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Resolving PMHS Upper Neck Loads In High Head Angular Acceleration Testing

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ABSTRACT

Initially, a series of rigid-arm pendulum tests were conducted to evaluate various methods of obtaining rotational head acceleration. Then a series of Hybrid-III dummy tests using only the head and neck system was conducted to validate the test methodology under high-rate chin loading. Finally, a preliminary series of post mortem human subject (PMHS) tests were conducted to derive the response of the human head-neck under high-rate chin loading. The results of the error analysis indicate that precision in locating the externally mounted head accelerometer instrumentation should be within 1 mm and 1 degree. Such accuracy in locating instrumentation relative to anatomical axes requires the use of a 3D positioning device such as a Faro Arm. The pyramid NAP was the best mounting device for a 3-2-2-2 accelerometer array to derive angular accelerations on the PMHS head. The head CG and mass moments of inertia should be directly measured for each preparation to obtain desired accuracy of results. PMHS testing produced upper cervical spine distraction injuries of varying severity. Occipital condyle tension load was found to be the best predictor of these injuries in the PMHS.

INTRODUCTION

The motivation for this paper comes from the scenario of the out-of-position occupant that experiences airbag loading under the chin. Controversy exists as to whether the current anthropomorphic test device used in frontal impact assessments (Hybrid-III) is biofidelic enough in the head neck region to assess a potentially injurious scenario. The purpose of the initial experiments presented in this paper were to develop appropriate instrumentation, validate the instrumentation, and obtain preliminary information to characterize the response of the head-neck complex under this loading scenario.

METHODS

This study was conducted in phases. Initially, a series of rigid-arm pendulum tests were conducted to evaluate various methods of obtaining rotational head acceleration. Then a series of Hybrid-III dummy tests using only the head and neck system was conducted to validate the test methodology under high-rate chin loading. Finally, a preliminary series of post mortem human subject (PMHS) tests were conducted to derive the response of the human head-neck under high-rate chin loading. For the sake of laboratory control, airbag loading was idealized as a point load to the chin of the subject. This was accomplished by using a cable system strapped under the chin of the subject and fixed above to a high-speed electrohydraulic testing system.

Hybrid-III Rigid Arm Pendulum Tests

The Hybrid-III head neck was set up in a rigid-arm pendulum device used for dummy neck calibration procedures (Figure 1). The set up included an externally mounted nine-accelerometer package (NAP) as well as an internal NAP. Two different NAP designs were evaluated: a traditional "finger" type with a tri-axial accelerometer in the middle and two accelerometers at each of three protruding rods (i.e., fingers); and a pyramid NAP (pNAP) with a tri-axial accelerometer package at the tip of the pyramid and two accelerometers at each of the three legs of the pyramid (Figure 2). Upper neck load cell data was collected along with externally mounted tri-axial accelerometer arrays for redundant measurements. All data was collected according to SAE J211 standards. Tests were conducted at impact speeds of 4.7 to 7.1 m/s to force the neck into an extension motion. This design allowed for head rotations without direct head contact.

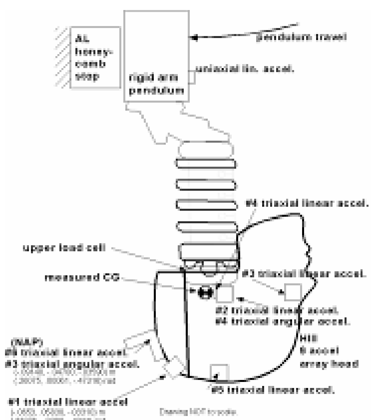

Figure 1: Test set up for Hybrid III rigid arm pendulum tests.

Figure 2: Photo of pyramid NAP used in both Hybrid III and PMHS testing.

It was determined that the center of gravity (CG) of the head and its mass moment of inertia needed to be obtained experimentally with the instrumentation configuration used in each test. A Faro® arm three-dimensional positioning device was used to obtain the position of the NAP and other external accelerometers relative to the CG. The resulting recordings from the NAP were used to calculate the rotational accelerations at the center of gravity of the head according to the equations given by Padgaonkar, et al. (1975). A parametric sensitivity analysis was conducted to determine the accuracy needed in the external accelerometer location measurements. Rigid body mechanics principles were used to calculate the occipital condyle forces and moments using only the accelerometer packages compared to those calculated from the upper neck load cell.

Hybrid-III Cable Pull Piston Tests

The Hybrid-III head neck was fixed at the base of the neck to the frame of a custom-designed high-speed electrohydraulic piston actuator system (Figure 3). The set up included an externally mounted nine-accelerometer package (pNAP) as well as an internal NAP. Upper neck load cell data was collected along with accelerometer responses and piston forces. In some of the tests, a custom designed three-axis chin load cell (Denton, Inc) was used to directly record chin loads. The piston was set to displace at rates from 1 to 8 m/s. Again, recordings from the NAP were used to calculate the rotational accelerations at the center of gravity of the head, and the occipital condyle forces and moments were calculated using the accelerometer packages compared to those calculated from the upper neck load cell.

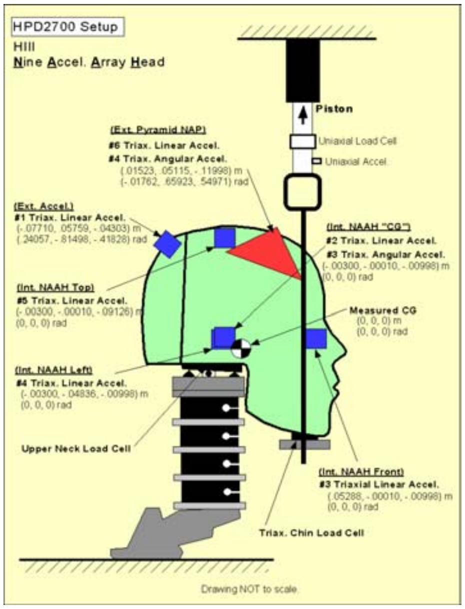

Figure 3: Test set up for Hybrid III cable pull piston tests.

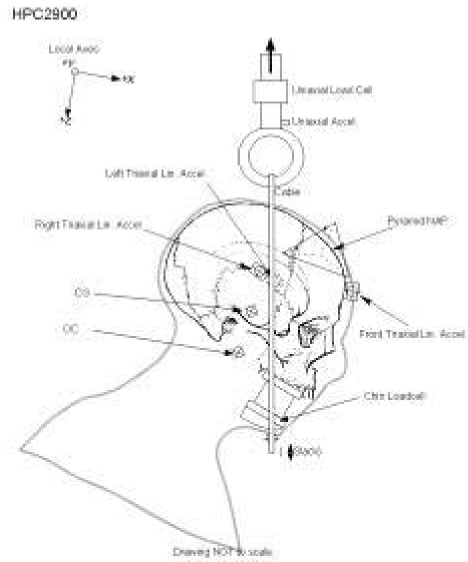

Figure 4: Test set up for PMHS cable pull piston tests.

PMHS Cable Pull Piston Tests

Several post mortem human subject tests were completed. The PMHS heads were instrumented with a NAP and one to three redundant tri-axial accelerometer arrays (Figure 4). The torso was strapped to the frame of the piston apparatus using a harness. The mandible of the PMHS was removed and the three-axis load cell used in the above dummy tests was fixed to the hard pallet such that the application of the loading cable was at the same location as if the mandible was intact and the cable applied load directly to the chin. The T1 vertebra was instrumented with a tri-axial accelerometer mount. A single incision was made on the neck tissues from the tip of the mastoid process, running along the facet pillar line to about C5. Retroreflective targets were inserted into the lateral masses of each vertebra to optically record vertebral movement. A high-speed video camera recorded the target movement. Initial runs were conducted to determine that the instrumentation was recording correctly. These runs were not designed to produce injury to the neck structures. A final injury run at piston speeds from 6 to 8 m/s was done on each preparation. Injuries were evaluated using palpation, gross dissection, x-ray, CT, and finally cryomicrotome sectioning.

RESULTS

The rigid arm pendulum tests with the finger NAP systems indicated that under the highest velocity test conditions, there was greater disagreement between the resulting CG acceleration calculations compared to those measured internally in the dummy head. This also resulted in disagreement between upper neck load cell measurements and those neck loads derived from the NAP system. The location and orientation error analysis using the externally mounted NAP to calculate CG accelerations demonstrated the following. If the linear location of the externally mounted accelerometer was in error by ± 2 mm, the CG acceleration magnitudes were in error by at most 7.2 %. If the angular location of an externally mounted accelerometer was in error by ± 2 degrees, the CG acceleration magnitudes were in error by at most 16.0 %. If the angular orientation of the externally mounted NAP was in error by ± 2 degrees, the resulting CG acceleration magnitudes were affected by at most 8.2 %.

The error analysis for CG location determined that if the location of the CG was in error by ± 2 mm, the force and moment calculations were affected by as much as 18 %. If the moment of inertia was incorrectly measured by 5 %, results indicate that the force and moment calculations were affected by as much as 19 %. If the published values of the moment of inertia on the manufacturers drawings of the Hybrid III were used to calculate the forces and moments at the occipital condyles errors up to 300 % were found.

The results from the Hybrid III cable pull piston tests demonstrated close agreement between CG accelerations derived from the internal NAP and the externally mounted NAP. There was at most a 5.8% disagreement in peak magnitudes of rotational acceleration at around 38,000 rad/sec^2. between the two methods of measurement (Figure 5). Forces and moments at the occipital condyles also agreed well between those calculated using the pNAP and those derived from measurements at the upper neck load cell of the dummy (Figure 6).

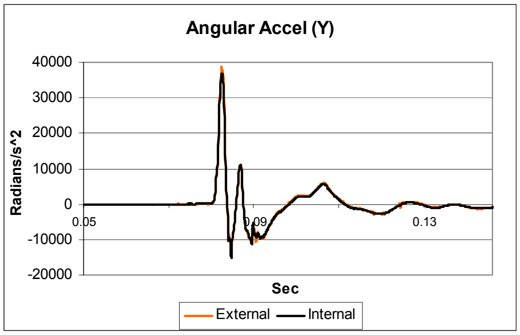

Figure 5: Calculated angular acceleration using external NAP and internal NAP during Hybrid III cable pull piston test.

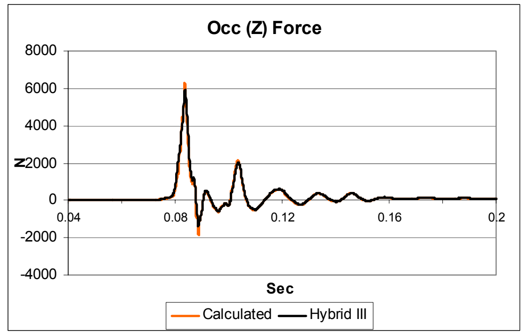

Figure 6: Occipital condyle Z-axis force derived from external NAP (calculated) and from upper neck load cell (Hybrid III).

In total, seven PMHS were tested. There were four females and three males; the ages ranged from 41 to 73 years with a mean age of 57 years. A total of fifteen runs on these seven PMHS were analyzed to derive forces and moments at the occipital condyles (Table 1). The preliminary runs on each specimen consisted of lower velocity tests that only rotated the head at accelerations lower than 3,000 rad/sec^2. A neurosurgeon was in the laboratory to assess the integrity of the neck structures after each run using palpation and plane x-ray films. No injuries were recorded prior to the final failure run. The final run on each preparation was designed to fail the neck at head rotational accelerations from 6,500 to 33,000 rad/sec^2.

Table 1. Results From PMHS Testing Using Cable Pull System.

PMHS ID	Head Angular Accel (rad/s^2)	Fz Tension (N)	My Extension (Nm)	AIS
HPC1404	6,500	3,200	80	2
HPC2002	25,000	2,500	210	2
HPC2102	25,000	3,200	280	2
HPC2203	15,000	2,200	120	1
HPC2801	1,100	140	7	0
HPC2802	1,000	115	5	0
HPC2803	983	123	5	0
HPC2804	2,700	260	14	0
HPC2805	25,335	1,700	100	2
HPC2901	950	110	4	0
HPC2902	2,720	235	12	0
HPC2903	18,000	3,200	50	3
HPC3001	453	90	2	0
HPC3003	2,600	390	5	0
HPC3004	33,000	2,500	100	3

The final injury run on each specimen resulted in predominantly C1-C2 separations. These upper neck injuries were graded according to the AIS scale from 1 to 3. The fifteen runs were used as a preliminary attempt to define neck injury criteria under the above loading mode. The 50th percentile probability of AIS=2+ neck injury when using tensile force was about 1800 N; for AIS=3+ neck injury the 50th percentile was about 3200 N (Figure 7). When inserting extension moment as the criteria, the 50th percentile probability of an AIS=2+ injury was around 70 Nm (Figure 8). The AIS=3+ probability curve using extension moment was indeterminant.

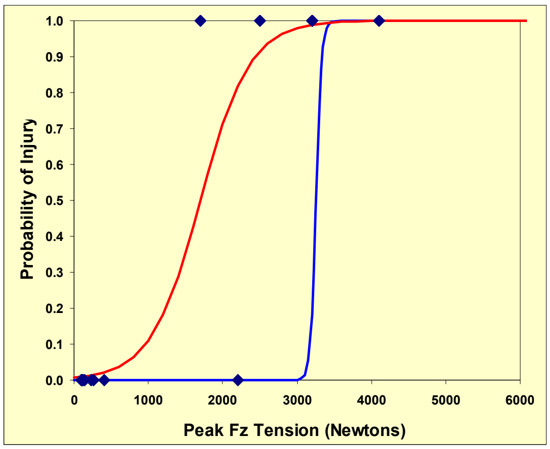

Figure 7: Probability of upper neck injury using peak occipital condyle neck tension.

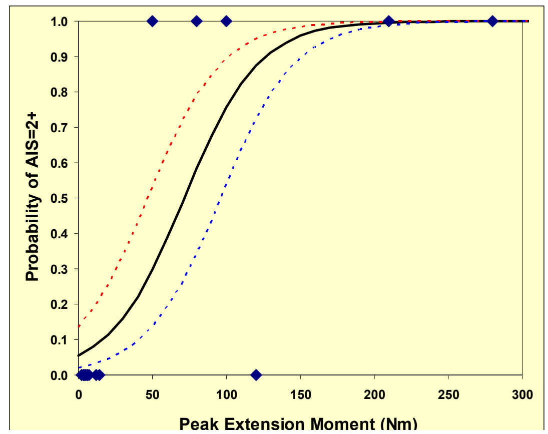

Figure 8: Probability of upper neck injury using peak occipital condyle neck extension moment..

CONCLUSIONS

The results of the error analysis indicate that precision in locating the externally mounted head accelerometer instrumentation should be within 1 mm and 1 degree. Such accuracy in locating instrumentation relative to anatomical axes requires the use of a 3D positioning device such as a Faro Arm. The pyramid NAP was the best mounting device for a 3-2-2-2 accelerometer array to derive angular accelerations on the PMHS head. The head CG and mass moments of inertia should be directly measured for each preparation to obtain desired accuracy of results. PMHS testing produced upper cervical spine distraction injuries of varying severity. Occipital condyle tension load was found to be the best predictor of these injuries in the PMHS.

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REFERENCES

PADGAONKAR, A. J., KRIEGER, K. W., and KING, A. I. (1975). Measurement of angular acceleration of a rigid body using linear accelerometers. Journal of Applied Mechanics 42, 552-556.

DISCUSSION

PAPER: **Resolving PMHS Upper Neck Loads in High Head Angular Acceleration Testing**

PRESENTER: ***Frank Pintar, Department of Neurosurgery at the Medical College of Wisconsin***

QUESTION: *Guy Nusholtz, DaimlerChrysler*
Did you do any comparison between the moments estimated by the post-mortem human surrogates and the dummy and how they compared?

ANSWER: Not directly yet. We're going to put the dummy into the same configuration now that we have with the cadaver. If you look at the, some of the dummy tests where we just did head and neck, where we had a rigid mounting of T-1, we looked a little bit at those and the curves are quite different. Specifically, the moments are, the moments on the cadaver give you an initial flexion moment and down, and then an extension where the dummy doesn't give you that.

Q: Okay. Did you measure the moments of inertia with or without the accelerometer packs?

A: With the accelerometer packs but without the cables because the cables are one of those variables that are hard to deal with.

Q: Okay. And, the final question is: It looked pretty much like your statistical analysis showed, really, no relationship between moment and injury.

A: Yeah, not.

Q: Which is possible, but there's a couple things. Did you consider that maybe the distribution you're looking at is not the correct distribution? It looked like you just used a standard.

A: Oh, that was just a logistic regression. Yeah.

Q: Logistic regression. Yeah.

A: Yeah, you're right. It could be.

Q: It could be.

A: Liable or something.

Q: Yeah, it could be—It could be either moment is meaningless or your process—

A: It could be a wrong distribution. Yeah, that was my first thought.

Q: Okay. Thank you.

A: You got some suggestion on a type of distribution then maybe we'll—

Q: Well, the easiest way to do it is do a CT and get a shape, and that'll suggest what your distribution should be.

A: Okay.

Q: Okay. Thank you.

QUESTION: *Peter Martin, NHTSA*
Frank, I want to get a little clarification on this moment of inertia of the head. Is it possible to get two separate heads—Hybrid III heads—that both pass the certification test but one has a moment of inertia, according to the drawings, and the other has a moment of inertia that you found? In other words, they're 300% off or whatever. And then if that's possible, what does that say that if you put those heads—one at a time—in this OOP position that you're trying to simulate, does that mean that you're

going to get drastically different moments and forces at the OC depending on which head you get, you use?

A: The moment of inertia is really not used unless you do the calculations. Because you measure load directly in the dummy, upper neck load is measured directly. So you never really use that MOI in calculations. Is that what you mean?

Q: I guess.

A: I think that if you put it through a certification test—like that pendulum test—yes, you could theoretically have two heads, two dummy heads that are way off in moment of inertia. Whether that affects the final moment that you're measuring the upper load cell, maybe it doesn't have that big of an effect on the actual measured load cell measurement. I don't know. I haven't looked yet. Potentially, if the MOI's are that much different, then the upper load cell could give you different answers. Yeah.

Q: Okay. Thanks.

QUESTION: *Erik Takhounts, NHTSA*

I don't have my question. Joe McFadden asked me that question and I didn't have the answer. The free body diagram of the head: It's about the wires. Where do we cut off the head? I mean, where do we cut off the wires to calculate the moment of inertia?

A: Yeah.

Q: Because their moment of inertia is changing as the head is moving.

A: Yeah, I mean, it's a problem. I mean, we felt that in that short time domain, the wires were—the mass of the wires was essentially decoupled in that time because the package moves with the head whereas the wires are kind of floating. So in that short time domain, we assume that they didn't have a great effect, but they could. You're right.

Q: But your moments looked pretty good compared to the previous ones.

A: Yeah. So, that's why we thought it wasn't a bad assumption! I mean, I don't know. With pendulums, they take a certain percentage of the wire length to get those kind of constants, so maybe there's some other formula that we could apply.

Q: Well, I think Peter's question is very important with the head experiencing the moment, not the loading, but the inertial motion.

A: Yeah.

Q: That moment of inertia is extremely important on what you are recognizing in the cross-section.

A: Yeah. It would be interesting. I know, as Guy has said, that the corridors to get dummies to calibrate are pretty wide. So yeah, I could see where you could have different ones that would affect that.

Q: Okay. Thanks.