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Objective Seat Comfort Assessment using Finite Element Human Body Model Simulations

Master's thesis in Automotive Engineering and Applied Mechanics

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DEPARTMENT OF MECHANICS AND MARITIME SCIENCES

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Abstract

Finite Element (FE) Human Body Models (HBMs) are used for crash safety assessment but are potential tools for seat comfort assessment. However, it is unclear what parameters from such simulations that predict comfort. In this thesis, potential modifications of a HBM are outlined to make it more suitable for seat comfort assessment. The thesis also proposes an objective method for predicting seat comfort using a HBM and models of car seats.

The fat and muscle material models were updated in a HBM to potentially enable proper modelling of trunk to seat cushion interactions. Then, based on data in relevant literature an objective method for predicting seat comfort was suggested. The displacement ratio for the backrest, defined as the ratio between maximum and average displacement, measured from seat comfort simulations, showed the highest average correlation with subjective comfort scores measured in past volunteer tests. The maximum von Mises stress in the simulated buttocks muscles showed the second highest average correlation with comfort scores. Due to a lack of validation data and multiple error sources in the seat comfort simulations, further research is needed before any significant conclusions can be drawn regarding objective seat comfort prediction.

Keywords: Human Body Model (HBM), seat comfort simulation, finite element method, objective prediction method, muscle material model.

Preface

This is a report on our master thesis project which represents the ending part of our studies at the Chalmers University of Technology. Hemanth has studied the Automotive Engineering master programme and Joshua has studied the Applied Mechanics master's programme, both at the department of Mechanics and Maritime Sciences. The supervisors at Volvo Car Corporation (VCC) for the project were Chella Ganesan Thangam, Seats Senior CAE Engineer at Seat and Safety, and Jonas Östh, Ph.D, First CAE Engineer at Safety. The examiner and supervisor at the Chalmers University of Technology was Johan Davidsson, PhD and Associate Professor at Mechanics and Maritime Sciences, Division of Vehicle Safety.

The thesis work was conducted at the Seat and Safety team at VCC in Torshälla, Gothenburg during the spring of 2022. The allocated amount of time for the thesis project was 20 weeks of working full time. All the simulations were performed on VCCs servers.

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Hemanth Gowda Hanumantha & Joshua Smith

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1 Introduction

When buying a new premium car, one of the growing factors taken into consideration by customers is seat comfort, both while driving and while sitting stationary (Kolic and Taboun, 2004). It is difficult for customers to fully assess the seat comfort in a car before making a purchasing decision. At the same time, it is important in the long run for customers to feel comfortable when sitting in the car. Hence having comfortable car seats is beneficial for automotive original equipment manufacturers (OEMs) in two ways. Firstly, in the way that content customers will be more likely to choose the same car brand for their next potential car purchases. Secondly, by making the car more attractive to customers at car dealerships when seated in the car and during test drives (Na *et al.*, 2005).

1.1 Background

For many years so-called comfort clinics have been a common approach to assessing seat comfort in the automotive OEMs (Kolic, 2008). A seat comfort clinic is carried out by having people volunteer as occupants of the evaluated car seats. The volunteers give their subjective scores in a survey and the automotive OEM can use this information in the design of comfortable seats. This is both time-consuming and costly as there is a need to have an adequately large number of participants for the results to be considered useful. In addition, these tests are being carried out at a late stage in the design process where it is usually more costly to introduce design changes compared to in the earlier stages.

Methods are being developed for using Computer-Aided Engineering (CAE) to objectively predict the comfort of seats in an early stage of the design process before physical prototypes are made available. For example, Siefert *et al.* (2008) demonstrated the potential of virtual seat comfort testing using a Human Body Model (HBM) called CASIMIR. For static conditions, the resulting posture of the HBM and the pressure distribution in the seat model were predicted when gravity was applied. In a follow up paper by Siefert (2016), results from a German national research project called UDASim was used to objectively evaluate discomfort. Here an artificial neural network was used to assess universal discomfort for a car passenger. Multiple HBMs were used to extract different types of objective measurements to be used as input for calculations using the artificial neural network.

Furthermore, Laurent *et al.* (2014) tried to correlate the stresses between the different soft-tissue layers of an HBM to subjective comfort scores from conducted surveys. In particular, they found that seat comfort was closely linked to the inverse variation of stresses at the interface between muscle tissue and femur bone. The development of objective methods to predict seat comfort is in its early stages and there are lots of questions still to be answered. What kind of objective measurements from CAE simulations should be used to objectively predict seat comfort?

In addition to the studies summarized above, which used HBMs for seat comfort analyses, several HBMs are being developed for vehicle safety assessment

(Schmitt *et al.*, 2019). The simulations performed with these HBMs are done, in the same way as for seat comfort, using FE solvers. Synergies between seat comfort development and crash safety development could be achieved if the type of tools developed for safety assessment, i.e., seat models and FE HBMs, could also be used for comfort analysis. At Volvo Car Corporation (VCC), a HBM called SAFER HBM is being used for crash simulations in the FE software LS-DYNA. This model needs to be modified to make it more suitable for comfort simulations.

This thesis is a continuation of previous thesis work at VCC that has been done for seat comfort simulations using HBMs (Ramanjaneya and Avineedi 2017; Karlsson and Öhrskog 2019). In both thesis projects the HBM called Total Human Model for Safety (THUMS), developed by Toyota Motor Company, was made more suitable for seat comfort simulations by modifying the material geometries and the material models in the areas of interest (buttocks and thighs). Both studies also tried to correlate objective measurements from CAE simulations to subjective comfort scores. In the thesis made by Ramanjaneya and Avineedi (2017), the strongest correlation found was between von Mises stress in the gluteus muscles of the buttock and initial cushion comfort scores. In the thesis made by Karlsson and Öhrskog (2019), the strongest correlation to comfort scores was found to be maximum von Mises stress, followed by average von Mises stress in the seat foam in the vicinity of the hip and thigh when the occupant was seated in the seat. Both studies state that further research needs to be carried out to draw any firm conclusions from the obtained results.

1.2 Aim and Tasks

This master thesis main aim was to develop an objective method for predicting seat comfort for the SAFER HBM. To reach this aim two sub aims were identified; to investigate how the SAFER HBM can be modified to be more suited for seat comfort analyses and to identify parameters that correlates with seat comfort scores. The following tasks have been identified to achieve this:

- Understand the current trends in HBMs used for automotive applications and HBMs used in seat simulations.
- For a chosen FE model of a seat, successfully set up and run a non-linear CAE analysis of comfort prediction for SAFER HBM.
- Investigate and implement potential improvements that could be made to the SAFER HBM for better comfort simulation results.
- Validate the simulation results from the updated and improved SAFER HBM with pressure map data from physical testing.
- Identify suitable parameters to be measured from seat comfort simulations and used for correlation with seat comfort scores.

1.3 Outline of Work Performed

The first step was to perform a review of the literature within the field of seat comfort, modelling of seat comfort and HBMs. Previous thesis reports about seat comfort analyses using HBMs were studied closely. The review made it possible to explore the potential method for the project and a planning report was made based on this.

Introduction tutorials were conducted for the FE software LS-DYNA, LS-PrePost, and ANSA. Additional FE software such as META and PRIMER was explored and learned without a specific introduction course. This was done to enable investigations of HBMs in FE software and potential modifications to the SAFER HBM as desired to better suit comfort simulations.

Quasi-static comfort simulations were performed using two different FE crash simulation seat models together with different HBMs. The results from simulations were analysed and used to investigate what changes could be made to the SAFER HBM model within the given time plan. The muscle material model for the SAFER HBM was investigated by running simulations to test the stress-strain relationship of the material. The muscle material model was then modified to better suit comfort simulations. The same procedure was done for the fat material model.

A literature study was made to understand what ways of objectively predicting seat comfort had been explored so far. Based on this, and the available resources for the project, a method for objectively predicting seat comfort was proposed. The measurements from the CAE simulations that were deemed to be of interest for seat comfort analysis were extracted and a correlation study could be performed.

1.4 Delimitations

- The comfort simulations were done using FE crash simulation seat models. These seats remained un-modified, apart from changes to the backrest angle.
- The HBM represents a 50th percentile male and its overall shape and size was not modified to account for the other sex or other anthropometries.
- The comfort simulation analyses consisted of the extraction of stresses, displacements, and pressures in various parts of the simulation setup under quasi-static conditions. Any muscle forces or posture was not taken into consideration.
- Potential anatomical modifications of the HBM consisted of the geometry and the material models of fat, muscle, and skin. More detailed parts such as blood vessels, tendons, etc. were not taken into consideration.

- The comfort simulations in FE software were for static conditions where gravity is the only force acting on the HBM. No thermal or dynamic effects were taken into consideration.

2 Theoretical Framework

In this chapter, the theory regarded as most relevant for the project is presented.

2.1 Finite Element Method

Ottosen and Petersson (1992, p. 1) describe the Finite Element (FE) Method as a numerical approach to solving, in an approximate manner, differential equations that describe physical phenomena. The method consists of dividing the area of interest into finite elements that are all connected through specific rules. The area of interest containing all the elements can be called “finite element mesh”. At the boundaries of each element so-called nodal points are located where the output variable is assumed to be known. In mechanical problems, the output of the calculations is usually the displacement of each node. This physical quantity can be converted into stresses, strains, etc. through constitutive equations and material models. The physical measurements obtained indirectly in this way are computed at so-called integration points (Petersson and Ottosen, 1992, pp. 396-402). Depending on the type of elements used, the number of integration points per element varies and they can be located both on the nodal points and/or in other locations within the element.

2.1.1 Pre-Processing

The first step to solving a problem using the FE method in numerical software is to set up the problem. FE software that solves this task is called pre-processors. These have the capabilities to create the desired geometry, generate a mesh by dividing the geometry into finite elements, assign material properties to the different elements, and specify boundary conditions such as loading, constraints, gravity, etc. Three different pre-processors were used in this thesis:

- ANSA v21.1.4 (BETA CAE Systems, Luzern, Switzerland) for inspecting the FE models.
- Oasys PRIMER for making changes to the FE models and positioning the HBM onto the seat.
- LS-PrePost for general pre-processing and checking certain results in post-processing.

2.1.2 Processing

The main processing software for FE analysis problems is known as the solver. The FE-solver used for this thesis was LS-DYNA version 9 (LST/ANSYS, Livermore, CA, USA) which is a code for multi-physics solutions. It can be used across multiple applications and is commonly used within the automotive industry. It is suitable for linear and non-linear static and dynamic problems.

2.1.3 Post-Processing

To visualize the results from the processor a post-processing software is used. Depending on what results have been requested during pre-processing these can be visualized here using contour plots for instance. Physical measurements can be taken from different locations in the elements by selecting between nodes and integration points. The main post-processor used was META v20.0.1 (BETA CAE Systems, Luzern, Switzerland).

2.2 Human Body Models

Digital Human Body Models are developed for crash simulations, occupant packaging, H-point measurement, etc. But the acronym HBM is referred to only for the crash safety analysis. They can be modified according to the load cases and the type of impact. Some studies indicate using the HBMs results in the best seating comfort analysis (Verver, 2004). Usually, FE HBM's are developed by scanning the Human body through MRI e.g., THUMS , or by taking photographs of a sliced-up human cadaver e.g., HUMOS (T. Serre *et al.* 2006) developed the CAD geometry after reconstructing the image with the help of image processing tools.

There are many HBMs available in the market ex. CASIMIR (Dynamore, 2022), THUMS, MADYMO (Tass international, 2022), GHBM (Schoell, et al., 2015), and most of them are developed for crash analysis. For the crash analysis, all the parts which are more likely to get injured will be having detailed modelling except MADYMO which is of lower detail. But the parts like muscle, fat, and skin which are important for comfort analysis will be lumped together to simplify the models. But the recent developments in the automotive industry, which is moving towards self-driving cars, are focusing on lower injury severities than in the past and hence the HBMs are getting to become very sophisticated. One of the drawbacks of using the most updated HBMs for comfort analysis is the computational cost while another is the lack of tools to set up the simulation. But there are some setup tools for example J-seat designer, which is used to position either a model of a crash test dummy, or an HBM.

2.2.1 THUMS

The Total Human Body model for Safety (THUMS) is a FE HBM which represents the precise shape and durability of the human body. It was jointly developed by Toyota Motor Corporation and Toyota Central R&D Labs in 2000 (Toyota Motor Corporation, 2021). THUMS model can be used for various applications including research and development of occupant safety. The anthropometry of the model is of 50th percentile American male (Schneider *et al.* 1983) in the sitting position which includes anatomical structures of bones, ligaments, internal organs, muscles, fat, and a brain with different material modelling. Major versions of THUMS have been validated in a series of publications. The THUMS v9 model was validated in 2015 (Masami & Hideyuki, 2015) using 35 series of cadaver or volunteer tests on frontal, lateral, and rear impacts.

Before this project, another thesis work (Karlsson & Öhrskog, 2019) was carried out with focus on comfort analysis using CAE-models. They modified and used the last version of THUMS (v9.0.1, see Figure 1); the updated version was named THYMS-LIU. Since THUMS was tuned for crash simulation there were some changes made in the model in order to use this model for comfort analysis. Some major updates were to refine the mesh in several parts. Erector spinae was added between the vertebrae and muscle tissue to get extra support for the backrest. The lumped tissue in the torso was segmented into fat and muscle. Skin thickness was increased from 1 mm to 2.5 mm. A detailed explanation of these changes is provided in section 3.1



Figure 1: THUMS v9.0.1

2.2.2 SAFER HBM V10

The SAFER HBM v10, which is an advancement of the THUMS v3, has features that enable the prediction of pre-crash and in-crash occupant kinematics and injury risk predictions. The model has a muscle package, Angular position Feedback (APF) muscle controller, and Muscle Length Feedback controller. Several partners

at the SAFER Traffic and Vehicle Safety Centre at Chalmers that have developed the SAFER HBM: the main partners have been Chalmers University of Technology, Autoliv Research, and VCC (Jonas *et al.*, 2021). The SAFER HBM v10 with 175 cm height and 77 kg weight, is representing a 50th percentile adult male as shown in Figure 2. The HBM is mainly used for crash analysis, and it has been validated in several studies, most recently by Bengt Pipkorn *et al.*, (2021). It has an active muscle package that can be implemented to control human posture according to the application. SAFER HBM v10 has been updated from THUMS v9 and Some updates which are relevant to comfort assessment are mentioned below:

- Ribcage has been updated with statistical based 50th percentile male shape and with updated cervical and lumbar spines.
- New 50th percentile male pelvis model by Erik Brynskog has been adapted with a 45 deg pelvis angle representative of the male population.
- By replacing the Surface-to-surface contact with one general single surface contact, the number of contacts was reduced to 43 from 160. The new contact covered the axial skeleton, the thoracic and abdominal cavities, and the proximal part of the extremities.
- Since the model has been updated with a single contact from the thorax, thighs, and upper extremities,
- Hexa mesh was implemented for the new continuous torso and upper extremities.
- Updated internal meshes, new lower arms, and legs, etc are some other modifications. A detailed explanation of the updates can be found in (Jonas *et al.*, 2021)



Figure 2: SAFER HBM v10

2.3 Material models

All parts in FE models must be assigned physical properties, e.g., shell element stiffness and beam element stiffness. In the case of human tissues, some of the materials are difficult to model and implement in FE HBMs. The outer layers of the human body, the skin, fat, and muscle tissues, are influencing perceived seat comfort and should be carefully modelled in any seat comfort analyses. All these soft materials are challenging to model in most FE software as they are viscoelastic, nonlinear, anisotropic, and inhomogeneous. In addition, the properties are to some extent unique for every person and the ranges in properties in the population are vast. Muscle properties are also dependent on the amount of exercise and activation level. Skin properties have, in addition to the forth-mentioned properties, been shown to vary significantly with temperature (Xu *et al.*, 2008).

To validate a material model in FE software simulation results are typically compared with experimental data. It is difficult to obtain experimental data for materials in the human body as the materials have different behaviour in vivo (when the human is alive) compared to in vitro (post-mortem). In some cases, experimental data from animals in vitro are used to compare with data from material model simulations. The most important behaviour to study for materials is the stress-strain relationship.

2.3.1 Muscle

The type of muscle modelled in the HBMs for this thesis was skeletal muscles. Morrow *et al.* (2010) concluded that skeletal muscles can be considered to be hyperelastic and transversely isotropic with a significantly higher elastic modulus in the fibre direction compared to the transverse fibre direction. Wheatley *et al.* (2016) showed that the viscoelastic response of skeletal muscle depends significantly on strain level. This was evaluated by comparing the relaxation response of five consecutive load-relaxation cycles. They managed to implement a hyperviscoelastic non-linear muscle material model and achieved a good fit for experimental data.

Skeletal muscles have varying properties depending on the level of muscle activation. For this thesis, only the passive muscle response was included; this simplification was justified by the quasi-static nature of the application. This is, however, a simplification of the seating situation as people usually tense some of their muscles while sitting. There are a few muscle material models available that include active behaviour (Hedenstierna *et al.*, 2008; Khodaei *et al.*, 2013), but these are according to Pelschus and Wagner (2021) currently too complex for use in industrial HBM applications. All the muscle material models used in this thesis were isotropic due to limitations in the existing codes (Pelschus & Wagner, 2021).

The muscle material model implemented in the THUMS-LIU model by Karlsson and Öhrskog (2019) was an LS-DYNA model called Piecewise Linear Plasticity.

This is an elastoplastic material model where one can define arbitrary stress as a function of a strain curve and an arbitrary strain rate dependency (LST, 2021). This was developed by matching the stress-strain curves for different strain rates in the tensile tests of a rabbit tibialis anterior presented by Myers *et al.* (1998).

The muscle material model implemented in both the SAFER HBM and the SAFER HBM modified is a non-linear LS-DYNA model called Ogden rubber. This is a nearly incompressible hyperelastic material model that can account for viscoelastic effects. The strain energy functional for the Ogden rubber model is expressed below where K is the bulk modulus, J is the Jacobian determinant, λ is the principal standard stretch α_j and μ_j are constants (Hedenstierna *et al.*, 2008).

$$W = \sum_{i=1}^3 \sum_{j=1}^n \frac{\mu_j}{\alpha_j} (\lambda_i^{\alpha_j} - 1) + \frac{1}{2} K (J - 1)^2$$

The Cauchy stress for the hyperelastic part was derived from (Ogden, 1973) as

$$\sigma^e = \sum_i \mu_i \left(\lambda^{\alpha_i - 1} - \lambda^{-\left(\frac{1}{2}\right)\alpha_i - 1} \right)$$

The viscoelastic stress component outlined by Christensen (1980) was given as

$$\sigma_{ij}^v = \int_0^t g_{ijkl}(t - \tau) \frac{\partial \sigma_{kl}^E}{\partial \tau} d\tau$$

The term σ_{kl}^E is the instantaneous stress evaluated from the internal energy functional and $g_{ijkl}(t - \tau)$ is the Prony series representing the relaxation function expressed here (LST, 2021):

$$g(t) = \sum_{i=1}^n G_i e^{-\beta_i t}$$

The term G_i represents shear moduli and β_i decay constants. To combine the hyperelastic and viscoelastic behaviour into the Ogden model the stress components are added together creating the constitutive equation

$$\sigma = \sigma^v + \sigma^e$$

The specific muscle model used in the SAFER HBM was developed by Hedenstierna *et al.* (2008) and fitted to the same experimental stress-strain curves by Myers *et al.* (1998) through tensile testing. The fit was not perfect as the material showed a stiffer response compared to the experimental curves.

2.3.2 Fat

In the human body there exists different types of fat. The two main categories of fat are brown adipose tissue (BAT) and white adipose tissue (WAT). The amount of BAT compared to the amount of WAT in human bodies is small (Cinti, 2006) and only WAT has been modelled in the HBMs used in this thesis.

Engelbrektsson (2011) generally describes WAT material as hyperelastic and viscoelastic. Comley and Fleck (2012) made a study showing that WAT also could be considered to be isotropic (same properties in all directions), incompressible and nonlinear in terms of strain stiffening and strain rate stiffening. The incompressible behaviour is problematic to implement in FE software. This problem can be avoided by setting Poisson's ratio to almost 0.5 instead of exactly 0.5 making the material almost incompressible. When approaching 0.5 very small changes in the Poisson's ratio will cause big changes to the stress-strain relationship for compression.

The LS-DYNA fat material model implemented in all three HBMs (SAFER HBM, SAFER HBM modified, and THUMS-LIU) was the same as for the muscle material model, Ogden rubber. The fat material model used in the THUMS-LIU model was developed by Engelbrektsson (2011). This material was only tested and compared to experimental data in tension. The fat material models used in the SAFER HBM and SAFER HBM modified were developed by Naseri (2021). This material was tested and compared to experimental data in both tension and compression. All these fat material models have been developed for car crash scenarios. Considering how complex these material models are, it is likely that they do not behave realistically for load cases that signify differently from intended, quasi-static seat comfort analyses for instance.

2.4 Comfort

2.4.1 Definition

The term "comfort" refers to an individual's state of well-being during an activity (Nicola Cappetti et al., 2021). Webster's Third International Dictionary defines comfort as "a feeling of physical ease or a state of relief and enjoyment." According to the Ergonomics Society (2011), comfort is "the pleasant state or relaxed feeling of a human being in reaction to its environment," whereas discomfort is "the unpleasant state of the human body in reaction to its environment". Several researchers have raised concerns about the nature of comfort and discomfort. Shackel et al. (1969) state that "comfort and discomfort are two opposites on a continuous scale, ranging from extreme discomfort through neutral and extreme comfort," and Hertzberg (1972) states that "comfort is a feeling that lacks discomfort". According to Zhang et al. (1996), "comfort and discomfort are not on the same linear scale but are two distinct entities that are related nonlinearly."

2.4.2 Seat comfort

In recent years globalized market competition among the automobile industries and the customer approach towards automotive comfort are increasing. This leads car manufacturers to design more comfortable and more aesthetic seats for their cars. This has been a challenge because comfort is difficult to predict and analyse. Seat comfort is a short-term effect of the seat on the human body while seating and automotive seats are designed to accommodate human beings of different sizes and should provide both static and dynamic comfort. The most accepted definition of seating comfort was from *Zhang et al.*, (1996) because of the variations shown in terms of comfort and discomfort. According to him, Comfort is associated with feelings, and aesthetics of the surroundings, and discomfort is associated with biomechanical factors. De looze *et al.* (2003) introduced a comfort model which explains the main parameters for comfort/discomfort assessment. This model as seen in Figure 3 shows a relationship between comfort and discomfort.

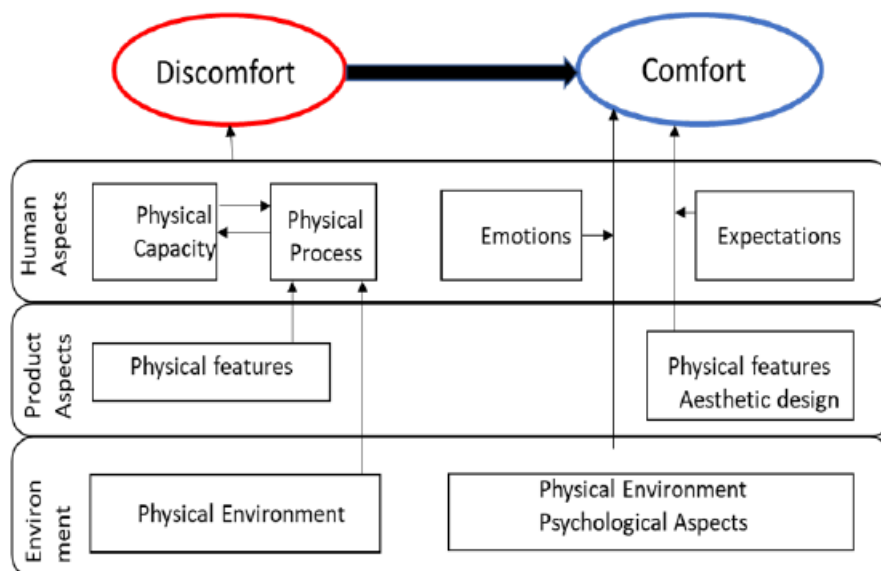


Figure 3: de looze comfort model

Comfort in a passenger car seat can be divided into 2 subcategories:

- Static or Posture comfort – This is the initial comfort that a person feels when he or she sits on a car seat while the car is stationary. It is determined by the sitting position, the seat material, the shape and position of the seat, bolsters, and the backrest.
- Vibrational comfort or dynamic comfort – Driving comfort that is determined by the vehicle chassis, suspension system, vehicle dynamics, and steering system.

2.5 Car Seat Comfort Evaluation

Numerous different car seat comfort measuring methods have been developed so far (Dama *et al.*, 2015). They can be divided into two main categories: subjective comfort measurements and objective comfort measurements. Subjective comfort measurements usually rely on subjective measures from comfort clinics. Objective

comfort measurements are much more varied, especially when it comes to measurements from simulations with FE models. Ideally, measurements from FE simulations can be validated to be accurate through physical measurements.

Pressure distribution on the surface of the seat has been shown to correlate well with subjective comfort scores. Oudenhuijzen *et al.* (2003) made a review on performed seat comfort experiments investigating the relationship between comfort and seat pressure. In combination with their own performed test, they concluded that pressure distribution on the surface of a car seat related directly to comfort. The reason was that they found a difference in comfort for different pressure distributions but not for similar pressure distributions with different pressure values. They also concluded that the fit of the seat was more important for comfort than the seat firmness. With this theory, it would often be the case that firm seats are judged to be less comfortable than soft seats due to the seat's poor fit, not due to the seats increased firmness.

Moving on from pressure distribution, Milivojevich *et al.* (2000) found a good correlation between contact area on the seat surface, including both the cushion and backrest, and subjective comfort scores. Moreover, regarding thigh and the ischial pressures, an optimal seat contact area was defined.

2.5.1 Comfort Clinics

The subjective measurements used in this thesis were seat comfort scores provided by clinics that had been conducted by VCC. The participants for these clinics were chosen to be between the 5th percentile female to the 95th percentile male concerning stature, weight, and body dimensions. Both static and dynamic conditions were tested but as this thesis was not concerned with dynamic seat comfort the static scores, known as initial comfort scores, were used.

The nature of seat comfort scores is very subjective in the sense that it all depends on what the participants are comparing with when asked to give their ratings. Usually, when performing a seat comfort clinic, one of the seats is chosen as the reference seat that the participants can use for their comparison. Consequently, all the comfort scores will be about the reference seat. This means that comfort scores from one seat can only be compared to comfort scores from another seat if the seats are included in the same clinic.

2.5.2 Pressure Mapping

Numerous studies have used pressure mapping/pressure mats for obtaining physical objective measurements of pressure distribution in car seats (Lindberg and Strömberg, 2016; Kyung and Nussbaum, 2008; Dama *et al.*, 2015). By placing a piece of fabric with pressure sensors fitted inside, it has been proven possible to measure the pressure distribution on the surface of a car seat that is in contact with an occupant without significantly influencing the seat properties. These measurements can be used to validate FE HBMs but has proven to be difficult. For example, Lindberg and Strömberg (2016) found that the underlying material

softness affected the absolute levels of pressure measured. They also concluded that the absolute levels of pressure were not always accurate and that the relative pressure distribution was a more reliable result.

2.5.3 FE Simulations

Numerical simulations are indeed recently used in passenger safety studies because they allow the repeatability of the tests without high setup costs as declared in Hayashi and Taylor (2014).

As mentioned in Section 1.1, different measurements have been used from FE HBMs in attempts to find a correlation to comfort. Both Ramanjaneya and Avineedi (2017) and Laurent *et al.* (2014) found a good correlation between comfort and maximum stresses in the muscles under the ischial tuberosities bones. However, these measurements from FE software were not validated using data from physical tests.

The CASIMIR model mentioned in has been used for static comfort simulations also. Lazarov *et al.* (2015) and Siefert *et al.* (2008) used the displacement in the z-direction on the cushion and in the x-direction on the backrest to estimate comfort. The location of the hip joint was also tracked to evaluate comfort through static comfort simulations. These measurements are likely more easily validated through physical measurements compared to localized internal muscle stress.

Since different foam hardness was used for the seats, it was decided to measure the L-index and compare the results between the HBMs. For crash analysis, if that value is greater than 1, then there will be a fracture on the rib and vertebrae. But in our case, since the load is only the gravity it should be somewhere near 0.1. This can be evaluated by comparing different seats and the foam hardness. The measurements have been taken for L1 because of the high ratio among lumbar

3 Methods

In this chapter, the methods chosen for the project are described. The reasoning behind the choices of methods are explained. First, the updates that were introduced to the SAFER HBM are described. Then, several methods on comfort measurements used in the analyses.

3.1 Updates for HBM from V9 to V10

3.1 Transfer of updates from THUMS-LIU to SAFER HBM.

One of the objectives of this project work was to identify the improvements introduced in the THUMS_LIU that can be implemented into the SAFER-HBM. Several of these improvements had already been implemented in the SAFER HBM v10 by (Jonas *et al.*, 2021). The implementations are:

THUMS-LIU model was updated with finer mesh in buttock muscle, buttock fat, thigh muscle, and thigh soft tissue parts that are important for assessing comfort. In order to have a high level of nodal connectivity, node-to-node contact was implemented between the parts. But the SAFER HBM v10 was updated with continuous Hexa-mesh in the torso, neck, upper extremity soft tissues, Pelvis, and thigh soft tissues, similar to THUMS-LIU.

Because all posterior muscle tissue, including the erector spine and gluteus maximus, was lumped together to reduce model complexity, THUMS - LIU was updated with erector spinae. The erector spinae is the second closest muscle to the spine and aids in postural maintenance; by including it in the model, the backrest cushion deformation can be more accurate. But the SAFER HBM v10 has more detailed muscle and fat structures. When the von misses stress of these two models was compared, any modifications to the posterior muscle tissue appeared unnecessary.

THUMS-LIU model was updated with a new skin, fat, and muscle material model. The skin was made of MAT 34 Fabric, fat was made of a converted version of Engelbrektsson material, and muscle was made of MAT 24 material. Material models for both torso and pelvic soft tissues in SAFER HBM v10 are differentiated into a deep muscle layer modelled by Hedenstierna Ogden-muscle material and a subcutaneous fat layer modelled by Naseri fat tissue Ogden-model (stiff formulation). Langer-line data was used to implement skin anisotropy. According to an internal source, the muscle material used in the SAFER HBM v10 was probably too stiff for comfort analysis. Both this material and the fat material were investigated in LS-DYNA by running tension and compression simulations. Following a review, it was determined that muscle material modeling for SAFER HBM v10 should be updated for comfort studies. Section 3.3 contains a more detailed explanation.

3.2 Comfort Simulations

3.2.1 HBM positioning

The SAFER HBM v10 model came with global coordination, and it needed to be positioned in the seat where it should resemble a human in a driving position. Human Body posture is an important aspect of the comfort level and the position of the HBM in the seat was to define the von misses stress and pressure due to weight distribution. The positioning of the model was performed in PRIMER software. SAFER HBM v10 is designed as per the standard sitting position in a car seat from the late 70ies (Schneider et al 1983).

The first step was to simulate the HBM for its change. The body parts like arms, lower legs, and head were manipulated by rotating them with a small change in an angle because extreme positions might cause penetrations and errors later in the simulation. Then the virtual cables will be generated with the help of the script which pulls the model into the desired shape. The first simulation was run only with the HBM to get to the desired posture.

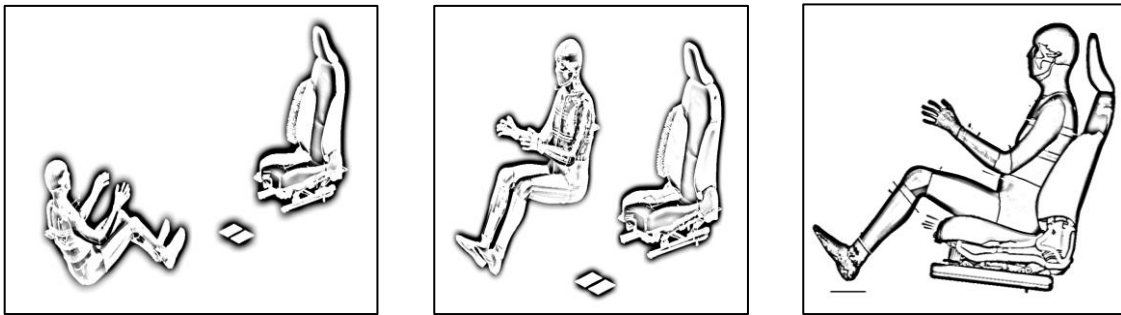


Figure 4: Positioning of the HBM on Seat

The HBM was then loaded into the PRIMER software along with the seat and floor models. Seats used in VCC will have a Seating reference point (SRP), which is also the seat's H-point. The H-point is the theoretical location of the occupant's hip (hip centre) which was used to position the HBM. And the floor position is determined by the car's model and is defined by the Accelerator heel point (AHP). After placing the seat and floor in the desired coordinates, they will be constrained in all the directions. The HBM was placed approximately above the SRP point of the seat. It should be placed as close to the seat as possible, but not in contact with it. The positioning of the HBM can be seen in Figure 4.

3.2.2 Seat Selection

In this project, two seat models, of which one comes from a line of large premium cars, Seat 1 in Figure 5, and one from a mid-sized premium Sports Utility Vehicle (SUV), Seat 2 in Figure 6. These seats were evaluated with four different foam hardnesses, denoted a, b, c, and d, for the cushion, backrest, and bolsters. Where a being the soft foam and d being the hard foam. In total eight seats were included in the analysis of this thesis.

This type of analysis was chosen because of the comfort clinic which was conducted with the same seat with different foam hardness. The seats used are the simple CAE models without massage functions and a heating map which gives extra comfort to the occupant.

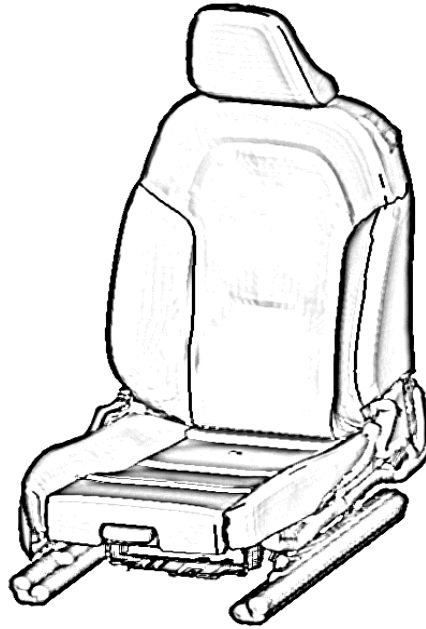


Figure 5: Seat 1



Figure 6: Seat 2

3.2.3 Contacts and Boundary Conditions

Boundary conditions are a set of constraints within the boundary that can be specified by differential equations. The model under consideration has a few constraints. The seat is constrained near the clamping area at the bottom to limit movement in all directions when the HBM falls on it. The same holds true for the floor. Surface-to-surface contact was used between the seat and the HBM, and the same was done between the floor and the HBM. To avoid the overlapping of two contacts, which could affect the results, HBM was removed from the global contact. Global contact is frequently defined as a single surface type contact that includes all of the components that may interact during the crash event.

Because the project's focus was on static comfort, the model only has one force acting on it: gravity loading on the HBM. This gravitational force is converted into a generalized body force that acts on the HBM. When two surfaces make contact, friction becomes an important parameter. The contact between the seat and the HBM has a static friction coefficient (FS) of 0.4 and a dynamic friction coefficient (FD) of 0.4. Before finalizing the value, a few test runs were performed to verify the coefficient of friction and its effect.

Hands were tied in all directions to reduce arm oscillation during the simulation. To prevent unnecessary movements of body parts, global damping was used to reduce the velocity of the HBM. The damping applied to all parts of the model to slow down the simulation process without affecting the results. Total termination time for the HBM was 1900 milliseconds. The HBM was subjected to global damping of 0.0428 from 0 to 600 milliseconds and 0.0627 from 600 to 1200 milliseconds. After 1200 milliseconds, the global damping was lifted, and measurements were taken when the model reached a quasi-static state.

3.2.4 Backrest Angle Sensitivity Study

A sensitivity study was carried out to see the model's behaviour from different angles. Since the torso angle alone is difficult to modify, the simplest way was adapted to rotate the HBM around its pelvis by 10 degrees backward (in x direction), and the legs and arms were rotated by 10 degrees as well. Seat 1 was used in this study and the backrest of the seat was moved 10 degrees backward in x direction. The simulation setup resembles the driver in a relaxing mode which can be used for future work in designing self-driving cars. The changes made in the model can be seen in Figure 7.



Figure 7: SAFER HBM in seat 1 with backrest angle

3.3 Material Model Modifications

An internal investigation was performed to obtain a basic understanding of the different soft tissue materials used in the HBMs such as skin, fat, and muscle. For the THUMS-LIU model, the skin material model was considered verified to be accurate according to Karlsson and Öhrskog (2019). The same anisotropic material was used in the SAFER HBM and therefore the skin material model was not developed further. The fat material model was also considered to be verified and accurate according to Karlsson and Öhrskog (2019), but this material had been changed in the SAFER HBM to one developed by Naseri (2021). After performing an internal investigation of this material with the project supervisor and colleague, it was decided that this material should be changed to Naseri's softer fat material model to better suit seat comfort analyses.

The muscle material used in the SAFER HBM was probably too stiff for comfort analyses according to an internal source at VCC. Both this material and the fat material were investigated in LS-DYNA by running simulations for both tension and compression to see the stress-strain relationship for different strain rates. The simulations were done with a single solid element that was fully integrated, which means it had eight integration points. The stresses and strains were measured at all eight integration points and averaged to generate one value. The boundary conditions at each of the eight nodes are demonstrated in Figure 8.

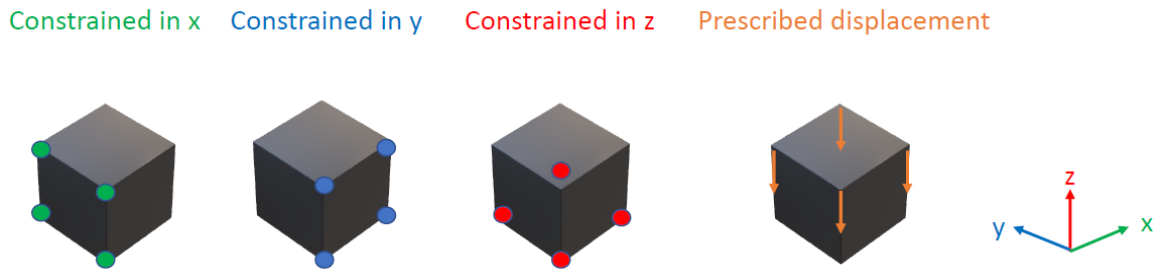


Figure 8: Boundary conditions for single element compression evaluations.

The HBMs were investigated using FE pre-processors to see what materials were assigned to what elements. The areas of interest for quasi-static seat comfort analyses were deemed to be the torso and the upper legs. For these areas the same muscle material and the same fat material was used throughout. This is illustrated in Figure 9 where the fat layer is outermost in brown and the muscle layer is in red. The rest of that parts of the HBMs had slight variations in muscle and fat material but were not regarded as relevant for the project.

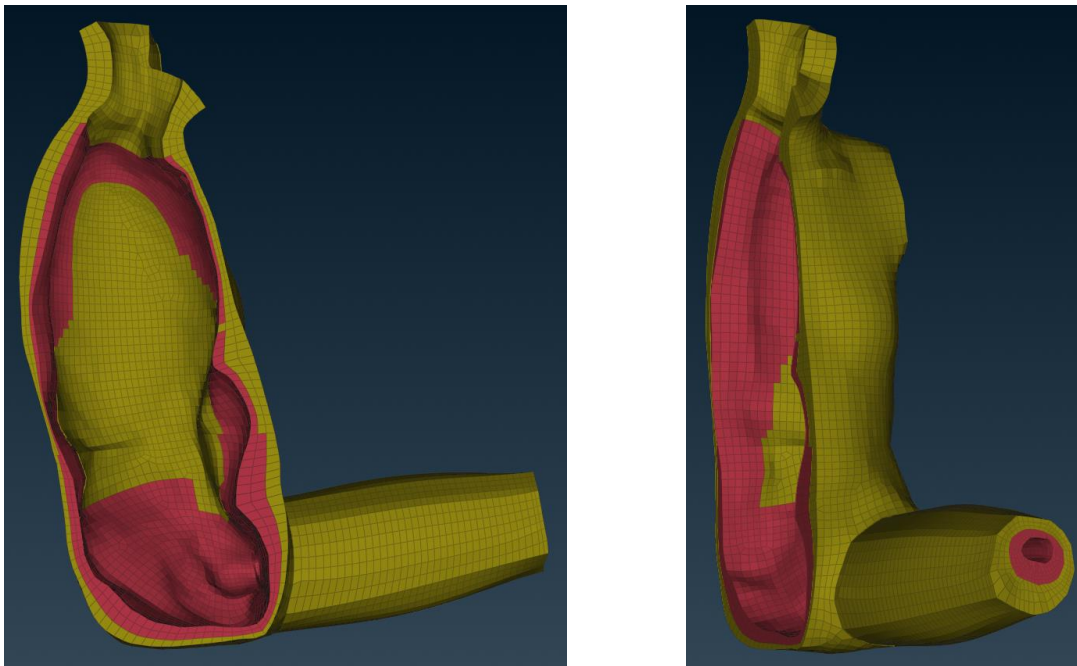


Figure 9: Cross-section of the parts of the muscle and fat material that were changed in the SAFER HBM.

3.3.1 Muscle Material Model

The first step was to verify that the muscle material model in the SAFER HBM was stiffer than the one used in the THUMS-LIU model. If this was verified the material could be regarded as too stiff considering how the THUMS-LIU muscle material was fitted to experimental data from tensile load cases. Single element simulations in tension were run in LS-DYNA. Displacement boundary conditions that matched the strain rates 1/s and 10/s used by Karlsson and Öhrskog (2019) were prescribed to the four top nodes of the elements.

A new softer muscle material model was implemented (Pelschus & Wagner, 2021) in the SAFER HBM modified. This was made for a compression load case in the transverse fibre direction, which was seen as more suitable for quasi-static seat comfort analyses. The data used in the development of this material model, generated by Van Loocke *et al.* (2008), presented much lower stiffness compared to data used for the standard muscle material model of the SAFER HBM.

The same setup that was used for previous single element simulations was used, except for the material chosen and the direction of the prescribed boundary displacement. The strain rate was also changed to 0.1/s to match the new experimental data used by Pelschus and Wagner (2021) where porcine muscle was tested. The muscle materials used in the THUMS-LIU model and the SAFER HBM were also tested in compression with 0.1/s strain rate. A conversion had to be made for the strains on the x-axis to stretch ratio.

3.3.2 Fat Material Model

The fat materials used in all three HBMs were tested through single element simulations described previously. The stress-strain behaviour of these simulations was compared against experimental data from an unconfined compression test of a piece of abdominal human adipose tissue. This experimental data, generated by Calvo-Gallego *et al.* (2018), had a strain rate of 0.6/s. The true strains output from the simulations in LS-DYNA had to be converted to nominal strain to match the experimental data in used in the report by Naseri (2021).

3.4 Validation of Comfort Simulations

The aim was to use newer seat models compared to the ones used by Karlsson and Öhrskog (2019) if available. Since no updated seat models were available, the same pressure data were used in this study as was used by Karlsson and Öhrskog (2019). This pressure mapping was done by the seat supplier Adient plc, Plymouth, Michigan, United States. The pressure mats (X-sensor, model X3 Pro V7) used were calibrated prior to testing. The pressure data only included the relative pressure distribution, which were used for validation in Section 4.2.

The validation consisted of comparing the pressure map data to the normal interface pressure distribution on the seat trim. This distribution could not be extracted with the THUMS-LIU. The validation was done for the SAFER HBM modified with Seat 1 and Seat 2 with standard foam hardness. The other measurements taken from the quasi-static comfort simulations were not validated for this thesis.

3.5 Correlation of Comfort Analysis

Once the validation of the normal interface pressure distribution was done, the next step in the quasi-static seat comfort analysis was to try and correlate

objective measurements from FE simulations with subjective comfort scores. A literature study was performed to investigate what measurements, both physical and simulated, that had been found to correlate well to subjective comfort score data. Based on this, and what resources that were available for the project, the measurements to be taken from FE simulations were specified.

The method for correlation included all three HBMs (THUMS-LIU, SAFER HBM and SAFER HBM modified) for each measurement type with a few exceptions for the THUMS-LIU model. Contact area, pressure ration and L-index was not measured for the THUMS-LIU model. For each seat version one value for each chosen measurement type was computed from the simulations. These values were plotted against their suitable comfort scores, and a coefficient of determination and a standard error was calculated for each measurement type. Coefficient of determination (R^2) and Standard Error (SE) was calculated using the following equations:

$$R = \frac{n(\Sigma xy) - (\Sigma x)(\Sigma y)}{\sqrt{[n * (\Sigma x^2 - (\Sigma x)^2)] * [n * (\Sigma y^2 - (\Sigma y)^2)]}}$$

Where x and y are the averages of each chosen measurement and comfort scores respectively.

$$Standard\ Error = \frac{Standard\ Deviation}{\sqrt{n}}$$

Finally, a correlation study was made on the comfort scores used to find correlation with FE measurements and the overall seat comfort scores, which included all the tested aspects of comfort, not just initial comfort. As the project only investigated quasi-static seat comfort, this correlation study was performed to get an understanding of how much the initial comfort scores affect the overall seat comfort scores. If the correlation would turn out to be high, one could argue that the initial comfort scores are sufficient to also determine the overall seat comfort.

3.5.1 Measurements from FE Simulations

To predict the comfort of the seat and to draw the correlation between the subjective and objective data, several measurements should be taken from the results of the simulations performed. Post processing software called META is used to obtain the measurements. Some potential ways of predicting the comfort is to measure the following parameters:

- Pressure distribution on trim
- Contact area in cushion and backrest trim
- Von Mises stress distribution in foam and the HBM
- Normal displacement in cushion and backrest
- L index in the spine

3.5.2 Comfort Scores

When investigating what seats that could be used for this thesis many different comfort clinics were examined. An internal investigation was made with the aim to use comfort scores from other clinics than those used by Karlsson and Öhrskog (2019). It was concluded that very few new comfort clinics had been conducted in general and none for new seats being developed. Comfort clinics that had Seat 1 and Seat 2 in the same clinic were searched for, but none were found. As a consequence, the decision was made use the same comfort clinics data that was used by Karlsson and Öhrskog (2019).

The two clinics used for this thesis were done with four seats in each clinic. The only thing changing between the four seats was the foam hardness in the entire seat. Hence the aim was to see if a pattern could be seen between comfort scores and foam hardness. The initial comfort scores were divided into a few sub-categories. The three categories considered to be useful were the initial comfort in the cushion, initial comfort in the backrest and the overall initial comfort. The seats used in these comfort clinics were similar to the FE models in the way that they were of the simplest possible configuration e.g., without massage functions.

4 Results

In total, 24 simulations were run, with 8 each for seat 1, seat 2, and THUMS-LIU models. The parameters and boundary conditions were the same for all models except for the foam hardness of the seats. The main findings are illustrated in figures, scatter plots and tables. Both Seat 1 and Seat 2 were used for the validation section but the correlation plots for Seat 2 are excluded from this chapter and shown in Appendix A instead.

4.1 Material Model Modifications

The results from the material model modifications are the initial testing of the muscle material used in the SAFER HBM and a comparison between the new material models and the old ones for both muscle and fat. As previously mentioned, the simulations were all performed in LS-DYNA using a single element.

4.1.1 Muscle Material Model

In Figure 10 the results are shown from the tensile test of the muscle material models Piecewise linear plasticity used in the THUMS-LIU model and Ogden rubber used in the SAFER HBM.

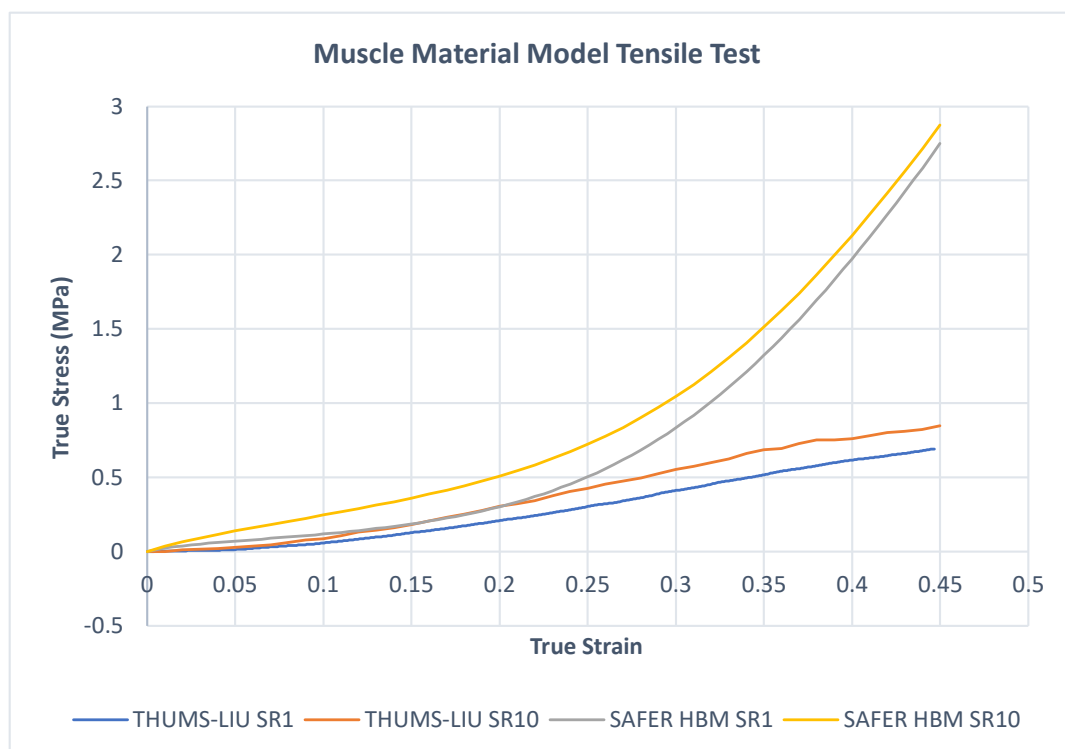


Figure 10: Stress-strain response curves of the muscle materials used in the two HBMs for the strain rates 1/s and 10/s.

For both strain rates there was a clear difference in stiffness between the two materials where the Ogden rubber had higher true stresses for all strains compared to the corresponding strain rates of the Piecewise linear plasticity model. When reaching a true strain of 0.2, the gradient of the Ogden rubber

started increasing and the true stress at the final true strain of 0.45 was roughly four times higher for the Ogden rubber compared to the Piecewise linear plasticity model.

The results from the compression tests for the muscle materials are shown in Figure 12 and Figure 12. The SAFER HBM modified together with the experimental data from Van Loocke *et al.* (2008) had to be plotted in a separate graph, Figure 12, due to the vast difference in Cauchy stress values. The Cauchy stress values were on average a factor of 100 higher in Figure 11 compared to in Figure 12. The stretch ratio assigned to the horizontal axis was computed from engineering strain.

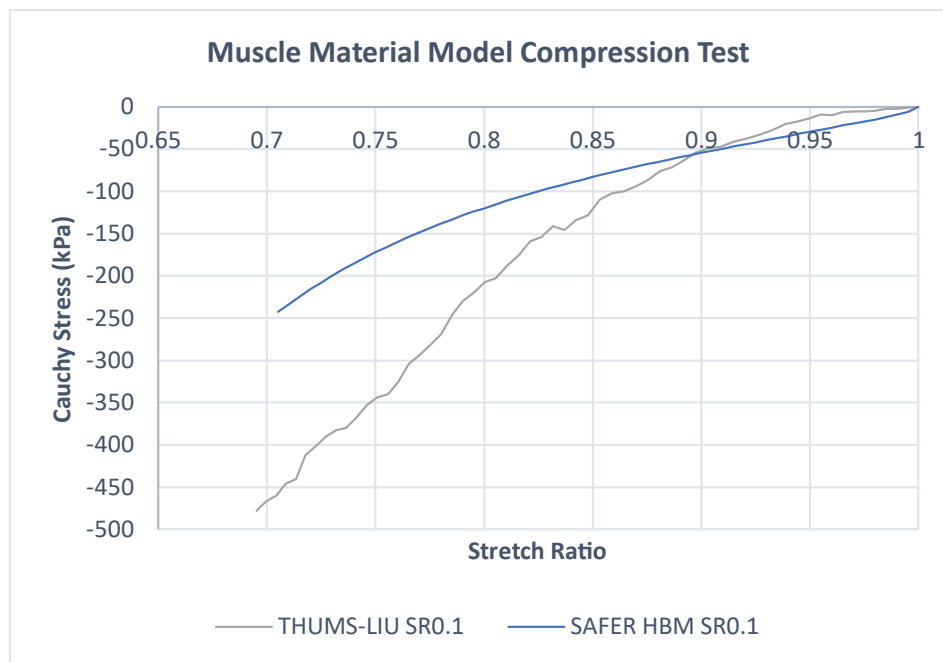


Figure 11: Stress-strain response curves of the muscle materials used in the mentioned HBMs for the strain rate 0.1/s.

Figure 11 showed the opposite result compared to Figure 10 in that way that the muscle material for the THUMS-LIU model was stiffer than the muscle material in the SAFER HBM. This was, however, only the case once a stretch ratio of 0.9 had been surpassed.

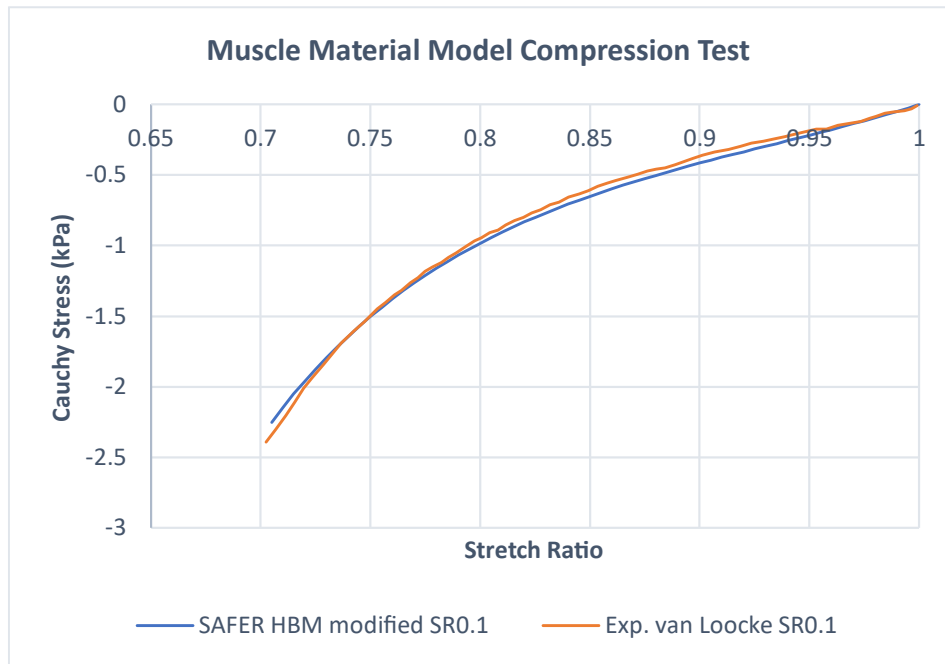


Figure 12: Stress-strain response curves of the muscle material used in the SAFER HBM modified for the strain rate 0.1/s.

The results in Figure 12 were similar to each other.

4.1.2 Fat Material Model

In Figure 13 the results are shown from the compression tests of the different fat material models together with the chosen experimental data provided by Naseri (2021). As previously mentioned, all the fat material models were implemented with the LS-DYNA model called Ogden rubber.

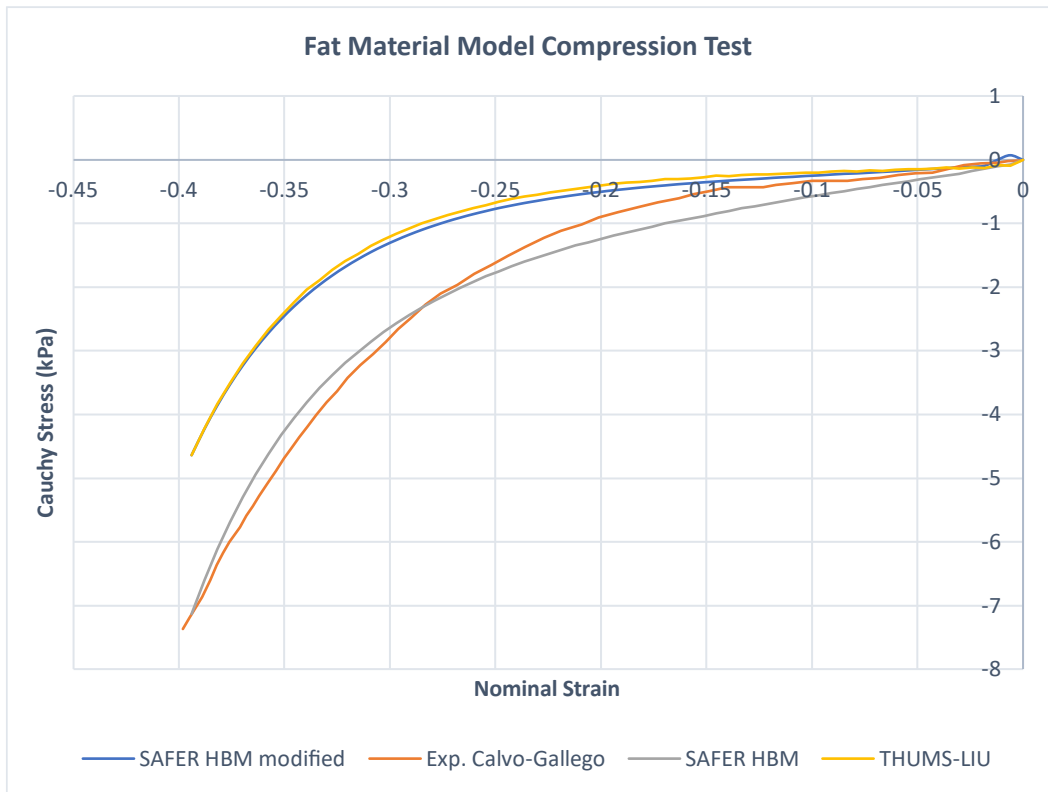


Figure 13: Stress-strain response curves of the fat material used in all three HBMs for the strain rate 0.6/s.

The softest material off all was shown to be the THUMS-LIU fat material in yellow and the stiffest material was shown to be the SAFER HBM fat material in grey. The new fat material implemented in the SAFER HBM modified showed a similar response in compression as the THUMS-LIU fat material, except for the small hump in the beginning that showed a positive Cauchy stress. The reasons for this hump are unknown. The fat material best fitted to the experimental data was the one used in the SAFER HBM. It showed a stiffer response for strains up to approximately -0.28 and then a softer response up until the final strain of -0.4.

4.2 Validation of Quasi-Static Comfort Simulation

In Figure 14 and Figure 15 the pressure map data from Adient are shown on the left-hand side and the extracted normal interface pressure distribution from the quasi-static comfort simulations of SAFER HBM modified are shown on the right hand side. Only the relative pressure distribution is shown without absolute values. The maximum value for the pressure range in the simulated results was reduced compared to the normal interface pressure distribution figures used in Section 4.3. This was done to make the results more comparable to the pressure map data. The pressure map data from Adient for the backrest is not aligned with the pressure map data for the cushion. The backrest and the cushion should therefore be judged independently.

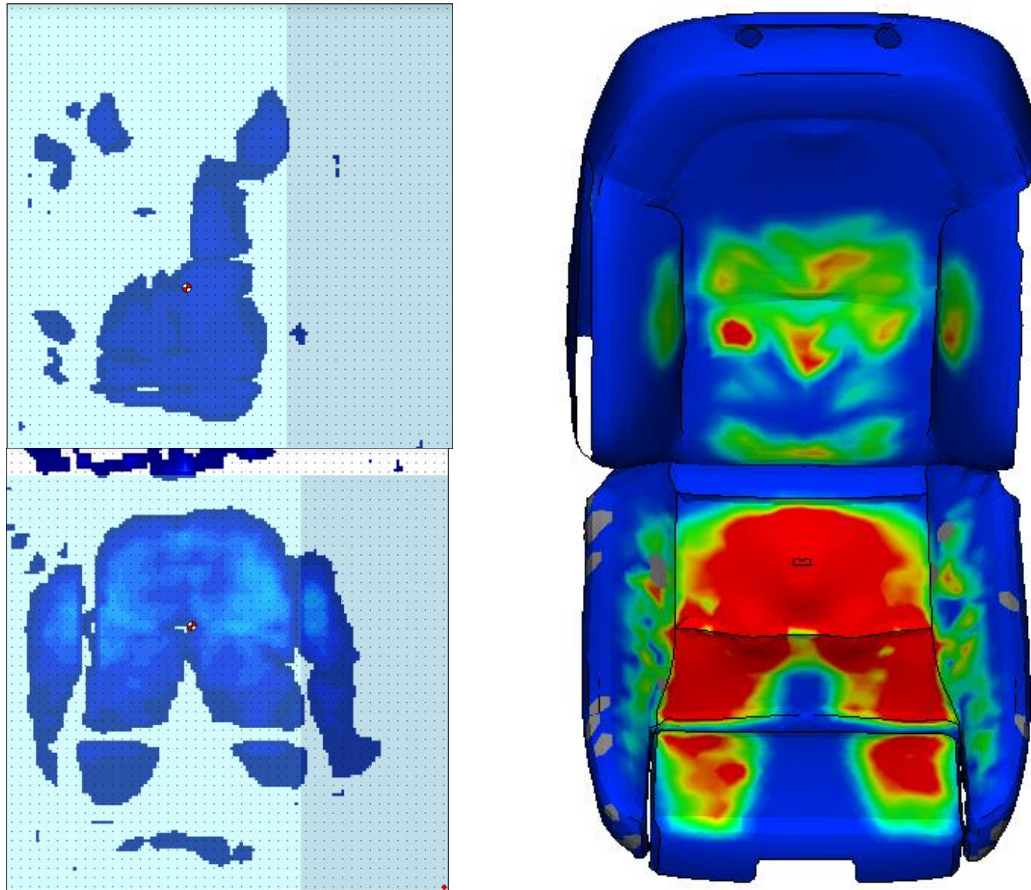


Figure 14: Pressure distribution comparison for Seat 1b

In Figure 14 the lighter blue shade within the darker blue area for the measured data represents higher pressure. The cushion was the portion of the seats that was more similar to each other as both showed pressure in the similar main areas. The main difference was at the three points of high pressure concentration, below the tailbone and below both ischial tuberosities bones, for the simulated results. Since the maximum value of the normal interface pressure distribution had been decreased for this contour plot, these three points were not highlighted via pressure as clearly as in previous pressure distribution figures.

The backrest did not show a similar result. The main area of pressure was at the thoracic area for the simulated results and at the lumbar area for the pressure map data. In addition, the pressure map data was not symmetrical as the left-hand side of the upper backrest showed almost no pressure at all.

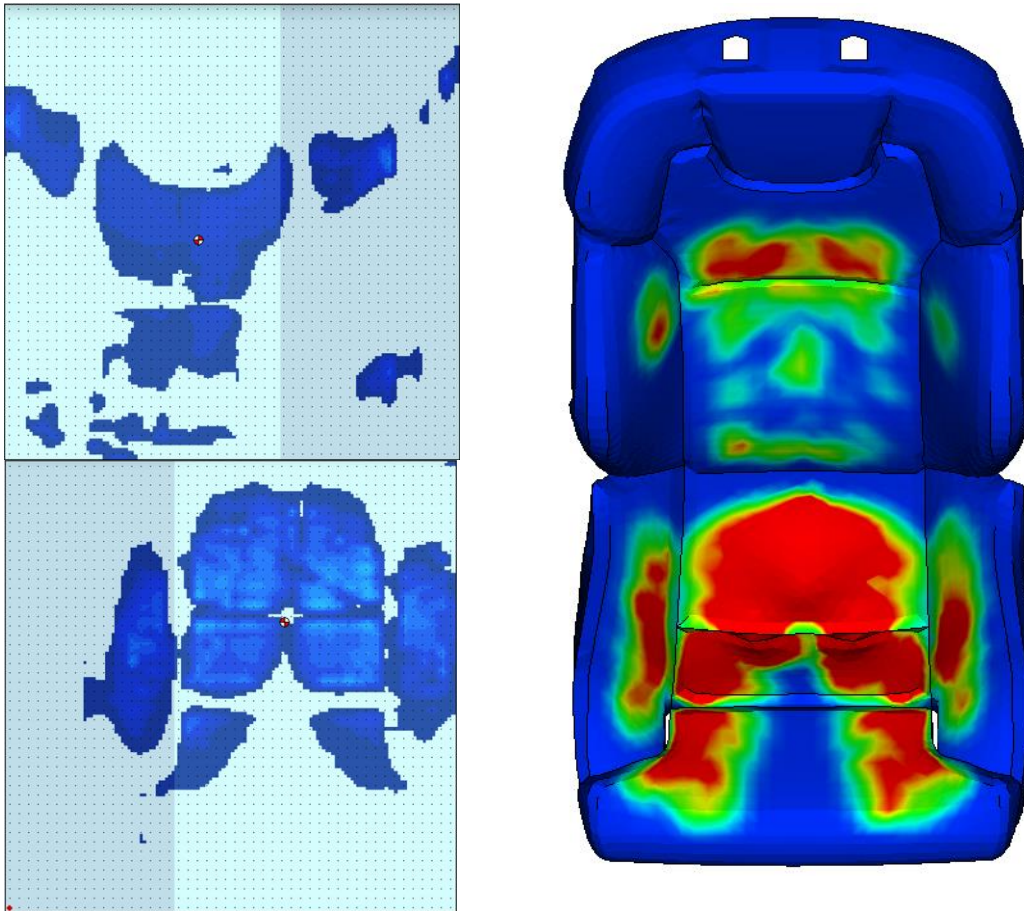


Figure 15: Pressure distribution comparison for Seat 2b.

The normal interface pressure distribution for the simulated results and the pressure map data in Figure 15 were more similar to each other compared to in Figure 14. The backrest was more similar with both main areas of contact located at the thoracic area. The cushion parts showed potential towards the simulated results being considered valid. The difference between the two cushions was, as in Figure 17, at the three points of high pressure concentration for the simulated results.

4.3 Comfort Simulations

In this section, the normal interface pressure distribution is shown for most of the seat comfort simulations that were performed. As mentioned in Section 3.4, the normal interface pressure distribution could not be extracted for the THUMS-LIU model. The von Mises stress distribution in the foam was used instead. This meant that stresses appeared that were not associated with direct contact between the seat and the HBM. This was most clear for the THUMS-LIU model in Seat 1 in Figure 18 on the outer areas of the cushion bolsters.

4.3.1 SAFER HBM Modified

The resulting normal interface pressure distribution from the simulations performed with the SAFER HBM modified are shown below in Figure 16 and

Figure 17. A colour scaling was used where the maximum pressure values are indicated in red and the minimum pressure values are indicated in blue. The maximum value of the pressure range was decreased for the backrest results in Figure 16 to better show the pressure distribution. The purpose of showing these results is to see potential difference in pressure distribution for different foam hardnesses.

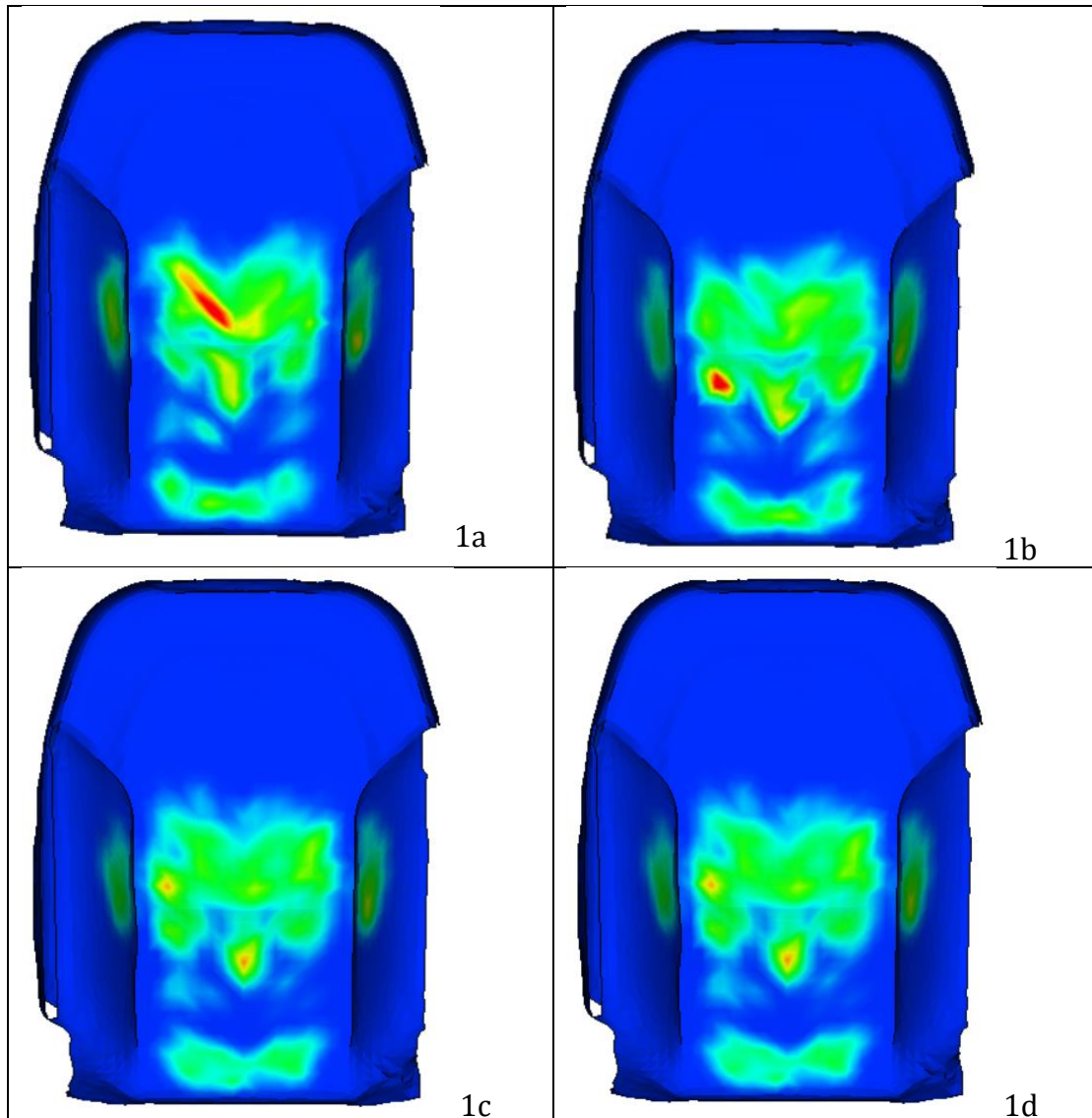


Figure 16: Normal interface pressure distribution on backrest trim for SAFER HBM modified Seat 1 simulations where the foam hardness in Seat 1a is the lowest and the foam hardness in Seat 1d the highest.

All four seat backrests showed a similar pressure distribution to each other. The backrest with the highest pressure concentration was the one for Seat 1a.

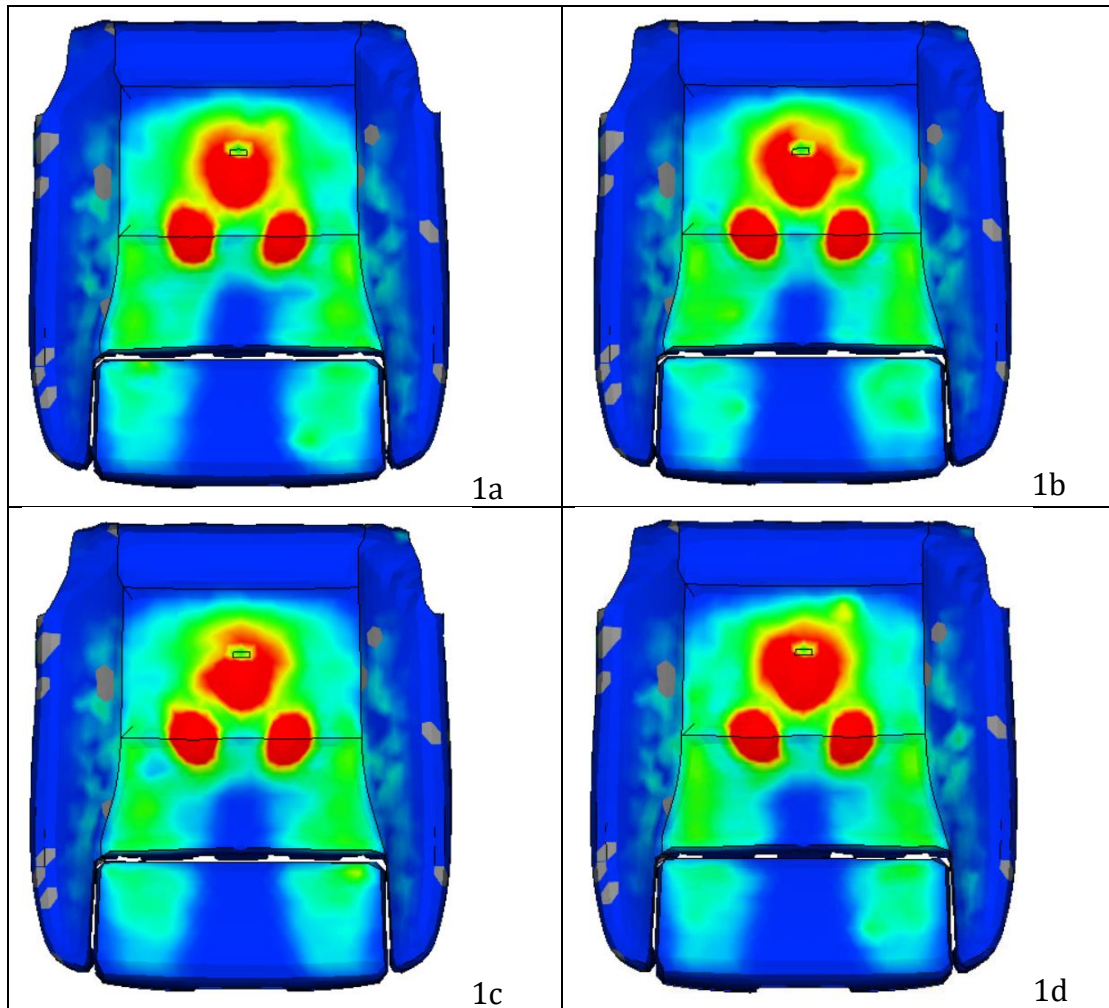


Figure 17: Normal interface pressure distribution on cushion trim for SAFER HBM modified Seat 1 simulations where the foam hardness in Seat 1a is the lowest and the foam hardness in Seat 1d the highest.

In Figure 17, the four seat cushions also showed a similar pressure distribution to each other. They all had three areas of high pressure concentration: one under the tailbone and one under each ischial tuberosities bone.

4.3.2 HBM Comparison

In this section, a comparison between the results from the simulations performed with the different HBMs is made. The same fringe levels were used for the SAFER HBM and the SAFER HBM modified in Figure 18 and Figure 19.

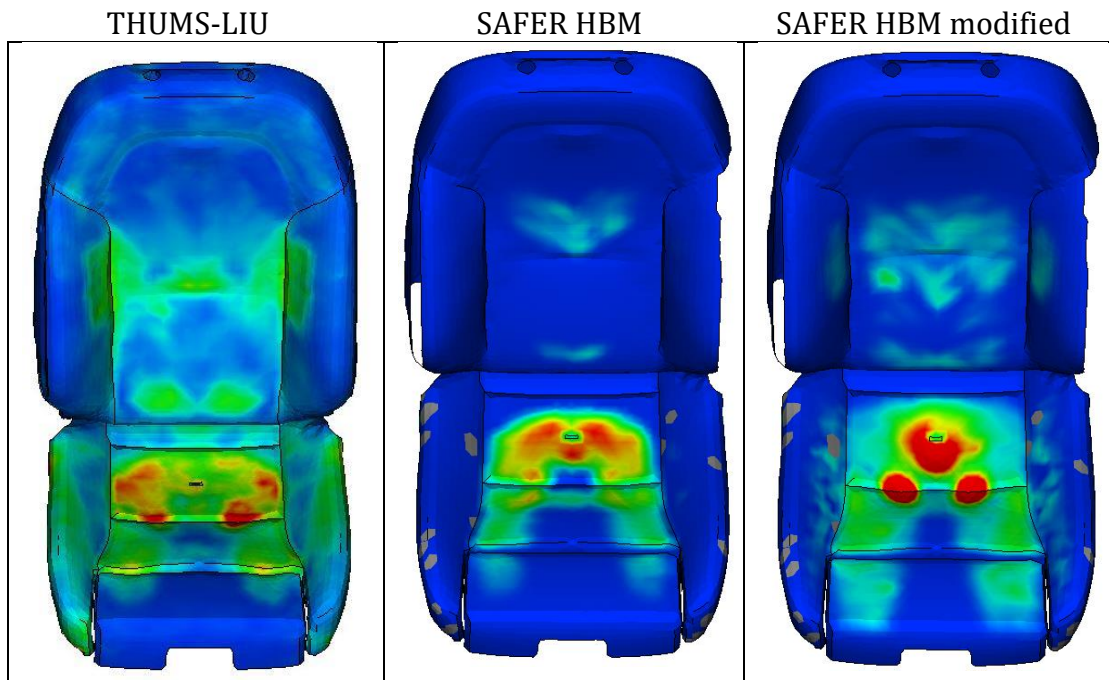


Figure 18: Von Mises stress distribution in foam for the THUMS-LIU Seat 1b and normal interface pressure distribution on trim for the SAFER HBM and SAFER HBM modified on Seat 1b.

The distributions shown in Figure 18 were all different to each other. The highest stress/pressure was found underneath the buttocks for all three HBMs. The THUMS-LIU model had less concentration below the tailbone compared to the other two. On the other hand, it had more concentration in the backrest compared to the SAFER HBM especially. The SAFER HBM modified had the areas with the highest pressure concentration and also more pressure in the backrest compared to the SAFER HBM.

The distributions shown in Figure 19 showed a similar trend in difference between the three HBMs as for Seat 1. There was less stress on the two cushion bolsters for the THUMS-LIU model compared to Seat 1. In addition, the THUMS-LIU model had a larger area of stress concentration on the cushion covering the area under the tailbone.

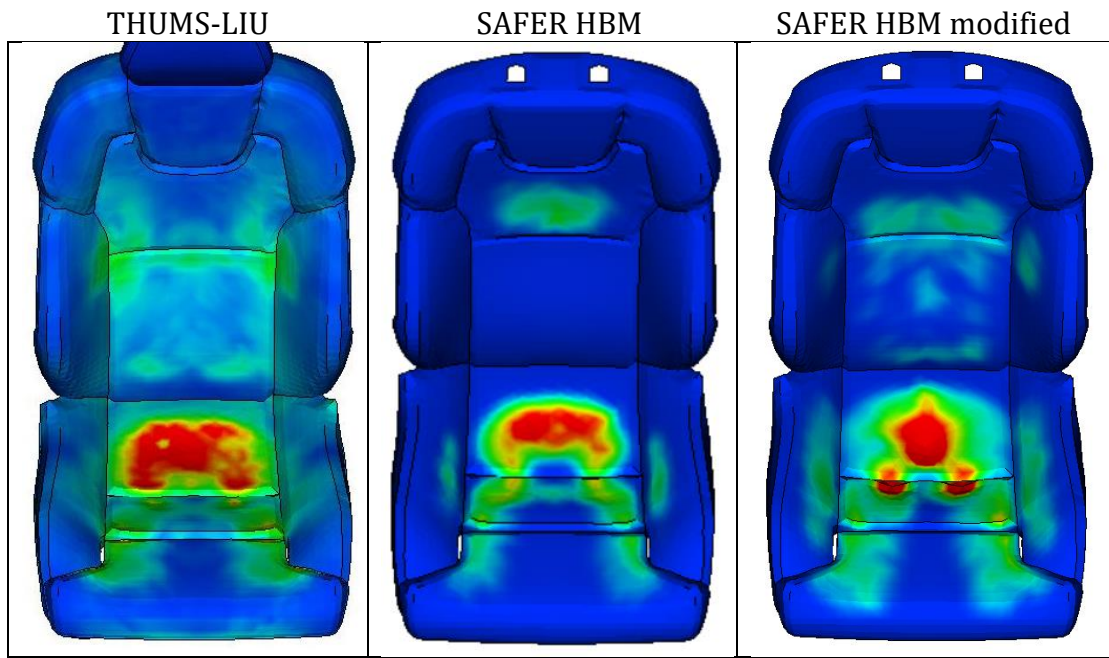


Figure 19: Von Mises stress distribution in foam for the THUMS-LIU Seat 2b and normal interface pressure distribution on trim for the SAFER HBM and SAFER HBM modified on Seat 2b.

4.4 Correlation of Comfort Analysis

The results from the correlation study for Seat 1 are shown in this chapter, and the results for Seat 2 are included in Appendix A. The correlation plots in this chapter were made with seat hardness a, b, c and d for both Seat 1 and Seat 2. The three HBMs were compared to the same volunteer data discussed in sub-section 2.5.1 for each measurement. This is also the case where the THUMS-LIU model was excluded. In Figure 20 the extracted contact area of the cushion from FE software for Seat 1a, 1b, 1c and 1d are plotted against the initial cushion comfort scores for Seat 1.

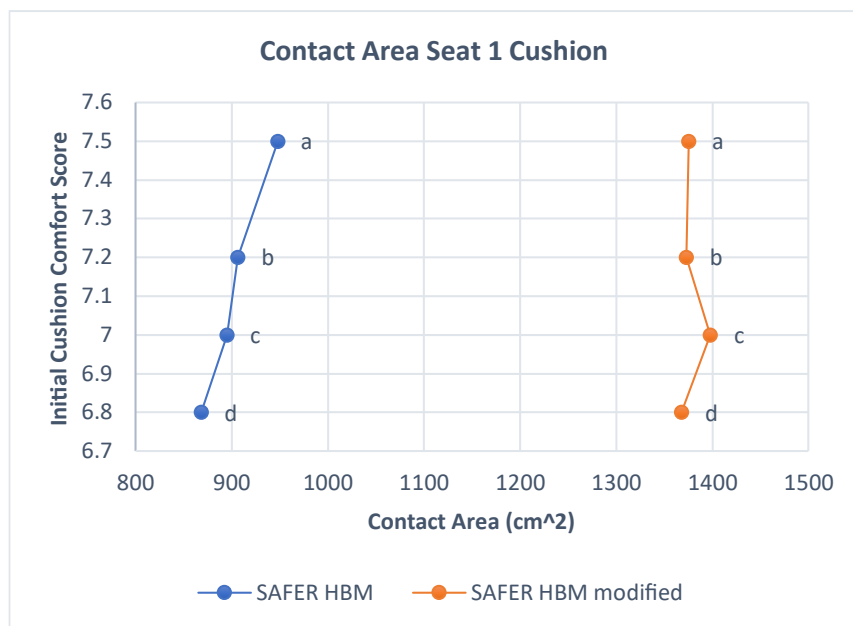


Figure 20: Contact area correlation plot.

Figure 21 was plotted in the same way as Figure 20 but for the backrest and with the corresponding backrest comfort scores.

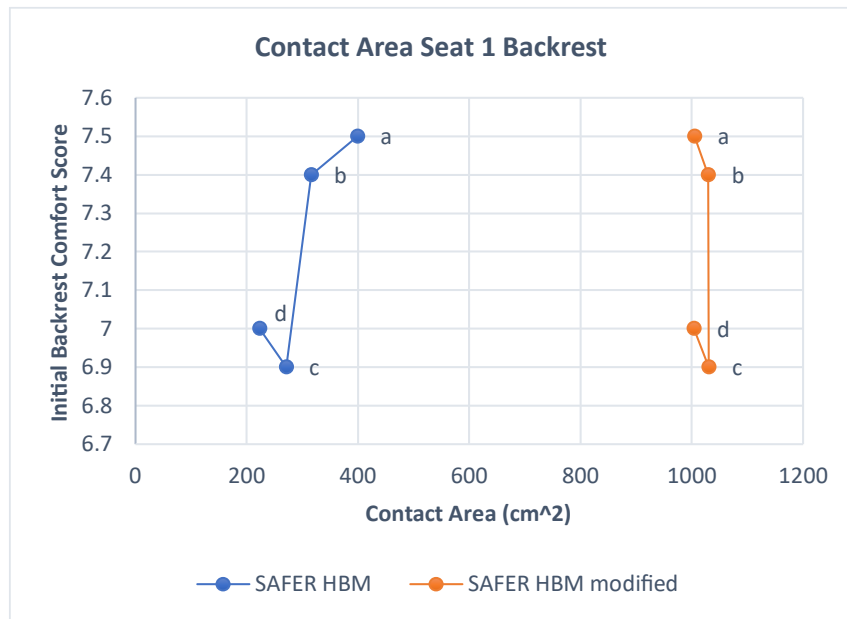


Figure 21: Contact area correlation plot.

The results in Figure 20 and Figure 21 show a big difference in measured contact area between the two HBMs. This makes the graphs less clear in terms of showing trends between comfort scores and contact area. The coefficients of determination along with the corresponding standard errors are shown in Table 2 for a better understanding of the correlation.

For both figures, the SAFER HBM modified showed no correlation. The SAFER HBM showed good correlation between increased contact area and increased comfort scores for both the cushion and the backrest. Since the initial backrest comfort score for Seat 1c deviated from the trend of increasing comfort with decreasing foam hardness, the correlation was weaker for the backrest plot. The standard error was also more than twice as high for the backrest plot.

The next measurement to be illustrated is the maximum von Mises stress in the muscle layer for each HBM at the cushion area and backrest area. Once again there was a big difference in the measured values for the three HBMs making the graphs less clear when trying to demonstrate trends.



Figure 22: Buttock muscle stress correlation plot.

In Figure 22 the coefficient of determination was the highest for the SAFER HBM modified, 0.76, and around 0.5 for the other two HBMs. The THUMS-LIU model showed correlation in the opposite direction to what was expected, as increased maximum von Mises stress in the buttock muscle was weakly matched with increased comfort scores. The standard error varied dramatically where it was below 1 kPa for the SAFER HBM and above 50 kPa for the THUMS-LIU model. The maximum von Mises stress for the cushion region could be found below the tailbone and below the ischial tuberosities bones of the HBMs.

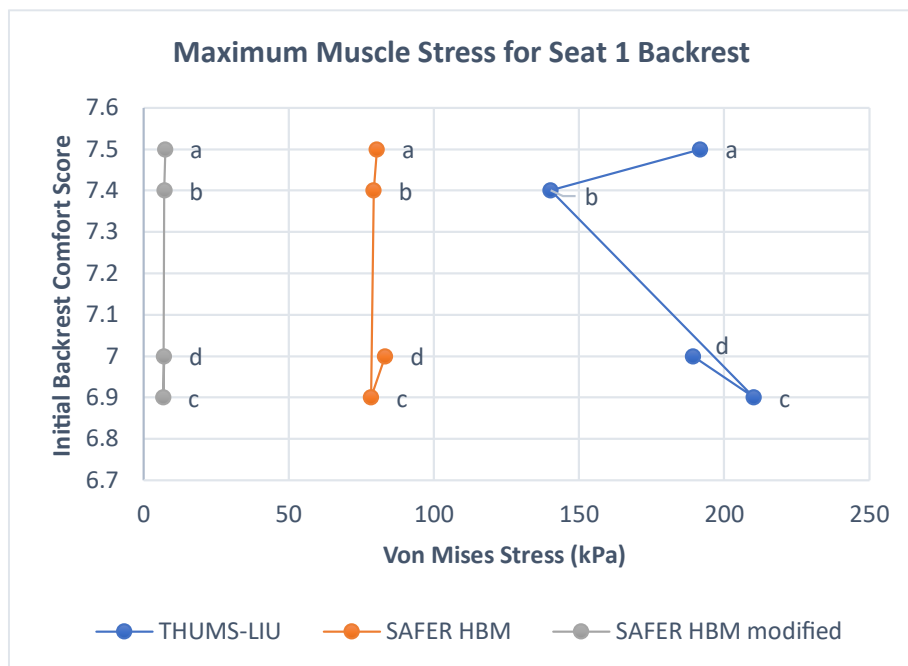


Figure 23: Back muscle stress correlation plot.

As can be seen in Table 2 there was no correlation of interest for the backrest measurements apart from the SAFER HBM modified, which had a coefficient of determination of 0.72. The maximum von Mises stress in the back of the THUMS-

LIU model and the SAFER HBM was found in the thoracic region. The SAFER HBM modified behaved differently as the maximum von Mises stress was found in the lumbar region instead. The difference in overall stress magnitude varied extremely as the THUMS-LIU model had more than 10 times higher stress values compared to SAFER HBM modified.

The pressure ratio measurements for the cushion in Figure 24 showed relatively good correlation in the expected direction. The maximum pressure measurements were found in the same location as the maximum von Mises stress in the buttock muscles. There was a big difference in overall pressure ratios for the two HBMs. The difference in pressure ratio values for each HBM was lower for the SAFER HBM as it had a low standard error in comparison to the SAFER HBM modified.

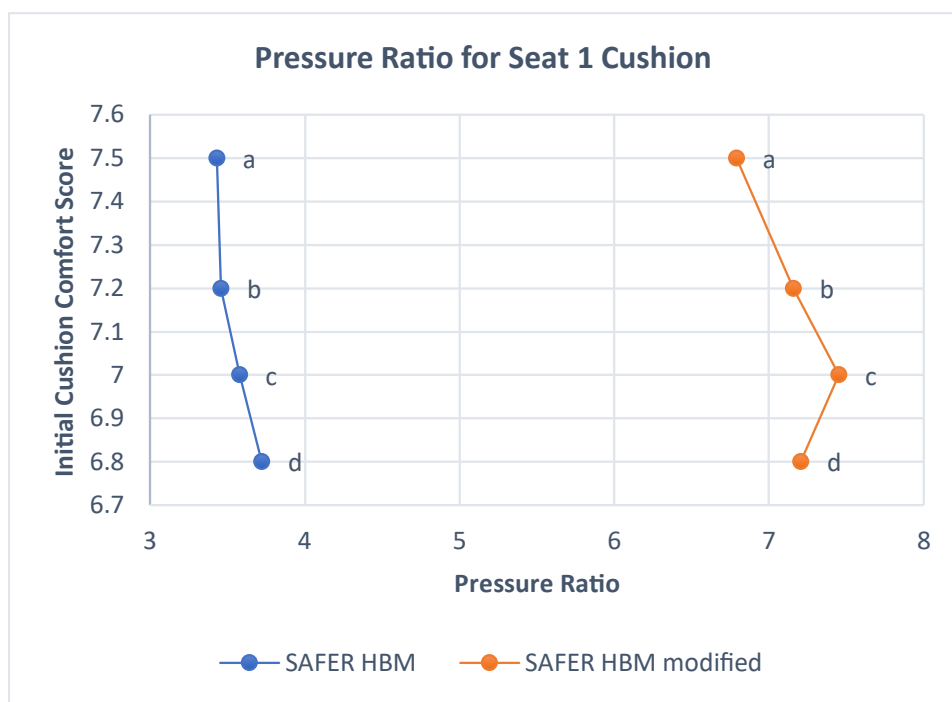


Figure 24: Pressure ratio correlation plot.

The pressure ratios for the backrest in Figure 25 showed good correlation in the opposite direction for the SAFER HBM modified. The SAFER HBM showed no correlation of interest.

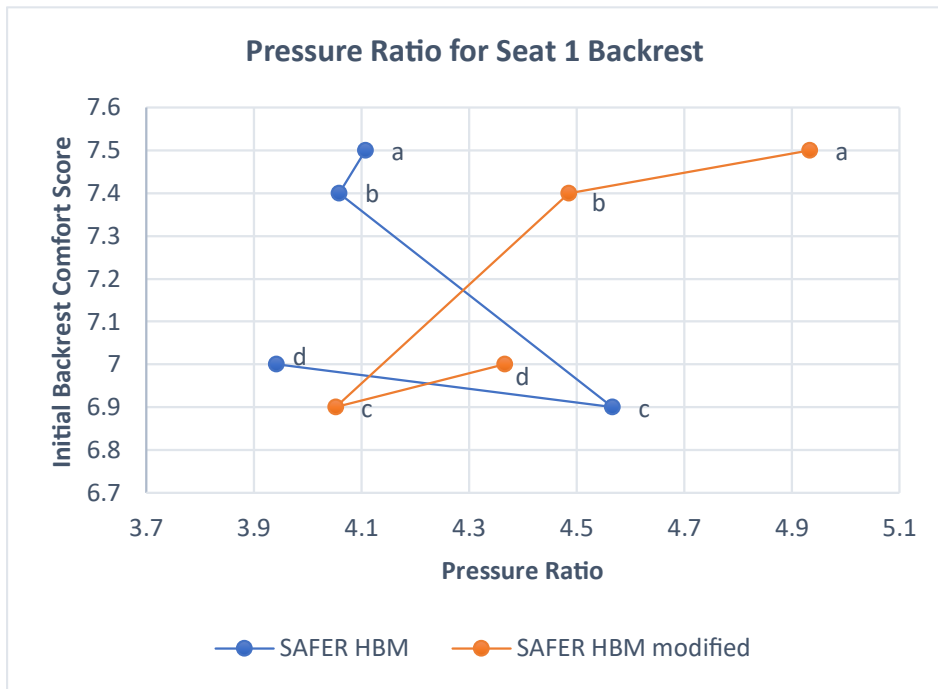


Figure 25: Pressure ratio correlation plot.

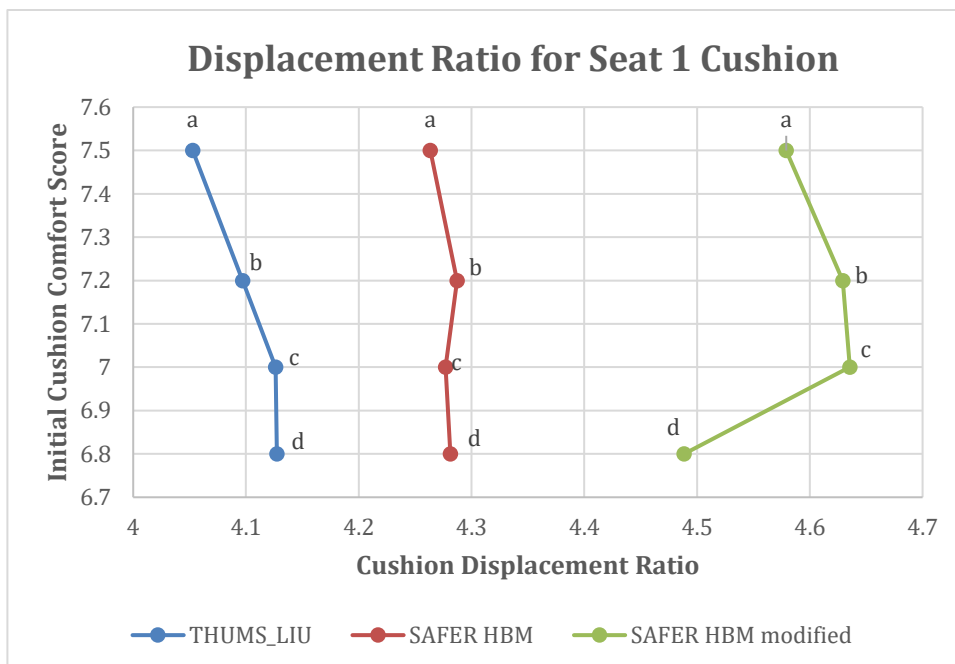


Figure 26: Displacement ratio correlation plot for cushion

In fig 9 the displacement ratio of cushion was correlated for all three HBM's. The THUMS-LIU showed a good correlation among three with no big differences in standard error. SAFER HBM modified and SAFER HBM showed no correlation.

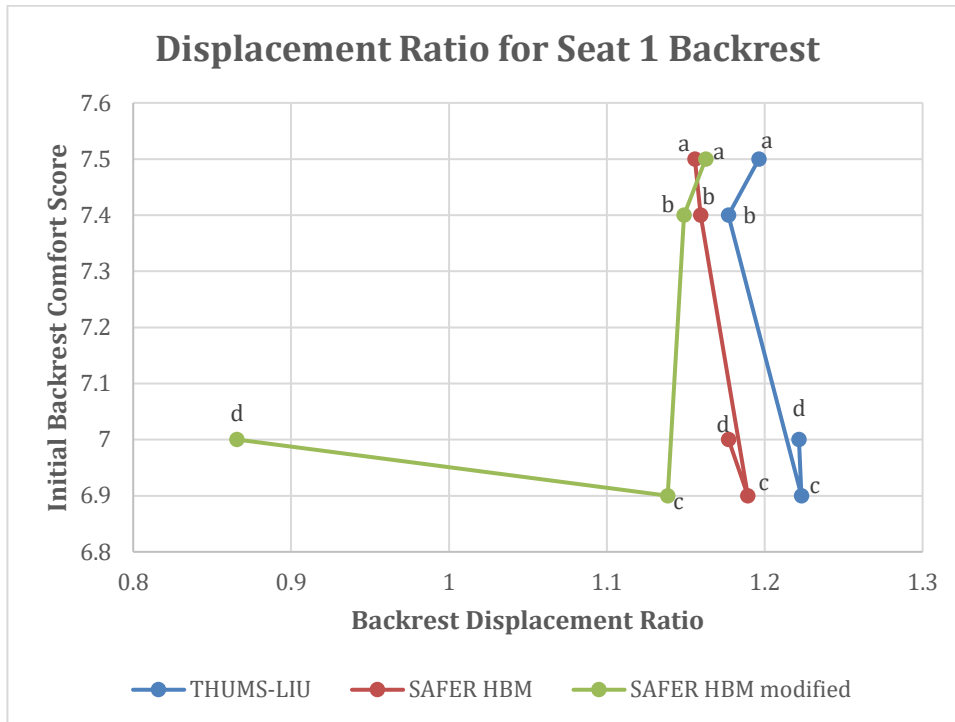


Figure 27: Displacement ratio correlation plot for backrest

In Figure 27, the displacement ratio for backrest was correlated for all three HBM's as well. THUMS-LIU and SAFER HBM showed a good correlation with less deviation in standard error. SAFER HBM modified showed correlation in the opposite direction to what was expected as increased standard error when compared to other two HBM's.

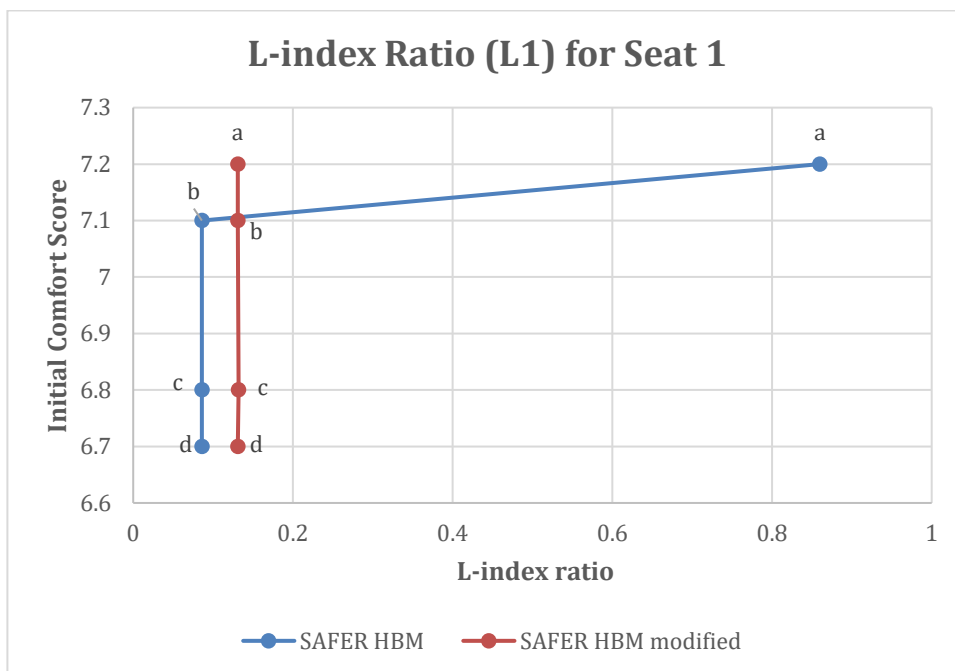


Figure 28: L-index correlation plot

In fig 11, the L-index of Lumbar spine L1 is correlated for two of the HBMs i.e., SAFER HBM and SAFER HBM modified. The later showed no correlation with 0 Standard error and the SAFER HBM showed the correlation in opposite direction with the standard error of 0.19

In Figure 29, the results are shown from the correlation study between the different initial comfort scores and the overall seat comfort scores. As the overall seat comfort score for Seat 1a and Seat 1b was the same, the correlation becomes hard to see. According to Table 4 the initial backrest score had the lowest coefficient of determination (0.35).

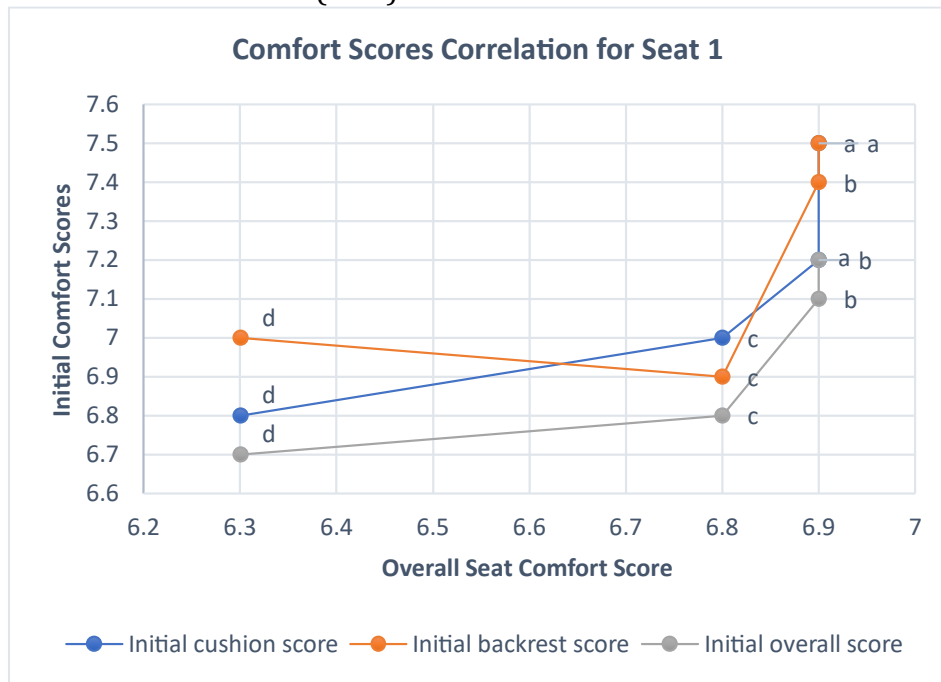


Figure 29: Correlation graph for comfort scores.

In Table 1 the colour scaling for the coefficient of determination is illustrated.

Table 1: Correlation of determination (R^2) colour bar scaling.

0.00-0.20	0.21-0.40	0.41-0.60	0.61-0.80	0.81-1.0
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The computed coefficients of determination for both Seat 1 and Seat 2 are given in Table 2 and Table 3 respectively. All values were reported with two decimal points and the colour bar was used for the coefficient of determination of each measurement. Some of the measurements were not done for all the HBMs and these cells were left empty.

Table 2: Coefficient of determination (R^2) with standard error given in brackets for Seat 1.

	THUMS-LIU	SAFER HBM	SAFER HBM modified
Contact Area Cushion		0.98 (16.50 cm^2)	0.00 (6.67 cm^2)
Contact Area Backrest		0.74 (37.34 cm^2)	0.04 (7.49 cm^2)
Muscle Stress Cushion	0.46 (53.50 kPa)	0.59 (0.81 kPa)	0.76 (5.52 kPa)
Muscle Stress Backrest	0.34 (14.96 kPa)	0.01 (1.04 kPa)	0.72 (0.13 kPa)
Pressure Ratio Cushion		0.87 (0.07)	0.60 (0.14)
Pressure Ratio Backrest		0.22 (0.14)	0.80 (0.18)
Displacement Ratio Cushion	0.92 (0.01)	0.39 (0.01)	0.18 (0.03)
Displacement Ratio Backrest	0.75 (0.01)	0.96 (0.01)	0.59 (0.07)
L-index		0.49 (0.19)	0.17 (0.00)

Table 3: Coefficient of determination (R^2) with standard error given in brackets for Seat 2.

	THUMS-LIU	SAFER HBM	SAFER HBM modified
Contact Area Cushion		0.79 (24.20 cm^2)	0.98 (6.29 cm^2)
Contact Area Backrest		0.00 (6.24 cm^2)	0.61 (17.10 cm^2)
Muscle Stress Cushion	0.00 (4.64 kPa)	0.61 (4.11 kPa)	0.66 (4.35 kPa)
Muscle Stress Backrest	0.21 (1.71 kPa)	0.75 (1.49 kPa)	0.09 (0.37 kPa)
Pressure Ratio Cushion		0.03 (0.28)	0.66 (0.20)
Pressure Ratio Backrest		0.92 (0.22)	0.00 (0.20)
Displacement Ratio Cushion	0.10 (0.01)	0.56 (0.07)	0.48 (0.04)
Displacement Ratio Backrest	0.74 (0.04)	0.95 (0.08)	0.92 (0.01)
L-index		0.21 (0.00)	0.47 (0.00)

In Table 3 for the SAFER HBM modified, the backrest measurements showed a lower correlation, on average, compared to the cushion measurements. In addition, a lower correlation in general can be seen for Seat 1 compared to Seat 2. This was not the case for the THUMS-LIU model as it had a lower correlation for

Seat 2 than for Seat 1 on average. The measurements highlighted in red usually had relatively small standard errors in both Table 2 and Table 3.

The measurement with the highest average correlation was the displacement ratio in the backrest. The lowest coefficient of determination for this measurement was 0.59 in Table 2, which was high compared to the other measurements. The second highest average correlation was found for the muscle stress in the cushion. This measurement showed no correlation in Table 3 for the THUMS-LIU model, but the rest of the coefficients of determination were relatively high.

The correlation parameters for the comfort score correlation study is given in Table 4. Seat 2 had a relatively high coefficient of determination for all three initial comfort scores. In general, the standard error was twice the amount for the Seat 2 scores compared to the Seat 1 scores. This indicates that there was a bigger difference in comfort scores between seats 2a – 2d compared to seats 1a-1d.

Table 4: Coefficient of determination (R^2) with standard error given in brackets for seat comfort scores correlated with overall seat comfort scores.

	Initial Cushion Comfort Score	Initial Backrest Comfort Score	Initial Overall Comfort Score
Seat 1	0.65 (0.15)	0.35 (0.15)	0.65 (0.12)
Seat 2	0.95 (0.30)	0.94 (0.30)	0.93 (0.25)

5 Discussion

The main aim for this was to develop an objective method for predicting seat comfort. Prior to these developments the model used in this study was updated. The validity of the FE simulations and the seat comfort correlation study is discussed in this section.

5.1 Material Model Modifications

The new material models for muscle and fat were both tested through single element simulations. Naseri (2021), however, did not perform single element tests. Instead, a FE model of an adipose tissue specimen was compressed. The response from this setup generated slightly different results compared to the single element simulations that were performed. This was mainly due to friction taking place between the FE model of adipose tissue and the plates in the study by Naseri (2021). However, according to Engelbrektsson (2011), the sensitivity towards friction is small as WAT has a low friction coefficient. The fat materials used in the SAFER HBM and the SAFER HBM modified behaved as expected when comparing with the graph in the report by Naseri (2021). They can therefore be regarded as verified to have been correctly implemented in the LS-DYNA simulations that were done.

The muscle material developed by Pelschus and Wagner (2021) was verified to have been implemented correctly based on the results in Figure 12. The figure in the study by Pelschus and Wagner (2021) comparing the experimental data with the simulated response is not for single element tests. It was therefore expected to see a slightly different response when performing single element simulations. There was, however, no apparent difference when comparing the two.

5.2 Comfort Simulations

Performing quasi-static comfort simulations has been proven to be challenging considering the complexity of HBMs. The quasi-static comfort simulations that were performed in LS-DYNA had multiple sources of error. Some errors were concerned with the HBM, and some were concerned with the FE crash simulation seat models. The main identified sources of error are listed below, starting with the ones concerning the HBM.

- *Hands holding virtual steering wheel:* As explained earlier, the node in the centre of each hand was locked in translation to reduce arm movement. This was considered to be a standard driving position as the hands were locked near the virtual steering wheel. The arms should initially have no effect on the quasi-static comfort simulation. Unfortunately, they did because the solution resulted in the arms exerting a pulling force on the HBM away from the backrest. The amount of pulling force depended on the stiffness of the material surrounding the shoulder joint. This is believed to be the main reason for the difference in the overall magnitude of contact pressure in Figure 18 and Figure 19.

The solution chosen to stop the arms from moving and causing the simulation run time to increase significantly was suggested by an internal source. Due to a lack of time this solution was not further developed to minimize the impact of the arms on the HBM. The solution was inspected by ocular inspection and the pulling force of the arms was not noticeable.

- *Quasi-static state:* When extracting measurements from the FE simulations, a particular state in time had to be selected. It was evident that most of the measurements were changing significantly between one state to the next, when scanning for the most static part of the simulation. This is potentially a major source of error that needs to be addressed before any significant conclusions can be drawn from this kind of analysis. One way to make the HBM behave in a more stable manner would be to use damping in LS-DYNA. This would make the measurements more precise from one state to another. However, it is unclear how the accuracy of the measurements would be affected by this.

Error sources concerning the FE crash simulation seat models:

- *Foam material uncertainties:* According to internal sources, the seat foam material has uncertainties in the level of hardness due to changing environment conditions in the factory. In addition, foam material is challenging to model in FE software. When inspecting internal sources, validation against physical samples is a work in progress for the FE crash simulation seat models.
- *Trim membrane forces:* The membrane forces applied by the trim are not taken into consideration in the FE crash simulation seat models. For a physical seat, the membrane forces depend on how firmly the trim has been mounted onto the foam. According to internal sources, these forces are small, hence this can be regarded as a small source of error.
- *Trim and foam friction:* The trim and foam interaction is yet to be fine-tuned in the FE crash simulation seat models, as the trim and foam are glued together. Consequently, there is no friction taking place between the two in the simulations performed. The physical seats are mounted in a way that the trim is fastened to the foam at numerous points on the foam. In the areas between the points of fastening, friction is acting between the foam and trim. This discrepancy in behaviour is believed to have a small effect on the results.
- *Seats different:* the seats used in FE software and the physical seats used for the comfort clinics were not identical. This is seen as an expected and small source of error. The seats were also not always fitted in the same car in FE software as in the comfort clinics. This caused small variations in seating position between the FE simulation and physical tests.

Overall, the simulations went well and showed expected results. A further improvement that could be made would be to ramp up the gravity to allow for a less violent impact of the HBM falling into the seat. This would have to be fine-

tuned with the applied damping in order for the time taken to reach quasi-static state to decrease.

5.2.1 SAFER HBM Modified

The reason(s) for the lack of difference between the normal interface pressure distributions in Figure 17 are uncertain. One possible reason for why it was difficult to see trends in pressure distribution for increasing foam hardness, is that the transition areas between the red areas and the green areas were too small. They were marginally the smallest for Seat 1d, which was expected. There are other possible reasons from the error sources, such as the HBM never fully stabilising during the simulation. This error source was more noticeable for the backrests in Figure 16. This could potentially be remedied by running significantly longer simulations. This was, however, not recommended by internal sources as the simulation times were already long.

5.2.2 HBM Comparison

To start off, the backrests in Figure 18 and Figure 19 were all different to each other. The main reason for the small area of pressure shown for the SAFER HBM is the arms exerting a pulling force on the HBM away from the backrest. As the muscle material had been changed for the SAFER HBM modified to a softer material, the arms could move more freely in that simulation. This caused less pulling force and hence more pressure on the backrest trim. This behaviour could be seen for both Seat 1 and Seat 2.

As von Mises stress in the foam was plotted for the THUMS-LIU model, the friction between the HBM and the seat was captured in the results. Since the trim and foam of the FE seat models were glued together, this effect was likely larger than what would have been the case if physical testing had been done. The friction was not deemed to interfere with the analysis in a significant way as the HBM comparison plots were only analysed via ocular inspection.

Moving on to the cushion, a major difference between the SAFER HBM modified and the other HBMs was the three points of high-pressure concentrations. These indicate that the soft tissue of the SAFER HBM modified presented in Section 3.3 was too soft since this is not a realistic behaviour. The stiffness of the muscle material was decreased a lot more than the stiffness of the fat material. The muscle material was also closer to the bones as the fat layer was the outermost of the two. This makes it likely that the muscle material is more responsible for this unrealistic behaviour.

5.3 Objective Method for Predicting Seat Comfort

The results from the correlation analysis should be seen as potential indicators for what measurements that are likely to correlate to subjective comfort scores. This is mainly due to the error sources listed above and other potential error sources

that are yet to be identified. In addition, the whole correlation analysis is based on the assumption that the FE model is validated with physical tests. This was only the case to a certain extent for this analysis. One should also keep in mind that correlation does not mean that there is causation.

The subjective comfort scores are generated with comfort in mind, which is a very abstract phenomenon. What one person believes to be comfortable might be uncomfortable for someone else. One way to decrease this source of error would be to increase the sample size, in this case the number of participants in the comfort clinics. A way to improve the comfort score data for this application would be to use participants that have physical characteristics that are as close to the HBM's physical characteristics as possible. Understandably, comfort clinics for car seats are usually performed with people that represent a wide spread of the population's physical characteristics. Since the HBMs used in this analysis cannot be morphed into different shapes and sizes, this modification to the comfort clinic strategy would improve the correlation analysis.

5.3.1 Validation

The results from the validation showed a better match for Seat 2 than for Seat 1. This was partly the case since the pressure map data was asymmetrical for Seat 1. The pressure map data was obtained from the seat supplier, and they have performed the test with single individual per seat. This was unexpected and it is likely that the test was not executed in the best way. The validation method also has its limitations and can be improved. For example, the absolute values of the pressure could be measured for the pressure map data to give a better validation with the FE model.

Both seats in FE software showed an unrealistic behaviour with three areas of high pressure concentration in the cushion. This could be remedied by improving the muscle material model. Moreover, the accuracy and level of detail of the soft tissues geometries in the buttock area could be increased. For instance, Al-Dirini *et al.* (2016) made a study on validating a high anatomical fidelity FE model for the buttock and thigh of a seated human. They concluded that the mechanical strains in muscles and fat tissues from their FE model, suggested that the muscles bear the highest mechanical loads. Furthermore, Al-Dirini *et al.* (2017) found evidence to suggest that muscle strain is more sensitive to changes in seat support surface load and load distribution than fat strain. This indicates that muscle geometry needs to be modelled accurately in order for HBMs to perform in a realistic manner. Modelling the muscles accurately is therefore likely to improve the validation of the quasi-static comfort simulations.

5.3.2 Correlation

The coefficient of determination is the correlation coefficient squared. When computing the correlation coefficient, it is important to have an adequately large sample size. If the sample size is six or below there is a risk that a relationship might appear even though none actually exists according to Aggarwal and

Ranganathan (2016). As the sample size of the performed analysis was four, the coefficients of determination must be viewed with caution. They were used to give a quick indicative overview of the potential correlation for the different measurements.

Some of the comfort scores used did not decrease linearly with increasing foam hardness. For instance, in Figure 21 the initial backrest comfort score for Seat 1 was lower for Seat 1c compared to Seat 1d even though Seat 1c was softer. Here the expected trend of increasing contact area with decreasing foam hardness was clear for the SAFER HBM. Had the comfort score for Seat 1c been higher the correlation would have increased significantly from the current 0.74. The noisy nature of subjective comfort scores shows its limitations for objective seat comfort predictions here. The same can be said for the maximum muscle stress and the pressure ratio for the Seat 2 cushion part in Appendix A.

In Figure 25 the SAFER HBM modified had an unexpected result that was likely due to a coincidence. The same unexpected initial backrest comfort score mentioned previously, corresponded with the unexpected results from the measured pressure ratio. More specifically, the pressure ratio was expected to either decrease or increase continuously with increased foam hardness. For Seat 1d, however, the pressure ratio increased instead of decreased and so did the respective comfort score.

The THUMS-LIU model showed much higher maximum von Mises stress in the muscles for both the cushion area and the backrest area of Seat 1. As mentioned in Section 5.2, one of the sources of error was that the arms ended up exerting a pulling force away from the backrest. Figure 23 shows potential evidence for this as the difference in overall stress magnitude between SAFER HBM and SAFER HBM modified, is much bigger than what can be seen in Figure 22. The same can be said for the corresponding figures in Appendix A for Seat 2. For those figures, however, the THUMS-LIU model did not have a higher maximum von Mises stress in the muscles compared to the other HBMs. This was unexpected and makes the stress measurements for the muscles in the THUMS-LIU model less credible.

The standard error computed for Table 2 and Table 3 showed no trend with respect to high or low coefficient of determination. It can be said, however, that a low standard error is a potential reason for why some measurements showed low correlation. If there is small overall difference in the measurements, there is a higher risk for errors in the simulation or potential mistakes in the measurement extraction process, to have a large influence on the coefficient of determination.

It was unexpected that the displacement ratio in the backrest for both Seat 1 and Seat 2 showed the highest correlation out of all the measurements taken. No papers were found regarding car seat comfort assessment that generated good correlation between displacement and comfort scores. In addition, Karlsson and Öhrskog (2019) found the lowest correlation out of all their measurements for the average pressure in the lumbar back area. As the same comfort scores have been used for this thesis, it was likely that the backrest measurements would show lower correlation compared to the cushion measurements. The second highest correlating measurement, maximum von Mises stress in the buttock muscle, was

expected as Ramanjaneya and Avineedi (2017) and Laurent *et al.* (2014) also found good correlation with this measurement.

The comfort score correlation study made for Seat 1 and Seat 2 in Figure 29 and Appendix A respectively, gave an indication of how representative the initial comfort scores can be with respect to the overall seat comfort score. If the correlation was high, one could argue that the initial comfort scores would be sufficient for future overall seat comfort assessments, including dynamic aspects of comfort. The highest coefficient of determination for both Seat 1 and Seat 2 was found for the initial cushion comfort scores. This was expected as the overall magnitude of pressure, displacement and contact area in the cushion does not change as much between different testing categories compared to the backrest measurements. More data points are required before any conclusions can be drawn from this study.

5.4 Potential of Methodology in Design Process

Car seats are an important part of the design (Serre, et al., 2006) process of premium cars, so prototype seats are built, tested, and improved in the comfort clinic. This clinic aims to evaluate the comfort of a seat and make alterations to make it more comfortable. If there is a compromise in the comfort of the seat, then they must redesign and perform the clinics again. But both the clinic and production of prototype seats consume valuable time and budget before a final design is complete. OEMs can use CAE method to analyse the comfort and speed up the process, design better seats, and beat the competition in the market.

6 Conclusion

Seat comfort is an important factor when customers select a premium car. This factor is growing in importance. To address this, OEMs want an objective way to predict seat comfort early in the design process. FE HBMs is a potential tool for assessing seat comfort virtually. The purpose of this thesis was to develop an objective method for predicting seat comfort using FE HBMs together with FE seat models. The SAFER HBM was also modified to better suit seat comfort assessment as it was developed for crash scenarios.

The material models for fat and muscle were changed for the SAFER HBM to potentially enable proper modelling of trunk to seat cushion interactions. These material models were verified by performing single element simulations and comparing to experimental data. Quasi-static seat comfort simulations were performed in LS-DYNA using different versions of the SAFER HBM. A validation analysis of the quasi-static seat comfort simulations was performed for the SAFER HBM modified. There were significant discrepancies for both the seats between the pressure map data and the FE pressure distribution. A more thorough validation method with better results is needed before any significant conclusions can be drawn from a seat comfort assessment of this kind. Suggested improvements to the validations method are discussed in Section 7.1.

The results deemed to be of interest from the simulations were extracted using post processing software and used in a correlation study with subjective comfort scores. The measurement that achieved the highest correlation, on average, with the subjective comfort scores was the displacement ratio for the backrest. The second highest average correlation was found for the muscle stress in the cushion area. These results should be seen as potential indicators for what measurements that are likely to correlate to subjective comfort scores. Further research is needed as described below.

7 Recommendation for Future Work

Many ideas for future work can be found when considering the limitations for this thesis project. Allocated time, available data (comfort scores) and capabilities of the HBMs used were the three main limitations.

7.1 HBM Seating Validation

Pressure mapping has been used to validate the pressure distribution on the seat trim in FE simulations. As discussed previously, this step is vital as the rest of the analysis is based on the assumptions made here. Therefore, it would be valuable to further validate the HBM sitting pressure distribution. Here are some of the potential improvements to the current validation method:

- Use more sophisticated and accurate pressure mats.
- Increase the amount of pressure map data (more participants testing the seats).
- Further investigate how friction between the seat trim and seat foam affects pressure distribution as this effect is not taken into consideration in the FE simulations.
- Record the exact seating position and adjustments used at the time of pressure mapping and use the same position in the FE simulations.
- Use participants for pressure mat tests that have physical characteristics that are as close to the HBM's physical characteristics as possible.

7.2 HBM Morphing

When working with HBMs physical characteristics are taken from averaged measurements of the population of interest. The SAFER HBM is based on a 50th percentile American male but there is no current method readily available for changing the physical characteristics of the SAFER HBM to represent other body types. Larsson *et al.* (2021) worked on morphing the SAFER HBM v9 and further work is being done regarding this issue. This would be valuable for seat comfort simulations as the human body's fit to the seat has been shown to be an important aspect of comfort (Oudenhuijzen *et al.*, 2003).

7.3 Dynamic Seat Comfort

Only quasi-static conditions were investigated for this thesis due to limitations in time and resources available. As people tend to spend most of their time in cars driving, dynamic conditions need to be investigated to obtain a method of evaluating overall seat comfort of a car. Dynamic conditions can be divided into two aspects:

- *Seat vibrations*: Cho *et al.* (2017) performed a vibration excitation test where acceleration was measured in three directions at the forehead, chest and thighs of human volunteers. These measurements were used to calibrate a similar test setup in FE software. It was recommended for future

work to develop a riding comfort index based on ergonomic criteria to enable dynamic seat comfort analyses.

- *Dynamic support*: Okiyama *et al.* (2001) made a study on lateral support of car seats where the movement and muscle activation of a car seat occupant while driving through a corner was measured. It was found that poor lateral support led to higher muscle activation at the torso and groin, which was considered to be less comfortable.

7.4 Further Correlation

As mentioned in Section 5.3.2, it is important to have an adequately large sample size when computing the correlation coefficient. This was not the case for this thesis but can be achieved by increasing the number of seats in a future comfort clinic. For example, a comfort clinic performed with both Seat 1 and Seat 2, resulting in eight data points, would be beneficial. Increasing the number of participants would also be beneficial for correlation as this would increase the validity of the comfort scores. Further measurements could also be extracted from FE simulations to allow for a deeper investigation into seat comfort correlation.

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Appendix A

The correlation plots for Seat 2 are shown here in figures A.1 – A.10.

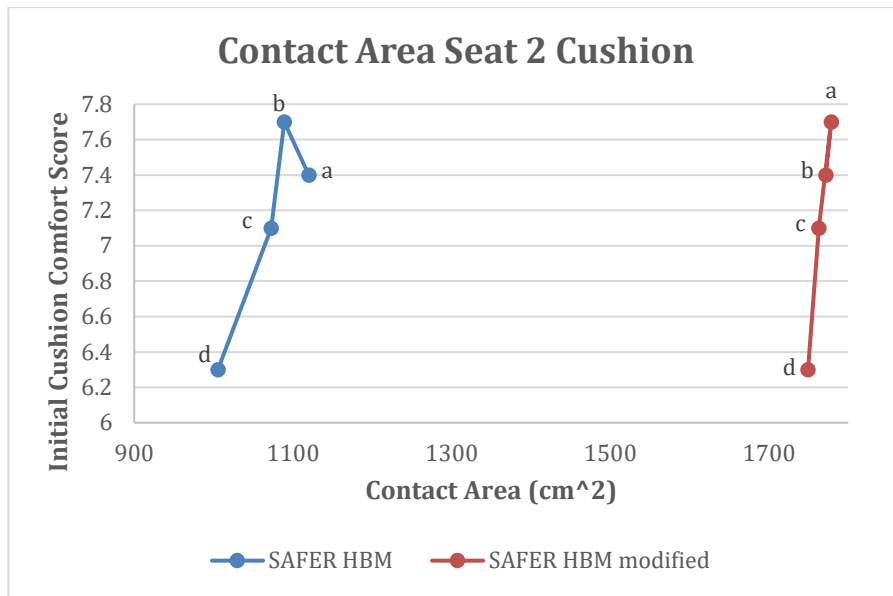


Figure A.1: Contact area correlation plot.

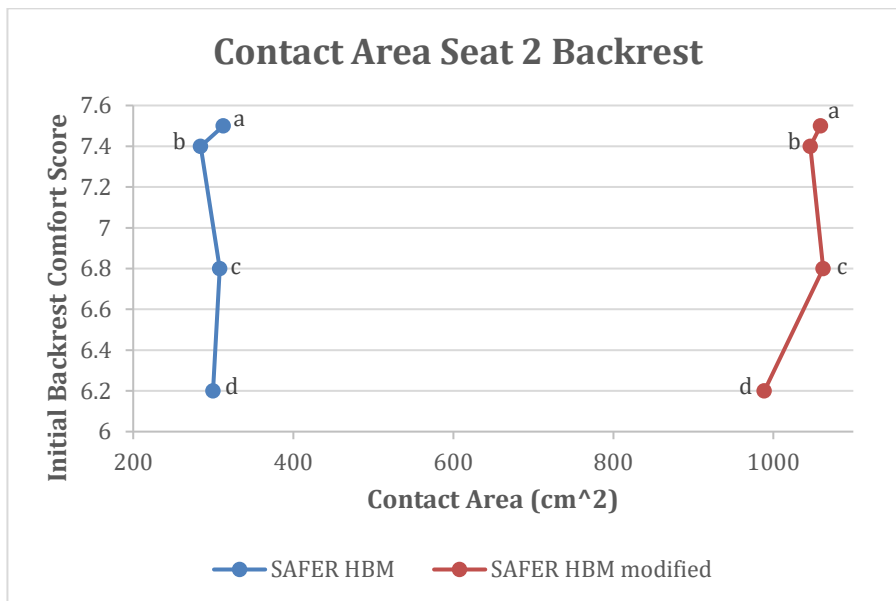


Figure A.2: Contact area correlation plot.

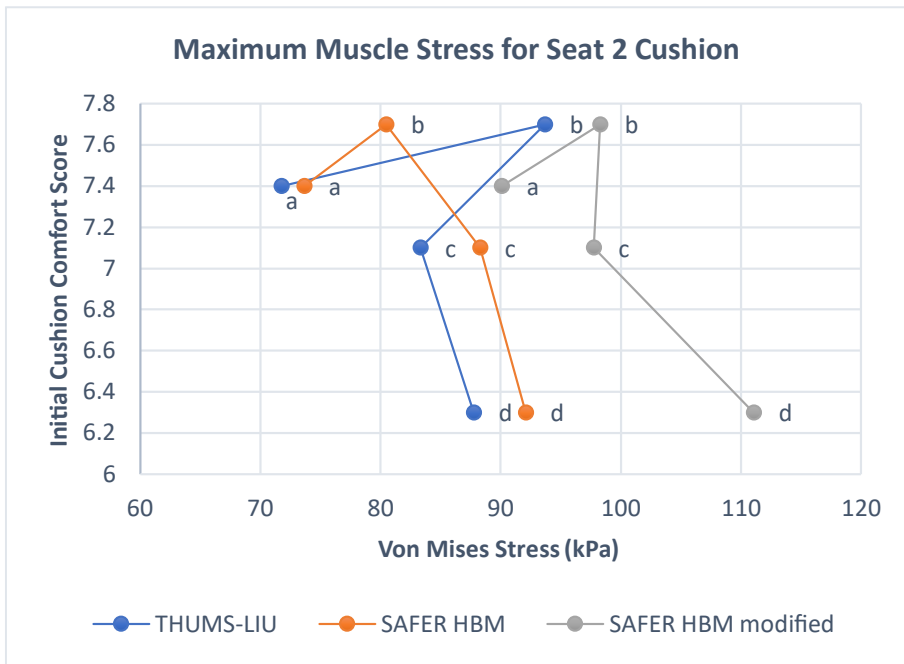


Figure A.3: Buttock muscle stress correlation plot.

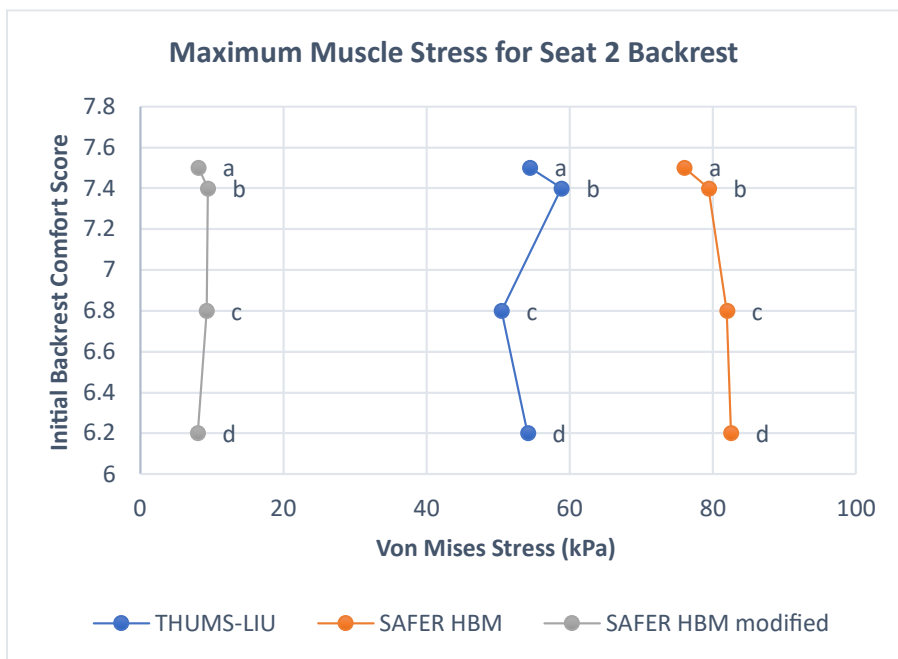


Figure A.4: Back muscle stress correlation plot.

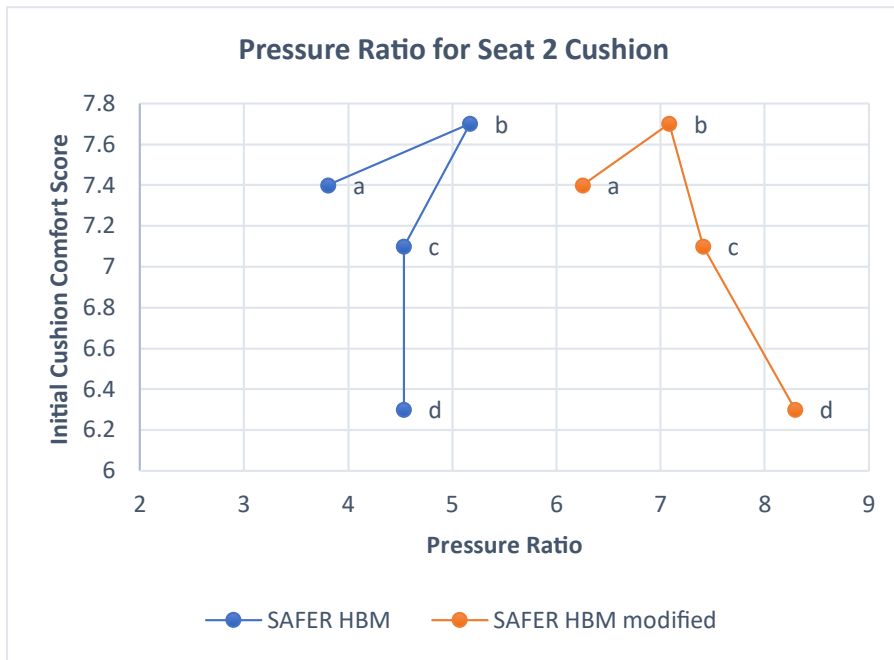


Figure A.5: Pressure ratio correlation plot.

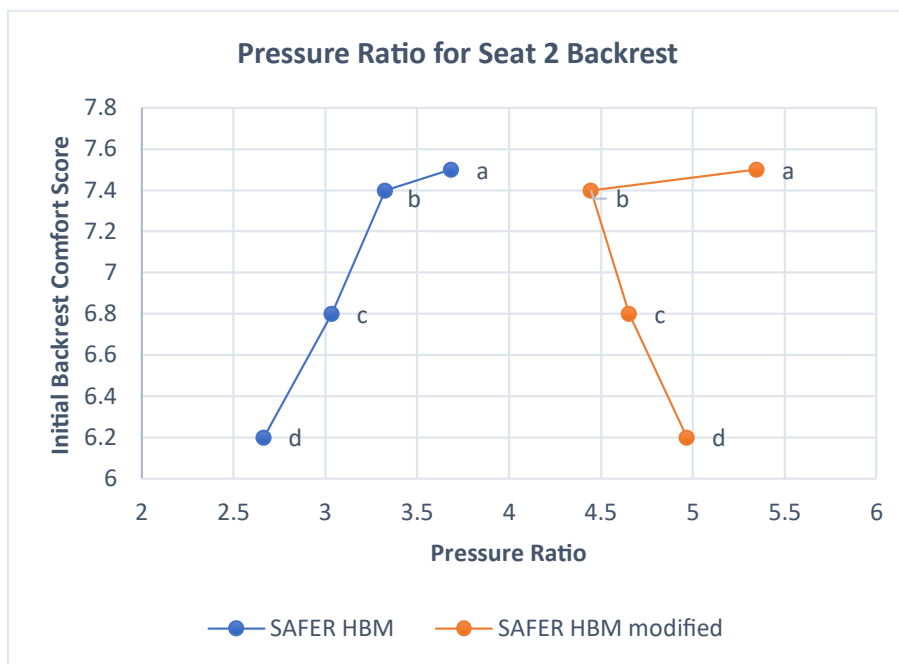


Figure A.6: Pressure ratio correlation plot.

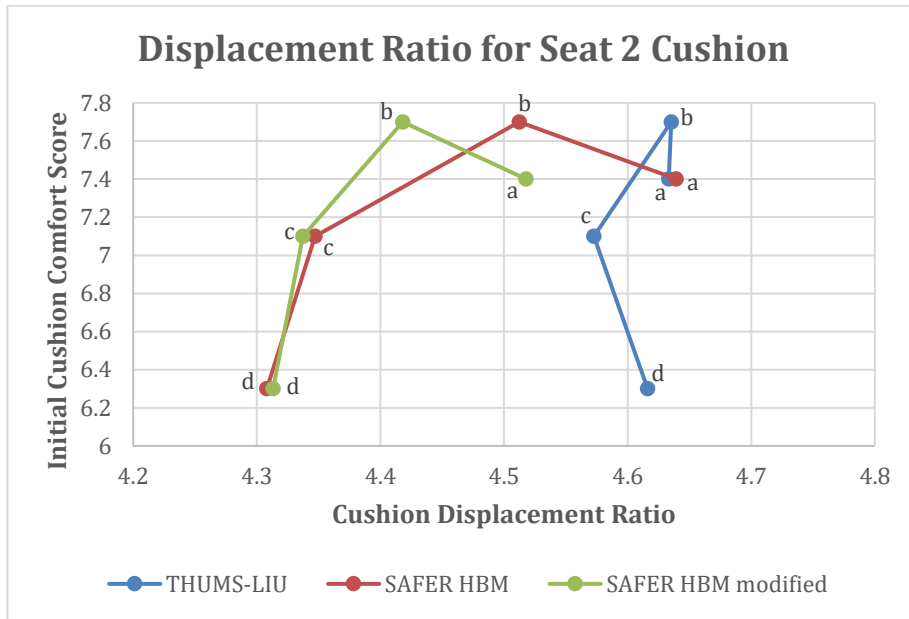


Figure A.7: Displacement ratio correlation plot for Cushion

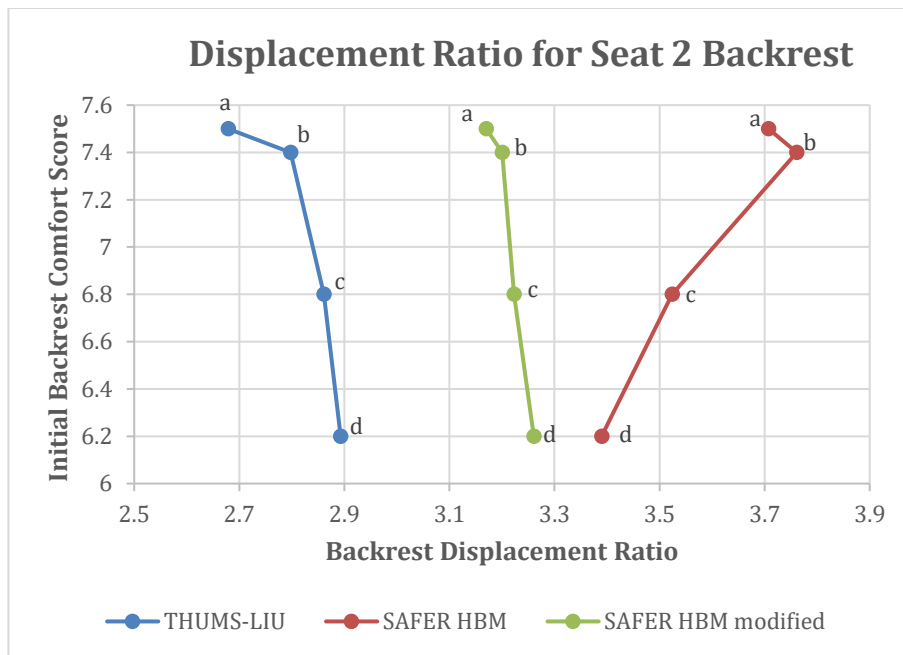


Figure A.8: Displacement ratio correlation plot for backrest

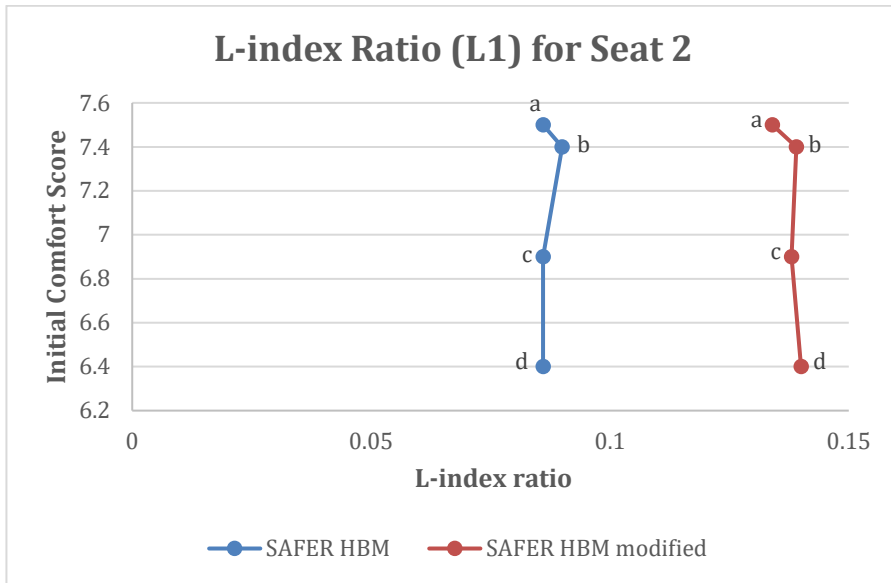


Figure A.9: L-index ratio correlation plot

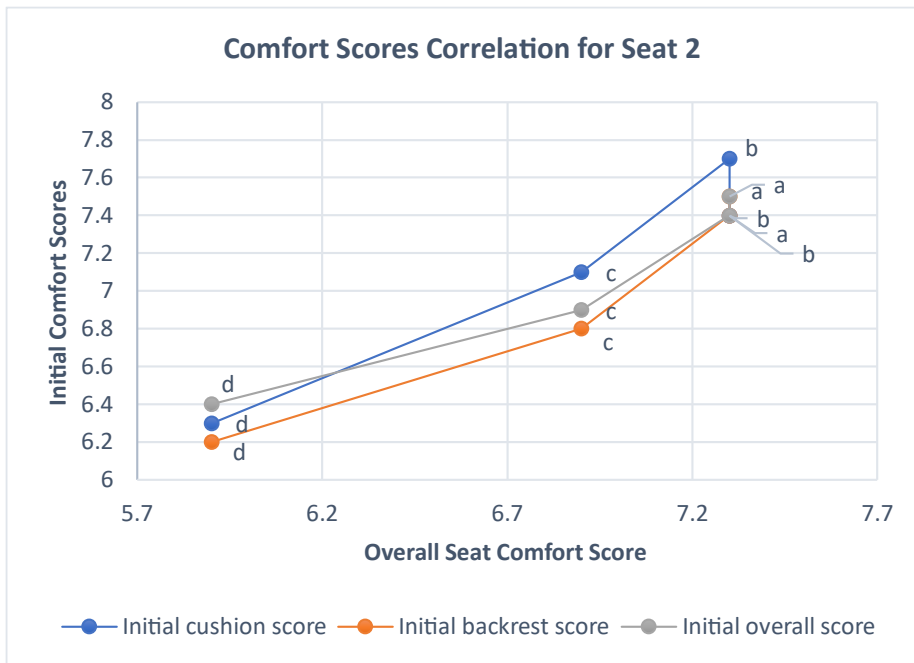


Figure A.10: Correlation graph for comfort scores.

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