DEVELOPMENT OF A FRAMEWORK FOR RESTRAINT SYSTEM OPTIMIZATION, AND ILLUSTRATION FOR AN OBESE ANTHROPOMETRY

A Dissertation

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Hamed Joodaki

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APPROVAL SHEET

This Dissertation
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Author Signature: Hamed Joodaki

This Dissertation has been read and approved by the examining committee:

Advisor: Jason Kerrigan

Committee Member: Robert Salzar

Committee Member: Shawn Russell

Committee Member: Timothy McMurry

Committee Member: Jason Forman

Committee Member: ______

Accepted for the School of Engineering and Applied Science:

Craig H. Benson, School of Engineering and Applied Science

May 2020

ABSTRACT

Restraint system optimization, which is performed through computational simulations and is a state-of-the-art approach to increase the safety of motor vehicle occupants, requires a substantial computational cost, which is a disadvantage. The primary objective of this dissertation was to develop a framework for restraint system optimization that incorporates metamodeling using machine learning to decrease the number of required simulations for the optimization. The optimization framework was used to investigate strategies for increased safety of occupants with obesity, who are shown to be at a higher risk of injury in motor vehicle collisions than occupants with normal Body Mass Index (BMI). Thus, the secondary objective of this study was to optimize the restraint system for two occupants, one with obese anthropometry (BMI=35) and one with a normal BMI (BMI=25), and compare the two designs.

This study consisted of five tasks. The objective of the first task was to statistically compare the injuries of occupants with obesity and normal BMI in frontal impact cases of a field crash database. The results showed that the occupants with obesity have a higher risk of injury to the extremities and spine compared to the occupants with normal BMI. The objective of the second task was to evaluate the performance of an obese (BMI=35) human body model (HBM) in frontal impact sled tests. The obese HBM was capable of representing biomechanical characteristics of occupants with obesity, which were reported to be potentially challenging for designing an effective restraint for obese. In task three, 450 frontal impact parametric simulations with 14 different restraint parameters and two HBM types (obese, BMI=35, and non-obese, BMI=25) were performed. Then, statistical and biomechanical analyses were carried out on the simulation results to study the effects of restraint parameters on the HBMs' responses and to compare the responses of the two occupants.

In task four, machine learning was leveraged to develop metamodels of occupants' responses as a function of different restraint parameters in simulations. In task five, a genetic algorithm was applied to the metamodels to optimize the restraint system for the obese and non-obese HBMs. The results revealed that while most of the restraint parameters between the optimized design for obese and non-obese HBMs were similar, the main difference was that the restraint for the obese HBM included an under-the-seat air bag, which improved the occupant's kinematics and decreased its lower extremity and lumbar spine injury risks. Several design recommendations were suggested, which should be considered to improve the safety of occupants with obesity. Also, the framework developed in this study can be used to optimize the restraint system for a variety of occupants and crash characteristics.

DEDICATION

To mom, dad, and Atena. Thank you for your support and love. Not seeing you for more than five years was the most difficult part of this journey.

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Any new experience makes us a more complete person. I think the most eye-opening experience of my life so far has been studying and living in the US. I am grateful to all CAB members who gave me the opportunity to study here and thought me something either through teaching in classes, having a discussion about a research project, or having a chat on different topics. In the end, I hope that among the fruits of this experience there have been critical thinking and open-mindedness, the quality of believing that I might be wrong even about my most cherished beliefs.

Contents

Chapter 1

Introduction

1. INTRODUCTION

1.1. Background and Motivations

This section provides background research and motivations for the content of this dissertation. Topics include restraint system optimization, metamodeling for engineering design application, the safety of occupants with obesity in car crashes, and human body modeling.

1.1.1. Restraint system optimization

Nearly 1.25 million people die and 20-50 million occupants get injured in motor vehicle collisions (MVCs) each year (World Health Organization, 2015). Restraint systems are the main source of occupant protection in the crash and thus, designing effective countermeasures is critical to protecting the occupants in the event that an MVC occurs. It is estimated that more than 600,000 lives were saved by vehicle safety technologies and associated Federal Motor Vehicle Safety Standards from 1960 through 2012 in the United States (Kahane, 2015).

Computational modeling is widely used by researchers in designing vehicle safety technologies like restraint systems because it facilitates evaluating conceptual designs before prototyping. For example, Zellmer et al. (1998) performed multibody simulations to investigate the strategies for increased safety of rear-seat passengers and found out that a load-limiter and a pretensioner can decrease the chest deflection and the viscous tolerance chest injury criterion (Viano and Lau, 1985), respectively. Kent et al. (2007) performed parametric simulations for rear-seat restraint system to assess chest deflection and head excursion trends for different belt load limits, pretensioner locations, and impact speeds and found out that a seat belt with load-limiter and pretensioner outperforms a standard seat belt in reducing head excursion while reducing chest deformation. To investigate how to improve the restraint environment for 6-12 years old children in rear-seat, Hu et al. (2013) ran 1000 multibody simulations and studied the effects of body size, seat belt anchorage locations, and rear seat design parameters on the injury risks in frontal crashes. Wang et al. (2015) performed 52 simulations using whole-body finite element HBMs with four BMI levels and reported that higher belt routing and anchor pretensioner increased and decreased, respectively, hip excursion and torso angle. In addition, they observed that while lower load limits decreased the normalized chest deflection, they increased the head excursion.

The optimization of vehicle restraint system is done by performing numerous computational simulations to find a set of restraint system parameters that results in the greatest safety for the occupant. For example, to optimize a driver-side airbag, Lee (2005) performed parametric multibody simulations followed by Kriging interpolation to obtain the surrogate approximation model of the system. He then used this approximation model to determine the optimized air bag parameters such as vent hole size, temperature controlling inflation pressure, and firing time. Hu et al. (2013) performed restraint design optimization by running more than 2500 simulations, through the iterative process of guessing a solution, running a simulation with that guessed solution, and assessing the appropriateness of the results. That study used head and knee excursion as the two objective functions and made recommendations about the seat belt anchorage locations. In an effort to optimize restraint systems for protecting rear seat occupants with four different body sizes under two different frontal crash pulses (soft and severe), Hu et al. (2017b) performed a parametric study based on the full-factorial design of the optimization parameters. They performed a total of 384 multibody simulations but only 5 designs met the optimization constraints under the soft crash pulse and no design could meet all the constraints under severe crash pulse.

Since restraint system optimization is a complex and non-linear problem and to avoid confusing a local minimum with a global minimum, the whole optimization domain should be explored. Nonetheless, an exhaustive exploration of the optimization domain requires notable computational resources, especially if it is done using detailed Finite Element (FE) models. To decrease the required computational expenses, some studies utilized multibody modeling (rather than FE modeling) to optimize the restraint system (Hu et al., 2017b, Hu et al., 2013, Kent et al., 2007, Lee, 2005). The FE models are often computationally more expensive than the multibody models. Compared to multibody modeling, however, the FE method can be used to model the human body, vehicle, and restraints with more detail and potentially more accurately. Another method that researchers in the passive safety field use to circumvent this problem is to discretize the value range of optimization parameters with a relatively low resolution and run full-factorial simulation set of different testing conditions (Wang et al., 2015, Hu et al., 2017b). Eventually, the set of parameters in the simulation which achieved the most desired objective function value amongst all runs would be chosen as the optimized restraint system. Nonetheless, a significant limitation of this method is that the behavior of system between the widely distanced discretization points, where the best solution might be located, remains unknown. In addition to being computationally expensive, optimization can be very time consuming if it is done by iterative process of guessing a solution, running a computational simulation with the guessed solution, and assessing the appropriateness of the results (e.g. see Hu et al. (2013)), because the simulations have to be run in series. Running all simulations in parallel would be more time-efficient. An objective of this dissertation was to leverage advanced machine learning techniques to develop a framework for restraint system optimization which allows for running the vast majority of FE simulations in parallel, tuning a relatively high number of optimization parameters, and searching over the whole optimization domain.

1.1.2. Metamodeling

Restraint system optimization through the iterative process of guessing a solution, running a simulation with the guessed solution, and assessing the appropriateness of the guessed solution is computationally expensive. A method to use the computational resources efficiently is to run parametric simulations, develop metamodel of the simulation results, and apply the optimization algorithm to the metamodel. A metamodel is a model of an original model that represents the relationship between the input(s) and the output(s) mathematically. For the case of this study, the metamodel of the FE simulations should predict the response (output) of the system (simulation results) to any given set of restraint system parameters (input).

While there are several studies that used response surface models for engineering design optimization in general (see Wang and Shan (2006)), there are only a few studies that aimed at using metamodels for predicting the results of restraint design simulations, all of which were possibly poor models as they did not consider under-fitting and over-fitting problems. When using metamodels for optimization, it is essential to accurately capture the relationships between the outputs and the design parameters through avoiding over-fitting and under-fitting. If the shape of response surface is not accurately captured, the optimization process will fail to identify the optimum region.

Liu and Chang (1998) used Neural Network with a backpropagation algorithm to predict depowered air bag mass flow rate. The network had an input layer with four nodes consisting of occupant responses, two hidden layers each with eight nodes, and an output layer with 20 nodes, which represented the mass flow rate data. Nevertheless, they did not investigate how the number of neurons and hidden layers, transfer functions, and training algorithms could affect the prediction power of their network. Lee (2005) used Kriging interpolation (Giunta and Watson, 1998) followed by a global optimization method to optimize air bag and load limiter parameters. However, using Kriging might result in failing to locate the most favorable restraint design parameters because 1) the crash simulation results are expected to be not only non-linear but also noisy (Druecker, 2011) and 2) since a Kriging model passes through all sampling points, it is bound to overfitting.

Lee and Kim (2009) used multibody simulations, Neural Network with a bipolar sigmoid function, and a genetic algorithm to optimize four restraint parameters. They trained their Neural Network with simulation results and used testing data sets to adjust the number of hidden layers and the number of neurons of the hidden layers. However, they did not show how the performance of network could change by changing the transfer function or whether better fits could be achieved using other regression techniques. To compare the restraint design optimization results with and without unbelted safety requirements, Hu et al. (2017a) performed parametric simulations and developed response surface models based on a radial basis function (Hardy, 1971). They stated that the surrogate models could not accurately predict the occupant's risk of injury at the optimal design and had to perform more simulations in that predicted optimal region. While radial basis function could easily over-fit the data if too many free parameters are used (Orr, 1995), the study did not provide any detail about how the model was tuned. Also, the study did not investigate whether other regression techniques could outperform radial basis functions.

There are plenty of machine learning techniques that could potentially be predictive but are applied to restraint design application. Among the goals of this dissertation were to demonstrate in detail how machine learning techniques can be leveraged for restraint system optimization and how they should be tuned to accurately capture the shape of the response surface. Also, for the first time, this dissertation aimed to compare the ability of Ordinary Least Squares (OLS), Least Absolute Shrinkage and Selection Operator (LASSO), Neural Network (NN), Regression Forest (RF), Support Vector Regression (SVR), and an ensemble model, which combines LASSO, NN, RF, and SVR into one predictive model, in predicting the results of restraint design parametric simulations.

1.1.3. Safety of occupants with obesity in MVCs

Obesity has become an epidemic in the United States. Between the periods of 1988-1989 and 2003-2004, the mean waist circumference of US adults increased continuously (Li et al., 2007). In 2011-2012, 34.9 % and 14.5 % of the US adult population were reported to be obese (BMI≥30 kg/m^2) and severely obese (BMI≥35 kg/m^2), respectively (Ogden et al., 2014). Similarly, the prevalence of obesity has been increasing worldwide. A study on 19.2 million adults from 186 countries showed that the proportion of obese males (females) increased from 3.2 % (6.4%) in 1954 to 10.8 % (14.9 %) in 2014 (Collaboration, 2016).

Obesity is associated with an increased risk of fatality in MVCs. Viano et al. (2008) studied the risk of fatality for front-seat occupants in MVCs using the Crashworthiness Data System (CDS) of National Automotive Sampling System (NASS) and found out that for a given stature, the occupants with BMI of 30-35 kg/m^2 are 97 % more likely to die in MVCs than the occupants with BMI of 18-25 kg/m^2. Similarly, Zhu et al. (2006) found out that the risk of death due to MVCs increases at both ends of BMI (BMI<20 kg/m^2 and BMI≥35 kg/m^2) among men. Mock et al. (2002) observed an increased risk of death in MVCs with increased weight, and reported the odds ratio for death to be 1.013 for each kilogram increase in body weight.

Obesity also increases the risk of injury in MVCs. Viano et al. (2008) reported occupants with BMI of 30-35 kg/m^2 to have 17 % higher risk of MAIS 3+ injury than normal BMI occupants. After adjusting for the crash speed, Ma et al. (2011) showed that the male drivers with obesity have an increased risk of non-fatal injury compared to other male drivers. They also showed that this risk increases with the severity of injury. Mock et al. (2002) determined an odds ratio of 1.008 for sustaining an injury with Injury Severity Score ≥ 9 for each kilogram increase in body mass. Finkelstein et al. (2007) found that the occupants with normal BMI (20 kg/m^2 ≤BMI < 25 kg/m^2) have the lowest risk of sustaining an injury in MVCs amongst all BMI categories. On the other hand, Class I and Class III obesity were at the highest risk of injury in MVCs (odds ratio of 1.24 with respect to the normal BMI occupants).

To shed light on the injury mechanism and potential reasons for such observations, Forman et al. (2009) performed experimental frontal impact sled tests with obese and non-obese PMHS. It was observed that the obese PMHS tended to experience a larger lower extremity forward motion compared to non-obese. In addition, despite the non-obese PMHS, the torso angle of obese PMHS did not pitch forward which created an undesired posture for airbag deployment. Also, the obese PMHS tended to submarine, defined as the lap belt moving up over the pelvis into the abdomen. Besides that, a volunteer study showed that the occupants with obesity tend to don their lap belt higher and upper, with respect to the pelvis, compared to other occupants (Reed et al., 2012). Such behavior would also increase the risk of submarining (Kim et al., 2015).

The kinematic differences observed in Forman et al. (2009) could be attributed to three main reasons. First, most of the kinetic energy has to be absorbed by the work (work-energy theorem) that the seat belt does on the occupant to constrain him/her. The obese PMHS had a bigger body mass and consequently larger kinetic energy than the non-obese PMHS. Hence, with the same amount of seat belt force (controlled by the load limiter), a larger displacement was required to achieve a larger work (work = force × displacement). That is a reason why the obese PMHS stopped moving relative to the vehicle after a larger displacement than the non-obese PMHS. Second, the lap belt force was initially spent on the deformation of the obese PMHS' thick adipose tissue, which resulted in the delayed engagement of the belt with the bony structure of the pelvis. This caused the torso to begin pitching forward too late, which resulted in lower overall torso angle change. The delayed engagement and soft tissue deformation also contributed to the PMHS' large forward motion. Third, lap belt loading to the adipose tissue surrounding the pelvis resulted in a high compressive load and high shear deformation of the adipose tissue. The shear deformation allowed the lap belt to move upward and over the pelvis resulting in submarining (Gepner et al., 2018, Joodaki et al., 2015, Kent et al., 2010, Forman et al., 2009).

These studies implied that current restraint systems are not as effective for occupants with obesity as they are for normal BMI occupants. Also, since the two main design targets for assessment of vehicle safety performance are a 50th percentile male (height=175 cm, BMI=25) and 5th percentile female (height=152 cm, BMI=21) anthropometric test devices (ATDs), the restraint systems are often designed to maximize the safety for those specific ATDs (Hu et al., 2017c). With that in mind, a question that should be asked is whether the optimal restraint system designed for those ATDs is also optimal for other anthropometries. While this research question is investigated for a few other anthropometries, including a 95th percentile male ATD (height=188 cm, BMI=28, e.g. Iyota and Ishikawa (2003)), restraint system optimization for an obese anthropometry is yet to be studied. The restraint system optimization framework developed in this study was used to address this major public health issue. Hence, among the goals of this dissertation were to investigate whether an optimized restraint system for an occupant with obesity would be different than that for a midsize occupant, and how the restraint system should be modified to increase the safety of occupants with obesity.

1.1.4. Obese HBMs

To better understand details associated with injury risks of occupants with obesity in vehicle crashes, and to begin to address these risks through restraint system or other countermeasure designs, it is necessary to have biofidelic surrogates which can replicate the response of occupants with obesity in MVCs. To address this need, some obese HBMs have been developed by morphing the external body contour and exterior skeleton geometry of baseline (midsize male) HBMs. Such obese versions of the Total Human Model for Safety (THUMS) were evaluated in detail through previous studies (Shi et al., 2015, Zhang et al., 2017, Kitagawa et al., 2017). Additionally, Hu et al. (2016) performed a similar methodology to develop obese versions of the Global Human Body Modeling Consortium (GHBMC) M50-O model by adjusting BMI, height, and age. In this dissertation, an obese HBM, which was developed by morphing the detailed GHBMC midsize model, was evaluated and then used for restraint system optimization.

1.1.5. Background summary

In what follows, the summary of background and motivation for this dissertation is provided.

1- Restraint system optimization through the iterative process of guessing a solution, running a simulation with that guessed solution, and assessing the appropriateness of the guessed solution is computationally expensive.

2- Machine learning has been used in the field in a limited way. However, no study in the passive safety field optimized the model hyperparameters to improve the fit.

3- In the current study, machine learning was used to develop a restraint system optimization framework, which includes running a tractable number of simulations with the following steps

    a. Running parametric simulations with at least ten simulations per restraint parameter (Peduzzi et al., 1995)

b. Using machine learning to mathematically model the relationships between the simulation inputs (restraint parameters) and outputs (occupant's responses) in a continuous space, while under-fitting and over-fitting is avoided through hyperparameter optimization
c. Applying a genetic algorithm to the mathematical models from the previous step to find the optimized design

4- Obesity, which is an epidemic, is associated with an increased risk of injury and fatality in motor vehicle collisions.

5- The results of some studies in the literature implied that the current restraint systems might not be as effective for occupants with obesity as they are for normal BMI occupants.

6- Some obese HBMs are developed, which can be used for restraint system optimization for obese.

7- In the current study, the suggested restraint system optimization framework was utilized to design an optimized restraint system for an occupant with obesity, using a state-of-the-art obese HBM.

1.2. Goals and Aims

Considering the gaps in the literature described in the previous section, the goals of this dissertation were as follows.

1- To develop a robust framework for restraint system optimization, which allows for running the vast majority of required FE simulations in parallel, tuning a relatively high number of optimization parameters, and searching over the whole optimization domain using advanced machine learning techniques
2- To compare the capabilities of multiple machine learning techniques for predicting the results of occupant safety FE simulations under different loading conditions
3- To investigate the effect of BMI on the risk of injury to different body regions, and to determine the most frequent injuries of occupants with obesity through field data analysis
4- To identify restraint strategies that optimize safety for occupants with obesity
5- To determine whether an optimized restraint system for an obese anthropometry would be different than that for a non-obese anthropometry

The hypothesis was that the design parameters of an optimized restraint system for an occupant with obesity and those for a non-obese occupant would not be identical.

1.3. Tasks Overview and Appended Papers

This dissertation consists of five tasks (Figure 1):

- Task 1: Field Data Analysis
- Task 2: Human Body Model (HBM) Evaluation and Model Set-up
- Task 3: Parametric Simulations and Statistical Analysis
- Tasks 4: Metamodel Development
- Task 5: Restraint System Optimization

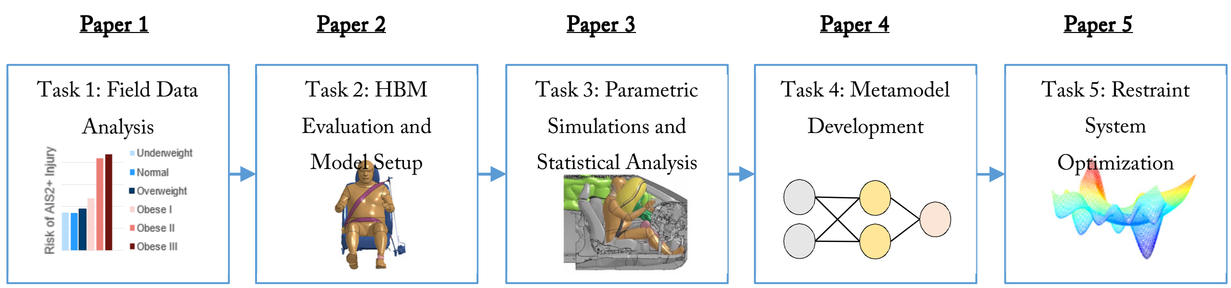

Figure 1: Tasks overview

The methodology and results of each task are written in the form of independent papers, which are appended to this document. In what follows, these papers are listed and their relevance is described.

<u>Paper 1</u>

Joodaki, H., Gepner, B., McMurry, T. and Kerrigan, J., 2019. Comparison of injuries of belted occupants among different BMI categories in frontal crashes. International journal of obesity, pp.1-11.

Relevance: This paper included the details of Task 1 (field data analysis). To investigate the strategies for increased safety of occupants with obesity, it was necessary to investigate what happens for them in the real-world car crashes. Any attempt to improve restraints for the obese population should incorporate the ability to predict injury risks of the frequently injured body regions of occupants with obesity. This paper determined the risk of injury to different body regions for different BMI categories, the most frequent injuries of occupants with obesity, and the mechanism of those frequently observed injuries.

<u>**Paper 2**</u>

Joodaki, H., Gepner, B., Katagiri, M., and Kerrigan, J., 2020. Evaluation of behavior of an obese human body model in frontal sled tests. International Journal of Crashworthiness. Submitted January 2020. Under Review.

Relevance: This paper included the details of Task 2 (HBM evaluation and model set-up). Prior to using an obese HBM for restraint system optimization, it was necessary to evaluate the obese HBM and ensure that it could accurately represent obese occupant kinematics and injury risks in frontal crashes. The main goal of this paper was to evaluate the behavior of the obese HBM by comparing its response to an obese PMHS in matched rear-seat frontal sled tests.

<u>**Paper 3:**</u>

Joodaki, H., Gepner, B., Katagiri, M., and Kerrigan, J., 2020. The effects of restraint parameters on the response of an occupant with obesity: A simulation study. Ready for submission.

Relevance: This paper included the details of Task 3 (parametric simulations). It described the methodology and results of restraint design parametric simulations with obese and non-obese HBMs, which were later used for training metamodels and restraint system optimization. Additionally, this paper included in-depth statistical and biomechanical analyses on the effects of different restraint parameters on the occupants' responses.

<u>**Paper 4:**</u>

Joodaki, H., Gepner, B., and Kerrigan, J., 2020. Leveraging machine learning for predicting human body model response in restraint design. Computer Methods in Biomechanics and Biomedical Engineering. Submitted February 2020. Under review.

Relevance: This paper included the details of Task 4 (metamodel development). It demonstrated the methodology for using machine learning techniques to develop metamodels of parametric simulation results, which were later (in Task 5) used for restraint system optimization.

Paper 5:

Joodaki, H., Gepner, B., Lee, S., Katagiri, M., Kim, T., and Kerrigan, J., 2020. Is optimized restraint system for an occupant with obesity different than that for a normal BMI occupant? Ready for submission.

Relevance: This paper included the details of Task 5 (restraint system optimization). In this paper, the metamodels, which were developed in Task 4, were used to optimize the restraint system for the HBMs with obese and non-obese anthropometry. The primary objective of the paper was to investigate whether the optimized restraint system for an occupant with obesity would be different than that for a normal BMI occupant. This paper also provided design recommendations for increased safety of occupants with obesity.

Chapter 2

Field Data Analysis

2. TASK1: FIELD DATA ANALYSIS

The details of this task are provided in Appendix A (Paper 1). In what follows, the goal, methods, results, and conclusions are briefly discussed.

2.1. Relevance and Goal

The goal of this task was to determine the risk of injury to different body regions amongst different BMI categories, the most frequent injuries of occupants with obesity, and potential injury mechanisms of those injuries. The results of this effort were used later in this dissertation to ensure that the approach to injury risk calculations included the injuries most frequently observed to occupants with obesity, and to ensure that the restraint parameters and countermeasures used could have an effect on these injuries.

2.2. Methods

Vehicle crash cases (n = 13,470) representing ~4.7 million adult occupants involved in frontal crashes (between 2000 and 2015) were selected from the U.S. NASS—CDS database. A retrospective cohort study was performed to study the effect of BMI on the risk of injury to different body regions and to identify the most frequent injuries to occupants with different BMIs. In addition, in-depth crash analysis cases from the U.S. Crash Injury Research and Engineering Network (CIREN) database were studied to elucidate the source of the most common injuries to occupants with obesity.

2.3. Results

- Occupants with obesity experienced a higher risk of upper extremity, lower extremity, and spine injuries than normal BMI occupants.
- After adjusting for other variables, the risks of spinal, thoracic, and extremities injuries were found to be affected by the BMI class.
- Seven out of the ten most common injuries sustained by occupants with obesity were lower extremity injuries, and talus fractures were the most common overall.
- Direct loading through the plantar surface of the foot by the vehicle toe pan was found to be a likely cause of many of those injuries based on CIREN cases.

2.4. Conclusions

- The risk of injury to each body region and the most frequent injuries sustained by occupants with obesity are different than those of normal BMI occupants, which can be attributed to differences in interaction with the seat belt and vehicle interior for both occupant types.
- The increased risk of injury observed for occupants with obesity compared to normal BMI occupants actually arises from their increased risk of injury to the extremities and spine. Their increased risk of injury to the extremities may possibly be the result of their large forward motion during the crash due to increased body mass, which results in increased kinetic energy, and thick adipose tissue, which results in delayed engagement of the lap belt with the bony structure of the pelvis. The increased body mass and delayed lap belt engagement also cause a decreased torso

rotation and consequently, increased compression force to the spine, which would increase the risk of spinal injuries.

- It is speculated that the key to increasing the safety for occupants with obesity is to mitigate their lower extremity excursion, which would not only decrease the risk of having an injurious impact with the vehicle interior but also force the occupant's torso to pitch forward, which would result in a more favorable posture for air bag deployment and decreased risk of spinal injuries.
- Any attempt to improve restraints for the population with obesity should incorporate the ability to predict the risk of injury to the extremities and spine, and should include restraint parameters that can address risks of injuries to both of those regions.
- HBMs used to investigate injury risk for occupants with obesity should be instrumented properly to make it possible to determine the risk of injuries, which were frequently observed in the field data.

Chapter 3

Model Evaluation and Simulation Set-up

3. TASK2: HBM EVALUATION AND SIMULATION SET-UP

The details of this task are provided in Appendix B (paper 2). In what follows, the goals, methods, results, and conclusions of this task are briefly discussed.

3.1. Relevance and Goal

Since this dissertation aimed to use an HBM to predict injury in simulations designed to optimize the restraint system for an occupant with obesity, it was necessary to identify an appropriate HBM to serve the goals of this study. Thus, the objectives of this task were as follows:

- To determine whether an available obese HBM can be a suitable tool for designing a restraint system optimized for an occupant with obese anthropometry in the driver-seat. To achieve this, the response of the HBM was compared to PMHS test results from the literature.
- To prepare the frontal impact driver-seat simulation environment necessary for restraint design parametric simulations, which are discussed in Task 3.

3.2. Methods

3.2.1. Obese HBM evaluation

The first subtask of Task 2 was performance evaluation of an obese HBM. A family of obese HBMs with various heights and BMIs were previously developed by morphing a detailed midsize male HBM of the Global Human Body Models Consortium (GHBMC, M50-O v4.4) to statistically-representative obese body shapes (Hu et al., 2016).

Rear-seat tests: The results of 29 km/h and 48 km/h rear-seat sled tests with an obese (BMI=35 kg/m^2, stature=189 cm) PMHS were used to evaluate the performance of one (BMI=35 kg/m^2, stature=188 cm) of the obese HBMs in replicate frontal sled test simulations. To provide correct boundary conditions, a FE model of the actual sled buck used in the PMHS tests were developed, validated, and used in the simulations (Figure 2-a).

Front-seat tests: The response of a midsize non-obese HBM (BMI=25 kg/m^2, stature=175 cm) and one of the obese HBMs (BMI=35 kg/m^2, stature=175 cm) were compared in a front-seat 56 km/h frontal impact test.

3.2.2. Model set up

The second subtask of Task 2 was to prepare the simulation environment for front-seat parametric simulations, which are discussed in Task 3. First, a simplified sled was generated from a Toyota Camry FE model. The simplified model included seat structure, steering wheel, collapsible steering column, instrumentation panel, center console, floor, pedals, A-pillar, B-pillar, and driver-side door. A driver air bag (DAB) equipped with an adaptive vent and two types of knee air bags (KAB, low-mount and mid-mount) were added to the sled model. An obese (stature = 175 cm, BMI 35 kg/m^2) HBM and a midsize non-obese (stature = 175 cm, BMI 25 kg/m^2) HBM were positioned in the simplified sled. Pre-simulations were performed to position them with similar head angle, torso angle, femur angle, and tibia angle. Virtual sensors were added to both HBMs to measure the risk of injury to different body regions. Proper instrumentation for predicting the most frequent injuries, as identified in Task 1, were included. Two types of seat belts, a regular seat belt and inflatable seat belt (ISB), were routed on each HBM. Finally, an average pulse, which was determined from US-NCAP 56 km/h frontal rigid-barrier tests with full-sized vehicles, was implemented into the sled (Figure 2-b).

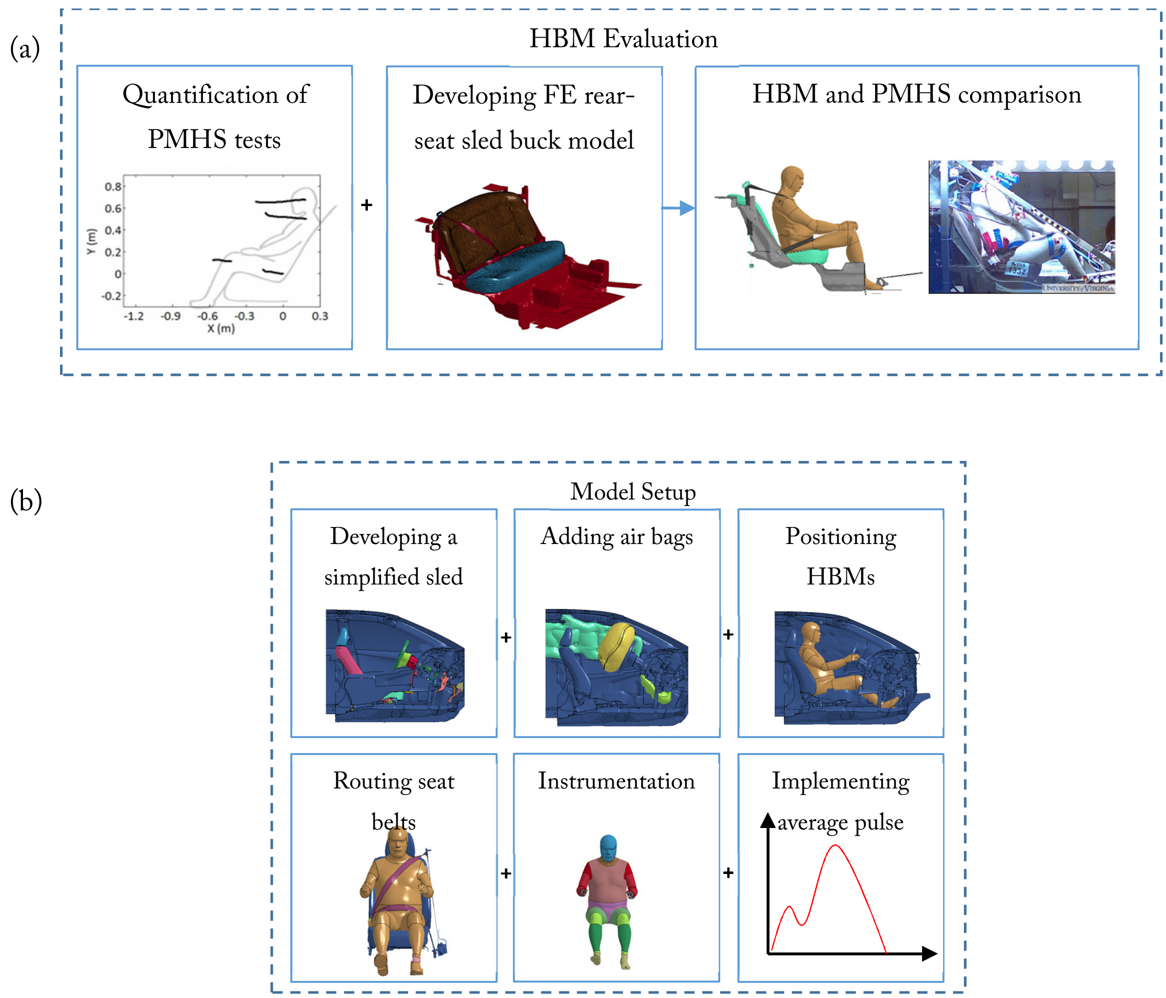

Figure 2: HBM evaluation (top) and model setup (bottom)

3.3. Results

In the rear-seat tests both the obese HBM and the obese PMHS experienced a large forward excursion, delayed lap belt engagement with the pelvis, and maintained a reclined-to-upright torso angle throughout the tests. The PMHS demonstrated a submarining behavior in the 48 km/h test, starting when the hip traveled 18 cm, which was a consequence of the lap belt first loading the pelvis through the surrounding flesh and then sliding up over the pelvis into the abdomen as the pelvis translated downward compressing the seat. The HBM did not show a similar behavior, possibly due to a high stiffness of the flesh under shear loading (Figure 3).

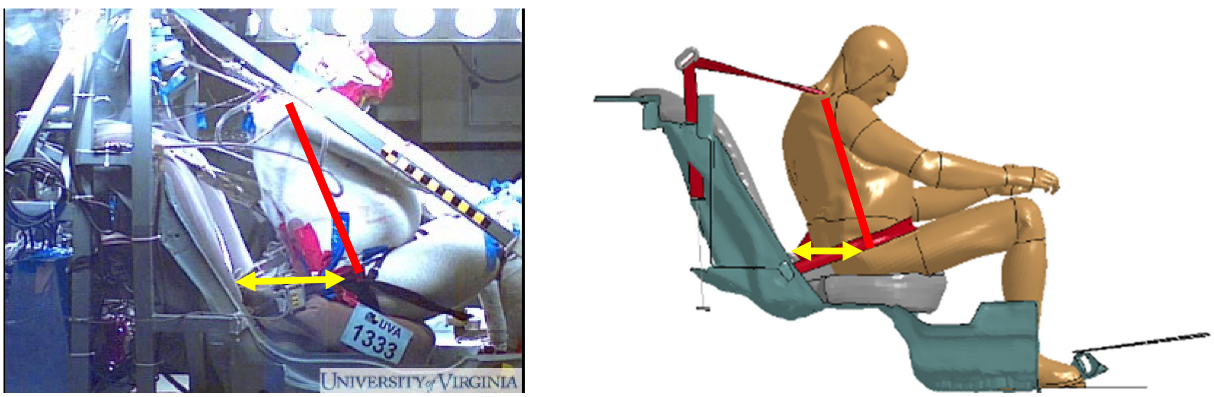

Figure 3: Comparison of behaviors of obese PMHS and obese HBM in rear-seat tests. Similarly to the obese PMHS, obese HBM experienced a large hip excursion and reclined torso throughout the test.

In the front-seat simulations, the obese HBM experienced a larger lower extremity excursion than the non-obese HBM. Furthermore, both obese and non-obese HBMs' pelvises traveled forward less than 12 cm because of the engagement between the knee and the knee air bag. This forward motion was shorter than the pelvis excursion of the PMHS (18 cm) at the moment that it started to show the submarining behavior in the 48 km/h rear-seat test.

3.4. Conclusions

- The obese HBMs were able to represent the effects of large body mass and delayed lap belt engagement with the pelvis similarly to the obese PMHS. These characteristics are critical for front-seat frontal impact simulations.
- The obese HBMs failed to replicate submarining behavior observed in the high-speed rear-seat PMHS test. Nevertheless, since forward excursion of the front-seat occupants is limited by the vehicle structure or injury countermeasures, submarining is expected to be a less important issue when simulating crashes with the obese HBMs in front-seat.
- Therefore, the obese HBMs can be useful tools to design and optimize restraint system for drivers with obesity.

Chapter 4

Parametric Simulations

4. TASK3: Parametric Simulations and Statistical Analysis

The details of this task are provided in Appendix C (paper 3). In what follows, the goals, methods, results, and conclusions of this task are briefly discussed.

4.1. Relevance and Goal

Once the simulation environment had been constructed and the HBMs had been evaluated for suitability (Task 2), the next step was to begin simulating frontal crashes with the HBMs to identify trends and examine the effects of various restraint components that could be incorporated in the optimization part. Thus, the objective of this task was to perform parametric simulations to determine and compare the effect of different restraint parameters on the response of obese and non-obese HBMs through statistical and biomechanical analyses. These simulations were also used to train metamodels (Task 4), which were later utilized for restraint system optimization (Task 5).

4.2. Methods

Fourteen different restraint parameters along with the HBM type (obese vs non-obese) were selected as the simulation variables. The lower-bound and upper-bound of each variable were specified. The Latin

Hypercube technique was used to sample 450 simulations in this 15-dimensional design domain. Then, the parametric simulations were performed and the results of the parametric simulations were extracted and used to determine excursion (kinematics) of, and risk of injury to, different body regions. This information along with the NASS-CDS field data (Task 1) were used to calculate Life Years Lost (LYL, (Kim et al., 2019, Bollapragada, 2019)). Multivariate regression analyses were performed to determine and compare the effects of different restraint parameters on the responses of obese and non-obese HBMs. Finally, the biomechanical reasons of the findings were discussed in detail (Figure 4).

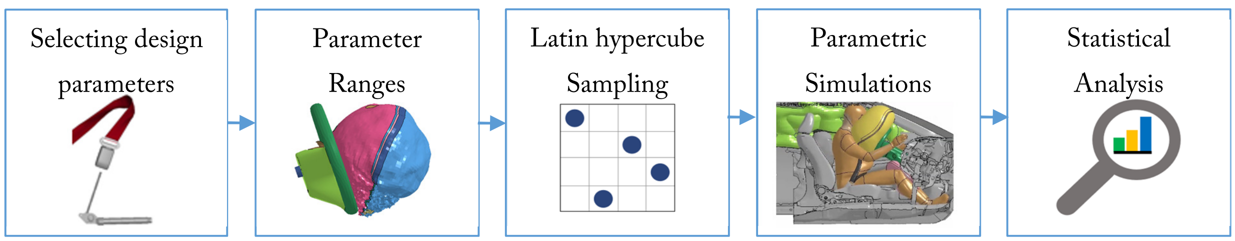

Figure 4: Flow-chart of the Task 3

4.3. Results

The obese HBM experienced significantly greater lower extremity excursion, and injury metric values for chest, neck, lumbar spine, femur, patella, and tibia than the non-obese HBM. For both occupants, increasing the seat belt load limiter level resulted in increased head, neck, and chest injury metrics. Also, the ISB decreased the HBMs' excursion, and chest and neck injury metrics. The USAB and mid-mount KAB decreased lower extremity excursion, and the USAB mitigated the obese HBM's femur, patella, and tibia injury metrics. The USAB increased the non-obese HBM's neck and lumbar spine injury metrics.

4.4. Conclusions

- The HBMs were capable of representing some key biomechanical differences between occupants with and without obesity.

- The general strategies typically used to improve safety of non-obese occupants were not found to have any compelling counter-effects for the occupant with obesity.
- However, the effect of obesity, which was included as a difference in the HBMs, resulted in a difference in the value of injury metrics across a range of parameters.
- The findings suggested that solutions should be focused on arresting lower extremity excursion to decrease the lower extremity injuries for the obese HBM, which confirmed the hypothesis in Task 1 that the key for increasing the safety of occupants with obesity is to mitigate their lower extremity excursion. For example, the USAB was found to be capable of reducing both the lower extremity excursion and injury metric values and thus, it might be a useful tool to improve the safety of occupants with obesity. Also, the ISB was found to be an effective countermeasure to decrease the occupant's chest and neck injuries.
- For several restraint parameters, manipulation was found to decrease the risk of injury to a body region but increase the risk to another region. Hence, a comprehensive restraint system optimization with a range of anthropometries is necessary to find the most favorable set of restraint parameters.

Chapter 5

Metamodel Development

5. TASK 4: METAMODEL DEVELOPMENT

The details of this task are provided in Appendix D (paper 4). In what follows, the goals, methods, results, and conclusions of this task are briefly discussed.

5.1. Relevance and Goal

Next, it was aimed to use the simulation results from Task 3 to mathematically model the relationships between the simulation inputs and outputs. The mathematical models (metamodels) were intended to mimic the behavior of the system (simulation results) in a continuous space, which would permit exploring the whole design domain (Task 5) with a more manageable computational cost than the traditional optimization approach (iterative process of guessing a solution and running simulation with the guessed solution). Thus, the objectives of this task were to

1) develop metamodels of the parametric simulation results (from Task 3), which were later used for restraint system optimization (Task 5).
2) demonstrate in detail how machine learning can be leveraged for predicting human body model (HBM) responses to avoid model over-fitting and under-fitting (Figure 5).

3) compare the ability of OLS, LASSO, NN, RF, SVR, and an ensemble model for predicting the results of restraint design parametric simulations.

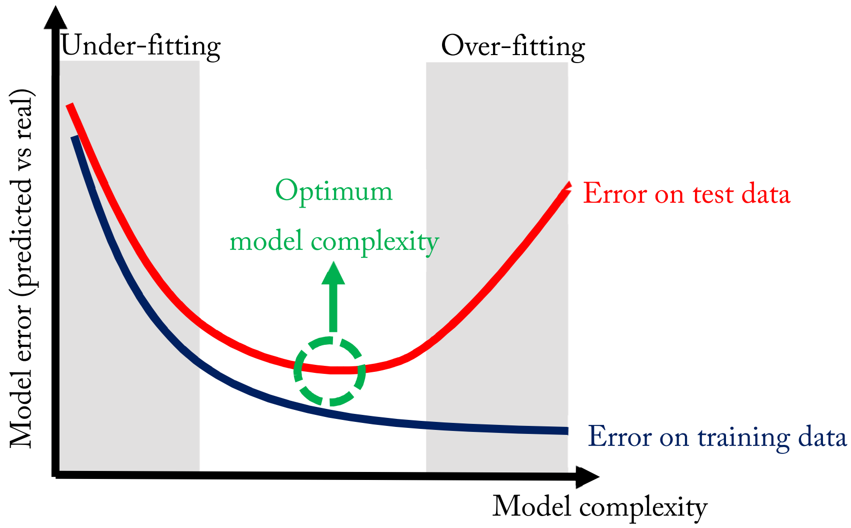

Figure 5: illustration of over-fitting and under-fitting

5.2. Methods

Metamodels for LYL (optimization objective function for Task 5), chest deflection, and head-steering column distance (optimization constraints for Task 5) were developed through a similar process. For each of those dependent variables, the hyperparameters (parameters whose values should be set by user before training) of LASSO, NN, RF, and SVR were optimized using grid search and 10-fold cross-validation to avoid over-fitting and under-fitting. A linear OLS fit and an ensemble model, which combined the optimized LASSO, NN, RF, and SVR models, were also developed. The accuracy of the models, which were developed using different techniques, were compared through Leave-One-Out cross-validation and the model with the highest accuracy was selected to be used for restraint system optimization (Task 5, Figure 6).

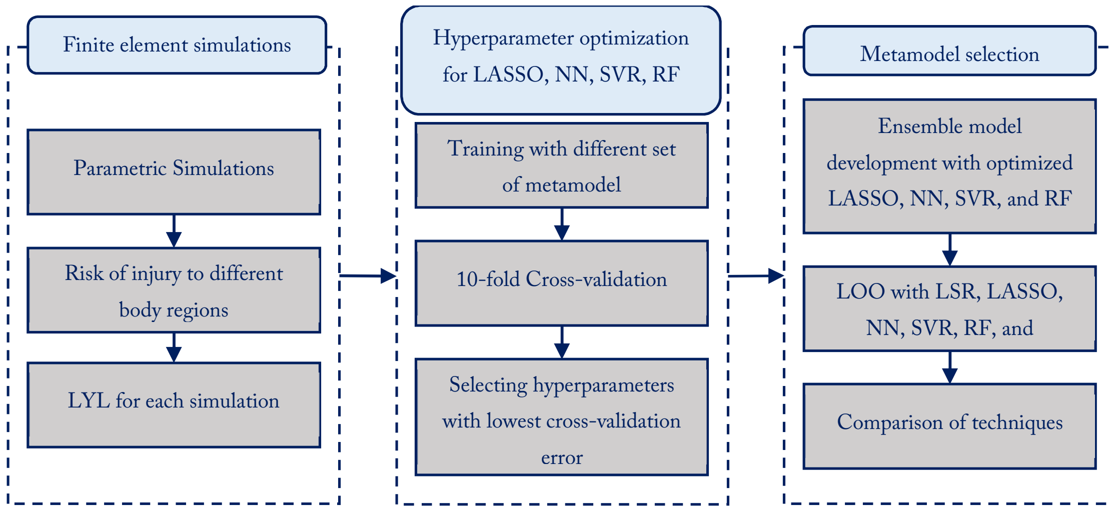

Figure 6: procedural flowchart for metamodel development

5.3. Results

- When the hyperparameters were optimized, the prediction error decreased by up to three times compared to some models with random (not optimized) hyperparameters, which were developed with the same regression technique.
- The shapes of the response surfaces predicted by the metamodels were shown to be dependent on the values of hyperparameters
- The Ensemble method outperformed all other techniques regardless of the dependent variable for which the metamodel was developed (LYL, chest deflection, head-steering column distance).

5.4. Conclusions

- Machine learning techniques showed a higher prediction accuracy compared to linear OLS. In addition, if linear OLS is used for the optimization, the optimization process would converge to the boundary of the design space. Hence, machine learning techniques used in this task are more suitable than the linear OLS for developing metamodels, which would be used for restraint system optimization.

- The goal here was to create metamodels that would be subjected to an optimization algorithm in the next task. Therefore, the metamodels should be able to capture the correlation pattern between the design parameters and the objective function. As the shape of the response surface approximated by the metamodels is dependent on the value of their hyperparameters, optimizing hyperparameters is crucial for the metamodels that are developed for restraint system optimization. Solely selecting some hyperparameters without optimization and then training the metamodel might result in failing to find the actual optimized design.
- Some commercial optimization software packages offer optimization approaches that involve training metamodels, but they do not offer the option to tune hyperparameters prior to training the models automatically. Data from this study suggests that tuning the hyperparameters prior to training the models results in better cross-validation errors across all methods.

Chapter 6

Restraint System Optimization

6. TASK 5: RESTRAINT SYSTEM OPTIMIZATION

The details of this task are provided in Appendix E (paper 5). In what follows, the goals, methods, results, and conclusions of this task are briefly discussed.

6.1. Relevance and Goal

In Task 4, tuned metamodels were developed for the LYL (the optimization objective function, see Task 5 methods), chest deflection (an optimization constraint, see Task 5 methods), and head-steering column displacement (an optimization constraint, see Task 5 methods) using the Ensemble method. Next, it was aimed to use those metamodels to perform restraint system optimization. Thus, the objective of this task was to optimize the restraint system for

1) an HBM with obese anthropometry
2) an HBM with non-obese anthropometry
3) obese and non-obese HBMs concurrently

The research question was whether an optimized restraint system for an occupant with obesity would be different than that for a midsize occupant.

6.2. Methods

Life Years Lost (LYL) was considered as the optimization objective function for the first two optimization cases (optimization for the obese and non-obese HBMs respectively). The objective function in the third case (concurrent optimization) weighted LYL between both occupants equally, but also included a difference term to avoid a solution which is substantially in favor of a single HBM: $\min[LYL_{obese} + LYL_{non-obese} + |LYL_{obese} - LYL_{non-obese}|]$. The NHTSA Injury Assessment Reference Values, as well as head-steering column distance, were considered as the optimization constraints. A genetic algorithm operated on the metamodels of the objective function and constraints (developed in Task 4) to find the optimum design (Figure 7). The functions used for the fitness scaling, selection, initial population creation, crossover, and mutation of this genetic algorithm were rank-based, stochastic uniform, uniform, scattered, and Gaussian, respectively (see Abramson (2004) for details about each of these functions).

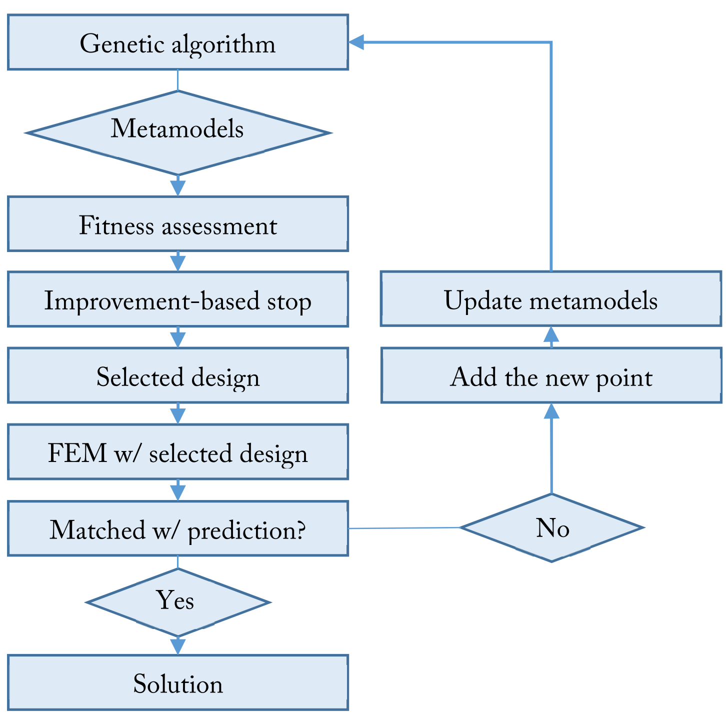

Figure 7: flow-chart of restraint system optimization

An improvement-based iteration stop criterion was used for the genetic algorithm. Once the genetic algorithm stopped the iterations, a full HBM simulation with the selected design parameters was performed and LYL was calculated. If the difference between the calculated LYL from the simulation and the predicted LYL from the metamodel was negligible (<0.1 LYL), the design was accepted as the solution. Otherwise, the simulation with the selected design was added to the point cloud, the metamodels were updated, and the optimization process was repeated.

6.3. Results

In general, while the restraint parameters were similarly distributed between the obese and non-obese HBM simulations, the obese HBM experienced a higher LYL value than the non-obese HBM. The LYL values with the optimized design for obese and non-obese HBMs were lower than the LYL value in any parametric simulation. In other words, the optimization process identified a combination of restraints that was not tried in the parametric simulations and yet, it was more advantageous than any of the combinations, which were tried in the parametric simulations. That suggests that the LYL metamodel developed in this study (Task 4) successfully modeled the response surface of the system and the genetic algorithm found the optimum of that surface. In addition, the injury risks to different body regions were lower with the optimized designs than the average of those injury risks in parametric simulations.

6.3.1. Optimum design for obese vs non-obese HBMs

The optimized value of some parameters was identical between the obese and non-obese HBMs. For both HBMs, a 65 kPa inflatable (vs regular) seat belt with anchor-side (vs buckle-side) pre-tensioner was found to be optimum. Also, the optimum restraint system for both occupants included a 47 kPa DAB with an adaptive vent and a 50 kPa mid-mount KAB.

However, there were some differences in the optimized design parameters between the two HBMs. The optimum load limiters for the obese and non-obese HBMs were constant (1.5 kN) and digressive (1.5 kN followed by 1 kN), respectively. Additionally, the optimum steering column failure levels for obese and non-obese HBMs were 4.6 kN and 5.4 kN, respectively. Also, the optimized restraint for the obese HBM included the USAB positioned close to the front edge of the seat, while the non-obese optimum design did not have the USAB (Table 1).

Table 1: Optimization parameters, their lower and upper bounds, and their optimized value for obese HBM, non-obese HBM, and concurrent optimizations.

	Parameter	Range	Optimized for obese	Optimized for non-obese	Optimized concurrently
1	Air-belt (vs regular belt)	Binary	Air-belt	Air-belt	Air-belt
2	Air-belt pressure (kPa)	65–300	65	65	65
3	Anchor (vs buckle) pre-tensioner	Binary	Anchor	Anchor	Anchor
4	Level of first LL (kN)	1.5–9	1.5	1.5	1.5
5	Digressive (vs constant) LL	Binary	Constant	Digressive	Constant
6	Level of second LL (kN)	1–6	-	1	-
7	DLT (vs regular tongue)	Binary	DLT	DLT	DLT
8	Active vent	Binary	Adaptive	Adaptive	Adaptive
9	Driver air bag pressure (kPa)	3–150	47	47	47
10	Mid-mount (vs low-mount) KAB	Binary	Mid-mount	Mid-mount	Mid-mount
11	KAB pressure (kPa)	50-300	50	50	50
12	USAB (vs no USAB)	Binary	USAB	No USAB	No USAB
13	USAB Position (mm)	-138–0	0	-	-
14	Steering column failure level (kN)	1.5–6.3	4.6	5.4	4.9
	LYL value	Obese_{avg}:5.82* Non-obese_{avg}:5.36*	Obese: 2.90	Non-obese: 2.99	Obese: 3.19 Non-obese: 3.07

*: Mean values from parametric simulations

LL: load limiter; DLT: dynamic locking tongue; KAB: knee air bag; USAB: under-the-seat air bag

USAB Position: fore-aft position of USAB with respect to the front edge of the seat

The air bag pressure lower bounds were the minimum pressure, at which, the air bag model could fully deploy.

A DLT was used in all simulations with the inflatable seat belt.

6.3.2. Concurrent optimization for obese and non-obese HBMs

The restraint system, which was optimized for obese and non-obese HBMs concurrently, included a 65 kPa inflatable seat belt with 1.5 kN constant load limiter, anchor pre-tensioner, 47 kPa adaptive vent DAB, 50 kPa mid-mount KAB, and 4.9 kN collapsible steering column. This restraint system did not include the USAB (Table 1). The LYL value for the obese HBM with this design was higher compared to the non-obese HBM. Further, the LYL values for the obese HBM and the non-obese HBM were higher than they were for the restraint systems optimized for each of the occupants separately.

6.4. Conclusions

- Overall, while the general strategy for restraining both HBMs was similar, the optimization results suggested considering the USAB as an additional countermeasure to better protect the obese HBM.
- The general restraint strategy for both occupants should be using a low load limiter level (e.g. 1.5 kN) to partially absorb the occupant's kinetic energy through a low force applied to the chest and a large displacement (work= force × displacement) and dissipating the remainder of this energy using other restraints including tuned driver air bag and collapsible steering column, which would apply the load to a wide area of the body.
- The optimized restraint for both HBMs included the ISB, as it mitigated the risk of thoracic injury by distributing the force over a wider area compared to the standard seat belt. It also decreased the risk of neck injury by partially covering the neck.
- The optimized restraint for the obese HBM included the USAB, which made the occupant's kinematics more favorable by decreasing the lower extremity excursion and increasing the occupant's tendency to pitch forward, and mitigated its lower extremity and spinal injury risk

predictions. The USAB can be an effective countermeasure for increased safety of occupants with obesity.

- The findings of this study can be used in designing adaptive restraint systems, which are effective for occupants with obesity. It is suggested to add a system to the vehicles, which can measure the occupant's weight using seat sensors, estimate the occupant's height from the seat position, and use this information to determine if the countermeasures, which are effective for occupants with obesity, including the USAB, should be activated during a crash.

Chapter 7

Final Remarks

7. CONCLUDING REMARKS

This section discusses the contributions, fulfilled items, assumptions, and summary of this dissertation. Lastly, future studies that can be carried out to continue this work are listed.

7.1. Contributions

This dissertation made numerous contributions to the field of occupant protection and automotive safety, which are as follows.

- This dissertation contributed the most detailed analysis available of the effect of obesity on the risk of injury to different body regions, and the most frequent injuries and injury mechanism of occupants with obesity.
- This dissertation was the first study that evaluated the response of morphed GHBMC models to an obese anthropometry in frontal impact tests.
- This dissertation investigated how the restraint system parameters affect the kinematics and injury risks of occupants with and without obesity.

- This study was the first to identify countermeasures that could effectively limit forward excursion for occupants with obesity in frontal crashes.
- This dissertation demonstrated in detail how machine learning techniques can be leveraged to mathematically model the response surface of an FE HBM frontal crash injury risk prediction while avoiding over-fitting and under-fitting. More importantly, it demonstrated that optimizing the hyperparameters of those techniques not only increased the prediction accuracy of metamodels, but also affected the predicted response surface shape. Therefore, optimizing hyperparameters are crucial for developing metamodels for restraint system optimization.
- To the author's knowledge, this dissertation was the first in the field of injury biomechanics that used and compared LASSO, NN, RF, SVR, and the ensemble technique for predicting the response of HBMs in parametric simulations.
- This study identified the optimum restraint parameters for a mid-sized male HBM, which were different than the typical restraint parameters currently used in the vehicles.
- This dissertation determined, through cutting edge optimization approach and using the existing technologies, an optimized restraint system for an obese anthropometry. It also investigated whether the optimized restraint system for an obese anthropometry would be different than that for a non-obese anthropometry (Task 5).
- This dissertation determined a restraint system optimized for an obese and non-obese HBMs concurrently, and predicted that design to be more advantageous than a typical restraint system currently used in the vehicles (Task 5).

7.2. Fulfilled Items

The following items were studied/provided by this dissertation work.

- The effect of obesity on the risk of injury to different body regions (Task 1)
- The most frequent injuries of occupants with and without obesity and the potential injury mechanism of the most frequent injuries of occupants with obesity (Task 1)
- Quantified comparison of the response of an obese GHBMC to an obese PMHS, who had a similar height and BMI, in rear-seat frontal impact sled tests (Task 2)
- The effects of restraint system parameters on the obese and non-obese HBM responses, including the HBMs' kinematics and the values of different injury metrics (Task 3)
- Assessment of the prediction ability of multiple advanced machine learning techniques for restraint design parametric simulations (Task 4)
- Demonstrating how machine learning can be leveraged to predict the response of simulations with HBMs to avoid over-fitting and under-fitting (Task 4)
- Comparison of the parameters defining the optimized restraint system for an obese HBM, non-obese HBM, and both HBMs concurrently. It was investigated whether the obese and non-obese anthropometries required different restraint strategies (Task 5).
- Design recommendations to increase the safety of occupants with elevated and normal BMI (Task 5).

7.3. Assumptions

The contributions and accomplishments of this study were made with some assumptions, which are discussed below.

7.3.1. Biofidelity of obese HBM

This study used state-of-the-art HBMs to investigate strategies for increased safety of occupants with obesity. The baseline GHBMC model (mid-size male) has been validated under a variety of impact conditions (Hayes et al., 2014, Yang et al., 2006, DeWit and Cronin, 2012, Li et al., 2010, Shin et al., 2012, Soni and Beillas, 2015, Decker et al., 2017). The obese HBM, which was used in this dissertation, was developed by morphing the external body contour and ribcage of the baseline GHBMC to those of a representative individual with a height of 175 cm and BMI of 35 kg/m^2 (Hu et al., 2016). After comparing the behavior of obese HBM to that of an obese PMHS in frontal impact sled tests, it was concluded that the obese HBM is capable of representing the biomechanical characteristics of a front-seat occupant with obesity in frontal impact collisions.

Three main characteristics were reported to be potentially challenging for designing an effective restraint system for occupants with obesity. First, since they have a bigger body mass, a higher force is required to constrain them for the same amount of excursion. Applying the same load limiter level on a larger mass results in more excursion for occupants with obesity. Second, the delayed engagement of the lap belt with the pelvis causes an occupant with obesity to travel further than an occupant with a thinner abdominal flesh during a crash. Third, the occupants with obesity tend to undergo submarining, especially when there is no barrier to forward motion, which results in decreased protection (Forman et al., 2009). The obese HBM exhibited the first two characteristics but was unable to replicate the submarining behavior seen in the PMHS test. The consequences of submarining are mitigated for a front-seat occupant because the knee bolster/air-bag interaction with the knees tends to limit pelvis forward motion. More discussion on this issue is provided in Appendix B (paper 2). Overall, it was assumed that the available obese HBM possessed sufficient biofidelity to investigate strategies for increased safety of occupants with obesity in the front-seat.

7.3.2. Obesity and seat belt donning

Previous studies have shown that a higher proportion of occupants with obesity fail to don their seat belts compared to other occupants (Lichtenstein et al., 1989). In addition, it has been shown that occupants with large BMI tend to place their lap belt higher and more anterior than normal BMI occupants (Reed et al., 2012). Such behavior would increase the risk of submarining because the lap belt might be initially positioned at the top of or above the anterior iliac spines of the pelvis (Kim et al., 2015). However, in this study the lap belts were routed as low as possible because the goal was to develop a restraint system that can protect the occupants. Failure to fasten the seat belt and/or using the seat belt incorrectly are issues that are beyond the scope of this dissertation and should be addressed in a different way (such as education).

7.3.3. Injury risk functions

It was assumed that the available injury risk functions can be used for occupants with obesity. Nonetheless, most of the injury risk functions available in the field of injury biomechanics, which were used in this study, were developed for mid-sized males. The injury risk curves for obese subjects might be different than those that apply to mid-sized male occupants. Funk et al. (2002), for example, found the subject's mass to be a significant factor in predicting the risk of foot/ankle complex injury and included the mass in the injury risk function formulation. In addition, the bone mineral density of people with obesity might be different than non-obese (Felson et al., 1993), which may affect the bone fracture threshold.

The framework developed in this study can be used in the future when the HBMs are improved and the injury risk functions consider different characteristics of the subjects such as mass, BMI, sex, and age, as well as different injuries. Although the available injury risk functions had some limitations for individuals with obesity, they were still useful tools to develop and assess countermeasures. The statistical and biomechanical analyses on the parametric simulations and the optimized results gave an insight into how to better protect the occupants with obesity.

7.3.4. Optimization objective function

The optimization objective function in this dissertation, namely LYL, was calculated using the available injury risk functions. Although, there might be some specific injuries that are not predicted by the currently available injury risk functions, the injury risk functions used in this study, which were incorporated into the LYL, could capture approximately all of the injuries observed in the field.

The objective function used in this study is believed to be more comprehensive than some other similar studies. For example, Hu et al. (2013) considered head and knee excursions as the two objective functions to find the optimal solutions and then made sure that HIC, Nij, and chest acceleration/deflection were below the injury criteria with the selected design. Hu et al. (2017a) created a single joint probability of injury by combining all four injury risks that are used in the current NCAP test star rating, namely head injury, neck injury, chest injury, and knee/thigh/hip injury, and used the joint probability as the objective function.

7.3.5. Restraint parameters, anthropometries, and crash mode

There were some limitations with the range of restraint parameters specified in the optimization problem. For some design parameters, namely load limiter levels, USAB fore-aft position, and KAB and air-belt pressure, the optimization converged to the lower bounds of those variable ranges. Therefore, if the lower bounds for those parameters were different, the optimized values for those parameters might have been even lower. However, due to physical limitations, the fore-aft position of the USAB could not be more forward than the front edge of the seat. For the air bag pressures, the lower bound was associated with the minimum mass flow rate scale factor, with which, the air bag FE model could fully deploy and thus, it was not possible to go any lower in the simulations. To make sure that the results did not imply that the KAB was unnecessary and that it actually contributed to lowering the LYL value, two simulations with the restraint designs individually optimized for obese and non-obese HBMs but with no KAB were performed. The results confirmed that excluding the KAB from optimized designs increased the LYL value for both HBMs (14 % and 4 % for obese and non-obese HBMs, respectively).

The restraint system was optimized for a single configuration in this study. Since frontal crashes are the most frequent crash mode (Durbin et al., 2015) and to the author's knowledge, the only mode in which, the kinematic and kinetic response of obese PMHS are studied and compared to those of non-obese PMHS, the optimization was performed for the frontal impact mode. Also, the optimization was performed for a sled pulse with delta-v=56 km/h, which is the speed used in US-NCAP frontal rigid barrier test. Additionally, the optimization was fulfilled for only two anthropometries as this study was meant to be a step forward towards improved safety of occupants with obesity and not designing an adaptive restraint system. This framework can be applied beyond this dissertation to design a restraint for a certain vehicle, a variety of crash modes and speeds, a range of occupant anthropometries, ages, and sexes, and different seating positions and orientations.

7.4. Summary

7.4.1. Restraint system optimization framework

This work demonstrated an efficient and practical way to perform restraint system optimization using FE modeling. In a nutshell, three steps should be taken:

1- Performing restraint design parametric simulations

2- Leveraging machine learning for developing metamodels, which capture the relationship between the restraint parameters and the occupant's response, while avoiding under- and over-fitting.

3- Using a genetic algorithm and the metamodels to find the optimum set of restraint parameters

7.4.2. Obesity and motor vehicle collisions

7.4.2.1. Problem

Due to larger body mass and delayed engagement of the lap belt with the bony structure of the pelvis, occupants with obesity tend to experience a larger lower extremity excursion and their torsos have a less tendency to pitch forward compared to the occupants with normal BMI. As a result, they experience a higher risk of injury to the extremities and spine than the occupants with normal BMI.

7.4.2.2. Solution

The key for increasing the safety of occupants with obesity is to mitigate their lower extremity excursion. That way, the risk of an injurious impact between the lower extremity and the vehicle interior would decrease. In addition, by restricting forward excursion of the lower extremities, the occupant's torso would pitch forward and be eased toward the air bag, which would result in decreased compression force in the spine and consequently, decreased risk of spinal injuries. Countermeasures such as the USAB and mid-mount KAB are effective tools to arrest the lower extremity excursion. Therefore, they can be added to the restraint system of the vehicles and get deployed during a crash when the occupant is obese.

7.5. Future Studies

Future studies include the following.

- Deep learning using the whole time history of the simulation results
  - Extracting the HBM response at every single time moment (e.g. 1 ms time step) of the simulation, instead of using a single data point from each simulation, to train the metamodels, which results in increasing the number of training data points drastically (e.g. roughly 100 times) with the expense of adding one more predictor (time)
  - Applying deep learning to this large data set for developing a more predictive metamodel
- Improving the biofidelity of HBMs
  - Performing experimental sled tests with multiple obese PMHS in driver-seat
  - Modification of the HBM flesh formulation and properties as the GHBMC's flesh is currently stiffer than the human adipose tissue (Gepner et al., 2018)
  - Developing subject-specific obese HBMs and performing biofidelity assessment of those obese HBMs by comparing their behaviors to those of obese PMHS in driver-seat sled tests
- Experimental tests with the design recommendations of this study
  - Conducting experimental tests with the design recommendations of this study, including using the USAB for mitigating the lower extremity and spinal injury risks of occupants with obesity
- Using the framework of this study for restraint system optimization for any other
  - Anthropometries

  - Sexes
  - Ages
  - Crash modes and speeds
  - Seating configurations
  - Vehicle
- Safety benefit analysis of the design recommendations of this study
  - Estimating how much injury reduction in the field will be observed if the recommendations of this study are implemented.
  - Example: steps to identify the safety benefits of using the USAB for occupants with obesity in frontal crashes
    - ➢ Extracting frontal impact cases from NASS-CDS
    - ➢ Identifying the significant predictors of injury risks. From Task 1, they included crash speed (delta-v), vehicle type, and occupant's age, sex and BMI.
    - ➢ Running parametric simulations with input parameters identified in the previous step plus the USAB as an additional simulation parameter (similar to Task 3). Other than the USAB, the restraint parameters can be typical of what is currently used in the vehicles (a baseline restraint system). Afterwards, the risk of injury to different body regions in the parametric simulations should be predicted using the available injury risk functions.
    - ➢ Developing metamodels of the results of parametric simulations of the previous step, which can predict the risk of injury to different body regions as a function of simulation inputs (similar to Task 4)

        - Calculating the weighted sum of injury risks of NASS-CDS cases with and without the USAB using metamodels
            - Without the USAB: Determining the weighted sum of injury risks of the cases with leaving the independent variables as they are in the NASS-CDS database, and using the baseline restraint system (no USAB)
            - With the USAB: determining the aforementioned values after assuming that the USAB was activated for all obese cases from NASS-CDS database
        - Comparison of values obtained from the previous step to determine the safety benefits of using the USAB for occupants with obesity
- Designing an adaptive restraint system via the framework used in this dissertation
    - Developing HBMs with a variety of anthropometries
    - Running parametric simulations using those HBMs with a variety of crash characteristics and seating positions (similar to Task 3)
    - Developing a single metamodel for each dependent variable, such as optimization objective function and constraint parameters, which is trained using all parametric simulations with different HBMs and crash configurations. The metamodels should include the anthropometric characteristics, such as height and BMI, and crash characteristics, such as speed and impact direction, as independent variables (predictors, similar to Task 4)
    - Finding optimized restraint system for a variety of anthropometries and crash characteristics (similar to Task 5)

- Leveraging machine learning to develop response surface models of the optimization results, which can output the optimized restraint parameters for any given anthropometry and crash characteristics (similar to Task 4)

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APPENDIX 1: PAPER 1

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APPENDIX 2: PAPER 2

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APPENDIX 3: PAPER 3

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APPENDIX 5: PAPER 5

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