

TITLE:

Classifying Diverse Population For Adaptive Restrain System By Using Finite Element Human Body Models

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ABSTRACT:

Objective: Vehicles are expected to meet standard crash tests requirements for both structural and occupant performance specified by governments and consumer advocacy groups. These tests command a specific ATD size in well-defined seating position with a certain impact speed of the vehicle or a moving barrier. In these standardized tests, typically, the 5th percentile female dummy and 50th percentile male dummy are specified, and the vehicle's occupant restraint system is optimized simultaneously for these dummies. With adaptive restraint system, the system can be optimized independently for 5th percentile, 50th percentile, and 95th dummies to maximize the protection. The objective of this research is to establish a methodology to classify diverse population such that a best set of optimized restraint systems derived from dummies can be tailored to an individual of any size.

Methods: A validated finite element vehicle sled model was selected for this study. US-NCAP standardized crash condition was simulated to optimize three vehicle restraint system designs for HIII small female, midsize male, and large size male independently. Twelve design variables of the airbag, seatbelt systems, and steering column were selected for such optimization. Fifty female and fifty male human body models (HBMs) morphed from GHBMCM50-OS model were used to represent diverse driver populations with various age, stature and BMI of the US population. Automated process was developed for positioning the HBMs into the driver position for occupant safety simulations. The three optimized restraint systems developed for small female, midsize male, and large size male dummies independently, were then applied to each of the 100 HBMs. To evaluate the safety performance of the three optimized designs on each of the HBM, the joint probability of injury for each of the simulations were calculated.

Results: Three sets of restraint systems were optimized for the Hybrid III 5th, 50th, and 95th by minimizing the occupant injury risk in a regulated 35mph impact condition. Each of the three sets of restraint systems was used to assess the safety performances of each of the 100 HBM's. Based on the best fit restraint system selected for each of the 100HBM's, the boundaries dividing the diverse population are drawn. The population classification methodology is established for a vehicle with adaptive restraint system.

Discussions and Limitations: The vehicle pulse used in this study was NCAP 35mph rigid barrier crash pulse only and the occupant classification boundary based on this pulse may change for lower speed or different types of barriers impacts. The

100HBMs were developed based on simplified GHBMC model and the classification boundary could be different if detailed GHBMC models were used to morph the 100 HBMs.

Conclusions: The processes discussed in this study show the potential of classifying a diverse population based on the best-fit restraint system from the three systems which were optimized originally for the dummy sizes: 5th female, 50th male, and 95th male.

Keywords: NCAP, human body models, diverse population, occupant injury, optimization of restraint system, occupant classification.

INTRODUCTION

Vehicle models are required to meet crash safety tests for both structural and occupant safety performance which are regulated by the governments and/or various consumer advocacy groups. These tests involve specific and well-defined dummy models and their seating positions with various test conditions. The dummies used in the tests are mainly the 5th percentile female, 50th percentile male, and 95th percentile male dummies. With those crash tests, the vehicle structure and its interior restraint system are developed and optimized for the dummies in those defined locations.

The three Hybrid III dummies, 5th, 50th, and 95th are the current standard anthropomorphic test devices (ATD) for the frontal crash tests. The heights of the three Hybrid III dummies (5th female, 50th male, and 95th male) are 152 cm, 175 cm, and 188cm with the weights of 50 kg, 78 kg, and 100 kg and they have the body mass index (BMI) of 21.6 kg/m², 25.4 kg/m², and 28.3 kg/m² respectively. BMI is a value calculated from the weight and height of a person and it has the classification of underweight, healthy weight, overweight, obesity, and severe obesity which correspond to the BMI of below 18.5, 18.5~24.9, 25.0~29.9, and 30.0~39.9, and 40 or above, respectively. Based on the weight category, the 5th female Hybrid III dummy has a healthy weight, while the 50th and 95th male dummies are classified as overweight. As reported in Reference 1, 39% of adults aged 18 years and over were overweight in 2016, and 13% were obese in 2016. The obesity group is not covered by the current standard three test dummies, and small, obese, and older occupants will have higher risk of injury in vehicle crashes (Hu et al. 2019). By adapting the restraint system for an individual, the protection of diverse occupant in vehicle crashes can be further improved.

Finite element (FE) human body models have the potential to represent diverse population by accounting for the body size and material variations in the human body. Yet, the greatest potential for FE human models in vehicle development lies in representing the large range of human variability in anthropometry and response that is not represented by the ATDs (Hu et al., 2019). The developed 100 FE human models (Hu et al., 2019), based on GHBMC M50-OS v1.8.1, were used to represent the diverse population with different genders, age, statures, and BMI values in this study.

METHODS

Baseline FE Sled Model & Classification of Driver Restraint System

A well correlated midsize finite element sedan sled model with Hybrid III 50th ATD for US NCAP frontal crash was used in this study, as shown in Figure 1. This sled model was also previously used for the study with and without unbelted occupant requirements (Hu et al., 2017).

[Fig. 1 here]

Three different ATD sizes (Hybrid III 5th, 50th, and 95th) in their perspective seating positions are selected for minimizing their injury risk and optimizing their respective restraint systems performances. The restraint systems were optimized such that the joint probability of injury is minimized for three sizes of ATDs. Input variables of the restraint system to be assessed in optimization were on three effective categories: 1) the seatbelt component, which includes the pretensioner (active or inactive), cinching plate (yes or no), retractor load profile; 2) the airbag component, including static vent diameter, dynamic vent diameter, dynamic venting time, lower tether length, upper tether length, inflator flow rate; 3) Steering column load. A set of 150 DOE (Design of Experiment) simulations for each of the ATD was generated by using LS-Opt. From the simulations, a set of the restraint design with the minimum joint probability of injury for each ATD was selected as the optimized design. The chest and neck had higher possibilities of injury when comparing with head and femur body regions. In the optimized design, the 95th ATD had a better performance with a larger and softer airbag when comparing with the 5th and 50th ATDs. To better protect the 95th ATD, the softer airbag was supplemented by a stiffer load limiter since the airbag, seatbelt, and steering column stroking force were an integral restraint system for protecting the occupant.

If the restraint system can be adaptive and tailored to individuals for a restraint system with three distinct designs optimized for the three ATDs, then it is important to know which one of the systems is the best system for an individual. So, it is important to classify the population based on the performance of the restraint systems. To enable to evaluate diverse population safety performance, a set of 50 female and 50 male HBMs (developed by Hu et al., 2019) is used to represent driver population in the US. The 100 occupants were developed based on age, sex, stature, and body mass index (BMI) using the Uniform Latin Hypercube method, and their anatomical geometries were predicted by the statistical geometry models developed previously. The morphed baseline models to be morphed to the 100 HBM had also gone through the following validation cases: 6.7 m/s and 23 kg hub impact, 6 m/s and 48 kg bar abdomen impact, 12 m/s and 23.4 kg plate shoulder impact, 6.7 m/s lateral sled test, and 11.1 m/s frontal sled test. To automate the simulation analysis, scripts were developed to automatically determine the h-pt position, seat cushion compression, and routing of the seatbelt for each of the 100 HBMs.

After minimizing the injury risk of the ATDs, the three optimized restraint systems were then applied to each of the HBM and the safety performances of the three systems, i.e., the potential injury risk, were calculated. One of the systems with the best occupant safety performance for individual was then selected and plotted on the height vs mass graph. After identifying the set of best fit restraint system from the three ATD designs for all the 100 HBMs, the boundaries dividing the population based on the selected restraint system were drawn (based on an individual's selection of the restraint system whether it is the Hybrid 5th, or 50th, or 95th design). The classification of a diverse population can be determined based on the selection of a restraint system. The schematic of the technical plan is shown in Figure 2.

[Fig. 2 here]

Optimizing Restraint Systems for Hybrid III 5th, 50th, and 95th

The current vehicles are required to pass the regulated physical crash tests (35 mph, 0-degree rigid wall impact test (NCAP)) using the standard crash test dummies. To meet such a physical crash test, firstly, we decided to optimize three restraint systems based on the three Hybrid III dummy sizes.

The design variables of the restraint system and the range of the parameters used for the optimization are shown in Table 1. This restraint system was started from the actual vehicle designs and has been well correlated to the occupant simulations. The range of the optimization parameters were based on experience, constraint of the technology and the limitations of other requirements (e.g., shoulder belt load limiter load should be higher than 2kN for the occupant's rollover protection). The LS-

Opt, a graphical optimization tool from ANSYS/LST, was used to perform the optimization. To optimize the restraint system, i.e., minimizing the joint probability of injury, a set of 150 DOE (Design of Experiment) runs were conducted for each ATD and the restraint system with the lowest joint probability of injury was selected as the optimized design for each of the ATDs. The optimized restraint parameters for the ATDs are shown in Table 2.

[Table 1 here]

[Table 2 here]

100 HBMs To Represent Diverse Population

The 50 female and 50 male HBMs co-developed with UMTRI (University of Michigan Transportation Research Institute) (Hu et al., 2019) were used to represent the diverse driver population. The 100 diverse HBMs were morphed from the simplified GHBMCM50-OS v1.8.4 to represent various age, stature and BMI of the US population. For developing the 100 HBMs, the National Health and Nutrition Examination Survey (NHANES) data was used to characterize the range of adult population (stature is 5th to 95th percentile, body mass is 5th to 95th percentile, and age is 19 to 80 years old for both genders). The weight and height distribution of females and males are shown in Figure 3 along with the three ATDs (shown in red diamonds).

[Figure 3 here]

Automated Process for Occupant Seatbelt Routing and Seat Cushion Squashing

To set up the sled model for simulating various BMIs and statures, each of the HBMs had to be positioned into the driver seat in a driving posture without penetrating into the interior components (seat cushion, seat back, and/or seat structure, instrumentation panel, and steering wheel). A flow chart showing the detailed steps in this automation process is shown in Figure 4.

To position the human body model into the driving posture such as the H-point and the coordinate of the seat position (i.e., the person's limb angles, and the seatbelt buckle assembly angle) are needed for the analysis. The human body parameters (height, gender, BMI and age) along with the vehicle parameters (vehicle compartment, seat cushion, and seatbelt) were required as inputs to position the human body models.

To determine the H-point of each HBM in this vehicle, the height of the HBM being repositioned was compared with the height of the three Hybrid III dummies (H3-05, H3-50 and H3-95 dummies). Two dummies (H3-05/H3-50 or H3-50/H3-95) are used for interpolation and deciding the h-pt fore and the aft positions. The vertical coordinate of the HBM h-pt was adjusted based on their BMIs. For the HBMs with higher BMI, a correction factor is used to move the seat further upward based on the obesity level. As shown in Figure 5, some of the HBMs with much higher BMI had to be placed manually without using the positioning scripts. Since their statures and BMIs are much higher, they created penetration issues for the HBM's belly to the steering wheel or knee to knee bolster.

After determining the H-point, occupant joint angles, seat position, seatbelt buckle angle, a Primer script was used to automatically reposition the HBM (i.e., moving the seat structure, adjusting seatbelt buckle angle, rerouting seatbelt, and for deforming/squashing seat cushion foam).

[Figure 4 here]

[Figure 5 here]

RESULTS

Selecting Restraint System for Each HBM

Three sets of restraint systems optimized for the Hybrid III 5th, 50th, and 95th dummies have been analyzed. The characteristics of the airbag and the seatbelt system are shown in Table 2. These restraint systems derived from ATDs were applied to each of the 100 HBMs (3x100 simulations) and the joint probability of injury for each of the simulations are calculated to evaluate their safety performance.

The occupant injury risk, i.e. joint probability of injury, is a function of the individual mass and body size (i.e., the neck cross section area, chest depth, and femur cross section area) and the injury risk curves was scaled based on the occupant size as previous study in (Hu et al., 2019). The aged skeleton material stiffness of an individual has a strong correlation to the probability of injury. In this study, however, we only consider the effects of the individual body's size on the probability of injury.

The probability of human body model injury risk (Hu et al. 2019) involving the HIC15, the neck axial force, the chest displacement, and the femur compressive force was used in this study. The whole-body joint probability, the same equation used by Hu et al. 2019, of injury was determined from the body region level probability of injury.

Classification of the Diverse Population

The best suited restraint system (i.e., lowest joint probability of injury) for the female and male population are shown separately in Figure 6. Both genders are then combined and shown in a single plot in Figure 7 which represents the whole diverse population. As shown in Figure 7, the population is divided into three regions by drawing the boundaries separating individuals based on the restraint system selection. A few data points of the occupant's best restraint systems are not consistent with the boundaries drawn. Most of these outlier data points, however, could use a different set of restraint system with little impact on the safety performance.

[Figure 6 here]

[Figure 7 here]

DISCUSSION

The boundaries of the restraint system drawn from our previous internal study using MADYMO simulations did not have similar results as of the LS-Dyna 100 HBMs simulations. The 100 LS-Dyna HBMs generated in our study have better geometry representation of obese people (abdominal fat) and could yield more representative results. With relatively smaller open space between the upper torso and the steering wheel for high BMI drivers, a smaller inflator with a softer airbag pressure (a smaller ATD's restraint system) is preferable for such a smaller space. The obese occupant HBM models in our study may present the obese occupant geometry well, however, the morphed models had not gone through validations with those obese PHMS (Post-Mortem Human Surrogates) tests. Seating positions of those obese driver may also have different seating H-pt or upper torso angle from those lower BMI occupants for ease of operating the steering wheel.

In the final classifications shown in Figure 7, there is an outlier individual (a high BMI female driver with a height of 170cm and weight of 104kg) whose restraint system cannot be switched from the system designed for the Hybrid III 50th to the 5th to conform with the drawn boundaries. The switch worsens her safety performance significantly, hence, her restraint system is kept the same which is shown as an outlier on the final classification.

For a given impact in the same vehicle environment, a heavier person has a larger momentum and requires higher energy to stop his/her forward motion in a frontal impact before contacting the vehicle interior structures (e.g., steering wheel or the windshield). With the larger forward momentum, a stiffer restraint system is preferred for a heavier person. In today's vehicles, the restraint system for a driver protection consists of the following subsystems: airbag, steering column, seatbelt, and knee bolster. Each of the subsystems has a few design variables which can affect the subsystem's stiffness for the occupant protection. The combination of the subsystems adds up to the overall stiffness of the restraint system. To avoid the outliers seen in this study, one might want to set a constraint in the ATDs' optimizations that a stiffer subsystem is required for a larger occupant size, e.g. a stronger load limiter for the 50th male than the 5th female and a higher inflator output for the 95th male than the 50th male, etc. From the optimized designs in Table 2, the 95th ATD would had a better performance with a larger and softer driver airbag when comparing with the 5th and 50th ATDs, which might be counterintuitive. However, the softer airbag was further supplemented with a stiffer load limiter to absorb the 95th ATD's higher momentum with the best protection.

The sets of optimized designs shown in Table 2.

CONCLUSIONS

Three sets of restraint systems were optimized for the Hybrid III 5th, 50th, and 95th by minimizing the occupant injury risk in a regulated 35mph impact condition. These three sets of restraint systems were used to examine the safety performance of the 100 HBMs to represent a diverse population. The boundaries dividing the population based on the selection of a best fit restraint system are drawn and classification of a diverse population based on the safety performance is determined for the vehicle with an adaptive restraint system.

ACKNOWLEDGEMENT

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REFERENCES

- Obesity and overweight, [https://www.who.int/news-room/fact-sheets/detail/obesity-and-overweight#:~:text=In%202016%2C%20more%20than%201.9%20billion%20adults%20aged%2018%20years,women\)%20were%20obese%20in%202016.](https://www.who.int/news-room/fact-sheets/detail/obesity-and-overweight#:~:text=In%202016%2C%20more%20than%201.9%20billion%20adults%20aged%2018%20years,women)%20were%20obese%20in%202016.)
- Hu J, Klinich KD, Manary MA, Flannagan CAC, Narayanaswamy P, Reed MP, Andreen M, Neal M, Lin C., et al. Does unbelted safety requirement affect protection for belted occupants? *Traffic injury prevention*. 2017 May 29; S85-S95 (doi: 10.1080/15389588.2017.1298096).
- Hu J, Zhang K, Reed M, Wang J, Neal M, Lin C et al. Frontal Crash Simulations Using Parametric Human Models Representing a Diverse Population, *Traffic Injury Prevention*, Volume 20, Supplement 1, 2019, Pages S97-S105
- Reed, M.P., Manary, M.A., Flannagan, C.A., Schneider, L.W., 2002. A statistical method for predicting automobile driving posture. *Hum Factors* 44, 557-568.

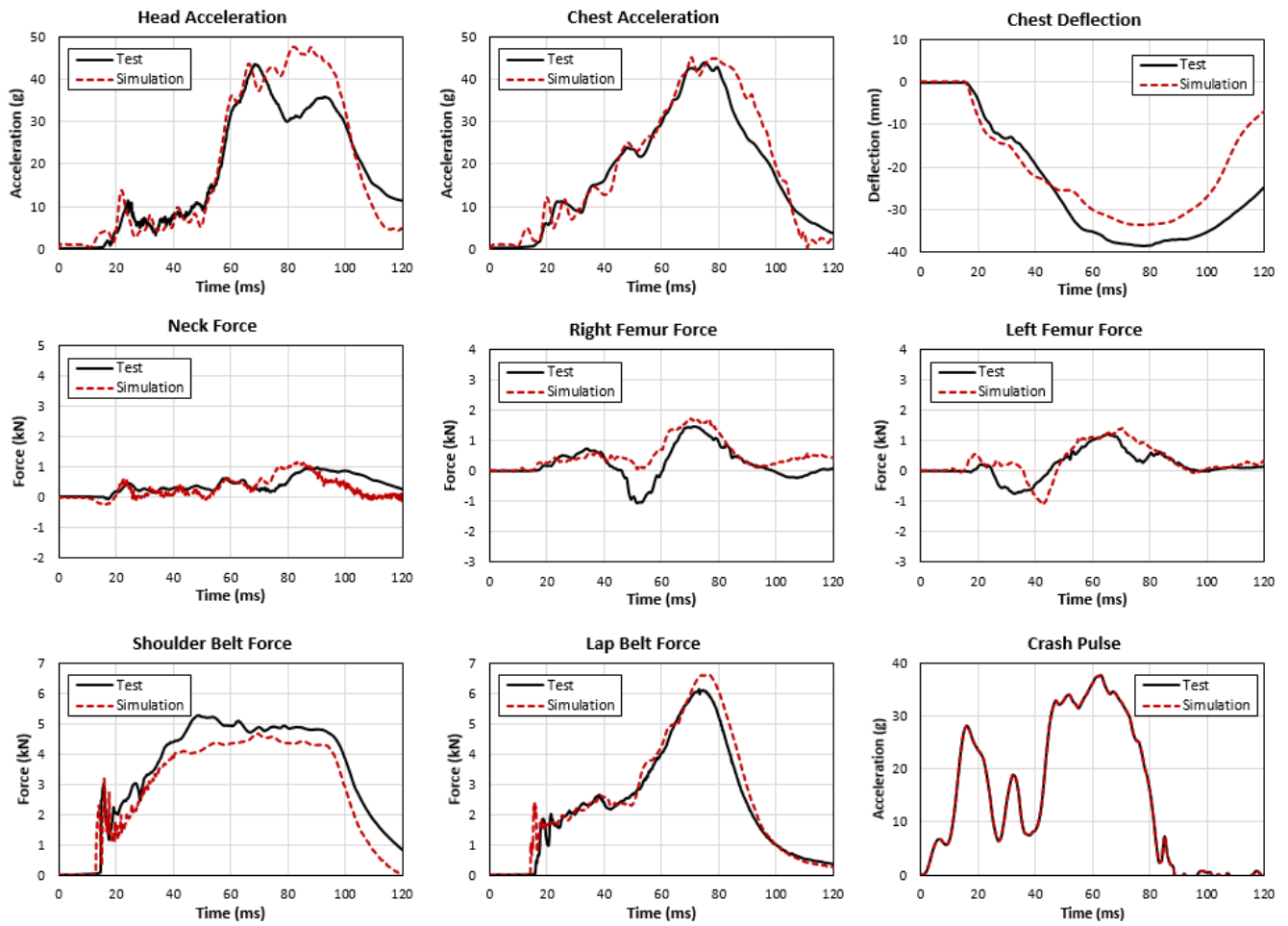


Fig. 1. 50th male driver validation of the NCAP frontal impact simulation.

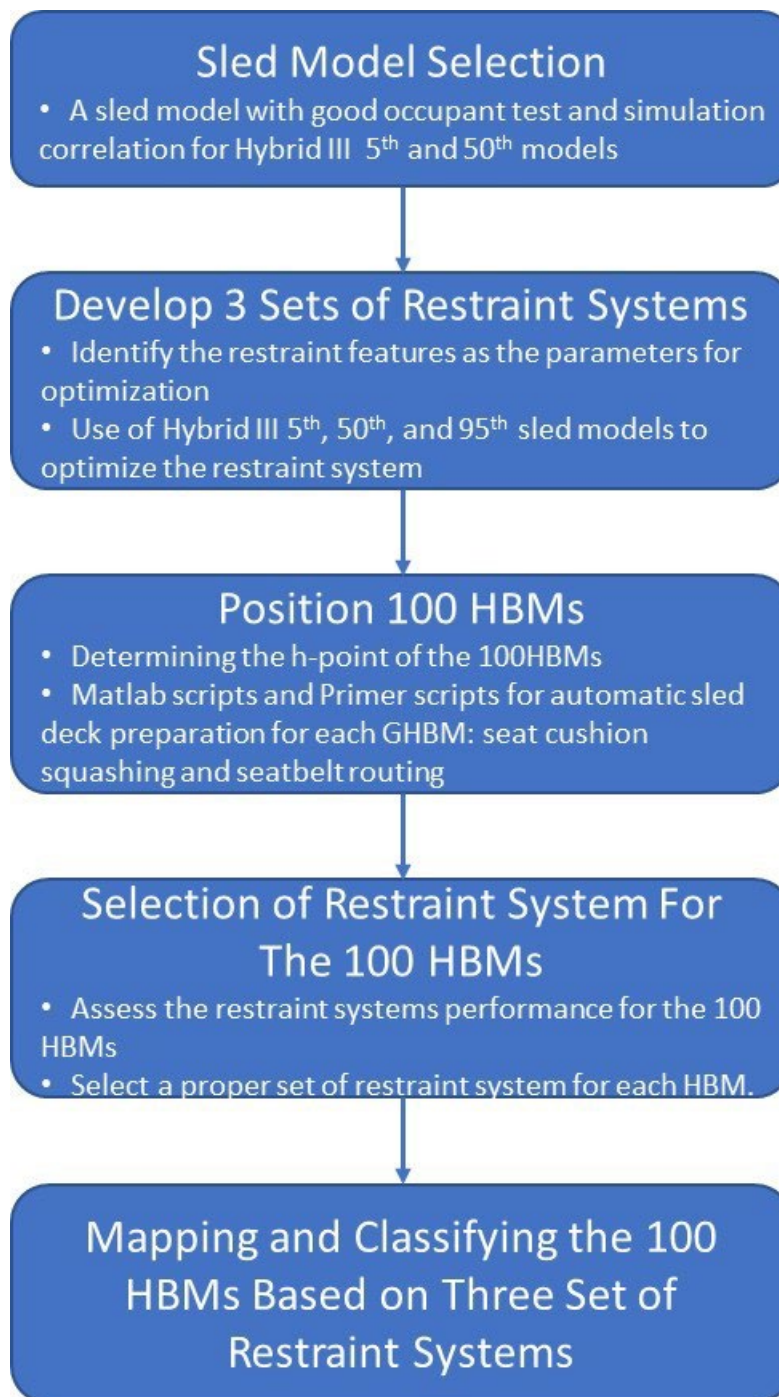


Fig. 2. Technical schematic plan of the driver classification.

Table 1. Optimization parameters and their range for obtaining the three sets of restraint designs for Hybrid III 5th, 50th, and 95th driver simulations.

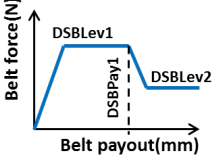
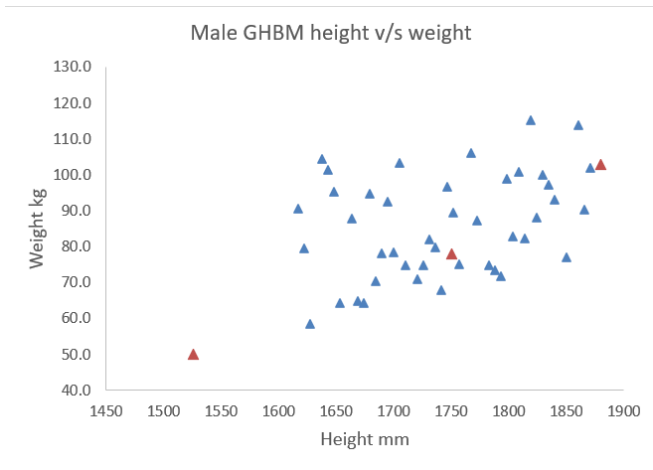
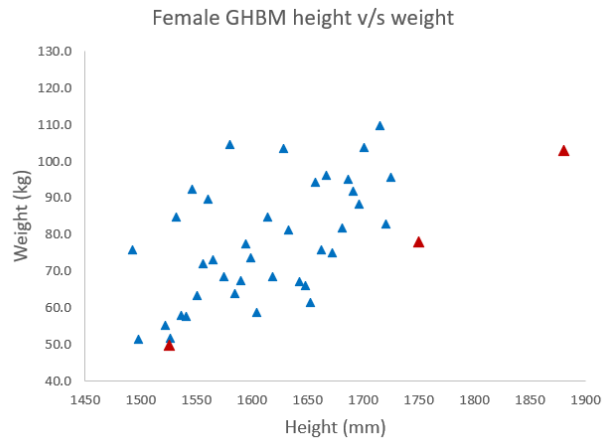
LS-DYNA parameter	Description	Baseline	Lower bound	Upper Bound
DCINCH	Cinching plate inactive/active	0	0	1
DAPTTB	Anchor pretensioner no/yes	1	0	1
DSBLev1 (N)		2850	2000	4000
DSBLev2 (N)		2850	2000	4000
DSBPay1 (mm)		N/A	100	200
DVentD (mm)	Static vent diameters (two holes)	35	25	45
DVentDD (mm)	Dynamic vent diameter (one hole)	0	0	50
DVentDT (ms)	Dynamic vent time	N/A	30	60
DtethA (mm)	Lower tether length	260	100	300
DtethC (mm)	Upper tether length	290	200	300
DMassR	Inflator flow factor	1	0.8	1.2
CBL (N)	Steering column load	3000	2000	4000

Table 2. The three set of restraint systems after the optimization using three different ATD sizes.

Optimization Parameters	Hybrid 5th	Hybrid 50th	Hybrid 95th
Cinching Plate (Inactive/Active) (0/1)	0	0	1
Anchor Pretensioner Firing @15 msec (No/Yes) (0/1)	1	1	1
Digressive Load Limiter Load Level one (N)	2000	2000	3043
Digressive Load Limiter Load Level two (N)	3006	2377	2000
Retractor Payout Length (mm)	151	200	102
DAB Static Vent Diameters - two vents (mm)	45	35	45
DAB Dynamic Vent Diameters - one vent (mm)	0	50	27
DAB Dynamic Venting Time (msec)	n/a	30	30
DAB Lower Tether Length (mm)	300	300	441
DAB Upper Tether Length (mm)	300	300	392
DAB Inflator Flow Scaling Factor	0.91	1.14	0.95
Steering Column Stroke Force (N)	2000	2795	2044



(a)



(b)

Fig. 3: Weight and height of the 100 HBMs in blue triangles, (a) 50 female HBMs, (b) 50 male HBMs. The three red diamonds on the plots are the Hybrid III 5th, 50th, and 95th.

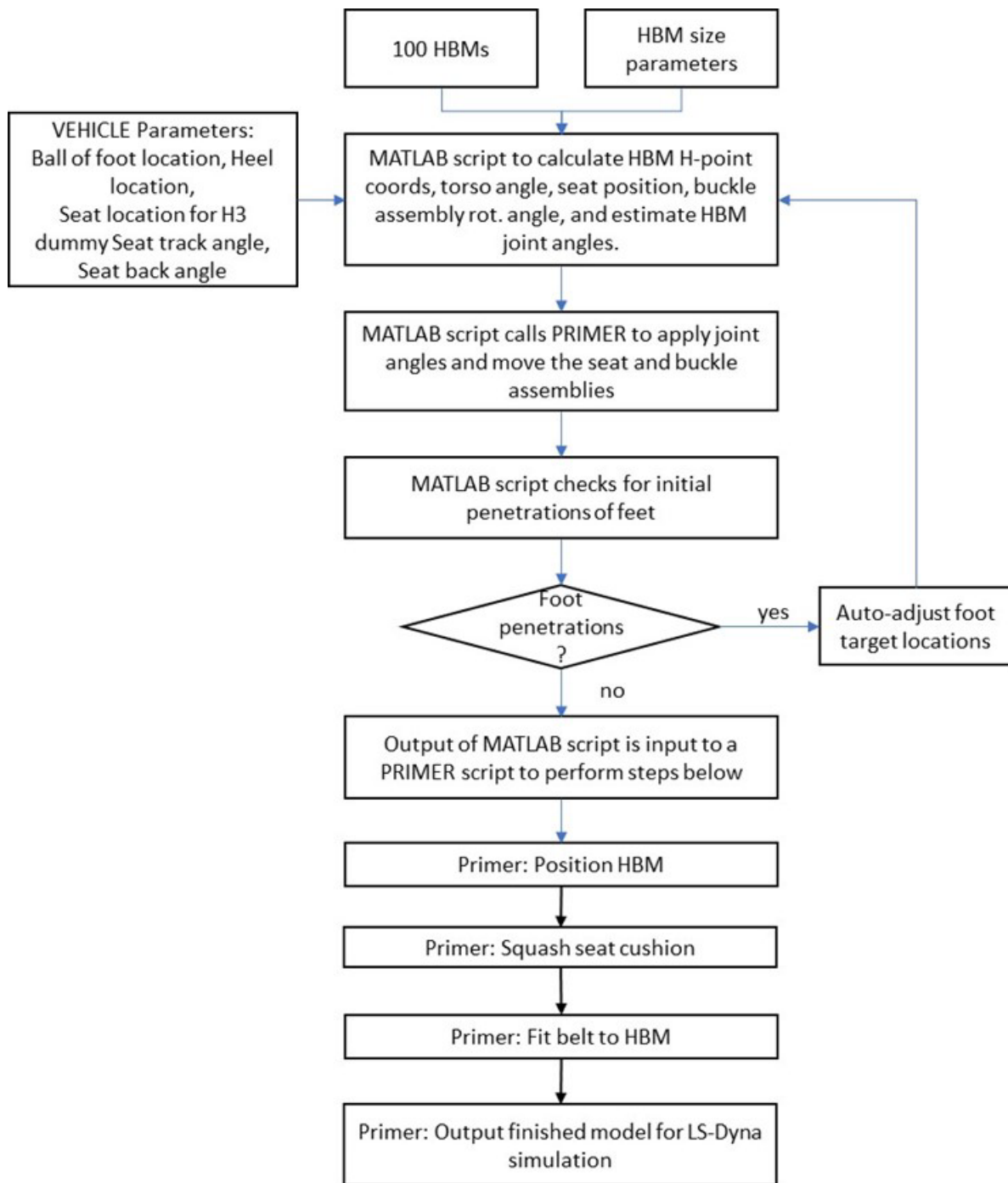


Fig. 4: Flow chart of the automated HBM position.

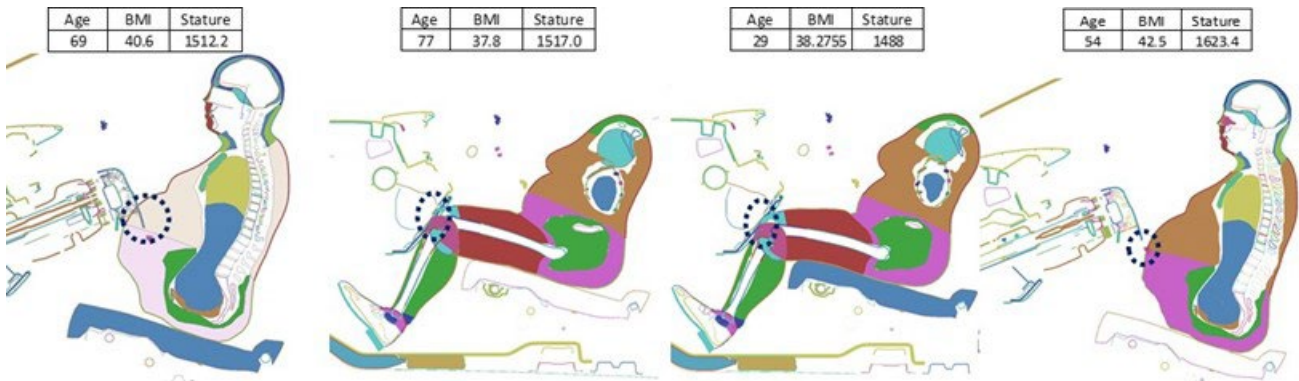


Fig. 5: Examples of the HBMs could not be positioned into the driving position automatically without penetrating into knee bolster or steering column.

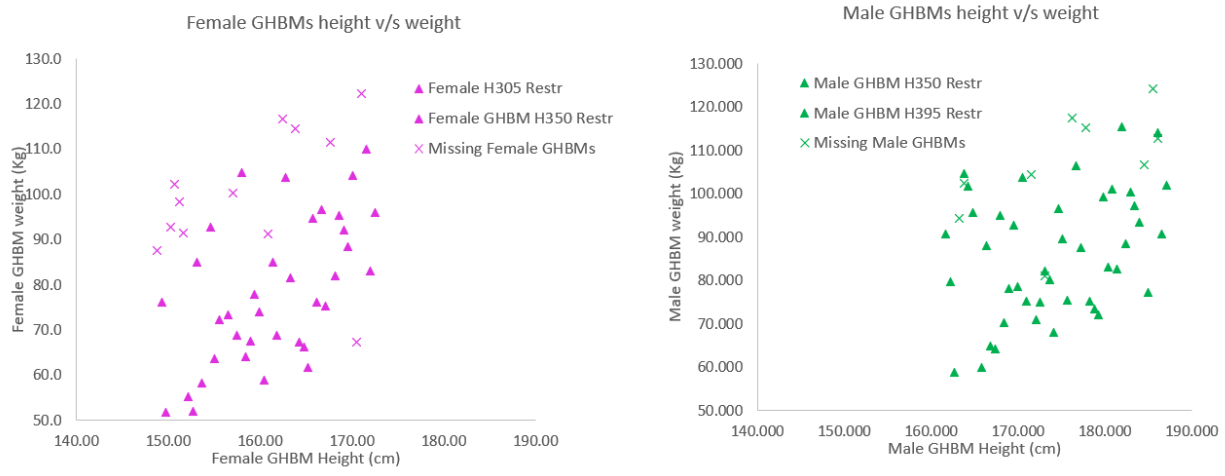


Fig. 6: Some of the obese female and male HBMs had early terminations and have no results and they are indicated by an x mark.

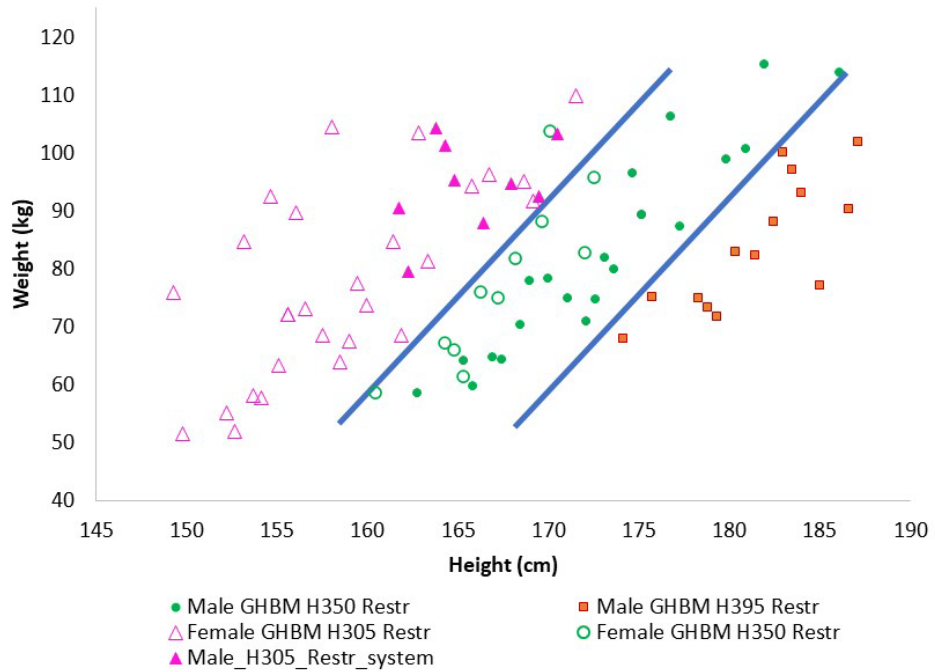


Figure 7. Breakdown of the restraint systems selected by male or female HBMs and the boundary based on the selection of three ATDs' restraint systems.FFigur