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Investigation on the Effect of Malaysian Anthropometric Size in Vehicle Crash Safety by using Finite Element Method

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Abstract *– In general, most vehicle safety is developed and optimized using a standard crash dummy, in which the sizes and mass of the anthropometric data are primarily referred to the US population. In other words, it can be deduced that the safety configuration of such vehicles is not optimized for Malaysian or even Asian populations, which might cause severe injury. Therefore, in this paper, the injury is investigated using the actual Malaysian anthropometric data. To be specific, the Hybrid III 50th percentile dummy H350 is scaled to Malaysian 50th percentile dummy H350M, integrated into the vehicle, and analyzed using the finite element method. Using the newly H350M, the results showed the neck forces and moments are slightly reduced while the other injury parameters remained similar. There is also a noticeable increase in chest acceleration from 54.1g to 58.0g. The most critical assessment on the head injury by using the HIC15 method has shown a significant increase from 596 to 913, which could lead to severe head injury.*

Keywords: Passive safety, occupant injury, finite element analysis, Anthropometric Test Device

1.0 INTRODUCTION

Prediction of occupant injury is one of the critical activities in the vehicle development program. With the advancement of the explicit finite element solvers, many vehicle manufacturers have been using the integrated occupant and structures simulation to assess the occupant injury, and further, optimize the desired target to reduce the injuries. For the manufacturer that using this approach, the finite element model of safety components such as airbags and seatbelts are usually correlated with the physical tests by its suppliers, which later can be integrated into the vehicle models developed by the vehicle manufacturer. Some of the components such as driver airbags, pretensioner and seatbelts can be considered modular. In this case, the analyst can opt to switch between different variants or just carry over the design for all vehicle models for more cost-effective. The models provided by the suppliers are usually modifiable to a certain extent such as the airbag time-to-fire (TTF), airbag vent diameter, pretensioner TTF, and seatbelt load limiter. This enables the user to optimize and check the design's robustness. To get the best vehicle safety configuration, a standard Anthropometric Test Device (ATD) that was specifically designed for a specific crash configuration is used throughout the development.

However, most of the ATDs or commonly known as the crash test dummy that is used by vehicle manufacturers are based on the anthropometric data that was measured in the country of origin. For example, the Hybrid III 50th Percentile (H350) is based on the US anthropometric data. It should be noted that such vehicles developed based on this anthropometric data are not optimized or directly fit the other populations with different anthropometric size and mass, hence, requires further investigation.

The effect of anthropometric sizes and mass in vehicle safety has been extensively studied by Happee et al. (1998), which covers various scaled ATD in terms of size, mass, and seating positions. The study was simulated using the multi-body dynamic system software, MADYMO. From the study, it was observed that the mass of the occupant is inversely proportional to the 3ms chest acceleration. Recently, there is other research to develop the frontal ATD based on Chinese anthropometric sizes by using the finite element method (Libo et al., 2014). In this study, the base H350 ATD was scaled to the 50th percentile male Chinese population. It was concluded that the biofidelity of the scaled ATD is consistent with the base ATD, which a similar conclusion is made by Happee et al (1998).

In this work, the injury effect of the Malaysian anthropometric in vehicle safety is analyzed using the finite element method. This allows for cost reduction of prototyping the physical components, which is a similar approach that is used by vehicle manufacturers. Using this approach, the H350 can be easily scaled to represent the 50th percentile of Malaysian size H350M.

2.0 METHODOLOGY

Figure 1 depicts the approach used in this work. Since there is no integrated vehicle-occupant finite element model that has been developed and available publicly, the available donor vehicle finite element model must be selected and reverse engineer its safety equipment parameters based on the available test data. The correlation between the donor vehicle model and a physical test should be first completed before the injury comparison between H350 and the newly H350M subjected to a similar crash event can be evaluated.

2.1 Vehicle Model Selection

There are very few finite element vehicle models that have been made available to the public. In this study, the B-segment car of the 2010 Toyota Yaris finite element model developed by the Center for Collision Safety and Analysis (CCSA), George Mason University (Marzougui et al., 2011) is used. The B-segment car model is very popular in the ASEAN region. It is interesting to analyze this segment since it is generally lighter than the higher segment cars, where the lighter car is usually excessively deformed in incompatibility crashes, thus lead to severe occupant injury (Faerber, 2001).

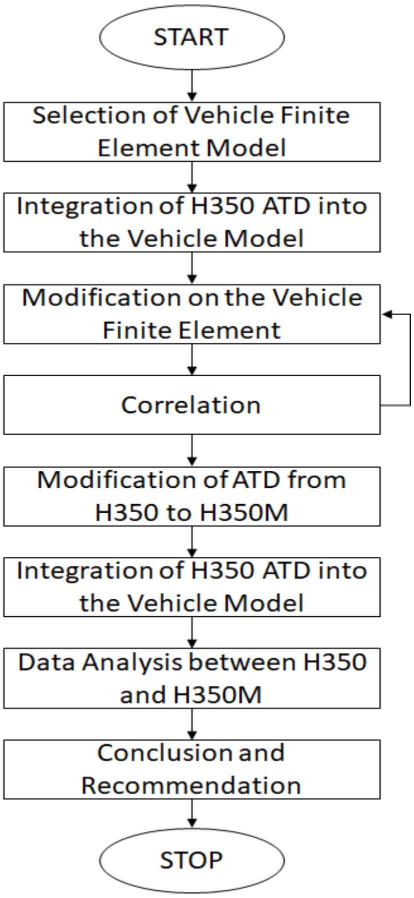

Figure 1: Flowchart of the study

Further, the vehicle finite element model of this segment has been correlated with multiple physical tests such as frontal offset deformable barrier 64 km/h (ODB64) and frontal rigid barrier 56 km/h (FRB56), especially in terms of vehicle acceleration response (Marzougui et al., 2012). Therefore, it is suitable to be used for occupant simulation. Only FRB56 simulation is considered in this work. The results of the analysis on this B-segment will be further used in other works and publications.

Figure 2 shows the 2010 Toyota Yaris finite element models that have been developed by CCSA. It should be noted that the footwell intrusions in the vehicle finite elements are higher than the physical tests (Marzougui et al., 2012). Thus, there is a high probability that the prediction of tibia and foot injury will be severer than the physical tests. The study is also limited to the upper body due to the absence of footrest, carpet, accelerator pedals, and the critical components required for lower leg injury assessment.

Figure 2: Donor finite element model developed by CCSA

2.1 Integration of H350 ATD into the Vehicle Finite Element Model

The H350 is one of the common ATDs used for frontal-impact safety regulatory assessment such as UN ECE R94. It is still being used by several New Car Assessment Program (NCAP) in its ODB64 load case. Many available H350 finite element models have been developed, see for example (Lai et al., 2011; Mohan et al., 2010; Noureddine et al., 2002). The most common H350 finite element model is the model developed by Humanetics (Shah et al., 2014), due to its extensive study on the correlation with the physical tests.

In this study, the Livermore Software Technology (LST) H350 that is available for the LS-Dyna user is used. This model has been calibrated to meet the injury corridor requirement such as head drop, neck extension, neck flexion, and thorax impact test (Mohan et al., 2010). However, there are no correlation report for the upper leg (knee and femur) and lower leg (tibia) provided by LST. Therefore, as aforementioned, the analysis is limited within the upper body. It should be noted the model was not encrypted, which makes it easier to be modified in the future compared to the other commercial models. Figure 3 depicts the detailed finite element model that was developed by LST.

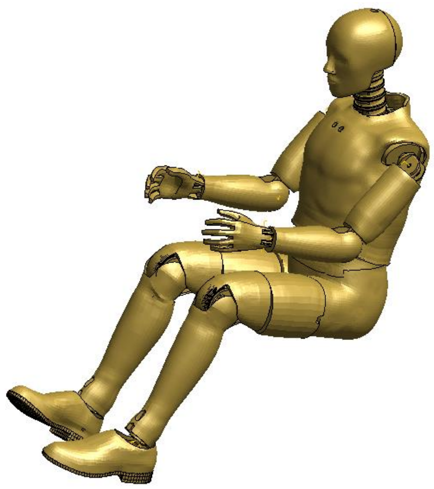

Figure 3: H350M developed by LST

To integrate the H350 into the vehicle model, the measurement taken from the report of crash test no. 05677 published by NHTSA is used as a point of reference (NHTSA, 2006). Figure 4 depicts all the positioning measurements. Table 1 provides a comparison between the physical test and simulation. Not all the measurements can be conducted in the finite element model due to missing components such as the pedals and carpet. The measurement can only be made in the finite element model whenever it is feasible.

In the test protocol, the left foot should be positioned on the footrest, and the right foot is positioned on the accelerator pedals. Without these components, the driver's foot is positioned on the floor, in the same way, the foot is positioned for the passenger. Hence, the injury result will not be compared between the finite element method and the physical test for the lower leg whereby it is expected that there will be a huge difference. It should be noted that the differences caused by the lower leg (tibia and foot) position are not significant to influence the upper body result.

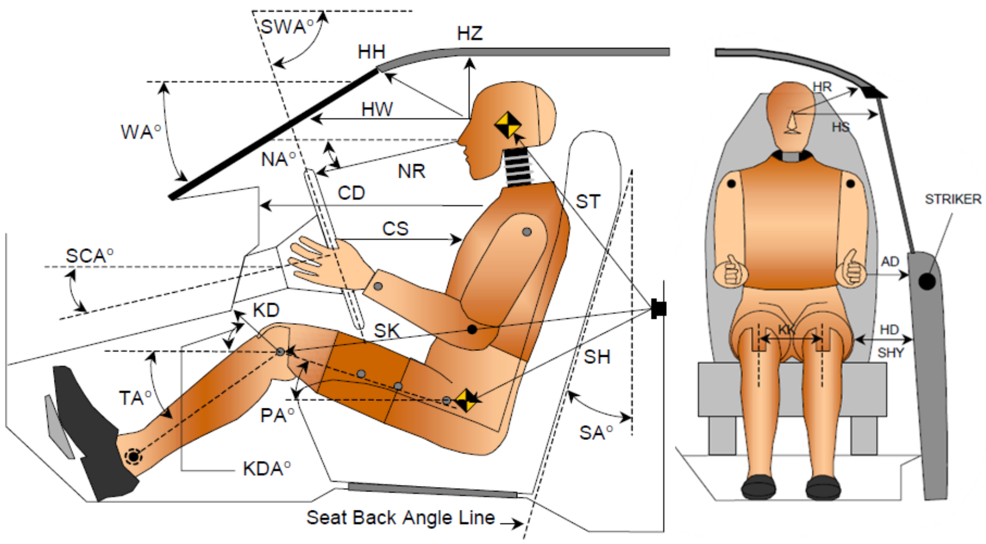

Figure 4: Total measurement point taken from the physical test (NHTSA, 2006)

Table 1: Static measurement for ATD positioning

		TEST No. 05677 (NHTSA, 2006)		Simulation	
Code	**Measurement Description**	**Length (mm)**	**Angle (°)**	**Length (mm)**	**Angle (°)**
SWA	Steering Wheel Angle		63.6		64.9
SCA	Steering Column Angle		26.4		25.8
HW	Head to Windshield	653	0.0	649	0.0
NR	Nose to Rim	437	14.0	455	18.1
CS	Chest to Steering Hub	352	6.9	333	0.0
KDL	Left Knee to Dash	139	27.3	128	23.2
KDR	Right Knee to Dash	137		146	
PA	Pelvic Angle		24.0		17.5
TA	Tibia Angle		48.5		49.0
KK	Knee to Knee (Y)	320		267	
SK	Striker to Knee	596	93.0	610	93.7
ST	Striker to Head	483	9.1	506	9.6
SH	Striker to H-Point	280	125.5	281	124.2
SHY	Striker to H-Point (Y)	255		237	
HD	H-Point to Door (Y)	143		140	
AA	Ankle to Ankle	320		243	

2.2 Structure Modification on the Vehicle Finite Element Model

In the initial study, it is observed that the steering column in the model developed by CCSA has no collapsible features. For the steering column, a simple modification was made by adding a cylindrical joint, with the addition of a non-linear spring to simulate the collapsible steering. A typical value of failure force for the collapsible is around 4kN. However, for the initial model, 6kN failure force is used to consider the worst-case scenario. Additionally, the connections between the steering column to the cross-car beam are also been changed to solid spot-weld type with 5kN shear force failure criteria; to represent the breakaway capsule resin, which is present in the physical parts. The modification of the models is depicted in Figure 5. The data used to develop the airbag finite element model is based on the occupant model developed by NHTSA using MADYMO software (NHTSA, 2016). From the occupant model, the data of airbag mass flow rate, pressure, temperature, gas content, airbag size, and volume can be identified. Figure 6 shows the gas content and its fraction over time, while Figure 7 is the corresponding mass flow rate of the gasses in the airbag. Each input was used in the *AIRBAG HYBRID JETTING keyword in LS-Dyna.

The material properties and coefficient of friction for the seatbelt modeling were taken from the literature (Kang et al., 2018). The retractor load limiter was set based on the physical test measurement, which is estimated to be around 3.5kN. For the sake of further study of this work, the lap pretensioner is integrated into the model. It was set to remain deactivated during the simulation since the lap pretensioner is not available in the physical model. Figure 8 shows the seatbelt modeling approach that was used in this study. Other than the seatbelt and the airbag, the seat also needs to be adjusted according to the ATD sitting position. In the frontal crash test, the seat is usually positioned based on the lowest point and the seat slider location is set in the middle. The mass-spring definition that was used to represent the seatbelt and driver mass has been removed and replaced by the ATD.

For the correlation study, the airbag TTF, vent diameter, seatbelt TTF, the steering collapse load, has been parameterized. It allows for easier value changes by just using a text editor compared to finite element pre-processor software, which requires a longer time. This approach also benefits the optimization stage and robustness study.

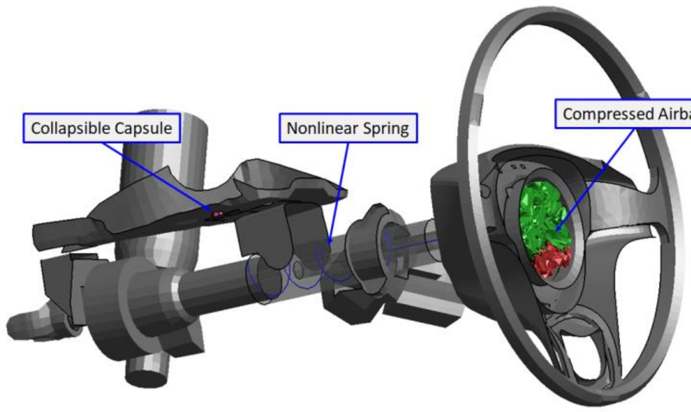

Figure 5: Modification of the steering system

2.3 Correlation of the Base Finite Element Model with Physical Test

Due to the modification of the vehicle model, it is necessary to recheck the correlation of the vehicle model. Based on the comparison of accelerometer output between the simulation and physical test, the vehicle model still retains a similar output, which is acceptable. Figure 9 depicts the correlation in terms of the structure, while Figure 10 shows the vehicle deformation during the simulation.

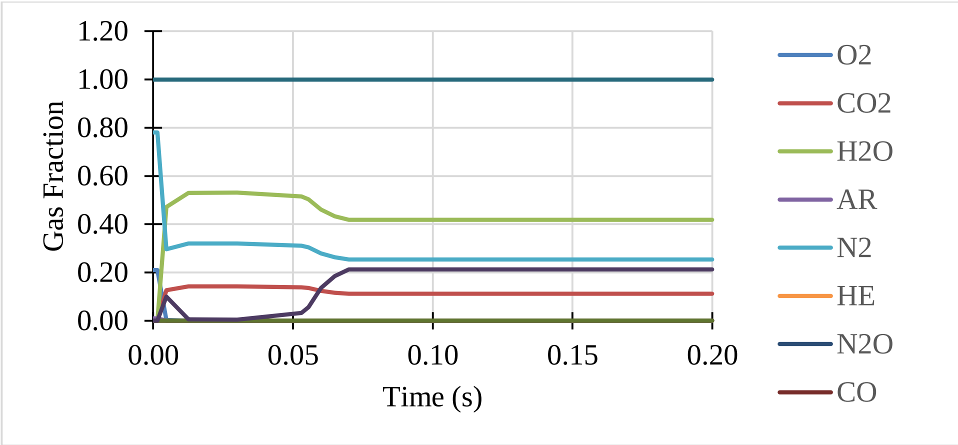

Figure 6: Gas fraction for the mass flow rate (NHTSA, 2016)

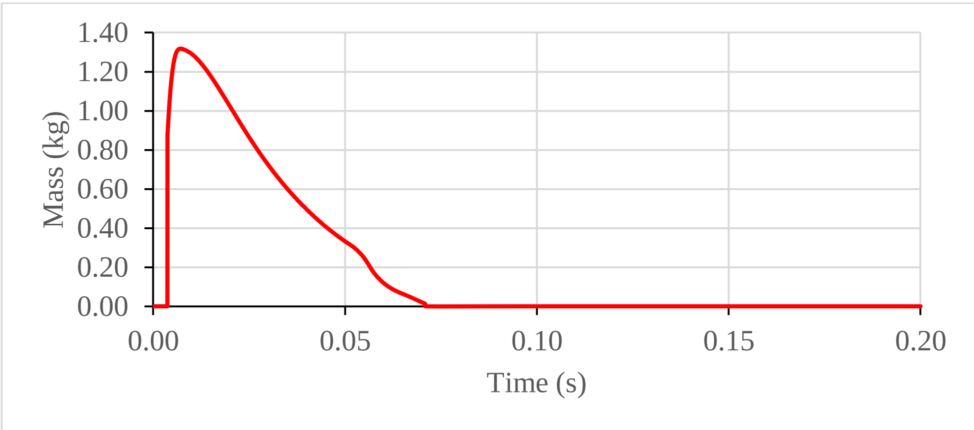

Figure 7: Input for airbag mass flow rate (NHTSA, 2016)

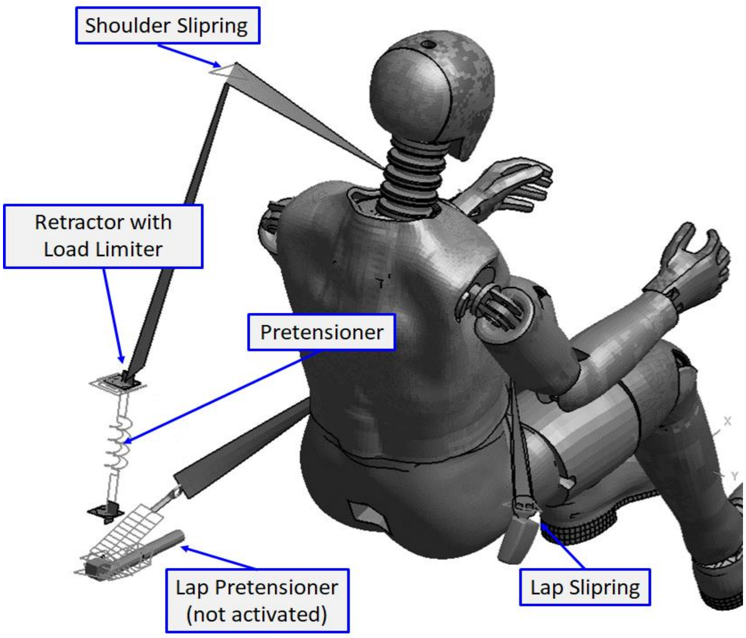

Figure 8: The seatbelt modeling method

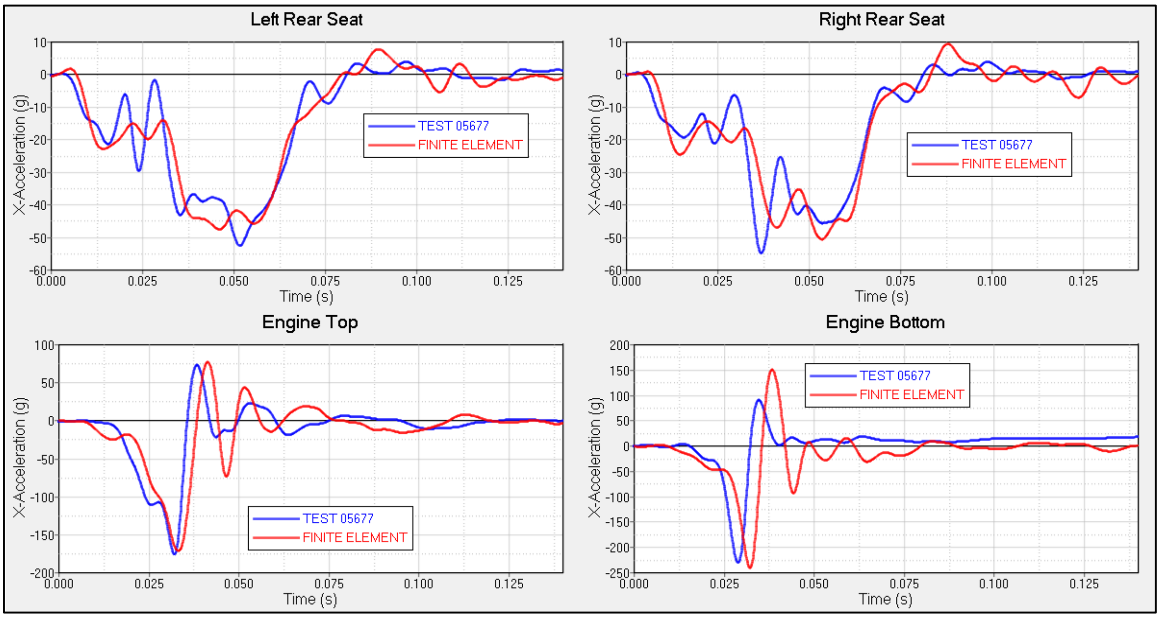

Figure 9: Structural correlation between physical test (NHTSA, 2006), and finite element model

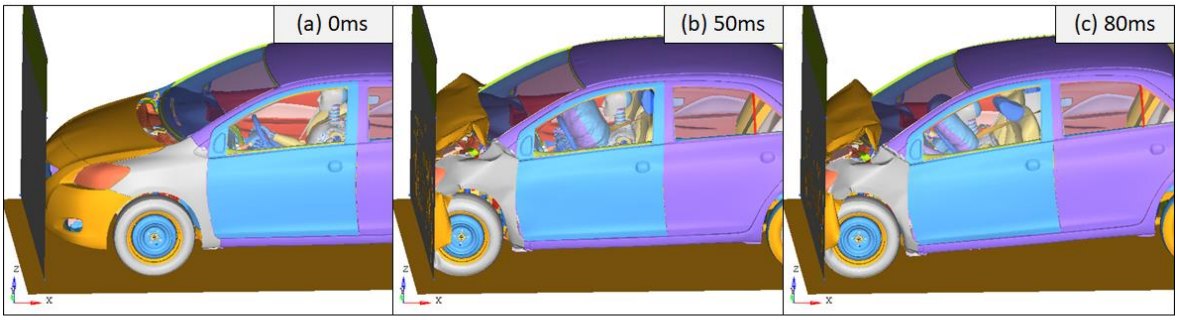

Figure 10: The simulation result at (a) 0ms, (b) 50ms, and (c) 80ms

The Correlation and Analysis (CORA) method is utilized to objectively evaluate the correlation between the physical test and the simulation (Gehre et al., 2009; Gehre & Stahlschmidt, 2011). To be specific a global CORA rating of 0.7 is targeted in this study. A total of 11 curves were generated and compared with the physical test. Even though the scope of this study is only focusing on the upper body, the correlation of the upper leg (femur forces) is also added. It should be noted that the contact between the knee, femur, and the instrumentation panel has a slight influence on the upper body kinematic as per the study conducted by Dolange and Lef (2015). Consequently, the weightage was set equal for all injury parameters, except for the femur forces which are set at half. The shoulder belt load and lap belt load are also added into the correlation even though they are not part of the injury assessment. This is necessary since the seatbelt load has a huge influence on the global ATD kinematic.

A couple of iteration was made by changing the parameter of the airbag and seatbelt TTF, steering collapsible load, knee bolsters strength, and changing the airbag tether length. The CORA rating for the initial model and the final model is tabulated in Table 2. As can be seen in F, the final iteration achieved the CORA rating of 0.708, hence acceptable to be used to study the effect of Malaysian anthropometric size. Figure 11 shows the comparison of injury curves between the initial iteration, the final iteration against the physical test.

Table 2: The CORA rating of the time history predicted by finite element against physical test

No.	Response	Weightage	INITIAL	FINAL
1	Head Magnitude Acceleration	0.100	0.635	0.671
2	Chest Magnitude Acceleration	0.100	0.722	0.852
3	Pelvis Magnitude Acceleration	0.100	0.850	0.916
4	Neck Moment, My	0.100	0.427	0.578
5	Neck Force, Fx	0.100	0.426	0.429
6	Neck Force, Fz	0.100	0.484	0.601
7	Chest Displacement	0.100	0.695	0.742
8	Left Femur Forces	0.050	0.255	0.737
9	Right Femur Forces	0.050	0.366	0.470
10	Shoulder Belt Load	0.100	0.914	0.902
11	Lap Belt Load	0.100	0.650	0.784
	Total CORA Rating		**0.611**	**0.708**

2.4 Integration of H350M into the Vehicle Model

The H350 finite element must be modified to H350M before it can be integrated into the vehicle model. For this purpose, the H350 is scaled between both populations referring to the global scale factor. Since the H350 was developed around the 1970s, and it is based on sitting conditions, it is necessary to get the US anthropometric data which was taken around that year as a point of reference. Therefore, the US anthropometric data is taken from Jordan (2002). On the other hand, Malaysian size anthropometric data has been measured by various researchers, see for example (Isa et al., 2016; Karmegam et al., 2011; Rashid et al., 2013). In this study, the measurement made by Abd Rahman et al. (2018) is considered. This anthropometric data was also taken based on sitting conditions.

A simple sum squared error method was adopted. The optimization then showed the global scale factor between H350 and H350M is 0.9437. Table 3 depicts the measurement for both populations, as well as the optimization of the global scale factor. Figure 12 shows a direct comparison between the H350 and H350M. By scaling the H350 to H350M using the optimized global scale factor, the mass of the H350M ATD becomes 67.7kg, compared to the target of 67.0kg, as measured by Abd Rahman et al. (2018). At this stage of the preliminary study, the value is acceptable. Moreover, further modifications on the body parts, especially the extremities can be made to achieve the targeted mass.

To integrate the H350M into the vehicle model, it was positioned by using heel point, similar to the vehicle package setup. Figure 13 shows the comparison between the H350 and H350M positioned into the vehicle model. As can be seen, the position of H350M is slightly closer to the steering and airbag compared to H350. Due to this different sitting position, the seat model is moved forward by approximately 30mm along the seat rail, and the seatbelt was rerouted as per H350. During the process, the tibia and foot of H350M are positioned as close as possible to the H350, to avoid discrepancies between the two dummies.

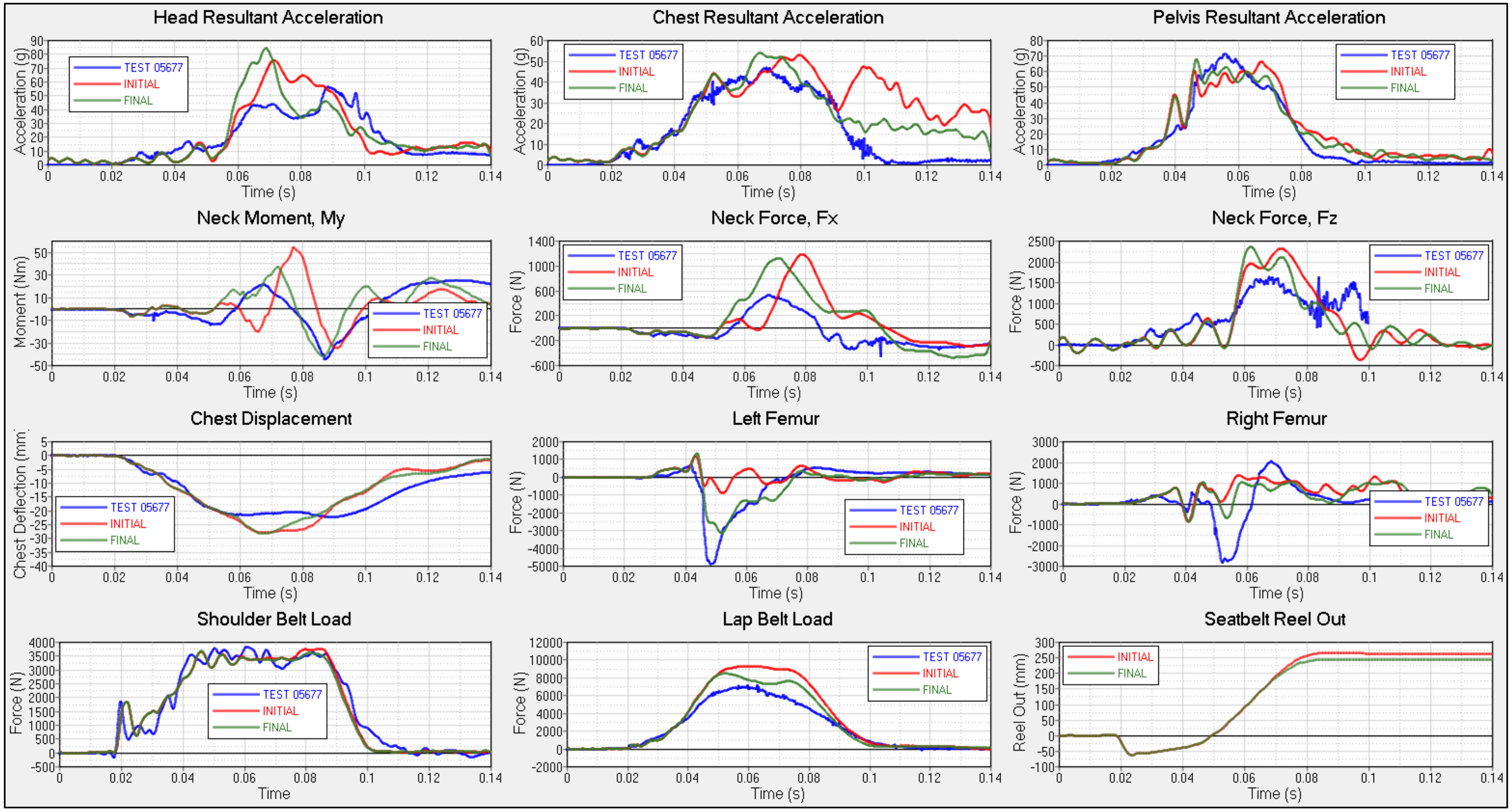

Figure 11: Comparison between the physical test (NHTSA, 2006), the initial finite element iteration, and the final finite element iteration

Table 3: The comparison between the US 50th percentile and Malaysian 50th percentile anthropometric data and estimation of global scale factor between both population

Scale Factor	Sum Squared Error
0.9437	45.978

Anthropometric measurement	Measurement (cm)				Squared Error
	US 50th Percentile (Jordan, 2002)	Malaysian 50th Percentile (Abd Rahman et al., 2018)	Optimized Value	Difference between Optimized Value and measured Malaysian 50th Percentile	
Shoulder breadth	40.0	41.0	37.75	3.25	10.567
Hip breadth sitting	36.0	34.1	33.97	0.13	0.016
Buttock–knee length	60.0	54.4	56.62	2.22	4.946
Buttock–popliteal length	50.0	43.3	47.19	3.89	15.106
Shoulder–elbow length	36.5	34.8	34.45	0.35	0.125
Thigh clearance	16.0	12.8	15.10	2.30	5.289
Sitting height	91.5	87.4	86.35	1.05	1.099
Sitting eye height	80.0	76.0	75.50	0.50	0.251
Sitting shoulder height	60.0	59.1	56.62	2.48	6.131
Sitting elbow height	24.5	23.1	23.12	0.02	0.000
Knee height	55.0	50.7	51.91	1.21	1.453
Head length	19.5	18.1	18.40	0.30	0.092
Head breadth	15.5	15.4	14.63	0.77	0.596
Hand length	19.1	18.2	18.03	0.17	0.031
Hand breadth	9.0	8.1	8.49	0.39	0.155
Foot length	26.5	24.7	25.01	0.31	0.095
Foot breadth	10.0	9.6	9.44	0.16	0.026

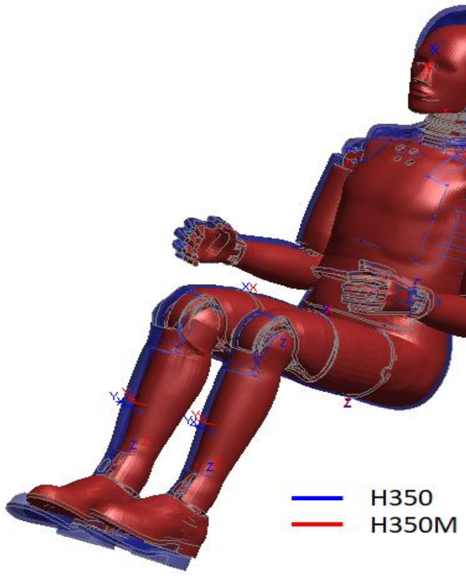

Figure 12: Comparison between the H350 (US 50th percentile anthropometric) and H350M (Malaysian 50th percentile anthropometric)

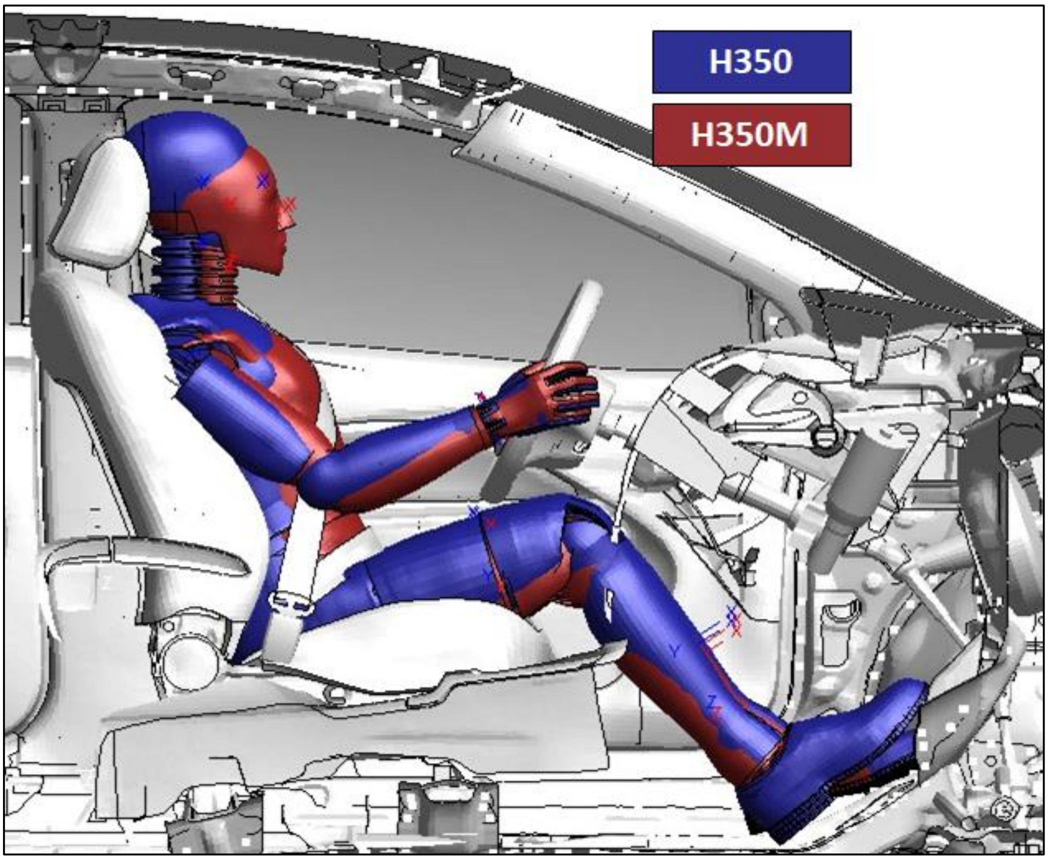

Figure 13: The ATD positioning of H350M and H350 in the vehicle model

3.0 RESULT AND DISCUSSION

Various methods have been developed to estimate the occupant injury based on the vehicle acceleration profile (Wusk & Gabler, 2017). One of the popular methods that are utilized by the vehicle manufacturer is the Vehicle Pulse Index (VPI). It can estimate the occupant response based on the vehicle acceleration curve (Tsoi & Gabler, 2015). It is also suitable to predict the female and child occupant acceleration (Prasad & Weston, 2011), hence, been used in this work to estimate the H350 acceleration. Figure 14 shows the schematics for the VPI system. Using the acceleration curve measured at the left front seat, the calculated VPI is 74.2g. However, the VPI value increases to 76.9g when a scaling mass of 0.868 (the mass ratio of H350M to H350) is used. Hence, it is expected that there will be an increase in acceleration for H350M.

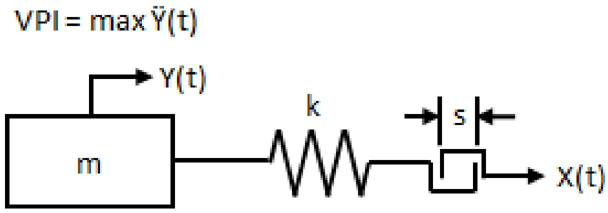

Figure 14: The VPI mass-spring system

From the analysis, it is observed the head and chest peak acceleration are increased. This is in line with the findings in Happee et al. (1998). The peak acceleration of the head injury is increased by 16.6%, from 84.4g to 98.4g. Referring to Figure 15, the H350M head acceleration curve seems to be shifted by -2 to -3ms compared to H350. The offset observed in head acceleration is due to the position of H350M that is slightly forward by 30mm, causing the head to come in contact with the airbag earlier. As depicted in Figure 16, the head of H350M has already in contact with the airbag at 50ms, whereby there is still some gap between both parts for H350M.

The current practice to assess the H350 head injury is by measuring the head injury criteria (HIC). There are two common HIC that are still being used currently: the HIC15 and HIC36. Using the HIC15, it was found that there is a significant increase from 596 to 913. The HIC15 value above 700 can account for the 5% risk of skull fracture (Prasad, 1999).

Besides the increase of the head acceleration for H350M, there is a slight increase in peak chest acceleration from 54.2g to 58.0g. However, the increase in chest acceleration can be considered negligible. From the literature related to car accident injury, the human body can withstand even higher chest acceleration without sustaining serious chest injuries (Melvin et al., 1998). Due to this reason, in modern injury assessment, chest acceleration is not included as an injury criterion anymore. For instance, referring to the current NCAP frontal crash test protocol, the only chest-related injury assessment is the chest deflection and chest viscous criterion. Therefore, in this study, only the evaluation for the chest deflection is considered.

For H350, the chest deflection is calculated by multiplying the rotation of the chest potentiometer with a linear factor of 146. Since the H350M is based on the scaled H350, chest deflection for H350M is calculated using the linear factor of 137.8. Bear in mind, the safety limit of chest deflection for H350 is currently set at 42mm. In this work, it is proposed to lower the limit to 39mm for H350M. As shown in Figure 17, by dividing both the H350 and the

H350M chest deflection against their safety limit, it is observed that the H350M has a lower injury ratio compared to H350.

The overall injury curves, from head to upper leg for both H350 and H350M are shown in Figure 18. As expected, the figure shows the H350M neck injury criteria such as the shear force, axial force, and neck moment recorded lower peak value compared to H350, due to lower head mass.

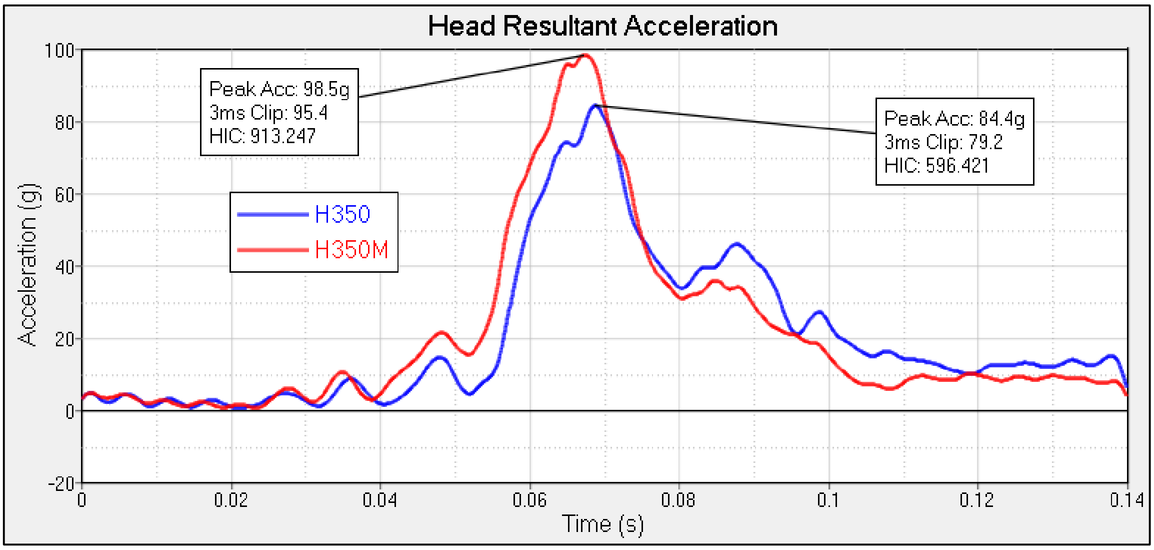

Figure 15: Magnitude of head acceleration with injury assessment

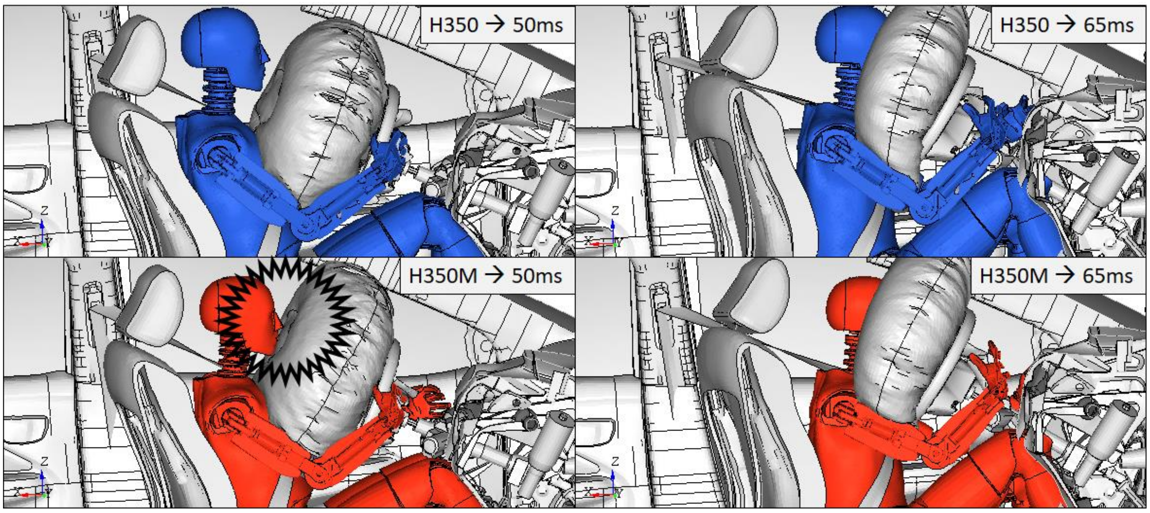

Figure 16: ATD kinematics of H350 and H350M at 50ms and 65ms

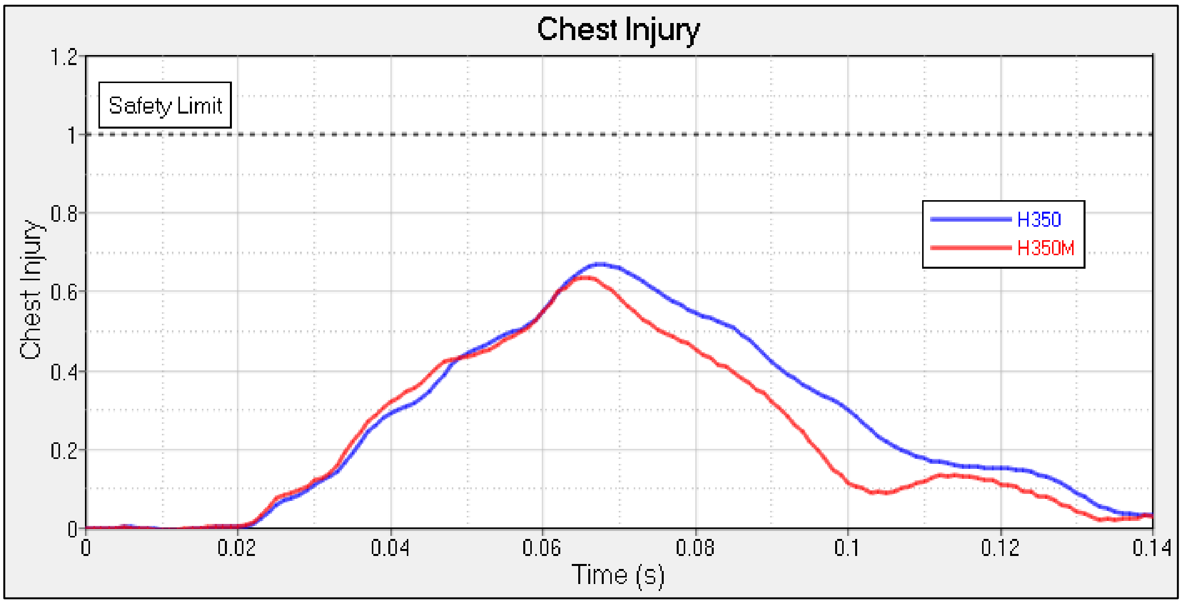

Figure 17: Ratio of chest deflection against its safety limit

4.0 CONCLUSION

The effect of Malaysian anthropometric size on vehicle safety is investigated by using the finite element method in this work. The H350 was scaled to fit the Malaysian anthropometric sizes. It was observed that the scale factor between the Malaysian anthropometric size and the US anthropometric size in sitting position is around 0.9437. A comparison in terms of the injury between H350 and H350M in the same crash configuration has been made. The results show that the neck forces and moment have been slightly reduced for H350M. Additionally, there is also a slight reduction of chest deflection, from 28.2mm to 24.8mm. On the other hand, the magnitude of the head acceleration also shows an increment from 84.4g to 98.4g. The HIC15 assessment for head injury shows an increment from 596 to 913, which might lead to severe head injury. Hence, it can be deduced that the safety assessment by using the newly H350M is important, specifically when the vehicle is designed to barely meet the safety limit. Further works are required to continually refine and develop the H350M for future study. This includes the H350M calibration against the injury corridor using the method proposed by Mertz et al. (1989). More comparisons will be performed, especially on other frontal crash load cases such as ODB64.

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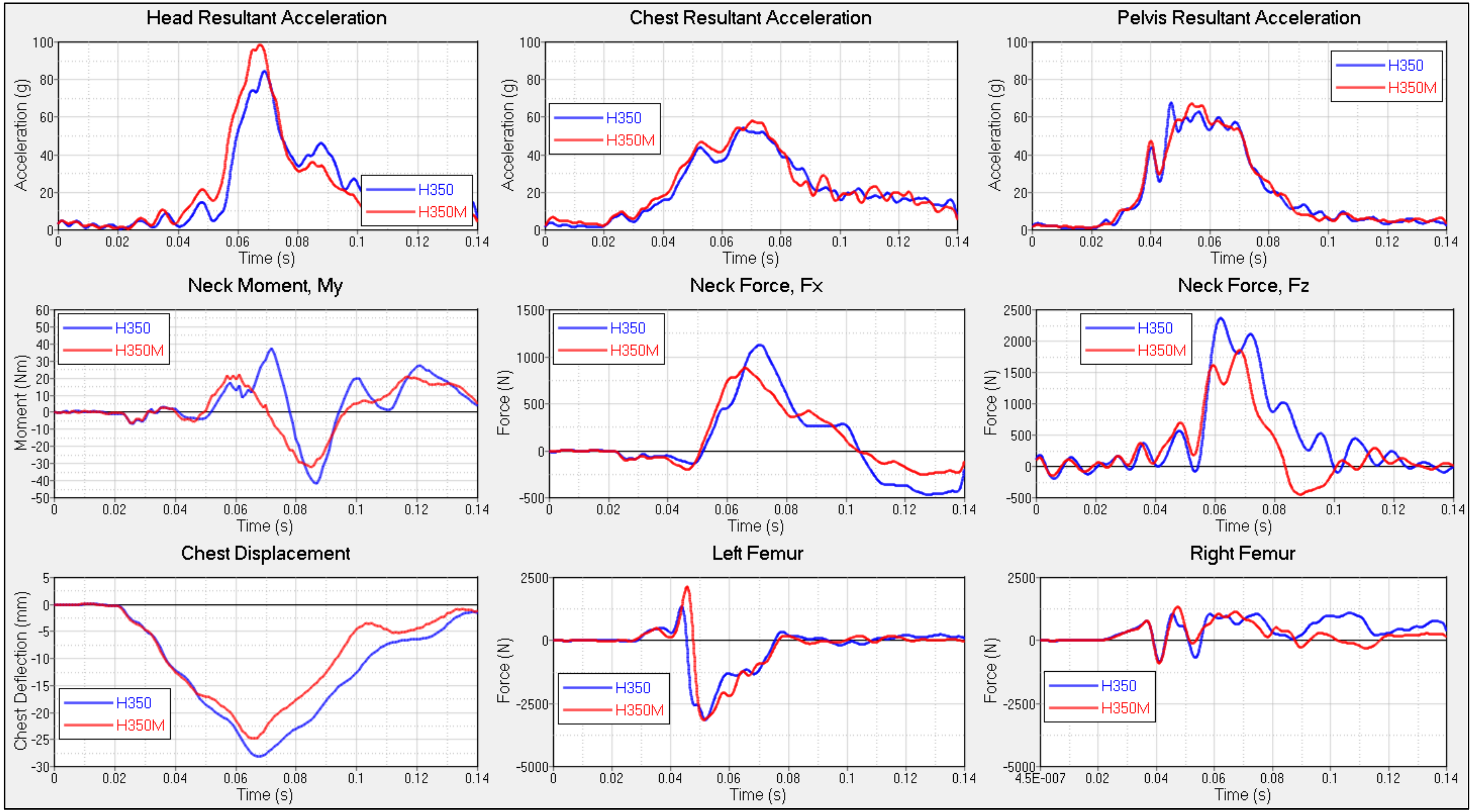

Figure 18: Summary of comparison between H350 and H350M

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