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Development of Rollover Injury Assessment Instrumentation and Criteria

J. G. Paver, D. Friedman, F. Carlin, J. Bish, and J. Caplinger

ABSTRACT

This study is part of an ongoing research project aimed at mitigating catastrophic human neck injuries in rollovers. To date, U.S. rollover standards test only vehicle structural crashworthiness; there is no regulatory rollover occupant protection requirement based on dummy injury criteria, as there are for frontal and side crashes. Dynamic vehicle rollover test devices have been developed like the Controlled Rollover Impact System and the Jordan Rollover System, which realistically recreate rollover neck injury impact scenarios and use human surrogates to evaluate occupant protection. At present, the Hybrid III dummy is considered to be the best available human surrogate for dynamic rollover tests. However, there are known biofidelity and instrumentation limitations associated with the use of this dummy to predict known catastrophic human neck injury potential in real-world rollover crashes. The biggest challenges have been:

- *the interpretation of occupant data measured with this non-biofidelic dummy, and*
- *the development of injury criteria for its stiff aligned neck that correlate to the more compliant human neck.*

Recent research questions the use of peak injury measures (i.e., upper neck compression and, more recently, the Nij) as the criteria for catastrophic human neck injury in rollover tests.

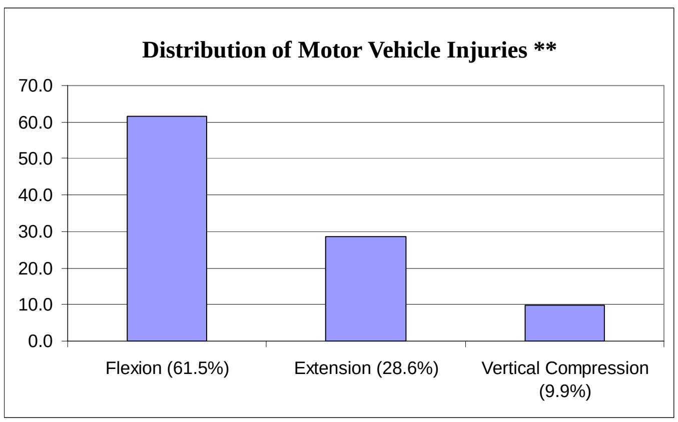
This study investigated the use of the non-biofidelic Hybrid III dummy in a dynamic rollover test to accurately predict the predominant human neck bending injury sustained in real-world rollover crashes. The Hybrid III dummy was specially instrumented to measure biomechanical parameters to evaluate human neck bending injury potential in rollovers. An empirical relationship between upper and lower Hybrid III neck loading was derived. The effects of neck preflexion angle, roof impact speed, roof crush, onset-to-peak neck axial forces and moments, and impact duration on neck bending injury were identified. The "nutcracker effect" was investigated. Peak neck injury measures were rejected and a neck flexion injury criteria, the integrated bending moment (IBM), was proposed that related catastrophic human neck bending injury to Hybrid III lower neck moment-time histories. Dynamic validation and comparison of the IBM with other injury criteria in dynamic tests was discussed.

INTRODUCTION

This study is part of an ongoing research project aimed at mitigating catastrophic human neck injuries in rollovers. In the U.S., there are approximately 27,000 occupants seriously injured or killed annually in rollover crashes. The typical rollover neck-injured victim is described:

- the occupant is seated on the trailing side of the vehicle, where roof crush is greatest,
- the occupant's neck is likely preflexed (straightened) due to braking, reflexive "ducking," belt lockup, and/or lack of headroom and the occupant's neck is not tensed,
- the occupant's neck is rarely aligned and oriented to the roof intrusion force vector as required to produce axial compression injury,
- the roof intrusion applies a force just posterior to the vertex of the head creating a flexion moment and injury.
- the catastrophic neck injury typically occurs in the lower cervical spine, and
- the neck injury residual is partial or complete paraplegia or quadriplegia.

In 1982, Allen, Jr. et al. studied mechanisms of cervical spine injuries in motor vehicle crashes. Figure 1 illustrates the distribution of neck injury mechanisms. Only 10% of motor vehicle cervical spine injuries resulted from axial compression. About 90% of these cervical spine injuries were due to bending (i.e., flexion and extension) often with axial loading.



** A Mechanistic Classification of Closed, Indirect Fractures and Lower Dislocations of the Lower Cervical Spine, Ben Allen Jr., Ron Ferguson, Thomas Lehmann, R.P. O'Brien, Spine Vol7, No 1, 1982

Figure 1: Distribution of Neck Injury Mechanisms in Motor Vehicle Crashes.

To date, U.S. rollover standards test only vehicle structural crashworthiness; there is no regulatory rollover occupant protection test based on dummy injury criteria, as there are for frontal and side crashes. Dynamic rollover test devices like the Controlled Rollover Impact System and the Jordan Rollover System (JRS), which can realistically recreate rollover crash scenarios, use human surrogates to evaluate occupant protection. At present, the Hybrid III dummy is considered to be the best available human surrogate. However, there are known biofidelity and instrumentation limitations associated with the use of this dummy to predict known catastrophic human neck injuries in rollovers.

- Regulation dummy instrumentation measure forces and moments only at the occipital condyles, not at the lower cervical spine, where catastrophic human neck injury occurs.
- Experimental studies show that, relative to the human neck, the dummy neck is approximately 3 times stiffer in compression, 10 times stiffer in untensed bending, and equally stiff in tensed bending (Sances et al., 1990).
- Unlike the preflexed, untensed, and neither aligned nor oriented human neck, the dummy neck is axially stiff, angularly tensed, aligned, and oriented to the roof intrusion force vector in rollover tests. The result is

that the dummy is predisposed to predicting axial compression injury, not the predominant flexion injury sustained by humans.

From 1978 to 1985, the criteria for catastrophic human neck injury was a 11.3 kph (7 mph) head impact speed based on the McElhaney et al. (1988) swimming pool diving neck injury study.

Since 1985, when the 1st Malibu rollover testing was published, peak injury measures (i.e., upper neck compression and, more recently, the Nij) have been utilized as the criteria for catastrophic neck injury. The following problems with peak injury measures have been identified:

- Most injury metrics are based on peak forces or peak moments. This leads to a misconception that all injury metrics, like HIC, are described by short-duration (16 or 32 ms) high-acceleration impulses. Real-world spinal cord injuries are perhaps empirically, but not directly related to peak values from a short stroke and short duration impulse.
- Analysis of recently-released, time-coordinated passenger-side leading Malibu dolly rollover test films show that peak neck bending occurs well after the peak axial force and after much more roof crush, which suggests that neck flexion injury is a function of momentum, not peak axial force or peak bending moment.

In 2008, Paver et al. (2008a, b) and Friedman et al. (2008) rejected peak neck injury measures and proposed a neck injury criteria that related catastrophic human neck bending injury to Hybrid III lower neck axial force and moment-time histories. This injury criteria, which is a function of both Mx and My, reflects dynamic rollover test results that show that neck bending is not isolated to the midsagittal plane.

The goal of this study was to investigate the use of the non-biofidelic Hybrid III dummy in a dynamic rollover test to accurately predict the predominant real-world rollover crash human neck bending injury. The specific objectives were to identify biomechanical parameters that affect neck bending injury in rollovers (impact speed, roof crush, neck axial force and moment time histories, and neck bending angle), instrument the dummy to measure these relevant parameters, position the dummy to produce known human neck bending injury patterns, and develop and relate dummy injury criteria to human injury criteria.

METHODS AND RESULTS

Platen drop test and pendulum tests were conducted at Xprts, LLC in Goleta, CA.

Instrumentation

The Hybrid III neck was instrumented with an upper neck load cell for the 1st set of dummy platen tests and upper and lower neck load cells for the 2nd set of dummy platen tests; axial neck force Fz and moments Mx and My were measured. Instrumentation also included real-time and high-speed rear and lateral view cameras. The high-speed cameras were equipped with tracking software used to analyze head-neck motion and neck flexion angle. An effective eccentricity was measured as the circumferential distance between the platen contact point and the vertex of the dummy's head. Preflexion neck angles were measured with a gravity-referenced inclinometer at the posterior neck (erect=90°). String potentiometers attached to the platen and to the dummy recorded the platen drop height and the fore-and-aft motion of head, upper neck, lower neck, and lumbar joint, respectively.

Platen Drop Tests

A guided, free-fall, displacement-instrumented, weighted rigid steel platen was placed or dropped onto the head of a human male volunteer or Hybrid III 50th percentile male dummy, respectively, seated in a production vehicle bucket seat. Results were used to determine how the Hybrid III dummy should be positioned to replicate realistic pre-roll human occupant positioning, derive relationships between Hybrid III upper and lower neck loading, and develop Hybrid III neck flexion bending injury criteria.

Human Male Volunteer Platen Drop Tests

The volunteer platen drop test setup is shown in Figure 2. The volunteer was 174 cm (5'8.5") tall with an 84 cm (35") seated height and weight of 75 kg (165 lbs). The preflexion neck angles were 80° and 60°. The platen weight was 16 kg (35 lbs) and drop height was 0 cm. Results indicate that, with quasi-static eccentric loading, the human head, neck, and spine could flex up to about 90° (with 10 cm to 23 cm downward head displacement) without injury.

Figure 2: Platen Drop Test Setup, Human Volunteer Test Subject.

Hybrid III 50th Percentile Male Dummy Platen Drop Tests

The dummy platen drop test setup is illustrated in Figure 3. The tests were performed as matched pairs to assess repeatability.

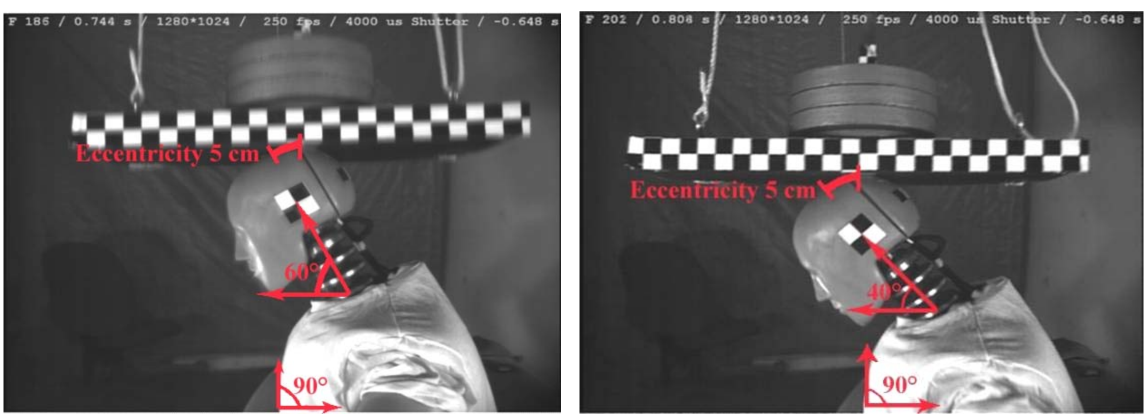


Figure 3: Platen Drop Test Setup, Hybrid III Dummy Test Subject.

In the 1st set of dummy tests, the platen weight was 16 kg (35 lbs) and the Hybrid III preflexion neck angle and platen drop height (impact speed) were varied. The dummy test matrix and results are summarized below in Table 1.

Table 1. Hybrid III Platen Drop Test Matrix #1 and Results.

Test #	Preflexion Neck Angle	Drop Height (cm) [in]	Impact Speed (kph) [mph]	Peak Upper Neck Fz (N)	Peak Upper Neck My (N-m)
1	80°	30.5 [12]	8.9 [5.5]	-3159	-17
7	80°	30.5 [12]	8.9 [5.5]	-3654	-15
5	80°	45.7 [18]	10.8 [6.7]	-4099	-21
6	80°	45.7 [18]	10.8 [6.7]	-4103	-21
4	50°	30.5 [12]	8.9 [5.5]	-2310	-37
9	50°	30.5 [12]	8.9 [5.5]	-2581	-38
3	50°	45.7 [18]	10.8 [6.7]	-2920	-46
8	50°	45.7 [18]	10.8 [6.7]	-3225	-48

In the 2nd set of dummy tests, the preflexion neck angle, effective eccentricity, and platen weights were varied. The dummy test matrix and results are summarized below in Table 2. Relationships between upper and lower neck loading were derived. A bending neck injury criteria was proposed.

Table 2. Hybrid III Platen Drop Test Matrix #2 and Results.

Test #	Preflexion Neck Angle (°)	Effective Eccentricity (cm)	Platen Weight (kg)	Impact Duration (ms)	Peak Upper Neck Fz* (N)	Peak Lower Neck Fz* (N)	Peak Upper Neck My* (N-m)	Peak Lower Neck My* (N-m)
1	80	0	16	44	-4587	-4247	-36	268
2	80	0	16	36				
3	65	-5	16	76	-4231	-3872	-53	252
4	65	-5	16	52				
5	35	-9	16	72	-2402	-2254	-32	158
6	35	-9	16	56				
7	90	0	16	44	-5202	-4801	13	286
8	90	0	16	36				
9	90	5	16	52	-4696	-4474	28	256
10	90	5	16	52				
11	90	10	16	48	-4294	-4027	31	233
12	90	10	16	56				
13	70	-4	23	96	-4861	-4479	-54	288
14	70	-4	23	108				
15**	60	-6	23	108	-4411	-4037	-67	263
16**	60	-6	23	88				

* Force, moment, and motion data were filtered at SAE J211b class 1000, 600, and 60, respectively.

** Foam placed under the dummy's buttocks allowed about 8 cm of vertical displacement before bottoming.

The dummy data measured in the matched-pair platen drop tests were repeatable. The following results were derived from the neck load cell data:

- A high-correlation (99%) linear relationship was found between the dummy peak upper neck axial force, Fz upper, and the dummy peak lower neck axial force, Fz lower:
  - Fz lower (N) = 0.920 * Fz upper (N) + 8.5
- A high-correlation (97%) linear relationship was found between the peak upper neck axial force, Fz upper, and peak lower neck moment, My lower.
  - My lower (N-m) = 0.048 Fz upper (N) + 42

No correlations were found between the Hybrid III neck upper My and lower neck My. These correlations between dummy upper and lower neck load cell data were virtually independent of neck orientation from the erect 90° body position to about 50° of forward flexion.

Using these correlations, lower neck forces and moments can be calculated from measured upper neck forces and moments for those tests, where the lower neck load cell data was not collected.

Based on the human and Hybrid III dummy platen drop test results, the dummy platen tests at 55° neck preflexion angle approximated the limit of the free range of voluntary human flexion. Human neck bending and injury patterns were best replicated with 50° to 60° of Hybrid III neck preflexion. Thus, dynamic rollover tests should be performed with 50° to 60° neck preflexion, axial neck compression responses should be measured with the upper neck load cell, and neck bending responses should be measured with the lower neck load cell.

Hybrid III Pendulum Tests

Pendulum tests were performed using the experimental setup illustrated in Figure 4. In these tests, a rotational pendulum-driven platen struck the head of the dummy head/neck/torso/pelvis assembly suspended approximately 2” above a production vehicle seat. Bungee cords were used to set the dummy at initial platen contact to have a torso angle of 10° relative to the vertical and the head-neck angle of 17° relative to the torso, resulting in a total angle relative to the vertical of 27°. This orientation is representative of the preflexed orientation of the human when inverted with the head in contact to the roof. The dummy was held in place by a breakable attachment that allowed the dummy to fall after initial contact with the platen. The rotational pendulum was set to impact the head of the dummy when horizontal and moved through an angle of 10° when depressing the head of the dummy by 6”. The fixture included an adjustable arresting stop for the pendulum arm. The pendulum was dropped to achieve head impact at 11.3 kph (7 mph) with a pendulum displacement (stroke) of 2.5 cm (1”) to 15.2 cm (6”) before being arrested. The stroke after head contact was analogous to the extent of roof crush.

For all of the pendulum tests, the platen weight was 16 kg (35 lbs), the dummy-to-seat distance was 5.1 cm (2”), the dummy-to-right side distance was 20.3 cm (8”), the dummy-to-front distance was 17.8 cm (7”), the preflexion neck angle was 60°, and the neck position was bent.

The dummy test matrix and results are summarized below in Table 3. Tests were conducted at different platen weights, platen drop heights, and allowable platen stroke distances after initial contact. Altering the platen weight and drop height changed the head impact speed and deltaV. The effects of impact speed and platen stroke (roof crush) on upper and lower neck loading were determined.

Table 3. Pendulum Test Matrix.

Test #	Platen Drop Height (cm) [in]	Platen Impact Speed (kph) [mph]	Platen Weight (kg) [#]	Platen Stroke (cm) [in]
9	15.2 [6]	6.3 [3.9]	43 [95]	10.2 [4]
7	30.5 [12]	8.9 [5.5]	43 [95]	10.2 [4]
8	45.7 [18]	10.8 [6.7]	43 [95]	10.2 [4]
11	76.2 [30]		70 [155]	5.1 [2]
10	76.2 [30]		70 [155]	10.2 [4]
12	76.2 [30]		70 [155]	15.2 [6]

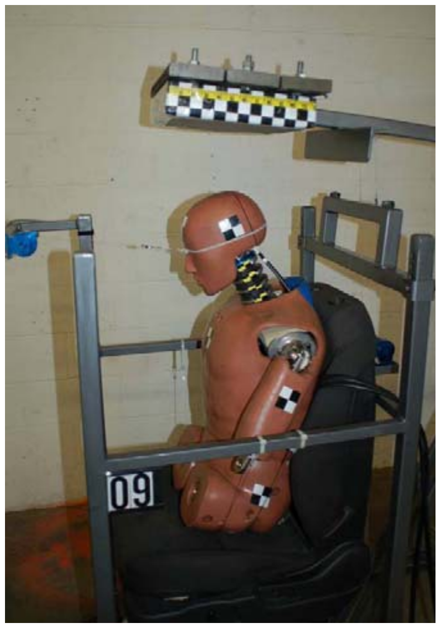


Figure 4: Pendulum Test Setup.

Pendulum Tests #7-#9: Effect of Drop Height (Platen Impact Speed) on Neck Loading

Figure 5 illustrates the effects of impact speed on dummy kinematics at head contact (0 ms), at peak neck load (6 ms), at 2” stroke (~16 ms), and at 167 ms. Figure 6 shows the upper neck force Fz and lower neck bending moment My time histories. Results indicate:

- the onset-to-peak neck force and onset-to-peak neck moment are independent of speed,
- the peak neck force and peak neck moment are dependent of speed, and
- the lower neck moment duration is independent of speed.

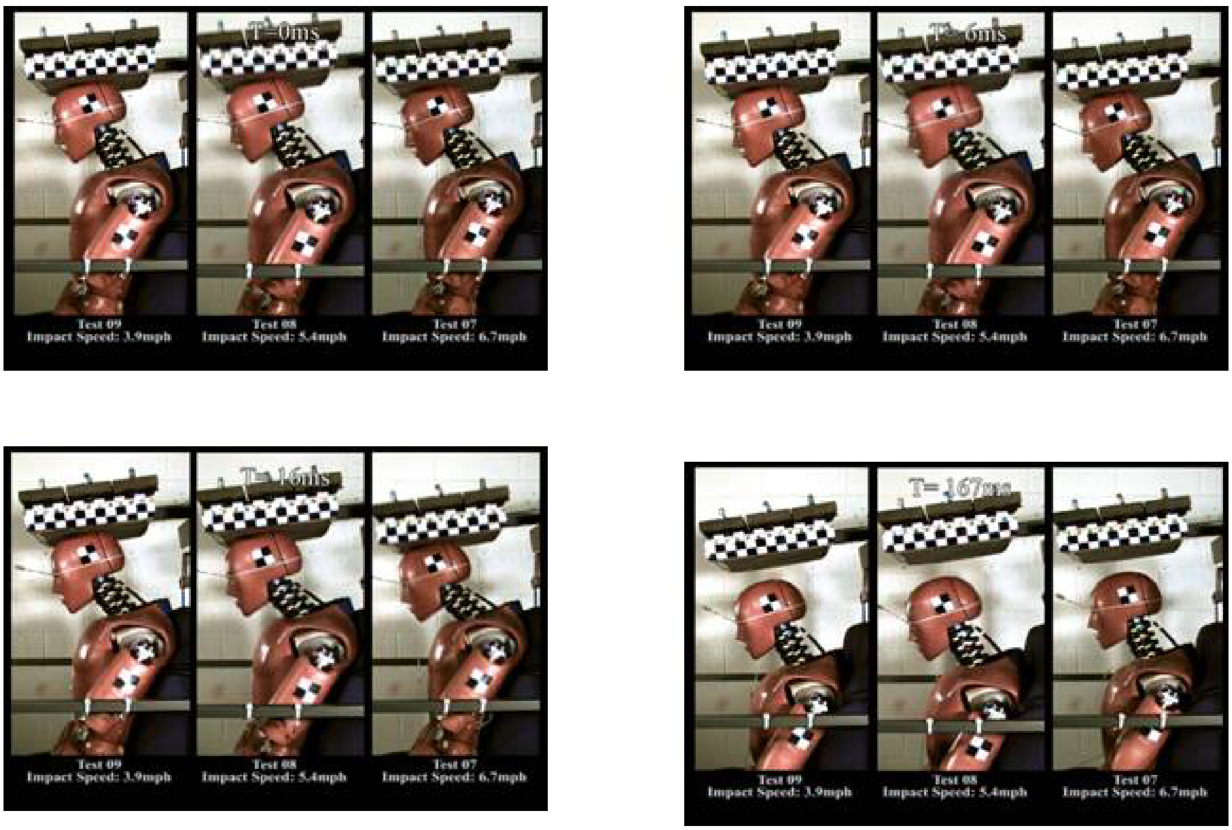
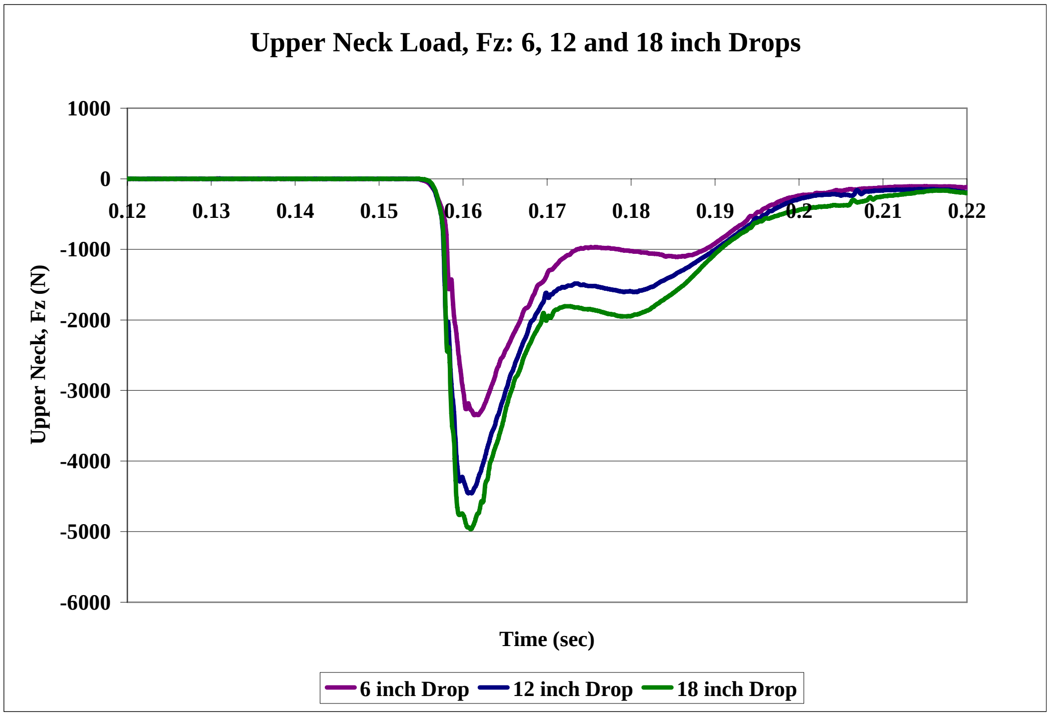


Figure 5: Pendulum Test Results -- Effect of Impact Speed on Dummy Kinematics.



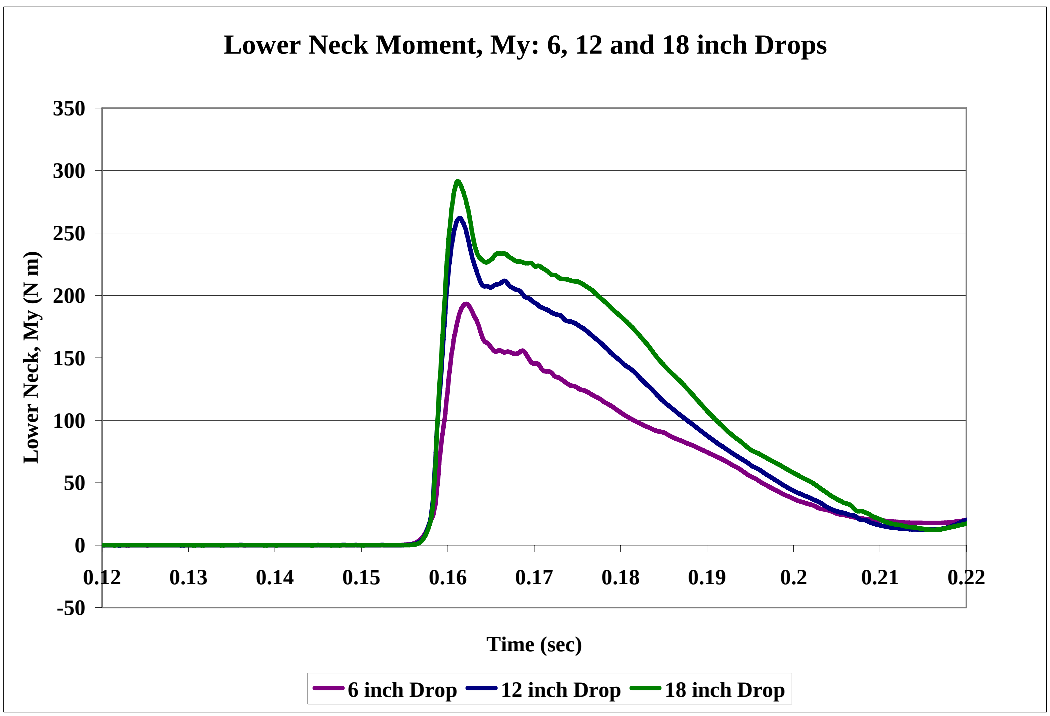


Figure 6: Effect of Drop Height (Platen Impact Speed) on Upper Neck Force Fz (top) and Lower Neck Moment My (bottom).

(Peak neck forces and moments were normalized in time to the 6” drop test time.)

Pendulum Tests #10-#12: Effect of Platen Stroke after Initial Head Contact on Neck Loading

Figure 7 illustrates the dummy kinematics for different strokes at head contact (0 ms), at 2” stroke (~17 ms), at seat contact (~40 ms), and, in Test 12, at seat bottoming (~60 ms with mid-neck bending). Figure 8 shows time histories of upper neck force Fz and lower neck bending moment My. Results indicate:

- the onset-to-peak neck force and onset-to-peak neck moment are independent of stroke,
- the peak neck force and peak neck moment are independent of stroke, and
- the lower neck moment duration is dependent on stroke.

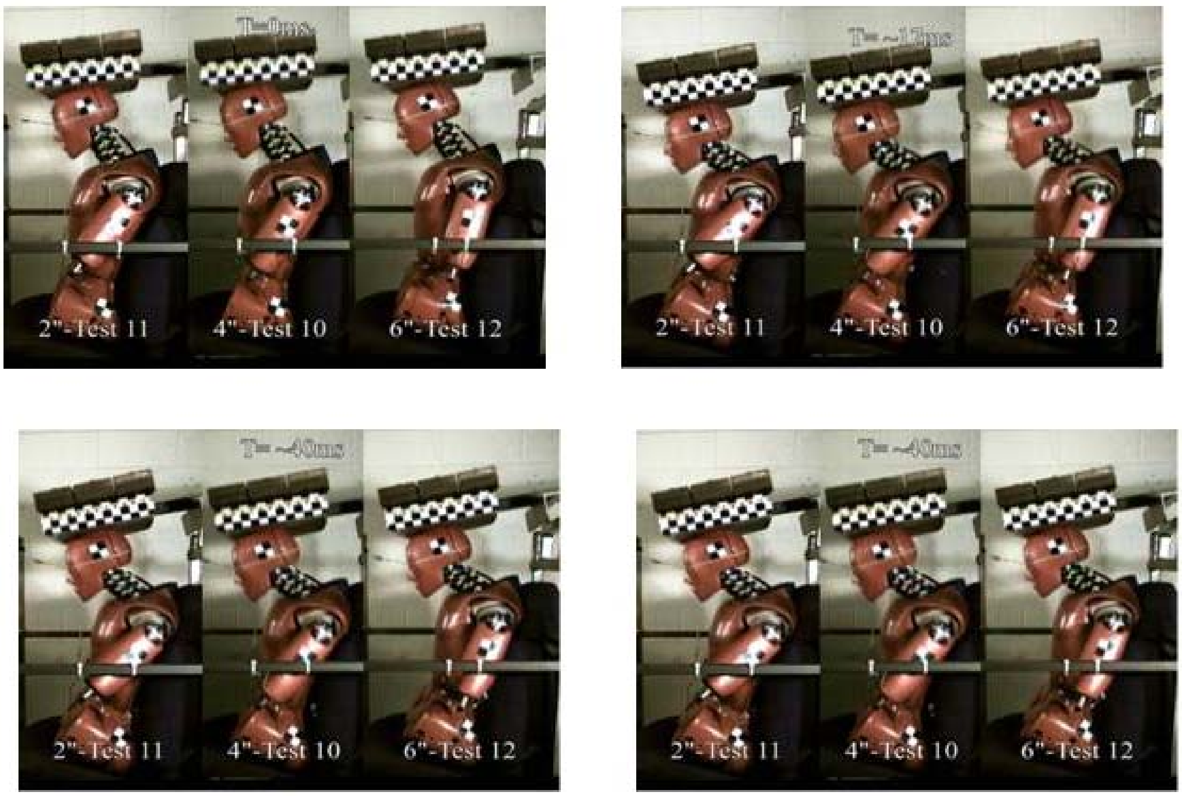
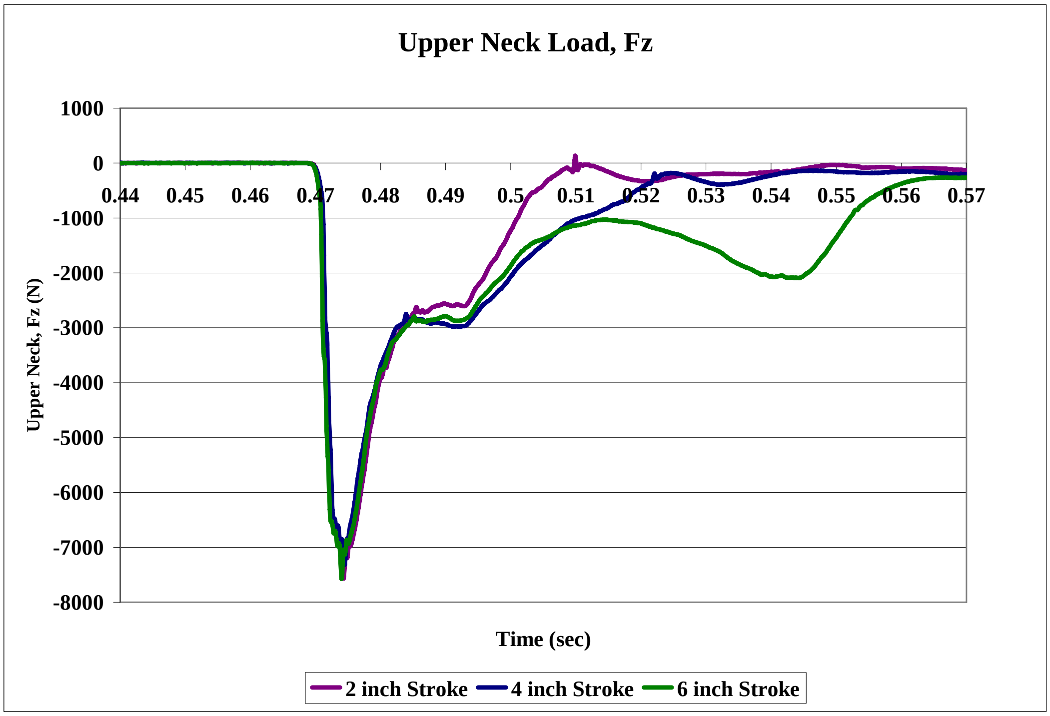


Figure 7: Pendulum Test Results -- Effect of Platen Stroke after Head Contact.



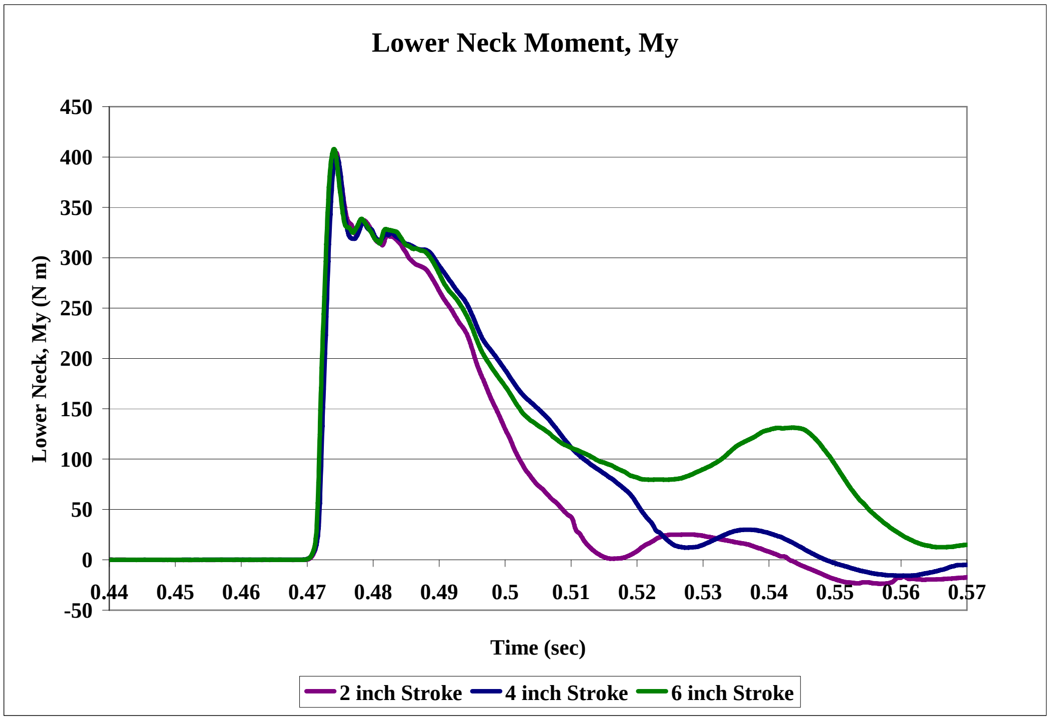


Figure 8: Effect of Platen Stroke after Head Contact on Upper Neck Force Fz (left) and Lower Neck Moment My (right).

(Peak neck forces and moments were normalized in time to the 2” stroke test time.)

Table 4 quantifies the lower neck moment durations from the test videos.

Table 4. Duration of Lower Neck Moment and Mid-Neck Bending from Videos.

	Test #11 2" Drop Height 3.9 mph Speed (ms)	Test #10 4" Drop Height 5.5 mph Speed (ms)	Test #12 6" Drop Height 6.7 mph Speed (ms)
At Impact	0	0	0
At 2" Stroke	~17	~17	~17
At 4" Stroke	NA	~40	~40
At 6" Stroke	NA	NA	~67

Table 4 shows that the duration of the lower neck bending moment is increased with increased pendulum stroke (or roof crush) and with seat impact. In the context of peak neck load, this "nutcracker effect" of the seat impact is small. However, in the context of lower neck moment loading and duration (neck bending), this "nutcracker effect" may be significant.

Proposed Hybrid III Neck Injury Criteria

The integrated bending moment (IBM) criteria was proposed to predict rollover neck flexion injuries with the Hybrid III dummy. The IBM integrates the resultant lower neck My and Mx over the time interval of the onset and reduction to 30 N-m or to a maximum of 140 ms. To account for muscle contraction, which may take 100 ms or more, the IBM combines measured lower neck Mx and My, integrated over the time duration of neck loading, multiplied by 0.048 plus 42 times that duration. This relationship is complicated because flexion injury is related both to the speed of the impact and the amount of roof crush. The IBM criterion reflects that combination.

For the 2nd set of dummy platen tests, the IBM was 10.4 at 2" stroke, 12.1 at 4" stroke and 16.2 at 6" stroke, compared to the preliminary IBM criteria of 14 for catastrophic neck flexion injury.

Dynamic rollover tests of 5 cars (roof strength-to-weight ratio [SWR] range = 2.3 to 5.1) were conducted and the IBM was validated dynamically as a function of SWR and compared with other injury criteria in dynamic tests. Figure 9 is a composite graph of injury criteria and injury rates v. SWR, including the:

- proposed IBM,
- NHTSA docket 2008-0015 post-crash negative-headroom criteria,
- IIHS ejection and potential injury rates for occupants with incapacitating or fatal injuries,
- Bish et al. side glazing JRS ejection failure measure,
- June 4, 2008 Senate Hearing/JRS 2-roll test cumulative roof crush criteria, and
- Friedman et al. 11.3 kph (7 mph) onset impact speed consensus injury measure for serious head and neck injury.

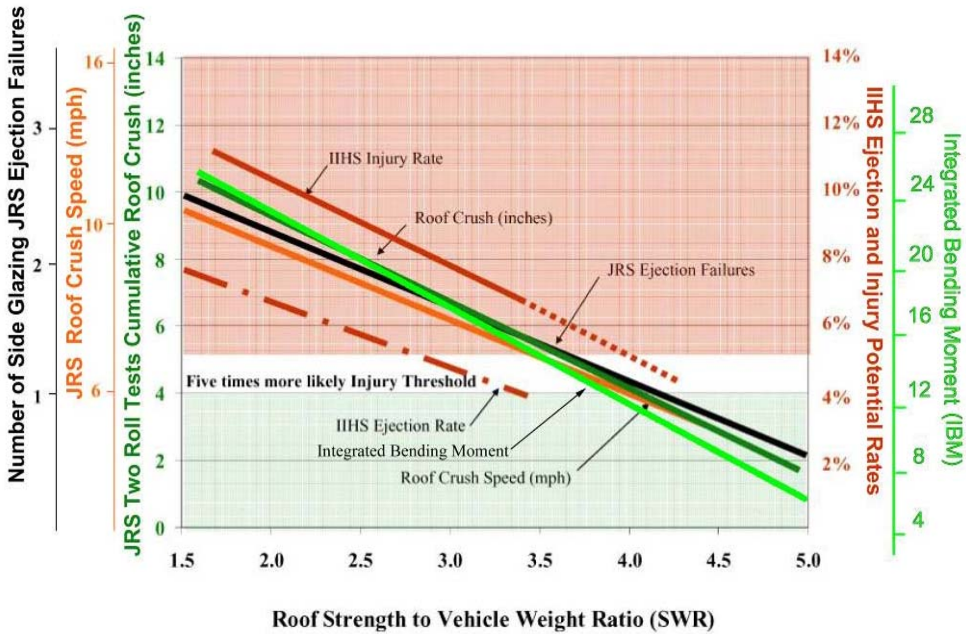


Figure 9: Composite injury criteria and injury rates v. SWR, including proposed IBM.

Figure 9 shows that the risk or likelihood of a serious-to-fatal injury is minimized by a SWR of about 3.5 to 4, and that an IBM greater than 14 or 15 is predictive of flexion neck injury. Each line on the composite injury criteria chart corresponds to one of the bodies of data from various sources. The red-hatched area of the chart describes those vehicles that cause injury. Only vehicles in the lower area of the chart are unlikely to cause injury (Austin et al., 2005; Strashny, 2007). The NHTSA injury criterion is essentially the same as the survival space criteria that was agreed to in 1973. Comparison with other injury measures and with a limited number of data points, the IBM serious flexion injury criteria is approximately 14 and the range is from 7 to 28.

CONCLUSIONS

This study investigated the use of the non-biofidelic Hybrid III dummy in a dynamic rollover test to accurately predict the predominant human neck bending injury sustained in real-world rollover crashes. The Hybrid III dummy was instrumented to measure biomechanical parameters used to evaluate human neck bending injury potential in rollovers. An empirical relationship between upper and lower Hybrid III neck loading was derived. The effects of neck preflexion angle, roof impact speed, roof crush, onset-to-peak neck axial forces and moments, and impact duration on neck bending injury were identified.

- The onset-to-peak neck loading is very fast, about 5 ms, and independent of impact speed and stroke (roof crush).
- Peak neck loading is dependent on speed, but independent of stroke (roof crush). Peak neck load occurs quickly, before injury and before the roof crushes significantly. Peak neck load is not equal to injury.
- Lower neck moment duration is dependent on stroke (roof crush), but independent of speed.

The "nutcracker effect" was investigated. Peak neck injury measures were rejected and a neck flexion injury criteria, the integrated bending moment (IBM), was proposed that relates catastrophic human neck bending injury to Hybrid III lower neck moment-time histories. The IBM was compared with other injury criteria in dynamic tests.

FUTURE WORK

In the next phase of this research, we plan to conduct identical pendulum tests with PMHS specimens and a Hybrid III dummy modified with a more biofidelic neck and spine. Results from future testing will be used to refine the relationship between human and dummy head and neck injury measures for rollover crashes and further validate the proposed IBM bending neck injury criteria.

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DISCUSSION

PAPER: **Development of Rollover Injury Assessment Instrumentation and Criteria**

PRESENTER: ***Jacqueline Paver, Consultant***

QUESTION: *Guy Nusholtz, Daimler Chrysler*

You showed, in one slide, that there were these large magnitudes between the stiffness of a Hybrid III neck and the human; but with numbers that large, I don't know how you could ever map any of this into something that would actually be seen in the field. Because first of all, those numbers are large. But then, it's not necessarily a linear or a point-wise and time-wise type of mapping. So it's not clear that any of this can be used for actual injury prediction. What you actually show is given the Hybrid III dummy and given the test conditions, these are the responses we've got; but, you can't go anywhere near the injury prediction using those estimations, at least based on the data you presented.

ANSWER: I think right now we aren't in a position to say that we've done enough work to utilize this data, in terms of injury criteria. Our key was really to see—to look at a parametric study of peak loads and to try and introduce the concept that duration and bending angles are important. If you look at bending at the neck beyond it's range of motion and introducing, say, the posterior ligaments, tearing, and the set dislocations, we need to account for what's happening later in the event rather than just looking at the peak neck load and ignoring everything after that. So, the focus is really trying to pose the question of -- Is peak load really the best indicator of a bending injury?

Q: Yes, but the point that I'm making is that I don't know that you can get that out of the Hybrid III in the test configurations. All you can do is say, "I did these tests on the Hybrid III. These are the results that I got." There's been a lot of stuff now done in the field that shows that you can get what looks like flexion injuries by compression.

A: Right. I understand that. The localized buckling is definitely a mode, but there's also—If you look at some of the crash tests, the neck is certainly bent beyond what is appearing to be its _____ range of motion and safe magnitude. We were initially looking for some way of being able to use the Hybrid III as a more biofidelic neck and we're now looking at, perhaps, modifying the neck or trying to use another neck instead of the Hybrid III, like another frontal neck dummy or the TRID something or the RID where we get a response in a lower magnitude of loading and we still get the increased stiffness in larger bending loading. So we're just a little frustrated with the use of the Hybrid III, but we're trying to see if there's a way we can modify it or at least address its limitations.

Q: At some point, you're going to have to find ground truth; in other words, a relationship to whatever methodology you're doing and what actually happens in the field as opposed to just evaluating the responses of the Hybrid III. Well, I've talked enough. I'll turn it over to the next person.

Q: *Jingwen Hu, UMTRI*

I'm not sure the type of set-up can represent a real rollover impact because during the rollover, the dummy or the human is moving and the impact roof is in parallel with the ground and no matter if you have roof crush or not. So I'm wondering why you don't just drop the dummy for human cadaver instead of [doing a] load test. What's the advantage of your test set-up?

A: Obviously, a rollover is going to have a different response. We were looking at the response of the dummy and trying to understand, for example, if the injury occurs at the lower neck. With this regulatory dummy, we just look at the upper neck load cells. So we were trying to introduce ways of looking at the Hybrid III dummy.

Q: But the thing is you are trying to propose a criteria for rollover and your set-up is not really the rollover kind of impact. So it's a little bit—I don't know. That's the first question. The other one is for the invert criteria: You can say the force is not a good predictor, but do you use other neck injury criteria, such as Nij, to evaluate your data? Or, why do you propose another one?

A: We have looked at Nij and it's based primarily on the upper neck load cell. We were trying to look at a criteria that utilized the lower neck load cell and what was happening at the area where the injury occurs. That's certainly a consideration. We were just looking at what happens with the peak neck load and the peak neck load is typically considered in a rollover to occur before the roof crush, or after the roof crush, and that's why we were looking at that specifically.

Q: Thank you.

Q: *Barry Myers, Duke University*
Let's talk about the premise. You showed quotes from Ben Allen and Frank Pintar. Ben Allen is a retrospective x-ray study involving no mechanistic analysis. And in Ben Allen's paper, he describes most of the injuries as being compressive flexion, distractive flexion. So to use Ben Allen on a mechanistic basis to describe rollovers is not, perhaps, what the study was designed to do and ignores that, at least in his thinking, axial loads—either compressive or distractive—are present in almost all his classifications. You cited the work of Pintar and Yoga and all that and said that also supports the notion of a flexion injury. And yet, the images you're using are from papers involving head impact. And again with their papers, the head impact resulted in large neck forces and injuries in relatively short periods of time. And then when you compare it to our data with curved necks, you see that axial loading/combined loading seems to sort out the injuries that we see quite well. So, this premise that bending is the sudden mode of injury really doesn't fly with about 20 or 30 years of experience and is a bit of a concern.

A: I'm not saying there's no compressions.

Q: My question, then, is if we go forward and look at an impulse-based criteria for a moment, what is it in this study that you've presented that actually says, "Peak neck force doesn't correlate with injury based on cadaver measurement epidemiology"? How does that conclusion follow from the work you've presented?

A: Well, the peak neck load that occurs—It's going to be the same peak neck load for different amounts of crush or different amounts of stroke. That certainly doesn't seem to make any sense given—I mean it makes sense, but it doesn't seem to apply to the real world. [end of side] …the test to use peak neck load as the criteria when you can get it in a really strong roof the same neck load as a weaker neck roof. There's something missing.

Q: So in that regard, we should titrate our injury criteria based on what we imagine occurs in rollover crashes. As a final point, if we were to move backwards to a momentum-based criterion, I think it would be really unfortunate for the field.

Q: *John Melvin, Tandelta Inc.*
You keep talking about roof crush, but all you've shown is relative velocity of the head to the whatever you're hitting it with and you can do that by falling on your head. So I don't see where roof crush enters into this at all.

A: Well, the roof crush is representative of the platen stroke, the distance to stopping the platen.

Q: But that could be falling on your head just as well, the distance you dropped. So it really isn't roof crush, it's just the relative velocity or the distance over which the dummy moved or is loaded. And, that isn't necessarily roof crush. These are diving injuries, in general, and falling on your head on the ground can cause these just as easily. So, the idea that you've got a roof crush test here: I don't believe that's quite accurate.

A: I didn't mean to imply I had a roof crush test and I think the issue of diving is certainly up for debate. We were looking at the effects of the motion and the bending and the duration and the impact speed; and, it's not trying to recreate a rollover event. It's just looking at the parameters of using that dummy and what it tells us and what it doesn't tell us.

Q: So your scenario is that the occupant just sits there waiting for the roof to hit him in the head, right? I don't think that's the way it works.

A: I think that's a little simplistic.