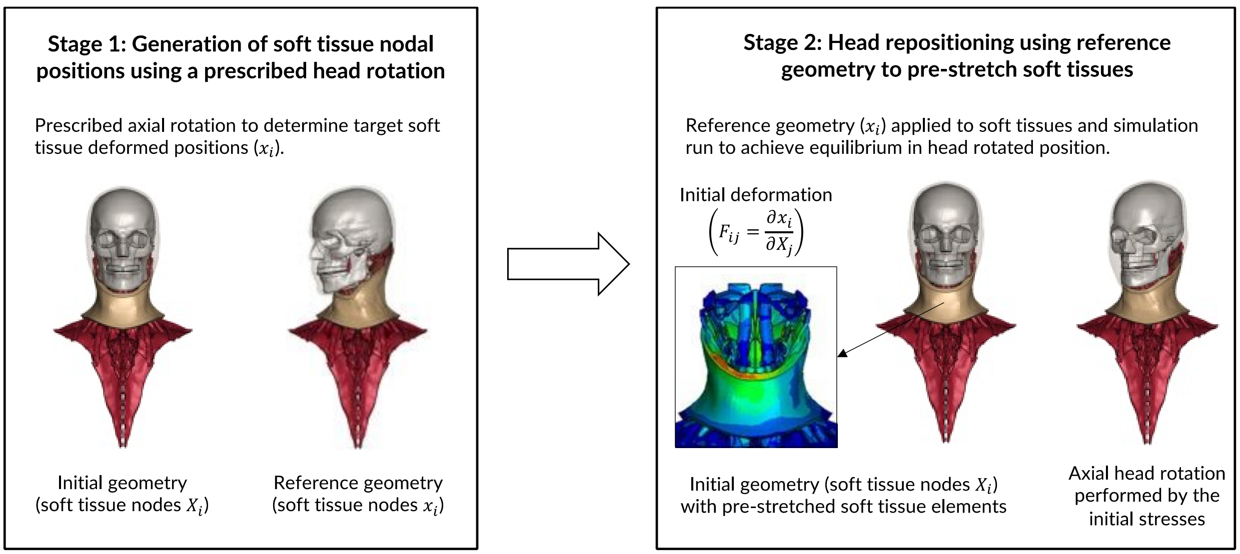

Figure 1: Implementation of the reference geometry-based head repositioning: prescribed skull rotation (Stage 1) and model repositioning to an equilibrium position resulting in soft tissue pre-stretching (Stage 2).

The right cervical average peak angle (42.5°) and the standard deviation (18.0°) from pilot measurements (Shugg et al., 2011) were used to define the three target axial rotations of 24.5°, 42.5°, and 60.5°. This division allowed for a sensitivity study between several rotations based on mean peak angles measured in real life. To guarantee that the equilibrium position was reached, the axial rotation, lateral bending, and flexion of the skull were monitored over time. A stabilization criterion of 5% of the target value for each head-T1 rotation (roll, pitch, and yaw) was used to define whether the model converged. To validate the axial repositioning method, a specific case was simulated with a target rotation of 53.3°. The spinal kinematics of the head-rotated model were compared with experimental data from an intact human cervical spine (Ivancic, 2013), which reported rotations for each intervertebral level. The set of experiments included right head axial rotation, resulting in an average range of motion between the head and T1 of 53.3° (SD 14.2°) for the unrestricted case. The cervical spine rotations of the model were calculated using Euler angles, the same approach used in the experiment, and the final axial rotation of each intervertebral level was compared with the measured values.

Injury Assessment of Neutral and Non-Neutral Position Models in Rear Impact Scenario

After completing previous verifications, the head-rotated models were simulated in a 7g rear impact scenario. The T1 kinematics in the sagittal plane, consisting of two translational (anterior and superior) and one rotational (lateral) profiles, were based on a cadaveric study (Deng, 1999) and applied to the neutral and repositioned models (axial head rotations of 0°, 24.5°, 42.5°, and 60.5°). The capsular ligament distractions, a potential source of pain response, were monitored during the impact. For the GHBMC M50-O v6.0, the capsular ligaments were represented as 1D discrete beam elements and described by non-linear force-displacement curves with strain rate effects defined from tensile tests (Mattucci et al., 2012, 2013). The injury evaluation was performed by comparing the maximum capsular ligament displacements for each intervertebral level with their measured response regions.

RESULTS

Verification of the Head Repositioning Models

The three head and neck models achieved the target head-T1 axial rotations of 25.6°, 43.0°, and 60.5° with maximum variations of 0.5° (2.0%), 0.5° (1.2%), and 0.6° (1.0%), respectively (Figure 2a). The simulation time required to achieve equilibrium was 150 ms. The lateral bending and flexion profiles indicated equilibrium for the same stabilization time, which was used to offset the T1 impact boundary conditions for the non-neutral position models. For validation, the target axial rotation of 53.5° was achieved at a level of 51.4°. The intervertebral measurements for the model with a 51.4° head rotation generally agreed with the reported ranges of motion for the experimental axial rotation of 53.5° (Figure 2b). C1-C2 and all intervertebral levels between C3 and C7 had axial rotations similar to the experimental values for a right axial head rotation. In contrast, C7-T1 showed the highest difference compared to the experimental range, being overpredicted by 3.5°. C0-C1 and C2-C3 rotations were also outside the measured ranges of motion with values of 0.9° and 0.4° below the lower measured boundary.

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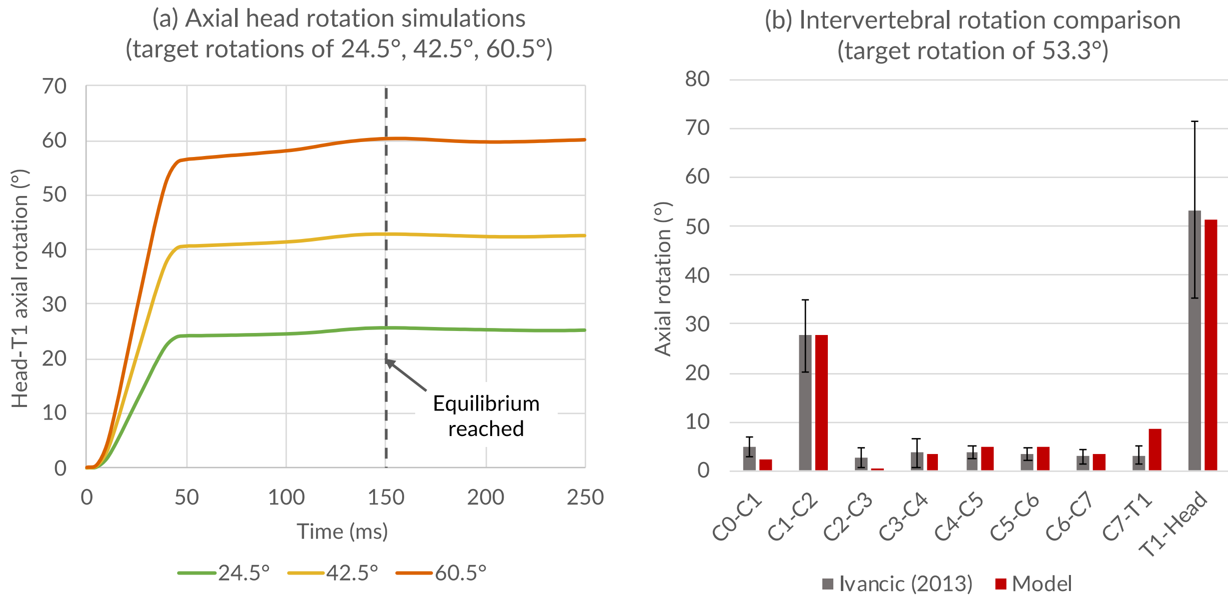

Figure 2: Verification of the reference geometry-based head repositioning: axial head rotation simulation (a) and intervertebral kinematics assessment (b).

Influence of Head Positioning in Rear Impact Scenario

The maximum capsular ligament displacements experienced during the impact were compared for the four cases (Figure 3). As a general trend, the ligament distractions were substantially affected by head position and showed increasing values for higher rotations. The 60.5° head-rotated impact experienced the highest ligament distractions, entering their traumatic region for three levels (C1-C2, C3-C4 and C5-C6) and being close to the linear limit for other three levels (below C4). In contrast, the neutral position case had the lowest capsular ligament displacements with maximum values entering the linear region. The models with head rotations of 24.5° and 42.5° had maximum distractions between the previous two cases, without any capsular ligament in the sub-failure region. The axial head repositioning also changed the location of these critical ligaments due to the asymmetry added. While the neutral position model experienced capsular ligaments with peak displacements on the frontal and lateral parts, the repositioned cases had a concentration of critical ligaments in the right portion of the facet joints.

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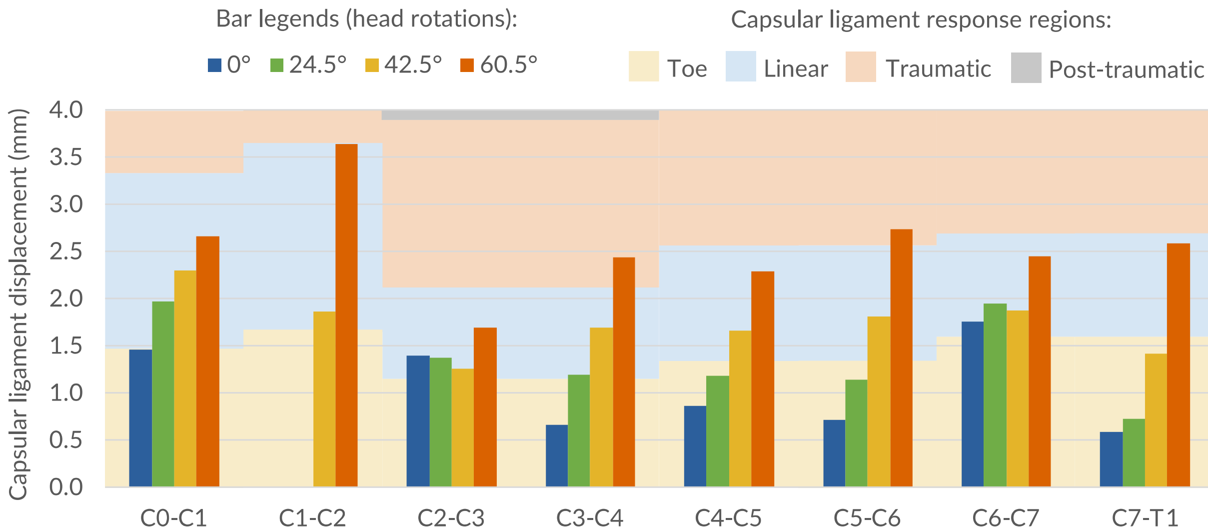

Figure 3: Maximum capsular ligament displacements during a 7g rear impact scenario compared with the response regions (Mattucci et al., 2012, 2013) for each ligament.

Increasing head rotation showed a transition in the critical distraction regions from the upper to the lower cervical spine. For higher head rotations, the capsular ligaments below C3 became more relevant to the evaluation, with elevated displacements that could lead to pain response. The exception was the C1-C2 ligaments that demonstrated a high sensitivity to head position, entering the traumatic zone for a head rotation of 60.5°. Further, large head rotations led to elevated distractions after repositioning, reducing the additional effect caused by the impact. The head-rotated models had increases of up to 1.45 mm (24.5°), 1.10 mm (42.5°), and 0.65 mm (60.5°) in the maximum capsular ligament displacement during the impact when compared to the moment after repositioning. For the 60.5° head rotation, the ligaments under C5 experienced maximum distractions immediately after the repositioning.

DISCUSSION

The novel repositioning method allowed the head to converge to the axial target rotations, retaining the stresses in the neck tissues for the subsequent impact scenario. Compared to experimental data (Ivancic, 2013), most intervertebral levels showed rotations close to the measured ranges of motion for a 51.4° head rotation. The level that contributed the most to the head axial movement, C1-C2, had approximately the same rotation as the experimental average, with a relative difference of 1.8%. In contrast, C7-T1 axial rotation, 8.6°, was considerably higher than the measured value, 3.3°. This difference can be explained by the constraint of the soft tissues in the thoracic region, which were not present in the head and neck model. Consequently, the evaluation of C7-T1 capsular ligaments may have been affected by the additional displacement added prior to the impact condition.

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The influence of head position on a rear impact scenario was assessed by evaluating the capsular ligament displacements, and the study demonstrated that higher distractions were experienced with increasing axial head rotation. This trend was in agreement with in-vitro tests in cervical spine motion segments that observed significant increases in the facet capsule strains for non-neutral head posture rear impacts (Siegmund et al., 2008). The intervertebral levels and facet joint regions that had elevated displacements also corresponded well with experimental data. For a similar rear impact severity of 8g, Panjabi et al. (2006) verified a significant increase in three-plane injury potentials for the lower cervical spine levels (below C3) when the head was rotated. The capsular ligament responses confirmed this behavior by showing that these same regions had the highest sensitivity to head rotation. Regarding the critical location of the facet joint, Siegmund et al. (2008) found that turning the head during rear impact increased the capsular ligament strains further on the side toward the cervical rotation. For the right axial head rotation, the model successfully predicted higher ligament distractions in the right portion of the facet joints.

In terms of injury potential, none of the cases had capsular ligaments entering the post-traumatic region, where the tissue experiences catastrophic failure. However, microlesions could potentially occur for a head rotation of 60.5° as three intervertebral levels had ligaments entering the traumatic region. Other levels also had ligaments reaching the end of the linear region, where the pain threshold was reportedly located (Lu et al., 2005). While the other head-rotated cases had higher ligament displacements than the neutral position case, neither represented a risk of tissue failure or pain response. These results showed that a 7g rear impact severity was sufficient to generate injurious ligament outcomes when the occupant experienced an elevated head rotation. Therefore, the reference geometry-based repositioning resulted in a realistic head rotation and, consequently, a biofidelic evaluation of injury risk in head-rotated rear impacts.

Limitations

While most intervertebral levels rotated according to the expected range of motion after repositioning, the model under and overpredicted C2-C3 and C7-T1 kinematics, respectively. This may have affected the capsular ligament distractions before the impact in those two regions. In addition, the proposed repositioning method was appropriate to simulate the hyperextension phase of out-of-position rear impacts but was limited to modelling the rebound phase. The soft tissue deformation leading to the axial reposition of the head was maintained throughout the simulation, so the head could not return to the neutral position after the impact. Finally, the model with a 60.5° head rotation had a few capsular ligaments experiencing large deformations after repositioning. The repositioning method may be limited to simulate some intervertebral movements for the highest target rotation due to the unphysical position used to obtain the reference nodes. The simplified ligament model based only on the tensile response also contributed to an inappropriate representation of complex modes of loading experienced from this elevated head rotation.

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CONCLUSIONS

The proposed repositioning method was able to rotate the head to three target positions with a reduced stabilization time and good agreement with the measured intervertebral axial ranges of motion. The rear impact simulations showed higher capsular ligament displacements with increasing head rotations and a transition of critical ligaments to the lower cervical spine. Among the three positions, the 60.5-deg head-rotated model had the most severe response with the highest ligament distractions in the lower cervical spinal capsular ligaments.

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REFERENCES

Barker, J. B., & Cronin, D. S. (2021). Multilevel Validation of a Male Neck Finite Element Model with Active Musculature. *Journal of Biomechanical Engineering*, *143*(1). https://doi.org/10.1115/1.4047866

Barker, J., & Cronin, D. S. (2022). Muscle Activation Affects Kinematic Response and Injury Risk in Non-Traditional Oblique Impact Scenarios Assessed with a Head and Neck Finite Element Model. *SAE International Journal of Transportation Safety*, *10*(2), 135–162. https://doi.org/10.4271/09-10-02-0008

Cronin, D. S. (2014). Finite element modeling of potential cervical spine pain sources in neutral position low speed rear impact. *Journal of the Mechanical Behavior of Biomedical Materials*, *33*(1), 55–66. https://doi.org/10.1016/j.jmbbm.2013.01.006

Deng, B. (1999). *Kinematics of Human Cadaver Cervical Spine during Low Speed Rear End Impacts*. Wayne State University, Detroit, MI.

Haldorsen, T., Waterloo, K., Dahl, A., Mellgren, S. I., Davidsen, P. E., & Molin, P. K. (2003). Symptoms and cognitive dysfunction in patients with the late whiplash syndrome. *Applied Neuropsychology*, *10*(3). https://doi.org/10.1207/S15324826AN1003_06

Ivancic, P. C. (2013). Effects of orthoses on three-dimensional load-displacement properties of the cervical spine. *European Spine Journal*, *22*(1), 169–177. https://doi.org/10.1007/s00586-012-2552-0

Jakobsson, L. (2004). Field analysis of AIS1 neck injuries in rear-end car impacts - Injury reducing effect of the WHIPS seat. *Journal of Whiplash and Related Disorders*, *3*(2), 37–53. https://doi.org/10.1300/J180v03n02_04

Lu, Y., Chen, C., Kallakuri, S., Patwardhan, A., & Cavanaugh, J. M. (2005). Neurophysiological and biomechanical characterization of goat cervical facet joint capsules. *Journal of*

Orthopaedic Research, *23*(4), 779–787. https://doi.org/10.1016/j.orthres.2005.01.002

Mattucci, S. F. E., Moulton, J. A., Chandrashekar, N., & Cronin, D. S. (2012). Strain rate dependent properties of younger human cervical spine ligaments. *Journal of the Mechanical Behavior of Biomedical Materials*, *10*, 216–226. https://doi.org/10.1016/j.jmbbm.2012.02.004

Mattucci, S. F. E., Moulton, J. A., Chandrashekar, N., & Cronin, D. S. (2013). Strain rate dependent properties of human craniovertebral ligaments. *Journal of the Mechanical Behavior of Biomedical Materials*, *23*, 71–79. https://doi.org/10.1016/j.jmbbm.2013.04.005

Panjabi, M. M., Ivancic, P. C., Tominaga, Y., & Malcolmson, G. F. (2006). Predicting multiplanar cervical spine injury due to head-turned rear impacts using IV-NIC. *Traffic Injury Prevention*, *7*(3), 264–275. https://doi.org/10.1080/15389580500488499

Pearson, A. M., Ivancic, P. C., Ito, S., & Panjabi, M. M. (2004). Facet Joint Kinematics and Injury Mechanisms during Simulated Whiplash. *Spine*, *29*(4), 390–397. https://doi.org/10.1097/01.BRS.0000090836.50508.F7

Reed, M., Ebert, S., & Jones, M. (2020). *Naturalistic Passenger Behavior: Postures and Activities* (Issue February).

Shateri, H., & Cronin, D. S. (2015). Out-of-Position Rear Impact Tissue-Level Investigation Using Detailed Finite Element Neck Model. *Traffic Injury Prevention*, *16*(7), 698–708. https://doi.org/10.1080/15389588.2014.1003551

Shugg, J. A. J., Jackson, C. D., & Dickey, J. P. (2011). Cervical spine rotation and range of motion: Pilot measurements during driving. *Traffic Injury Prevention*, *12*(1), 82–87. https://doi.org/10.1080/15389588.2010.529973

Siegmund, G. P., Davis, M. B., Quinn, K. P., Hines, E., Myers, B. S., Ejima, S., Ono, K., Kamiji, K., Yasuki, T., & Winkelstein, B. A. (2008). Head-turned postures increase the risk of cervical facet capsule injury during whiplash. *Spine*, *33*(15), 1643–1649. https://doi.org/10.1097/BRS.0b013e31817b5bcf

Storvik, S. G., & Stemper, B. D. (2011). Axial head rotation increases facet joint capsular ligament strains in automotive rear impact. *Medical and Biological Engineering and Computing*, *49*(2), 153–161. https://doi.org/10.1007/s11517-010-0682-2

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