Rollover Crash Neck Injury Replication and Injury Potential Assessment

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ABSTRACT: Catastrophic neck compression and flexion injuries with quadriplegia are foreseeable outcomes of rollover crashes. However, current static regulatory tests cannot directly predict real-world rollover neck injuries. In this study, a dynamic test was developed and integrated bending moment (IBM) criteria proposed that can replicate/predict rollover neck flexion injuries with the Hybrid III dummy, upper and lower neck load cells, and a lateral vehicle camera. Platen drop tests were performed, revealing realistic pre-trip occupant positioning and a relationship between upper and lower neck loading. Dynamic rollover tests of 5 cars (FMVSS roof SWR range = 2.3 to 5.1) showed reduced neck flexion injury potential with increasing SWR and minimum roof SWR threshold of about 3.5 consistent with other proposed rollover injury criteria.
Keywords: Crashworthiness, Rollover Accidents, Biofidelity, Neck, Injury Criteria

Catastrophic neck compression and, more predominantly, neck flexion injuries with quadriplegia are foreseeable outcomes of rollover crashes. However, current static regulatory tests cannot directly predict neck injuries that occur in real-world rollover crashes. Existing dynamic tests with frontal impact occupant positioning, measurement of only dummy upper neck forces and moments, and current criteria can predict neck compression injury, but do not replicate or predict neck flexion injury. The prediction of neck flexion injuries (48 to 70% of all neck injuries) requires a dynamic test that replicates the pre-trip cervical spine curvature of rollover occupants, evaluates neck loading at the lower cervical spine, where these injuries occur, consideration of the duration of neck bending, and the development of a flexion neck injury criteria. Results of tests of vehicles with a range of roof SWR are compared with other rollover test criteria.

BIOMECHANICAL ANALYSIS OF ROLLOVER INJURIES: In rollover crashes, catastrophic neck compression injuries (i.e., compression, burst, and wedge compression fractures), as well as neck flexion injuries (e.g., bilateral facet dislocations [BFD]) with quadriplegia are a direct result of head interaction with the vehicle roof. Utilizing accepted scientific methodology,

- mechanical determinants (e.g., neck preflexion, end conditions and the applied neck loading direction, eccentricity. and magnitude) dictate the resulting neck injury pattern, and
- conversely, the neck injury pattern dictates the relevant mechanical determinants.

BFD are injuries whereby the facets of the superior vertebra are displaced anteriorly over the inferior vertebra and locked in a tooth-on-tooth fashion.

MECHANISM OF INJURY: Bending moment is an indication of the torque that results from or produces bending, and bending that produces injury is the result of the duration of the torque (or the distance through which the torque is applied). Experimental studies of human cadaveric spine suggest that flexion bending moments may be the dominant form of loading resulting in BFD. Flexion produces tearing of the lower cervical spine posterior ligaments, where the bending moments are greatest, and then neurologic cord trauma occurs when the anterior muscles contract (at least 100 ms after insult), sliding the upper portion of the dislocated spine forward and down causing the superior facet to lock in front of the inferior facet.

HUMAN CADAVERIC EXPERIMENTAL STUDIES: Lower cervical spine BFD with posterior ligamentous and intervertebral disc disruption, but no vertebral body damage, was produced with rotation-constraint end conditions (“ducking”). The neck load tended to peak before the bending moment and BFD with primarily ligamentous disruption best correlated to bending.

CERVICAL SPINE CURVATURE**:** The neutral position is the normal cervical lordosis. With 15° to 30° preflexion, the cervical spine becomes straight.

PREFLEXION**:** The pre-trip cervical spine curvature of restrained occupants in rollover crashes is often preflexed due to the initial locking of the safety belt, pre-impact braking and yawing, neck flexion and/or “ducking” as a protective reflex, and/or preflexion due to lack of headroom of large stature occupants.

THE HYBRID III NECK consists of molded alternating aluminum and butyl rubber elements representing vertebral bodies and intervertebral discs. Butyl rubber nodding blocks act as occipital condyles. A steel cable runs through the center of the neck to provide axial strength, but the neck has no compliant compressive element.

METHODS

DUMMY MODIFICATION: The Hybrid III 50th percentile male dummy was modified to incorporate both upper and lower 6-axis neck load cells.

PLATEN DROP TESTS: Platen tests were performed. The tests were modeled after the set-up and protocol developed by Pintar, et al. (1990). The impactor was a guided, free-fall, displacement-instrumented, weighted platen oriented above the seated dummy's head. Neck angles were varied.

PLATEN TEST RESULTS: Dummy responses are summarized in Table 1 and illustrated in Figure 1. The key to generically replicating neck injury loading patterns appears to be 50° preflexion. A high-correlation (97%) linear relationship between the peak upper neck axial force, Fz upper, and peak lower neck moment, My lower, was found, virtually independent of neck orientation from an erect 90° to about 50° of forward flexion: My lower = 0.048 Fz upper + 42.

Table 1. Platen Test Results.

Test #	Neck Angle (deg)	Effective Eccentricity (cm)	Platen Weight (kg)	Upper Neck Fz (N)	Lower Neck Fz (N)	Upper Neck My (N-m)	Lower Neck My (N-m)
001	80	0	16	-4587	-4247	-36	268
002	80	0	16				
003	65	-5	16	-4231	-3872	-53	252
004	65	-5	16				
005	35	-9	16	-2402	-2254	-32	158
006	35	-9	16				
007	90	0	16	-5202	-4801	13	286
008	90	0	16				
009	90	5	16	-4696	-4474	28	256
010	90	5	16				
011	90	10	16	-4294	-4027	31	233
012	90	10	16				
013	70	-4	23	-4861	-4479	-54	288
014	70	-4	23				
015	60	-6	23	-4411	-4037	-67	263
016	60	-6	23				

Figure 1: Platen Test Photographs.

PROPOSED NECK FLEXION INJURY CRITERIA: Most injury metrics are based on peak forces or moments. This leads to a misconception that all injury metrics, like HIC, are described by short-duration (16 or 32 ms) high-acceleration impulses. Dummy neck data and time-coordinated videos of rollover impacts show that the neck bending occurs after the peak axial force, which suggests that neck flexion injury is a function of momentum, not peak force or peak moment. Testing also shows that neck bending is not isolated to the midsagittal plane, which suggests that a flexion neck injury criteria should be a function of both neck Mx and neck My. To account for muscle contraction, which may take 100 ms or more, a neck flexion injury metric is proposed, called the integrated bending moment (IBM), that combines measured lower neck Mx and My, integrated over the time duration of neck loading. For tests with only upper neck load cell data (vehicles with SWR =3.2 and 4.3), the calculated IBM was defined as a combination of upper Mx and My, integrated over the duration of neck loading, multiplied by 0.048 plus 42 times that duration.

DYNAMIC FULL-SCALE ROLLOVER TESTS: To develop a flexion injury criteria and test the upper Fz-to-My relationship, dynamic passenger-side leading rollover tests of 5 passenger cars (FMVSS 216 SWR range: 2.3-5.1) were conducted with the Jordan Rollover System (JRS). The 1st and 2nd roll test conditions were 15 mph road speed, 5° and 10° negative vehicle pitch, respectively, 161°/sec roll rate, and 146° near-side impact roll angle. The test subject was an untethered 50th percentile male Hybrid III dummy instrumented with upper and lower neck load cells for 3 tests and upper load cells only for 2 tests. Vertical motion sensor, lap-and-shoulder belt load sensors, and time-coordinated high-speed rear and lateral video cameras were used on all 5 tests. The dummy was seated on the far side in the mid-seat position with a -5° seat back angle. This resulted in about 30° of initial head-neck flexion relative to the vertical vehicle axis and represented the more realistic real-world pre-trip occupant position.

JRS TEST RESULTS FOR THE SWR = 2.5 VEHICLE: In Figure 2, results of roll 1 of 2 show the vehicle roof A-pillar intruded 21.3 cm dynamically at about 11.3 kph and 12.2 cm residual crush such that the roof rail and panel intruded with a negative pitch angle from 0° to 12° with a residual angle of 9°. Analyzing dummy responses for injury potential according to established (although controversial) injury criteria, the dummy experienced a 5,598 N peak upper neck Fz at the vertex of the head from the aligned orientation of the initial impact, which then shifted rearward and produced neck flexion with a large peak lower neck My (414 Nm) and long duration (140 ms overall, 64 ms over 100 Nm, 76 ms over 50 Nm). The Nij was greater than 1, consistent with a neck injury-producing event.

The measured and calculated IBM for the 5 vehicles tested are plotted in Figure 3.

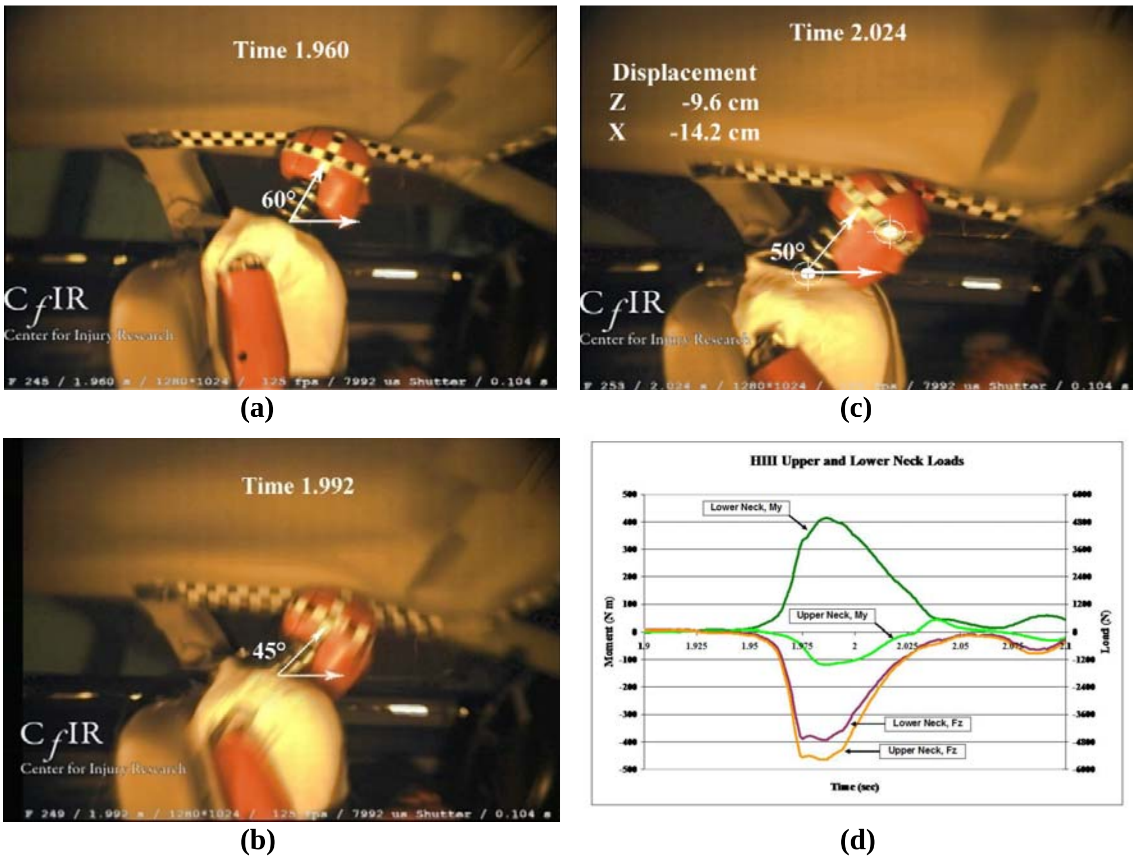

Figure 2: JRS Test Results of SWR = 2.5 Vehicle, (a-c) Interior Views from Lateral Camera, (d) Test Time Histories.

DISCUSSION:

Figure 3 is a composite graph of injury criteria and injury rates v. SWR, including the proposed IBM and the (a) NHTSA docket 2008-0015 post-crash negative-headroom criteria, (b) IIHS ejection and potential injury rates for occupants with incapacitating or fatal injuries, (c) Bish et al. side glazing JRS ejection failure measure, (d) June 4, 2008 Senate Hearing JRS 2-roll test cumulative roof crush criteria, and (e) Friedman et al. 7 mph onset impact speed consensus injury measure for serious head and neck injury. The graph shows that the risk or likelihood of a serious-to-fatal injury is minimized by a SWR of about 3.5, and that an IBM greater than 15 is predictive of flexion neck injury. Corroboration by other scientists, more tests, and correlation with Pintar's human flexion injury probability curves will be the focus of future research.

An interesting outcome of this study is that, although the dummy's head was not located in the same position or orientation in these tests at the time and location of roof intrusion and head impact and the impact did not occur with similar Fz severity or duration, the measured and calculated IBM (for the vehicles with SWR=3.2 and 4.3) predict neck flexion injury potential very well. The visual data confirms the bending duration and integration time.

CONCLUSIONS:

Neck flexion injury was replicated and predicted in dynamic rollover tests using the Hybrid III dummy and the proposed injury criteria, IBM. Platen drop tests identified realistic pre-trip occupant positioning and the relationship between upper and lower Hybrid III neck loading, which dynamic tests confirmed. Dynamic tests also showed that the proposed IBM as a function of SWR was consistent with other injury criteria. Continuing research will confirm or refine this finding.

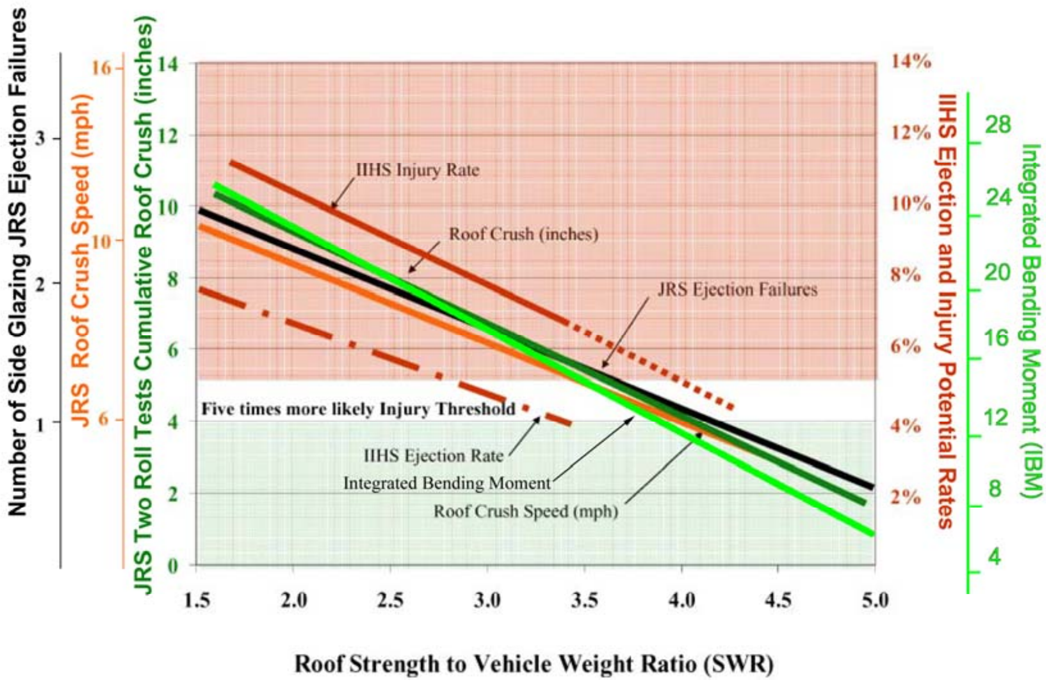

Figure 3: Composite injury criteria and injury rates v. SWR, including proposed IBM

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