

An Evaluation of the BioRID II and Hybrid III During Low- and Moderate-Speed Rear Impact

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ABSTRACT

Debate surrounds the utility of the Biofidelic Rear Impact Dummy (BioRID) anthropomorphic test device (ATD) for providing meaningful biomechanical metrics during rear impact and the appropriate criteria for interpreting the ATD response. In the current study, we performed a comparison of the kinematic and kinetic responses of the BioRID II and Hybrid III ATDs over a range of low- and moderate-speed rear impact conditions. A BioRID II and a midsize male Hybrid III were tested side-by-side in a series of rear impact sled tests. To evaluate occupant response in rear impact, the ATDs were positioned into front row standard production bucket seats, restrained by 3-point safety belts, and subjected to rear impacts with delta-Vs (ΔV s) of 2.2, 3.6, 5.4, and 6.7 m/s (5, 8, 12, and 15 mph). To further evaluate the effects of seat/restraint design on occupant responses, the ATDs were positioned into front row seats with integrated seat belts (all-belts-to-seats) and subjected to rear impacts with ΔV s of 2.2 and 5.4 m/s (5 and 12 mph). In all test configurations, we measured head accelerations and rotation rates, upper and lower neck forces and moments, T1 accelerations, lumbar forces and moments, and axial femoral force. The kinematic and kinetic responses of the BioRID II and Hybrid III ATDs were compared across impact severity and seat conditions. Observed neck loading measures are discussed in the context of proposed and accepted injury assessment reference values.

208 until September 1997. In 1976, General Motors introduced the Hybrid III 50th-percentile (midsize) male for use in both frontal and rear impacts. The Hybrid III incorporated extensive instrumentation and is the current standard for the assessment of automobile performance worldwide, including the United States FMVSS 208 compliance testing. In addition to the midsize male, several other Hybrid III ATDs are currently available including a three-year-old child, six-year-old child, small female, and large male. Injury Assessment Reference Values (IARVs) have been developed for the family of Hybrid III ATDs, with the values “chosen such that if the IARVs were not exceeded in a prescribed test, then the risks of the associated injuries would be unlikely for that size occupant in the accident condition being simulated” [2]. Extensive testing and validation procedures were completed on the Hybrid III ATD to establish IARVs to relate ATD measurements to the likelihood of objective injury in human occupants. This relies on the use of the Abbreviated Injury Scale (AIS), which codes injuries from minor (AIS 1) to maximum (AIS 6). The current neck IARVs are based on low percentage risk of serious or greater injury (AIS 3+) [2]. The Hybrid III has been used extensively for evaluating kinematics and injury potential in rear impact, particularly at higher severities [3,4,5,6,7,8,9]. The Hybrid III ATD was also recently selected for use in the dynamic evaluation of head restraint performance as part of the upgrade for FMVSS 202.

INTRODUCTION

Anthropomorphic test devices (ATDs), commonly known as crash test dummies, have been used by the automotive industry to assess vehicle performance since the 1940's [1]. In 1972, General Motors developed the Hybrid II 50th-percentile male ATD for use in frontal impact, which was specified for use in the Federal Motor Vehicle Safety Standard (FMVSS)

Over the last decade, additional ATDs specifically designed to evaluate rear impact performance have been under development. One of these ATDs, known as the Biofidelic Rear Impact Dummy (BioRID), was introduced in 1999 after being developed at Chalmers University of Technology [10]. Testing and validation of the BioRID ATD has focused on kinematic aspects of the ATD response as they compare to the responses of human subjects under low-speed impact

conditions. Evaluation of biomechanical measures, as they relate to human injury potential, has focused on parameters correlated to symptomology that would be coded, at most, as minor (AIS 1).

PREVIOUS EVALUATIONS OF THE HYBRID III AND BIORID ATDS

Several previous studies have compared the responses of the Hybrid III and BioRID ATDs under rear impact conditions. As part of the development work for the earlier ATD model BioRID I, the kinematic responses of the head and neck of the BioRID I were compared to those of the Hybrid III and volunteers [11] in low severity rear impacts ($\Delta V = 1.9$ m/s or 4.3 mph) [12]; it was concluded that the BioRID I head displacement and angulation behavior better matched the responses of human volunteers at this severity and that the BioRID I was “more humanlike.” In a follow-up study [13], higher severity HYGE sled tests with the Hybrid III and the prototype BioRID P3 were performed utilizing the same pulse shape [12], but at ΔV s of 4.2 and 6.9 m/s (9.3 and 15.5 mph). This test series was performed in seats equipped with a head restraint, reportedly in consideration of ATD durability, suggesting concern regarding damage to the BioRID ATD. The authors reported limited data on head accelerations, neck moments, and dummy kinematics, concluding that the BioRID P3 and Hybrid III responses differed and the BioRID P3 had higher biofidelity at low (2.5 m/s or 5.6 mph) and moderate speeds (4.2 and 6.9 m/s; 9.3 and 15.5 mph) than the Hybrid III. Despite this conclusion, no comparisons were made between ATD and volunteer or post-mortem human subject (PMHS) responses in this study. An additional study comparing the Hybrid III and BioRID P3 to human volunteers in low-severity rear impact (1.9 and 2.5 m/s; 4.3 and 5.6 mph) used a cumulative variance ratio to develop biofidelity ratings for the ATDs, which focused on kinematic variables which included hip and T1 motions [14]. The authors of this study concluded that the BioRID P3 provided good biofidelity scores in the test setup on which it was based, while Hybrid III performance at these minimal severities was “relatively poor.”

Kinematic response biofidelity was also evaluated by comparing Hybrid III and BioRID II responses in rigid seat tests at moderate and high severity [15] to the responses of a volunteer (4.7 m/s or 10.6 mph only) and 2 PMHSs (4.7 and 6.7 m/s; 10.6 and 15 mph), previously evaluated under similar test conditions [16]. On this basis, the authors concluded that the overall flexibility and neck flexibility of the Hybrid III was between that of a tensed volunteer and a PMHS, while the BioRID II flexibility was greater than a tensed volunteer or a PMHS [15]. The same authors subsequently reported on an extensive series of rear impact sled tests comparing the Hybrid III and BioRID II, as well as the RID2 ATDs [17]; these tests were conducted in production seats and ranged in severity from 2.5 to 7.5 m/s

(5.6 to 16.8 mph). This work quantified the relative responses of the ATDs and demonstrated significant differences in the measured responses under paired impact conditions.

The response of the BioRID I (P2) was also evaluated in a series of rear barrier tests conducted at 6.7 and 13.4 m/s (15 and 30 mph), as well as the response of the Hybrid III to a series of rear HYGE sled tests at ΔV s ranging from 1.4 to 10.6 m/s (3.1 and 23.6 mph) [18]. Based on the findings of this study, it was suggested that neck displacement should be evaluated in addition to other criteria currently under consideration when investigating the set of injuries referred to as “whiplash.” Additional studies have focused on the modulation in the BioRID response to various pulse characteristics, ranging in ΔV from 0.85 to 2.9 m/s (1.9 to 6.6 mph) [19] and seatback angle at a ΔV of 2.8 m/s (6.2 mph) [20]. Notably absent from the majority of these evaluations of the BioRID are measurements derived from the lower neck, as the lower neck load cell was not available in the BioRID at the time of most of these investigations.

REAR IMPACT AND LOWER NECK LOADING

While numerous studies have theorized on the site and mechanics underlying cervical spine injury in rear impact, only a handful of studies have documented ligamentous, disc, and bony injuries following rear impact exposure. An investigation of neck injury tolerance in non-severe ($\Delta V = 3.9$ m/s or 8.7 mph; duration = ~ 150 ms) and severe ($\Delta V = 6.7$ m/s or 15 mph; duration = ~ 190 ms) rear impact sled tests, with a volunteer and two male PMHSs positioned in a rigid seatback without a head restraint, demonstrated that only the smaller PMHS sustained minor ligamentous damage to the mid-cervical spine, between C3 and C4 under severe impact conditions [16]. Another study without head restraints exposed two small female PMHSs to low velocity impacts (sled $\Delta V = 4.1$ to 4.4 m/s; 9.2 to 9.8 mph); while one PMHS did not sustain injury, the other sustained trauma including a widening of the facet joint at the C5-6 level with a ligamentum flavum tear at the level below [21]. Three PMHSs exposed to higher velocity impacts (sled $\Delta V = 6.6$ to 6.9 m/s; 14.8 to 15.4 mph) all sustained injury to the lower cervical spine, including combinations of a vertebral chip fracture, disc tears, facet joint widening/ disruption, and ligamentous injury [21]. An extensive series of rear impact mini-sled tests, exposing PMHS torsos positioned against a rigid “backrest” without head restraint to impact speeds ranging from 6.1 to 7.1 m/s (13.7 to 15.9 mph), produced lower cervical spine injuries concentrated in the C5-C6 area [22]. These included injuries ranging from isolated intervertebral disc injury to compound injuries involving various combinations of injuries to the disc, joint capsule, anterior longitudinal ligament, posterior longitudinal ligament, and ligamentum flavum, as well as fractures of the vertebrae. An additional 5 tests without head restraints run at



lower speeds (5.3 to 5.6 m/s; 11.9 to 12.6 mph), as well as tests with head restraints at 6.9 m/s (15.5 mph), all resulted in no observed injuries to the PMHSs [22]. Another set of sled tests were performed at a nominal impact speed of 7 m/s (15.7 mph) with PMHSs seat-belted in vehicle seats with both rigid and deflecting seatbacks [23]. Although the seats were equipped with head restraints, tests were conducted with these in the lowest position, which reportedly prevented contact between the head of the test subject and the head restraint. Two of the PMHSs in rigid seats and the three in deflecting seats were found to have lower cervical spine injuries, while one PMHS in a rigid seat was uninjured. The injuries sustained in the rigid seat tests were described as C6 compression fractures and C5-C6 vertebral arch fractures for one PMHS, and C6-C7 disk injury for the other. Injuries were observed in each of the tests with deflecting seats, and included subluxation, fracture, and disk injury concentrated at in the lower cervical spine (C5-C7). Collectively, these works point to a concentration of injurious loading in the lower cervical spine at increasing rear impact severity. Further, these studies demonstrate an apparent transition in injury potential over the approximate range of 5 to 7 m/s (11.2 to 15.7 mph, when muscle tone and head restraints are absent).

Although biomechanical studies have identified objective patterns of cervical spine injury following high-severity rear-end collisions, controversy still exists regarding cervical spine injury as it relates to exposure in low severity collisions. Many research groups have focused on this issue, but to date there is no consensus on mechanism or appropriate metrics. Hyperextension of the neck has been cited as a factor that may contribute to injury during rear-end collisions with relatively low ΔV s [24, 25], but biomechanical and field accident research has shown that a simple hyperextension mechanism is not likely the complete explanation of such injuries [26, 27]. The role of the rebound phase of rear-end collisions has also been discussed in literature regarding neck injury, and some studies have proposed that seatbelt use may increase neck loading during the rebound [28]. Other research has reported that neck injury in lower severity rear-end collisions is related to the kinematics of the “S” shaped curve of the cervical spine, although this mechanism is also in dispute [29]. It has further been proposed that a change in volume occurs in the spinal canal during rapid extension-flexion, resulting in pressure changes in the central nervous system [30, 31]. Consistent with these variously theorized mechanisms, a variety of injury criteria have been proposed for evaluating injury potential in low severity rear impact; however, an objective biomechanical basis to identify and validate an appropriate set of IARVs remains elusive.

In the present study, we conducted side-by-side evaluations of BioRID II and the Hybrid III ATDs in sled tests simulating rear-end collisions of low and moderate severity to evaluate the relative kinetic response of the ATDs, with emphasis on

upper and lower neck loading and injury criteria. To evaluate how the biomechanical responses of the ATDs differed from what would be expected from increases in impact severity alone, a head-neck complex from another Hybrid III ATD was also mounted directly to the test sled.

METHODS

To examine the effect of a rear impact on ATD biomechanical response, a series of sled tests at varying crash severities was conducted using ATDs in two seat configurations (Table 1). Maximum severity was constrained by manufacturer limitations on the BioRID II (6.7 m/s or 15 mph), above which components of the spine were expected to sustain permanent damage. Tests were conducted using a pneumatic acceleration system, a programmable wire-bending decelerator, and a 170-ft rail that minimized test article disturbance during the acceleration phase (Seattle Safety LLC; Kent, WA).

Standard production front row bucket seats were rigidly secured to the test sled (Tests A-D). The three-point continuous restraint system included a retractor pretensioner and energy management feature; however, the pretensioner was not active during testing. The pillar-mounted seat belt restraint system and corresponding mounting points were set to match the dimensions of the source passenger vehicle. These seats were tested at ΔV s of 2.2, 3.6, 5.4, and 6.7 m/s (5, 8, 12, and 15 mph).

Front row bucket seats with an all-belts-to-seats restraint system were then rigidly secured to the test sled (Tests E and F). These seats had an integrated restraint system in which the entire seat belt system is mounted directly to the seat (all-belts-to-seats), rather than to the floor or pillar. The restraint system did not include a pretensioner or energy management feature. The seats were tested at ΔV s of 2.2 and 5.4 m/s (5 and 12 mph).

For each test, a midsize male Hybrid III was placed in the passenger's seat and a BioRID II was placed in the driver's seat. For both seat types, driver's and passenger's seats were symmetric about the vehicle center line. Both ATDs were placed in a normal seated position consistent with FMVSS 208. The ATDs were positioned with level head, torso against the seat back, and legs bent at the knee with feet on the floorboard, and they were secured using the three-point restraint system (Figure 1). In addition, the distance between the back of the head and the head restraint was matched between ATDs. Seating positions were consistent across crash severities and seat types, and the ATDs were repositioned to this standard position prior to each test. For both seat types, the seatback angle was set to that used during safety compliance testing for FMVSS 208 by the respective auto manufacturer. Seat fore-aft adjustments were set at the mid-position for all tests. Seats were replaced after Tests B

and C, because deformation of the seats was noted. The head-neck complex of a Hybrid III ATD was mounted directly to the bed of the test sled during all experimental tests, with the adjustable lower neck load cell positioned at the lowest setting (6.55 degrees relative to the base).

<table 1 here>

<figure 1 here>

REAR IMPACT IMPULSE DESIGN

The rail-guided decelerator sled used in this study was propelled using a pneumatic accelerator. The acceleration system was designed to keep average sled accelerations below 0.2 g, while having no acceleration during the last 1.6 meters of pre-impact sled travel. After the sled is at the prescribed impact velocity, the sled is decelerated by impacting a series of steel wires and extruding them through an arrangement of rollers. By changing the length and configuration of the steel wires, deceleration pulse shape, pulse duration, and pulse magnitude can be programmed to impart particular dynamic conditions to the test vehicle and/or components. When this pulse is numerically integrated, the ΔV time history is also defined. Due to the complexity in generating high frequency deceleration changes during a programmed pulse, most test or certification standards specify an ideal pulse shape. These ideal pulse shapes vary in duration and magnitude and typically follow triangular, haversine, trapezoidal, or sinusoidal profiles.

In the current study, pulse parameters were defined to replicate rear impact conditions. The general pulse design used for this study was based on accelerometer data derived from a series of low-speed front-into-rear impact tests [32]. The sled test pulses were created to match ΔV requirements [33] and made use of an idealized acceleration waveform shape. Rear impact ΔV was calculated from the published vehicle-to-vehicle accelerometer data [32]. By comparing this ΔV from several idealized pulse shapes, it was determined that a half-sine acceleration pulse produced the best ΔV representation (Figure 2). In order to create pulses specific for this study, the half-sine pulse data was scaled from the published ΔV of 2.9 m/s (6.5 mph) to create pulses with ΔV of 2.2, 3.6, 5.4, and 6.7 m/s (5, 8, 12, and 15 mph).

<figure 2 here>

INSTRUMENTATION

The impact velocity of the sled was measured using a velocity trap and the sled acceleration was measured using sled-mounted accelerometers. High-speed video was recorded using an on-board digital camera on the right and left side of the sled (Figure 1). Target markers were placed on the rigid sled frame and at the approximate center of gravity of the ATD head as viewed from the side.

A similar set of instrumentation was used in each ATD (Table 2). Head acceleration and rate sensors were mounted at the head center of gravity. Load cells measured forces and moments in the upper neck, lower neck, lower lumbar spine, and bilateral femurs. Accelerations were also measured using a triaxial accelerometer mounted at the location of the T1 spinal segment. The Hybrid III head-neck complex was instrumented with upper and lower neck load cells.

<table 2 here>

DATA ANALYSIS

Each channel of data was recorded at 10,000 samples per second and filtered according to crash test standards (SAE J211). High-speed digital video was recorded at 500 frames per second. Large spikes of electrical noise were present during some tests on a small number of data channels; in the instances where this noise affected the maximum/minimum value on that data channel, the noise spikes were removed and the missing data were replaced with an interpolation of the surrounding data.

Peak resultant acceleration, HIC_{15} , and HIC_{36} were calculated from the head acceleration data acquired. Tensile load, peak neck moment and neck injury criteria (N_{ij}) [34] were calculated using the data obtained from the upper neck load cell. N_{ij} was calculated according to FMVSS 208 specifications. Additional neck injury parameters, including NIC [35], WIC [36], Nkm [37], and LNL [38], were also calculated for comparison. Where applicable, data maxima for all biomechanical measures and parameters were then compared to established IARVs, derived from FMVSS 208 injury criteria for in-position occupants and standards proposed by Mertz and colleagues [2]. Data pertaining to lower lumbar loads were addressed and presented separately [39].

RESULTS

Sled pulse parameters were designed according to previous rear impact testing [32], and the resultant pulse shape, duration, and magnitude for each of the impact severity levels conducted are shown in Figure 3. Sled peak accelerations of 3.8, 5.7, 8.5, and 10.6 g corresponded with sled ΔV s of 2.2, 3.6, 5.4, and 6.7 m/s (5, 8, 12, and 15 mph), respectively (Figure 3). Sled ΔV was highly repeatable between seat type conditions; the linear correlation coefficient of ΔV time histories was 0.9999 in 2.2 m/s (5 mph) tests and 0.9997 in 5.4 m/s (12 mph) tests. A table of maximum and minimum biomechanical measures for each test is presented in Appendix A for the BioRID II and in Appendix B for the Hybrid III.

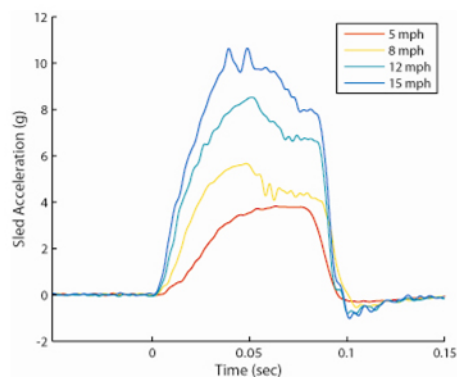


Figure 3. The deceleration pulses for the test sled are illustrated for Tests A-D, performed on standard production front row bucket seats.

KINEMATIC RESPONSE OF THE ATDS

The ATDs were placed in normal seated positions (Figure 4A), and they experienced a forward-directed acceleration as the sled decelerated during rear impact. For both ATDs and seat types, the kinematic response during the initial phase was dominated by rearward motion of the head, neck, and torso relative to the pelvis. The hip was extended from its initial configuration as the ATD body traveled up the angled, rearward-flexing seatback. This motion created tension in the lumbar spine, and these tensile forces continued further as the lap belt arrested upward motion of the ATD torso. The lower extremity followed as the hip traveled rearward and up the seatback, and knee angle changes were observed as the posterior portion of the distal leg contacted the seat bottom, creating tensile loads within the femurs of both legs. Tensile loads were also experienced in the upper and lower neck of both ATDs during this phase, although the Hybrid III lower neck showed initial compression loading in Tests A and E. The BioRID II upper neck experienced flexion as the head moved rearward, whereas motion of the Hybrid III upper neck depended on crash severity (extension first for Tests A, B, E, and F; flexion first for Tests C and D). Both ATDs experienced lower neck extension during this phase.

Subsequently, resistive forces in the seatback arrested rearward motion of the ATD torso, and the ATD head contacted the head restraint (Figure 4B). As the seats deformed and, in higher severity impacts, rotated away from the stiffer outboard side of the seat, the ATD head and torso rotated inboard; this appeared more pronounced at higher severities. Energy stored during the primary phase was released, and the ATD rebounded in a forward motion (Figure 4C). During this rebound phase, the ATD head moved forward while the ATD torso moved down the seatback and began to flex at the hip. The articulating segments in the BioRID II spinal structure allowed the BioRID II to flex forward further and for a longer duration when compared to the Hybrid III. Forward torso motion was

quickly arrested by the shoulder belt restraint, which resulted in neck flexion in both ATDs. The ATD bodies then oscillated to their equilibrium positions (Figure 4D). Motions of the head, neck, and torso were more damped in the Hybrid III than in the BioRID II.

This overall kinematic response scaled with impact severity, with more pronounced interaction with the seat back and head restraint in tests with higher ΔV . Further, this kinematic response was more exaggerated in standard production seats, which exhibited 1.6 to 2 times more dynamic angular deformation compared to the all-belts-to-seats system. ATD peak head accelerations, rotation rates, and rotational accelerations are shown in Figure 5. The BioRID II had higher resultant linear head accelerations than the Hybrid III across all impact severity levels. Similar trends were observed for component linear accelerations in the longitudinal, lateral, and vertical directions (A_x , A_y , and A_z). The peak linear head acceleration, which occurred in the BioRID II during the 6.7 m/s (15 mph) impact, was 30.0 g. It should be noted that this value is 6-fold lower than the established IARV of 180 g.

The Hybrid III had higher resultant head rotational velocities than the BioRID II across all impact severity levels. The peak velocity of 29.3 rad/s occurred in the Hybrid III during the 6.7 m/s (15 mph) impact. Both ATDs sustained similar head rotational accelerations during the 2.2 m/s (5 mph) impact. However, higher resultant rotational accelerations were achieved by the BioRID II in the 3.4 m/s (8 mph) and the Hybrid III at higher impact speeds. The maximum peak rotational acceleration of 1784 rad/s² occurred during the 5.4 m/s (12 mph) impact in the Hybrid III.

KINETIC RESPONSE OF THE ATDS

Occupant upper and lower neck loads were measured, and results for standard production seats are shown in Figure 6. The BioRID II experienced higher upper neck loads than the Hybrid III. The peak longitudinal (aft) upper neck force of 412 N occurred during the 5.6 m/s (12 mph) impact, and the peak tensile force of 1267 N occurred at the 6.7 m/s (15 mph) impact. It should be noted that these peak forces were 7-fold lower than the established IARV of 3100 N for shear and 3-fold lower than the IARV of 4170 N for tension. Upper neck tensile load (F_z) scaled proportionally with the severity of impact, with the highest loads recorded during the most severe tests. Upper neck extension moments were similar between ATDs and did not appear to be modulated by impact severity. The peak extension moment of 8.9 Nm was recorded in the Hybrid III during the 2.2 m/s (5 mph) impact. This value is 10-fold lower than the IARV of 96 Nm.

The lower neck loads measured in the Hybrid III were higher than the BioRID II, with peak loads occurring during the 6.7 m/s (15 mph) impact. The peak longitudinal (aft) and tensile

forces were 653 N and 917 N, respectively, and the peak extension moment was 67.8 Nm. These peak loads were 4-fold lower than the IARVs of 3100 N for shear and 4170 N for tension, and nearly 3-fold lower than the IARV of 192 Nm for extension moment.

<figure 4 here>

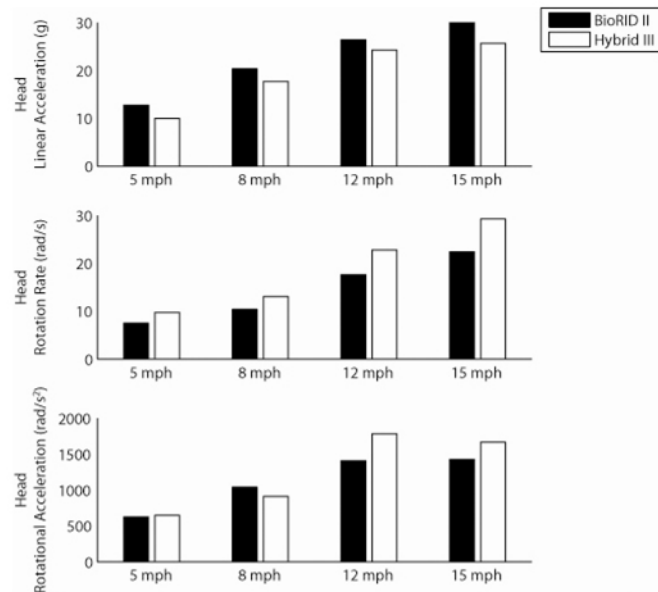


Figure 5. Head linear acceleration, rotational velocity, and rotational acceleration are illustrated across rear impact severity levels for standard production front row bucket seats in both BioRID II (black bars) and Hybrid III (white bars) ATDs.

<figure 6 here>

Neck loads appeared to show modulation in response with increasing severity, with the greatest relative change for both ATDs observed in lower neck tension. Scaling peak responses for all tests by IARVs showed that the parameter closest to its respective IARV was upper neck tension for the BioRID II and lower neck extension moment for the Hybrid III. Despite differences in magnitude, the time histories of the neck forces and moments were seen to be qualitatively similar, particularly in the initial loading phase. Small differences were seen in time to peak for the BioRID II versus the Hybrid III (e.g., -9 ms to +17 ms for upper neck tension, +5 ms to +10 ms for lower neck moment); however, these subtle timing differences are not clearly attributable to the ATD characteristics.

ATD upper thoracic accelerations were measured at the T1 level using a triaxial accelerometer, and resultant linear accelerations for tests with standard production seats are shown in Figure 7. The BioRID II experienced higher T1 accelerations than the Hybrid III across all levels of impact

severity, and peak T1 accelerations were larger at higher impact severities. The highest T1 acceleration measured in the BioRID II was 17.0 g, and occurred during the 6.7 m/s (15 mph) impact. It should be noted that this value is 3-fold lower than the accepted IARV of 60 g for accelerations measured at T4.

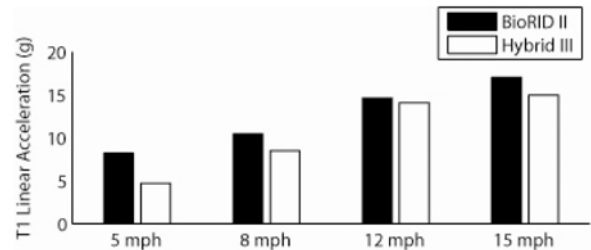


Figure 7. The resultant linear acceleration measured at the T1 level is illustrated across rear impact severity levels for standard production front row bucket seats in both BioRID II (black bars) and Hybrid III (white bars) ATDs.

Bilateral axial femur forces (F_z) were measured, and maximum tensile and compressive loads for standard production seats are reported in Figure 8. In all tests, the primary mode of femur loading was in tension. Peak compressive loads occurred 150-300 ms after peak tensile loads for both ATDs. Both left and right femur tensile loads were similar for the BioRID II and Hybrid III at each impact speed. The BioRID II experienced higher forces at higher impact severities, and the peak tensile force of 646 N occurred in the right femur during the 6.7 m/s (15 mph) impact. The corresponding peak force in the left femur was 642 N. The peak compressive force of 190 N occurred in Hybrid III at the 6.7 m/s (15 mph) impact. In comparison to the accepted IARV of 10,000 N for axial femur loads, the maximum tensile force was 15-fold lower and the maximum compressive load was 52-fold lower. Femoral tensile loads generally increased with impact severity.

<figure 8 here>

Head and upper neck injury criteria were also calculated for both ATDs to evaluate the potential for injury during low-speed rear impacts in standard production seats (Figure 9). The peak HIC₁₅ value of 51.2 occurred in the BioRID II during the 6.7 m/s (15 mph) impact, which is 13-fold lower than the accepted HIC₁₅ value of 700. Upper neck N_{ij} for tension-extension and tension-flexion were highest in the BioRID II during the same impact, and these values were 0.2 and 0.3, respectively. Upper neck N_{ij} values for compression-extension and compression-flexion did not exceed 0.1 for either ATD, as might be expected for rear impacts where tension dominates at the upper neck.

Neck injury parameters NIC, WIC, Nkm, LNL, and lower neck extension moment, shown for comparison in [Figure 10](#), all showed modulation with impact severity for standard production seats; however, NIC showed much greater change in value over the severity range tested, increasing by factors of 4 and 7 for BioRID II and Hybrid III, respectively. All other parameters increased by approximately twofold, while the ΔV increased by threefold. For comparison, when these same parameters (*i.e.*, all except NIC) were calculated for the Hybrid III head-neck complex, their values tracked the increase in ΔV , up to a threefold increase for the highest severity test.

<[figure 9, 10 here](#)>

The performance of each neck injury parameter was also compared between standard production seat and all-belts-to-seats tests at similar severities ([Figure 11](#)). As an additional check on variations in impact pulse, all parameters but NIC were compared for the Hybrid III head-neck complex for the paired tests, and the parameters were found to change by 5% or less indicating input pulses and output neck measures were similar. For both BioRID II and Hybrid III, lower neck extension moment and LNL both produced lower values for all-belts-to-seats in the lower severity test, and higher values for all-belts-to-seats at the higher severity (13-18% for BioRID II; 20-30% for Hybrid III). For the BioRID II, the NIC, WIC, and Nkm were 13-14% lower for all-belts-to-seats than the standard production seats at the higher test severity (5.4 m/s or 12 mph). WIC also predicted a substantially lower result (-50%) for the BioRID II in all-belts-to-seats at the lower severity (2.2 m/s or 5 mph). For the Hybrid III, NIC predicted higher risk of injury for all-belts-to-seats at low severity, but lower risk at high severity, while Nkm showed no change with seat type and WIC demonstrated results similar to those of LNL and lower neck moment.

DISCUSSION

In the current study, we evaluated the biomechanical responses of the Hybrid III and BioRID II ATDs under rear impacts of varying severity, as well as in standard production and all-belts-to-seats front row bucket seats. In general, results from both ATDs indicated that the loads and accelerations experienced during rear impact tests were several fold less than the established and accepted IARVs for the Hybrid III, suggesting that the impact configurations in this study have very low risk of serious injury. In fact, despite the proclivity for claims of compressive injury following rear impact (*e.g.*, herniated discs, hip injury), the primary peak loads experienced in the cervical and lumbar spine and bilateral femurs during the rear impacts of this study were in tension. This is further demonstrated by comparing compression and tension N_{ij} components, in which tension portions of the response dominate. Additionally, the present results suggest the importance of the lower neck response in

evaluating neck injury potential in rear impact. Lower neck extension moments in this study far exceeded those measured in the upper neck and were modulated with impact severity, suggesting the lower neck as an important site in rear impact injury assessment. This premise is confirmed by the prevalence of injuries to the lower segments of the cervical spine in PMHS subjects observed historically [[22](#), [23](#)].

Neck injury parameters WIC, Nkm, LNL, and lower neck extension moment demonstrated modulation with impact severity that tracked increases in ΔV in the Hybrid III head-neck complex; however, this modulation was muted in the seated ATDs. Although T1 accelerations for the complete ATDs were not identical to sled accelerations, they appeared to be modulated similarly, and dominated by the longitudinal component. Therefore, the difference in injury measures between the results of the Hybrid III head-neck complex and the seated Hybrid III ATD are consistent with the well-known protective effect of head restraint contact. This effect was not only expressed in the ATD results observed in this study, but has also been previously demonstrated in tests involving PMHSs [[22](#)]. Since NIC is based only on the initial “S-bending” phase of head/neck motion, it does not capture the effect of head restraint contact and predicts the higher severity tests to have greatly increased risk, well above the often-quoted reference value $15 \text{ m}^2/\text{s}^2$.

<[figure 11 here](#)>

The seated Hybrid III ATD was found to have a higher peak lower neck extension moment than the Hybrid III head-neck complex for the lower severity tests for both standard production seats and all-belts-to-seats. The difference was lessened and eventually reversed at higher severities, such that the peak moment for the Hybrid III head-neck complex was 44% greater than that of the seated Hybrid III ATD for the 6.7 m/s (15 mph) test. LNL showed a similar trend, while WIC was always lower for the Hybrid III head-neck complex and Nkm was always higher. The WIC results would appear to imply that a rigid seat without head restraint would represent a lower risk of injury, which seems unlikely. While the Nkm result may seem intuitively obvious - that is, the presence of a head restraint will always reduce the risk of neck injury - the situation is more complex due to the dynamic interactions between the ATD and the seat. Review of test videos indicates that seatback cushion compression and seatback deformation interact to delay the T1 acceleration pulse and, therefore, the onset of head/neck extension relative to that of the rigidly coupled head-neck complex. When the combination of yielding structures begins to bottom out, the rate of head/neck extension of the seated ATD is more rapid than that of the head-neck complex, leading to higher peak extension moments when interaction with the head restraint is minimal. However, as severity increases, this rapid rise is just as rapidly reversed by head

restraint contact, limiting total head/neck motion and producing a concomitant decrease in peak neck moment (and other measures). This accounts for the apparent saturation effect seen in most of the injury parameters at higher severities, and indicates that lower neck moment and LNL may more accurately reflect the expected trend in injury risk with increasing impact severity than Nkm.

A significant issue in the interpretation of the BioRID II responses observed in the current study is the absence of an established set of IARVs for this ATD. The differences in the BioRID II and Hybrid III responses under paired conditions, as demonstrated here and in prior studies [15, 20], indicate that the IARVs established and validated for use with one ATD cannot simply be applied to a new test device. Moreover, if the BioRID II is to be used over the range of impact severities where injury is hypothesized and known to occur, this ATD and its accompanying IARVs must be validated for the assessment of injuries beyond those categorized as minor (AIS 1). A significant limitation in this regard is the fact that the structure of the BioRID II neck, which was originally developed and validated in relation to low severity impacts, renders the device subject to damage at higher rear impact severities. For example, the BioRID II is not recommended for testing at ΔV s greater than 6.7 m/s (15 mph), and it is likely this limit is meant to apply to rear impact testing in the typical automobile seating environment with a head restraint. This would preclude use of the BioRID II under many of the rear impact conditions (ΔV s > 6.7 m/s or 15 mph; rigid seat; no head restraint [39]) that have been demonstrated to produce objective cervical spine injuries in PMHSs [e.g., 22, 23]. In addition, the BioRID II neck structure is not designed to evaluate 3-dimensional head motion relative to the torso. Testing in production automotive seats at severities where objective injuries have been identified or under pulse conditions reflective of field accidents (other than low-severity pure longitudinal pulses), demonstrates that perfectly sagittal head/neck motion of the ATD is unlikely to occur. A robust injury measure should be broadly applicable and predictive in evaluating, for example, out-of-position occupants and ramping over seatback, as well as impact modes other than rear impact.

While the NIC criterion was developed and has been widely reported in tests utilizing the BioRID ATD, the maximum value observed in this study occurred only during the early portion of the impact event and grew progressively larger in the higher severity impacts, despite subsequent head restraint interaction. This finding is contradicted by prior rear impact testing with PMHSs [22], where the presence of a head restraint dramatically reduced the incidence of objective injuries. Other prior studies have identified this issue and found that the NIC criterion does not correlate well with real world seat performance [18, 38, 40]. Indeed, this criterion was initially evaluated against only a limited dataset and has

limited biomechanical meaning; a reference value of 15 m²/s² is defined as the level below which no long-term symptoms are expected to occur.

Although the BioRID II has been adopted for dynamic rear impact testing by the Insurance Institute for Highway Safety (IIHS) as part of its consumer information program for evaluating seat and head restraints [41], the underlying evaluation criteria used by the IIHS appear to reflect these limitations. In the test protocol, the BioRID II is positioned in a test seat exposed to a rear impact sled test at ΔV s of 4.2 to 4.4 m/s (9.2 to 10 mph). Criteria evaluated include the time to head restraint contact (less than 70 ms), peak T1 acceleration (less than 9.5 g), and upper neck shear and axial load. Interestingly, the criteria for the evaluation of upper neck loads (low, moderate, and high) were not derived from biomechanical evaluations of human tolerance. Rather, ATD measures are categorized based on comparison to a database of prior dynamic test results conducted on seats that were rated as having “good” static geometry. A low upper neck force corresponds to loads that are equal to or less than the lower 30th percentile for seats with good geometry, moderate corresponds to the 31st to 75th percentile, and high to the loads above the 75th percentile of seats evaluated.

In contrast, the Hybrid III has a wealth of studies supporting its use and interpretation across a wide range of impact severities and impact modes, including those which have been documented to produce objective injury in rear impact. Hybrid III ATDs have been utilized to study occupant responses in moderate-to-high severity rear impacts. Rigid seatback tests were performed at 4.4 and 6.7 m/s (10 and 15 mph) with Hybrid III ATDs [5], replicating the PMHS tests of Mertz and Patrick [16], indicating that Hybrid III responses were similar to those of the PMHSs. In testing of production seats, Hybrid III lower neck moment was well correlated with Neck Injury Factor (NIF), first reported by Eichberger and colleagues [4] as a measure of insurance claim frequency for different seat designs. It was also noted, in a companion study with various production seat designs [6], that Hybrid III lower neck extension moment was sensitive to increasing impact severity. More recently, the Hybrid III was utilized to evaluate the influence of seatback characteristics on risk of upper and lower neck injury in high ΔV (>11.1 m/s or 24.9 mph) impacts [3]. The Hybrid III biomechanical response has further been evaluated in stiff versus yielding seats [8]. Testing with Hybrid III ATDs has also shown the influence of seat design on injury risk for out-of-position occupants [7, 9].

Of critical importance in the usefulness of the Hybrid III in these and other studies is the establishment of IARVs to assess risk of injury. In addition to well-established upper neck injury criteria which are incorporated into FMVSS 208, lower neck IARVs have also been proposed. Measured lower

neck loads from ATD testing, matched to non-injured and injured PMHS testing [16], were used to derive an IARV for Hybrid III lower neck extension [5]. Subsequently, Mertz and colleagues [2] proposed IARVs for lower neck loads/moments based on scaled upper neck values. More recently, refinements to lower neck N_{ij} intercepts [42] and extension moment IARVs [43] have been proposed, based on matching of Hybrid III test data with non-injured and injured PMHS test data. On the basis of the injury distribution in PMHSs and the modulation of ATD responses within the range of severities spanning low and high probability of injury, these studies have implicated lower neck loading in neck injury potential.

Although the biofidelity of the Hybrid III response in low severity impacts has been criticized, kinematic and dynamic responses of this ATD have been shown to correlate to retrospective, real world rear impact data [18, 38]. Insurance claim data were utilized to identify vehicle models with seats that demonstrated a range of field performance as related to soft tissue neck injury claims described as AIS 1 [38]. Three distinct vehicles were identified for examination, and were associated with AIS 1 injury rates of 13%, 25%, and 36%, denoted as good, moderate and poor, respectively. Lower neck responses from the Hybrid III ATD, measured in 4.4 m/s (10 mph) sled tests, were found to correlate with seat field performance. Focusing on head/neck kinematic response, Kuppala and colleagues [40, 44] proposed a kinematics-based whiplash criterion for use with the Hybrid III. This criterion correctly ranked seat and head restraint effectiveness derived from previously published field claim data [40]. The proposed criterion is the same as published in the final upgrade to FMVSS 202, and evaluates head-to-torso rotation; this rotational angle is strongly correlated with the lower neck moment in the Hybrid III ATD [40]. Interestingly, the NIC injury criterion derived from measurements made with BioRID II was negatively correlated with soft tissue neck injury claims.

In this study, as well as in prior works, the BioRID II has been demonstrated to provide a graded mechanical response with changes in impact parameters that have been related to injury potential, such as impact severity and occupant-seat and occupant-to-seatback geometry. However, the interpretation of these parameters is hampered by the lack of suitable IARVs for the BioRID II. We propose that further work is required to develop suitable IARVs for the BioRID family of ATDs, and that this ATD needs to be sufficiently robust to be suitable for testing across a continuum of impact conditions that include the low severity test environment (where injury mechanisms are variously theorized) and the high severity environment where objective injuries have been documented. While fundamental biomechanical testing has identified objective injuries in higher severity impacts, similar testing does not exist at low severity. Matching

BioRID II test impacts to impacts of exposed biological specimen under conditions that produce a spectrum of objective findings (ranging from non-injurious to injurious) will be critical in this regard.

SUMMARY/CONCLUSIONS

1. The biomechanical response of Hybrid III and BioRID II ATDs was examined over a range of rear impact severities, ranging from low severity (2.2 m/s or 5 mph) to the maximum allowable severity for the BioRID II (6.7 m/s or 15 mph). Over this range of severities, both Hybrid III and BioRID II demonstrated biomechanical responses that were well below established and validated IARVs.
2. The BioRID II and Hybrid III both generated graded responses with changes in impact severity; however, differences in these responses indicate that the IARVs derived for the Hybrid III should not be used to interpret BioRID data.
3. ATD lower neck measures, such as peak extension moment or related injury parameters, appear well suited to characterize impact severity and neck injury potential in rear impact.
4. In order for the BioRID II to be useful in evaluating injury potential, it must be made more structurally robust to withstand impacts at severities that have been previously shown to cause objective injuries. Further, IARVs specific to the BioRID family of ATDs must be developed.

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