Finite Element Modeling of Reconstructed Vehicle Rear Seats with Adult Male ATDs

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Abstract

Most car crash fatalities occur in the front seats, so experimentation and regulations involving car crash occupant protection typically focus on the front seats. Because of this, the safety of the front seats has increased greatly over the years, and in some circumstances, the front seats now perform better than rear seats. This represents a problem because the rise of ridesharing transportation and automated driving systems has the potential to increase rear seat occupancy by adults, which could result in an increase in injury and death. To help inform the design of new vehicle rear seat safety systems, it is important to understand the performance of current vehicle rear seats with adult occupants. The rear seats of eight vehicles were reconstructed from scans of the seat surfaces as well as the seat pan and seatbelt components. Seat foam material properties were taken from quasistatic tests of each seat. The THOR and Hybrid III male 50th percentile ATD FE models were positioned and settled in each seat. The vehicles frontal NCAP crash pulse as well as a less severe pulse were applied to each vehicle in LS-DYNA®. Injury likelihood was assessed by a summary of the AIS3+ risk curves for the head, neck, chest, and femurs. Overall, the results with a frontal NCAP pulse ranged from a near certainty of AIS3+ injury to around a 35% chance. Additionally, the best performance was seen with vehicles that contain pretensioners and load limiters in the rear seats. These results indicate that such technologies may be necessary in the rear seat to improve crash performance. Additionally, these results have helped select a range of vehicles for further experimentation and identified variables of interest for further simulation.

Introduction

The vast majority (91%) of motor vehicle deaths occur in one of the front seats, largely due to occupancy rates[1]. This has led to increased regulations for the front seats, while the requirements for the rear seats have been less strict. Over the years, large advancements in occupant safety technology such as seat belt and airbag design have made the front seat much safer. Historically, the rear seat was the safest place to sit in a vehicle, but the front seat seems to have outpaced the rear seat such that in some cases the front seat is safer than the rear seat [2]. Despite the relatively low percentage of adults sitting in the rear seats, overall exposure is still high, and an increase in ridesharing and/or automation could increase exposure. Designing a safe rear seat is not as simple as replicating the front seat. Features such as airbags cannot be installed the same way, and there are additional considerations such as size constraints or ensuring the seats are also safe for children. In order to create a safer rear seat, it is important to understand the nature of injuries in the rear seats. Adults are more often unbelted in the rear seats [3], which greatly increases injury rates. When belted, the thorax is the most common seriously injured body region followed by the abdomen [3]. For both of these regions, injuries are primarily due to interaction with the belt [4]. Experimental and computational studies have shown that pretensioners and load limiters, common only in the front seats, could decrease the risk and severity of thoracic injury in the rear seats. Typical experimental and computational approaches to studying injury in the rear seat involve either a simplified seat or a single seat from a commercial vehicle. These studies have focused on modifying the restraint system, such as airbags and seat belts [5], or modifying seat parameters such as the angle or stiffness [6]. The objective of this study; however, was to investigate several reconstructed rear seats from a variety of vehicles with both the Hybrid III and THOR 50th percentile male ATD FE models to examine the risk of injury with different seat designs as well as to identify geometric or other variables for further study. Additionally, this study was used to identify a subset of vehicles for future experimentation.

Methods

To study injury risk in the rear seat, it is necessary to investigate a range of rear seats currently on the market. In total, eight vehicles were selected for evaluation (Table 1). These vehicles spanned a range of passenger vehicles. Vehicle rear seat FE models were created based on geometric data reconstructed from 3D digitizer scans. First, a scan was taken to note the position of the seat bottom surface, seat back surface, and floor. Next, a scan was taken with a passenger wearing the seatbelt to note the path of the seatbelt as well as the location of important components such as the buckle, D-ring, retractor, and anchors. Finally, the seat bottom cushion was removed, and a detailed scan was taken of the underlying seat pan. The resulting scans were then used to construct enclosed seat geometries in Rhinoceros (v5.0, Robert McNeel & Associates, Seattle, WA). An example of an initial scan and the resulting seat geometry is shown in Figure 1.

Table 1. Simple vehicle information

Vehicle	Seat pan angle (°)	Stiffness (N/mm)	Other
A	17	10	
B	19	12	Pretensioner
C	13	10	Pretensioner
D	20	10	
E	11	7	Spring seat bottom
F	18	17	
G	21	13	
H	11	7	

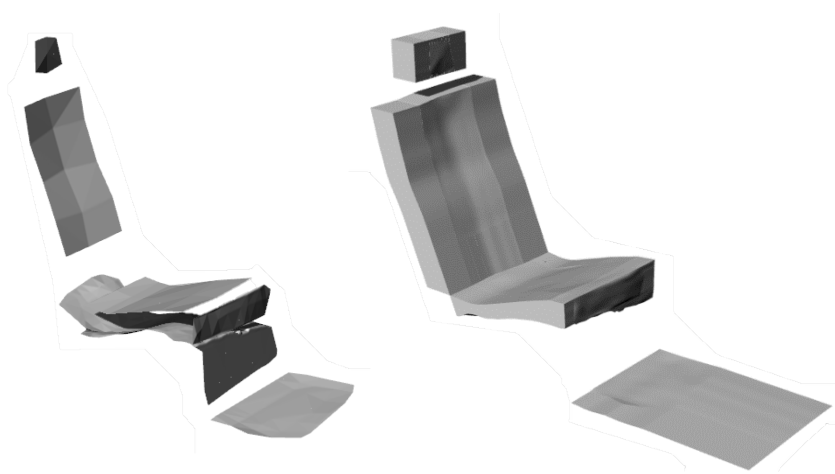

Figure 1. Scanned surfaces of a vehicle seat and resulting simplified CAD geometry

The geometries were then meshed using Hypermesh (v13.0, Altair, Troy, MI) with primarily hexahedral elements. For one of the seats modeled (E), there was a spring-type seat bottom, which was modeled by fitting pictures of the seat bottom to the CAD geometry. The springs were modeled using compliant beam elements with the diameter based on images/field measurements, and a stiffness of 207 GPa. For all other seats, the seat pan was modeled as rigid. The stiffness of the seat foam was measured quasi-statically in the vehicles with a rigid plate impactor [6]. Force displacement curves were estimated by scaling an average curve from previous work to the stiffness measured on each seat (Figure 2). These curves were converted to rough stress-strain curves by dividing the force by the area of the plate, and the displacement by the average thickness of the seat cushion. The stress-strain curves were then used as the inputs to the material model (*MAT_LOW_DENSITY_FOAM in LS-DYNA).

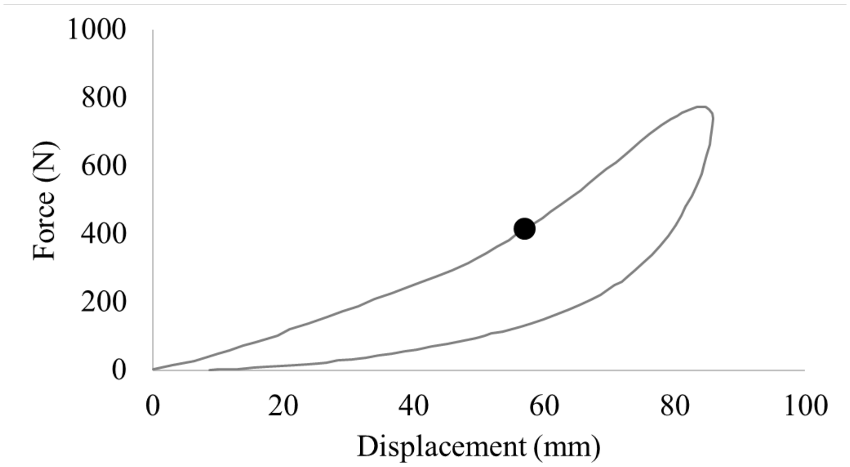

Figure 2. Seat force – displacement: measurement point and estimated curve (Vehicle H).

The THOR-50M (v1.6) and Hybrid III (v1.0.7) 50th percentile male ATD finite element models from Humanetics Innovative Solutions, Inc. (Farmington Hills, MI) were used to evaluate the seats. While both are validated 50th percentile male models, these models have different methods of evaluating injury risk, so they offer a degree of corroboration. Since the rear seat is often much smaller than the front seat, the ATD did not always fit well when in the standard driver posture. To position the ATDs prior to seating, slight modifications were made from the Humanetics release (driver) posture. These changes were made to create a balance between preserving the ideal front seat posture and creating a posture that worked for all vehicle rear seats. First, the arms were rotated downward to place the hands on the thighs. Then, the lower legs were flexed to -75 degrees, and the feet were positioned as parallel to the floor as possible. These moves were performed using the marionette method [7] to eliminate the need for manual effort to remove penetration in the flesh components at the joints. The ATDs were then settled into the seat models. To allow for consistent comparison of the simulations, the following procedure was used for each seat. First, the ATD was moved as far back and down into the seat as possible without any penetration occurring between the ATD and the seat. Next, the entire ATD was raised until the feet no longer penetrated the floor. Finally, the ATDs were settled by applying gravity during a 250 ms simulation in LS-DYNA. ATD and seat node locations and stresses were saved from these simulations. The ATD posture was largely preserved from before the simulation, with the main differences in the lower leg, as the foot was able to slide into a natural position (Figure 3).

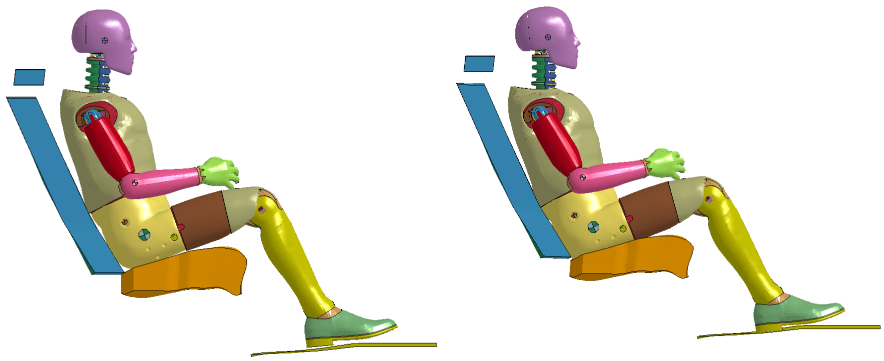

Figure 3. Example of HIII prior to and after gravity settling in a seat

The final step before impact simulations was the fitting of the seatbelt. The fabric of the seatbelt was routed following the path from the digitizer scan using the LS-PrePost® (LSTC, v. 4.3.14) BeltFit tool (Figure 4).

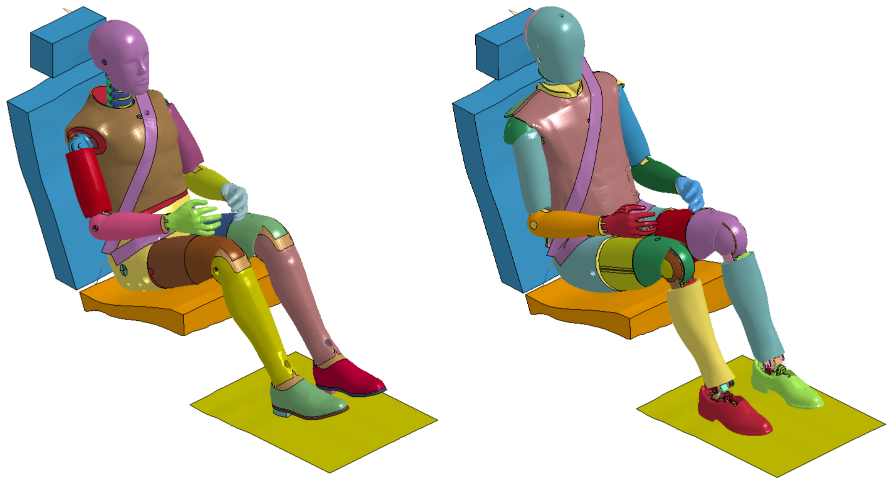

Figure 4. Hybrid III and THOR ATDs seated with belts fit

The simplified rear seat models were used in two types of simulations: a) frontal NCAP simulations (35 mph initial velocity) and b) lower severity impacts, with the NCAP crash pulses scaled down to FMVSS 208 pulse levels (30 mph initial velocity). Each vehicle's unique NCAP/FMVSS 208 crash pulses were applied to the floor of the vehicle. The floor was rigidly coupled to the seat pan/seat back support as well as the seatbelt components. The crash was simulated for 150 ms, by which time all injury metrics had peaked, and all simulations ran to completion. Overall, the motion of the ATDs was similar in all cases but some differences were observed. Since the seats were modeled in isolation without a seat in front, the ATD legs were free to move upward. Therefore, some simulations showed the ATD head contacting the knee around 125 ms into the simulation, leading to large accelerations late in the simulation in the head and neck. Since interaction with the front seat in current vehicles might prevent head-knee impact (in current seat configurations), injury risks were calculated up to 110 ms (before head-knee impact) as well as the entire simulation (150 ms). It is also important to note that the head-knee impact occurred well after the maximum forward head and pelvis excursion while the ATD was rebounding back from the restraints. To quantify injury risk, several measures were investigated; Head Injury Criterion (HIC15), Brain Injury Criterion (BrIC) [8], Neck Injury Criteria (Nij), max chest deflection, and max femur force. Risk of an AIS3+ injury was calculated for each of these metrics in the Hybrid III and THOR-50M models [9], [10] (Table 2). Injury risk in the THOR-50M chest, however, was calculated according to Poplin, et al. [11] with a default age of 45. Additionally, to summarize injury risk, the Occupant

Injury Metric (OIM) AIS3+ [9], which uses the risk of AIS3+ injury to one or more body regions as defined by the previously mentioned metrics, was calculated for each simulation.

Table 2. AIS3+ risk curves used for each metric as well as the OIM

HIC_{15}	$\Phi(\frac{\ln(HIC) - 7.45231}{.73998})$
BrIC	$1 - e^{-(\frac{BrIC}{.987})^{2.84}}$
Nij	$\frac{1}{1 + e^{3.227 - 1.969Nij}}$
Chest Deflection	$\frac{1}{1 + e^{3.7124 - .0475D_{max}}}$
Femur Force	$\frac{1}{1 + e^{4.9795 - .326F_{max}}}$
OIM	$1 - (1 - p(HIC) * (1 - p(BrIC) * (1 - p(Nij) * (1 - p(Chest\ Deflection) * (1 - p(Femur\ Force)$

Results and Discussion

Overall, trends were very similar between the Hybrid III and THOR-50M simulations, with the best performance seen in the two vehicles with pretensioners (B and C). Good performance was also seen with vehicles that had a steep seat pan angle (D and G). The OIM from the THOR-50M simulations was generally higher than the Hybrid III simulations (Figure 5). Much of this difference can be attributed to the different risks to the chest, likely due to the differences in how chest deflections are measured by the Hybrid III and THOR-50M ATDs (single x deflection vs. four 3D measurements).

The AIS3+ risk according to each body injury metric is also shown (Figure 6). Again, similar trends are seen between the Hybrid III and THOR-50M simulations. For Hybrid III, the head was more likely to hit the knee at the end of simulation than for THOR-50M. Disregarding these impacts, HIC was fairly low for most vehicles. BrIC was by far the metric predicting the highest risk of injury in all cases, with the risk ranging from 0.2 to 0.98 for the Hybrid III and from 0.4 to 0.98 for the THOR-50M (when calculated for the first 110 ms). Nij and chest deflection showed a moderate level of risk (8–20%) for all simulations, with an outlier in the Hybrid III simulation with vehicle E showing high risk (63%) of injury due to Nij. To better estimate the head and neck injuries for rear occupants, a review of all corresponding injury criteria with and without head contact may be beneficial. Finally, risk of injury to the femur was low in all cases (< 10%). The impacts with the scaled down (FMVSS 208 level) crash pulse followed the same trends as the NCAP tests, but with reduced injury risk. In summary, the vehicles with pretensioners (B and C) often performed the best, while D and G also performed well. Vehicle E performed the worst, particularly in terms of BrIC and Nij. At around 70 ms, the ATD pelvises reached the rigid support at the front edge of the seat and stopped moving forward, generating a large relative rotation in the head shortly after.

While the seat backs were in a range of angles, the ATDs in this study were seated with a consistent procedure resulting in relatively constant pelvis angles from vehicle to vehicle. It is likely that a passenger sitting in one of these seats would do so with different pelvis angles, which would most likely have an effect on injury outcomes. Furthermore, there are many characteristics of each vehicle that are currently unknown, such as the exact seat belt retractor parameters, so the same properties were assigned to all models (except those with a pretensioner). This could also have an effect on the injury outcomes.

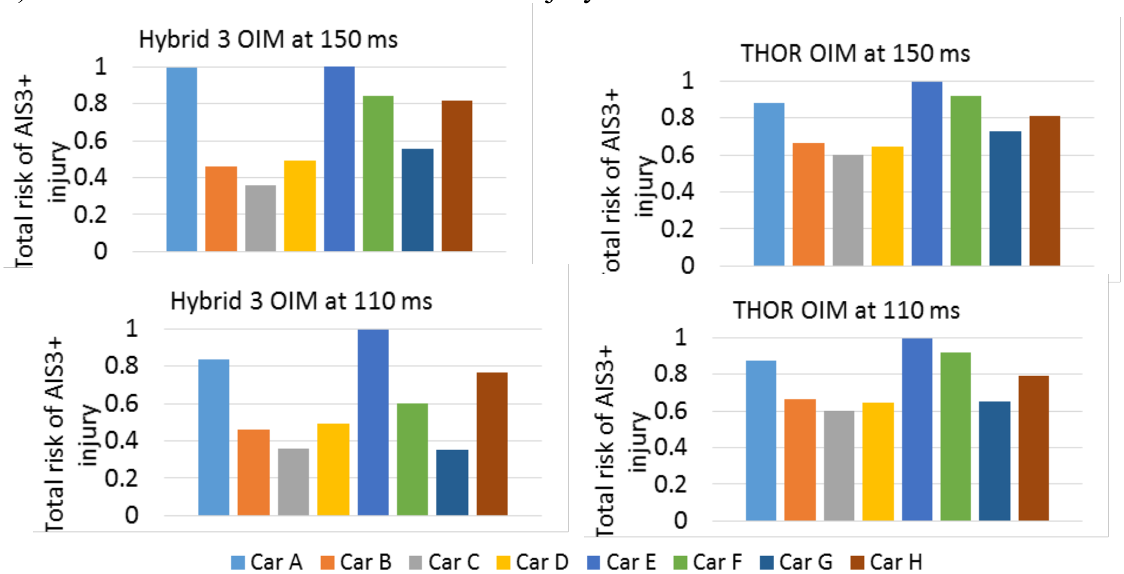

Figure 5. Occupant injury metric (OIM) with the Hybrid III and THOR ATDs at 150 ms and 110 ms in the frontal NCAP simulations. Note: In simulations where the ATD head contacted the knee, this occurred at roughly 125 ms.

Future work will involve validating the FE models with the results from the sled tests. The results of this study have been used to select a subset of the vehicles for sled testing. As the purpose of this study was exploratory in nature, the crash pulse used was unique to each vehicle, preventing rigorous vehicle-to-vehicle comparisons. These models will be used with a generic crash pulse to provide for better vehicle-to-vehicle comparisons. Finally, a design of experiments (DOE) will be conducted with a simplified seat model using the range of parameters seen in this study.

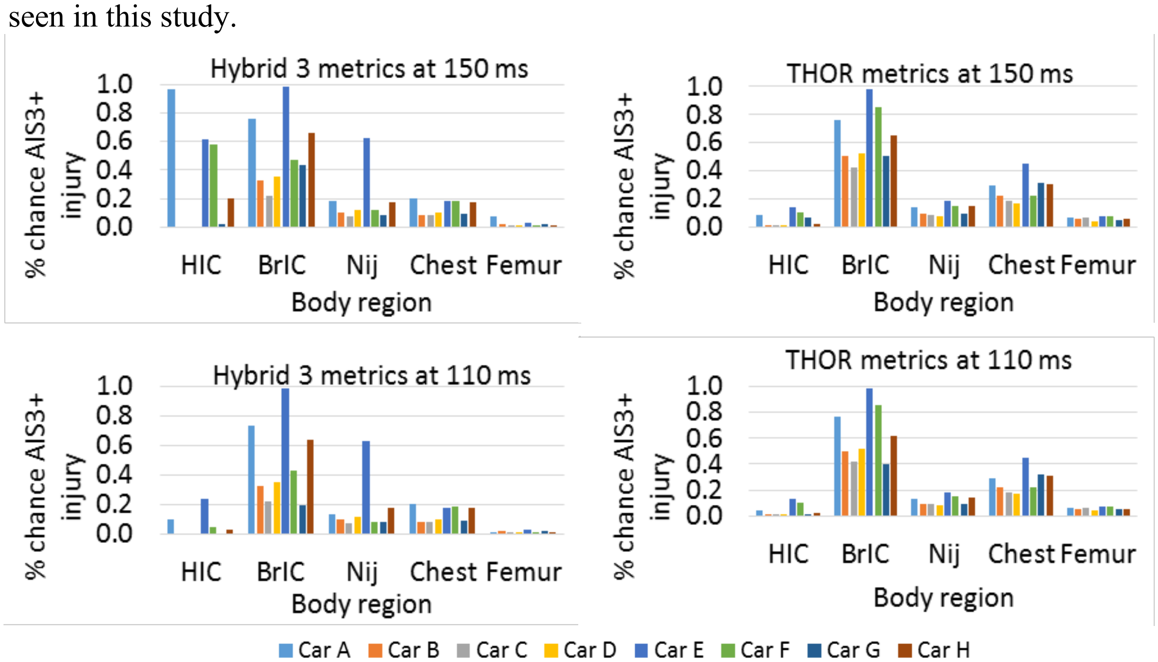

Figure 6. Injury metrics with the Hybrid III and THOR ATDs at 150 ms and 110 ms in the frontal NCAP simulations. Note: In simulations where the ATD head contacted the knee, this occurred at roughly 125 ms.

Conclusion

In this study, several FE models of recent model-year vehicle rear seats were created. Frontal crashes were then simulated with the THOR and Hybrid III M50 ATD FE models, and injury risk was calculated. Total injury risk at an AIS3+ level ranged from ~36% to near certainty, indicating that there is significant room for improvement in the design of rear seats. The best performing vehicles had pretensioners and/or steeper seat pan angles, suggesting that these features could reduce injury likelihood or severity if added to more rear seats. These variables are therefore of primary interest in further studies.

Acknowledgments

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