Is BFD a Hyperflexion Injury or Compression with Localized Bending Injury or Both?

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Abstract - Few biomechanical engineers have had the opportunity to study post-mortem human subjects or anthropomorphic test dummies in an instrumented, controlled rollover test environment. It is no surprise that there is a lack of consensus with respect to human cervical spine injury mechanisms in rollovers and head-neck alignment with respect to the roof intrusion vector. In the 1980's and 1990's, this lead author conducted experiments on fresh cadaveric head-neck specimens that produced bilateral facet dislocation (BFD) injuries with rotation constraint. Pintar et al. produced BFD with hyperflexion. Nightingale et al. produced BFD with compression, causing column buckling and localized lower neck flexion. The authors of this paper opine that mechanical determinants dictate the injury patterns when the neck is overloaded and fails. BFD failure occurs by 3 known mechanisms: hyperflexion; compression with rotation constraints; or compression with higher-order buckling (i.e., localized bending). The validity of the hyperflexion mechanism does not preclude the validity of compression mechanisms, or vice versa. It is possible for the roof intrusion force vector to be aligned with the head, neck, and spine. However, because the varying vehicle yaw and pitch upon ground-roof contact, it is more likely that the preponderance of the catastrophic rollover neck injuries are bending injuries.

Keywords: Rollover Crash, Cervical Spine Injury, Compression, Bending

INTRODUCTION

Principles of injury mechanism analysis

A biomechanical engineer approaches the issue of injury causation and injury potential by viewing the human body as an engineering system. For years, scientists have tested engineering systems (i.e., simple materials, as well as complex structures) to determine their responses to applied loading. They found that failure occurs in patterns that relate to the applied loading in accordance to scientific principles. Using the same methodology, the applied external loading associated with a causative "event" and the human body's response to that loading can be analyzed with respect to its injury patterns. Mechanical tests of human structures and studies of human injury mechanisms relate mechanical determinants of injury to the resultant injury patterns. To establish a relationship between a crash and injury, injury patterns must be consistent with the mechanical determinants of injury.

The cervical spine as an engineering system

The cervical spine is a nonhomogeneous, nonisotropic, and nonlinear engineering structure. Its motions and loadings are coupled. The cervical spine has 2 primary functions:

- to support the head, and
- to protect the spinal cord.

Failure of the spine is the result of coupled motion beyond its physiological range and coupled loading exceeding human tolerance. The strength of the cervical spine is more than adequate for most activities of daily living; however, it can be exceeded when subjected to the energies associated with motor vehicle crashes.

BIOMECHANICAL ANALYSIS OF NECK INJURY PATTERNS AND MECHANISMS

For catastrophic spinal injury, mechanical determinants may include:

- initial neck curvature (e.g., preflexion),
- end conditions or constraints (e.g., stiffness, damping, and frictional characteristics of the head impact surface),
- position (e.g., eccentricity), type/direction, magnitude and speed of the applied loading, and/or
- muscular response.

Utilizing accepted scientific methodology:

- engineers define mechanical determinants that describe the applied loading and dictate the resulting injury patterns, and
- conversely, the injury patterns dictate the relevant mechanical determinants.

Given an injury pattern(s), the applied loading and head-neck alignment can be determined.

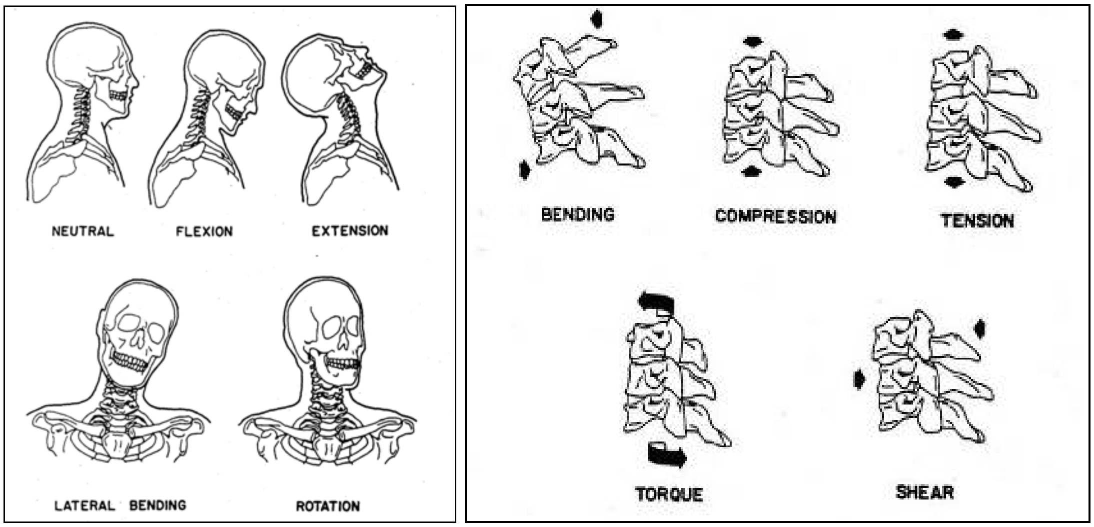

Figure 1. Types/directions of head motion and neck loading [1]

Mechanical determinants that dictate cervical spine injury patterns

Catastrophic cervical spine injuries commonly seen in rollover crashes result from head impact with varying magnitudes of axial and shear neck loading and varying degrees of head-neck torsion and bending. Clinically-established injury patterns have been produced experimentally in the laboratory using isolated cadaveric cervical spine segments and whole cadavers subjected to head impacts. Clearly, testing cadaveric spines in the laboratory provides valuable biomechanical information; however, the lack of musculature is a significant limitation known to affect injury patterns.

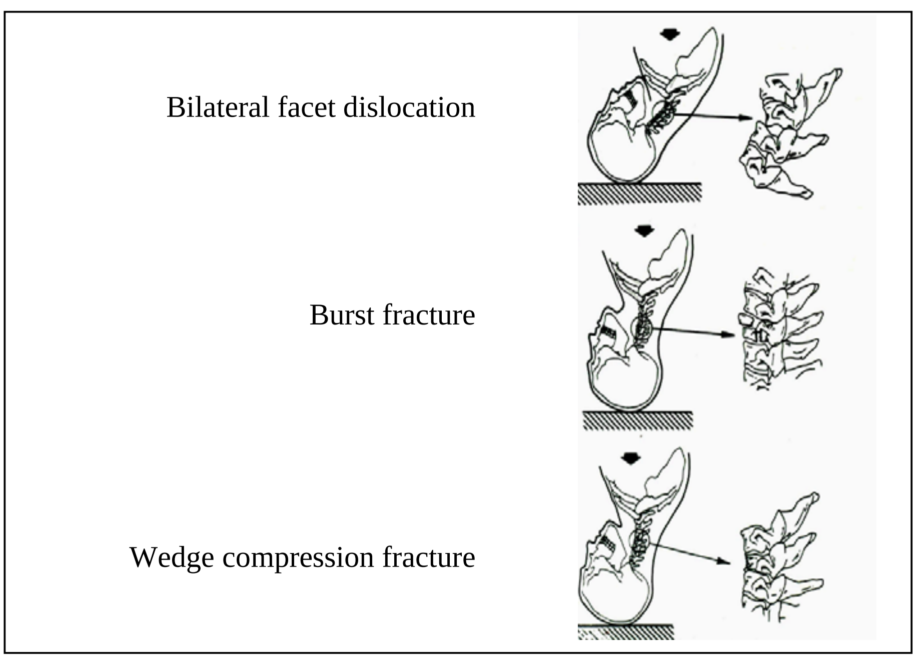

Figure 2. Typical cervical spine injury patterns that occur with head impact [2]

The effect of the initial curvature (e.g., preflexion) of the head and neck relative to the thorax and impact surface on neck injury patterns was investigated. In rollovers, preflexion due to braking, reflexive "ducking," belt lockup, and/or lack of headroom removes the natural lordosis of the neck, producing an axially-aligned or straightened structure approximating a segmented column. Nightingale et al. reported that a burst fracture was more likely to occur in the straightened spine than in the neutrally-positioned (i.e., lordotic) spine, and that a BFD was more likely to occur in the lordotic spine than in the straightened spine [3].

End conditions or constraints, and the magnitude and speed of the applied loading are mechanical determinants that dictate the resulting cervical spine injury patterns that occur with head impact [4].

- With full-constraints, head impact speeds of 11 kph (7 mph or 10 ft/sec), equivalent to a 46 cm (18") drop height, produce neck compression, wedge compression, and/or burst fractures.
- With rotation-constraints, lower head impact speeds (and drop heights) produce BFD.

End conditions are defined in part by the stiffness, damping, and frictional characteristics of the head impact surface [5]. Injury risk is greatest in padded impacts, where the head pockets in the impact surface (e.g., a gymnastics mat or bounce house for kids), because the head and neck cannot escape the path of the free-and-following torso. Injury risk is less in rigid impacts because the head and neck can escape the path of the free-and-following torso and thereby avoid failure.

Winkelstein and Myers related eccentricity, defined as the perpendicular distance from the sagittal plane resultant force to the spine, to cervical spine injury patterns [6]. They found that increasing eccentricity from posterior to anterior changed the injury pattern from posterior element failure to vertebral body failure (i.e., compression, burst, and wedge compression fractures) and, when located most anteriorly, to facet dislocation. McElhaney et al. demonstrated that eccentricities of about 1 cm (0.4") anterior to those that cause compression or burst fracture produced wedge compression fracture; thus, a wedge compression fracture requires a larger ratio of bending moment to compressive force than a compression or burst fracture. A change of as little as 15º in head orientation relative to the impact surface can make the difference between "no neck injury" and quadriplegia [7].

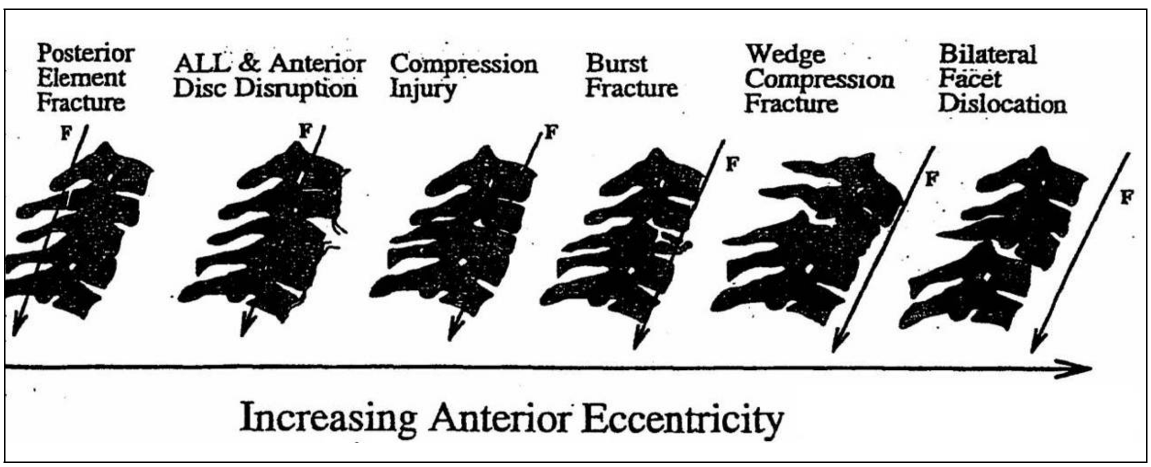

Figure 3. Effect of eccentricity on neck injury patterns [8]

The type/direction of the applied neck loading dictates the resulting neck injury pattern. Examples include, but are not limited to compression, which produces vertebral body compression and burst fractures; hyperflexion, which produces BFD; tension, which produces occipitoatlantal dislocation; extension, which produces anterior longitudinal ligament tears with disc compromise; and torsion, which produces unilateral atlantoaxial facet dislocation [9].

Recent laboratory tests indicate that peak neck loads occur almost instantaneously, whereas the momentum exchange takes longer and requires neck preflexion and significantly greater stroke [10].

- The onset-to-peak neck loading was fast and independent of speed.
- Lower neck moment duration was independent of speed.
- The onset-to-peak neck loading was fast and independent of stroke.
- Peak neck loading, which occurred quickly, was independent of stroke.
- Lower neck moment duration was dependent on stroke.

BFD injury pattern

Key features of the BFD injury pattern are illustrated in Figure 4 and described below. BFD occurs primarily in the lower cervical spine with [11]:

- disruption of posterior ligamentous structures,
- sliding up of the upper facet (perched facets) over the top (jumped facets) of the lower facet and locking in a tooth-to-tooth manner (locked facets) with anterior dislocation, and
- facet compromise and/or vertebral body compression or anterior wedge compression.

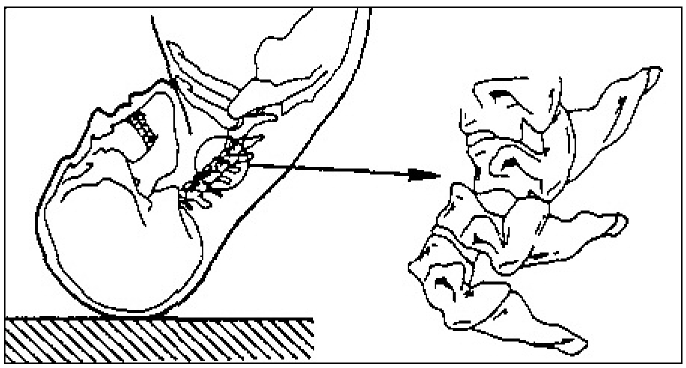

Figure 4. BFD [12]

BFD mechanism of injury

The mechanism of the BFD has been disputed over the years. In 1960, Roaf reported difficulties producing neck flexion injury [13]. In 1978, Bauze and Ardran produced BFD by applying compression while restricting head rotation [14]. In 1991, Myers et al. produced BFD, similar to Bauze and Ardran, by applying compression while restricting head rotation, but could not produce BFD with flexion [15]. In 1996 and 1997, Nightingale et al. produced BFD [16]. They found that the neck acted like a segmented column beam, and opined that only buckling with localized flexion produced BFD. It is noteworthy that the noncontiguous injuries that occurred with higher-order buckling modes in the laboratory are rarely seen clinically.

In 1998, Pintar et al. reported that BFD could be produced when the force vector to the head placed the spine in a predominantly flexion bending mode, as illustrated in Figure 5 [17]. First, flexion produced tearing of the lower cervical spine posterior ligaments, where the bending moments were greatest. Then, as hyperflexion disrupted the joint, contraction of the extensor and flexor muscles slid the upper portion of the dislocated cervical spine forward and down (i.e., compression), causing the superior facet to lock in front of the inferior facet. An important finding of this study was that, absent neck musculature in the cadaver specimens in the laboratory, Pintar et al. produced BFD, but could not lock the facets.

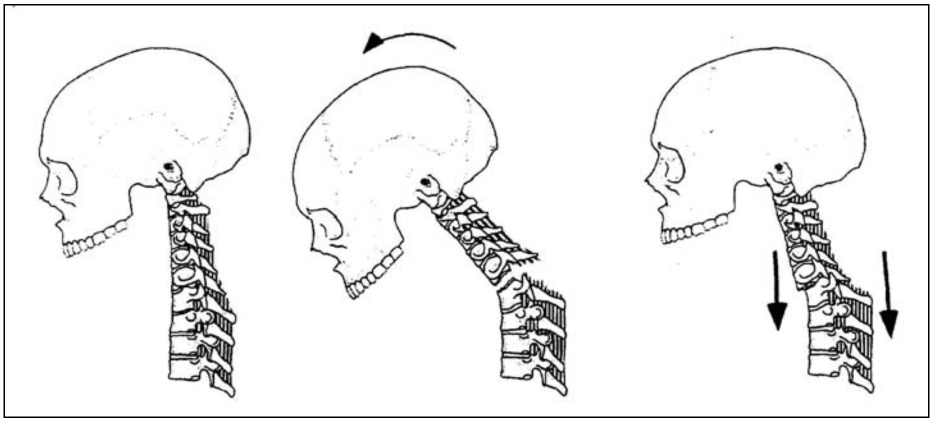

Figure 5. Mechanism of BFD with locked facets [18]

Neck injury tolerance

Almost all cervical spine fractures occur when the neck is required to manage the energy of the torso. Typically, upon head contact, the head stops and the neck must stop the free-and-following torso. Fractures of the cervical spine, due to compression, occurred at axial forces of [19,20]:

- 3,600-4,000 N for average healthy males, and
- 2,200-2,400 N for females.

Pintar et al. found that neck axial loads tended to peak before neck bending moments and before neck injury [21]. Vertebral body fractures were caused by axial forces, whereas BFD with ligamentous disruption was caused by bending. They opined a BFD threshold as a function of both axial neck load and neck bending moment at the site of injury:

- Compression force = 1,850 N
- Injury bending moment = 62 N-m.

Others opine that flexion bending moments are the dominant form of loading resulting in BFD [22,23]. Voo et al. suggested that compression fractures result from forces greater than 2,000 N, whereas bending injuries result from forces less than 2,000 N and moments exceeding 65 N-m [24]. McElhaney et al. opined that, "When the load is eccentric (as it almost always is), the primary deformation mode is bending. Axial load is a poor indicator of the type and magnitude of failure stress [25]."

Cervical spine compression at failure

The magnitude of neck compression at failure has been documented. Pintar et al. reported a mean of 1.8 cm (0.7") in straightened spines [26]. Myers et al. reported a mean of 1.4 cm (0.6") in neutrally-positioned (lordotic) spines [27]. McElhaney et al. measured 2.9 cm for BFD [28].

Onset time to injury

The time to injury is important in rollover crashes because manufacturers use the temporal relationship between peak load (and injury) and significant roof crush to refute any causal relationship between them. Pintar et al. produced neck fracture in straightened spines less than 7 ms after impact, and Nightingale et al. produced injury in lordotic spines in 2 to 6 ms in rigid impacts and 15 to 30 ms in padded impacts [29].

These onset times to injury are significantly shorter than the reported 60 ms required for muscle activation [30]. Nightingale et al. concluded that active muscle response plays a minimal role in compression injuries [31]. However, in real-world rollover crashes, the elapsed time from loss of control to head impact is significantly greater than 60 ms. Clearly, the occupant has ample time for muscle activation, and its role cannot be discounted.

Head motion as a predictor of injury

Nightingale et al. claimed that, since compression neck fracture occurs so fast, there is simply insufficient time for the head and neck to flex beyond its physiological range of motion. Specifically, head rotations greater than 20° occurred as much as 80 ms after impact and prior to significant head rotations, which peak at least 150 ms after impact [32,33]. The flaw in this logic is that peak neck load, although a good predictor of neck compression fracture, is not a good predictor of other neck injury patterns (e.g., hyperflexion). The implication is that muscles do not play an important role in stabilizing the cervical spine during impact loading.

THE ROLLOVER ENVIRONMENT

A primary objective of NHTSA's dynamic rollover program in 2009 was the development of a real-world rollover test protocol. The Center for Injury Research responded with an analysis of a 2-roll road-tripped event characterized by 10 segments from loss of control to rest. Findings included:

- Pre-trip yaw results in 0.7 to 1 G near-side lateral loading on occupants typically at 60° to 80° to the front of the vehicle.
- Angular acceleration during trip results in 0.6 to 2 G loading on the far-side occupant producing head-neck flexion.
- The 20+ mph high-speed ballistic trajectory of the 1st roll is the most likely source of far-side head-neck roof contact injury.
- Structural deformation of the front far-side roof is typically greater than 10° in pitch and yaw.

CATASTROPHIC NECK INJURIES IN ROLLOVER CRASHES

Catastrophic spine and spinal cord injuries resulting in quadriplegia are common foreseeable outcomes of rollover crashes. For contained occupants, these injuries are typically a direct result of head interaction with a vehicle's roof structure. Compression injuries are not disputed. However, bending injuries occur with much greater frequency than compression injuries [34] because:

- the neck is not tensed;
- preflexion of the human neck due to braking, reflexive "ducking," belt lockup, and/or lack of headroom removes the natural lordosis of the human neck, producing an axially-aligned or straightened structure approximating a segmented column;
- the human spinal column is not usually aligned at the time of roof impact due to its curvature (lordosis in the cervical and lumbar spines and kyphosis in the thoracic spine);
- the orientation and application of roof crush force and speed is eccentric, not aligned with respect to the center of mass of the head, neck, and thorax of restrained and unrestrained occupants; and
- it is extremely unlikely that the axially-aligned head and neck are aligned with the intruding roof vector, which itself is varying with vehicle pitch and yaw.

Cervical spine injury mechanisms in rollovers: Diving theory vs. roof crush theory [35]

Diving theory

Automobile manufacturers hypothesize that the mechanism of neck injury in rollover crashes is diving, where the head stops suddenly upon roof-ground contact, and the neck is loaded by the momentum of the free-and-following torso and extremities [36,37,38]. For example, in shallow-water diving, catastrophic neck injury occurs when the diver's head impacts the ocean bottom. The head stops in the sand and rebounds while the remainder of the body continues moving toward the ocean bottom, loading the neck to failure primarily in compression, as shown in Figure 6. Neck injury typically occurs in the lower cervical spine without head injury because the force to fail the neck is less than the force required to fracture the skull. Compression, burst, and wedge compression fractures are the typical diving neck injury patterns.

This "diving" or "torso augmentation" theory is based on the industry interpretation of the Malibu II test results, where belted Hybrid III 50th percentile anthropomorphic test dummy responses were measured during dynamic rollover tests of production and roll-caged vehicles. Potentially Injurious Impacts (PII's) were defined in terms of the peak upper neck compression force. The Malibu authors asserted that, since PII's occurred before significant roof crush, there was no causal relationship between roof crush and neck injury. They opined that injurious spinal compression loading occurred with minimal or no roof deformation. They concluded that neck injury occurs before roof crush, there was no difference in the protection afforded by roll-caged roofs vs. production roofs and, therefore, there was no reason to increase roof strength.

Roof crush theory

Other biomechanical engineers assert that injurious spinal loads developed simultaneously with or after significant roof crush [39]. Rollover occupants only sustain injury when the weak roof crushes into the occupant compartment in the area that the occupant is located. The belted rollover occupant's head does not stop upon roof contact and the torso is not free and following. The differential velocity required to produce catastrophic cervical spine injury is due to the combined effect of the occupant's falling speed relative to the vehicle and the vehicle's center-of-gravity (cg) speed, where the latter is equivalent to the roof intrusion speed [40,41]. "Diving" alone is insufficient to produce these injuries, as shown in Figure 7.

Diving Theory: In this misrepresention, the occupant's head stops upon roof-ground contact and the torso is free and following. In a real-world rollover, the occupant's head does not stop upon roof-ground contact, and the lap-and-shoulder belted occupant's torso is not free and following. Belt usage limits the occupant's falling speed relative to the vehicle.

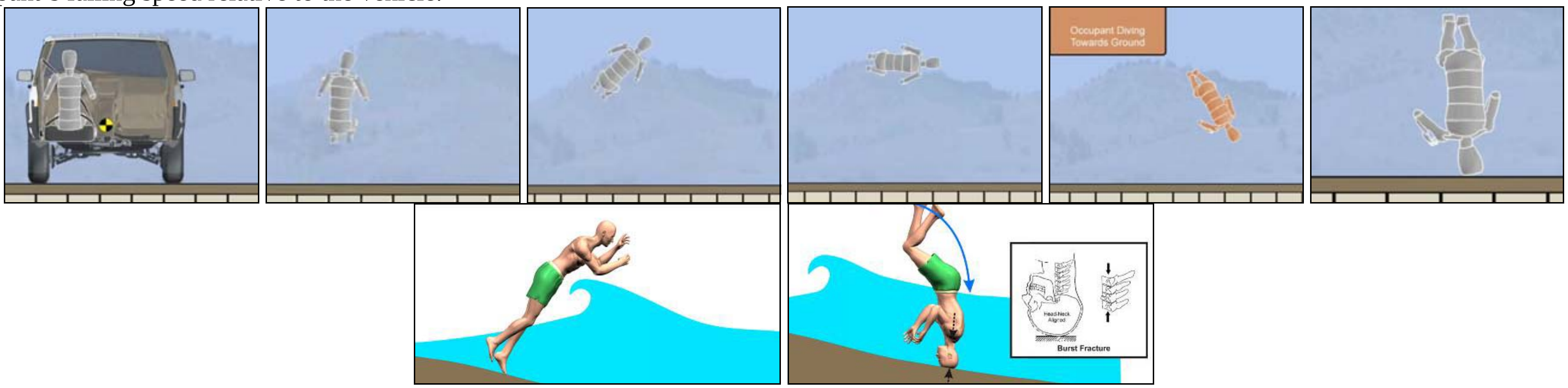

Figure 6. Diving theory

Roof Crush Theory: Upon roof-ground contact, the belted occupant continues to move within the moving vehicle and the restrained torso is not free and following. The weak roof deforms and buckles. The loading transmitted to the occupant's spine is quantified in terms of the relative head impact speed, which is a function of the occupant's falling speed relative to the vehicle and the vehicle's cg speed, where the latter is equivalent to the roof intrusion speed.

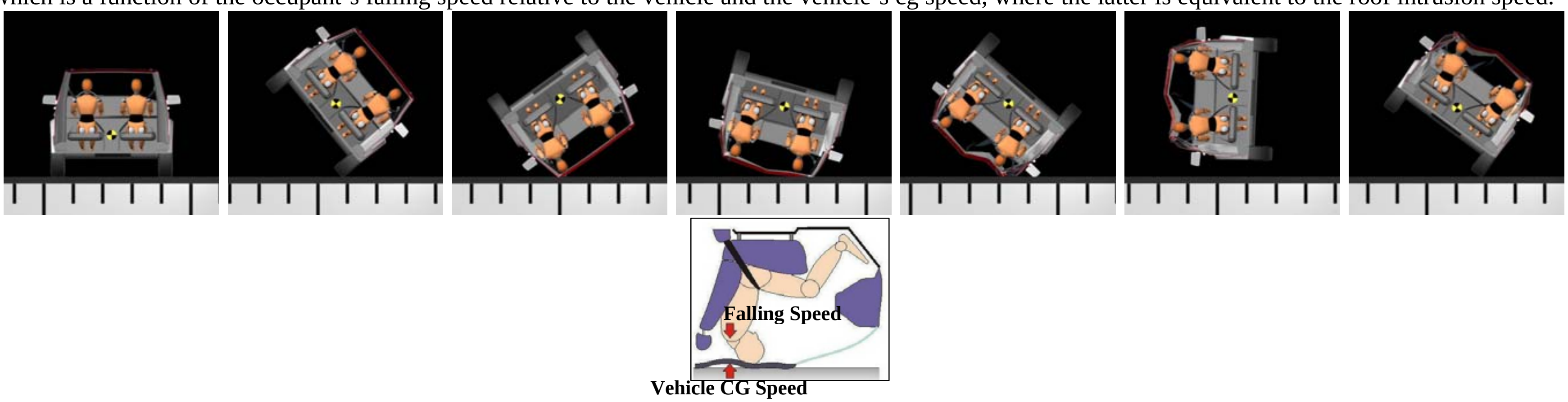

Figure 7. Roof Crush Theory

NASS/CIREN statistical injury risk

Neck injury risk analysis results, based on residual crush of the U.S. fleet and the NASS/CIREN files, are shown in Figure 8 [42]. The probability of fatality or spinal and/or spinal cord injuries can be predicted as a function of residual crush.

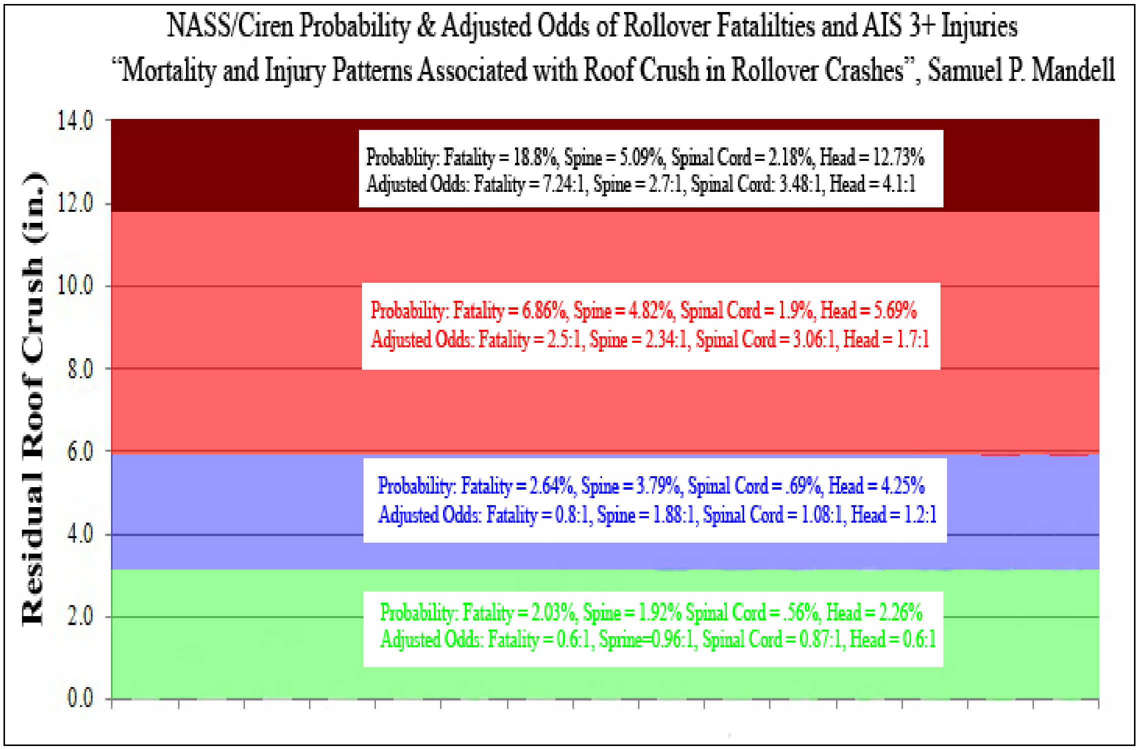

Figure 8. The residual crush injury risk criteria

The probability of fatality and AIS 3+ head, spinal, and spinal cord injury is shown in Figure 9 [43].

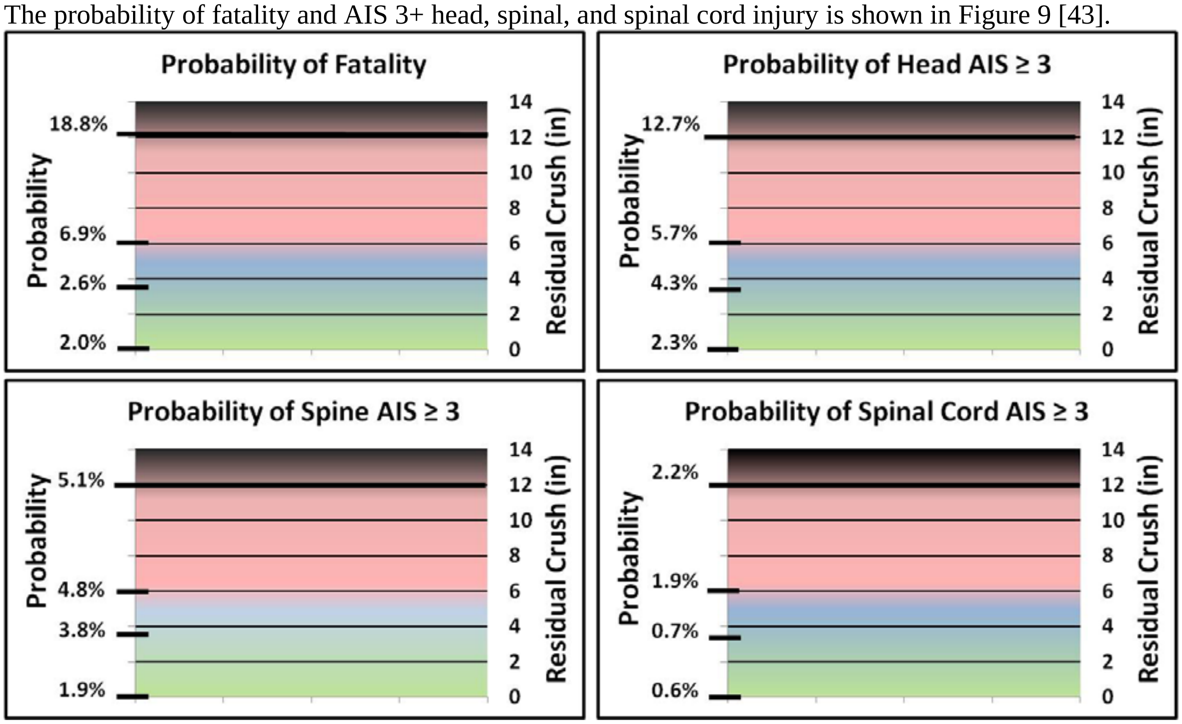

Figure 9. Probabilities of fatality, head, spine and spinal cord injuries

These results show that the injury probability of a spinal fracture at 14 cm (6”) of residual roof crush is about 4.8%, while the injury probability of a spinal cord injury is 1.9%. This is a key to the opposing viewpoints of lower neck injuries. The real-world data describes the spinal fractures as almost 3 times more frequent than spinal cord injuries. It is hypothesized that this disparity has more to do with spinal cord impingement than bone fracture.

Experiments in the rollover environment

Catastrophic neck injuries in rollover crashes were studied experimentally to understand the relationship between mechanical determinants (e.g., natural lordosis in cervical and lumbar spines and kyphosis in the thoracic spine, neck preflexion, and the eccentricity of applied loads), injury pattern and mechanism, and roof crush.

Full-scale dyanamic rollover tests were performed on 2 sets of matched-pair vehicles (production and internally-reinforced 1999 Hyundai Sonatas and 1998 Ford Explorers). A production Scion xB was also tested. These tests were performed using the Jordan Rollover System (JRS). The JRS is a repeatable dynamic laboratory fixture capable of rolling full-size vehicles and impacting a roadbed to precisely-controlled impact parameters. The JRS, vehicle and belted production Hybrid III dummy were redundantly instrumented electronically and with high-speed tracking video cameras. Since most catastrophic neck injuries in rollover crashes occur in the lower cervical spine, the dummy was also instrumented with upper and lower cervical spine load cells. More than 380 rolls have been conducted forming an unparalleled database of vehicle and dummy interaction in the rollover environment. Table 1 compares Hybrid III dummy peak lower neck compression forces and moments.

Table 1. Comparison of Hybrid III dummy responses in the production and reinforced vehicle tests

1999 Hyundai Sonata								
	Production				**Reinforced**			
		Peak (cm)	**Residual (cm)**	**Speed (kph)**		**Peak (cm)**	**Residual (cm)**	**Speed (kph)**
Intrusion		28	18	21		11	6	12
Upper neck Fz	-8057 N				-523 N			
Lower neck My	538 Nm				345 Nm			
1998 Ford Explorer - Roll 1								
	Production				**Reinforced**			
		Peak (cm)	**Residual (cm)**	**Speed (kph)**		**Peak (cm)**	**Residual (cm)**	**Speed (kph)**
Intrusion		18	11	7		5	2	7
Upper neck Fz	-6561 N				-5798 N			
Lower neck My	410 Nm				316 Nm			
1998 Ford Explorer - Roll 2								
	Production				**Reinforced**			
		Peak (cm)	**Residual (cm)**	**Speed (kph)**		**Peak (cm)**	**Residual (cm)**	**Speed (kph)**
Intrusion		20	12	15		6	2	5
Upper neck Fz	-8955 N				-3753 N			
Lower neck My	357 Nm				237 Nm			

Figure 10 shows interior frames of the matched pair of 1999 Hyundai Sonatas in 21 mph rollover tests at 10° of pitch.

Figure 10. Production and reinforced 1999 Hyundai Sonata7

In the tests of the production and reinforced Hyundai Sonatas and Ford Explorers, the Hybrid III dummy was seated erect with its head, neck and torso aligned. The production vehicle results are 30% larger than the reinforced vehicle (8,057 N vs. 5,723 N). Roof crush plays a critical role in cervical spine injury.

Figure 11 shows interior frames of a matched pair of 1998 Ford Explorers in 15 mph rollover tests at 10° of pitch. For these tests, the dummy head and neck in the reinforced vehicle was preflexed forward by 25°. Instead of a comparable reduction in injury measures, the effect of the misalignment (8,955 N vs. 3,753 N) was a further 30% reduction in compression force compared to the Sonatas under the same conditions.

Figure 11. Reinforced and production 1998 Ford Explorer

The Scion xB was tested at 15 mph and 10° of pitch with a more humanlike low-durometer neck preflexed 30°. The frame sequence in Figure 12 shows neck bending and twisting as the roof crushed.

Figure 12. Dummy in roll 2 of the Scion xB test

CONCLUSIONS

In summary, mechanical determinants dictate the injury patterns when the neck is overloaded and fails. BFD failure occurs by 3 known mechanisms: hyperflexion; compression with rotation constraints; or compression with higher-order buckling (i.e., localized bending). The validity of the hyperflexion mechanism does not preclude the validity of compression mechanisms, or vice versa. It is possible for the roof intrusion force vector to be aligned with the head, neck, and spine. However, because the varying vehicle yaw and pitch upon ground-roof contact, it is more likely that the preponderance of the catastrophic rollover neck injuries are bending injuries.

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