ARAI Journal of Mobility Technology
Volume 2 • Issue 2 • April–June, 2022, pp. 169-174
Research Paper
https://doi.org/10.37285/ajmt.1.2.1

Bilateral Facet Dislocations With and Without Head Impact Sustained by Restrained Occupants

Chandrashekhar K. Thorbole

Thorbole Simulation Technologies, LLC, 2524 Horizon Blvd. Rogers, Arkansas - 72758, USA

ABSTRACT

This paper aims to understand the different injury mechanism involved with traumatic Bilateral Facet Dislocation (BFD) and fracture of the cervical spine. The intent is to demonstrate and elucidate tensile and compression induced injury mechanisms producing BFD by employing real-world crash investigations in association with all the past laboratory testing and studies done by numerous researchers. The study indicates that in a frontal crash scenario, maintaining the position of the shoulder belt is paramount, and any migration towards the base of the neck allows the fulcrum formation that amplifies distractive moments on the neck producing BFD. Similarly, in a rollover crash scenario, roof intrusion magnitude, and its rate along with roof deformation pattern can impose a rotational constraint on the head and plays a vital role in producing BFD. Roof design must address the formation of pocketing in the roof due to deformations imposing rotational head constraint exposing neck to buckling and subsequent BFD as the roof intrusion continues.

KEYWORDS: Frontal crash scenario, Human cervical spine, Bilateral Facet Dislocation (BFD), Head impact, Rollover crash scenario, Zygapophysial joints, Neural arch, Safety.

Introduction

The human cervical spine consists of seven vertebrae interconnected by articulating joints and tissues supporting the human head. Facet joints, also known as Zygapophysial joints, can be best visualized from the side laterally. The neural arch (dorsal part) of typical vertebrae supports seven processes: four articular processes, two transverse processes, and one spinous process. The superior and inferior articular process on each side forms an articular pillar. The articulating joints between these pillars are called facet joints. The articulating surfaces of these pillars are at an angle steeper in the upper region than in the lower region. Figure 1 shows the side view of the cervical spine highlighting the facets joints and pillars, forming articulating joints of the cervical spine.

The facet dislocation injury pattern typically involves upper superior vertebral body displacement relative to the inferior vertebral body, mostly in the forward direction. The anterior displacement disrupts ligaments and locking of facet surfaces, significantly reducing the spinal canal's anteroposterior diameter. Figure 2 shows the schematics of facet dislocation at the C5-C6 level that compares normal with the dislocated condition. Facet dislocation with fracture mainly of the facet or lamina is termed as Facet fracture-dislocation. The dislocation injury produces devastating outcomes due to sever dynamic cord compression at the instant of dislocation injury. Figure 3 shows the schematics of cord injury due to facet dislocation. This paper focuses on neck injuries involving spinal cord mainly produced by facet dislocations with or without fracture. The vehicle kinematics and structural deformations govern the restrained occupant kinematics during a collision. Furthermore, the head and neck kinematics of a restrained occupant is modulated by several factors such as crash type, restraint performance, and compartment intrusions. This paper describes real-world frontal and rollover crashes to elucidate the role of head and neck kinematics with and without compartment intrusion in producing BFD at C5-C6 level inducing spinal cord injury. Mechanistic classification by Allen Jr et al. [1] for the lower cervical spine injury and dislocation is based on the mechanism of injuries such as compression-flexion, vertical compression, distractive-flexion, and other combinations.

The motivation of this paper is to demonstrate using real-world frontal and rollover crash about the production of BFD injury with different injury mechanism. In doing so, the study will demonstrate the concomitant injuries that accompany the BFD injury mechanism and facilitate differentiating the injury mechanism producing similar C5-C6 BFD injury patterns.

ABBREVIATIONS: BFD - Bilateral Facet Dislocation; GCS - Glasgow Coma Scale; CT - Computerized Tomography; MRI - Magnetic Resonance Imaging; EMS - Emergency Medical Services; A.S.I. S - Anterior Superior Iliac Spine

Fig. 1. Schematic of cervical spine from side showing facet joints and pillars.

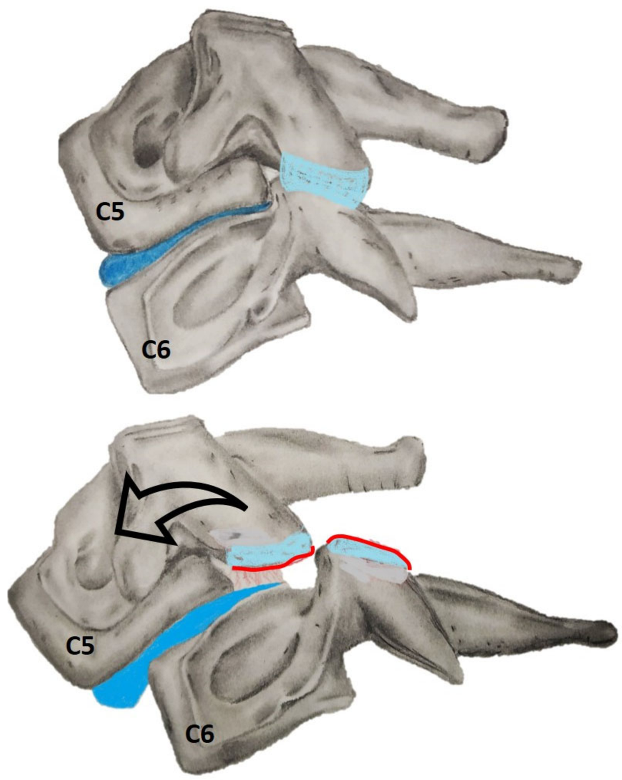

Fig. 2. Schematics of Facet dislocation at C5-C6.

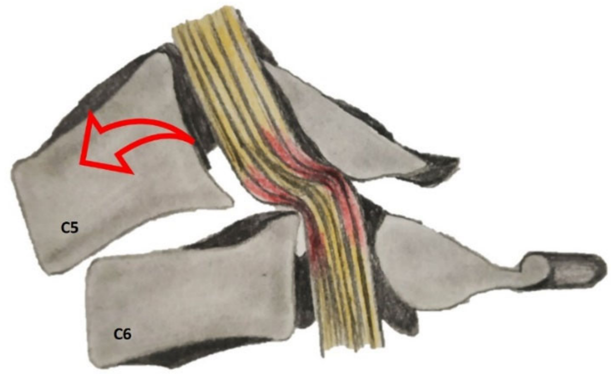

Fig. 3. Schematics of cord injury due to canal narrowing at the instant of dislocation.

Method

In this study, the field crash investigations conducted by the author on the selected matter are presented to elucidate more on facet dislocation and fracture injury mechanism under different loading conditions. The selected case matter involved a frontal and a rollover crash. The case selection criteria for the frontal crash involved the following.

1. Presence of cervical cord injury at the dislocation level.
2. Anterolisthesis of C5 over C6.
3. Ligamentous disruption at the injury level.
4. Concomitant cerebrovascular injury at the injury level.
5. Properly restrained occupants at the time of collision.
6. No external or internal head or face injury.
7. No structural intrusion at the location of the subject occupant.

Similarly, for the rollover crash the selection criteria was the following.

1. Presence of cervical cord injury at the dislocation level.
2. Anterolisthesis of C5 over C6.
3. Ligamentous disruption at the injury level.
4. Concomitant cerebrovascular injury at the injury level.
5. Properly restrained occupants at the time of collision.
6. Presence of head injury.
7. Significant roof intrusion into the survival space.

Frontal Crash Case Report with C5-C6 BFD

The crash involves a 30-year-old female who was the left rear belted passenger of a four-door sedan. She weighed 72.5 Kg (160 lbs.) at the time and is 170.18 cm (~5ft 7 in) in height.

At the crash scene, she was alert and oriented to person, place, and event with her GCS (Glass glow coma scale) of 13. Her physical assessment at the scene showed abrasion to both hips, abrasion, and avulsion to her left neck and chest area with no other visible injury. She complained about abdominal pain and complete numbness in all four extremities. The vehicle inspection showed that the vehicle's damage was limited to the frontal body, with almost no intrusion into the front occupant's survival space.

Figure 4 shows the damage pattern on the vehicle. The vehicle EDR data recorded 39.0 mph as longitudinal Delta-V in 100 ms and 6.2 mph for lateral Delta-V. All available frontal airbags for the driver and the front passenger also deployed along with the driver side curtain airbag and the driver seat-mounted thorax airbag.

The inspection of left rear seatbelt webbing and the hardware showed load marks consistent with proper use of the seatbelt. Furthermore, the fat stranding analysis using CT (Computed tomography) imaging scans of pelvis and abdomen indicates proper placement of the lap belt before the crash.

Figure 5 shows the fat stranding at the ASIS (anterior superior iliac spine) due to lap belt loading during the subject frontal crash. Figure 6 shows the shoulder belt loading marks on the body near the base of the neck on the left. Figure 7 shows the C5-C6 dislocation pattern that involves bilateral facet dislocation with the widening of posterior disc space and interspinous space with disruption of the disc. The imaging studies also revealed cerebrovascular injury at the dislocation level.

Fig. 4. Exterior damage pattern on the vehicle.

Fig. 5. Fat stranding as visible on the CT abdomen at A.S.I.S level.

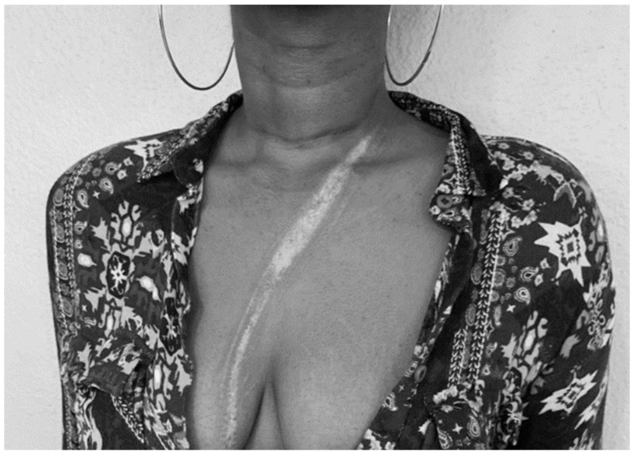

Fig. 6. Shoulder belt injury marks.

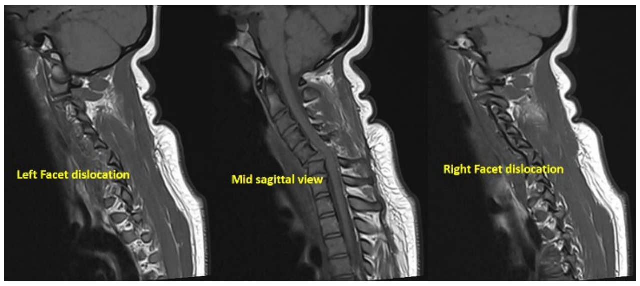

Fig. 7. C5-C6 level dislocation with ligamentous injury occurred in the frontal crash.

Rollover Crash Case Report with C5-C6 BFD

The crash involves a 22-year-old female who was the front belted passenger of a four-door sedan. She weighed 74.8 Kg (165 lbs.) at the time and is 172.7 cm (~5ft 8 in) in height. At the crash scene based on EMS records, she was alert and oriented to person, place, and event with her GCS (Glass glow coma scale) of 15. The CT and MRI studies at the hospital showed C5-C6 level BFD with 3-column injury and severe compression of the cervical cord.

She was unable to move or feel anything below her upper chest at the scene. She also sustained an acute bilateral traumatic cerebrovascular injury at the dislocation level. The imaging studies also showed the scalp head injury with no underlying skull fracture.

Figure 8 shows the roof crush profile of the vehicle from outside and inside. Figure 9 shows the hair deposit on the roof substrate, as observed during the vehicle inspection. Figure 10 shows the local roof deformation pattern from inside above the occupant's head.

The belt inspection shows consistent load marks on the webbing and the hardware confirming the proper use of the seatbelt. Figure 11 shows the head scan that shows the location of scalp hematoma on her head.

Figure 12 shows the MRI scan of her neck, showing severe canal stenosis at C5-C6 level due to BFD.

The vehicle rolled the driver's side, making the subject front passenger a far side occupant. Accident reconstruction shows four quarter turns (one complete rotation) driver side with tripping mechanism. The vehicle was found on its all four wheels at its rest position.

Fig. 8. Vehicle roof crush profile.

Fig. 9. Hair deposit on the interior roof substrate above occupant's head.

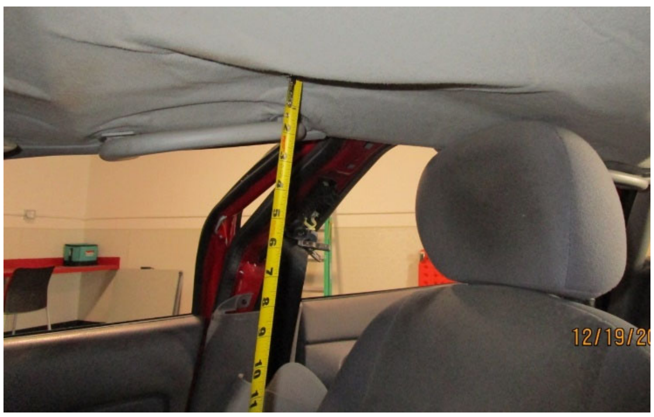

Fig. 10. Roof deformation pattern above the occupant's head.

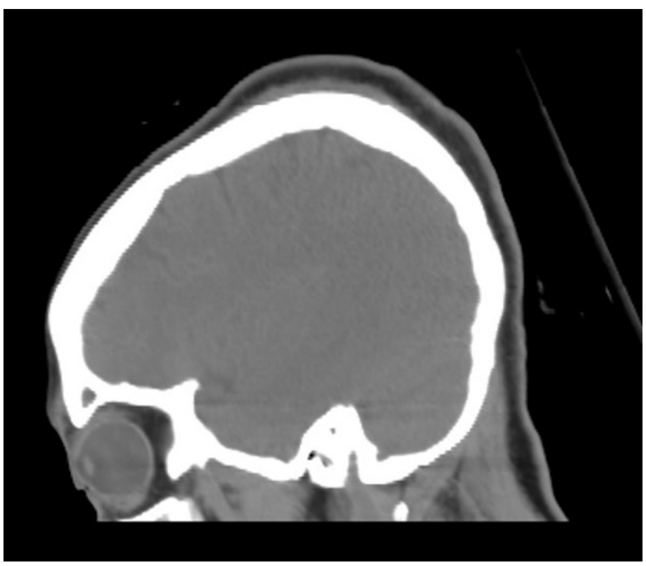

Fig. 11. Location of subcutaneous hematoma over the head.

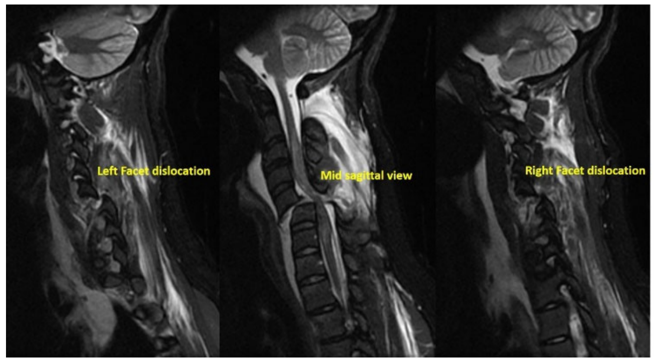

Fig. 12. C5-C6 level dislocation with ligamentous injury occurred in the rollover crash.

Discussion

BFD (Bilateral facet dislocation) produces a narrowing of the spinal canal as the superior vertebrae move anteriorly relative to the inferior vertebrae [1,2]. The spinal cord is subjected to a high rate dynamic pinching produced at the instant of dislocation [3,4]. In this study, two different crash modes resulting in entirely different overall occupant kinematics produced cervical spine BFD with spinal cord injury. In the frontal crash scenario, the neck tensile loading, and the rollover crash, the compressive neck loading superimposed with neck moments resulted in injury-producing facet joint kinematics. The current study aims to elucidate facet joint kinematics using real-world traffic crashes and laboratory testing as done in the past.

In the frontal crash scenario, based on the injury diagnosis and vehicle inspection, no evidence of head impact is available. The BFD produced is entirely due to the inertial loading of the neck exerted by the mass of the occupant's head. Punjabi et al. [5] conducted a laboratory experiment to quantify facet joint kinematics in a high-speed frontal loading condition. The experiment employed a bench-top sled to produce frontal impact decelerations of the FSU (Functional Spinal Units) mounted on the sled. The mass attached to the superior vertebrae of the FSU produced inertial forces and moments modulated by the sled deceleration severity. The high loading rate testing showed that facet joints separate first with significantly higher separation at the posterior edge of the facet compared to the anterior. Followed by peak flexion rotation and facet forward sliding occurred. The CT and MRI imaging confirms the kinematics, as observed by Punjabi et al. in their testing. The final rest position of the C5 inferior facets and widening of the posterior disc space and interspinous space validates the kinematic observations made by Punjabi et al. in their experiment. Flexion-distraction loading pattern produces BFD in the frontal crash scenario.

Several studies from the past explain BFD injuries to occupants in the absence of any head impact during the frontal crash. Shanahan Dennis [6], in his research paper based on real-world crash analysis, reported seven cases involving neck fractures and dislocations in the frontal crash scenario. According to this study, the impingement of the shoulder belt near the neck during the frontal crash amplifies forces on the spine. The study further states that the belt creates a fulcrum over which the neck flexes. Smith et al. [7] explain the amplification of moments due to belt fulcrum formation that shifts the center of rotation forward, producing injuries. Huelke et al. [8] reported several cases with neck fracture-dislocation in a frontal crash without any head impacts. Furthermore, they noted no correlation between neck injury and crash severity when an injury occurs without any head impact.

This conclusion supports observations of Shanahan regarding the amplification of forces and moments due to belt fulcrum about which the neck flexes. Moreover, the author of this paper has investigated low severity frontal crash with delta V less 20mph producing BFD with spinal cord injury for front passenger further supporting the conclusions drawn by Huelke and Shanahan.

In the rollover crash scenario, the overall body kinematics are significantly different compared to a frontal crash. The loading on the head from the roof structure mainly modulates the neck kinematics.

The neck is predominantly acted upon by the compressive load as opposed to tensile, as observed in the frontal crash without head impact. Despite compressive loading, the second case's neck injury pattern is like the first case with some minor difference. It has been shown by various researchers employing laboratory testing in the past that compressive load on the head and neck complex producing BFD injury pattern. Factors such as neck orientation, location of blunt impact on top of the head, padding, and head constraint boundary conditions have been shown to modulate the neck injury pattern [9,10]. Bauze et al. [11] may be the first ones to produce a BFD injury pattern in the laboratory while applying compressive loading on the cervical spine while the head was constrained such that its rotation was restricted. Hodgson et al. [12], in their laboratory testing's with rotationally constrained helmeted heads, showed cervical spine buckling after head crown impacts.

Nightingale et al. [13] imposed several end conditions to the cervical spine to understand failure modes under compressive loading. The study showed that with rotational constraint alone, all specimens produced BFD. All the past research points to rotational constraints of the head as a significant factor in BFD production under compressive. The head rotational constraint produces buckling kinematics that positions and orients some regions of the cervical vertebrae to flex and extend.

While buckling is not injury, but the buckled spine can lead to compression-flexion or compression-extension type of injury with a continued increase in load. Henceforth, any surface capable of producing such end conditions due to its deformation and failure patterns is highly likely to produce BFD under compressive loading. In the second case study involving the rollover crash, the medical evidence of scalp hematoma shows the traumatic force acting on the head near the crown.

Furthermore, the vehicle roof's failure pattern shows the pocketing effects in the headliner substrate, confirming head rotational constraint produced by the roof. The roof intrusion caused a traumatic head impact near the crown while the head is rotationally constrained produced BFD.

The detailed knowledge of the injury mechanism facilitates a crucial understanding of the design requirements to eliminate design induced hazards. The two case studies in association with all the laboratory testing's done in the past by numerous researchers show the importance of boundary conditions imposed on the head and neck modulating the neck injury pattern.

In the frontal crash scenario, the shoulder belt migration near the base of the neck and acting as a fulcrum imposes constraints and kinematics capable of producing BFD and cord injury, and hence, it must be a vital restraint design performance criteria.

Occupant submarining on the seat causes the seatbelt migrations from the stronger skeletal sites to the undesirable sites such as the abdomen and the neck [14,15,16,17]. Hence, to eliminate the BFD injury risk due to the belt fulcrum formation in a frontal crash, it is reasonable to implement a restraint design that prevents occupant submarining.

Similarly, in the rollover crash scenario, the roof high rate intrusion and the roof's capability to impose head rotational constraint must be eliminated to design out the hazard of severe neck BFD injury. The alternative designs that prevent submarining or roof designs maintaining structural integrity are not the focus of this paper. However, the study focuses on the conditions required to produce BFD in frontal and rollover crashes, which have been discussed using real-world examples.

Conclusion

Two real-world investigations are presented involving traumatic BFD at the C5-C6 level. In the frontal crash scenario, the shoulder belt transition towards the base of the neck and forming a fulcrum amplifying force and moments above the level of the fulcrum produced BFD at the C5-C6 level. In the rollover crash scenario, the head's traumatic impact from the intruding roof buckled the cervical spine and exposed it to BFD at the C5-C6 under continued increasing load from the roof. In both the crashes, the occupants sustained cervical cord injury. The case studies in association with all the laboratory testing by numerous researchers in the past confirm that tensile or compressive loading of the cervical spine under certain conditions produce BFD. Furthermore, in the absence of any information about the related accidents, the presence and absence of head injury play a vital role in describing the mechanism that produced BFD.

In the frontal crash scenario, the amplification of loading due to the belt fulcrum point formation produces vertebrae kinematics as required to cause BFD. The vertebral body kinematics has been produced in the laboratory in the past. In the rollover crash scenario, the roof intrusion and local deformation pattern of the roof produce rotational constraint of the head causing buckling of the cervical spine followed by BFD as the load continues to increase on the head from the intruding roof. The buckling of the cervical spine has been produced in the laboratory and provides excellent details of explanation regarding the neck injury sustained in the rollover case study. The concomitant scalp hematoma and the hair deposit found on the headliner substrate confirm the roof's role in producing the BFD in a rollover crash.

The injury mechanism analysis and study are crucial for automotive passive safety. These two real-world cases, in conjunction with laboratory testing, shows that preventing occupant submarining that repositions the shoulder belt near the neck can eliminate the risk of BFD in frontal crash scenarios. Furthermore, limiting the roof intrusion and maintaining the roof structure can prevent the traumatic head impact and formation of the rotational constraint for the head, eliminating the risk of spine buckling and subsequent BFD.

References

[1] Allen Jr, B. L., R. L. Ferguson, THOMAS R. Lehmann, and R. P. O'brien. "A mechanistic classification of closed, indirect fractures and dislocations of the lower cervical spine." Spine 7, no. 1 (1982): 1-27. https://pubmed.ncbi.nlm.nih.gov/7071658/

[2] Daffner, Scott D., and Richard H. Daffner. "Computed tomography diagnosis of facet dislocations: the “hamburger bun” and “reverse hamburger bun” signs." The Journal of emergency medicine 23, no. 4 (2002): 387-394. https://pubmed.ncbi.nlm.nih.gov/12480021/

[3] Ivancic, Paul C., Manohar M. Panjabi, Yasuhiro Tominaga, Adam M. Pearson, S. Elena Gimenez, and Travis G. Maak. "Spinal canal narrowing during simulated frontal impact." European spine journal 15, no. 6 (2006): 891-901. https://pubmed.ncbi.nlm.nih.gov/16220351/

[4] Ivancic, Paul C., Adam M. Pearson, Yasuhiro Tominaga, Andrew K. Simpson, James J. Yue, and Manohar M. Panjabi. "Mechanism of cervical spinal cord injury during bilateral facet dislocation." Spine 32, no. 22 (2007): 2467-2473. https://pubmed.ncbi.nlm.nih.gov/18090087/

[5] Gomes, Shanda, Scott Rudkin, Fong Tsai, and Shahram Lotfipour. "Bilateral cervical spine facet fracture-dislocation." The western journal of emergency medicine 10, no. 1 (2009): 19. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2672293/

[6] Panjabi, Manohar M., Andrew K. Simpson, Paul C. Ivancic, Adam M. Pearson, Yasuhiro Tominaga, and James J. Yue. "Cervical facet joint kinematics during bilateral facet dislocation." European Spine Journal 16, no. 10 (2007): 1680-1688. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2078308/

[7] Shanahan, Dennis F. "Shoulder belt-induced flexion–distraction fractures of the cervical spine." International Journal of Crashworthiness 18, no. 6 (2013): 559-569.[https://www.tandfonline.com/doi/abs/10.1080/13588265.2013.825387

[8] Smith, William S., and Herbert Kaufer. "Patterns and mechanisms of lumbar injuries associated with lap seat belts." JBJS 51, no. 2 (1969): 239-254. https://pubmed.ncbi.nlm.nih.gov/5767317/

[9] Huelke, Donald F., G. Murray Mackay, Andrew Morris, and Maureen Bradford. "A review of cervical fractures and fracture-dislocations without head impacts sustained by restrained occupants." Accident Analysis & Prevention 25, no. 6 (1993): 731-743. https://pubmed.ncbi.nlm.nih.gov/8297440/

[10] Nusholtz, Guy S., D. E. Huelke, P. Lux, Nabih M. Alem, and F. Montalvo. Cervical spine injury mechanisms. No. 831616. SAE Technical Paper, 1983.[https://www.sae.org/publications/technical-papers/content/831616/

[11] Nightingale, Roger W., William J. Richardson, and Barry S. Myers. "The effects of padded surfaces on the risk for cervical spine injury." Spine 22, no. 20 (1997): 2380-2387. https://pubmed.ncbi.nlm.nih.gov/9355219/

[12] Bauze, ROBERT J., and Gordon M. Ardran. "Experimental production of forward dislocation in the human cervical spine." The Journal of bone and joint surgery. British volume 60, no. 2 (1978): 239-245. [https://pubmed.ncbi.nlm.nih.gov/659473/]

[13] Hodgson, Voigt R., and L. Murray Thomas. "Mechanisms of cervical spine injury during impact to the protected head." SAE Transactions (1980): 3792-3805. https://www.sae.org/publications/technical-papers/content/801300/

[14] Nightingale, Roger W., James H. McElhaney, Daniel L. Camacho, Michael Kleinberger, Beth A. Winkelstein, and Barry S. Myers. "The dynamic responses of the cervical spine: buckling, end conditions, and tolerance in compressive impacts." SAE transactions (1997): 3968-3988. https://www.sae.org/publications/technicalpapers/content/973344/

[15] Adomeit, Dieter, and Alfred Heger. "Motion sequence criteria and design proposals for restraint devices in order to avoid unfavorable biomechanic conditions and submarining." SAE Transactions (1975): 3150-3159. https://www.sae.org/publications/technicalpapers/content/751146/

[16] Thorbole, Chandrashekhar K. "Seatbelt submarining injury and its prevention countermeasures: How a cantilever seat pan structure exacerbates submarining." Journal of family medicine and primary care 4, no. 4 (2015): 587. https://pubmed.ncbi.nlm.nih.gov/26985421/

[17] Thorbole, Chandrashekhar K., and Prashant Naik. "role of traumatic seatbelt fat stranding in automotive crash injury analysis." 26th ESV Conference, Eindhoven Netherlands,[https://www-esv.nhtsa.dot.gov/Proceedings/26/26ESV-000137.pdf

[18] Thorbole, Chandrashekhar K. "Dangers of seatback recline in a moving vehicle: how seatback recline increases the injury severity and shifts injury pattern." In ASME 2015 International Mechanical Engineering Congress and Exposition. American Society of Mechanical Engineers Digital Collection, 2015. https://asmedigitalcollection.asme.org/IMECE/proceedingsabstract/IMECE2015/57380/V003T03A056/264306

Address correspondence to: *Dr. Chandrashekhar K. Thorbole, Thorbole Simulation Technologies, LLC, 2524 Horizon Blvd. Rogers, Arkansas - 72758, USA.*
Ph: +1 (479) 466-7050
E-mail: thorsimtech@gmail.com; chandrathorbole@injurybiomechanics.com