Analysis of Cervical Spine Injuries and Mechanisms for CIREN Rollover Crashes

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Abstract Associated mechanisms of injuries sustained by rollover-involved occupants are absent from the existing literature, which restricts the applicability of existing studies on cervical spine injury tolerance in the development of injury criteria for rollover-induced injuries. The objective of this study was to analyze the pathologies and specific spinal injury mechanisms from rollover crash occupants using existing data from cadaver cervical spine compressive tests. Sampled cases (n=23), representing single-vehicle, single-event rollovers from the Crash Injury Research and Engineering Network (CIREN) database were analyzed. A review of 19 experimental studies of cervical spine literature was conducted to support the mechanism determination for occupant injuries. Axial loading in the cephalocaudal direction was found to be the predominant loading component responsible for cervical spine injury in all of the CIREN occupants. Discrepancies between CIREN injuries and cadaver test pathologies exist, primarily with regard to asymmetry in the AIS 2 fractures. Seventeen of the 23 CIREN occupants sustained asymmetric fracture (66.7% of total fractures), an injury type seldom produced in experimental cadaver tests (14.4% of total fractures). The difference was less for catastrophic cervical spine injuries (AIS 4+). Differences between the field injuries and cadaver tests can be accounted for by inherent limitations of cadaver tissue and/or the paucity of non-sagittal cadavers tests. Regardless, the results emphasize that further investigation into non-sagittal cervical spine compression injury is needed to understand or improve the level of correlation between cadaver tests and the clinical outcomes seen in the field.

Keywords Cervical spine, rollover, CIREN, bilateral facet dislocation (BFD)

I. INTRODUCTION

Vehicle rollovers result in over one-third of automotive fatalities in the United States; of the injuries sustained by rollover-involved occupants, trauma to the cervical spine is among the most frequent and life-threatening. From a National Automotive Sampling System (NASS) study of all adult, front row-seated, non-ejected occupants involved in rollovers between 2003 and 2007, over 55% of all AIS3+ injuries suffered in pure rollovers were to the head or spine, with six of the top ten most common rollover AIS3+ injuries being cervical spine fractures or injuries to the head or brain [1]. Head interaction with roof structures within the vehicle likely occurs during many rollover crashes, leaving the head and cervical spine vulnerable to compressive forces [2]. Countermeasure development aimed at mitigating cervical spine injury in rollover-involved occupants requires a biofidelic dummy and appropriate injury criteria. A biofidelic dummy and an appropriate, or multiple, injury criteria could be useful in predicting the onset of cervical spine injury. The biomechanics literature contains numerous studies aimed at determining loading response and injury thresholds in cadaver cervical spines loaded in axial compression, which are an appropriate starting point for the development of such injury criteria. However, much of the existing literature was not originally designed for rollover application; stated applications involve diving-related injuries [3,4], contact sports [5], other modes of automotive crashes [6-8] and injury due to falls [9]. Most studies state several of these potential applications without reference to vehicular rollover [10-13].

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In one recent study, Toomey et al. [14] performed tests on cadaver specimens in the same fashion as in Nightingale et al. [15], who tested cadaveric head-neck complexes in controlled drop tests. Instead of loading the specimen solely along the midline of the cadaver, Toomey studied the effects of lateral eccentricity and bending, laterally flexing two specimens and angling the impact plate 15-degrees from the horizontal for three specimens. The authors list rollover crashes as a reason for deviating from Nightingale's methods. Their tests were performed to mimic events where either the neck maintains a vertically aligned posture and lateral flexion is produced by an angled impact orientation relative to the roof, or the neck is initially laterally bent and compressed axially [14]. This study is one of the few to examine asymmetric cervical spine loading effects for rollover applications. They produced clinically relevant injuries in 3 of 5 cadaver specimens, having one specimen fail at the potting fixture and another showing no injuries.

Nonetheless, all the aforementioned studies exhibit potential for application to rollover injury mechanism research since cervical spine injuries in rollover-involved occupants are hypothesized to be the result of axial loading [1,16,17]. To evaluate the applicability of individual studies, injuries produced in cadavers were compared directly to injuries seen in the field data to determine their clinical relevance. Additionally, investigation of individual crash cases from the field data provided some information regarding global and local loading modes and injury mechanisms that can be used to further evaluate existing biomechanical test results. Thus, the goal of this study was two-fold: to assess the applicability of the existing biomechanical data to rollover-involved occupants and, as a long-term goal, to determine injury mechanisms in real-world rollovers. This was accomplished through the evaluation of associated mechanisms and descriptions of cervical spine injuries in both the existing literature and clinical injury analysis.

II. METHODS

Cervical Spine Database Formulation

Biomechanics literature from the last 40 years was surveyed to identify studies where data from cervical spine loading tests on cadavers were presented. Each specimen from each test was included in a database of loading tests if it met the following criteria:

- Tests were performed on human cadavera (i.e., not involving non-human primates);
- Test specimens contained no previous traumatic spine injuries or spinal conditions;
- The specimen must have included no fewer than 5 consecutive cervical vertebrae. Full head-neck complexes, full cadaver, full osteoligamentous cervical spine (C1-T1), or any five consecutive vertebrae were accepted;
- Loading was directed to the crown of the head or to the most superior vertebra in a superior-to-inferior loading direction or other environments where axial loading was applied in a compressive nature (such as inferior-to-superior loading via T1);
- The authors' full test methodologies were provided, including initial orientations of the head and neck;
- Complete injury detail of each specimen was provided;
- No re-tested specimens were included (i.e., single impact only).

The information captured from each test included the cadaveric segment used (e.g., full cadaver, transected segment), the loading surface used, the loading type (e.g., pneumatic piston, drop test), the orientation of the neck prior to loading, the loading velocity range used, the peak contact force generated, and detailed pathology information. After inclusion, each cadaver test injury was organized by location of fracture (e.g., C3), type of fracture (e.g., Hangman's), presence of dislocation (e.g., BFD), injury detail (e.g., left-sided) and absence of fracture (e.g., ligament disruption only).

In-Depth CIREN Analysis

The next portion of the study was performed using information drawn from the NHTSA-sponsored Crash Injury Research and Engineering Network (CIREN) database. This database contains information collected from approximately 5,000 crashes where at least one serious (AIS => 3) or two moderate (AIS = 2) injuries occurred to one of the vehicle occupants. A complete list of CIREN inclusion criteria may be found in the United States Federal Register [18]. For each case, the following information was compiled to construct the case file:

- Crash Information: scene diagram, scene photos, crash description (from a crash reconstruction);
- Occupant Information: anthropometry, injuries (with AIS codes), injury photographs, occupant-to-vehicle contacts (with certainty level);
- Vehicle Information: make, model, year, interior and exterior photographs, deformation measurements (measured as intrusions into the occupant compartment) and directions;
- Medical Records: radiological images and reports, operating room reports, clinical photographs, discharge reports, follow-up assessment and detailed descriptions of injuries.

The CIREN database was queried for cases that involved belted-only occupants in single-event rollover crashes involving 10-quarter turns or less that sustained an AIS 2+ injury to the spine. The resulting cases were fully reviewed. The review process consisted of a group of biomechanical engineers, accident reconstruction experts, and emergency medicine physicians reviewing the available case data and identifying qualifying injuries, which were defined as AIS 2 fractures and AIS 3+ injuries to the head, spine and thorax. For each case, the review team used case information to identify the vehicle kinematics, which were used to identify the occupant kinematics and the certainty with which they could be determined. The case information was then used with the vehicle and occupant kinematics to identify the particular injury causation scenario for each of the AIS 3+ injuries and AIS 2 fractures to the cervical spine, including the perceived loading direction, injury mechanism, rollover phase in which the injury was assumed to have occurred, and any other details associated with the injury. As many AIS codes provide limited injury description, each injury to the cervical spine was logged based on operating room transcripts, pathology reports and radiology notes. Additionally, the likelihood that the occupant was partially ejected from the vehicle (e.g., lacerations and degloving injuries) during the rollover crash was also determined.

Integrating CIREN and Cervical Spine Database

Each injury sustained by the CIREN case occupants and the cadavers was organized and compared by vertebral level, nature of the fracture, presence of dislocation, and by location relative to the mid-sagittal plane. Injuries to the case occupants were compared with existing cadaver test specimens in an attempt to determine global and local injury mechanisms (i.e., kinematics and external loadings that lead to injury) for each case. To characterize the location of individual vertebral fractures, a classification scheme was developed to determine the location of the fracture relative to the mid-sagittal plane of the vertebra. The lateral aspect of a vertebra is defined as any anatomical structure of the vertebra that can fracture on one side (left or right) but not the other. These include the laminae, pedicles, transverse processes and superior and inferior articular facets. The numbers of unilateral and bilateral fractures were recorded and tabulated. Fractures occurring along the mid-sagittal plane, or anterior-posterior (AP) axis, were also tabulated. Structures in this mid-sagittal area, such as the vertebral body and spinous processes, do not contain lateral elements and typically fracture close to the midline [14].

Distributions of fractures based on vertebral level, type of fracture and lateral nature were compared between the CIREN occupants' injuries and the fractures sustained by cadavera in biomechanical testing. The presence or absence of interfacetal dislocation was also recorded. Once an injury seen in a case occupant was closely linked with an injury produced *in vitro*, the mechanism explained by the author of that study was determined to be a possible mechanism for the case occupant's injury.

III. RESULTS

Cervical Spine Database Formulation

Of the current body of spine biomechanics, 19 published studies by eleven different corresponding authors spanning four decades of biomechanical literature satisfied the inclusion criteria. In total, 170 cadaver specimens from the 19 papers were added with complete detail to the database. The orientation of the head and loading surface was often found to determine the global injury mechanism to the neck, whether it was compression, flexion, extension or a combination thereof. While the cadavers' injuries could have been attributed to any of the local injury mechanisms, all the specimens were loaded in the cephalocaudal direction. It is important to note that all were intended to be loaded along the mid-sagittal plane except for four specimens [14,19].

Authors used several different methods to induce injuries. Some studies provided an input displacement with either a controlled fixed displacement or displacement until failure, while other studies applied an input energy (e.g., drop tests from a specified height). Studies involved full cadavers loaded axially with a pneumatic piston [20-24], full cadaver drop tests [9,19,25], head and cervical spine complexes loaded axially [6,7,10,11,14,15,24,26,27], and isolated ligamentous cervical spine sections fixed in load frames and axially compressed [8,13,23,24,28].

Using descriptions of injuries and CT images provided by the authors, the detailed database of all 170 specimens' injuries was formed and summarized in Table 5. A total of 215 fractures and 19 facet dislocations were produced in the 170 cadaver specimens. The most commonly produced injuries were vertebral body fractures (including wedge, burst, compression and teardrop fractures) and spinous process fractures, together making up 65.1% of the total number of fractures (Table 1). Fractures to the lateral aspects, which include the superior and inferior articular facets, the pedicles, laminae and transverse processes, made up 45 of the 215 total fractures (20.9%).

Table 1

Individual Fractures by Type of Fracture in CIREN Occupants and Cadavera

Anatomical Structure		CIREN Occupants	Cadaver Specimens
Anterior/Posterior Arch		5 (*6.9%*)	20 (*9.3%*)
Articular Facet		25 (*34.7%*)	9 (*4.2%*)
Lamina		9 (*12.5%*)	18 (*8.4%*)
Odontoid		1 (*1.3%*)	10 (*4.7%*)
Pedicle		6 (*8.3%*)	11 (*5.1%*)
Spinous Process		3 (*4.2%*)	44 (*20.5%*)
Transverse Process		13 (*18.1%*)	7 (*3.2%*)
Vertebral Body		10 (*13.9%*)	96 (*44.7%*)
	Total	*72*	*215*

Nineteen dislocations were identified, produced in eighteen cadavers from eight test-series by five different corresponding authors [6,8-10,15,23,25,27]. These included three atlanto-axial separations, nine instances of anterolisthesis exhibiting locked facets, six instances of retrolisthesis and one instance of perched facets. All 18 cadavers exhibited bilateral dislocations (BFD) at the intervertebral level (i.e., no instance of unilateral facet dislocation). Eleven (57.9%) were produced quasi-statically and eight (42.1%) were produced dynamically.

There were a substantially greater number of mid-sagittal fractures than unilateral fractures produced in the cadaver tests. Thirty-one fractures were produced to only one lateral aspect, making up 14.4% of the total fractures. In cadavers subjected to axial loading to the head, 159 fractures along the mid-sagittal plane were produced. These comprise of 74.0% of the total fractures in the literature database (Table 2).

In-Depth CIREN Analysis

Following the query of the CIREN database to select single-event rollovers of 10 or fewer quarter turns involving only belted occupants, the research team was presented with 46 pure rollovers cases. Twenty-three of the cases involved occupants with AIS 3+ or AIS 2 fracture to the cervical spine (Tables 3 and 6).

The 23 case occupants consisted of 14 males and nine females, spanning ages from 18-76 (mean= 41.2 years ±19.5 years), with average statures and weights of 172 cm (± 11 cm) and 81 kg (± 19 kg), respectively. All of the occupants were seated in the first row with 13 drivers and 10 right front passengers (RFPs), with 17 (73.9%) of the occupants seated on the far side of the roll. Crashes occurred in seven sedans, two sports cars, 11 SUVs, two trucks and one van from model years between 1998 and 2008. Nine of the occupants sustained only one roof-to-ground contact, 13 sustained two roof contacts, and one occupant sustained three roof contacts.

Table 2
Individual Fractures by Lateral Nature

Anatomical Location of Fracture in the Transverse Plane of Affected Vertebra	Cadaver Specimens	CIREN Occupants	CIREN MAIS 3+	CIREN MAIS 4+
Unilateral	31 (*14.4%*)	48 (*66.7%*)	2 (*20.0%*)	0 (*0.0%*)
Bilateral	25 (*11.6%*)	8 (*11.1%*)	6 (*60.0%*)	5 (83.3%)
Along Mid-Sagittal Plane (Mid-line)	159(*74.0%*)	16 (*22.2%*)	2 (20.0%)	1 (*16.7%*)
Total	*215*	*72*	*10*	*6*

Among the 23 case occupants whose cases were fully reviewed by the CIREN team, 17 sustained cervical trauma as their most significant injury. Of these, 6 involved permanent cord injury or death (AIS4+). The remaining six occupants sustained brain, thoracic or lower extremity injuries that were more severe in terms of threat to life than their cervical spine damage. Eighteen of the 23 occupants sustained as least one unilateral fracture, including fractures to the facet, lamina, pedicle or transverse process. Of the 72 total fractures sustained by the CIREN case occupants, 48 (66.7%) were unilateral with 26 occurring on the right-side and 22 on the left-side facets, laminae, pedicles or transverse processes (Table 2). Sometimes an injury to the lateral aspect occurred on both sides of the same vertebra (bilaterally), indicating a load applied symmetrically to both sides by adjacent vertebra. The maximum AIS (MAIS) values for serious (AIS 3+) and catastrophic (AIS 4+) injuries were tabulated based on lateral nature to show that 80.0% of serious and 100.0% of catastrophic injuries in the CIREN occupants were oriented bilaterally or along the mid-sagittal line.

Table 3
CIREN Case Occupant Information

CIREN #	Height, [m]	Weight, [kg]	Age	Gender	Make	Model	Model Year	Occupant Position	Quarter Turns	Roll Direction
103304	1.8	82	76	Male	Chevrolet	Impala	2004	RFP	6	R
125299	1.75	66	53	Male	Chevrolet	Cavalier	2004	RFP	4	L
163690	1.78	77	42	Male	Chevrolet	Cavalier	2002	RFP	4	L
163694	1.6	91	21	Female	Chrysler	Sebring	2008	Driver	6	L
100074514	1.83	130	73	Male	Ford	F350 Crew Cab	2002	Driver	2	R
100084523	1.7	50	33	Female	Toyota	4-Runner	1999	Driver	8	R
100112055	1.57	68	34	Female	Ford	Taurus	2000	Driver	8	R
160110274	1.83	86	59	Male	Mazda	Miata	2000	Driver	2	R
160139536	1.52	52	20	Female	Suzuki	Reno	2006	Driver	8	L
537103134	1.55	86	43	Female	Jeep	Grand Cherokee	1998	RFP	6	L
551068562	1.83	79	21	Male	Chevrolet	Blazer	2000	RFP	4	L
558030923	1.8	88	72	Male	Ford	Escape	2006	RFP	4	R
590123589	1.65	54	25	Female	Ford	Mustang	2004	Driver	8	L
590144150	1.85	77	26	Male	Honda	Element	2004	Driver	8	R
781125527	1.6	102	50	Female	Kia	Sorrento	2006	Driver	6	R
852126192	1.91	95	50	Male	Chevrolet	Express Van	2006	Driver	4	R
852130600	1.57	86	78	Female	Buick	Regal	2000	Driver	2	R
852162058	1.73	76	32	Male	BMW	Z4 Roadster	2008	RFP	4	L
852172396	NA	NA	25	Female	Kia	Sportage	2006	RFP	8	R
852177768	1.8	77	28	Male	Ford	F150 SuperCrew	2008	Driver	8	R
857069807	1.7	102	44	Male	Ford	Explorer	2003	RFP	8	L
857076778	1.81	104	24	Male	Jeep	Cherokee	2001	RFP	10	L
965066489	1.73	61	18	Male	Jeep	Liberty	2002	Driver	6	R

Nine bilateral or unilateral facet dislocations or subluxations were observed in the case occupants. There were five instances of Grade I spondylolisthesis, including instances of perched facets. There were four instances of Grade II spondylolisthesis, accounting for locked facet dislocations of up to 50% antero-posterior slippage. There were three unilateral facet dislocations (UFDs). In eight of the nine cases of facet dislocation there was evidence of shearing at the intervertebral space. Shearing evidence consists of fractures to the facet and/or lateral mass at the zygapophyseal joint in question.

Table 4
Numbers of individual fractures by vertebral level

Cervical Vertebra	CIREN Occupants	Cadaver Specimens
C1	7 (*9.7%*)	22 (*10.2%*)
C2	7 (*9.7%*)	35 (*16.3%*)
C3	3 (*4.2%*)	30 (*14.0%*)
C4	8 (*11.1%*)	44 (*20.5%*)
C5	7 (*9.7%*)	40 (*18.6%*)
C6	15 (*20.8%*)	25 (*11.6%*)
C7	25 (*34.7%*)	19 (*8.8%*)
Total	*72*	*215*

IV. DISCUSSION

The compressive tolerance of the cervical spine has been well explored for applications including diving, contact sports, injuries due to falls, and automobile crashes. This study attempts to provide insight on the applicability of existing cervical spine compression literature to rollover crash injuries. Accurate pathology is targeted in any cadaveric biomechanical test; a goal of this study was to show whether or not consistencies exist between the clinical injuries sustained by rollover crash victims and the injuries produced in cadavera for the purpose of investigating injury mechanism in rollovers. A number of authors have documented that cervical spine traumas are some of the most frequent and debilitating injuries suffered by rollover-involved occupants [1,29,30]. It is important that accurate pathology and tolerance levels are ascertained from cadaver studies to make evident key loading patterns responsible for cervical spine trauma in rollover crashes.

The inclusion criteria for the literature assessment were based on cadaver tests where the cervical column was subjected to axial compression, as compressive spine injuries have been routinely linked with rollovers. Papers containing the published results of biomechanical tests involving single or a few connecting functional spinal units were not included in the database of cadaver specimens subjected to rollover-type loading because they cannot properly model the buckling kinematics of the cervical spine. In addition, tests on smaller segments cannot produce the concomitant and non-contiguous injuries that are common in both the field data and in full cervical spine experiments [27].

Other highly cited cervical spine papers did not include detailed injury description and were omitted [4,5,31]. A goal of this study was to compare clinical cervical spine injuries with those produced in cadaveric tests; this step could not be done for papers where injury description was not provided. Some experimental studies ascertained the believed injury mechanism for a specific fracture, dislocation or ligamentous injury by using high-speed film to track the motions of reflective targets attached to the cadaver spinous processes and vertebral bodies during mechanical loading. Other studies use papers that specify fractures and injuries in separate injury classifications to indicate injury mechanisms. Studies by Allen et al. and White and Panjabi were used to retrospectively link an injury outcome with its surmised mechanism [32,33]. One limit to this method exists in that Allen's classifications were initially performed for lower cervical spine injury, but have been used by researchers to classify injuries throughout the entire cervical column [15,27]. Still, a similar analytical approach was used for the CIREN occupants in this study to classify injury mechanism.

Table 5
List of Studies Used in the Analyses of Compression Cervical Spine Injury Assessment

Reference Source	No. Specimens Studied	Cadaveric Segment(s) Used	Padded/Rigid Impact	Lordosis Intact/Removed	Impact/Loading Velocity Range (cm/s)	Peak Contact Force Range (kN)	No. Passed Inclusion Criteria	Specimen IDs Not Included
Alem et al., 1984	19	Full cadaver	Padded	Intact	690-1090	3.0-17.0	19	
Culver et al., 1978	11	Full cadaver	Padded	Intact	676-1020	4.71-8.85	10	78H110 (swan neck)
Maiman et al., 1983	13	Full cadaver, Isolated (C1-T3)	Actuator-attached	Intact	0.25-152	0.645-7.439	13	
McElhaney et al., 1983	14	Isolated (varied)	Actuator-attached	Pre-flexed	45-92	0.96-6.84	10	A80-289, 364, 368, 384 (retested specimens, lacks injury description)
McElhaney et al., 1988	7	Isolated (C7-T1, BOS-T1)	Actuator-attached	Pre-flexed	Not provided	0.108-2.305	6	5C (load information missing)
Myers et al., 1991	18	Isolated (BOS-T1)	Actuator-attached	Intact	Not provided	0.169-6.84	18	
Nightingale et al., 1996	11	Isolated (head-T1)	Rigid (x7) Padded (x4)	Intact	243-351	1.759-11.62	11	
Nightingale et al., 1997	Nightingale '96 data + 11 add.	Isolated (head-T1)	Rigid (x3) Padded (x8)	Intact	307-320	3.115-8.604	11	
Nusholtz et al., 1981	12	Full cadaver	Padded	Intact (x8) Pre-flexed (x4)	460-570	1.80-11.10	11	79L088 (lacks injury description)
Nusholtz et al., 1983	8	Full cadaver	Padded	Pre-flexed	400-590	5.60-10.8	5	82L489, 82L494, 83L499 (retested specimens)
Pintar et al., 1989	7	Isolated (Frankfurt plane -T1)	Actuator-attached	Pre-flexed	0.2	1.355-3.613	7	
Pintar et al., 1990	6	Isolated (head-T1)	Padded	Pre-flexed	295-813	5.856-19.205	6	
Pintar et al., 1995	Yoganandan '94 data + 11 add.	Isolated (head-T1)	Padded	Pre-flexed	250-800	Not provided	11	
Sances et al., 1986	15	Full cadaver	Rigid (x9) Padded (x6)	Pre-flexed	Not provided	3.00-14.66	15	
Toomey et al., 2009	5	Isolated (head-T1)	Rigid	Intact	291-326	6.064-17.48	4	2 (casting failure)
Yoganandan et al., 1986	Sances '86 data	Full cadaver	Rigid (x9) Padded (x6)	Pre-flexed	Not provided	3.00-14.66	0	Sances et al., 1986 specimens with additional pathology
Yoganandan et al., 1989	10	Full cadaver, Isolated (head-T2, C2-T2)	Actuator-attached	Intact (x5) Pre-flexed (x5)	0.254-142	0.50-2.936	10	
Yoganandan et al., 1990	Pintar '89 + Pintar '90 data	Isolated (head-T1, Frankfurt plane -T1)	Actuator-attached	Pre-flexed	0.2-570	1.08-3.04	0	Pintar et al., 1989,1990 specimens with additional data
Yoganandan et al., 1994	Pintar '90 data + 3 add. tests	Isolated (head-T1)	Padded	Pre-flexed	540-782	Not provided	3	
						n=	*170*	

Table 6

CIREN case occupant injury information

CIREN #	Loading evidence on Head	C-Spine Injury AIS Codes	Description	Notes	Quarter Turn of Head-Neck Loading	Other AIS 2 Fx and AIS3+ Injuries	Most Sig Injury
103304	Hematoma slightly anterior to vertex	6502262\6502242\ 6502302\6502322\ 6502202	C2, C4 pedicle fxs\ C3-C4 right lamina fxs\ C1 anterior ring 2-part fx\ C3-C4 body fx with minor compression\ C2-C4 trans proc	Hangman's fracture with bilateral foramen transversaria fractures\ C4 foramen and right pedicle\ comminuted, displaced\\ bilateral at C2, C3-4 right foramen transversaria (S5,R3)	2 or 6	Multiple stable rib fxs, T2 transverse process fx	C-spine
125299	Abrasions to forehead	6502283\6502222\ 6502202\6502322	C2 (Type-III) odontoid fx\ C6-C7 right facet fxs\ C7 right transverse process fx\ C2 vertebral body fx	Anteriorly displaced dens fx\\\ dens fx extended into vert body (S2,R3)	2		C-spine
163690	Scalp abrasion at vertex	6402144\6502242\ 6502202	Cord contusion incomplete cord syndrome with fracture\ C6 laminae fx\ C7 lateral mass fx	BLF C5 on C6\with C6 right trans process fx, C5 left lamina fx and C5-C6 right facet fx\ C7 right transverse process (S1,L1,R4)	2		C-spine
163694	Scalp laceration left frontal to parietal region	6402766	Cervical Spine Cord laceration C-3 or above with fracture	Separated fracture of AO interface (S1)	2 or 6		C-spine
100074514	Scalp abrasion left side near vertex	6402184	Cervical Spine Cord contusion with fracture and dislocation	C7 laminae fxs (S1)	2	T1, T2 vertebral body fxs	C-spine
100084523	No head/facial injury	6502222	C7 left facet fx	Superior articular facet (L1)	2 or 6		C-spine
100112055	Superior scalp lacerations	6502242\6502262\ 6502322	C1 lateral mass fx\ C1 right pedicle fx\ C7 vertebral body fx	Extends to right posterior arch\ including right foramen\ anterior aspect (S1,R2)	2 or 6	T4-T10 fxs w/ complete cord laceration, multiple rib fxs w/ pheumothorax, clavicle fx, humerus fx	Thorax
160110274	Laceration to middle upper forehead	6402043\6502022	Cord contusion with transient neurological signs with fracture\ disc injury w/out nerve root damage	Left side fracture subluxation of C6-7 with perched facet, C6-7 left facet fxs\ displaced anterior wedge fx and small central disc herniation (S1,L3)	2	Cerebral hematoma	TBI
160139536	Abrasion right side anterior to vertex	6502302\6502123\ 6502182\6502222	C1 anterior arch fracture\ C6-7 BFD\ C7 spinous process fx\ C7 facet fx	\perched facets\\bilateral superior articular facets (S4)	6	Cerebral hematoma, T1 facet fx, T3-4 vert body fxs	TBI
537103134	Bruising right posterior temporal region	6402285\6502222\ 6502242\6502322	Cord contusion complete cord syndrome C-4 or below with fracture and dislocation\ C5-C7 left facet fxs\ C6-C7 left lamina fx\C7 wedge fx	Grade I anterolisthesis C5-C6. Grade II antero C6-C7 resulting in quadriplegia\ Inferior facet C5, C6, Superior facet C6, C7\\ (S2,L6)	2 or 6		C-spine
551068562	Hematoma left parietal region	6402184\6502242\ 6502262	Cord contusion incomplete C4 or below with fracture and dislocation\ C5-C6 right lamina fxs\ C5-C6 right pedicle fxs	C6-7 Grade I anterolisthesis, Posterior ligamentous injury from C3-7, with cord contusion at C4-5\\ (S1,R4)	2		C-spine
558030923	Abrasion to forehead	6402285\6502242\ 6502322\6502182\ 6502202	Complete cord syndrome C4 or below \ C2,C6 laminae fx\ C7 wedge fx\ C2, C6 spinous process fx\ C7 left transverse process fx	C6-7 Anterolisthesis, locked on left, perched on right\ bilateral, undisplaced\\ (S5,L2)	2		C-spine
590123589	No head/facial injury	6502022\6502222\ 6502202	C6-7 intravertebral disc injury\ C7 left facet fx\ C7 left transverse process fx	Without nerve root damage\ superior articulating facet\ (S1,L2)	6 or 7		C-spine
590144150	Abrasion to forehead	3210183\6502222	Vertebral artery thrombosis (occlusion) secondary to trauma\ C5 right facet fx	Right side caused by C5 facet fx\ into foramen transversarium (R2)	2 or 6	Right lung contusion	C-spine

Table 6:
CIREN case occupant injury information continued

CIREN #	Loading evidence on Head	C-Spine Injury AIS Codes	Description	Notes	Quarter Turn of Head-Neck Loading	Other AIS 2 Fx and AIS3+ Injuries	Most Sig Injury
781125527	Abrasion to left temporal region	6502302\6502302	C2 teardrop fx\ C1 anterior body fx	Mildly displaced inferior anterior aspect of vert body\ displaced left superior anterior aspect (S2)	2 or 6	Clavicle fx	C-spine
852126192	Right side scalp abrasion	6502102\6502242\ 6502222\6502202	C5-6 unilateral facet dislocation\ C5 laminae fx\ C6 left facet fx\ C4, C6 left transverse process fx	Left-sided, jumped facet\ bilateral\\ moderately comminuted, involves transverse foramen (S1,L4)	2		C-spine
852130600	Contusion above left eye	6402063	C6-7 BFD	Grade II Anterolisthesis with transient neurological signs (S1)	2	Lumbar spine fxs, subarachnoid hemorrhage	C-spine
852162058	Right side facial lacerations	6502222\6502262	C3-C4 right facet fx\ C4 right pedicle fx	C4 superior, C3-C4 inferior, involving lateral mass\ involving transverse foramen (R4)	2		C-spine
852172396	Contusion to right side temporal region	6502242\6502222	C6 left lamina fx\ C6 left facet fx	Minimally displaced\ left inferior articulating facet (L2)	6		C-spine
852177768	No head/facial injury	6502222\6502202	C7 right facet fx\ C7 right transverse process fx	Superior articulating facet\ (R2)	2 or 6	Pulmonary contusion w/ rib fxs, right tibia fx, right fibula fx	Thorax
857069807	Laceration to posterior scalp	6502222\6502322	C6-C7 right facet fx\ C7 vertebral body endplate fx	\with retropulsion into spinal canal (S1,R2)	2 or 6	Clavicle fx	C-spine
857076778	Facial skin contusion	6502242\ 6502202	C1 posterior ring fx\ C7 left transverse process fx	Jefferson fracture probable\ including superior facet (S1,L1)	2 or 6	Right tibia fx, T3-T4 vert body fx, right fibula fx, talus fx	Lower Extremity
965066489	Superficial avulsion to posterior scalp	6502202	C7 left transverse process fx	Extending into superior facet (L1)	2 or 6	Bilateral pulmonary contusions	Thorax

Table 6. Cervical spine injury details for each CIREN case occupant. Number of symmetric (S), left-sided (L), and right-sided (R) injuries are displayed in parentheses.

While the current body of cervical spine compression literature seems to capture the distribution and mechanism of catastrophic cervical spine injuries in rollover, the representation of the full spectrum of field injuries seems to be significantly different. One suggested reason for this difference is that cadaveric specimens lack musculature, inferring that the clinical presentation of injury to a live subject could be altered or aggravated by the contraction of active neck musculature [12,34]. However, data exist that show muscle contraction occurring after bony fracture to the spine, thus too late in the loading time-history for active musculature to have effect [15,27,35,36].

Passive musculature, however, which preloads the cervical column, could have an effect on injury outcome and could be a possible reason for injury differences in CIREN occupants and cadaver specimens. In the crash cases, eight of the 23 case occupants exhibited bilateral or unilateral facet dislocations or subluxations, almost always (7 out of 8) with evidence of shearing at the intervertebral space (i.e., facet fracture). Evidence of shearing involves articular facet, or lateral aspect fractures at the level of subluxation. These “impaction fractures” have been closely associated with facet dislocations [37]. Although they typically do not have significance to the patient's outcome, fractures to the articular masses during facet dislocation further evidence a shearing translation without distraction of the upper motion segment with respect to the inferior vertebra. Facet dislocations have previously been associated with a distractive-flexion mechanism at the local level [15,32]. The high incidence of facet dislocation impaction fractures *in vivo* indicates an injury mechanism where the inferior articular facets are shearing through the superior facets of the inferior vertebra and not “jumping” the facets as its colloquial name implies. Such adjoining articular mass fractures are absent in the 19 facet dislocations found in the existing literature. One specimen, 202 from Pintar et al. [6], had contiguous facet fractures, or evidence of possible shearing. However, this specimen displayed retrolisthesis, or posterior dislocation, which is not clinically seen in compressive neck trauma. Passive musculature or pre-loading due to bracing before impact could explain why shearing fractures are present in the field and not in cadaveric specimens.

None of the case occupants chosen for this study sustained a collection of injuries that have been fully replicated by a single specimen *in vitro*. In other words, in no case did one experimental specimen fully encapsulate an entire case occupant's injuries. It should also be noted than injury patterns within each set of experiments were not internally consistent either, despite the best efforts of the researchers to control the impact orientations and energies. When determining the injury mechanisms on the local level for each of the CIREN occupant's neck injuries, multiple specimens had to be used to describe the complete injury pattern. For example, CIREN case occupant 163690, a 42 year-old male seated as the front right passenger, was involved in a 4-quarter turn rollover. He was positioned on the far side of the roll. The vehicle traveled down an embankment and underwent significant intrusion over the passenger seat from the A-pillar and B-pillar. He sustained a bilateral facet dislocation at the C5-C6 level, with fractures to the C5 laminae, the right C5 superior facet, C6 right facet and transverse process, and right C7 transverse process. The occupant suffered a scalp abrasion and contact evidence (hair) indicated contact with the roof near the roof side rail. When considering the biomechanical literature, three bilateral facet dislocations to the C5-C6 interfacetal level have been produced in cadavers: Specimens 207 [6], HS77 [9] and G [8]. The right C7 transverse process fracture in the case occupant was shown in Specimen 77H109 [22]. However, there was also a C7 spinous process fracture in this cadaver, which was not present in the case occupant. No other C7 transverse process fracture has been produced experimentally. Transverse process fractures are underrepresented in the experimental studies as their mechanism is likely due to tractions from the active levator, longissimus and intertransversarii muscles, which all insert or originate on the tubercles of the transverse processes. This is an inherent limitation of cadaveric tissue. This example demonstrates that global axial compression was the key loading component, but deducing injury mechanism at the local level can be more complicated due to lack of representation *in vitro*.

Major differences between the current body of literature and the epidemiological findings lie in the distributions of clinically-relevant rollover injury types, location of fracture and symmetry of fracture. It is well understood that the distribution of injuries in the CIREN cases should in no way match the distribution of injuries in the biomechanics literature; the percentages have been compared as a way of describing the discrepancies in injury distributions between field data and laboratory tests. Exact distributions are not necessary, but it should be expected that the relative rankings of the type of injury and fracture location be fairly similar. Discrepancies in the distribution of injuries by vertebral level can be explained by Ryan and Henderson [38]. From an epidemiology study of 657 patients with cervical spine injury, the authors found that older age groups were more likely to sustain upper cervical spine trauma, while a greater percentage of younger age groups sustained lower cervical spine trauma. Age could account for the higher number of C6-C7 fractures seen in the case occupants versus the cadaver specimens (Table 4). The average age of cadavers included in this study was 63.8 years (±12.4 years), which is 22.6 years older than the average age of the CIREN occupants.

Axial loading in the cephalocaudal direction was found to be the predominant loading component responsible for injury in all of the CIREN occupants. Previously, authors have surmised that axial loading takes place during the rollover event based on dummy loading in dynamic rollover tests [2,39,40]. The current study tested this hypothesis by analyzing clinical rollover injuries. Through assessing this finding, laterally eccentric load vectors were found to be associated with injury in the field data at a high level of incidence. This is not the case in existing cadaver studies. Fracture of the articular facets was the most common injury sustained by the rollover-involved CIREN occupants at 34.7% of their total fractures, while this fracture was only seen 9 times in the 170 cadaver specimens. Vertebral body fractures, including burst, teardrop, and wedge fractures, were the most prevalent injuries produced in cadaver tests; 96 of these injuries were produced. In contrast, vertebral body fractures were the third most common injury in the CIREN occupants. The second most prevalent injuries in cadaver studies were spinous process fracture, which occurred 44 times (20.5%) in the cadaver but only three times (4.2%) in the CIREN occupants.

The anterior bony vertebral body and posterior spinous process both lie along the AP axis. The vertebral body fractures mentioned were most likely sustained by a vertical compression or compression-flexion mechanism, while spinous process fractures usually have a pure-extension or compression-extension injury mechanism [15,32]. Injuries to the vertebral body and spinous process usually do not require any lateral, asymmetric loading to occur. The combined value of vertebral body and spinous process fractures shows that 65.1% of the total fractures in cadaver tests have no lateral nature. In the CIREN case occupants, the vertebral body and spinous process fractures made up 18.1% of the total injuries. Further, fractures that occur bilaterally at a given vertebral level indicate forces aligned in the sagittal plane [23], while unilateral fractures indicate a situation where compressive force, shearing, or torsional force was greater on one side [41]. In a bilateral fracture, these forces are assumed to be symmetrically dissipated. Since both bilateral fractures and AP fractures involve symmetric sagittal plane loading, bilateral fractures can be combined with mid-sagittal plane fractures to show that 85.6% of the cadaver test fractures resulted from sagittal plane loading, versus 33.3% in CIREN occupants.

Injuries pertaining to lateral bending and lateral loading have been studied for the purposes of automotive side impacts [42]. Thus, the component of axial compression associated with rollover has rarely been combined with lateral loading in experimental tests. A number of authors believe that preexisting structural asymmetries in the human spine can lead to out-of-plane bending and unilateral injuries [43]. It is likely that lateral bending, torsion or twist, and anatomical asymmetries when combined with a compressive load could help to explain common rollover-related injuries, but have been seldom explored. Panjabi et al. [44] loaded ten human cervical spine specimens with axial rotation (about the longitudinal axis) and lateral bending. However, the study was performed to determine physiological motion parameters of only the occiput to C2 and injurious levels were not reached. Panjabi et al. [45] later loaded eight osteoligamentous cervical spines, allowing lateral bending until buckling occurred; yet injury may not have been produced as no pathology is provided.

Nusholtz et al. [19] conducted a test series attempting to study the effects of loading upon non-mid-sagittal initial postures. Eight cadaver specimens were dropped on their heads in seated positions with their head, neck, and mid-spine positioned in various orientations. Multiple specimens were given lateral eccentricities of the head and neck, as well as initial torsion or twist about the neck's longitudinal axis before impact. However, all but one of these specimens (Specimen 8) were retested several times. Toomey et al. [14] loaded head-cervical spine specimens obliquely or with initial lateral eccentricity, citing rollover as an experimental motivation. As a result, the authors produced injuries similar in fracture type and location to those seen in the CIREN occupants. As they loaded the skull with an oblique vector, they produced 12 fractures, eight of which were purely unilateral in nature, including facet, pedicle and lamina fractures. These data associate the authors' methods to a spectrum of injuries that is more similar to the CIREN field data. As their study involved only three cadaver tests that displayed injury, future investigations are needed and should involve a similar asymmetric load vector.

The unilateral articular facet fracture that extends into the ipsilateral pedicle or transverse process is one of the most common cervical spine injuries sustained in rollover crashes, present in eleven different CIREN case occupants. This fracture was present in 2 of 6 AIS 4+ injuries. Allen et al. [32] attributes a compression-extension mechanism to this injury, 27 years before the first of its type was produced experimentally in a cadaver (Specimen 3 [14]). While this fracture pattern may be associated with extension and compression, it is typically seen on one side rather than bilaterally in rollover-involved occupants. Further, three of the CIREN case occupants sustained unilateral facet dislocations. While the mechanism associated with this injury is believed to be flexion with simultaneous rotation about the longitudinal axis [46], no UFDs have been produced in the 170 cadaver tests. It is the understanding of the authors of this study that tested cadaver specimens have displayed facet dislocations visible in high speed video that were not detected in post-test necropsy due to the lack of musculature that would hold the locked facet configuration in place. Therefore, the number of UFDs and BFDs may be underrepresented in the cadaver population.

Reasons for the infrequent employment of lateral loading bias in the literature may be related to the lower severity nature of unilateral injuries compared to bilateral or AP injuries. Of the 51 unilateral fractures and dislocations, 48 (94.1%) were AIS 2 fractures; the remaining were two AIS 3 unilateral facet dislocations and an AIS 5 unilateral locked facet resulting in a cord contusion. Fifty percent of bilateral injuries were AIS 3 or higher, reinforcing the conventional wisdom that AP and bilateral injuries are more catastrophic and a reason why unilateral injuries have been less extensively investigated.

V. CONCLUSIONS

This study examined the applicability of existing literature to rollover and rollover-involved occupants' injuries. Specific descriptions and associated mechanisms of injuries sustained by rollover-involved occupants are absent from the existing literature, which limits the applicability of existing studies on cervical spine injury tolerance in developing injury criteria for rollover-induced injuries. The current study examined this by analyzing the pathologies and specific spinal injury mechanisms from 23 CIREN rollover crash cases and comparing the cervical spine injuries suffered by the case occupants to those produced in 170 cadaver tests. This methodology for determining injury mechanism was applied to each CIREN case, where single cadaveric specimens could not be used to fully explain a CIREN occupant's collection of injuries. In most CIREN cases, occupants suffered at least one unilateral fracture, indicating an asymmetric loading scenario, one that has been infrequently recreated *in vitro*. Possible reasons for this may be due to the less severe nature of lateral injuries compared to AP or bilateral injuries, such as BFD. Facet dislocations were produced experimentally, but often lacking the associated fractures evidenced in most of the case occupants with facet dislocations. Passive musculature and muscle tensing may be responsible for the associated fractures in the living population and muscle spasms may also explain the deficit in UFDs in the cadaveric population. The overarching conclusion of the study is that all rollover-involved CIREN occupants appeared to experience an axial load in the cephalocaudal direction as the primary loading mechanism. However, more compressive neck injury tolerance studies are needed to highlight the differences in injury patterns in rollovers versus the current experimental body of literature. The presence of non-sagittal loading can alter the injury pattern and is a likely cause of this difference. These findings further suggest the need to examine the effects of asymmetric loading and active musculature on cervical spine injury patterns to further understand the differences between experimental studies and those in the field.

VI. REFERENCES

[1] Ridella SA, Eigen AM, Biomechanical investigation of injury mechanism in rollover crashes from the CIREN database, *Proceedings of IRCOBI Conference,* Bern, Switzerland, pages 33-47, 2008.

[2] Viano DC, Parenteau CS, Analysis of head impacts causing neck compression injury, *Traffic Injury Prevention*, 9, 2, 144-52, 2008.

[3] McElhaney J, Snyder RG, States JD, Gabrielsen MA, Biomechanical analysis of swimming pool neck injuries. *Society of Automotive Engineers, Inc.*, 47-53, 1979.

[4] Bauze RJ, Ardran GM, Experimental production of forward dislocation in the human cervical spine, *J Bone Joint Surgery*, 60, 239-45, 1978.

[5] Hodgson VR, Thomas LM, Mechanisms of cervical spine injury during impact to the protected head, *Society of Automotive Engineers, Inc.*, 17-42, 1980.

[6] Pintar FA, Larson SJ, Harris G, Reinartz J, Sances A, Yoganandan N, Kinematic and Anatomical Analysis of the Human Cervical Spinal Column Under Axial Loading, *Proceedings of the 33rd Stapp Car Crash Conference*, Washington, DC, pages 191-214, 1989.

[7] Pintar FA, Sances A, Yoganandan N, Biodynamics of the total human cervical spine, *Proceedings of the 34th Stapp Car Crash Conference*, Orlando, FL, pages 55-72, 1990.

[8] Myers BS, Nightingale RW, McElhaney JH, Doherty DJ, Richardson WJ, The Influence of end condition on human cervical spine injury mechanisms, *Society of Automotive Engineers, Inc.*, 391-99, 1991.

[9] Yoganandan N, Sances A, Maiman DJ, Myklebust JB, Pech P, Larson SJ, Experimental Spinal Injuries with Vertical Impact, *Spine*, 11, 9, 855-60, 1986.

[10] Yoganandan N, Sances A, Pintar F, Maiman DJ, Reinartz J, Cusick JF, Larson SJ, Injury biomechanics of the human cervical column, *Spine*, 15, 10, 1031-9, 1990.

[11] Pintar FA, Yoganandan N, Voo L, Cusick JF, Maiman DJ, Sances A, Dynamic Characteristics of the Human Cervical Spine, *Society of Automotive Engineers, Inc.*, 195-202, 1995.

[12] Pintar FA, Voo LM, Yoganandan N, Cho TH, Maiman DJ, Mechanisms of hyperflexion cervical spine injury, *IRCOBI Conference Proceedings*, Goteborg, Sweden, pages 249-60, 1998.

[13] McElhaney JH, Doherty BJ, Paver JG, Myers BS, Gray L, Combined bending and axial loading responses of the human cervical spine, *Proceedings of the 32nd Stapp Car Crash Conference*, Atlanta, GA, pages 21-28, 1988.

[14] Toomey DE, Mason MJ, Hardy WN, Yang KH, Kopacz JM, Exploring the role of lateral bending postures and asymmetric loading on cervical spine compression responses, *Proceedings of the ASME 2009 International Mechanical Engineering Congress & Exposition*, Lake Buena Vista, FL, pages 1-8, 2009.

[15] Nightingale RW, McElhaney JH, Camacho DL, Kleinberger M, Winkelstein BA, Myers BS, The dynamic responses of the cervical spine: buckling, end conditions, and tolerance in compressive impacts, *Proceedings of the 41st Stapp Car Crash Conference*, Lake Buena Vista, FL, pages 451–71, 1997.

[16] Raddin J, Cormier J, Smyth B, Croteau J, Cooper E, Compressive neck injury and its relationship to head contact and torso motion during vehicle rollovers, *Society of Automotive Engineers, Inc*, 2009.

[17] Young D, Grzebieta R, McIntosh A, Bambach M, Frechede B, Diving versus roof intrusion: a review of rollover injury causation, *International Journal of Crashworthiness,* 12, 6, 609-28, 2007.

[18] Crash Injury Research Engineering Network Coding Manual Version 2.0.July, 2010.

[19] Nusholtz GS, Huelke DF, Lux P, Alem NM, Montalvo F, Cervical spine injury mechanisms, *Proceedings of the 27th Stapp Car Crash Conference*, pages 179-97, 1983.

[20] Alem NM, Nusholtz GS, Melvin JW, Head and Neck Response to Axial Impacts, *Proceedings of the 28thStapp Car Crash Conference*, Chicago, IL, pages 275-88, 1984.

[21] Nusholtz GS, Melvin JW, Huelke DF, Alen NM, Blank JG, Response of the cervical spine to superior-inferior head impact, *Proceedings of the 25th Stapp Car Crash Conference*, San Francisco, CA, pages 197-237, 1981.

[22] Culver RH, Bender M, Melvin JS, Mechanisms, Tolerances, and Responses obtained under dynamic superior-inferior head impact. Final Report: UM-HSRI-78-21, 1978.

[23] Maiman DJ, Sances A, Myklebust JB, Compression injuries of the cervical spine; a biomechanical analysis, *Neurosurgery*, 13, 3, 254-60, 1983.

[24] Yoganandan N, Sances, A, Pintar F, Biomechanical evaluation of the axial compressive responses of the human cadaveric and manakin necksm, *J Biomech Eng*, 111, 250-5, 1989.

[25] Sances AJ, Yoganandan N, Maiman DJ, Myklebust JB, Larson SJ, Pintar F, Myers T, Spinal Injuries with Vertical Impact, *Mechanisms of Head and Spine Injuries*, Aloray Publisher, Goshen, NY, pages 305-48, 1986.

[26] Yoganandan N, Pintar FA, Arnold P, Reinartz J, Cusick JF, Maiman DJ, Continuous motion analysis of the head–neck complex under impact, *J Spinal Disord*, 7, 420–8, 1994.

[27] Nightingale RW, McElhaney JH, Richardson WJ, Myers BS, Dynamic responses of the head and cervical spine to axial impact loading, *J Biomechanics*, 29, 307–18, 1996.

[28] McElhaney JH, Paver JG, McCrackin HJ, Maxwell GM, Cervical spine compression responses, *Proceedings of the 27th Stapp Car Crash Conference*, San Diego, CA, pages 163-77, 1983.

[29] Paver JG, Friedman D, Carlin F, Bish J, Caplinger J, Rohde D, Rollover crash neck injury replication and injury potential assessment, *IRCOBI Conference Proceedings*, Bern, Switzerland, pages 421-4, 2008.

[30] Moffatt EA, James MB. Headroom, roof crush, and belted excursion in rollovers, *SAE World Congress Technical Paper*, Detroit, MI, 2005.

[31] Roaf R. A study of the mechanics of spinal injury, *J Bone Joint Surg*, 42B, 810-23, 1960.

[32] Allen BL, Ferguson RL, Lehmann TR, O'Brien RP, A mechanistic classification of closed, indirect fractures and dislocations of the lower cervical spine, *Spine,* 7, 1, 1-27, 1982.

[33] White AA, Panjabi MM, *Clinical Biomechanics of the Spine 1st Ed.*, JB Lippincott Company, Philadelphia, PA, 1978.

[34] Crawford NR, Duggal N, Chamberlain RH, Park SC, Sonntag VK, Dickman CA, Unilateral cervical facet dislocation: injury mechanism and biomechanical consequences, *Spine,* 27, 17, 1858-64, 2002.

[35] Cusick FJ, Yoganandan N, Biomechanics of the cervical spine 4: major injuries, *Clinical Biomechanics*, 17, 1-20, 2002.

[36] Foust DR, Chaffin DB, Snyder RG, Baum JK, Cervical range of motion and dynamic response and strength of cervical muscles, *Proceedings of the 17th Stapp Car Crash Conference*, Oklahoma City, OK, pages 285-308, 1973.

[37] Harris JH Jr, Edeiken-Monroe B, Kopaniky DR, A practical classification of acute cervical spine injuries, *Orthopedic Clinics of North America*, 17, 1, 15-30, 1986.

[38] Ryan MD, Henderson JJ, The epidemiology of fractures and fracture-dislocations of the cervical spine. *Injury: the British Journal of Accident Surgery*, 23, 1, 38-40, 1992.

[39] Bahling GS, Bundorf RT, Kaspzyk GS, Moffatt EA, Orlowski KF, Stocke JE, Rollovers and drop tests: the influence of roof strength on injury mechanics using belted dummies, *Proceedings of the 34th Stapp Car Crash Conference*, Orlando, FL, pages 101-12, 1990.

[40] James MB, Nordhagen RP, Schneider DC, Kosh SW, Occupant injury in rollover crashes: a reexamination of Malibu II, SAE World Congress Technical Paper, Detroit, Michigan, 2007.

[41] Myers BS, Winkelstein BA, Epidemiology, classification, mechanism, and tolerance of human cervical spine injuries, *Critical Reviews in Biomedical Engineering*, 23, 5, 307-409, 1995.

[42] Kallieris D, Schmidt G, Neck response and injury assessment using cadavers and the US-SID for far-side lateral impacts of rear seat occupants with inboard-anchored shoulder belts, *Proceedings of the 34th Stapp Car Crash Conference,* Orlando, FL, pages 93-100, 1990.

[43] McElhaney JH, Nightingale RW, Winkelstein BA, Chancey VC, and Myers BS, Biomechanical aspects of cervical trauma. *Accidental Injury: Biomechanics and Prevention, 2nd ed.*, Springer-Berlag, New York, New York, 2002.

[44] Panjabi MM, Dvorak J, Duranceau J, Yamamoto I, Gerber M, Raushning W, Bueff HU, Three-dimensional movements of the upper cervical spine, *Spine*, 13, 7, 726-30, 1988.

[45] Panjabi MM, Cholewicki J, Nibu K, Grauer J, Babat LB, Dvorak J, Critical load of the human cervical spine: an in vitro experimental study, *Clinical Biomechanics*, 13, 1, 11-17, 1998.

[46] Braakman R, Vinken PJ, Unilateral facet interlocking in the lower cervical spine, *J Bone Joint Surgery*, 49B, 2, 249-257, 1967.