Assessment of Head and Neck Injury Potential During Aircraft Longitudinal Impacts

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Background

- **Current aircraft seat dynamic qualification tests use the Head Injury Criteria (HIC) to evaluate head protection.**
  - HIC of 1000 equates to a 16% to 43% chance of an AIS-3 injury (unconscious from 1-6 hours).
  - This level of injury means that occupants may not be alert and able to assist with their own evacuation after a crash.

Background

- **Current aircraft seat qualification tests do not regularly assess neck injury potential.**
  - HIC reduction methods could have the unintended consequence of inducing injuries to the neck.
  - ATD technology and injury criteria are now available to assess neck injuries.

Purpose

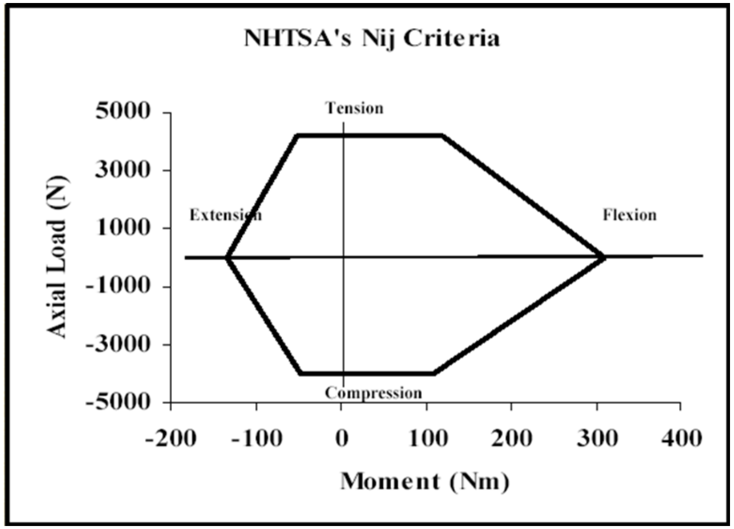
- **Use state-of-the-art techniques to evaluate the potential for head and neck injury for occupants of typical seat configurations during aircraft-longitudinal impacts.**
  - Selected configurations are those with greatest perceived risk of injury.
  - Configurations to be representative of those that would meet the current Head Injury Criteria limit.

Neck Injury Assessment Technique

- **Federal Motor Vehicle Safety Standard 208 requires evaluation of neck injury potential during new vehicle assessments.**
  - Injury Criteria cited are applicable to aircraft occupants (people are people).
  - Can be assessed using Hybrid-III ATD (an approved version is available for aviation use).
  - Combines axial loading and bending moment at the top of the neck (occipital condoyle location).

Neck Injury Assessment Technique

- **Nij Criteria**
  - Formula: $N_{ij} = \frac{F_z}{F_{zc}} + \frac{M_y}{M_{yc}}$
  - Intercepts for 50% Male ATD
    - Fzc Tension = 1530 lb
    - Fzc Compression = 1385 lb
    - Myc Flexion = 2748 in-lb
    - Myc Extension = 1200 in-lb



- **Tension and Compression also limited**
    - Tension = 937 lb   Compression = 899 lb

Head Injury Assessment Technique

- **Head Injury Criteria**

  Time weighted function that uses resultant acceleration measured at the head center of gravity in the following calculation:

$$HIC = \left\{ (t_2 - t_1) \left[\frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} a(t)dt \right]^{2.5} \right\}_{max}$$

  Where a(t) is the acceleration time history, and t1 and t2 are the points in time that produce the maximum possible HIC value.

Head Injury Assessment Technique

- **Head Injury Criteria**
  - **HIC Unlimited** [limit = 1000]: Selects the maximizing time interval from the entire head acceleration time history.
  - **Aviation HIC** [limit = 1000]: Method cited in aviation regulations that considers only the data after head contact. Body to body contact also excluded. Duration is unlimited.
  - **HIC 36** [limit = 1000]: Considers the entire head acceleration time history, but limits the duration of the maximizing time interval to 36 milliseconds.
  - **HIC 15** [limit = 700] : Considers the entire head acceleration time history, but limits the duration of the maximizing time interval to 15 milliseconds. The interval is limited to compensate for HIC's tendency to overestimate injury risk of long periods of low acceleration produced by airbag contacts.

Head Injury Assessment Technique

- **Skull Fracture Correlate (SFC)**
  - Developed by NHTSA and Medical College of Wisconsin.
  - HIC-type calculation that correlates better to fracture than any of the standard HIC formulations.
  - Average acceleration during the HIC 15 interval.
  - 15% probability of skull fracture corresponds to a SFC value of 120 G.

Head Injury Assessment Technique

- **Brain Injury Criteria (BrIC)**
  - Developed by the National Highway Traffic Safety Administration (NHTSA) as a correlate to a subset of Traumatic Brain Injuries (TBI).
  - Correlated with two physical parameters, Cumulative Strain Damage Measure (CSDM) and Max Principal Strain (MPS) which are calculated by finite element models of the skull and brain.
  - Two independent models, SIMon (Simulated Injury Monitor) and the Global Human Body Modeling Consortium (GHBMC) head model were used in the criteria's development.

Head Injury Assessment Technique

- **Brain Injury Criteria (BrIC)**

  BrIC is calculated using only the measured angular velocity in each orthogonal axis.

$$BrIC = \sqrt{\left(\frac{\omega_x}{\omega_{xC}}\right)^2 + \left(\frac{\omega_y}{\omega_{yC}}\right)^2 + \left(\frac{\omega_z}{\omega_{zC}}\right)^2}$$

  Where ωx, ωy, and ωz are maximum angular velocities (calculated irrespective of the time it has occurred) about the X-, Y-, and Z-axes respectively, and ωxC, ωyC, and ωzC are the critical angular velocities in their respective directions.

Head Injury Assessment Technique

- **Brain Injury Criteria (BrIC)**

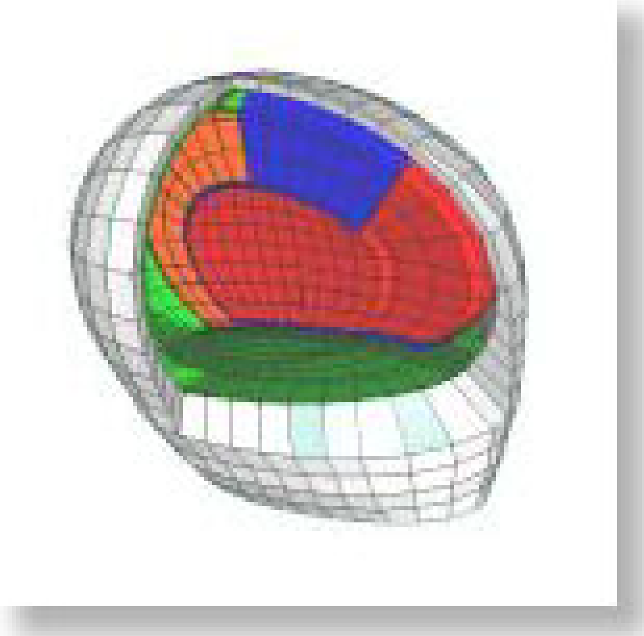
The critical values based on CSDM and MPS are:

$\omega xC = 66.25$ rad/s

$\omega yC = 56.45$ rad/s

$\omega zC = 42.87$ rad/s

A BrIC value of 1.0 corresponds to a 50% probability of AIS 4 or greater anatomic brain injuries.



Test Protocol

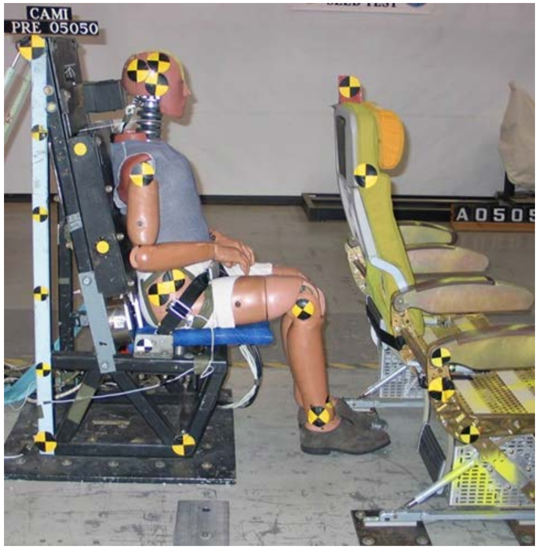
- **Typical** seating configurations found in both transport and general aviation chosen for study. Choices based on highest perceived likelihood of head and / or neck injury.
- **Rigid seat** used to control variability. (one row-to-row test used a real launch row seat).
- Tests conducted **without yaw** to reduce variability and simplify analysis of results. (one row-to-row test run at 10 degrees yaw).
- Total of 26 tests conducted. Some **tests repeated** to assess data spread.

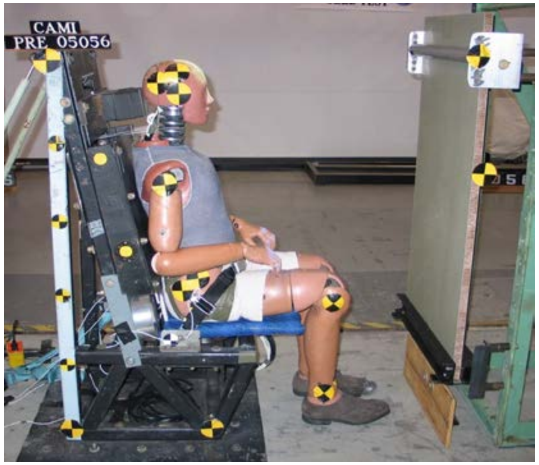
Test Protocol

- **Non-Contact Test Configurations**
  - 4-Point restrained occupant subjected to 26 G forward deceleration.
  - Lap belt restrained occupant subjected to a 16 G forward deceleration.

Test Protocol

- **Head Impact Test Configurations**
  - Lap belt restrained occupant impacting an economy-class seat back designed to limit head injury.
  - Lap belt restrained occupant impacting a wall.
    - Wall made from 1” thick, fiberglass faced, Nomex® honeycomb panel supported at the top and bottom.
    - Intended to emulate the stiffness of a class divider panel.





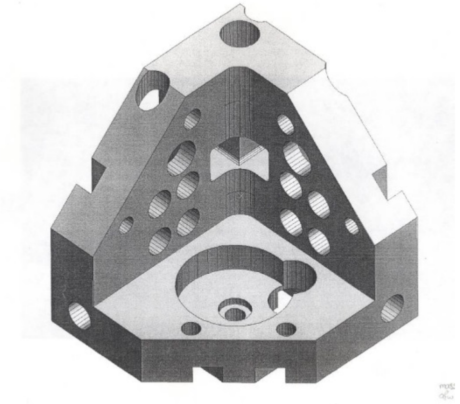
Test Protocol

- **Side-Facing Seat Configurations:**
  - Assessment of head and neck injury included as part of a project to evaluate the ES-2 side-impact dummy.
  - 3-point restrained occupant subjected to a 16 G lateral deceleration. Conventional and inflatable torso restraint both evaluated.


Test Protocol

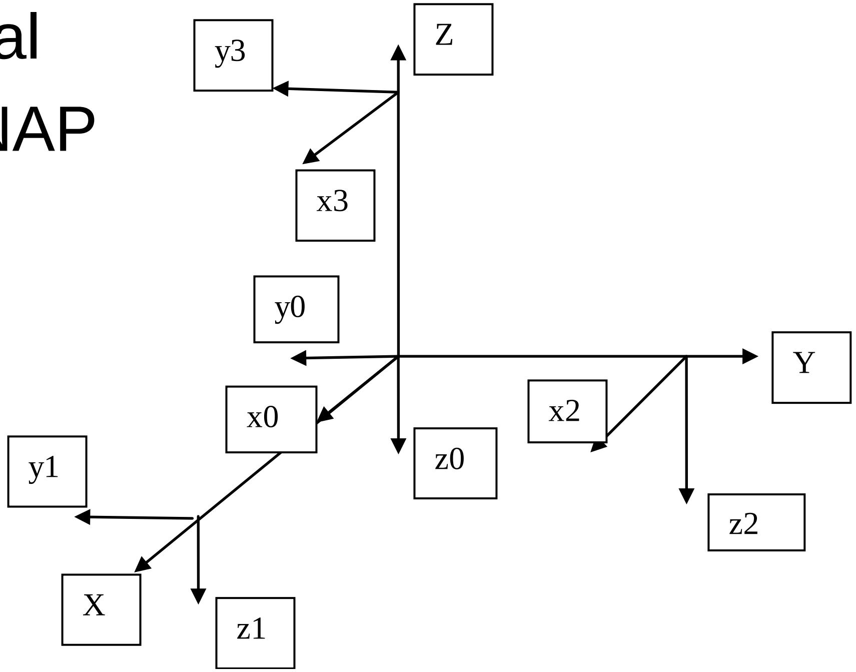
- **FAA Hybrid-III and ES-2 ATDs used with specialized instrumentation**
  - Upper- and lower-neck load cells to directly measure neck loads.
  - A nine-accelerometer array package (NAP) and computational algorithm to gather angular head acceleration data was provided by TNO (a research firm from the Netherlands).

Designed to reduce resonant responses and location inaccuracies found in some other NAP arrangements



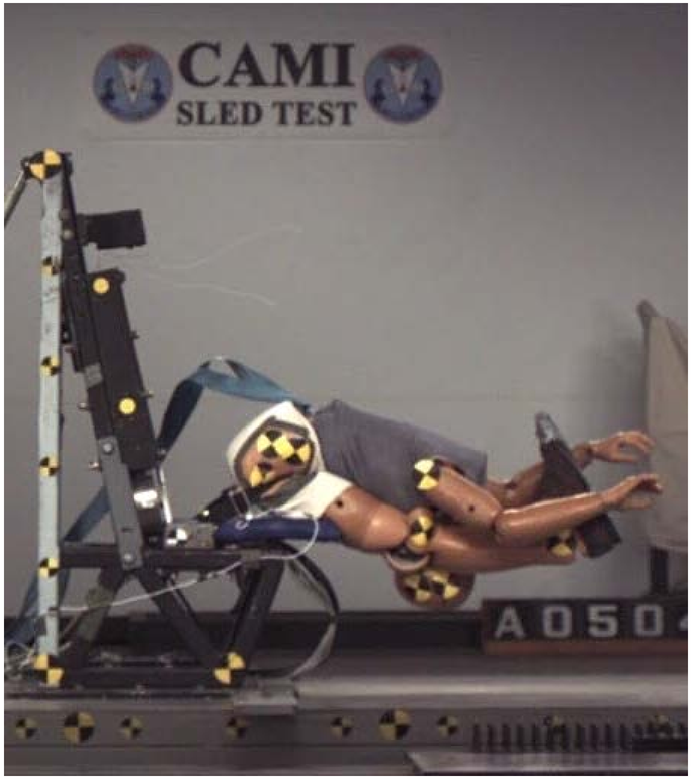
Test Protocol

- **FAA Hybrid-III and ES-2 ATDs used with specialized instrumentation**
  - Angular acceleration derived using measured differential linear accelerations and NAP geometry.
  - Computational algorithm implemented in Matlab.



Injury Assessment

- **Forward-Facing: Inertial Loading**
  - The 4-point belt configuration produced low HIC values, BrIC values below the limit, and Nij values that were about half of the limit, even at the 26 G test condition.
  - Lap belt configuration produced excessive values of HIC unlimited, HIC 15, BrIC and Nij values. Even without head contact, the head whipping downward after the torso contacted the thighs was sufficient to exceed these injury criteria.



Injury Assessment

Row-to-Row (repeated tests)

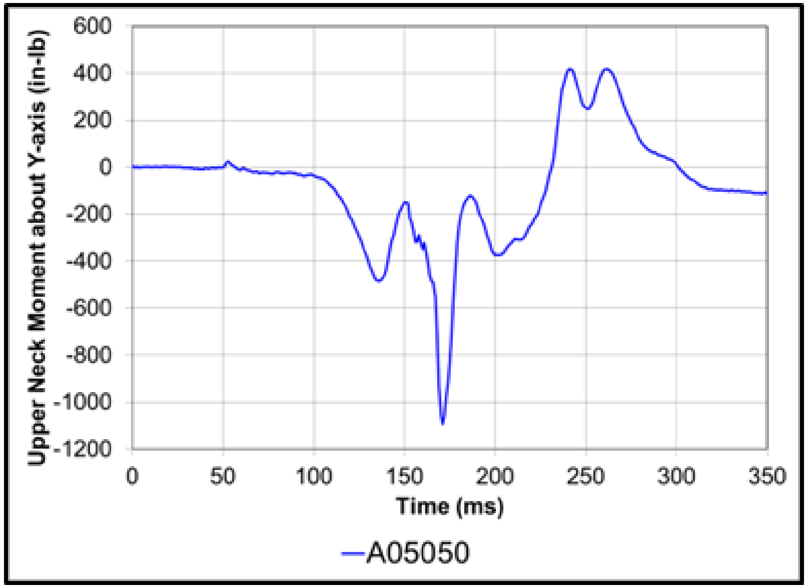
Injury Assessment

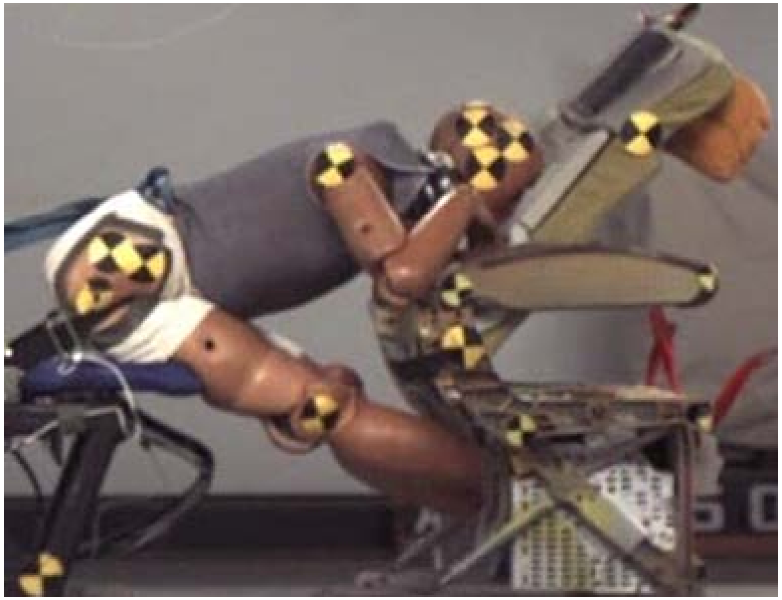
- **Forward-Facing: Row-to-Row**
  - 3 tests were repeated, but differences in head strike location on the seatback affected results.
    - The ATD arms interacted with the seat back in each test and caused the seat back to move forward prior to head contact.
    - These differing head strike locations affected the way the head interacted with the seat back, producing the following results for the three tests:

Test No.	Aviation HIC	BrIC	Nij
A05049	774	0.84	0.80
A05050	1350	0.98	1.06
A05051	948	0.77	0.67

Injury Assessment

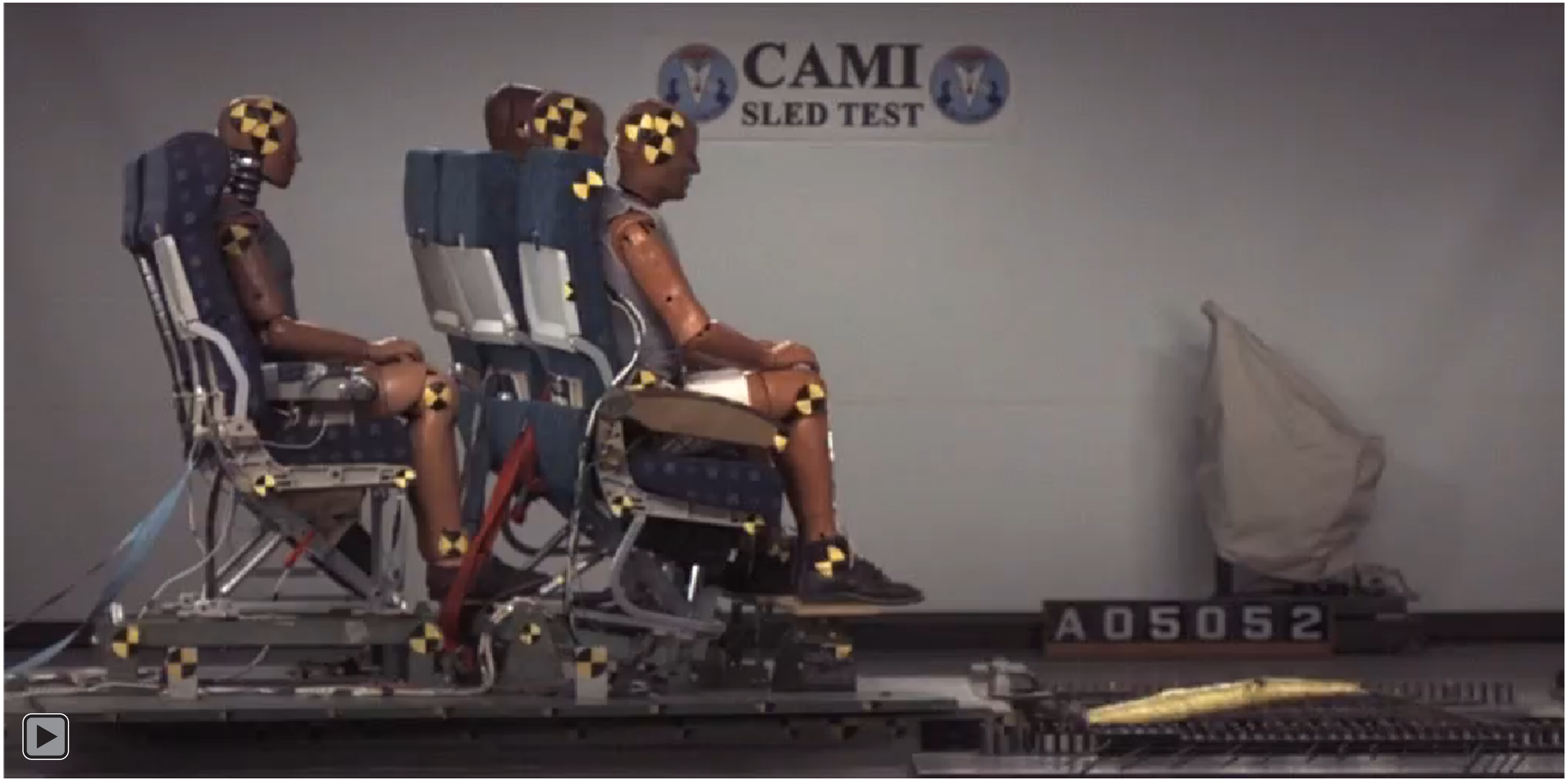
- **Forward-Facing: Row-to-Row (cont.)**
  - The test with the high HIC also had the high Nij. In this test the sliding motion of the head down the seat back was stopped for about 10 ms while the torso was still moving downward. This produced tension and extension moments high enough to result in an Nij value just over the limit.





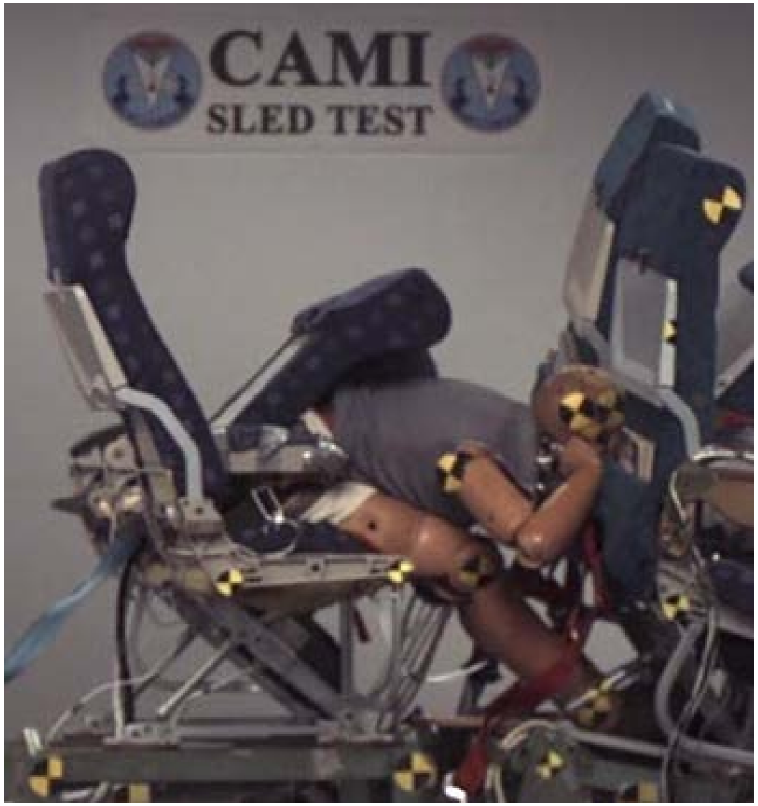
Injury Assessment

Row-to-Row (real seats, fully occupied front row)



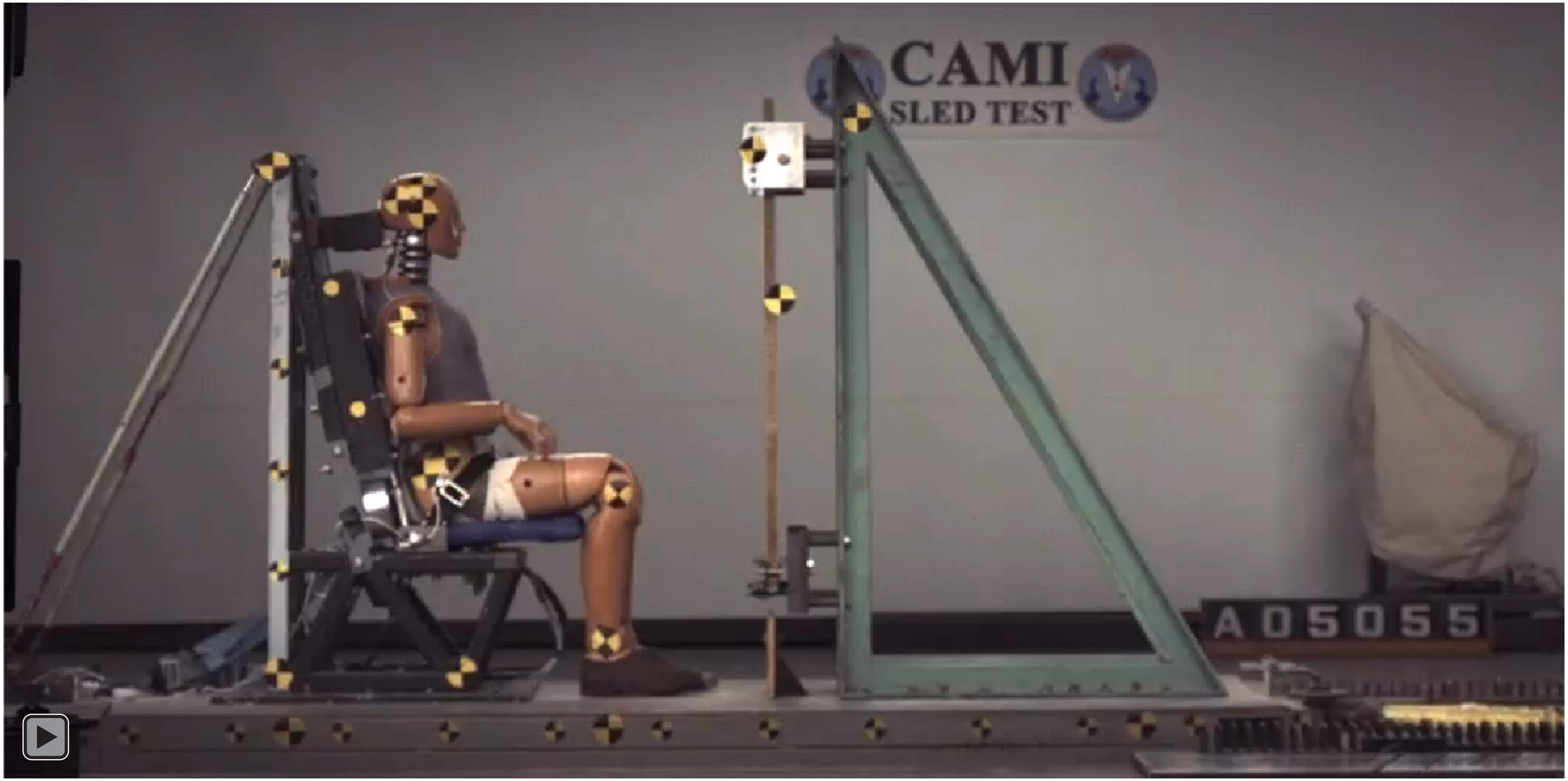
Injury Assessment

- **Forward-Facing: Row-to-Row (cont.)**
  - 1 test was run with a real launch seat and a fully occupied target seat at 10 degrees yaw.
  - Occupancy of the front seat caused it to move forward prior to impact of the aft row occupant, which struck low on the seat back. This low impact point produce a high HIC and BrIC, but <u>not</u> a high Nij (an outcome that is not intuitive given the amount of neck extension observed).



Injury Assessment

Wall Impact



Injury Assessment

- **Forward-Facing: Wall Impact**
  - 3 tests were repeated, but as in the row-to-row tests, the force of the hands on the wall caused it to deflect forward to varying degrees, affecting test results.
  - These differing head interactions produced the following results for the three tests:

Test No.	Aviation HIC	BrIC	Nij
A05054	974	1.44	0.83
A05055	1560	1.26	0.74
A05056	1202	1.57	0.76

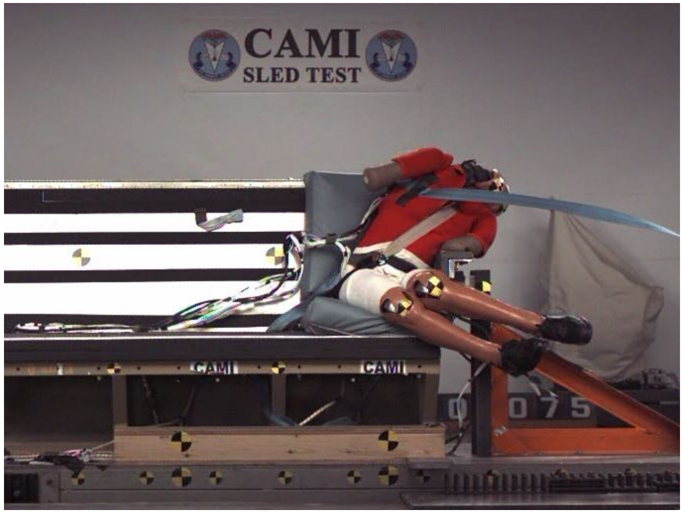
  - 2 other wall tests were run to assess secondary impact onto a low, fixed structure. Interaction with the wall did not dissipate much of the ATD's momentum before it struck the fixed structure. This resulted in very high head accelerations.

Injury Assessment

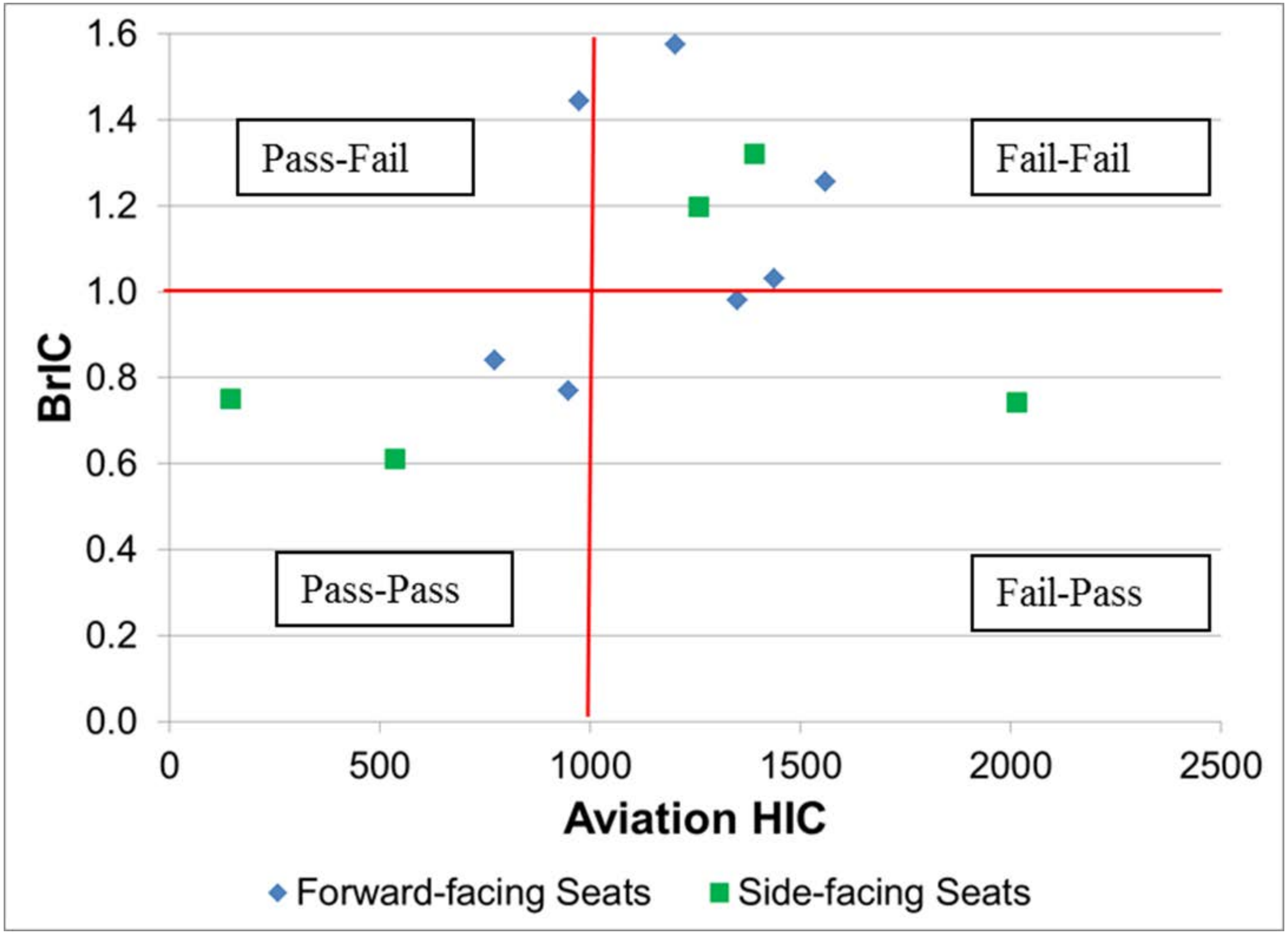
- **Side-Facing: Center Seat**
  - With a conventional torso restraint, the ATD rotates sufficiently for the head to contact the seat back. Values of HIC, BrIC, neck tension, and neck shear all above their respective limits.
  - With an inflatable torso restraint, the ATD head is prevented from impacting the seat. All measured injury parameters below their limits.
- **Side-Facing: Next to Wall**
  - ATD wearing a conventional torso restraint, seated 3 inches from the wall, translates sideways into the wall, producing injury parameters that are relatively low.
  - ATD wearing a conventional torso restraint, seated 6 inches from the wall, hits with more velocity, resulting in high HIC and SFC, although BrIC was low. Addition of an inflatable torso restraint significantly reduces head impact severity.

Injury Assessment

- **Side-Facing: Armrest**
  - When the ATD is wearing a conventional torso restraint and seated next to an armrest, the ATD flails extremely but does not have a head contact (other than striking its own shoulder). This produced high HIC, BrIC, neck tension, and shear.
  - Addition of an inflatable torso restraint significantly reduced the flailing and the resulting head and neck injury measures.



Discussion



1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
BrIC
Pass-Fail
Fail-Fail
Pass-Pass
Fail-Pass
0
500
1000
1500
2000
2500
Aviation HIC
Forward-facing Seats
Side-facing Seats

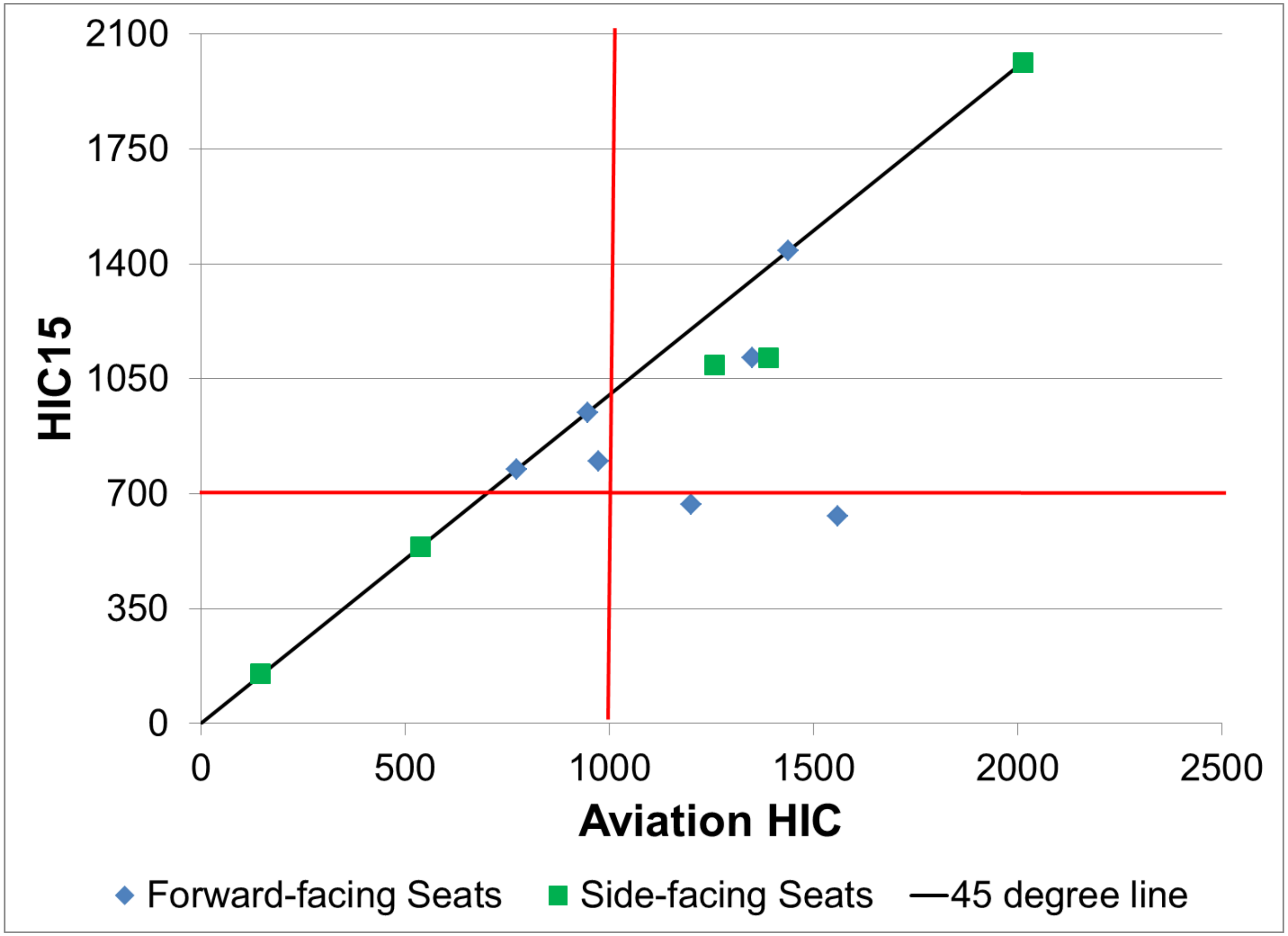
Discussion

- **HIC versus BrIC**
  - A comparison of aviation HIC and BrIC results was made to evaluate the utility of the two assessments.
    - In nine cases, the tests either pass both or fail both.
    - In only one test was the aviation HIC a pass when BrIC indicated a fail. However, all the other HIC calculations indicated a fail also.
    - Based on this limited sample, BrIC does not appear to capture a risk of injury beyond the aviation HIC for these seat configurations

Discussion

- **HIC versus BrIC (cont.)**
  - The added safety benefit of BrIC may lie in the scenarios where aviation HIC is not calculated.
    - In the 5 forward facing seat tests with no contact, BrIC was exceeded in both of the lap belt tests, and was 0.85 or greater in the three tests with a 4-point restraint.
    - The two tests in a center side-facing seat place with an inflatable restraint did not produce a head impact, but had BrIC values near the limit.
    - For the side-facing armrest tests, with a conventional belt, BrIC was well above the limit, as were all the non-aviation versions of HIC.
    - This limited sample suggests that the aviation HIC may miss some potentially injurious configurations.

Discussion



2100
1750
1400
1050
700
350
0
HIC15
0
500
1000
1500
2000
2500
Aviation HIC
Forward-facing Seats
Side-facing Seats
45 degree line

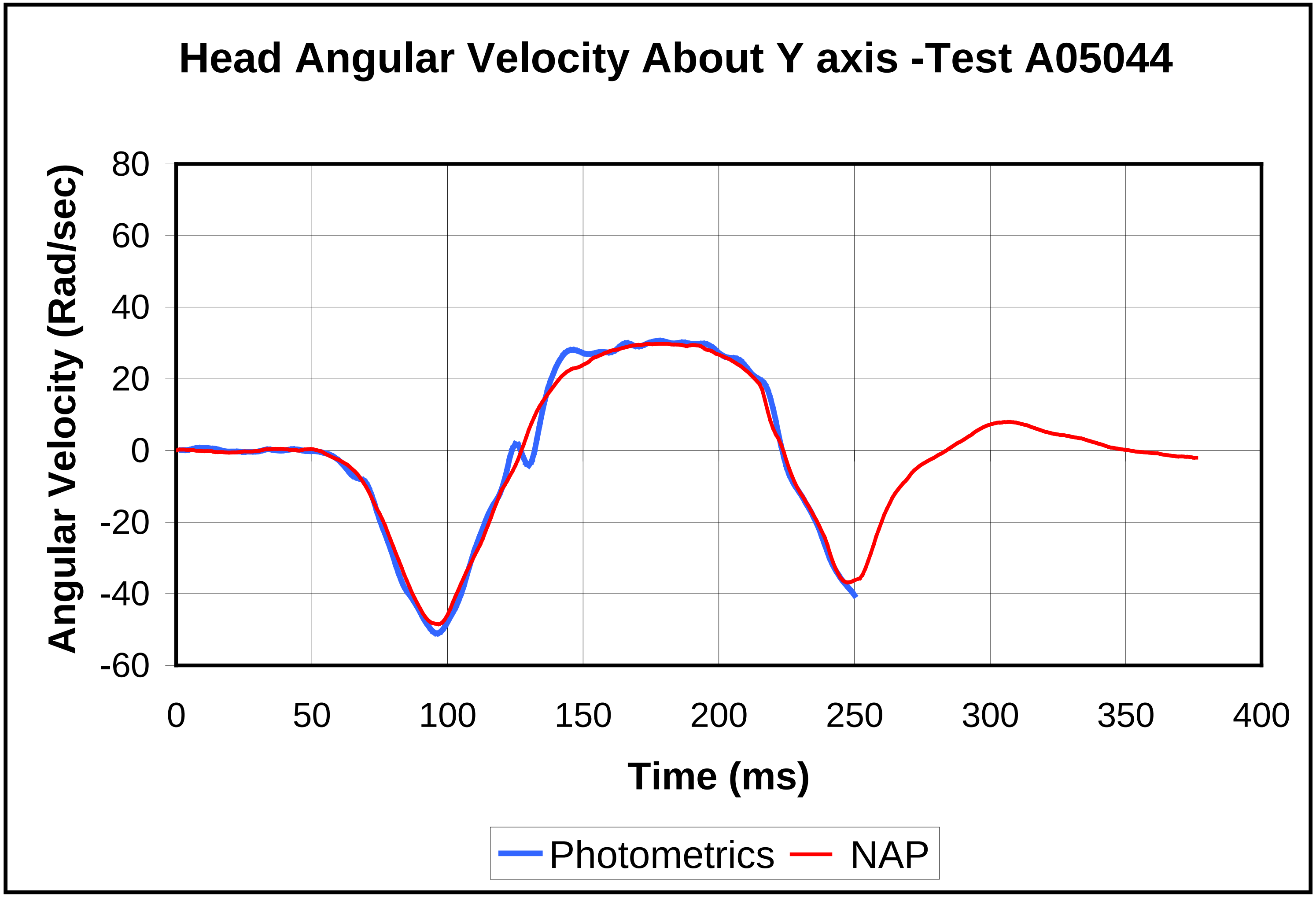
Discussion

- **Aviation HIC versus HIC 15**
  - A comparison was made between aviation HIC and HIC 15 results.
    - Two tests had a failing aviation HIC, while HIC 15 was under 700.
    - Three tests had a HIC 15 above 700 while the aviation HIC is below 1000.
    - Of the 12 tests where aviation HIC was not calculated (no head impact), 3 fail HIC 15.
    - Based on this limited sample using HIC 15 instead of aviation HIC would result in a shift in the configurations that would meet the regulations.

Technical Lessons Learned

- **Angular Acceleration Derivation Issues**
  - Difference routines in the NAP algorithm multiply errors. Some sources of error are:
    - Relatively high noise floor of 12 bit A/D in data acquisition system used.
    - Excessive cross-axis sensitivity and resonant response of some accelerometers used.
  - Errors compensated for by setting boundary conditions and comparing results with photometric analysis results.

Technical Lessons Learned



Technical Lessons Learned

- Head rotational velocity measurements needed for brain injury assessment can now be directly measured using angular rate sensors. Use of that technology for future testing would avoid the complexity of deriving that data using accelerometer arrays.
- Head mounted accelerometers should be set to full scale (at least 2000g for un-damped ones) to avoid resonant response issues. This issue now addressed in the 2014 version of SAE J211.

Conclusions

- **Neck Injury**
  - Not a significant risk in most forward facing seat configurations tested.
    - Nij exceeded in only one case (an impact onto a tray table) and in that case the HIC was also exceeded.
    - Peak tension and compression not exceeded in any of the tested loading scenarios.
  - Is a significant risk in some side facing configurations tested. The configurations that did not provide support to the head and neck by means of a padded wall or inflatable restraint generated excessive neck forces.

Conclusions

- **Head Injury**
  - For head impacts onto seatbacks or walls, there was considerable overlap between the aviation HIC and BrIC pass/fail determinations, suggesting the BrIC does not capture an injury risk that the HIC is not already capturing for the tested configurations.
  - BrIC did suggest the potential for injury in several tests where aviation HIC was not calculated because the ATD head did not contact anything or only contacted another part of the ATD.

Conclusions

- **Head Injury**
  - When comparing aviation HIC to HIC 15, many tests produced a different pass/fail determination depending on which criteria was used. Further research is needed to understand the effect of this shift and determine if there is a safety benefit to adopting a different HIC formulation.
  - Overall, these results indicate that combining HIC and BrIC to evaluate seating systems could provide a safety benefit by directly evaluating the risks of skull fracture and traumatic brain injury.

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- **Test Articles:**
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  - U.S. Army supplied the 4-point restraint systems

References

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