

Investigation of Rear Occupant Head Restraint Interaction in High-Severity Rear Impact using BioRID and HIII

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ABSTRACT

The rear seat occupant has been the subject of an increasing number of research efforts in recent years. However, the majority of the research has focused on frontal impact, while there are also a number of studies concerned with low to moderate delta-V rear impact. Very limited work exists regarding the fate of the rear seat occupant involved in high-severity rear impact, especially when utilizing the BioRID anthropomorphic test device (ATD). Furthermore, it is evident that the out of position rear occupant, as defined by leaning forward prior to rear impact, is also of relevance to this line of research.

The objective of this study is to explore and compare the response of BioRID and 50th percentile Hybrid III in conjunction with the effects of head restraint geometry and the occupant seating configuration (normal seating versus forward leaning) in high-severity rear impact tests.

Using a deceleration sled, BioRID and 50th percentile Hybrid III were placed in the rear seat and subjected to a series of 22-mph delta-V rear impact tests. The pulse shape was representative of FMVSS 301 tests involving sedans. Six sled tests were conducted using two different head restraints and two ATD seating configurations. The ATD response data were analyzed with regard to three categories: 1) comparison of HIII and BioRID response, 2) influence of out-of-position seating configuration, and 3) effect of head restraint height.

The data interpretation was augmented with motion tracking analysis to highlight potential kinematic root causes for the differences between HIII and BioRID response. It was found that the timing in impact response differed for both ATDs due

to the structural disparity of their spines. Differences in time-histories of head acceleration, neck loads and moments were also discussed for the various testing configurations. It was also shown that HIII and BioRID produced contradictory neck data as a result of switching from a low profile to a high profile head restraint when tested in the leaning forward out-of-position setting.

INTRODUCTION

Despite the relatively low priority of rear impact protection compared to other areas of automobile crash protection, and despite the relatively small percentage (5%) of fatality associated with rear impact accidents, rear crashes account for more than 30% of injuries reported for all field accidents [18,27]. According to National Automotive Sampling System (NASS) [30], rear impacts rank second only to frontal impacts in terms of cost to society.

The great majority of the literature available on rear impact covers the front seat occupant subjected to low as well as high-severity delta-V [1,9,11,13,20,22,28]. These studies are mainly concerned with whiplash injury and the roll of the seatback kinematics (deformation) on the front seat occupant. As might be expected, a number of studies have observed substantially lesser risk of injury for the rear seat occupant under low-severity rear impact [10,15]. Only a few researchers have addressed the fate of the rear seat adult occupant involved in a moderate (10 to 20 mph) to high-severity (>20 mph) rear impact. Viano et al [26] conducted a moderate-severity (17.5 mph) study while Shetty et al [25] performed a high-severity (30 mph) experiment concerning the rear seat adult occupant.

The role of the head restraint in injury mitigation has also been studied substantially with regards to the front seat occupant. Several studies of injured population have found head restraints to be beneficial in reducing injury by approximately 10-30% [5,8,17]. Also, tests have found a decrease in occupant kinematics and injury indices with increasing head restraint height [12,19,24]. Several authors [9,10,28] have concluded that both the head restraint height and the head backset distance have the greatest impact on head and neck motion during rear impact collision. However, the effect of head restraint on the rear seat occupant under high-severity rear collision has not been specifically addressed.

NASS database observations [30] point to another phenomenon in rear collisions where pre-impact vehicle motion in a significant percentage of rear impact collisions may cause occupants to not be in the normal seated position (i.e. leaning forward) when the rear impact occurs. Shetty et al [25] showed that such out of position configuration can drastically change the ATD kinematics in high-severity rear impact when using a low-profile head restraint. However, the influence of head restraint height on mitigating the risk of injury in high-severity rear impact needs to be further investigated.

Both HIII 50th percentile and BioRID ATDs have been used in rear impact studies. Both ATDs represent the mid-size adult male. The HIII was developed in the early 1970s by General Motors [6,21]. Although it was primarily used for frontal impacts, it has also been used in high and low-severity rear impact tests. BioRID was introduced in 1999 and was intended specifically for use in low-severity rear impact [2,3]. Studies have shown that BioRID has better biofidelity than HIII when compared to volunteer and cadaver response in low-severity rear impact [2,3,4,7,14,24]. Little is known about BioRID's performance in rear impact at elevated delta-V in the moderate to high-severity range.

In this study, we conducted comparative evaluations of rear seated BioRID versus HIII in high-severity rear impact collision. We evaluated various attributes of the contact between head and head restraint, with emphasis on head acceleration and neck loads and moments. Further we examined the effects of normal seating and leaning forward seating positions on ATD response. Finally the influence of low profile and high profile head restraint for each ATD in the forward leaning position was studied.

METHODOLOGY

The sled tests were conducted at Kettering University Crash Safety Center. The rear section of a 2004 four-door sedan vehicle was used as the sled buck as shown in Figures 1 and 2. The buck was mounted rearward onto a pneumatically

actuated, rail guided deceleration sled which was impacted into a fixed decelerator.



Figure 1. Front View of Buck



Figure 2. Side View of Buck

For each test, a 50th percentile Hybrid III and a BioRID II anthropomorphic test device (ATD) were placed in the rear seat. Both HIII and BioRID weighed 171.3lbs (77.7Kg) with a seated height of 88.4cm (34.8 in). The ATDs were tested in the same seat individually, and they were instrumented as shown in Table 1. Continuous three-point seat belts were used mainly to hold the ATD in position during the sled run-up to the impact. The seat belts did not include any pretensioner or energy management feature. The retractors were disabled and the belts were locked in a snug position using a webbing locking device.

Table 1. ATD Instrumentation

BioRID	Channel Description	Measurement	Data Channel
	Head	Acceleration (x/y/z)	3
	Neck	Moments & Forces (x/y/z)	6
	Thorax (C4)	Acceleration (x/y/z)	3
	Thorax (T1)	Acceleration (x/y/z)	3
	Thorax (T8)	Acceleration (x/y/z)	3
	Thorax (L1)	Acceleration (x/y/z)	3
	Pelvis	Acceleration (x/y/z)	3
Total			24

HiII	Channel Description	Measurement	Data Channel
	Head	Acceleration (x/y/z)	3
	Neck	Moments & Forces (x/y/z)	6
	Chest	Acceleration (x/y/z)	3
	Pelvis	Acceleration (x/y/z)	3
	Lower Lumbar	Moments & Forces	3
Total			18

Tests were carried out with two types of head restraints: a) original low profile head restraint (LHR) seen in [Figure 3](#) and b) adapted high profile head restraint (HHR) shown in [Figure 4](#). The integrated head restraint of the standard production rear seat of the 300C was used as the LHR. As for the HHR, a typical front seat head restraint from a 2005 Chevy Malibu was adapted for the rear seat using a rigid base-bracket with minimal interference with the seat itself. The height of the HHR was adjustable.



Figure 3. Low Profile Head Restraint



Figure 4. High Profile Head Restraint

ATDs were placed in the rear seat in two different seating configurations: 1) Nominal Seating Position (NS) ([Figure 5](#)) and 2) Leaning Forward Seating Position (LFS) ([Figures 6](#) and [7](#)). In NS position, the ATDs were positioned with level head, legs bent at the knee with the feet on the floor board and they were secured using the three-point restraint system as previously described. The torso was positioned against the seat back with a backset of 50mm between the back of the head and the frontal vertical plane of the head restraint. The LFS position was accomplished by leaning the upper torso forward while keeping the hip in the same position as for NS. A backset of 300mm was prescribed for LFS position. The HHR was adjusted to match the top of the head restraint with the head CG. LFS was used to approximate a pre-impact forward movement of the rear passenger due to a braking action that may precede the rear impact. The backset distance was matched for both ATDs. The consistency of the seating positions was ensured in each test using a multi-axis coordinate measuring arm. In all tests, the head CG, shoulder and hip target locations were kept to within a 10mm variation from test to test.

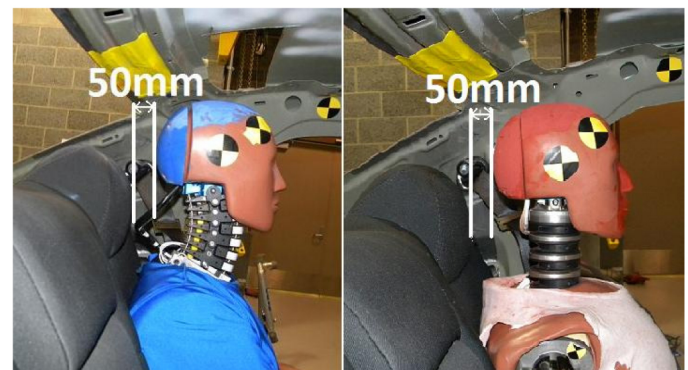


Figure 5. Normal Seating Position with LHR

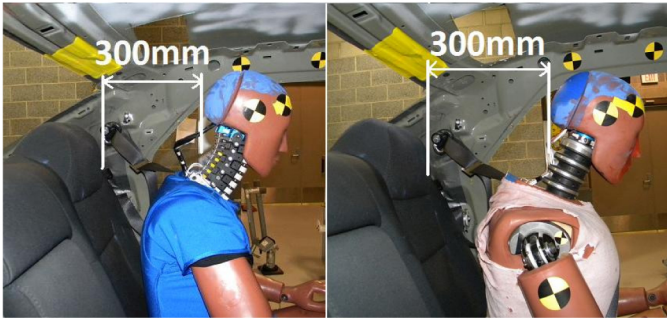


Figure 6. Leaning Forward Seating Position with LHR

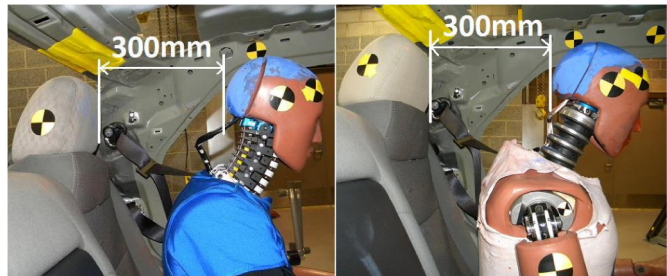


Figure 7. Leaning Forward Seating Position with HHR

The impact pulse for the test series was designed to provide a deceleration profile typical of the revised FMVSS 301- “Fuel System Integrity” tests where the vehicle at rest is rear impacted at 50mph by a 1361Kg deformable barrier with a 30% offset. The vehicles chosen belonged to the same category as the buck. Since the vehicles were hit at an offset, it was observed that the impacted side exhibited moderate intrusion into the rear passenger compartment resulting in seat deformation. Therefore, the pulse for this work was obtained from accelerometers placed on the opposite side from the impacted side. [Figure 8](#) shows the representative pulse, which was formed by staying above the average of all the pulses from different vehicles researched. The pulse that was produced on the deceleration sled is shown in [Figure 9](#). The simulated pulse had a peak acceleration of 9.6G, and duration of 180msec representing a delta-V of 22mph.

Two on-board high speed video cameras were mounted perpendicular to the rear occupant positions to capture the motion of the head, head restraint and the pelvis. The cameras recorded the impact at 1000 frames per second with a shutter speed of 1/4000. Video collection was synchronized with the data acquisition system by using a sled impact trigger, which actuates an optical flash to signal the time of initial sled impact. Upon impact, the video and sensor data were collected synchronously. All data were collected and processed in accordance with the procedures specified in SAE Recommended Practice J211/1.

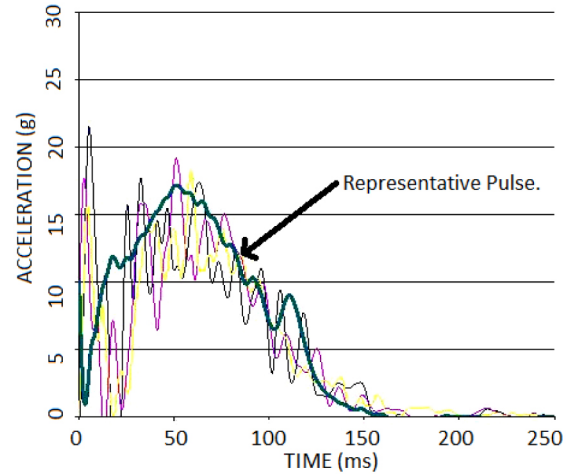


Figure 8. FMVSS 301 Pulse Composite

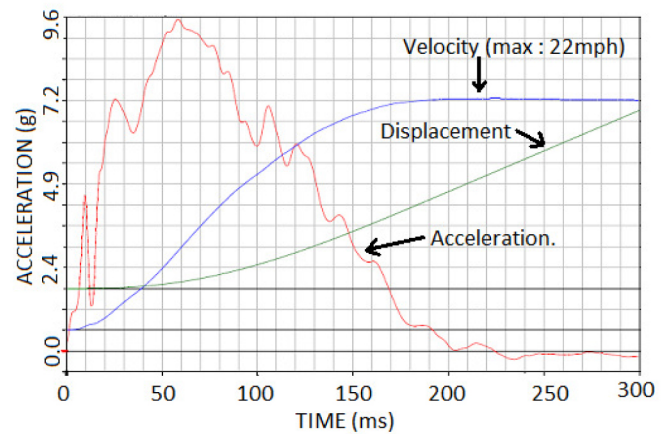


Figure 9. 22mph Rear Impact Sled Pulse

A series of six tests were conducted as shown in [Table 2](#). Each test was conducted twice to ascertain consistency. Due to the inadequate resources, BioRID was tested without recalibrating the cable tension from test to test. An average of the results for the two repeat tests was reported in the results section. No repeat test was conducted with the BioRID in LFS with LHR configuration due to the severe kinematics of this configuration which even resulted in a head scrape with the roof. The HHR was changed after each test since the head impact bent the stay bars every time.

Table 2. Test Matrix

ATD	Test Configuration	No. of Tests
HiII/BioRID	NS-LHR	2/2
HiII/BioRID	LFS-LHR	2/1
HiII/BioRID	LFS-HHR	2/2

RESULTS AND DISCUSSIONS

The objectives of this study were to 1) compare HIII and BioRID response, 2) study the influence of out-of-position seating configuration and 3) investigate the effect of head restraint height. The results were grouped and analyzed under the following categories:

Category 1: Comparison of BioRID and HIII - The response of both ATDs were compared for each seating position (NS vs. LFS), and then again for each head restraint height (LHR vs. HHR).

Category 2: Influence of out-of-position seating - The response of each ATD was analyzed to highlight the influence of change in seating position (NS vs. LFS) when using LHR.

Category 3: Effect of head restraint height - The response of each ATD was analyzed to highlight the effect of head restraint height (LHR vs. HHR) in the LFS position.

As previously mentioned, all reported data represent the average of the two repeat tests except in the case of BioRID in LFS with LHR for which only one test was conducted for the reasons mentioned earlier.

For each repeat test, a percent deviation was calculated to assess consistency, which is given in Eq. (1)

$$\text{Percent Deviation} = \frac{\left(\frac{\text{Range}}{2}\right)}{\text{Average}} * 100 \quad (1)$$

where, Range = Difference in values obtained from repeat tests.

The average and maximum percent for each ATD and test configuration are reported in Table 3. For the repeat tests, the percent deviation for each ATD was well within 15%, except for four values of BioRID which ranged from 15 to 25% and two values of HIII which ranged from 15 to 28%. Additionally, as mentioned previously, BioRID was not recalibrated from test to test, nevertheless, it showed an overall variability of less than 6% (Table 3). The complete set of data for all the tests covered in this paper can be found in Braganza [31].

Table 3. Percent Deviation

ATD	Overall		NS-LHR		LFS-LHR		LFS-HHR	
	Avg	Max	Avg	Max	Avg	Max	Avg	Max
HIII [50th]	5.3	25	5.1	15	3.3	12.2	7.4	25
BioRID	5.9	27.9	6.2	27.9	n/a	n/a	5.7	19.4

Category 1a - Comparison of BioRID and HIII in NS Position with LHR

The overlaid graphs in Figure 10 show the resultant head acceleration data for both ATDs. Between 50 and 60ms, the head began to accelerate rearward contacting the head restraint between 70 and 75ms, which is marked by the sudden increase in acceleration. Both ATDs exhibited similar head acceleration profiles except that the peak head acceleration for the HIII was about 10% higher and occurred earlier. Also, peak head acceleration was attained around the time of maximum head displacement for both ATDs (Table 4). Figure 11 shows that both HIC₁₅ and HIC₃₆ indices were higher for HIII.

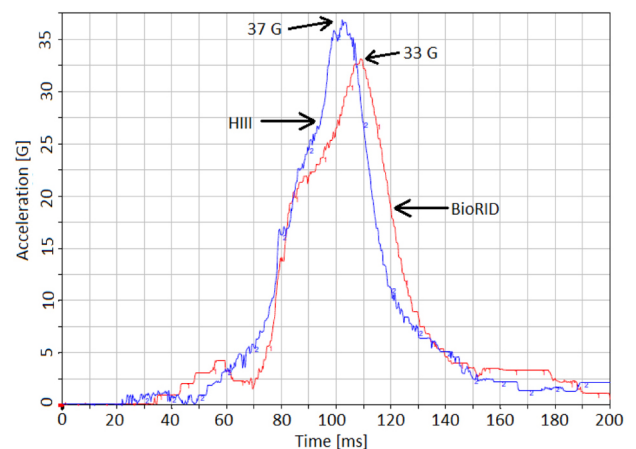


Figure 10. Resultant Head Acceleration

Table 4. Rearward Head Displacement

ATD	Disp. to Contact (mm)	Time (ms)	Max Rearward Disp. (mm)	Time (ms)
HIII [50th]	134	71	246	104
BioRID	131	71	275	113

The rearward head displacement is given in Table 4. The distance to contact the head restraint was more than the 50-mm backset since the head contact for both ATDs was behind the front vertical plane due to the low height and sloping surface profile of the head restraint which led to the first contact point being at the base of the head (Figure A1). The BioRID head travelled approximately 12% more, perhaps due to the same observation made by Gotou et al [7] at delta-V of 10-16mph: the BioRID neck has more motion than HIII neck relative to the upper torso.

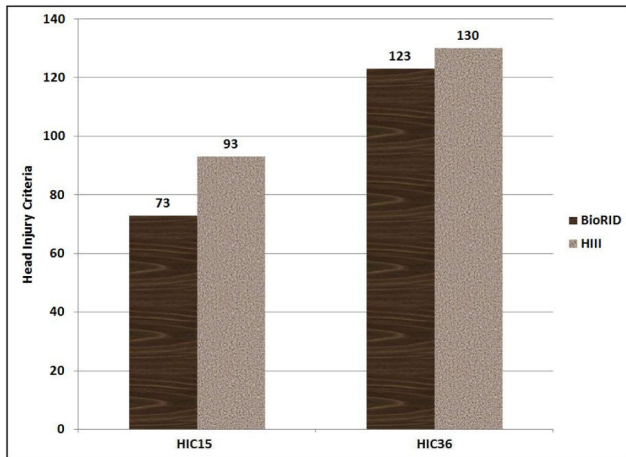


Figure 11. Head Injury Criteria

The maximum vertical pelvis and head displacement for both ATDs was determined using high speed film analysis. The results are given in rose 12 mm higher than HIII's head at the same time. This observation shows that the structural differences between the two ATDs affect their interaction with the seat and the head restraint.

Table 5. BioRid's pelvis rose 5 mm less than HIII's pelvis at impact with the head restraint, while its head rose 12 mm higher than HIII's head at the same time. This observation shows that the structural differences between the two ATDs affect their interaction with the seat and the head restraint.

Table 5. Vertical Displacement

ATD	Disp. at head restraint contact (mm)		Disp. at Max Head Disp. (mm)	
	Head	Pelvis	Head	Pelvis
HIII [50th]	15	8	11	19
BioRID	27	3	13	26

The upper and lower neck loads and moments are shown in Figures 12, 13, 14. Lower neck showed higher shear for HIII, potentially due to the higher shear stiffness of the HIII neck. HIII experienced higher upper and lower neck tension. For both ATDs, tension was the dominant axial load at the upper neck. These results are consistent with Welch et al [29] and Kim et al [11] (5-15mph delta-V, in-position, front occupant) except for the upper neck tension which Kim et al [11] reported to be similar for both ATDs (with the head restraint in "down" position), and Welch et al [29] reported to be higher for BioRID. HIII also showed higher upper neck positive shear which is contrary to Kim et al [11]. Further, the difference in the two ATDs was especially remarkable in the lower neck tension and compression. The tension recorded by HIII was twice and the compression was half of that achieved by BioRID.

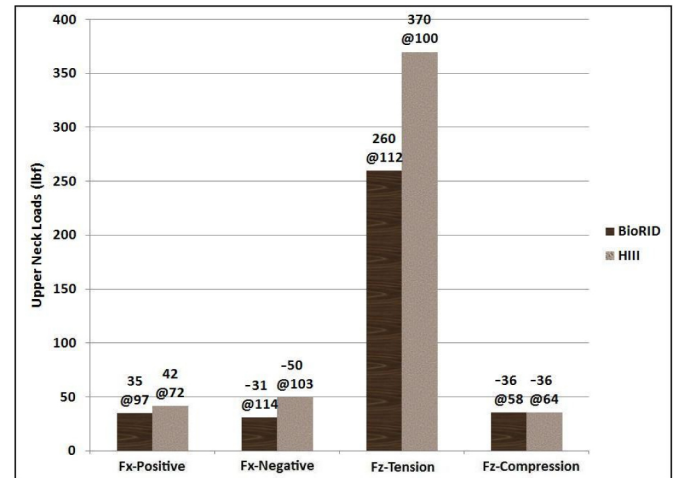


Figure 12. Upper Neck Loads

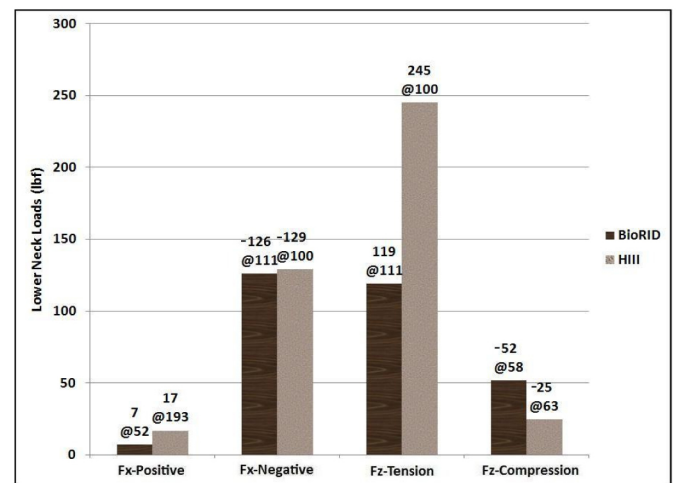


Figure 13. Lower Neck Loads

The upper neck moment started with extension and changed to flexion while the lower neck moment went from flexion to extension for both ATDs (e.g. Figure 15). The peak upper neck extension was recorded around the time of head restraint contact for both ATDs. BioRID had lesser upper neck extension (almost half) at the time of head contact (70-72ms), but this difference was lessened and eventually reversed for the flexion which took place around the time of maximum rearward head displacement (Figure 15). HIII attained higher extension at upper neck while BioRID showed higher extension at lower neck. Welch et al [29] reported similar extension at the upper neck for both ATDs but higher extension for HIII at lower neck. Also, Kim et al [11] reported higher upper neck extension for BioRID with the head restraint in "down" position. Additionally, for both ATDs, the lower neck extension far exceeded the upper neck extension pointing to the lower neck as an important site in high-severity rear impact. Welch et al [29] also observed that

the difference between lower and upper neck extension increased with increasing impact speed.

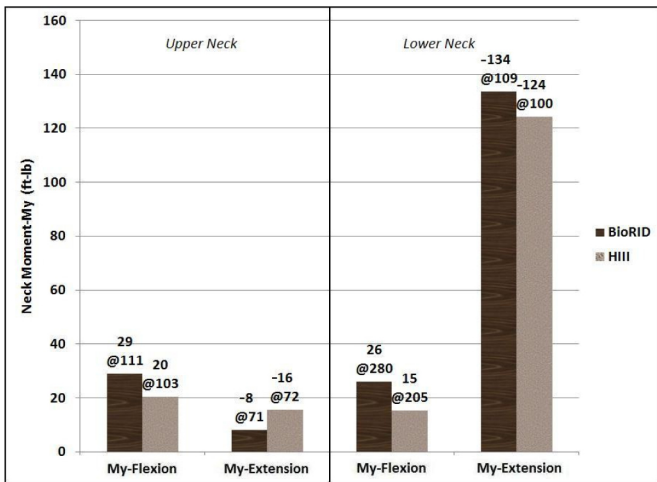


Figure 14. Upper and Lower Neck Moment

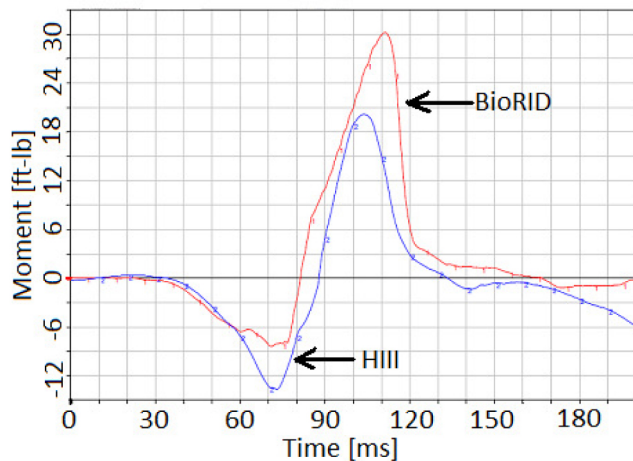


Figure 15. Upper Neck Moment

Figures 16 and 17 show the upper and lower neck N_{ij} values. All N_{ij} values in the upper neck were higher for HIII. For both ATDs, the upper neck tension N_{ij} values exceeded the compression N_{ij} values. This observation is in agreement with Welch et al [29]. All lower neck N_{ij} values were higher for BioRID except for tension-extension. The differences in the lower neck N_{ij} values for the two ATDs were subtle. Also the lower neck tension-extension N_{ij} values were the highest (>1.3) for both ATDs.

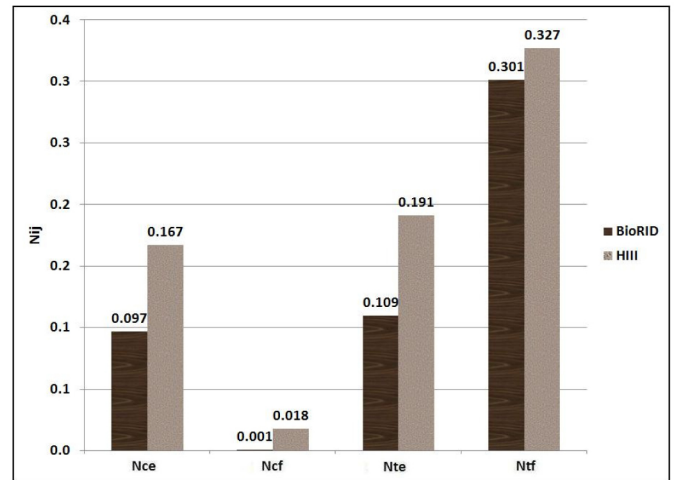


Figure 16. Upper Neck N_{ij} Results

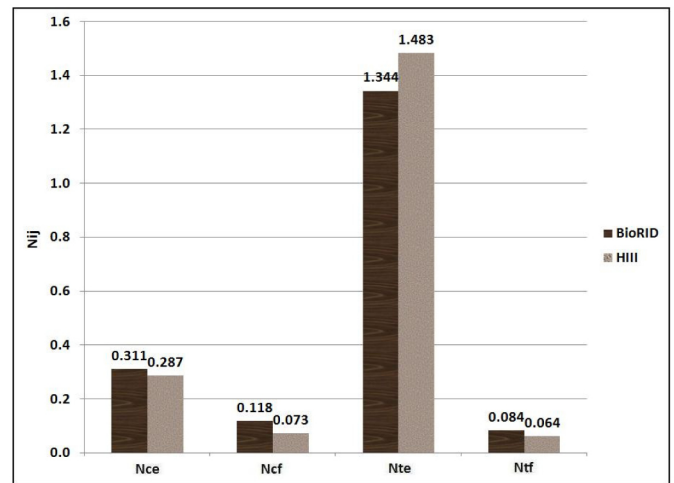


Figure 17. Lower Neck N_{ij} Results

Category 1b - Comparison of BioRID and HIII in LFS Position with LHR

The head resultant accelerations are shown in Figure 18. BioRID and HIII had similar peaks, but BioRID reached its peak prior to head restraint contact, while HIII reached its peak around the time of maximum head displacement. In this test, BioRID head made contact with the roof starting at 104ms and continued scraping the roof while contacting the head restraint (until 130 ms). The scrape decreased the head-to-restraint impact speed and ultimately the head peak G's of BioRID. In Figures 18 and 19 (a-d) the head scrape against the roof has been marked. From Table 6, HIII head contacted the head restraint before BioRID, but BioRID head travelled over the top of the head restraint, scraping the roof while impacting the head restraint, and finally reaching a larger rearward head displacement (Figure A2). Given that the pelvis height for both ATDs remained within 17mm (0.7") of each other at the time of head restraint contact, the difference