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Manikin and Cadaver Neck Response to Dynamic Tensile Loading

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ABSTRACT

Serious cervical spine injuries may occur due to tensile forces from windblast during pilot ejection; however, human tensile neck injury tolerance data are not readily available. This study made a preliminary assessment of the human tensile neck injury tolerance and showed some differences between manikin and human cadaver responses to dynamic tensile neck forces. A manikin (ADAM) and three adult human cadaver specimens were subjected to dynamic tensile loading of the cervical spine at 500 mm/s. Out of three specimens tested, only one had catastrophic neck failure, identified as a bilateral facet dislocation at C5-6 with a peak load of 3900 N. The other two specimens experienced loads of 3500 N and 3900 N without catastrophic failure. The ADAM neck was 4-7 times stiffer than the cadaver necks in tension.

INTRODUCTION

Dynamic tensile loading of the cervical spine has been observed by the Air Force Research Laboratory (AFRL) in manikin necks during simulated pilot ejections, parachute deployment, and other scenarios. These tests indicated tensile loading rates from 5,000-10,000 lb/s for the ADAM (Hybrid III) manikin neck. Despite the potential for serious and even fatal injuries due to dynamic tensile loading of the cervical spine, little has been reported on the failure limits of the human neck under these conditions.

Many tensile neck studies have been performed on osteoligamentous specimens under quasi-static loading. Van Ee et al. (2000) performed tensile tests on osteoligamentous cervical functional spinal units at 2 mm/s and found the upper cervical spine was able to carry 2.4 ± 0.3 kN, while the lower cervical spine had a tolerance of 1.8 ± 0.2 kN. Yoganandan et al. (1996) loaded four (4) osteoligamentous spine specimens from skull to T3 in tension; they failed at 0.8, 1.7, 1.8 and 1.9 kN. The limitations of these studies include the lack of musculature and non-dynamic conditions.

Dynamic (1 m/s) tensile tests (Schlick 2002) were also conducted by Yoganandan et al. (1996) on three (3) specimens with skin and musculature intact from head through torso; the failure loads were 2.4, 3.8, and 3.9 kN. The limitations of this study were the small number of specimens tested and the unreported demographics of the test subjects.

The Hybrid III neck is stiffer than cadaver necks under axial compressive loading (Kleinberger et al., 1996). Test data show that the manikin neck is 4-5 times stiffer in compression than cadaver necks (Yoganandan, 1989). While some data are available for compressive loading, stiffness values for the manikin neck under axial tension are not readily available.

The purpose of this study was to (1) preliminarily assess the human tensile neck injury tolerance, (2) observe differences between manikin and cadaver neck responses to dynamic tensile loading, and (3) develop an experimental methodology for future testing. Hence, tensile testing was performed on an Advanced Dynamic Anthropometric Manikin (ADAM) and three (3) adult human cadaver upper torso specimens (head- to- mid-thoracic) at dynamic loading rates.

METHODS

Manikin Test

To conduct a mock-up of the testing protocol and to determine the appropriate displacement rate before using cadaver specimens, an ADAM segment (head to torso) was tested. (The ADAM contains a Hybrid II head and a Hybrid III neck and torso.) Figure 1 shows the experimental setup for the manikin test. An appropriate displacement rate for the cadaver tests was determined by loading the manikin at various displacement rates until the desired loading rate was achieved. The displacement rate producing the desired 33,000 N/s (7,500 lb/s) in the manikin was 500 mm/s. Subsequently, this displacement rate was used in the cadaver tests to simulate the loading environment seen by manikins during rocket-sled ejection tests.

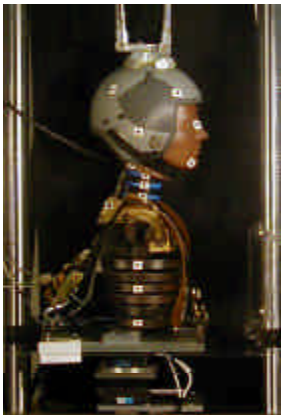

Figure 1: The ADAM was used to evaluate the testing protocol and determine an appropriate displacement rate for the cadaver tests.

Cadaver Tests

Specimen Criteria. The tissues were harvested from fresh frozen (unembalmed) cadavers shortly after death and stored at -20°C. Frozen storage of unembalmed cadaver spinal tissues has previously been shown not to have a significant effect on their mechanical properties (Panjabi et al., 1985). The three (3) cadaveric specimens (intact from head to T11) showed no pre-existing musculoskeletal pathology of the spine. Each specimen was less than 60 years of age and had a height greater than or equal to 64 inches. Table 1 shows the demographics for each specimen.

Table 1. Specimen Demographics.

	Age (yr)	Gender	Height (in)	Weight (lb)
Specimen 1	48	F	64	120
Specimen 2	35	M	69	129
Specimen 3	48	M	69	160

Specimen Preparation. The torso was prepared by removing all internal organs while leaving intact the skin and musculoskeletal structures of the head, cervical spine, thoracic spine (down to T11), ribs (1st through 7th), sternum, scapula, and clavicle. The thoracic vertebrae (T8-T11) were embedded in a 114-mm PVC pipe using polymethylmethacrylate (PMMA) to secure the caudal (lower) spinal structures within the test fixture. Wires were inserted into levels T8 through T10 for increased purchase. In addition, a 9.5-mm diameter steel rod was placed transversely through the T10 vertebra to facilitate specimen mounting to an aluminum plate. Finally, Steinmann pins were inserted into the T1 spinous process, the occiput, and sternum to enable high-speed video tracking.

Experimental Setup. Each head and torso specimen was subjected to loading in axial tension using a custom servohydraulic materials testing system (Model 318s, MTS Corp., Eden Prairie, MN). Figure 2 shows the general test schematic, and Figure 3 shows Specimen 3 in the test fixture. The head was constrained by an HGU-55/P military helmet (Gentex Corp., Carbondale, PA) with integrated chin-nape strap (ICNS). The caudal (embedded) end of the specimen was secured to an aluminum plate via a mounting bracket (not shown in figure) over the steel rod. Additionally, the torso was secured to the aluminum plate using ratcheting nylon straps to provide load sharing similar to a five-point harness. An x-y bearing at the base and a helmet-ram interface with multiple degrees-of-freedom allowed the specimen to self-align during the test to minimize off-axis loading.

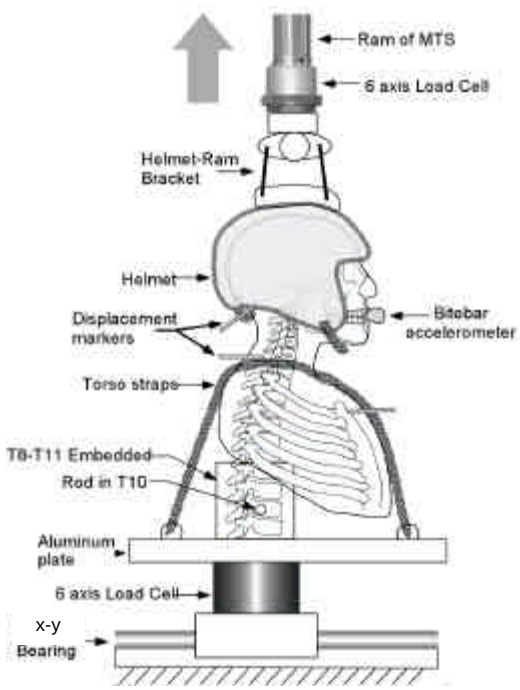

Figure 2: Schematic of test setup.

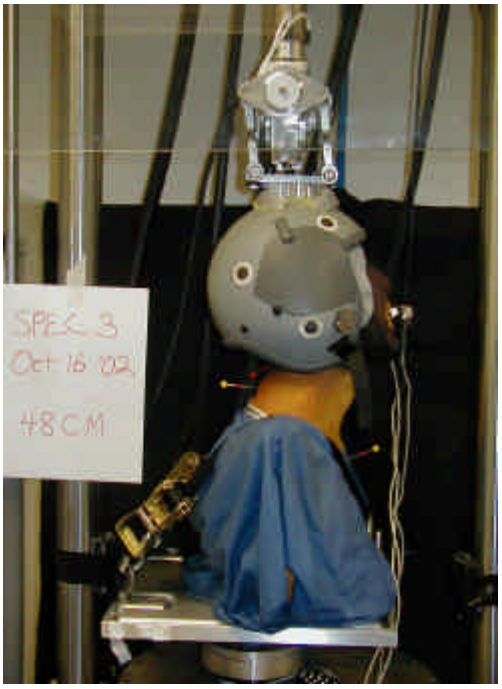

Figure 3: Specimen 3 (48 year-old male) in test apparatus prior to tensile loading.

Instrumentation. Two 6-axis load cells (one between the aluminum plate and bearing track and one between the MTS ram and the head constraint) recorded the force/moment time histories. An instrumented bite-bar with x- and z-axis linear accelerometers (2270, Endevco, San Juan Capistrano, CA) and an Ry angular accelerometer (7302BM2, Endevco) were placed in each specimen's mouth. Displacement markers in the occiput, T1, and sternum were tracked at 1000 frames/s using high-speed video.

Data Acquisition. A high-speed data acquisition board (PCI-6071-E, National Instruments, Austin, TX) acquired the signals from the two 6-axis load cells, three accelerometers, and MTS actuator LVDT at a sampling frequency of 4 kHz. The load cell data went through a 1650-Hz low-pass filter. A FastCam-X1280PCI (Photron, San Diego, CA) high-speed color video camera system captured images at 1000 frames/s.

Loading. To remove initial slack in the system, an initial pretension of 10 N was applied to the system. A displacement rate of 500 mm/s (based on the loading rate derived from the manikin tests) was applied to human tissue. The MTS ram was programmed to displace until the lower load cell saw a significant drop in load indicating failure (320 N within 4 ms) or until the stroke reached 110 mm.

Post-Test Analysis. Upon completion of testing, each specimen was radiographed in both the sagittal and A-P planes with 22-N traction on the cervical spine to assist in exposing injuries. Video tracking of the displacement markers was done using WINAnalyze software (Mikromak, Erlangen, Germany). Direct linear transformation techniques were employed to remove rotational motion components, thereby allowing determination of the displacement between the occipital condyles (OC) and T1.

RESULTS

Loads

The maximum forces experienced by the specimens ranged from 3500 N to 3900 N. Figure 4 shows the force time histories for all three specimens.

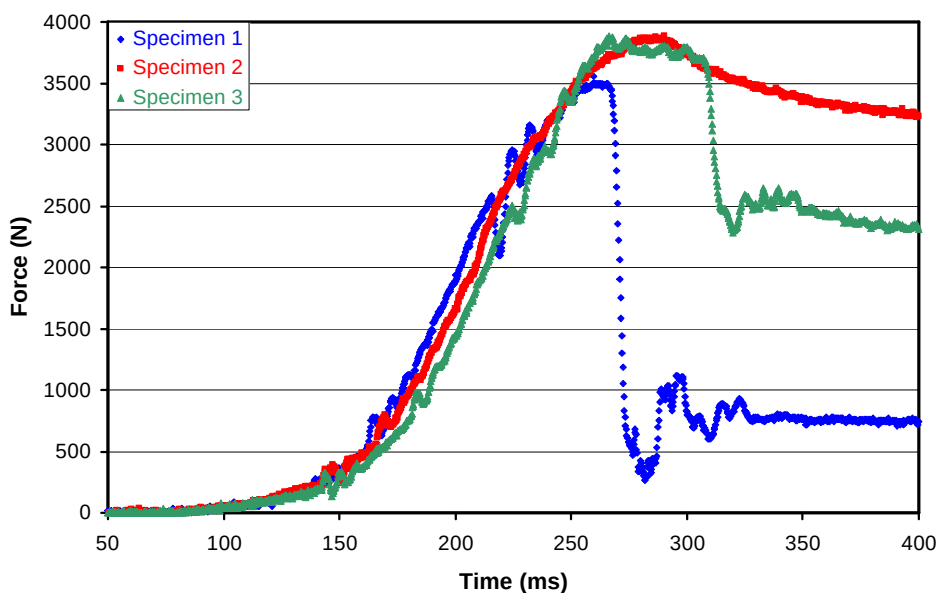

Figure 4: Tensile force time histories for specimens 1, 2, and 3.

Out of the three tests performed, only one specimen showed radiographic evidence of catastrophic failure. Specimen 1 was loaded until the chin strap failed. The maximum axial force through the neck seen by Specimen 1 was 3500 N, but radiographs did not show evidence of failure in the cervical spine. The helmet and ICNS stayed intact for Specimen 2; however, displacement stopped when the ram reached the set "safety limit" of 110 mm. Again, radiographs showed no evidence of failure even though a maximum force of 3900 N had been applied. Specimen 3 saw a maximum load of 3900 N before catastrophic failure occurred in the neck. Shortly after cervical failure, the helmet shell fractured in two places. The lateral radiograph of this specimen showed a bilateral facet dislocation at the C5-C6 level, which is shown in Figure 5. The tissues were not dissected, so soft tissue and ligamentous structures were not examined for damage.

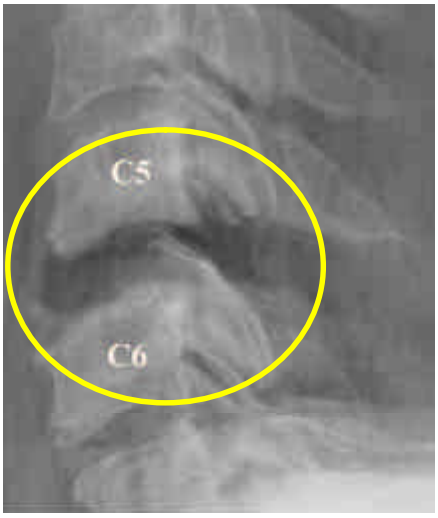

Figure 5: Bilateral facet dislocation at C5-C6 in Specimen 3.

Displacement

Displacement markers placed in the occiput and T1 allowed the measurement of overall neck displacement between the OC and the center-of-rotation of T1 after removing rotational components. (The measurement for Specimen 3 is from the OC to the center-of-rotation of C7 since the pin was inadvertently placed in C7 instead of T1.) Figure 6 shows the force versus displacement curves for the three cadaver specimens as well as for the ADAM. The ADAM was not loaded to the same level as the cadavers to avoid structural damage.

The maximum neck displacements are much lower than the maximum ram displacement of 110 mm because most of the displacement took place in the helmet and ICNS.

Stiffness

A stiffness value for each cervical spine and ADAM neck was determined based on the linear portion of the force versus displacement curve (> 500 N). Although it may have been more appropriate to determine stiffness from the z-force versus z-displacement between the OC and T1, due to limitations of the video analysis, only the z-force versus the overall neck displacement was available to determine neck stiffness. Figure 7 shows linear regression lines in which the slope is the neck stiffness value in N/mm.

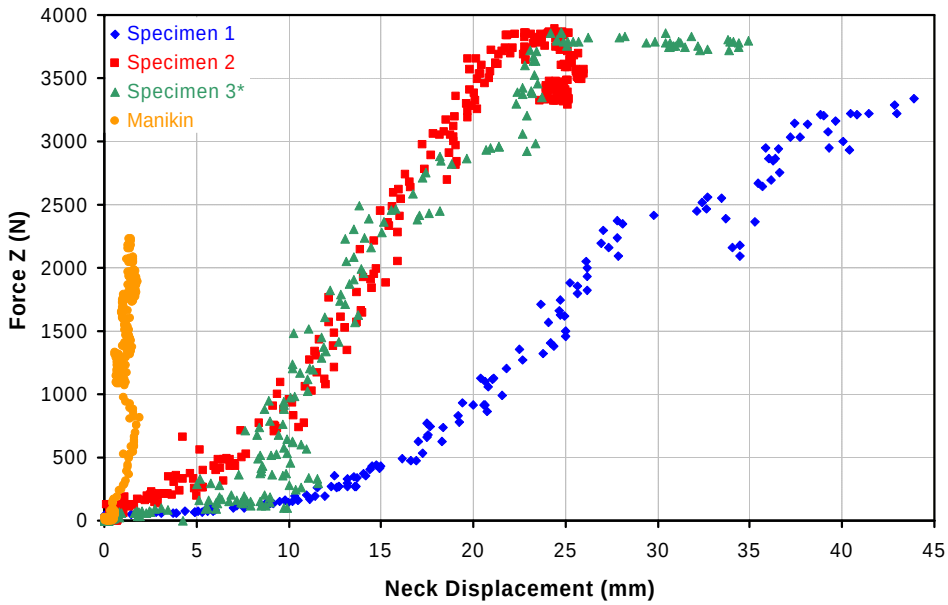

Figure 6: Neck z-force versus overall neck displacement between OC and T1. *Specimen 3 displacement is between OC and C7.

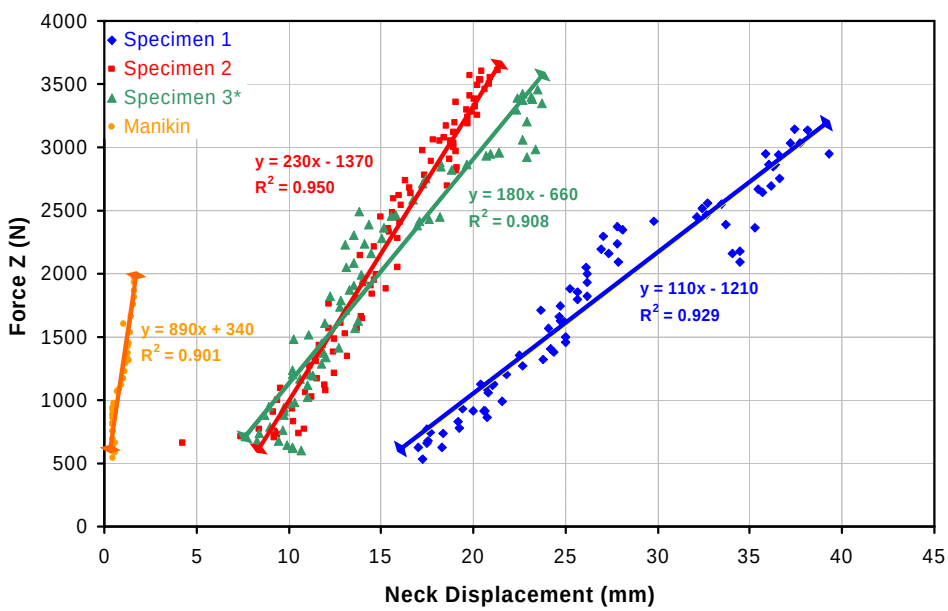

Figure 7: Linear regression of the linear region of the force-displacement curves. The slope depicts overall neck stiffness from OC-T1. *Specimen 3 stiffness is from OC-C7.

A summary of the stiffness values and correlating maximum forces from the manikin and cadaver tests is presented in Table 2. The only catastrophic failure load shown is for Specimen 3, which was 3900 N. The stiffness of the manikin neck in tension was 4-7 times stiffer than the cadaver necks. This was similar to the relationship between manikin and cadaver neck stiffness values in compression (Yoganandan, 1989).

Table 2. Stiffness and Force Summary Table.

	Stiffness (N/mm)	**Tensile Force (N)**
Spec. 1	110	3500+
Spec. 2	230	3900+
Spec. 3	180*	3900
Manikin	890	2200+

* OC-C7 +Non-failure loads

DISCUSSION

Although bilateral facet dislocations are typically caused by flexion, flexion rotation, or extension (O'Brien et al., 1982), tensile forces may also cause bilateral facet dislocations (Wong et al., 1998). Therefore, the injury resulting in this study is in accordance with previous clinical research. Cervical failure did not occur in two of the three specimens due to insufficient load sharing in the ICNS (causing the chin strap to fail before the specimen neck) and a conservative ram displacement safety limit.

Figure 8 compares the data from this study with data from the study done by the Medical College of Wisconsin (Yoganandan, 1996). Because the sample size in each study was small (n=3), statistical comparisons between the data sets were not performed. Therefore, the figure shows only that the results from each study are very comparable. It should be noted, however, that UW Specimens 1 and 2 did not fail during the prescribed loading, whereas, the other specimens did. Also, the region over which the MCW stiffness values were determined was not reported.

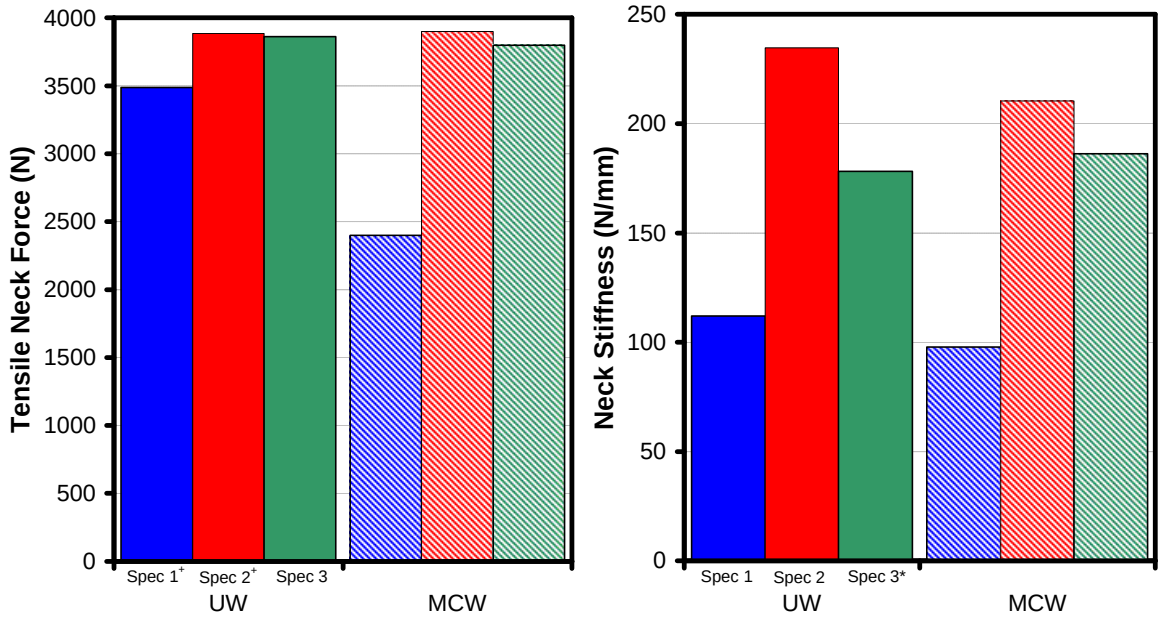

Figure 8: Neck tensile force and stiffness comparisons between UW (2002) and MCW (Yoganandan, 1996). +Loads for specimens 1 and 2 were maximum non-failure loads. * Specimen 3 stiffness is between OC-C7; stiffness range for MCW data is not given.

CONCLUSIONS

This study attempted to make a preliminary assessment of the human tensile neck injury tolerance. Out of three specimens tested, only one had catastrophic neck failure. It had a bilateral facet dislocation at C5-6 with a peak load of 3900 N. The other two specimens had loads of 3500 N and 3900 N without catastrophic failure. This study also showed a noteworthy difference between manikin and human cadaver tensile stiffness values, with the ADAM neck being 4-7 times stiffer than the human cadaver necks. Finally, an experimental methodology was developed for further testing to determine the human tensile neck injury tolerance.

ACKNOWLEDGEMENTS

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DISCUSSION

PAPER: **Manikin and Cadaveric Neck Response to Dynamic Tensile Loading**

PRESENTER: ***E. Yliniemi, University of Washington***

QUESTION: *Guy NuSholtz, DaimlerChrysler*
Well, hello there. Which manikin were you using?

ANSWER: Oh, I'm sorry. I didn't specify—I didn't say that. It was the Adam Manikin (what the Air Force uses) which is essentially the hybrid III manikin with the hybrid II head so that the helmet will fit onto the head.

Q: You're measuring the force at the helmet, top of the helmet?

A: No. Well, there was a load cell at the top, but there was also a load cell underneath the plate that we used to report the loads.

Q: Down at t-8 or wherever you…?

A: Yeah. T-11, just underneath the plate.

Q: And, how much stretch were you getting at the neck?

A: In the manikin?

Q: No, in the cadavers. It looked like you really stretched it quite a bit without an injury.

A: I'll back up just real quickly and show you that the limit—It was about 44 mm for the female, 36 for the male, or 35 for third male and 26 for the first manikin.

Q: And one more quick question: How representative do you think the force that you're measuring is of the force that might be seen at the head-neck junction?

A: Well, the—I think it's actually pretty close because we measured the load above the helmet on the ram and the load underneath. We had two load cells in the path and they were, like, nearly identical in the loading.

Q: Thank you.

Q: *Erik Takhounts, NHTSA*
I have a problem with this particular chart because you relate forces that you measured to the displacements of ram, not the displacement of the neck. Or, you calculated the displacements of the neck?

A: I calculated the displacement of the neck based on the video data, with markers in the occiput and in t-1. And then by doing the video analysis of that, I was able to measure the structure.

Q: So how did you control, then, the constant rate, the displacement rate? Was it also constant?

A: That was controlled through the ram. The displacement rate was controlled through the ram, but this is the actual displacement of the neck, the distraction of the neck.

Q: Thanks.