THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

in

MACHINE AND VEHICLE SYSTEMS

Rib and Thoracic Response in Frontal Car Crashes: A Study Using a Finite Element Human Body Model

by

MANUEL MENDOZA VAZQUEZ

Vehicle Safety Division
Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden, 2012

Rib and Thoracic Response in Frontal Car Crashes: A Study Using a Finite Element Human Body Model

M A N U E L   M E N D O Z A   V A Z Q U E Z

THESIS FOR LICENTIATE OF ENGINEERING no 2012:17
ISSN 1652-8565

Department of Applied Mechanics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone +46 (0)31 772 1000

Chalmers Reproservice
Gothenburg, Sweden 2012

ABSTRACT

Traditionally, restraint systems have been evaluated with Anthropomorphic Test Devices (ATDs) and the thoracic injury criteria have been based on parameters assessed using ATDs, such as chest compression. ATDs have limitations since they are only a gross representation of the human body. ATDs and injury criteria have shown insensitivity to modern restraint systems, such as seat belts and air bags. The evaluation of current and development of new restraint systems require improved tools and injury criteria. Using Finite Element (FE) Human Body Models (HBMs) may be a possible complement. FE HBMs offer a more detailed description of the human anatomy compared to ATDs and potentially they may also allow the study of injuries at tissue level.

In this thesis, the FE HBM Total HUman Model for Safety version 3.0 (THUMS v3.0) was improved and the biofidelity of the resultant model, THUMS v3-M, was assessed in table top, pendulum and sled tests. THUMS v3-M was used to study the rib response and thoracic stiffness and coupling responses under loads representative of modern restraint systems in frontal impacts. The knowledge on rib response was applied to identify characteristics of future rib and thoracic injury criteria candidates. The knowledge on thoracic deformation was applied to make recommendations for the improvement of THOR.

THUMS v3-M performed better than THUMS v3.0 in the biofidelity assessment tests used in this thesis. It was found that injury criteria candidates should be sensitive to bending, shear and torsion loads in the rib. The recommendations to improve THOR were to decrease the rib stiffness and include the stiffness of the thoracic organs as spring-damper mechanisms, and to represent the intercostal muscles by means of a mechanical structure.

KEYWORDS: Frontal crash, thoracic injury criteria, rib fracture, Human Body Model, Finite Element, THUMS

ACKNOWLEDGEMENTS

This work was carried out as a part of the project THORAX, funded by the European Commission Seventh Framework Programme 7, Transport, SST.2007.4.1.2: Human physical and behavioural components, grant number: 218516, and the project Improved injury prediction using HBM, funded by SAFER - Vehicle and Traffic Safety Centre at Chalmers, Sweden. Project partners were Autoliv, Volvo Car Corporation, Volvo Technology, Umeå University and Chalmers University of Technology.

I would like to thank my academic supervisor Professor Jac Wismans, and co-supervisors Associate Professor Karin Brolin and Assistant Professor Johan Davidsson for their support and guidance.

I would like to acknowledge the project partners: Ph.D. Bengt Pipkorn at Autoliv Research, Adjunct Professor Lotta Jakobsson and Merete Östman at Volvo Car Corporation, Ph.D. Stefan Thorn and Ph.D. Fredrik Törnvall at Volvo Technology, Ph.D. Mats Lindkvist at Umeå University.

I would like to show my gratitude to my colleagues at the Vehicle Safety Division and SAFER.

Special thanks to my family and to Andrea for their love and support.

APPENDED PAPERS

Paper I

Mendoza-Vazquez, M., Brolin, K., Davidsson, J., (2012), Human rib response to different restraint systems in frontal impacts: a study using a Human Body Model

To be submitted for publication in International Journal of Crashworthiness

Paper II

Brolin, K., Mendoza-Vazquez, M., Song, E., Lecuyer, E., Davidsson, J. (2012), Design implication for improving an anthropometric test device based on human body simulations, International IRCOBI Conference on the Biomechanics of Impact, Sept 12-14, Dublin, Ireland

AUTHOR’S STATEMENT OF CONTRIBUTIONS

Paper I

Mendoza-Vazquez carried out the simulations, the analyses of the results and the interpretation of the results, and wrote the paper under supervision of Brolin and Davidsson.

Paper II

Mendoza-Vazquez planned and executed the simulations with THUMS as well as performed the post processing and analysis of the results. Song and Lecuyer performed the analysis of the rib strain. The paper was written by Brolin with contributions by the co-authors.

TABLE OF CONTENTS

ACRONYMS

AIS	Abbreviated Injury Scale
ATD	Anthropomorphic Test Device
Cmax	Maximum Chest Compression Criterion
DC	Combined Deflection Criterion
FE	Finite Element
GHBMC	Global Human Body Model Consortium
HBM	Human Body Model
HUMOS2	Human Model for Safety 2
NHTSA	National Highway Traffic Safety Administration
PMHS	Post Mortem Human Subject
THOR	Test device for Human Occupant Restraint
THUMS	Total Human Model for Safety
VCmax	Viscous Injury Criterion

1 INTRODUCTION

The introduction of seat belts and air bags has significantly contributed to the decline in the number of fatalities and severe injuries in frontal impacts. Bean, et al. (2009) estimated that the fatality risk for occupants wearing a seat belt in a vehicle fitted with air bags in frontal impacts can be reduced by 61 percent compared to an occupant travelling unbelted in a vehicle not fitted with air bags. Despite the seat belt and air bag effectiveness, the National Highway Traffic Safety Administration (NHTSA) reported in 2012 that 9,934 restrained vehicle occupants died in the US in 2010. Klanner (2001) reported that in Europe, 40 percent of all car crash fatalities were occupants in frontal impacts. In these impacts, injuries to the thorax are common, and account for 13 percent of all moderate injuries on the Abbreviated Injury Scale(AIS 2), and 29 percent of all severe injuries (AIS 3+) as reported by Ruan et al. (2003). Rib fractures are the most common thoracic injury sustained in frontal impacts as described by Carroll (2010). Furthermore, Wanek and Mayberry (2004) pointed at the importance of rib fractures as these lead to serious intrathoracic and abdominal injuries, and as predictors for pulmonary deterioration. To reduce the number of rib fractures it is necessary to improve currently available restraint systems.

Tools are required to evaluate improvements made to restraint systems. These tools should be required to predict injuries occupants may sustain in a specific impact. Clearly, the best restraint system for a particular impact will be the one predicting low risk of serious injury. Anthropomorphic Test Devices (ATDs) are mechanical representations of the human body and is one of the tools used. Although the ATD´s numerical representations are commonly used today within the car industry, they still aim to model a mechanical representation of the human body. Human Body Models (HBMs) used in a testing and regulatory environment. Numerical models of ATDs and of the human body are one more type of tools that have been developed to evaluate restraint systems.

These tools need a metric to estimate the risk of injury during a certain impact. ATDs have been instrumented to measure global parameters such as displacement, velocity, acceleration and force. These parameters or their combinations have been used as the metric to estimate injury risk; these equations commonly referred to as injury criteria. Injury criteria measured with ATDs have been used in regulatory testing for new cars and to predict the protective potential of new restraint systems during their design phase. For the thorax, among the most widely used injury criteria we find:

Maximum chest compression (Cmax). Is used to assess the injury risk based on rib fractures (Kroell et al., 1974). It is defined as the ratio of chest deflection to initial chest depth.

Viscous Criterion (VCmax). Is used to assess risk of injury for the thoracic and abdominal organs (Lau and Viano, 1986). It is defined as the maximum of the product of the chest compression and the derivative of deflection with respect to time.

An issue with these injury criteria is that they were developed to be assessed with ATDs and their limitations in instrumentation. They are based on the chest compression measurements from the ATDs.

The thoraxes of Hybrid III and its intended successor, THOR, were developed and validated mainly against pendulum impacts to the mid sternum (Foster et al., 1977, Shams et al., 2005). The Hybrid III instrumentation was designed to assess the chest compression with respect to the spine of the mid-point of the sternum. THOR is able to measure three dimensional displacements at four points on the rib cage, but there is no widely accepted injury criterion that includes those displacements. Recently, the combined deflection criterion (DC) was proposed by Song (2011). This criterion takes into account the sternal compression and the difference in deflection between the left and right sides of the ribcage, however, the procedure to assess it with THOR is still under development. In conclusion, the common frontal ATDs still rely on chest compression to predict injury and the most common thoracic injury criteria are still based on this parameter.

Modern restraint systems include air bags and seat belts that impose a quite different load to the chest compared to that from the pendulum. The pendulum impacts to the sternum load the chest symmetrically, in contrast with the asymmetrical loads imposed by a seat belt. This could be a reason for the restraint system dependency of the maximum chest compression criterion while measured with Hybrid III. An example of this dependency is that Hybrid III, while restrained by a seat belt, predicts a 50% AIS 3+ injury risk for a 50 mm chest compression. When Hybrid III is exposed to blunt chest loading, a 61 mm chest compression is allowed for the same injury risk (Mertz et al., 1997). It has also been shown that Cmax, as measured with THOR is not sensitive to modern restraint systems. Furthermore, the maximum chest compression has occurred at other points than the mid sternum. In conclusion, there is a need to improve the injury criteria and the frontal ATDs.

As mentioned before, there are numerical models of ATDs and of the human body. At present, two methods are available to create such models, multi body and Finite Element (FE). The multi body method allows the calculation of kinematic response, while the FE method allows the calculation of dynamic and material response, i.e., strains and stresses. An advantage of the FE HBMs over the ATDs is that the FE HBMs offer a more detailed description of the human anatomy, potentially allowing studies of injury mechanisms at tissue level (Wismans et al., 2005). HBMs are often used to study restraint interaction and to assess injury risk. The knowledge on injury mechanisms obtained through FE HBM studies can also be used to identify the organs and tissues that should be present in the ATDs and parameters that are related to injury and which should also be measured in the ATDs.

Kent (2002) noted that injury criteria could be correlated to injury without being functionally related to it. In other words, these injury criteria are not related to the injury mechanism. An injury criterion that is functionally related to an injury (like stresses and strain) is to prefer but are difficult to measure in an ATD.

The most common thoracic injury is rib fractures. Ribs, as any other bone, consist of collagen fibres and mineral salts in a complex microstructural arrangement. Because of this arrangement, bone has different load thresholds depending on the loading applied (Kent, 2002). Bone tissue is weakest in tension or shear and strongest in compression (Turner, 2006). Understanding of how ribs are loaded in a frontal crash is a step towards establishing a rib fracture criterion that is functionally related to an injury. The difficulties to install instruments to and perform a test with Post Mortem Human Subjects (PMHSs) to study detailed rib response during frontal impact are numerous. The use of HBM simulations is a complement to advanced PMHS tests in order to better understand the rib response in PMHS.

The use of HBMs to study how human ribs respond to frontal impacts and modern restraint systems requires a biofidelic model. Wismans (2005) defined biofidelity as the process where a model's reliability is assessed against a set of PMHS tests. These tests should be relevant for the load cases of interest, in this case, frontal impact with modern restraint systems such as seat belts and air bags.

As presented here, current thoracic injury criteria are based on chest deflection measured at the mid sternum of Hybrid III or THOR. It has also been described that injury criteria assessed with these ATDs is not sensitive to modern restraint systems (Petitjean et al., 2002). This is in part because of limitations with the ATDs and in part limitations with the criterion. ATDs have shown non-biofidelic stiffness distributions on the thorax (Shaw et al., 2005), leading to non-biofidelic deformations of the rib cage. A limitation with the criterion is that chest compression is evaluated at the mid-sternum, with only one point it is difficult to capture the deformation of the thorax under asymmetric loads like the ones from seat belts (Song et al., 2011). A biofidelic HBM can be used to study how human ribs and thorax respond in frontal impacts when wearing modern restraint systems. The way ribs respond is of interest since they are the most common thoracic injuries during frontal car crashes and are associated with injuries of the thoracic organs. Studying the rib response can allow insight into the different types of internal loads that appear in the ribs and that ultimately produce their fractures.

1.1 Aims

The aims of this thesis are:

To evaluate the biofidelity of an HBM based on a set of PMHS tests representative of frontal impact and modern restraint system loadings.

To use THUMS to gain knowledge on how the human ribs responds to frontal impact and modern restraint system loadings. Apply that knowledge to define characteristics of rib and thoracic injury criteria candidates.

To use THUMS to gain knowledge on how the different tissues in the thorax influence its response to loads typical of frontal impact and modern restraint systems. Apply that knowledge to make suggestions on modifications to the THOR design.

1.2 Experiments on thoracic response

Several PMHS experiments have focused on the global response of the thorax which includes its stiffness, mid sternum deflection, spine acceleration, etc. The first PMHS experiments were pendulum tests, as those performed by Kroell et al. (1971) where a pendulum possessing a certain mass and speed impacted the mid sternum of the PMHS while chest compression and force were measured. These tests were representative of unrestrained car occupants who impacted the steering wheel hub or the instrument panel. These tests have been used as a biofidelity assessment test for ATDs and HBMs. As more people began to wear seat belts, it became necessary to investigate the thoracic response to seat belt loads. To name a few of these tests, L'Abbé (1982) performed experiments on volunteers lying on a table while loaded by a seat belt, tracking the chest deflection at eleven different points. Thoracic response to air bags alone or air bag loads in combination with different types of seat belts has also been studied, as seen in Morgan et al. (1994). The measurements obtained in all of the above mentioned tests include the outer deflection of the thorax, with forces applied to it, as well as spine accelerations. Kent et al. (2001) showed that the flesh acted as a filter and the rib cage deformed differently to the external soft tissue. Hence, to improve the current restraint systems and make them distribute the load in a frontal crash in a less injurious fashion, it is necessary to understand how the rib cage and the individual ribs and rib cages are loaded and deformed, not just what the global response of the thorax is.

To gain knowledge on how ribs are loaded, researchers have added strain gages to the ribs and performed impactor tests, similar to those performed by (Trosseille et al., 2008). Vezin and Berthet (2009), and Kindig et al. (2010) tested the response of rib cages to localised loads. In these experiments, the spine of the specimens was fixed, internal organs and superficial tissue were removed, and the load was applied by an indenter. Shaw et al. (2009) attached photo targets to the bones and tracked their displacement in space during sled tests. The obtained information is valuable for understanding the rib response to frontal impacts, but it is limited because the number of photo targets should be kept to the minimum to avoid affecting the PMHS response. Single ribs have also been tested in anteroposterior compression and instrumented with strain gages as seen in (Charpail et al., 2005) and (Kindig, 2009). In these experiments, the ribs were isolated and tested under anteroposterior deflection and their ends were constrained to remain in the same plane. These experiments established the timing and location of the fracture, however, the experimental environment differs from the rib environment inside the human body. As described, rib response during frontal impacts is difficult and expensive to study using PMHS tests and simulations comprising HBMs is an alternative way to study the rib response in frontal impacts. Paper I presents a study based on HBM simulations aimed at understanding how ribs are loaded during frontal impacts.

1.3 Anthropomorphic Test Devices

Nowadays, Hybrid III is the type of ATD most widely used in the automotive industry to predict thoracic injuries in frontal crashes and THOR is its proposed successor. Both ATDs have been subjected to several studies designed to compare their thoracic response to PMHS tests. In a series of eighteen sled tests, nine at 50 km/h with air bags and force limited seat belts and nine at 30 km/h with force limited seat belts only, Vezin et al. (2002) compared THOR and Hybrid III accelerations to PMHS results. This test concluded that THOR showed a better agreement with the PMHS accelerations than Hybrid III. Shaw et al. (2002) conducted 48 km/h frontal sled tests, three with THOR, three with Hybrid III and four with PMHS. The sled was equipped with force limited seat belts, pretensioners and air bags in order to compare the response of the ATDs with PMHS results. The THOR results correlated more to those of the PMHS than those of the Hybrid III.

THOR has showed a more humanlike response than the Hybrid III, but would still benefit from being improved. Petitjean et al. (2002) found that the chest deflection as measured on THOR did not verify the empirical fact that a 4 kN load limiting belt and air bag produces less chest injuries than a 6 kN load limiting belt without air bag. Kent et al. (2003) found indications that THOR is less biofidelic for some restraints than for others when comparing the THOR dummy and PMHS responses in table top tests. THOR displayed a stiffer response than the PMHS´s to indenter tests and non biofidelic regional stiffness as reported by Shaw et al (2005). THOR includes several simplifications compared to a human body and their influence on the thoracic response in terms of stiffness and coupling is partly unclear. To investigate the influence of these simplifications on response by means of PMHS tests is, if not impossible, very difficult.

Simulations comprising HBMs can be of considerable benefit in this task, which is studied further in Paper II.

1.4 Human Body Models

Several HBMs representing the 50th percentile male have been developed in recent years in different FE codes. For example, the Human Model for Safety (HUMOS2), by (Vezin and Verriest, 2005) in the Radioss™ code and Total HUman Model for Safety version 3.0 (THUMS v3.0, Toyota Central R&D Labs., Inc.) coded in LS-DYNA® (Hallquist, 2006). Holmqvist (2009) evaluated both models and found that THUMS v3.0 performed better than the HUMOS2 in pendulum impacts. Song et al. (2009) developed HUMOS2LAB based on HUMOS2. Recently, THUMS version 4.0 (Shigeta et al., 2009) was released, incorporating improvements such as individual models of the thoracic internal organs. A model that is under development and evaluation is the Global Human Body Models Consortium (GHBMC), a model comprising approximately two million elements and individual models of the internal organs (Gayzik et al., 2012). The purpose of these models is to evaluate the occupant kinematics during a crash and to investigate injury mechanisms (Yang, 2001).

1.4.1 THUMS

The HBM used in this study was THUMS v3.0. It represents a 50th percentile male occupant, with a mass of 77 kg and stature of 1.75 m. It roughly consists of 150,000 elements and 110,000 nodes. Bones were modelled using shell elements for the cortical bones and solid elements for the trabecular bones. Joints were modelled anatomically including the major ligaments and bone to bone contact, no mechanical joints were included (Iwamoto et al., 2002).

Figure 1. THUMS v3-M in the pendulum test. Tissues were removed to make the rib cage visible.

The biofidelity of the thoracic response of the different THUMS versions has been evaluated in several publications. Oshita et al. (2002) and Kimpara et al. (2006) compared the force-deflection response of the thorax to frontal and lateral pendulum impacts. Murakami et al. (2006) reproduced the table top tests by Kent et al. (2005) and found that the agreement between the model and the PMHS results were improved by changing properties on the rib cartilage. Pipkorn and Mroz (2009) compared THUMS v2.21 to PMHS sled tests and found that the chest compression measured with THUMS v2.21 was generally greater than that for the PMHSs. Pipkorn and Kent (2011) modified the mesh as well as the material data and added muscles to the THUMS v2.21. Their model reacted similar to the PMHS in the table top tests by Kent. In sum, numerous studies have been published on the subject of the thoracic biofidelity of THUMS; most report that modifications to the model are needed to improve its response. Furthermore, to the best of my knowledge, no publication has showed the thoracic response of any THUMS version to several load cases, i.e., sled and table top tests. Modifications and a biofidelity assessment of THUMS v3.0 is described in Paper I. These modifications to THUMS v3.0 resulted in THUMS v3-M, shown in Figure 1.

2 SUMMARY OF PAPER I

The first aim of this paper was to present the modifications made to THUMS v3.0 and the biofidelity assessment of the modified version. The second aim was to study the individual rib responses in THUMS during different load cases representative of frontal car crashes.

Modifications to THUMS v3.0 were needed to increase its numerical robustness and stability, and to improve its biofidelity. A finer mesh in the rib cage and in the soft tissues around the rib cage was the most relevant modification made to improve numerical robustness and stability. The tests used to modify the refined THUMS and improve its biofidelity response were the single rib tests by Kindig (2009), and table top tests with four different load cases (Figure 2) and three different rib cage states by Kent et al. (2005). The most important modification made was the change in material properties for the thoracic organs and the soft tissues around the rib cage, which included muscles, fat and skin. The refined THUMS overestimated the effective stiffness of the thorax by as much as a factor two in these tests. After the described modifications, the values predicted by the model in the twelve table top test cases (four load cases and three rib cage states) were within one standard deviation from the mean experimental results for eleven of the twelve cases.

The biofidelity of the modified THUMS was evaluated with the table top tests by Kent et al. (2004), the pendulum tests (GESAC, 2005) and sled tests (Figure 3) by Shaw et al. (2009). The table top tests used for the biofidelity assessment included fifteen PMHSs, in contrast with the three PMHSs for the model modifications. The model response was within the experimental corridors for the table top tests in the range of interest. The response of the model in the pendulum test was in the corridor, with exception of a force peak at maximum chest deflection. The maximum forward excursion and chest compression for the modified THUMS was within the range of the experimental results.

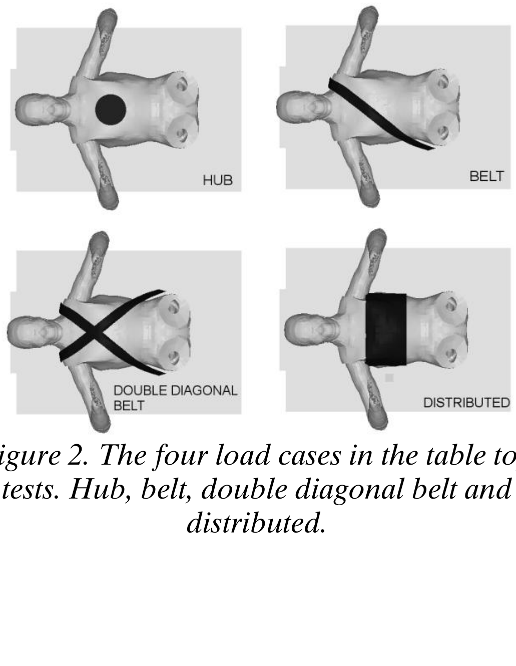

Figure 2. The four load cases in the table top tests. Hub, belt, double diagonal belt and distributed.

Figure 3. THUMS in the sled test

The study of rib response to frontal impacts was based on full body tests: a) distributed case in table top tests, b) pendulum test and c) sled test. The variables applied to characterise the rib response were: a) end-to-end displacement, b) aspect ratio, c) bending moment, d) torsion moment, and e) first principal strain. Bending and torsion moments were assessed at the cross section depicted in Figure 4. As expected, the ribs exhibited bending during the single rib tests. The distributed or air bag like case added torsion to the rib response. In the pendulum test, the ribs in the model presented a concentrated deformation close to the impacted region. Ribs in the modified THUMS presented a complex response during the sled test simulations. The rib response varied according to the belt position. The greatest end-to-end displacements were located on the lower ribs below the seat belt path, while the lower ribs on the free side were elongated. Furthermore, the ribs below the seat belt path experienced the greatest aspect ratio variations.

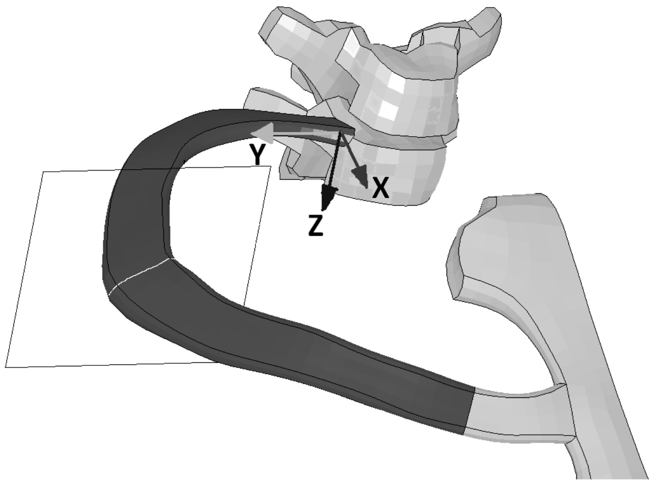

Figure 4. Cross section at the most lateral point of the rib and normal parallel to X axis. Moments were assessed in this cross section.

It was concluded that the information obtained regarding rib response would be beneficial when proposing possible rib fracture criteria candidates by defining some characteristics. A rib fracture criteria should be sensitive to bending, torsion and shear loads in accordance with the obtained results. These loads impose out of plane deformations on the rib, not only in the anteroposterior direction. On a material level, the von Mises strain appears to have better opportunities of predicting rib fracture than the axial strain. On the rib structural level, the preferred option appears to be a criterion including end-to-end displacement and aspect ratio rather than end-to-end displacement. A global criterion for the chest including the displacements of the anterior rib ends in three orthogonal directions may be more suitable than the current chest compression criterion.

3 SUMMARY OF PAPER II

The aim of this paper was to make recommendations for improving future ATD designs by introducing ATD-like simplifications into THUMS and estimating what the influence would be on thoracic response.

The thoracic effective stiffness, coupling and chest deflection were the parameters used to characterise the thoracic response. The thoracic effective stiffness was defined as the as the slope of curve plotted by the reaction force versus the mid-sternal chest compression curve, when the mid-sternal chest compression ranged from 0 to 20% (Kent et al., 2004). Shaw et al. (2007) defined coupling as the relative deflection response of sites remote to the loading site in the thorax, Figure 5. These parameters were evaluated using THUMS in simulations of the table top tests by Kent et al. (2004), and sled tests by Shaw et al. (2009), Figures 2 and 3. The first part of the study analysed the influence on effective stiffness and coupling had on different tissues and organs which was achieved by applying 50 percent less stiffness to the rib cartilage, sternum cortical bone, intercostal muscles, costovertebral ligaments and rib cortical bone. In the second part of the study, different simplifications present in THOR with respect to the human thorax, were introduced in THUMS. These simplifications were: a) a 50 percent increase in the rib cortical bone stiffness, b) shortening of the rib cartilage and extension of the rib bone in accordance with the size in THOR, c) a 50 percent increment in clavicle stiffness , and a 90 percent reduction in stiffness for a row of elements in the sternum, d) a 80 percent reduction in density for the thoracic and abdominal organs, compensated by adding mass to the thoracic and lumbar spine, and e) elimination of thoracic and abdominal organs, compensated by adding their mass to the thoracic and lumbar spine, a 150 percent increment in elastic modulus of the rib cortical bone and a 900 percent increment in elastic modulus of the costovertebral ligaments.

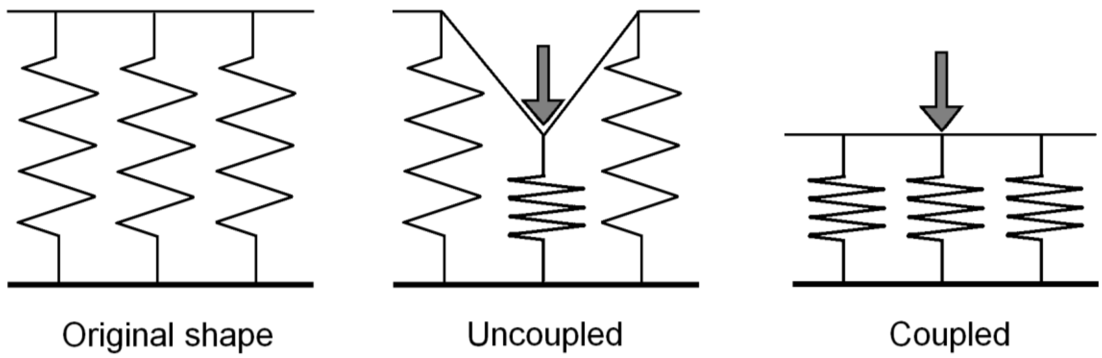

Figure 5. Sketch to illustrate coupling.

The results for the first part of the study showed that the rib cortical bone and the intercostal muscles had the greatest effect on thoracic effective stiffness and chest compression. Reducing the compliance of the rib cartilage and costovertebral ligaments displayed the least change in thoracic stiffness and chest deflections. The change in properties for the sternum resulted in different responses in the table top and sled tests as the model with the softer sternum responded with more considerable chest deflection during the sled test compared to the table top test. The rib cortical bone displayed similar behaviour. The difference in response is most likely due to how internal organs load the rib cage due to the inertia of the internal organs loading the chest during the sled tests and not during the table top tests. The lateral and vertical coupling was most affected by the intercostal muscles, rib cortical bone and sternum. The seat belt cases and in particular the sled test presented the greatest differences in coupling. It was also found that decreasing the stiffness decreased the coupling of the thorax.

Dividing the sternum and changing the position of the clavicle were the factors that least changed the stiffness and coupling. The greatest change in chest deflection was obtained following removal of the thoracic and abdominal organs and increasing the stiffness of the ribs and costovertebral ligaments. In this case, the deflection decreased in the table top tests but increased in the sled test. The lateral and vertical coupling increased in all tests for this case.

From the simulations it was concluded that an increase in rib stiffness is followed by an increase in thoracic coupling. Based on this conclusion, the recommendations made to improve the design of THOR, was to decrease the rib stiffness and include a spring-damper mechanism between the spine box and the rib anterior end to represent the stiffness of the thoracic organs.

4 GENERAL DISCUSSION

The long term aim of this project is to develop improved rib fracture criteria for THUMS in frontal impacts. In order to facilitate communication and comparisons, it is desirable that these criteria can be measured using an ATD and other HBMs. Before a rib fracture criteria can be developed, the model it is intended to be used for must be biofidelic. The THUMS biofidelity, with a focus on rib response, was studied in Paper I, while thoracic response was studied in Paper II. Rib response is relevant to gain better understanding of how ribs fail when impacted and such responses may illuminate the parameters describing rib failure. At present, ATDs include simplifications that do not allow for the use of rib level injury criteria. Therefore, Paper II focused on the thoracic response of THUMS with the objective to advice on how to design ATDs with improved biofidelity.

The first step in this study was to evaluate the biofidelity of THUMS v3.0. It was found that the original mesh size of the model´s rib cage was not fine enough and that it generated certain numerical errors during the interaction between the seat belt and the torso, which caused abnormal terminations of the simulation. A finer mesh eliminated such numerical errors, improving the model's numerical stability. The model with the finer mesh was tested in the table top tests and it was found that its response was much stiffer than the experimental results, as described in Paper I. The stiffness results were improved dramatically by changing the material properties of the thoracic organs and the flesh around the rib cage. The numerical errors in the interaction between the seat belt and torso were solved by refining the mesh of the flesh and rib cage. These two issues experienced in the original model illustrate two important aspects of HBMs: biofidelity and numerical stability.

The biofidelity assessment of simulation models was defined by Wismans et al. (2005) as the way to assess the reliability of a simulation model compared to a reference test with one or more human subjects. To improve HBMs even further, there is a need to obtain material properties for the human tissues and organs (i.e. lungs, muscles, cortical bone, etc.). Several experiments have been conducted to test these tissues and organs, but there is still a need for experimental data. Material properties for the lungs are an example of this need. Issues in respect of these experiments include the lack of available data that can be applied to the HBM´s lungs. Firstly, there is a shortage of results from tests performed on human lungs although several experiments have tested different animal lungs. Vawter et al. (1979) tested dog lungs, while rat lungs were tested by Stitzel et al. (2005) and pig lungs were tested by Hayamizu et al. (2003). The second issue is that it is not always viable to apply the relevant load rate for impact applications, which is of particular importance since lungs exhibit a strain rate dependency. Thirdly, the test conditions are generally ex vivo, whereby the lungs are removed from the animals prior to testing.

The size of the model is a limitation in the current study as it represents a 30 to 40 years old, 50th percentile male. It is known that several bodily changes occur with age, such as the bones and cartilages changing in material properties, as described in Zioupos and Currey (1998) and Tamura et al. (2005). Furthermore, the rib cage geometry changes which affect the rib cage deformation, as discussed by Gayzik et al. (2008). Gender differences in the size and shape of ribs has also been reported by Bellemare et al. (2006). The influence of such changes on the rib and thoracic response was, however, outside the scope of this study. The rib and rib cage response described in this study corresponds to that of the modified THUMS, a 50th percentile male. Publications reporting methods for scaling HBMs in size and age are available, as described in Ito et al. (2009) and El-Jawahri et al. (2011). The above mentioned methods may be applied to THUMS in the future to investigate how the ribs and thorax respond to such changes.

An FE HBM expected to evaluate restraint systems should not only be tested in relevant load cases and rates, it should also be biofidelic and numerically stable. These are two characteristics that may require contradictory modifications in the model, as increasing the stiffness of a material to gain in numerical stability but at expense of biofidelity. A challenge with regards to numerical stability in HBMs is the significant deformations to soft materials (i.e., lungs, fat, etc.) during impacts. Soft materials when experiencing large deformations tend to show negative volumes. A technique has been developed to avoid negative volumes without changing the mesh, but it implies increasing the stiffness of the materials. The biofidelity assessment of the modified THUMS included different load cases, pendulum, table top and sled tests, as well as different load rates. A compromise between biofidelity and numerical stability was obtained to model the thoracic organs. The thoracic response of the modified THUMS deviated from the experimental corridor in the pendulum test, however, it was inside the experimental results for the table top and sled tests. The results in table top and sled tests were prioritised over the pendulum tests due to the load rates in restrained occupants being closer to the load rates present in the table top and sled tests. The biofidelity response of the modified THUMS, described in Paper I, was considered satisfactory when analysing the rib and thoracic responses to loads representative of frontal impacts in cars equipped with modern restraint systems.

The rib response was described in Paper I in order to understand the loads present in a rib during a frontal impact. This is relevant, for example when selecting possible rib fracture criteria candidates; they should be able to respond to the loads present in ribs during frontal impacts. A focus was made on the ribs because they are the main structural components in the thorax and its most affected part in injuries sustained in frontal car impacts. Additionally, the thoracic response was the focus of Paper II, where it was found that ribs are indeed the most important structural component of the thorax since the thoracic effective stiffness was most sensitive to changes in the material properties of the rib cortical bone. The objective of the study on chest deflection was to make recommendations for improving the thorax in THOR.

The simulations of full body tests revealed a complex loading superposition in the ribs during the sled tests. In contrast, the simulations of single rib tests predominantly registered bending, and the ribs did not present significant out of plane motions. Single rib tests apply only one of the multiple loads a rib is subjected to in frontal impacts. Hence, using single rib tests to investigate injury criteria is limited by this fact.

Since several loads are superimposed in the ribs during a frontal impact, a rib fracture criterion sensitive to such loads would be advantageous. The end-to-end displacement was the most satisfactory rib fracture predictor for single rib tests according to Kindig (2009). As explained in Paper II, equivalent end-to-end displacements were achieved in the simulations by very different rib responses. End-to-end displacement alone is not enough to predict rib fracture during more complicated load cases than the single rib tests. Combining end-to-end displacement with other parameters such as changes in aspect ratio may be a suitable option.

The results of the rib response may also be applied to the design or the improvement of tests on PMHSs. In Paper I, the most simple load case studied was the single rib test. In the simulations, this load case predominantly generated rib bending, with a positive principal strain in the external rib surface parallel to the longitudinal axis of the rib. The complex load superposition present in the ribs during the simulations of full body tests generated principal strains that were not always aligned with the longitudinal rib axis. Many tests have used single-axis strain gages parallel to the longitudinal rib axis during full body tests, as in Trosseille et al. (2008) and Kemper et al. (2011). Since results from Paper I indicated that the principal strain was not always aligned with the rib axis, one way to complement the results of experiments with single-axis strain gages would be the use of gages in a rosette as in Duma et al. (2011) to study the strain components in ribs during full body tests. In this way, it is possible to improve the instrumentation of PMHS tests. The response of ribs to other loads than bending is also of interest according to the simulation results. In the experiments and the simulations of sled tests, the lower ribs on the unbelted side of the chest were elongated, probably as a response to the inertial load by the viscera. Rib fractures were registered in this area according to the results reported in Shaw et al. (2009). Torsion was another load which appeared in the ribs during the simulations of full body tests. Furthermore, single rib tests applying such loads to the ribs may be of interest on the quest to gain knowledge of how ribs fail under the above mentioned loads.

There are several factors that can influence the location and timing of a rib fracture. Variations in rib cortical bone thickness along the rib, irregular geometry of the ribs and interaction with surrounding tissues are among these factors. The level of detail in

HBMs is limited by the time step, which is a function of the material properties and size of the elements. A time step of 1 μs is the minimum requirement for an HBM in order to run overnight with currently available computers. At this time step, the size of the cortical bone elements should be at least 3 mm, which is the actual element size in the modified THUMS. However, this element size is not sufficient to describe the rib geometry accurately enough to be able to predict location and timing of a fracture, as Li et al. (2010) demonstrated. Although HBMs are intended to be a detailed representation of the human body, they still contain simplifications. These simplifications should be considered while developing injury criteria.

The simplifications present in THOR with respect to a human rib cage are several. Among these simplifications we find that: a) there are no thoracic organs inside the thoracic cavity as the organ´s mass is included by adding mass to the spine and ribs, b) the stiffness of the thoracic organs is represented by stiffer ribs, c) only seven pairs of ribs are included, compared to twelve pairs in a human body, d) no intercostal muscles are attached between the ribs, and e) the thoracic and lumbar spine only has two joints. All the above simplifications make THOR reliant on global criteria at a thoracic level, to predict thoracic injury. These criteria are essentially based on chest deflections. That is why improving the biofidelic thoracic stiffness and coupling of THOR is a priority. In Paper II it was identified that the rib cortical bone and the intercostal muscles were the tissues that contributed the most to thoracic stiffness, while the intercostal muscles and sternum contributed the most to the thoracic coupling. Eckert et al. (2000) measured larger chest displacements in the absence of intercostal muscles in tests comprising PMHSs and concluded that intercostal muscles help to maintain rib cage cohesion. This conclusion correlates with the simulation results.

A finding from Paper II is that an increase in rib cage stiffness is followed by an increase in coupling in THUMS. An increase in coupling reduces the differential deflections in the thorax which is important for THOR, where the ribs are stiffer to compensate for the absence of thoracic organs in the thoracic cavity. If THOR is to calculate a thoracic injury criterion that includes differential deflection measurements, its rib stiffness may be decreased and the internal organs included. The inclusion of internal organs may be achieved with dampers between the ribs and the spine boxes, since the inclusion of a balloon or foam is limited by the thoracic instrumentation.

The relevance of intercostal muscles in the thoracic coupling is one more finding that may improve the design of THOR. In THOR, there is no structure attached between the ribs, with exception of the spinal boxes and the bib. The structure representing the intercostal muscles is the jacket, and it is the friction between the jacket and the ribs, exclusively, that can keep them together. The frictional force, being a function of the normal force, is affected by the normal force acting between the jacket and the ribs. It is feasible to assume that the normal force is affected by the external load applied to the thorax. A concentrated load will register the most substantial normal forces close to the point where the load was applied, while a distributed load will register a distributed normal force. This may present a problem since the degree of coupling appears to be a function of the load. Attaching a piece of textile between the ribs may, however, be an alternative when modelling the intercostal muscles. It may improve the coupling and it may even be possible to decrease the rib stiffness. A numerical model of THOR has been under development (Untaroiu et al., 2009). The alternative proposals with regards to the internal organs, intercostal muscles and rib stiffness should be tested in this tool before implementing them in the physical ATD.

5 FUTURE WORK

The next step in the development of injury criteria for the THUMS is to establish and propose candidates sensitive to the different loads present in ribs during frontal impacts. Maximum principal strain, von Mises strain and stress are among the rib fracture criteria candidates at the material level. At the structural level, change in rib curvature, a combination of the end-to-end displacement and aspect ratio, as well as deformation energy should be considered. Within the global criteria for the thorax, possible candidates include the three-dimensional displacements of the anterior rib ends.

The injury criteria candidates for the different levels could be evaluated with an FE HBM in simulations of tests with known injury outcome and representative of frontal impacts. An FE HBM approach is convenient since it offers the possibility to assess different injury criteria candidates from the model, possibility that PMHS tests may not offer because limitations with their instrumentation.

6 CONCLUSIONS

THUMS v3.0 was modified and its biofidelity response improved. The biofidelity of the model including these modifications, THUMS v3-M, was assessed in the table top, pendulum and sled tests. The response of THUMS v3-M was mainly inside the experimental corridors, this was not the case for THUMS v3.0. The biofidelity assessment tests included load cases and load rates representative of frontal impacts and modern restraint systems.

Simulations with THUMS v3-M showed that ribs responded with bending, shear and torsion to loads representative of frontal impacts and modern restraint systems. These responses varied for the different ribs and load cases. It was concluded that rib and thoracic injury criteria candidates should be sensitive to rib bending, shear and torsion. A set of injury criteria candidates was suggested for the rib at its material and structural levels. Some thoughts about instrumentation and design of new PMHS tests were also discussed.

THUMS v3-M was used to study the influence of different thoracic tissues on thoracic response. It was concluded that an increase in rib stiffness was followed by an increase in thoracic coupling. The intercostal muscles were also identified as tissues that influence the thoracic coupling. The first recommendation to improve the THOR's design was to represent the stiffness of the internal organs as spring-damper mechanisms between the spine and ribs and decrease the rib stiffness. The second was to include a textile material to represent the intercostal muscles.

REFERENCES

Bean, J. D., Kahane, C. J., Mynatt, M., Rudd, R. W., Rush, C. J. & Wiacek, C. (2009) Fatalities in Frontal Crashes Despite Seat Belts and Air Bags – Review of All CDS Cases – Model and Calendar Years 2000-2007 – 122 Fatalities. Office of Vehicle Safety National Highway Traffic Safety Administration.

Bellemare, F., Fuamba, T. & Bourgeault, A. (2006) Sexual dimorphism of human ribs. Respiratory Physiology & Neurobiology, 150, 233-239.

Carroll, J., Adolph, T., Chauvel, C., Labrousse, M., Trosseille, X., ClausPastor, Eggers, A., Smith, S. & Hynd, D. (2010) Overview of serious thorax injuries in European frontal car crash accidents and implications for crash accidents and implications for crash test dummy development. International IRCOBI Conference on the Biomechanics of Impact, Sept 15-16, Hanover, Germany, 217-234.

Charpail, E., Trosseille, X., Petit, P., Laporte, S., Lavaste, F. & Vallancien, G. (2005) Characterization of PMHS Ribs: A New Test Methodology. Stapp Car Crash J, 49, 183-98.

Duma, S. M., Kemper, A. R., Stitzel, J. D., McNally, C., Kennedy, E. A. & Matsuoka, F. (2011) Rib fracture timing in dynamic belt tests with human cadavers. Clin Anat, 24, 327-38.

Eckert, M., Fayet, M., Cheze, L., Bouquet, R., Voiglio, E. & Verriest, J. (2000) Costovertebral joint behaviour during frontal loading of the thoracic cage. International IRCOBI Conference on the Biomechanics of Impact, Sept 20-22, Montpellier, France, 195-206.

El-Jawahri, R. E., Laituri, T. R., Ruan, J. S., Rouhana, S. W. & Barbat, S. D. (2011) Development and validation of age-dependent FE human models of a mid-sized male thorax. Stapp Car Crash J, 54, 407-30.

Foster, J., Kortge, J. & Wolanin, M. (1977) Hybrid III - A biomechanically based crash test dummy. Stapp Car Crash J, 21, 975-1014.

Gayzik, F. S., Moreno, D., Vavalle, N., Rhyne, A. & Stitzel, J. (2012) Development of a full human body finite element model for blunt injury prediction utilizing a multy-modality medical imaging protocol. 12th International LS-DYNA Users Conference, Dearborn, Michigan.

Gayzik, F. S., Yu, M. M., Danelson, K. A., Slice, D. E. & Stitzel, J. D. (2008) Quantification of age-related shape change of the human rib cage through geometric morphometrics. Journal of Biomechanics, 41, 1545-1554.

GESAC (2005) Biomechanical response requirements of the THOR NHTSA advanced frontal dummy (Revision 2005.1). Boonsboro.

Hallquist, J. O. (2006) LS-DYNA Keyword user's manual. Version 970. Livermore Software Technology Corporation.

Hayamizu, N., Watanabe, I., Ishihara, T. & Miki, K. (2003) Measurement of impact response of pig lung [in Japanese]. The Japan Society of Mechanical Engineers, 2003, 94-95.

Holmqvist, K. (2009) Chest injuries in heavy vehicle frontal collisions - Evaluation and adaptation of the Hybrid III dummy instrumentation and injury reference values by means of Human Body Modeling. Thesis for the degree of Licentiate, Applied Mechanics, Traffic Safety, Chalmers University of Technology, Gothenburg, Sweden.

Ito, O., Dokko, Y. & Ohashi, K. (2009) Development of Adult and Elderly FE Thorax Skeletal Models.

Iwamoto, M., Kisanuki, Y., Watanabe, I., Furusu, K., Miki, K. & Hasegawa, J. (2002) Development of a finite element model of the total human model for safety (THUMS) and application to injury reconstruction. International IRCOBI Conference on the Biomechanics of Impact, Sept 18-20, Munich, Germany.

Kemper, A. R., Kennedy, E. A., McNally, C., Manoogian, S. J., Stitzel, J. D. & Duma, S. M. (2011) Reducing chest injuries in automobile collisions: rib fracture timing and implications for thoracic injury criteria. Ann Biomed Eng*,* 39**,** 2141-51.

Kent, R. (2002) Dynamic response of the thorax: restraint specific hard tissue injury. Thesis for the degree of PhD, School of Engineering and Applied Science, University of Virginia, Charlottesville, Virginia, USA.

Kent, R., Lessley, D. & Sherwood, C. (2004) Thoracic response to dynamic, non-impact loading from a hub, distributed belt, diagonal belt, and double diagonal belts. Stapp Car Crash J*,* 48**,** 495-519.

Kent, R., Murakami, D. & Kobayashi, S. (2005) Frontal thoracic response to dynamic loading: the role of superficial tissues, viscera and the ribcage. International IRCOBI Conference on the Biomechanics of Impact, Sept 21-23, Prague, Czech Republic, 355-365.

Kent, R., Patrie, J., Poteau, F., Matsuoka, F. & Mullen, C. (2003) Development of an age dependent thoracic injury criterion for frontal restraint loading. International Technical Conference on the Enhanced Safety Vehicles Conference, May 19-22. Osaka, Japan.

Kent, R. W., Crandall, J. R., Bolton, J., Prasad, P., Nusholtz, G. & Mertz, H. (2001) The influence of superficial soft tissues and restraint condition on thoracic skeletal injury prediction. Stapp Car Crash J*,* 45**,** 183-204.

Kimpara, H., Iwamoto, M., Watanabe, I., Miki, K., Lee, J. B., Yang, K. H. & King, A. I. (2006) Effect of assumed stiffness and mass density on the impact response of the human chest using a three-dimensional FE model of the human body. J Biomech Eng*,* 128**,** 772-6.

Kindig, M. (2009) Tolerance to failure and geometric influenced on the stiffness of human ribs under anterior-posterior loading. Thesis for the degree of MSc. in Mechanical Engineering, School of Engineering and Applied Science, University of Virginia, Charlottesville, Virginia, USA.

Kindig, M. W., Lau, A. G., Forman, J. L. & Kent, R. W. (2010) Structural response of cadaveric ribcages under a localized loading: stiffness and kinematic trends. Stapp Car Crash J*,* 54**,** 337-80.

Klanner, W. (2001) Status report and future development of the Euro NCAP programme. International Technical Conference on the Enhanced Safety Vehicles Conference, June 4-7. Amsterdam, The Netherlands.

Kroell, C. K., Schneider, D. C. & Nahum, A. M. (1971) Impact tolerance and response of the human thorax. Stapp Car Crash J*,* 15**,** 84-134.

Kroell, C. K., Schneider, D. C. & Nahum, A. M. (1974) Impact tolerance and response of the human thorax II. SAE Technical paper*,* Paper No. 741187**,** 383-457.

L'Abbé, R., Dainty, D. & Newman, J. (1982) An Experimental Analysis of Thoracic Deflection Response to Belt Loading. International IRCOBI Conference on the Biomechanics of Impact, Sept 8-10, Cologne, Germany, 184-194.

Lau, I. & Viano, D. (1986) The viscous criterion - Bases and applications of an injury severity index for soft tissues. Stapp Car Crash Journal*,* 30**,** 123-142.

Li, Z., Kindig, M. W., Subit, D. & Kent, R. W. (2010) Influence of mesh density, cortical thickness and material properties on human rib fracture prediction. Med Eng Phys*,* 32**,** 998-1008.

Mertz, H., Prasad, P. & Irwin, A. (1997) Injury risk curves for children and adults in frontal and rear collisions. Stapp Car Crash J*,* 41**,** 13-30.

Morgan, R., Eppinger, R., Haffner, M., Yoganandan, N., Pintar, F. A., Sances, A., Crandall, J., Pilkey, W., Klopp, G., Kallieris, D., Miltner, E., Mattern, R., Kuppa, S. & Sharpless, C. (1994) Thoracic trauma assessment formulations for restrained drivers in simulated frontal impacts. Stapp Car Crash J*,* 38**,** 15-34.

Murakami, D., Kobayashi, S., Torigaki, T. & Kent, R. (2006) Finite element analysis of hard and soft tissue contributions to thoracic response: sensitivity analysis of fluctuations in boundary conditions. Stapp Car Crash J*,* 50**,** 169-89.

Oshita, F., Omori, K., Nakahira, Y. & Miki, K. (2002) Development of a finite element model of the human body. 7th International LS-DYNA user conference, Detroit, USA, (3-37)-(3-48).

Petitjean, A., Lebarbe, M., Potier, P., Trosseille, X. & Lassau, J. P. (2002) Laboratory Reconstructions of Real World Frontal Crash Configurations using the Hybrid III and THOR Dummies and PMHS. Stapp Car Crash Journal*,* 46**,** 27-54.

Pipkorn, B. & Kent, R. (2011) Validation of a human body thorax model and its use for force, energy and strain analysis in various loading conditions. International IRCOBI Conference on the Biomechanics of Impact, Sept 14-16, Krakow, Poland, 210-223.

Pipkorn, B. & Mroz, K. (2009) Validation of a Human Body Model for Frontal Crash and its Use for Chest Injury Prediction. SAE International Journal of Passenger Cars - Mechanical Systems*,* 1**,** 1094-1117.

Ruan, J., El-Jawahri, R., Chai, L., Barbat, S. & Prasad, P. (2003) Prediction and analysis of human thoracic impact responses and injuries in cadaver impacts using a full human body finite element model. Stapp Car Crash J*,* 47**,** 299-321.

Shams, T., Rangarajan, N., McDonald, J. P., Wang, Y., Platten, G., Spade, C. & Pope, P. (2005) Development of THOR-NT: Enhancement of THOR alpha - The

NHTSA advanced frontal dummy. International Technical Conference on the Enhanced Safety Vehicles Conference, June 6-9. Washington, D.C., USA.

Shaw, C. G., Lessley, D., Crandall, J., Kent, R. & Kitis, L. (2005) Dummy torso response to anterior quasi-static loading. International Technical Conference on the Enhanced Safety Vehicles Conference, June 6-9 Washington, D.C., USA.

Shaw, C. G., Lessley, D., Evans, J., Crandall, J., Shin, J., Portier, P. & Paoloni, G. (2007) Quasi-static and dynamic thoracic loading tests: cadaveric torsos. International IRCOBI Conference on the Biomechanics of Impact, Sept 19-21, Maastricht, Netherlands, 325-348.

Shaw, G., Crandall, J. & Butcher, J. (2002) Comparative evaluation of the THOR advanced frontal crash test dummy. International Journal of Crashworthiness, 7**,** 239-254.

Shaw, G., Parent, D., Purtsezov, S., Lessley, D., Crandall, J., Kent, R., Guillemot, H., Ridella, S. A., Takhounts, E. & Martin, P. (2009) Impact response of restrained PMHS in frontal sled tests: skeletal deformation patterns under seat belt loading. Stapp Car Crash J, 53**,** 1-48.

Shigeta, K., Kitagawa, Y. & Yasuki, T. (2009) Development of next generation human FE model capable of organ injury prediction. International Technical Conference on the Enhanced Safety Vehicles Conference, June 15-18. Stuttgart, Germany.

Song, E., Lecuyer, E. & Trosseille, X. (2011) Development of injury criteria for frontal impact using a human body FE model. International Technical Conference on the Enhanced Safety Vehicles Conference, June 13-16. Washington, D.C., USA.

Song, E., Trosseille, X. & Baudrit, P. (2009) Evaluation of thoracic deflection as an injury criterion for side impact using a finite elements thorax model. Stapp Car Crash J, 53**,** 155-91.

Stitzel, J. D., Gayzik, F. S., Hoth, J. J., Mercier, J., Gage, H. D., Morton, K. A., Duma, S. M. & Payne, R. M. (2005) Development of a finite element-based injury metric for pulmonary contusion part I: model development and validation. Stapp Car Crash J, 49**,** 271-89.

Tamura, A., Watanabe, I. & Miki, K. (2005) Elderly human thoracic FE model development and Validation. International Technical Conference on the Enhanced Safety Vehicles Conference, June 6-9 Washington, D.C., USA.

Trosseille, X., Baudrit, P., Leport, T. & Vallancien, G. (2008) Rib cage strain pattern as a function of chest loading configuration. Stapp Car Crash J, 52**,** 205-31.

Turner, C. H. (2006) Bone strength: Current concepts. Skeletal Development and Remodeling in Health, Disease, and Aging, 1068**,** 429-446.

Untaroiu, C. D., Lim, J. Y., Shin, J., Crandall, J., Malone, D. P. & Tannous, R. E. (2009) Evaluation of a finite element model of the THOR-NT dummy in frontal crash environment. International Technical Conference on the Enhanced Safety Vehicles Conference, June 15-18. Stuttgart, Germany.

Wanek, S. & Mayberry, J. C. (2004) Blunt thoracic trauma: flail chest, pulmonary contusion, and blast injury. Crit Care Clin, 20**,** 71-81.

Vawter, D. L., Fung, Y. C. & West, J. B. (1979) Constitutive Equation of Lung Tissue Elasticity. Journal of Biomechanical Engineering, 101, 38-45.

Vezin, P. & Berthet, F. (2009) Structural characterization of human rib cage behavior under dynamic loading. Stapp Car Crash J, 53, 93-125.

Vezin, P., Bruyere-Garnier, K., Bermond, F. & Verriest, J. P. (2002) Comparison of Hybrid III, Thor-alpha and PMHS Response in Frontal Sled Tests. Stapp Car Crash J, 46, 1-26.

Vezin, P. & Verriest, J. (2005) Development of a set of numerical human models for safety. International Technical Conference on the Enhanced Safety Vehicles Conference, June 6-9. Washington, D.C., USA.

Wismans, J., Happee, R. & van Dommelen, J. A. W. (2005) Computational human body models. Iutam Symposium on Impact Biomechanics: From Fundamental Insights to Applications, 124, 417-429.

Yang, K. H. (2001) Review of mathematical human models for incorporation into vehicle safety design. International Journal of Vehicle Design, 26, 430-441.

Zioupos, P. & Currey, J. D. (1998) Changes in the stiffness, strength, and toughness of human cortical bone with age. Bone, 22, 57-66.