

# POLITECNICO DI TORINO

Department of Mechanical and Aerospace Engineering

MSc Thesis  
in Biomedical engineering

## **Human Body Model and Passive Safety of Vehicles: Analysis of biomechanical results and study of injuries on abdominal organs**



**Politecnico  
di Torino**

**Supervisor:**

Prof. Eng. Alessandro Scattina

**Co-Supervisor:**

Prof. Eng. Christophe Bastien

**Candidate**

Giulia Mondino

October 2021



## Index

Index .....	3
Abstract.....	5
Preface.....	7
Thesis introduction.....	7
Chapter 1 .....	8
Human Body Models (HBMS) .....	8
1.1 Total Human Model for Safety .....	8
Chapter 2.....	10
Torso occupant validation.....	10
2.1 Thorax validation .....	10
2.1.1 Frontal impact .....	10
2.1.2 Belt impact .....	12
2.1.3 Lateral impact.....	13
2.2 Abdomen validation.....	14
2.2.1 Bar impact .....	14
2.2.2 Belt loading .....	15
2.3 Pelvis validation.....	16
2.3.1 Knee Thigh Hip.....	17
2.3.2 Acetabulum lateral impact .....	17
Chapter 3.....	19
Organs: Anatomy and FE model.....	19
3.1 Introduction.....	19
3.1.1 Ribs: anatomy.....	19
3.1.1.2 Ribs in the THUMS .....	21
3.1.2 Clavicle .....	23
3.1.2.2 Clavicle in the THUMS .....	23
Chapter 4.....	26
Abbreviated Injury Scale (AIS) and Peak Virtual Power method (PVP).....	26
Chapter 5.....	29
Changes in the THUMS.....	29
5.1 THUMS validation.....	29
5.1.1 Thorax .....	29

5.1.2 Abdomen .....	32
5.1.3 Pelvis .....	33
5.2 Changes in the ribs .....	35
5.2.1. Rib: cortical bone .....	35
5.2.2. Rib cortical bone: curve stress and strain .....	38
5.2.2.3 Rib cortical bone: curve stress and strain (18 years old cadaver).....	47
5.2.3 Thickness of ribs' cortical bone .....	48
5.2.3.1 First step .....	49
5.2.3.2 Second step.....	54
5.2.4 Fracture.....	61
5.3 Analysis of the clavicle .....	62
5.3.1 Geometry of the clavicles.....	63
5.3.2 Axial compression test .....	65
5.3.3 Three point bending test.....	68
Conclusions and future developments.....	71
Bibliography.....	73
Software .....	75
Acknowledgements .....	76

## Abstract

Car accidents are frequent in the world and, consequently, safety in the car becomes an important requirement and one of the more requested functionalities by people when buying a car. For this reason, crash safety tests were born to understand the security level of the vehicle, to discover which improvements can be introduced to increase security.

Crash tests have some problems. For these reasons, companies have begun to look at making safety systems more accurate than previous. Consequently, the application of a crash test virtual model, based on the Finite Element Method (FEM), was introduced. In this model, nowadays, the car test is modelled in FE using HBM (Human Body Computational) to simulate human behaviour. The human model used in this thesis is the THUMS (Total Human Model for Safety). It helps to understand how the human body reacts during the impacts and to better predict the types and locations of injuries with respect to classic rigid dummies tests.

Even if THUMS is a modern tool, it can be still improved. The purpose of this thesis is to modify it to have a more realistic one. In this way, it is possible to have a model which simulates better the properties and the behaviour of the human body.

Before to modify it, it is important to understand if the original model is reliable or not. For this reason, the work is tested with corridors, experimental data, obtained by cadavers. These curves are compared against the model's answer to see if it is acceptable or not.

By studying this comparison, it is noted a different behaviour in the response between the human thorax and the THUMS' thorax.

For this reason, ribs and collarbone are more investigated in this work. In particular, the material and the thickness of the ribs are investigated, and also the geometry and the material of the collarbone.

At the end of the work, some changes are made but the thorax has still a different behaviour than the real one. For this reason, it is important to underline that to see some changes in the response, more parts of the thorax have to study. In this way, a more accurate model can be obtained and, after that, the response of the thorax could be similar to reality.



## Preface

### Thesis introduction

All the work, shown in this thesis, is made in collaboration with Professor Bastien of Coventry University and with Giulia Vicini of Politecnico di Torino.

The crash tests are a significant tool to analyse the security and the level of safety of the cars. In this way, some improvements can be made to them and a better vehicle can be obtained, which can guarantee minor injuries to people involved in a collision.

The purpose of this thesis is to analyse the human body model, the THUMS. This has to be changed to improve the answer of thorax, abdomen and pelvis to obtain a model which is similar to the reality. To make this, in this thesis two bones are examined: ribs and collarbone.

The first chapter of this thesis will give more information about the human body model, in particular, the one which is used in this work, so the THUMS.

The second chapter will explain the tests, made to analyse the behaviour of cadavers after an impact, to understand the answer of different parts of the body. These experiments are used to obtain some curves, the corridors, which show the response of the body after a specific impact.

The third chapter will give a brief overview of ribs and collarbone. In particular, their anatomy and their functions are studied to understand better their role in the human body. It is summarised, also, how they are modelled in the THUMS.

In the fourth chapter, the injuries criterion, in particular the PVP, will be explained, because all this work starts to improve its response.

Finally, the fifth chapter will explain the work, followed to improve the THUMS. In particular, for the ribs, some changes about the material and their thickness are proposed. For the collarbones, instead, geometry and material are more investigated to understand if they are similar to reality or not.

## Chapter 1

### Human Body Models (HBMS)

Every day, in the world, we can see vehicles, and, in some cases, we also can drive them. But when we use these means of transportation, one of the first thing we can think is: “Is this vehicle safe or not?”.

According to World Health Organization report on road traffic injuries approximately 1.3 million people have died as consequences of car crashes, so this fact helps to understand why people look for safety on cars. For this reason, understand if a car is safe or not, crash safety tests are important.

An important part of these tests is crash test rigid dummy [1]. It can give an answer similar to the human body, without any ethical problems, unlike using cadavers. At this point, the purpose is to produce accurately different types of dummies. For this reason, some of these models are created over the years. In particular, every rigid dummy is created to be used in a particular impact, such as frontal impact, rear impact or side impact.

Despite the improvement in safety using dummies, they have some problems: the price, their inaccuracy in the results and the lack of some positions. To overtake these problems, a new tool was designed based on finite element (FE) Method: Human Body Models (HBMs). They are computational models, which simulate the human behaviour. To recreate them, all parts of the human body are studied. By associating each organ with a precise geometry and a particular material, these models can be used in a virtual model which represents a crash test. With the HBMs, different types of people are exemplified: male, female or children. Thanks to this tool, we can give a more accurate injury prediction than crash test dummies.

In conclusion, HBMs are a promising tool to understand the types and the location of injuries but it can be improved.

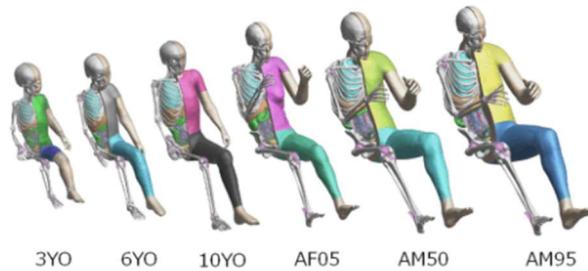
In this thesis, it is used the THUMS, original Academic Version 4.02 AM50 Occupant model.

#### 1.1 Total Human Model for Safety

THUMS (Total Human Model for Safety) is a human body finite element model developed by Toyota Motor Corporation and Toyota Central R&D Labs., Inc, to create a virtual model able to imitate and calculate human body injuries during car accidents [2].

THUMS represents not only the bone but also internal organs, muscles, and it is modelled also on different genders (male or female) and on different ages to ensure safety to the greatest

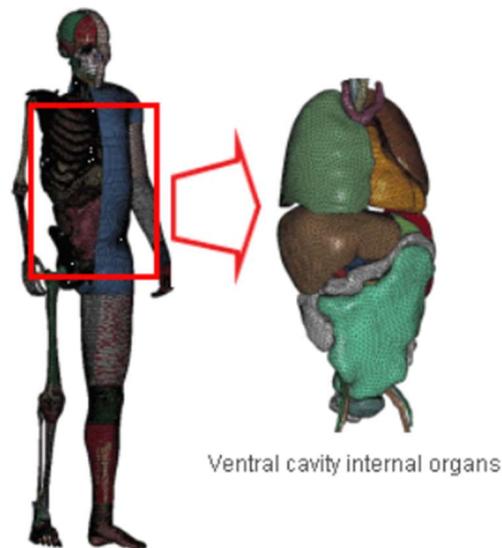
range of people. The purpose on which THUMS is based is to give a robust tool for car safety, for this reason, Toyota engineers work on modelling different parts of the body, through 3D meshes and material properties.



*Figure 1-THUMS occupant models for different ages and different percentile [2]*

In this thesis, we used an Academic Version 4.02 AM50 Occupant model, built to fit the 50<sup>th</sup> percentile of American male. The version 4 adds, compared to previous versions, a more detailed model for internal organs since they are one of the most fragile parts during accidents.

The occupant is a THUMS modelled on a person, sitting in a car, so it is different by the pedestrian only for the posture, in fact the pedestrian has a standing posture.



*Figure 2- THUMS version 4*

## Chapter 2

### Torso occupant validation

As mentioned in the previous chapter, an important tool is the Human Body Model. It simulates the behaviour of a real human body, so it has to be anatomically accurate. Therefore, it is made of bones, ligaments, organs, brain and muscles. Before using it to simulate a real accident, it has to validate by comparing its answer with the behaviour of cadavers.

The purpose of this thesis is to change the THUMS to try to improve it. To do this, the validation test is an important phase. Indeed, in this phase, simple impactors are used to hit some parts of the body to simplify some situations, which occur during a collision. Therefore, the purpose of this test is to understand if a model gives an answer that correctly simulates the human body. To can do it, for every impact (which compose the validation phase), some curves are extracted and then these are compared with the experimental data, obtained by cadavers. After this, the bio-fidelity is analysed.

In Japan, Zhao et al [3] analysed the auto accidents to discover the most problematic injuries and the organs more injured. With this study, they discovered that: frontal and lateral crashes are very common. They also found the most vulnerable parts: head, thorax and abdomen. The study, also, underlined the importance of seat belt use. Indeed, people with it have fewer problematic injuries. For this reason, to simplify the validation test, it is divided into different impacts, simpler than a crash test. So, the thorax, the abdomen and the pelvis, the parts more vulnerable as said in the article, are loaded with different types of impact and of impactors.

In this paragraph, all the validation tests, performed with cadavers, are presented. These tests are re-made, in the same way, with the THUMS with FE model.

#### 2.1 Thorax validation

##### *2.1.1 Frontal impact*

The first type of validation that is presented in this thesis is *Frontal impact validation*. This test is based on Kroell et al. [4] [5].

In this article, an impact steering wheel against the thorax is used. The purpose of this test is to simulate the impact during a frontal car crash and understand the main problems given by this type of impact.

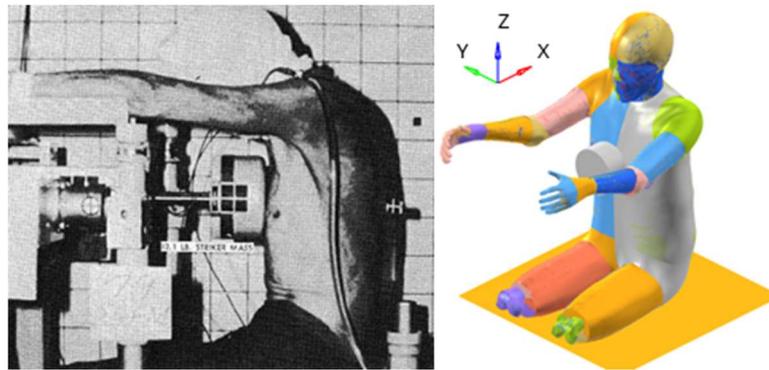


Figure 3 - PMHS and THUMS Ver.4.02 AM50 for Thorax validation

The cadaver, seated as shown in the figure 3, was hit by an impactor on the thorax. The impactor has a diameter of 152 mm. The impact collides the sternum between the 4th and 5th ribs with an impact velocity of 7.2 m/s for an impactor of 23.1 kg.

In response to the impact, the thorax moves and so it undergoes a displacement. In the article, force, as the reaction of the impactor, and deflection, as the movement of the chest, are measured with accelerometers and high-speed photographic. In this way, it is noted the moment in which the impactor encountered the chest.

After these experiments, the corridors are obtained.

To validate the THUMS, the force and the displacement are taken, and the THUMS' curves are analysed to see if they fall into corridors or not. If they are within the range, the model is validated. In the figure 4, it is shown an example of corridors, force versus deflection cross-plot.

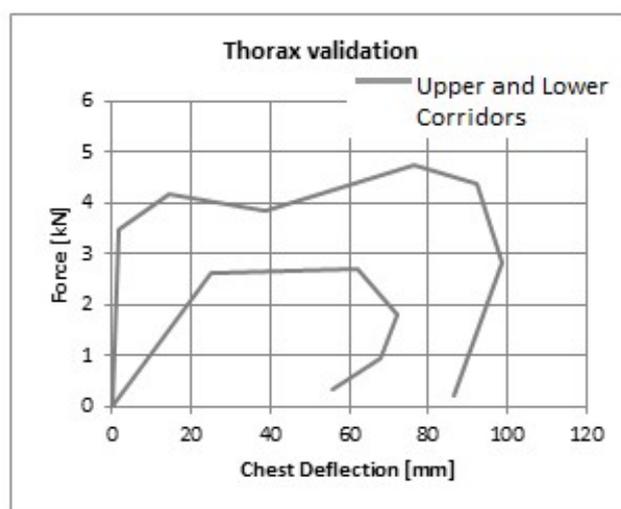
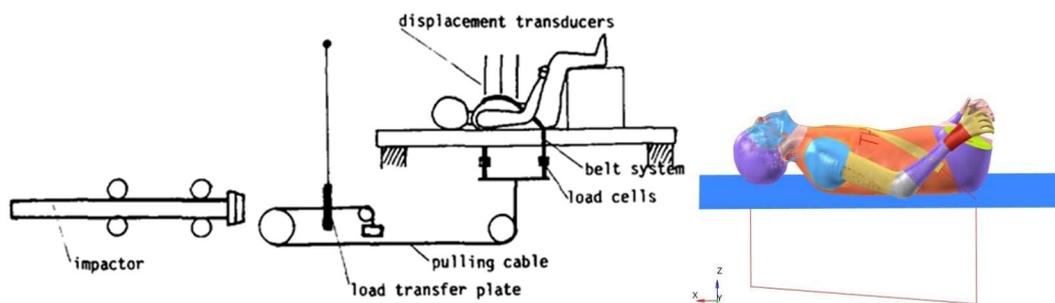


Figure 4 - Corridors for Thorax validation

### *2.1.2 Belt impact*

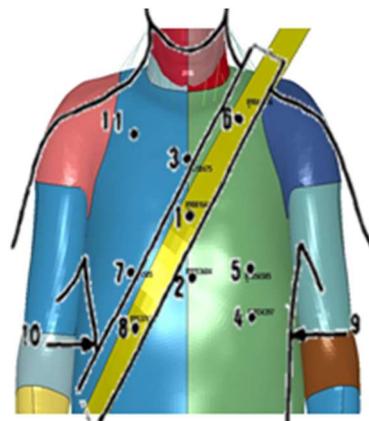
As already mentioned, the use of the belt is very important because, thanks to it, a person, during an impact, has fewer injuries. For this reason, the model must be validated also for belt loading. First, the thorax is considered, while in the next paragraph the abdomen, loaded with a belt, is considered.

In Cesari et al. [6], this test is explained. Through a bar, a seat-belt is set in motion and the thorax is stressed, as reported in the figure 5.



*Figure 5 - Representation and model of test apparatus*

Once the belt is loaded by the bar, the thorax must be analysed. This is done by taking the deflection at different instants of time and in different points are taken. In the figure 6, the location of the points, analysed, are shown.



*Figure 6 - Location of the nodes*

In the Cesari's article, several simulations were presented. In every test, the mass of the impactor was changed, and the ribs were studied with X-ray to see if the fractures occurred or not. All the tests were used to make the corridors, so maximum deflection interval.

In the thesis, not all the tests are used but only one: impactor with 22.4kg of mass and with 7.78m/s of velocity. Using this impact, the deflection of the THUMS is taken and compared with the corridor, the experimental data.

In the figure 7, the corridors are shown.

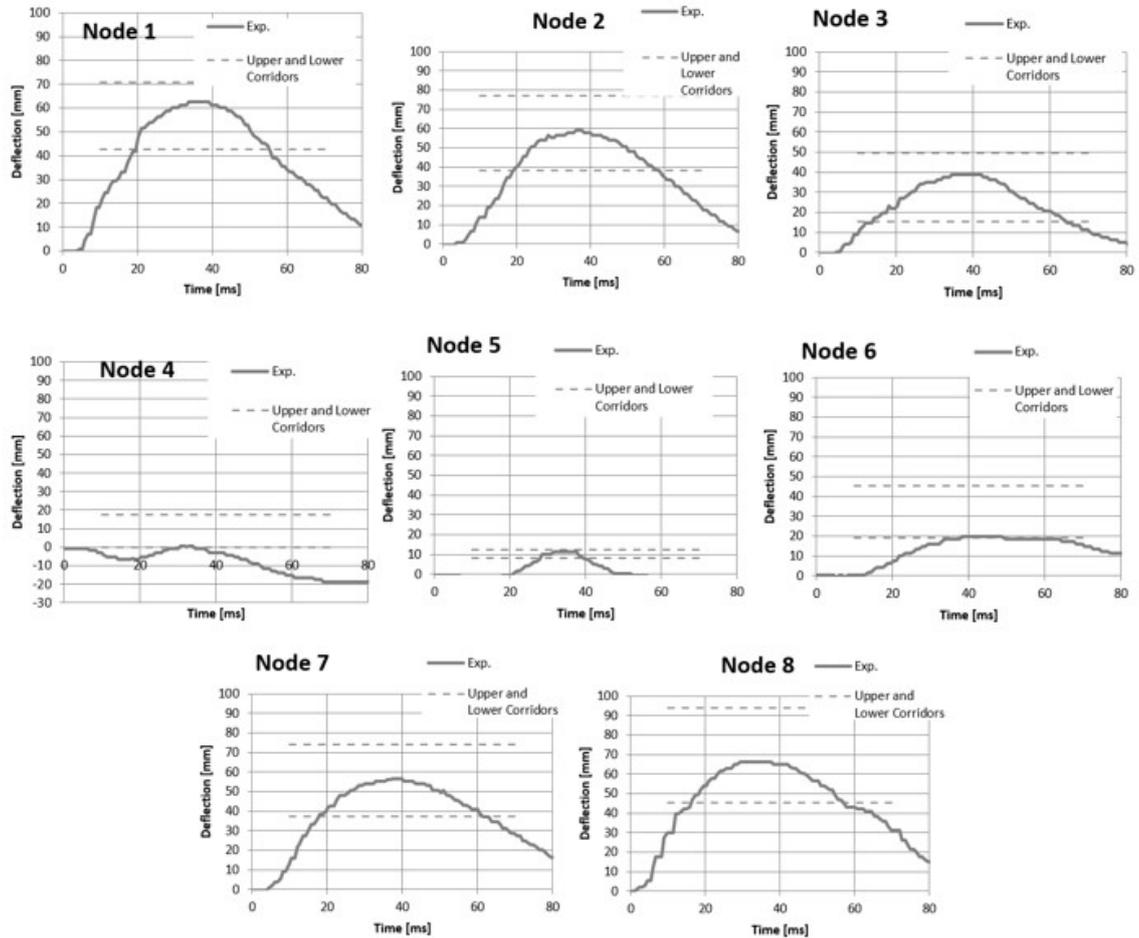


Figure 7 - Corridors for Belt impact validation

### 2.1.3 Lateral impact

The validation test is necessary to understand the behaviour of the THUMS during a lateral impact. For crossroads, curves and other reasons, during a crash test, a person can be hit laterally so it is important understand the response also in this case.

To validate the model another article is take as basis Shaw et al. [7]. In this article a pendulum, which hit the thorax laterally, was used to understand thorax behaviour after different directions of impact.

In the validation test, the model is hit by an impactor, as shown in the figure 8, in the thorax. To allow the lateral impact the arms are moved ahead, in this way the impactor can hit only the

thorax laterally. The impactor has a mass of 23.4 kg, a diameter of 152 mm and it is set in motion with a velocity of 2.76 m/s.

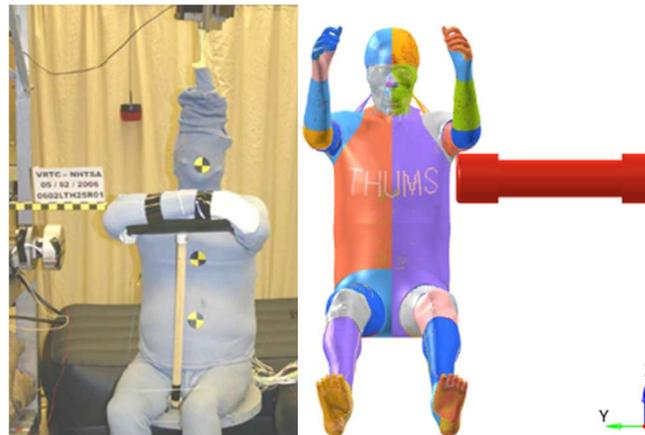


Figure 8 - PMHS and THUMS Ver.4.02 AM50 for Lateral impact validation

After the impact, in the article, the deflection, of the chest, was analysed along the y-direction with accelerometers. These results are re-taken in the validation test phase and used to obtain the corridors. The experimental data give a range as reported in the figure 9.

Therefore, to validate the model for this impact, force, as the reaction of impactor, versus time and deflection versus to force must be considered.

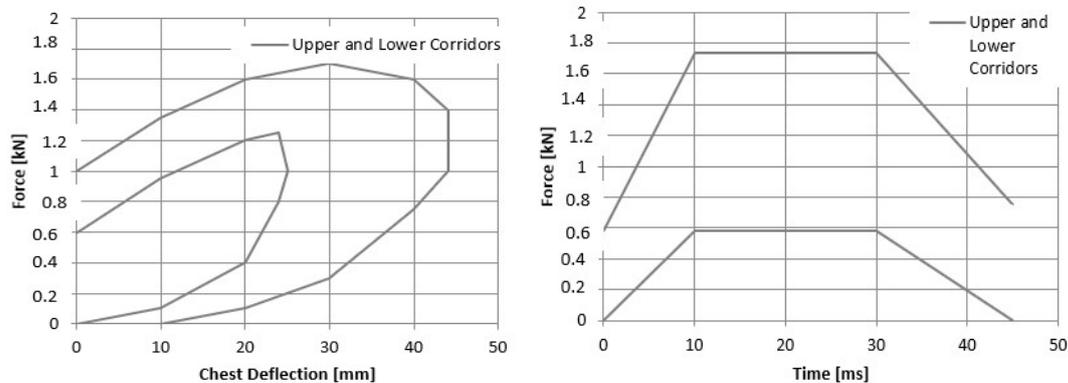


Figure 9 - Corridors for Lateral impact validation

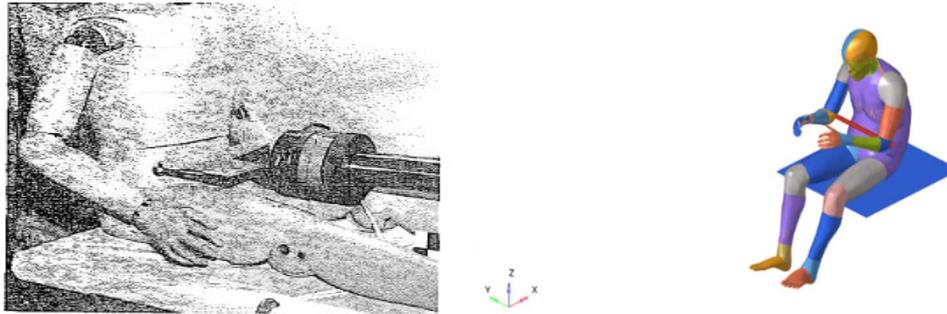
## 2.2 Abdomen validation

After the thorax validation, abdomen is validated in two different ways, before using a bar like impactor and then using a belt.

### 2.2.1 Bar impact

First, the abdomen is analysed when a bar impacts it, as in the studies of Cavanaugh et al. [8]. Cavanaugh et al, to investigate the behaviour of the liver, the kidney, and the spleen during

a frontal impact (these organs were found to be more injured during the crash), utilized human cadavers to evaluate the abdominal human response. For this purpose, they used 12 unbelted human cadavers hit by an impactor, that was an aluminium bar of 25 mm, diameter, long 381 mm with a variable mass between 32kg-64kg. The bar hit the abdomen at the level of the intestine. Different tests were developed with different masses of impactors, for different velocities from 4.9 to 13.1 m/s.

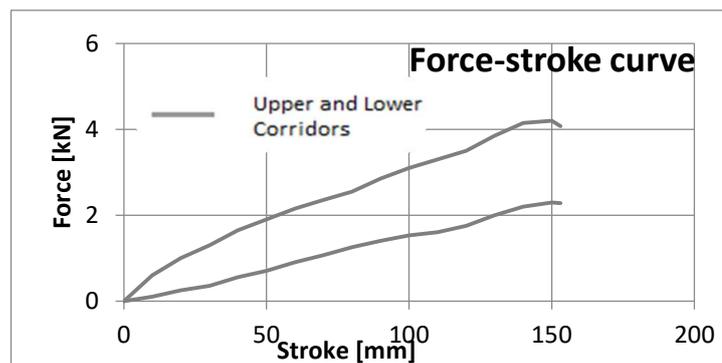


*Figure 10 - Dummy and THUMS in abdomen impact*

In this way, the corridors were created as a cross plot between force and displacement for the lower and the upper mean velocities, 6.1 m/s and 10.4 m/s respectively.

To measure the force and the displacement, uniaxial accelerometers were placed in the impactor and, also, the abdominal impacts were filmed with a speed camera.

Other studies were performed on this validation test to recreate the corridors but, in this thesis, we based on the Cavanaugh et al. 's study. The corridors, shown in figure 11 and used in this work, are obtained with a bar of 32 kg and a velocity of 6.1 m/s.



*Figure 11 - Corridors with bar impact (abdomen)*

### *2.2.2 Belt loading*

After the study of bar impact, another analysis is conduct, in which the abdomen is stressed with a high-speed seat-belt.

The test, explained in Hardy et al. [9], is conducted on cadavers, which are seated and loaded with a belt in abdominal area with different speed (from 3.0 m/s to 9.4 m/s). The output of the test is the displacement between the spine and the seatbelt, measured by potentiometers.

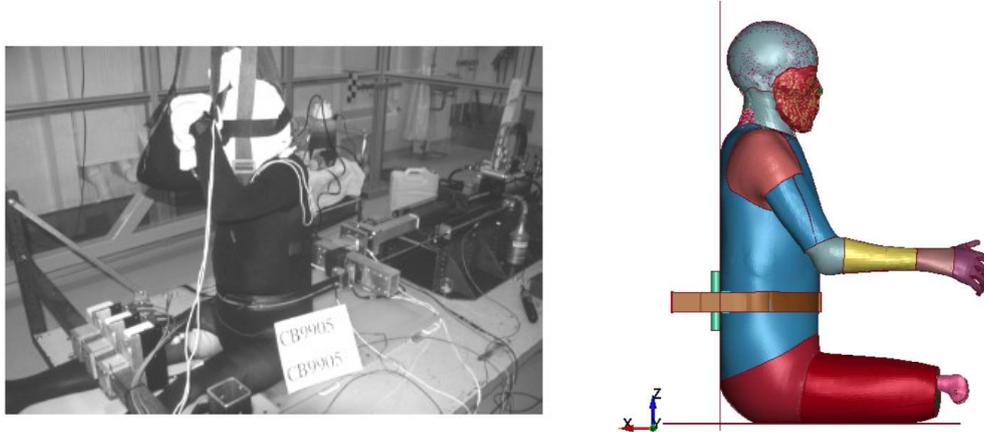


Figure 12 - Typical test for abdomen impact with seatbelt

In this thesis, the validation test is based on Cavanaugh et al.'s study, which is like the Hardy et al.'s analysis. With this article, the corridors are found as a correlation between the force, with which the seatbelt hit the abdomen, and displacement of abdomen when stressed, in two different situations, based on speed with which belt is loaded. In addition, the belt is loaded with a curve to obtain the same loading conditions of the Cavanaugh's article.

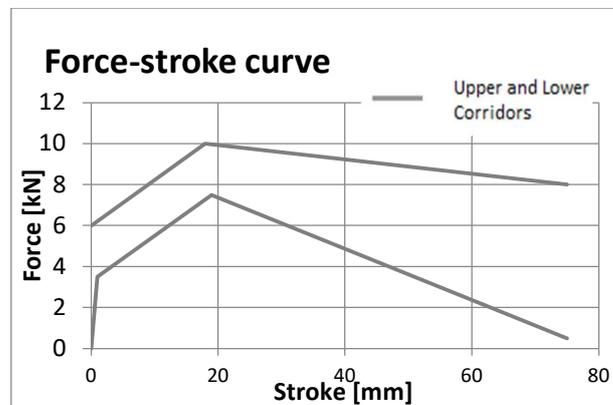


Figure 13 - Corridors for abdomen impact with seatbelt

### 2.3 Pelvis validation

According to studies on car accident, the vulnerability of the pelvis was found. For this reason, the model also need to be validated also for the response in an impact on pelvis.

### 2.3.1 Knee Thigh Hip

During a car accident, some parts of the car may hit the knees. This force is transmitted to other parts of the body, as thigh and hip. To understand how these parts of the body are loaded, some studies are made.

In Rupp et al. [10], a large number of tests are made. The knees are hit by a padded impactor, which has different velocities.

To recreate this test, the entire THUMS is used in the validation phase. The THUMS is seated, and the knees are hit by a table of 255 kg. The table is, also, set in motion with three different velocities: 1.2 m/s, 3.5 m/s and 4.9 m/s.

After the simulation, the force, as reaction of the table with the knees, at each time instant is taken and then the comparison with the experimental data, given by Rupp et al.'s study, is made.

In the figure 14, the method of the experiment, recreated with the THUMS, and the experimental data, obtained in the Rupp et al.' article, are shown.

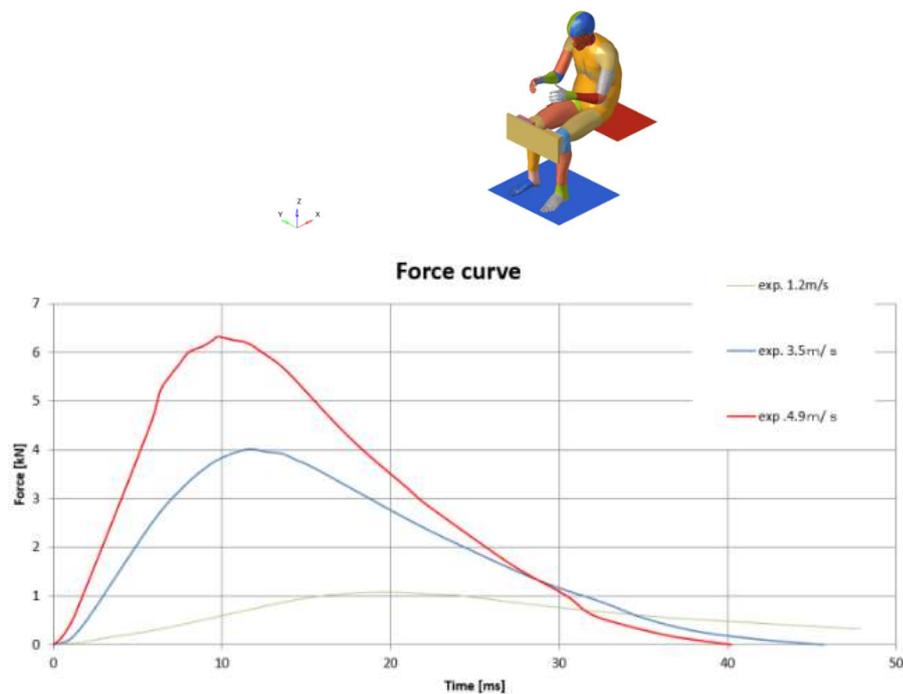


Figure 14 - Pelvis validation (Knee- Thigh -Hip): method and corridors

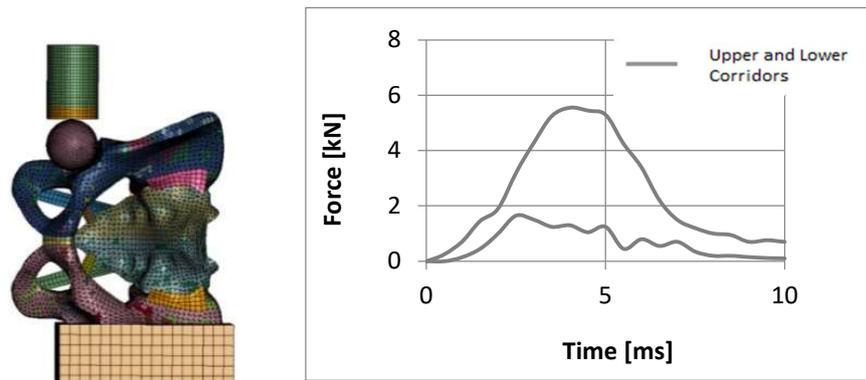
### 2.3.2 Acetabulum lateral impact

Another test, based on Guillemot et al. [11], is used to evaluate the problem of the pelvis. In this article, analysing different accidents, they discovered the most common injuries in the pelvis. Then, they made some dynamic tests to understand the behaviour of the bones. For this reason,

the pelvis was immobilised and put vertically. Then an impactor, with accelerometers, was brought down on the pelvis.

In the simulation, the analysis of a simplified model, as reported in the figure 15, is recreated. Then the validation is made with two different configurations for the failure of some materials. In this way, the lower and upper limit of the study can be recreated and the comparison can be made in the two limit cases. In particular, in both simulations, a spheric impactor of 50 mm with a diameter of 50 mm is used. The impactor is also put in motion with 4m/s. As just mentioned, the difference between the upper and lower corridors is related to the failure. In particular, the parts, composing the right hipbone, used as basis and therefore not impacted by the sphere, have different fail values. For the upper corridor, the fail was defined as  $2.8 \text{ E-}2$  strain: when the strain is over this value, the element is deleted. The strain rate parameters are 360.7 strain/s for C and 4.605 strain/s for P. For the lower corridors, instead, the fail was defined as  $5\text{E-}3$  strain strain and for C and P as 0 strain/s.

In the figures 15, the recreation of the test, presented in the article, and the corridors are shown.



*Figure 15 - Pelvis (Acetabulum Lateral Impact): method and corridors*

## Chapter 3

### Organs: Anatomy and FE model

#### 3.1 Introduction

How mentioned in the previous chapter, the purpose of this thesis is to change the THUMS to have a better model. In particular, the changes are related to the ribs and clavicle. For this reason, it is important to understand their role and their functionalities. This chapter focuses on these two aspects.

##### 3.1.1 Ribs: anatomy

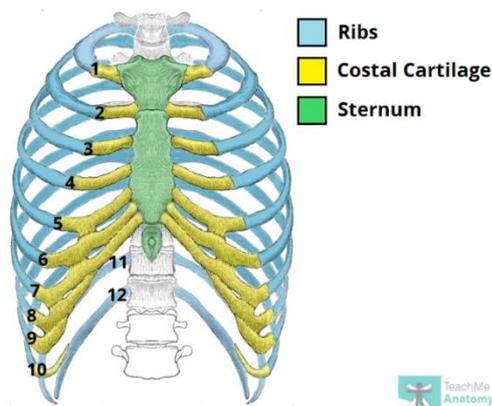


Figure 16 - ribcage (image taken by TeachMe Anatomy)

The ribs are located in the rib cage, which is, also, composed by costal cartilage and sternum.

The sternum [12] is a flat bone with a no uniform geometry. A cause of this, the angles of the sternum are variables. This part of the ribcage has several functions: it connects the first seven ribs and gives more protection to the inner organs.

The costal cartilage is located between the sternum and the ribs, and it connects these two parts but also it is tied to the other ribs, from eighth to tenth. The costal cartilage is more flexible than bones, so it gives more flexibility in the rib cage. This flexibility plays a crucial role because it allows to the ribcage to expand, to breathe, gives more stability to the ribs-sternum's connection and, also, it could prevent rib fracture.

The last components, the most interesting for this thesis, are the ribs [13]. The ribs, shown in the figure 16, are 12 pairs, the first seven are called true ribs, because they are connected to the

sternum, from 8<sup>th</sup> to 10<sup>th</sup> are called false ribs, because they are connected to the 7<sup>th</sup> ribs by the costal cartilage, the last ribs are called floating ribs.

The ribs are not considered long bone, because there is a lack of the medullary cavity. For this reason, they are considered flat bones.

They are composed, as all the bones, of water, organic matrix and inorganic substances. The organic part is the collagen while the inorganic compound is the hydroxyapatite. These three components are arranged in different way to form two types of bones: cortical and trabecular bones. On the surface there is a lamina of cortical bone and, inside it, there is the spongy bone.

Therefore, the cortical bone is more superficial, and it is more compact than the other one. In this type of bone, the basic unit is called osteon. Inside it, there is a canal where vital substances, such as blood, pass. It is made by fibres of collagen, distributed in precise method. This bone gives more resistance to mechanical stress and, also, more stability.

The trabecular bone has a particular shape, as a sponge. This conformation gives more lightness than the first type. For this reason, the muscles are able to move easily the bone. In addition, this type of bone can be loaded by stress, with a minor value but in all directions.

In all these types of bone, there are, also, some types of cells that can produce or destroy the bone tissue. With this cycle, the bone is always renewed.

With this composition, the bone gains its properties, as being anisotropic, its flexibility and its resistance.

These properties of the bone are also in the ribs. In this way, they are able to do several types of functions. The first function includes the respiration. The ribs modify their shape to allow a person to breathe. The second crucial property is about the protection of inner organs, as heart, liver and spleen.

It is important also to understand the consequences of a trauma on the ribs. After an accident, the ribs can break or bruise. This fact changes the properties of the rib cage and, also, a broken rib can pierce the inner organs. In addition, it can rip blood-vessel, giving other illnesses, as inflammations or respiratory difficulty.

3.1.1.2 Ribs in the THUMS

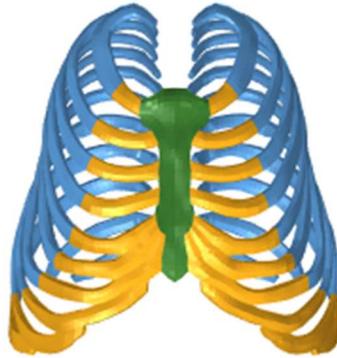


Figure 17 - Ribcage in THUMS model

It is also important to understand how the ribs are modelled in the THUMS, shown in the figure 17.

The ribs, in the model, are divided into cortical bone and trabecular bone.

The first one is made with shell elements with a uniform thickness of 0.7 and an element formulation option ‘Fully Integrated shell element’. Cortical bone properties are simulated with a material with plasticity and damage (card 81 on LS Dyna). The parameters, correlated to the failure, are not put to not cause un-stabilities, so the ribs cannot break. In the table 1, the parameters are shown.

Mass density	2.00e-9
Young's modulus	1.302e+04
Poisson's ratio	0.3
Yield stress	80
Tangent modulus	0
Strain rate parameter, C	360.7
Strain rate parameter, P	4.605
Effective plastic strain value, first (EPS1)	0
Effective plastic strain value, second (EPS2)	0.003
Effective plastic strain value, third (EPS3)	0.015
Effective plastic strain value, fourth (EPS4)	0.0204
Corresponding yield stress value to EPS1	80
Corresponding yield stress value to EPS2	110
Corresponding yield stress value to EPS3	120
Corresponding yield stress value to EPS4	124.5

Table 1- Cortical Rib Bone's parameters

The second one is simulated with solid elements, with ‘constant stress solid element’ as element formulation options. To have the behaviour of this type of bone a material with damage is used (card 105 on LS-Dyna). Also in this case, the failure parameter is not put to have major stability.

In the table 2, the parameters are reported.

Mass density	8.62e-10
Young’s modulus	40
Poisson's ratio	0.45
Yield stress	1.8
Tangent modulus	13.3
Damage effective plastic strain when material softening begin	1
Critical damage value	0.5
Effective plastic strain value, first (EPS1)	0.02
Effective plastic strain value, second (EPS2)	0.04
Effective plastic strain value, third (EPS3)	0.05
Effective plastic strain value, fourth (EPS4)	0.06
Corresponding yield stress value to EPS1	2.066
Corresponding yield stress value to EPS2	2.306
Corresponding yield stress value to EPS3	2.319
Corresponding yield stress value to EPS4	2.319

*Table 2 - Spongius Rib Bone's parameters*

The parameters, not shown in the table, are defined with a 0 value.

### 3.1.2 Clavicle

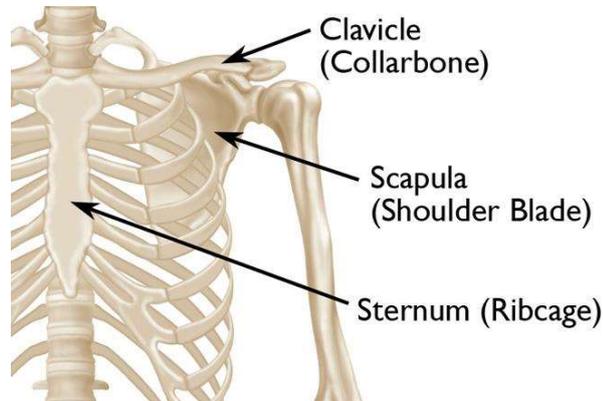


Figure 18 - Clavicle Anatomy

The clavicle [14] is a long bone, located between the ribcage and the shoulder, as reported in the figure 18. It is a curved bone, with an S shape, and it is linked with the acromion, laterally, and the sternum, medially.

The dimension of the clavicle is very small, but, despite this, it has a crucial role in the human body. For this reason, it is important to investigate it. Even if its movement is limited, its position allows it to protect the upper extremity. Indeed, the clavicle protects the upper extremity, because it discharges the force on it. In addition, through its location, the shoulder can move, because the ribcage is kept away from it by the clavicle. The site of this bone is important also for another reason: the protection of the neurovascular structure.

The clavicle is highly studied in clinical paper, because its fracture is the most common. The most problematic fracture is in the middle, because it can cause a lack of union and, therefore, instability. For this reason, the fracture of this bone is very critical. Indeed, after this, the clavicle can't fulfil its role and, hence, other bones can break.

#### 3.1.2.2 Clavicle in the THUMS

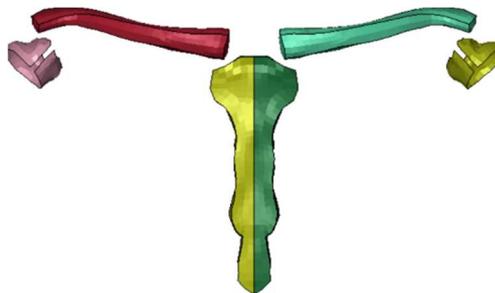


Figure 19 - Clavicle in THUMS model

The clavicle (shown in the figure 19, with shoulder and sternum), as the ribs, is made by cortical and spongy bone.

The first one is modelled with shell elements with a thickness of 1 mm and an element formulation options ‘Fully Integrated shell element’. The properties of the bone are simulated with a material piecewise linear plasticity (MAT 24 on Ls-Dyna), as reported in the table 3. Therefore, the representation of this bone is different between rib and clavicle, because these two parts have different role in the body.

Mass density	2.00e-9
Young's modulus	1.302e+04
Poisson's ratio	0.3
Yield stress	80
Tangent modulus	0
Strain rate parameter, C	360.7
Strain rate parameter, P	4.605
Effective plastic strain value, first (EPS1)	0
Effective plastic strain value, second (EPS2)	0.003
Effective plastic strain value, third (EPS3)	0.015
Corresponding yield stress value to EPS1	80
Corresponding yield stress value to EPS2	110
Corresponding yield stress value to EPS3	120

*Table 3 - Cortical Bone in Clavicle (parameters)*

The second one is modelled as the spongy rib bone for the solid formulation and for the material. Therefore, it is made with solid elements, with ‘constant stress solid element’ as element formulation options. To recreate the behaviour of this bone, a material with damage is used (card 105 on LS-Dyna).

In the table 4, the parameters are reported.

Mass density	8.62e-10
Young's modulus	40
Poisson's ratio	0.45
Yield stress	1.8
Tangent modulus	13.3

---

Damage effective plastic strain when material softening begin	1
Critical damage value	0.5
Effective plastic strain value, first (EPS1)	0.02
Effective plastic strain value, second (EPS2)	0.04
Effective plastic strain value, third (EPS3)	0.05
Effective plastic strain value, fourth (EPS4)	0.06
Corresponding yield stress value to EPS1	2.066
Corresponding yield stress value to EPS2	2.306
Corresponding yield stress value to EPS3	2.319
Corresponding yield stress value to EPS4	2.319

*Table 4 - Spongius Bone in Clavicle (parameters)*

## Chapter 4

### Abbreviated Injury Scale (AIS) and Peak Virtual Power method (PVP)

After the model of the accident, car and human body, it is important to understand how a trauma can be evaluated.

The AIS, Abbreviated Injury Scale, is a method, anatomically based, to understand the severity of an injury. It is given by medicals, and it is internationally accepted. The AIS surpasses the previous criteria, being more specific than them to evaluate trauma. In the AIS, every injury, located in a specific region of the human body, is classified with a value from 1 to 6, depending on its severity.

AIS Severity	Injury
1	Minor
2	Moderate
3	Serious
4	Severe
5	Critical
6	Un-survivable

Table 5 - AIS severity - injury

Several parts of the body are considered: head, face, neck, thorax, abdomen, spine, upper and lower extremity and external and other.

In forensic medicines or in medicine to evaluate the quality of the treatment, every score is decided basing on evidence. The proofs are different as medical consult or an exam (RX, TC).

In the models of accident, [15] [16] anthropometric test devices or human computer modelling are used to record displacements and forces. This works focuses only on the second one, the Human Body Model, which has a model of the organs. In addition, the PVP, Peak Virtual Power, is introduced to evaluate the injuries of the internal organs.

The PVP is an injury criterion, based on energy. This method has as basis the second law of thermodynamics, because after every impact the entropy increases. The PVP is a representation of the entropy, so it takes the peak of the virtual power. In the figure 20, the behaviour of the power-indicator, compared with the power, is shown.

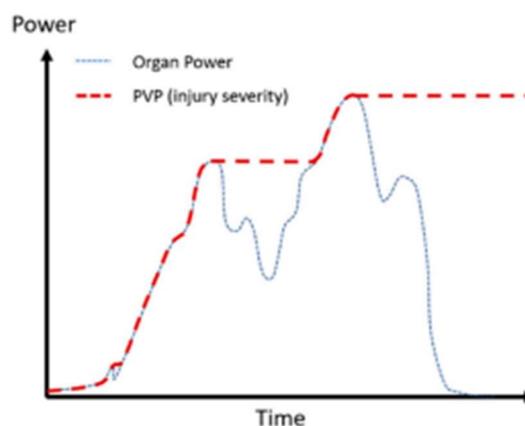


Figure 20 - PVP

This indicator is calculated, using the following Von Mises vector resultant:

$$PVP \propto AIS \propto \max (\sigma \cdot \dot{\epsilon})$$

In particular,  $\sigma$  is the stress, while  $\dot{\epsilon}$  is the strain rate. These two terms are multiplied. After the multiplication, the maximum value is taken. In this way, the indicator is calculated during all the impacts.

After the mathematical formulation of the PVP, it's important to understand how to correlate the energy-indicator with AIS levels. In this way, it is possible to evaluate the severity of an injury of a soft organ in a computer model.

Therefore, the purpose is to recreate the AIS curves, in correlation with the PVP and the velocity of the impact. The first step, so, is to simulate the model with different velocities of impact. For every velocity, the PVP, correlated to AIS 4, is taken. To make this, the strain is analysed and the first element, which reaches the limit of the strain, is saved. The limit of the strain to find the AIS depends on the analysed organ, according to the table 6.

Tissue/Organ	Currently-used injury measurement	Injury description	AIS
Brain grey matter	Maximum 30% principal strain	Brain contusion	3-4
Brain white matter	21% maximum principal strain	Diffuse Axonal Injury (DAI)	4
Heart	30% maximum principal strain	Rupture	4
Liver	30% maximum principal strain	Rupture	4
Spleen	30% maximum principal strain	Rupture	4
Kidneys	30% maximum principal strain	Rupture	4
Skull	Maximum 3% plastic strain	Fracture	2-3

Table 6 - Tissue/Organ: strain-injury-AIS

After that, the PVP is calculated, using the element just saved, according the formula, shown before, and, in this way, the PVP for every impact is obtained. Linking these points, the curve for the AIS 4 is extracted.

After the AIS 4, the other curves are extrapolated, using the correlation between the different AIS levels, as reported below.

$$PVP_{AIS-A} = PVP_{AIS-4} \times \frac{A_{AIS-A}^3}{4^3}$$

In this way, the corridors are obtained. So, the real PVP must be calculated, for the real impact, studying all the elements and taking the maximum value. This value will be put with the corridors. Evaluating where the value falls, the AIS score for a specific organ is gained and, so, the trauma is recognized.

## Chapter 5

### Changes in the THUMS

In this paragraph, the changes in the THUMS are reported to have a better model, more representative of the reality.

For this purpose, the first step is to understand the behaviour of the original model (THUMS), validating it in different points: pelvis, thorax and abdomen. With different impacts, as reported in chapter 2, the answer of the model is studied. Then, the response is analysed to see if it is inside or outside the corridors.

#### 5.1 THUMS validation

The THUMS model was hit by different impacts in different parts of the body and then, based on experimental data, different curves were analysed.

##### 5.1.1 Thorax

In the thorax, three simulations were analysed: frontal impact, belt impact and bar impact.

For the first simulation, a cylindrical impactor, with a diameter of 152 mm and a weight of 23.1 kg, hit the chest, between the 4<sup>th</sup> and the 5<sup>th</sup> ribs, with a velocity of 7.2 m/s.

In the figure 21, it is impossible to can note the response of the chest: the x-axis represents the chest deflection, given by the difference between the movement of the impactor and the movement of a node located in the torso, while the y-axis represents the force exerted by the impactor against the THUMS. The biomechanical answer is in the corridors (represented by ‘upper corridor’ and ‘lower corridor’) and therefore the model results to be realistic.

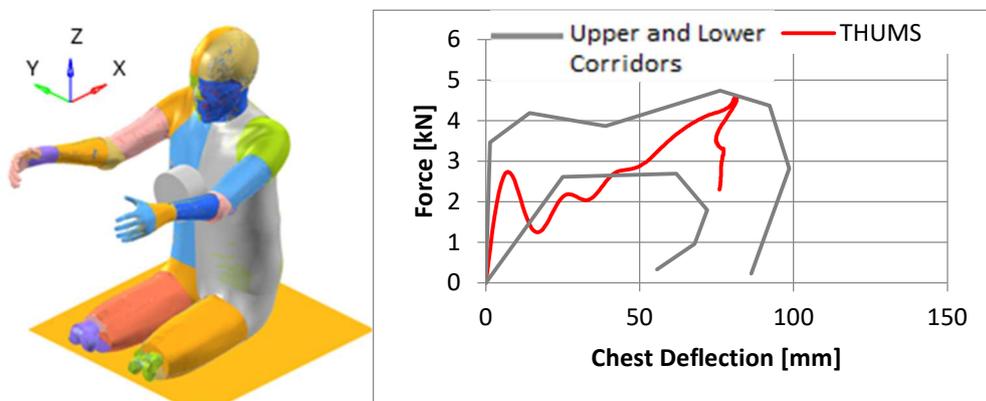
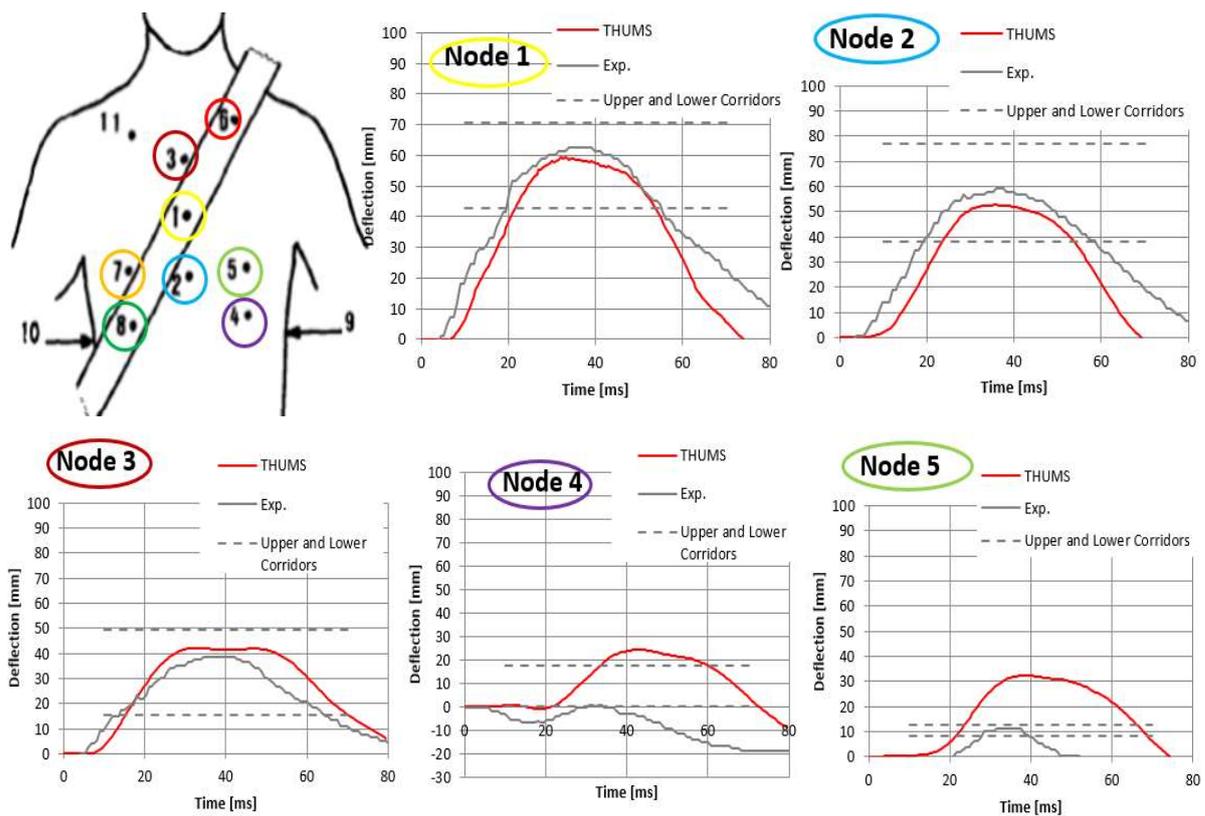


Figure 21 - Frontal impact (model and THUMS response)

The second simulation simulates the impact of the belt on the chest, just like during a crash test. As explained, in the chapter 2, the belt is linked with an impactor, which has a velocity of 7.78 m/s. Therefore, the belt is brought behind and, in this way, it hits the thorax on the ribcage. Indeed, the belt is anchored in two points, one point is above the left shoulder while the other point on the right side, near the hip.

In this case, the analysis involves the studies of different nodes, located in different parts: costal cartilage, seatbelt, or ribs. In the figures 22, the answers of the chest are reported. The x-axis is the time while the y-axis is the displacement of various nodes. This simulation is more problematic than previous ones, because, even if the most of nodes have a displacement inside the corridors, four nodes have a different stiffness to the experimental data (labelled in the figure with 'exp') and their behaviour is not inside the corridors (dotted lines), which represent the acceptable response to have a realistic answer. In particular, node 4, node 5 and node 6 are less stiff than the expected answer, while node 7 is stiffer than the real response.



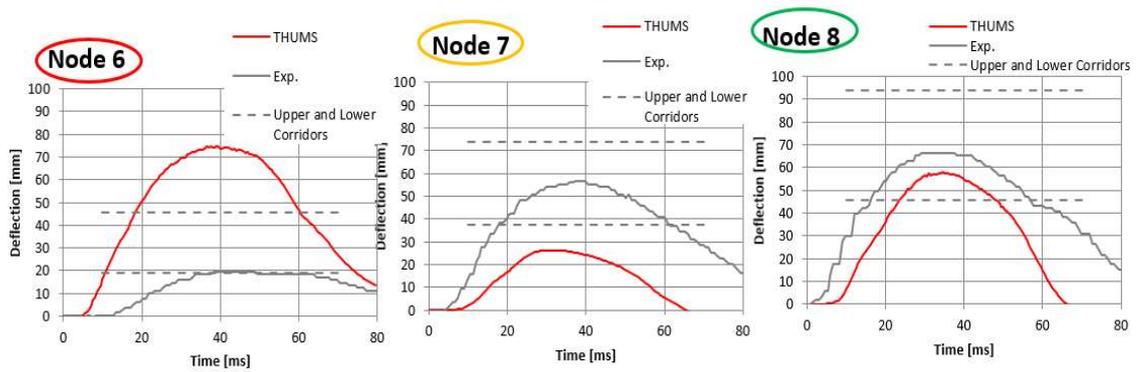


Figure 22 - Location of nodes and response of thorax

The last simulation of thorax is lateral impact, in which a bar hits the chest. The impactor has a diameter of 152 mm, weight of 23.4 kg. It is put in motion with a velocity of 2.76 m/s to hit the chest laterally. This test analyses the chest deflection, namely the movement of a node, located on the chest, compared to a node situated on impactor and the force applied by the bar, namely the impactor, during the simulation.

In this case, as it is possible to see on the figure 23, the response, in red, is acceptable because it is inside the limits, represented by the corridors, in grey.

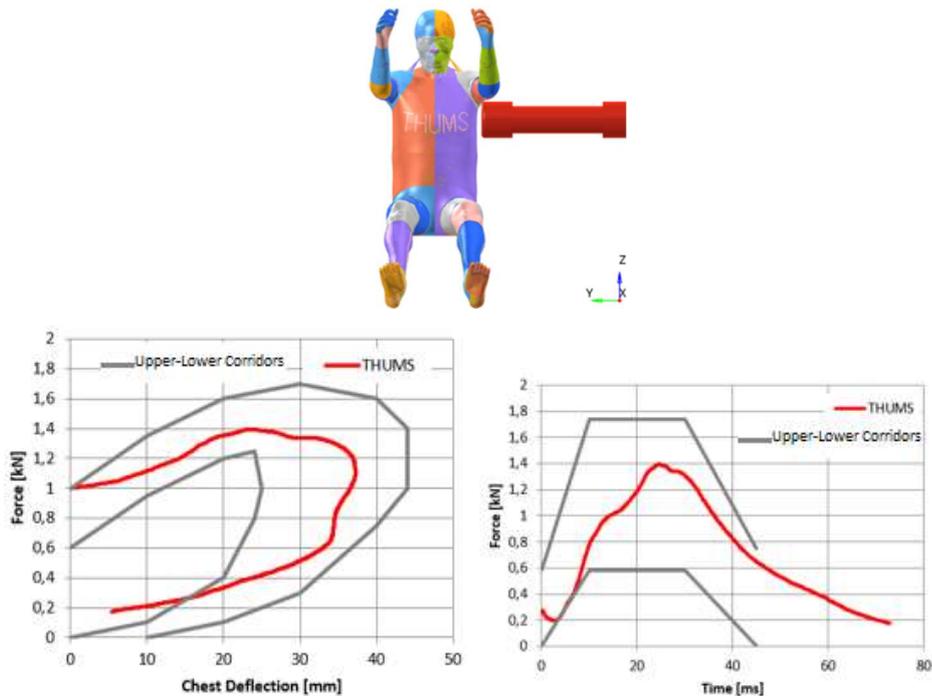


Figure 23 - Lateral Impact (model and THUMS' response)

5.1.2 Abdomen

After the study of thorax, another part of the body was studied, the abdomen, with two simulations: bar impact and belt impact.

The first simulation, bar impact, shown a bar, which hits the abdomen at the level of the intestine. The test analyses the force with which the abdomen is deflected and, also, the movement in mm of abdomen during the impact. In the figure 24, it is shown the force of impactor, filtered with a SAE filter 180, applied on the abdomen (y-axis) compared to the movement of abdomen, measured as the difference between a node on the impactor and a node on the abdomen (x-axis). In this case, the response of the abdomen is inside the corridors, limits calculated with real data or experimental data, for the largest part of the cross-plot, so the THUMS, under this impact, has a behaviour near to the real one.

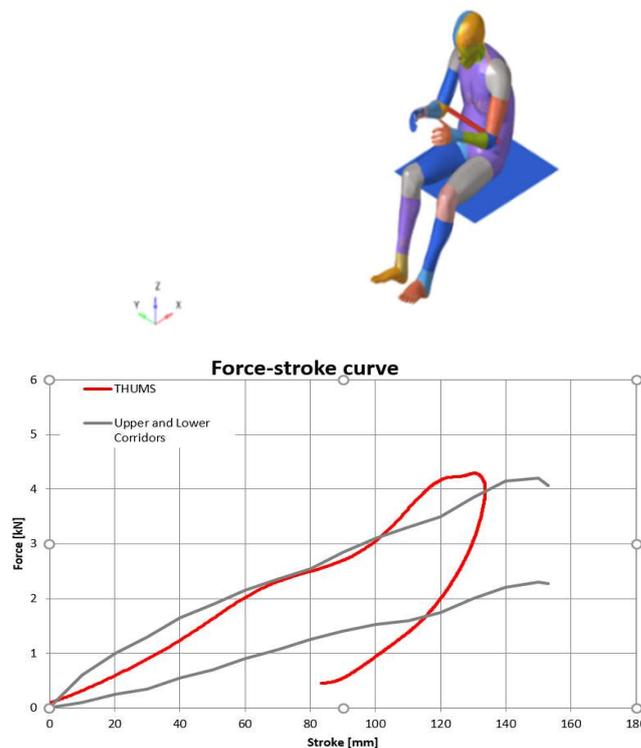


Figure 24 - Bar impact (model and THUMS' response)

In the second simulation, the abdomen is stressed by a seat belt. In this case, like in the previous simulation, the force of the abdomen and the displacement of the belt relative to the abdomen are studied, but in this case these two measures are calculated in a different way. Indeed, in this simulation, the force is calculated as the sum of the two cross-area forces, located at the

endpoints of the belt and filtered with a SAE filter 180, while the displacement is measured as the movement of a node, which is in the seatbelt. With the simulation you can note, in the figure 25, that the response of the THUMS is inside the corridors.

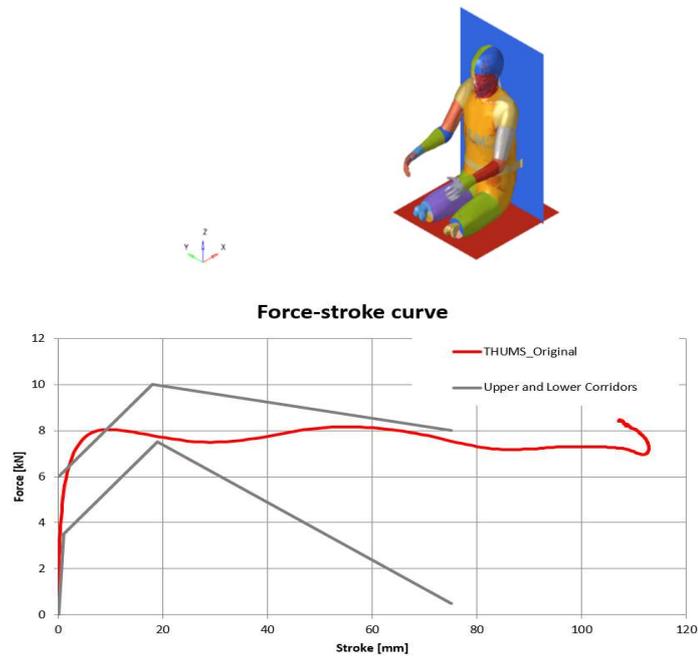


Figure 25 - Belt impact (model and THUMS' response)

### 5.1.3 Pelvis

The last part analysed is the pelvis, as explained in the chapter 2, with two simulations: the knee-thigh-hip and acetabulum lateral impact.

The first impact involves a table which hits the knee. To study if the THUMS is validated with this impact, the force, calculated as the average of the forces applied to each knee, is analysed at different instants of time and for different velocities of the table.

The answer of THUMS, under this impact, is acceptable because it follows the real behaviour.

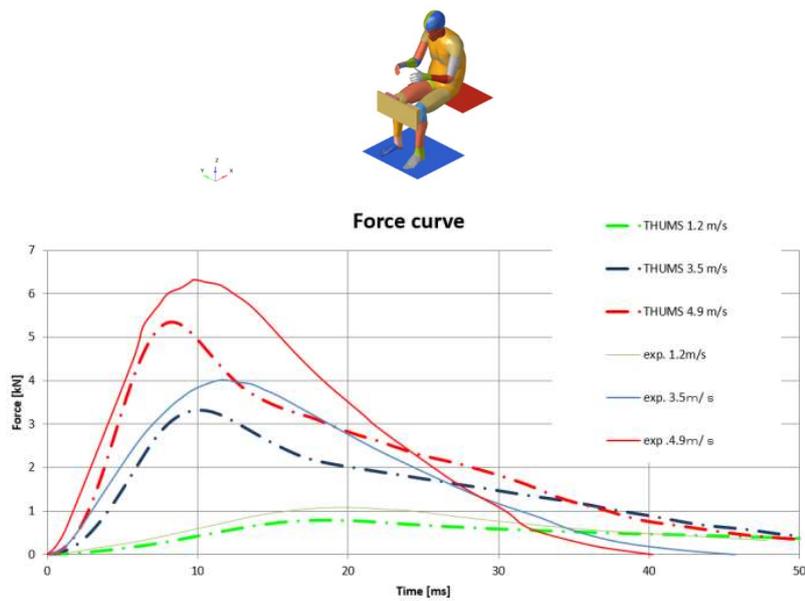


Figure 26 - Pelvis Knee-Thigh-Hip (model and THUMS' answer)

The last simulation does not use the whole THUMS but only the pelvis part, which is hit by a sphere and pad, loaded with a different behaviour to simulate two different situations: the fracture strain at 3% and at 1%. These two simulations are made with different parameters in the material, in particular the value of the failure.

In this simulation the force, obtained by the contact of the sphere and the impactor, is analysed at different instants of the time. With this simulation it is possible to note that the THUMS' response is inside the corridors for both situations, therefore this part of the THUMS is validated.

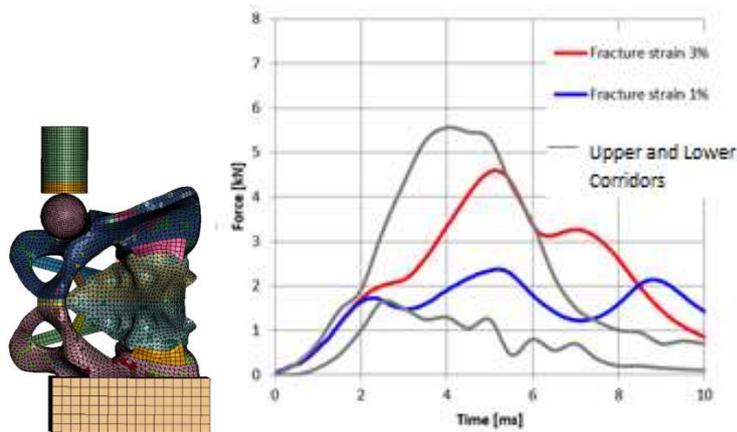


Figure 27 - Acetabulum lateral impact (model and THUMS' response)

## 5.2 Changes in the ribs

After the validation of the THUMS, a problem with some tests has emerged, in particular the simulation on the thorax with a belt and minor problem with the simulation with abdomen.

In the first case, some nodes showed different behaviour with respect to the reality, for this reason the location of these points was analysed. It was discovered that the problematic nodes were located on costal cartilage or muscles. Following this and knowing the link between costal cartilage, ribs and their position, the ribcage was studied in order to improve the answer of the THUMS. In this way, the response could go back in the corridors, and you could also have a model which represent the human body as precisely as possible. The first thing that was decided to study, was the ribs.

In the second case, the problem was evaluated as less problematic than the first case because the response was inside the limits for most of the curves and the behaviour was similar to the experimental data.

### 5.2.1. Rib: cortical bone

The ribs are a complex structure of the body. They are composed by two components: cortical bone and trabecular bone, which have a different composition and a different role. Indeed, cortical bone has better resistance to compressive and bending while the trabecular to compressive and tension.

The thesis was based on the change of rib cortical bone and not spongious because less experimental data about the second ones were found. In addition, the principal load, with which the ribcage is stressed, is a bending type and rib cortical bone has a major role in this type of stress.

The first thing was to find more information about the rib cortical bone on FEA analysis, namely in which way this component is modelled: material and section. For this purpose, different articles were found to understand better in which way this component is usually treated.

Kimpara et al. [17] wanted to improve the human model for female chest and, for this purpose, to analyse the chest, in particular sternum, internal organs, bones, muscles, cartilage and bones. For the ribs, the cortical and trabecular bones were modelled in two different ways, respectively with shell and solid elements keeping count of the geometry, cross sectional area and also inertia moment. Anyway, the main argument for the purpose of thesis, is the material chosen for rib cortical bone. Kimpara et al. [17] chose an elastic plastic material, MAT\_123, with failure. The

young's modulus was based on another article of the same authors, where they found, with some rib tests, a mass density of  $2.0 \text{ kg/m}^3$ , yield stress of  $66.6 \text{ GPa}$  and a poisson's rate of  $0.3$ .

The THUMS is built with a different material, different value for young' modulus and yield stress, but Kimpara's article wanted to improve a human model for female and not 50%ile male, like the THUMS used in this thesis. For this reason, more information was searched.

Iraeus et al. [18] published an article about the material of the ribs. Studying other articles, they found a new method to represent the cortical bones on LS-DYNA using an isotropic plasticity material, MAT\_24, where the young's modulus, tangent modulus, yield stress and ultimate strain are defined.

In the two articles, the choice of values is different. First of all, the card of materials is different, but in both cases, it represents a plastic material. Also, the values are different, indeed the young's modulus and the yield stress of the first article are less than the second, implying that the material in the first case is less deformable, therefore the plasticity occurs more quickly.

The differences between the two articles are given by the dissimilar situation indicated. Indeed, in the first article the THUMS was modified in order to find a suitable model for female, while in the second article the purpose was to find a more realistic model for ribs.

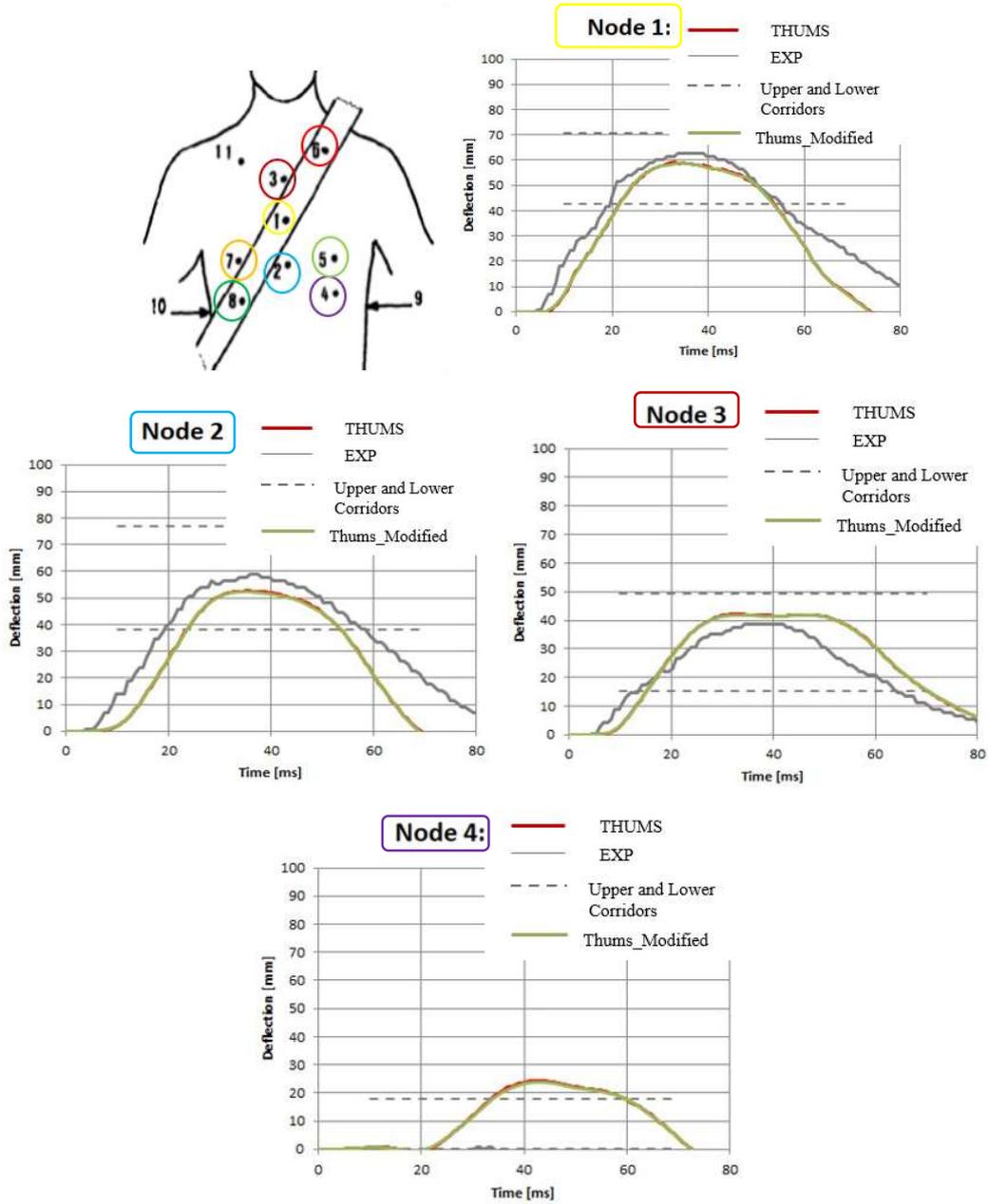
After these considerations the material was changed to better understand what a change of rib cortical bone could alter and, so, investigate more the cortical rib bone. For these reasons, the rib cortical was changed from original THUMS, of TOYOTA, to Iraeus et al.' [18] values. Thus, the material was changed from a plasticity material with damage, MAT\_81, to a piecewise linear plasticity, MAT\_24 and, also, the values were changed, the young's modulus from  $13.02 \text{ GPa}$  to  $14.7 \text{ GPa}$ , the yield stress from  $80 \text{ GPa}$  to  $100.7 \text{ GPa}$ , and two values were added, the tangent modulus and the failure, passing from  $0$  to  $1.940 \text{ GPa}$  and  $0.025$  strains.

After these changes, the model was re-tested and so re-validated to understand if these changes can improve the response of the model. All the tests, explained in chapter 2 and reported in chapter 5, paragraph 1, were remade and reanalysed, especially the problematic curves, as reported in the previous paragraph.

All the curves reveal a similar behaviour than previous studies, but there are some little differences for the impact on the thorax with the belt, indeed there is a lack of overlapping. Considering the slight differences, between the original THUMS and the new one, and the fact that the thorax loaded with belt loading is the most problematic simulation, only the comparison, concerning this test, are reported.

## Changes in the THUMS

Analysing these curves (time(s)-deflection(mm)), similar results are found, because the behaviour is the same and the curves of the problematic nodes are still outside the corridors, but in the case of the node 6 a slight difference could be noted, indeed the curve has lowered slightly.



## Changes in the THUMS

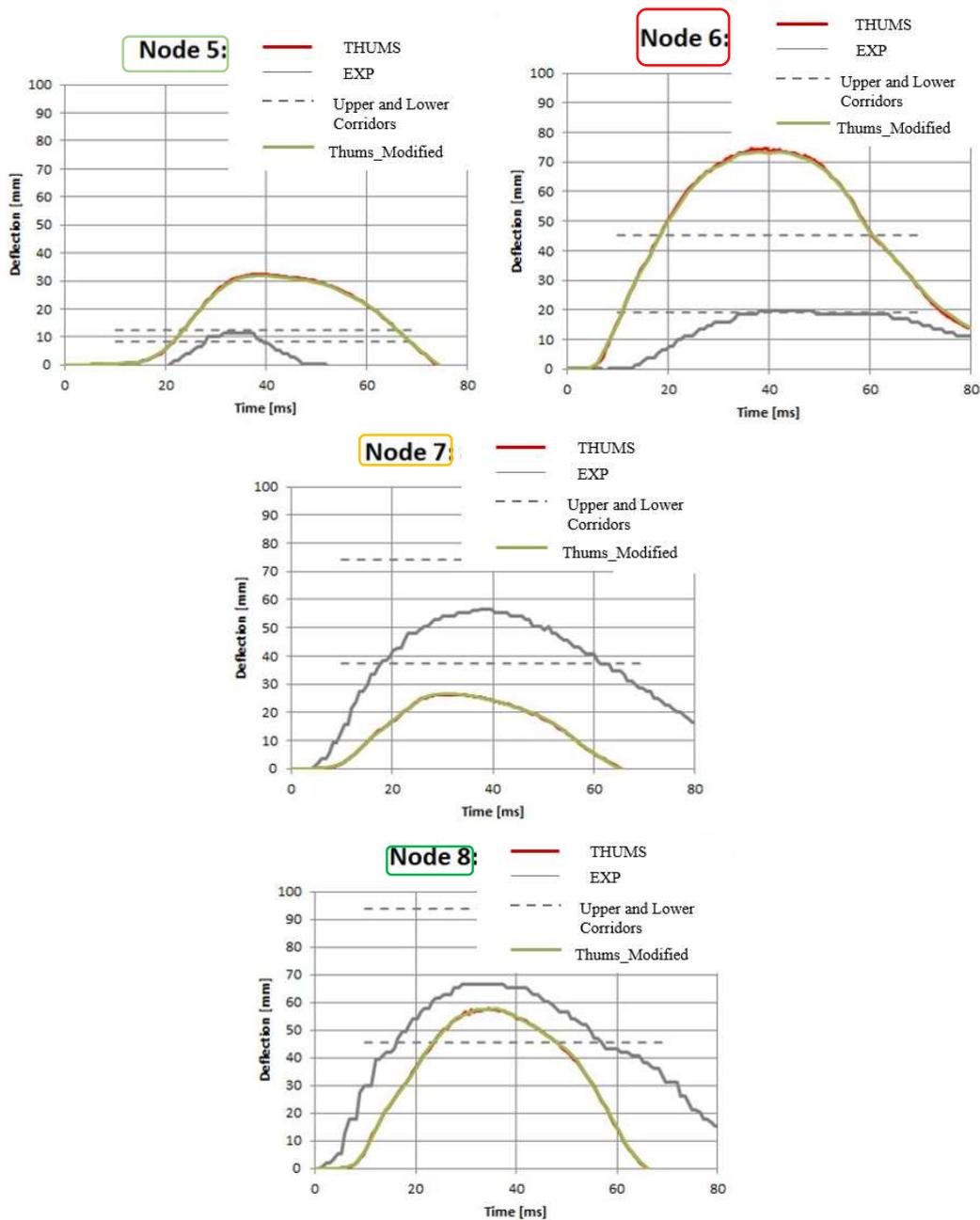


Figure 28 - Thorax (Belt loading) with cortical rib bone modified

### 5.2.2. Rib cortical bone: curve stress and strain

After the analysis of the rib cortical bone, it emerged that cortical bone of ribs gives a slightly different behaviour of one of the problematic nodes, so a major study could be interesting. In addition, it is considered important to make a material that better mimics the real cortical bone.

For these two reasons, in this thesis, it is decided to discover better the response of the ribs (the cortical part) in order to recreate a material similar to reality, initially without the failure because it could give more instability.

In Kemper et al. [19] it was analysed the cortical rib bone through a dynamic tension coupon testing to develop the material properties. In this study, the coupons were obtained by 117 human rib cortical bones, taking them in three different locations: anterior, lateral and posterior. The bones were obtained from different cadavers with a variable age, between 18-60 years old. In Kemper et al. it was, also explained how the specimens were created, the material used for it and the method to maintain the coupon during the preparation and the testing. At the end of the process, numerous specimens were obtained with a 'dog bone' shape, as reported in the figure 29.

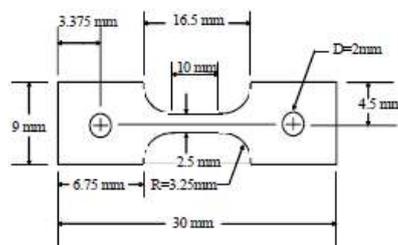


Figure 29 - Rib cortical bone 'dog bone' tension specimen dimensions

These tests are, then, loaded with a velocity of 0.5 strains/s using a specific machine, a high-rate servo hydraulic Material Testing System (MTS), in order to recreate the strain rate with which the rib cage is stressed by the seatbelt. After the simulation the stress-strain curves were obtained, using the extensometer. Not for all the specimens made was possible extract the curves, because in some case the test broke outside the gauge length and, for this reason, less data was acquired at the end. These data were used to find the material properties: elastic modulus, yield stress, yield strain, ultimate strain and ultimate stress for all ribs and on the average. The stress was calculated as the ratio between the calculated force and the cross-sectional area of the specimen gauge length, while the strain as the difference in length between gauge arms of extensometer and then, dividing this value with the initial length between the cage arms.

In this thesis the purpose is to recreate the study, just mentioned, with the FEM analysis, using LS-Dyna, to improve and make similar to the reality the cortical rib bone used in the THUMS. Initially, the failure is not put because it could give instabilities in the total model and, for this reason, the principal aim is to have a similar stress-strain curve before the fracture.

First of all, the specimen in FE model is created with the same geometry of the Kemper et al.'s article, to have a better comparison between the results of the study and the FE analysis. For

the creation of the tension coupon of rib cortical bone a shell was used, as in the THUMS model, while for the mesh, the tool 'auto mesher' is used to create a variable mesh without too little element. In the figure 30, the coupon is reported with the dimensions (in mm), which are the same of the study

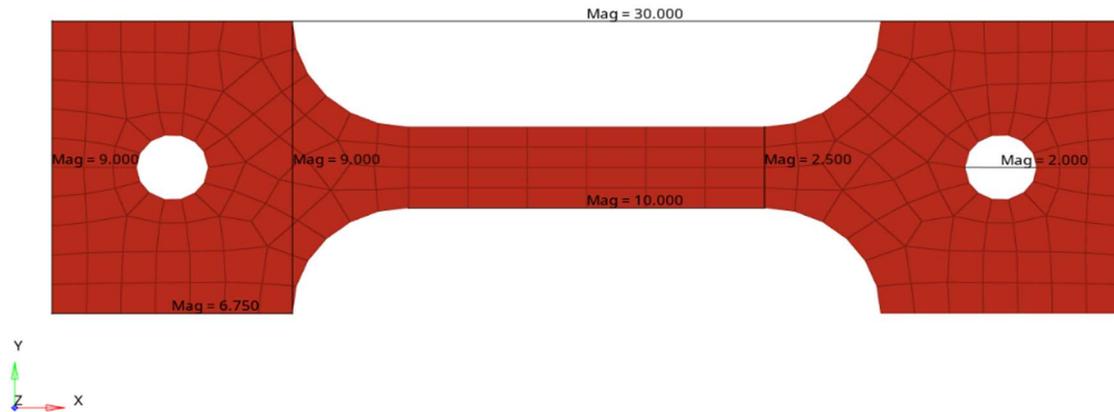


Figure 30 - Rib cortical bone "dog bone" and dimensions on LS-Dyna (Mag=magnitude)

After the creation, the coupon has to be loaded in some nodes and also constrained in other nodes to make the tension test.

For this reason, a set of nodes, reported in the figure 31 in black, is constrained therefore this set can't translate in X, Y and Z direction and also it can't rotate around the X-axis, Y-axis and Z-axis.

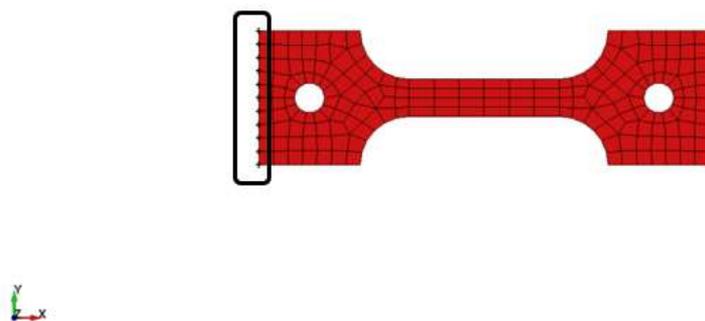


Figure 31 - Constrained nodes

Another set of nodes, placed in the opposite location of specimen than the previous set (in the figure the nodes are highlighted with an orange rectangle), is loaded with a velocity along x-direction. The value of the velocity is calculated analysing strain-time curve, reported in Kemper's

article. In particular, the following steps are done: the discretization of the curve, to have the variation of the strain in every interval of time, then the different variations are multiplied with the active length (10 mm) to obtain the variations of the length and then these values are compared to the interval of time. Following these steps, different values of velocity, one for every interval of time, are obtained and so the average of these are used, so 3.6 mm/s.



Figure 32 - Nodes with velocity imposed (right side)

After the creation of the specimen, the properties of material and section are defined.

First, the specimen is associated to the THUMS model, so the material and the section properties are imposed as in the human body model. Therefore, the material is simulated with a plasticity with damage type, MAT\_81, while the section shell with an element formulation fully integrated, so 16 in LS-Dyna, with a uniform thickness of 0.3 mm. This step is important to note if the behaviour of model and of rib specimen, taken by cadavers, are similar or not.

In the material card, the properties of rib cortical bone are defined as reported in the table 7.

Mass density	2.00e-9
Young's modulus	1.302e+04
Poisson's ratio	0.3
Yield stress	80
Tangent modulus	0
Strain rate parameter, C	360.7
Strain rate parameter, P	4.605
Effective plastic strain value, first (EPS1)	0
Effective plastic strain value, second (EPS2)	0.003
Effective plastic strain value, third (EPS3)	0.015
Effective plastic strain value, fourth (EPS4)	0.0204
Corresponding yield stress value to EPS1	80
Corresponding yield stress value to EPS2	110

## Changes in the THUMS

Corresponding yield stress value to EPS3	120
Corresponding yield stress value to EPS4	124.5

Table 7 - Material properties of rib cortical bone of THUMS

After the preparation of the coupon, the test is simulated, in this way, the curve strain-stress is extracted and then the comparison between the curves reported in the Kemper et al's article and the curve obtained for the THUMS is made.

In the figure 33, the curves are shown.

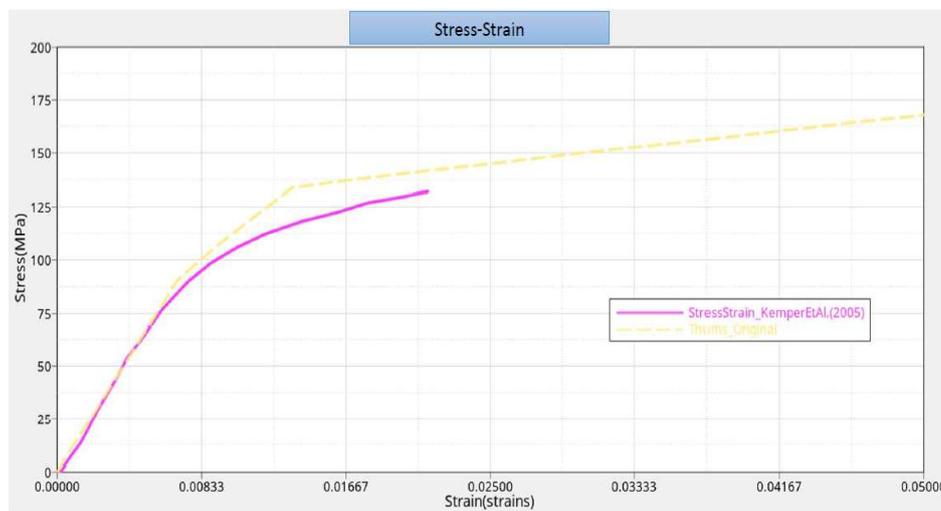


Figure 33 - Comparison between stress-strain curves for Kemper et al and THUMS

In the figure, it is displayed only a curve of the article, but during the study all the curves are analysed and all the curves of cadavers, over 18 years old, are similar in the slope. The behaviour of the curves for cadaver with 18 years old is analysed in the following chapter.

In the figure, you see the difference between two curves, in particular the yellow curve represents the behaviour of the tensile with the characteristic of the THUMS, while the purple one of the cadavers. The original THUMS' curve is higher than other curves and this can be seen especially at the end of the elastic part. Another difference is the duration of the yellow curve, because the purple curve stops at, approximately, 0.025 strains, while the yellow does not. This behaviour is associated to the lack of the failure in the material card of ribs in the THUMS to work initially with more stability.

To improve the material, firstly the result of young's modulus, found in the article, is put in the material card. The table 8, available in the article, is reported to understand better the choice about the value put, initially, in the THUMS.

Analysing the table, you can see a huge difference between the young's modulus of old cadavers, male or female, and the young cadavers. For this reason, as briefly mentioned, the values of old cadavers are used in this paragraph, while the bones for young cadaver are studied in the following paragraph.

Since the value of old female and old male cadaver are the same, it has been decided to focus on the older cadaver, in general, and for this reason the first step is to change the young's modulus from 13.02GPa to 14.8GPa.

KEMPER ET AL' VALUES	E (GPa)	$\sigma_{yield}$
ALL CADAVERS	13.9	93.9
ALL CADAVER BUT 18 YEARS OLD	14.8	101.9
ALL MALE CADAVERS	12.9	88.2
OLDER MALE CADAVERS (45 AND 67 YEARS OLD)	14.6	101.3
18 YEARS OLD MALE CADAVER	9.8	67.2
ALL FEMALE CADAVERS	15.2	102.7
OLDER FEMALE CADAVERS (61 AND 64)	14.8	101.9

*Table 8 - Material properties of ribs*

After this first change the simulation starts again and new results are analysed. In the figure 34, the comparison between the THUMS with the original material, yellow curve, and the THUMS with the material modified, thus with a different young's modulus, light blue curve, is reported.

You can note a slightly different behaviour in the initial part, in fact the two curves do not overlap, especially when the strain is between 0.005 strains and 0.125 strains, therefore when the curve is in the elastic region. Over the limit of elasticity, the two curves intersect and then they have the same behaviour, because the young's modulus affects only the first part of the curve.

## Changes in the THUMS

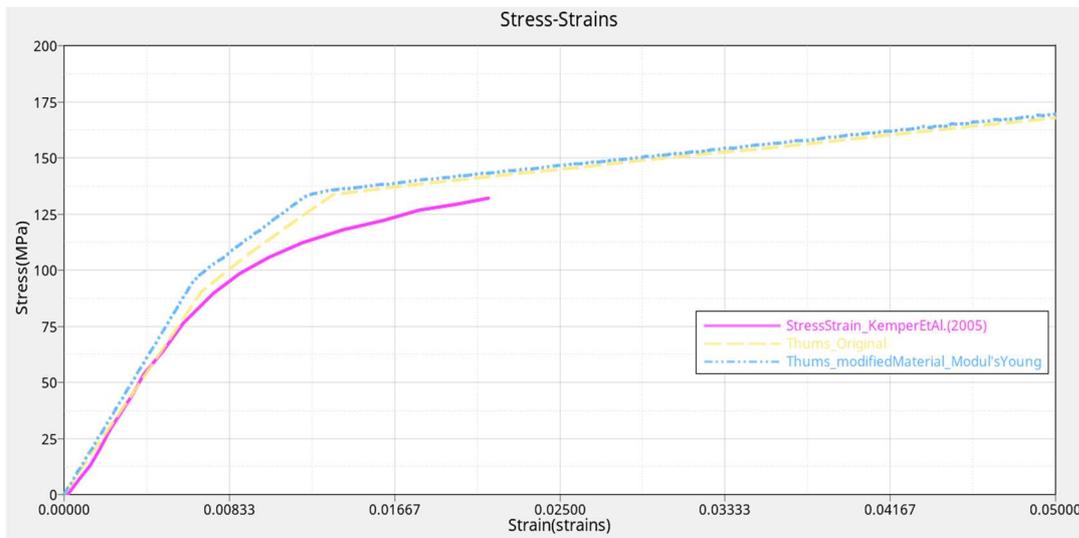


Figure 34 - Stress-Strain (young's modulus changed)

After the change in the elastic region, the plastic region is analysed. In this case the THUMS with the original material and the article's curve are more dissimilar than the previous part and for this region some parameters are changed. For this purpose, two methods are followed to change the effective plastic strain value and the yield stress corresponding. First, the stress reported in the article is turned from engineering stress to real stress, as used in the material card, to have a range of stress more accurate. Then it is used the 'Try and error method', thus some parameters are put in the material card. With these values, the curves are analysed and, if the curve is not acceptable, another parameter is tried.

In the table 9, the parameters changed, for which the curves give the most significant results, are reported. The EPS value is the effective plastic strain, while the ES is the  $\sigma$  yield corresponding to each EPS value.

In the left side of the table there is the name of the curve as reported in the figure 35.

Curve's name	EPS2	EPS3	EPS4	EPS5	EPS6	$\Sigma_{yield}$	ES2	ES3	ES4	ES5	ES6
Thums	0.003	0.015	0.0204	0	0	80	110	120	124.5	0	0
Thums11	0.009	0.013	0.0170	0	0	80	110	120	124.5	0	0
Thums13	0.002	0.009	0.013	0.0170	0	80	95	110	120	124.5	0
Thums21	0.001	0.003	0.009	0.013	0.017	75	85	95	110	120	124.5

Table 9 – Parameters changed (EPS -effective plastic strain,  $\sigma$  yield, ES –  $\sigma$  yield corresponding to effective plastic strain)

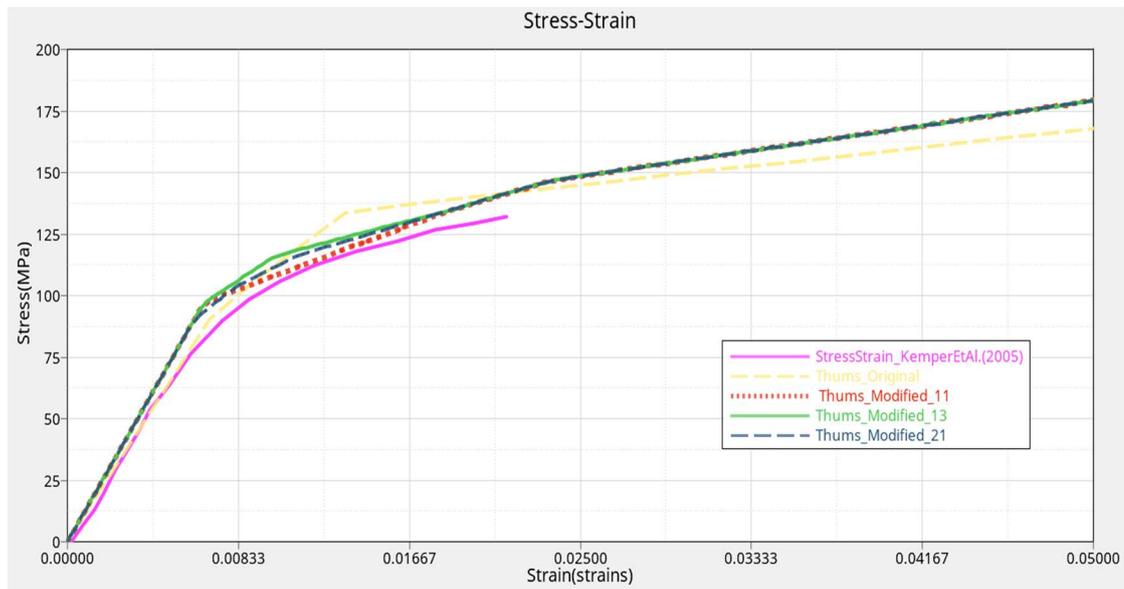


Figure 35 - Stress-strain

After the change, the results are again analysed (figure 35). In this case, you can note a more accurate behaviour with respect to the THUMS with the original material, especially between the two region, elastic and plastic, indeed the yellow curve has a peak at 0.01333 strains, peak not showed in the article's curves and in the new curves, for THUMS with material modified. Between the three curves shown in the figure, the blue curve, THUMS\_Modified\_21, is considered more accurate because it has the same slope of the Kemper et al.'s curves, but it is shifted along the y-axis. For this reason, another step is performed, therefore the parameters of

this curve are re-simulated in order to have a better fitting between the real curves and the human model, as reported in the figure 36.

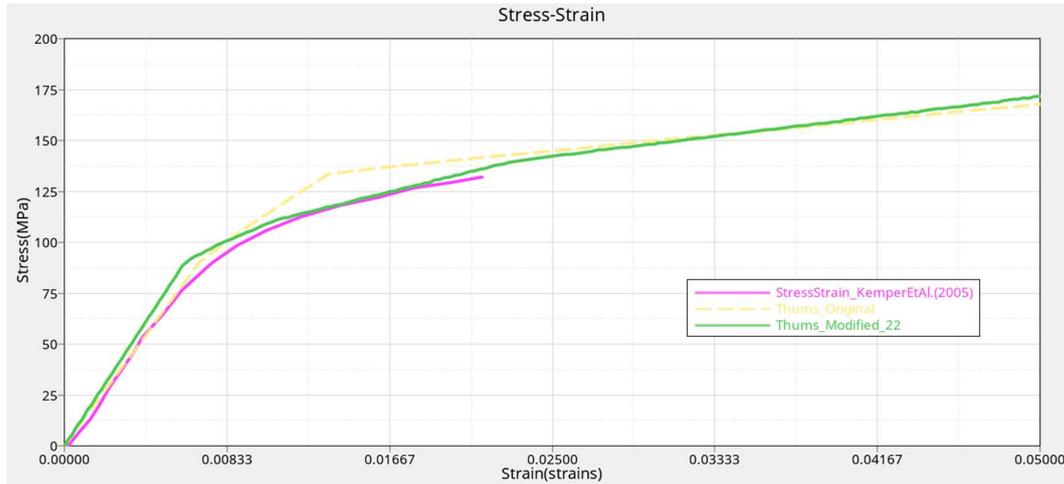


Figure 36 - Final stress-strain curve

For the last curve, Thums\_Modified\_22, the stress value of Thums\_modified\_21 (so from ES2 to ES6) are changed in, respectively, 81.1 MPa, 90.625 MPa, 104.93 MPa, 114.474 MPa and 118.766 MPa.

In this way a new stress-strain curve is obtained, in green in the figure, which respect more than the THUMS with the original material the behaviour of the real curve.

Once found the new parameters for the rib's cortical bone material, the validation is, again, performed, to see if these changes can solve or not the problem of different stiffness of some nodes with respect to the expected results. In the file of the original THUMS, every rib's cortical bone is modified with the values of the last curve, namely the THUMS\_Modified\_22.

After the simulation, the validation curves are again plotted, and they are analysed to see if all the curves are in the corridors or not. Unfortunately, the validation curves are not change and, therefore, the results before and after the changes are the same, indeed the curves overlaps. The positive thing is to have a material which simulates better the real material and thus more reliable than previous ones.

5.2.2.3 Rib cortical bone: curve stress and strain (18 years old cadaver)

After the study of the material of the rib cortical bone for older cadavers, also the material, for 18 years old cadavers, is analysed, as mentioned in the previous paragraph.

The reason of this study is to recreate the ribcage also for young men, even if this is not available for the THUMS used, because it is based on 50%ile male.

The steps followed are the same ones explained in the previous paragraph.

First, there is the preparation of the tensile test, the data are again based on Kemper et al. article, therefore the geometry, the velocity and the nodes loaded and constrained are recreated as for the coupon of older cadaver. Then, the THUMS with the original material is compared to the curves, related to young cadavers, reported in the article. After this step the young's modulus is changed following the Kemper et al.'s values, reported in the table 2 with the name '18 years old male cadaver' (9.8GPa). Then with 'try and error' method the curve is improved and, finally, the curve is created.

After the first change, the image 37 is obtained.

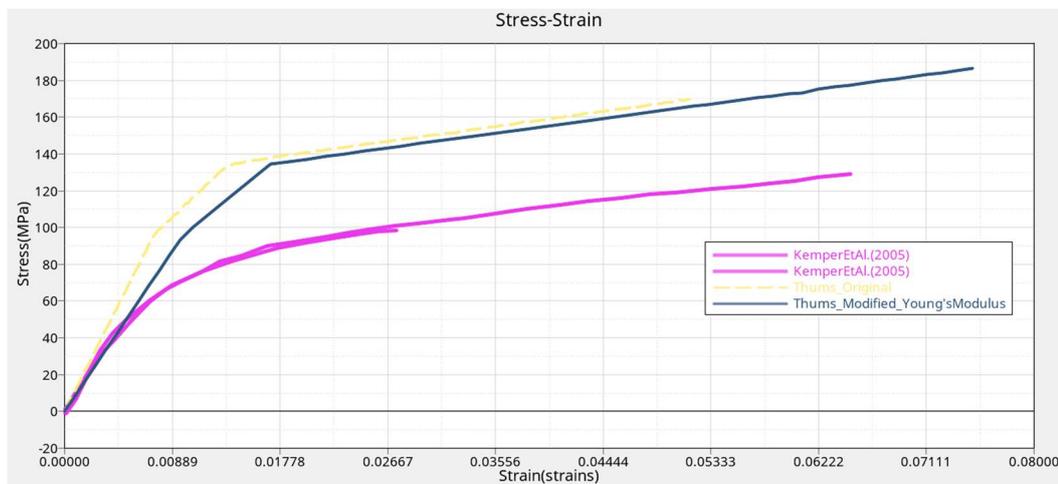


Figure 37 - Comparison between article's curve, THUMS with the original material and THUMS with the young's modulus changed

In the figure 37, you can note very different curves. The first thing, which is important to underline, is the fact that the yellow and blue curves, differently from the previous study, are stopped, because in this way the curves are more visible (and so more comparable), but again there is no failure in the material.

In purple it can be seen one of Kemper’s curves for young cadavers and, as you can see, it is lower than the other two. For this reason, the values of this curve, in terms of stress, are lower than other two. Furthermore, the yellow curve diverges more from purple curve than blue, therefore the change in young’s modulus results give an improvement in the materials. After this step, the ‘try and error’ method is followed, and a new curve is obtained.

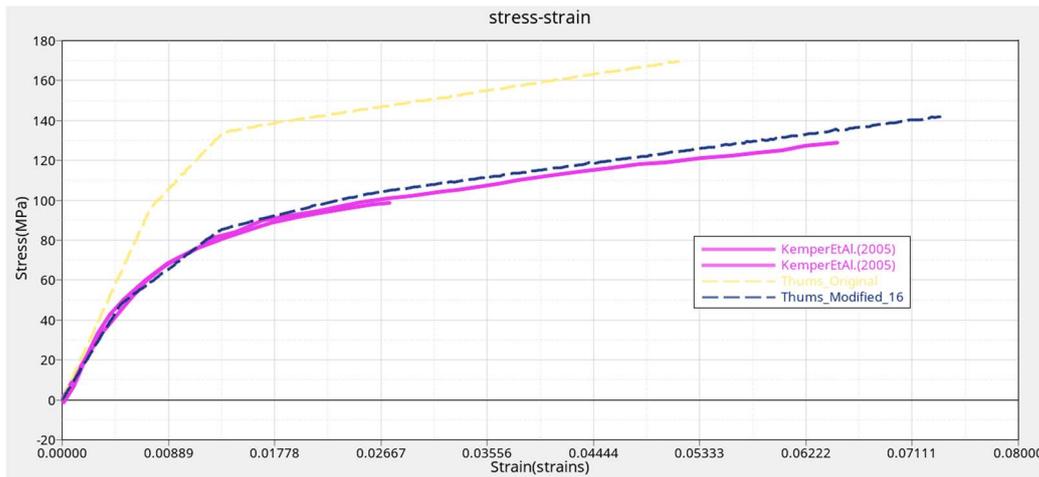


Figure 38 - Comparison between article's curve, THUMS with original material and THUMS with material changed

In the figure 38, the curve with the last change is obtained (the blue curve, labelled with Thums\_Modified\_16). This curve has a behaviour similar to the purple one. For this reason, it represents more the behaviour of young people than the yellow curve. To obtain this curve the eps end es values, in the material card, were changed as reported in the table 10.

Curve's name	EPS2	EPS3	EPS4	EPS5	EPS6	$\Sigma_{yield}$	ES2	ES3	ES4	ES5	ES6
Thums_Original	0.003	0.015	0.0204	0	0	80	110	120	124.5	0	0
Thums_Modified_16	0.0023	0.0043	0.011	0.015	0.0204	40	55	70	80	85	89

Table 10 - Comparison between the original and the new material of rib cortical bone

Following this analysis of the material, the validation test is not made because this material is the only modelled on young cadavers, while the other organs are modelled in older male.

### 5.2.3 Thickness of ribs’ cortical bone

Another important characteristic of cortical rib bone is the thickness. Indeed, it can be more or less thick based on the location, so it is not constant in the human body, but in the THUMS

model the thickness is approximate as uniform. For this reason, it's important investigate better this aspect to understand if the approximation can be considered acceptable or not.

In Kemper et al. [20], the thickness of the rib cortical bone was analysed, preparing some three-point bending specimen, taken by ribs from 4 to 7 in lateral and anterior locations. Using a micro-CT, the specimens were analysed to achieve the cross-sectional image, to which was applied a thresholding to have the shape of the cortical shell. After this step another software was used on this image, converted in binary, and some properties were obtained, like the cortical thickness (in mm).

To improve the human body model, this study was used as basis and two step are followed. In the first step, the thickness is changed uniformly in two position, lateral and anterior, in all ribs, while in the second step only some ribs, from ribs 4 to 7, were modified in thickness in lateral and anterior location.

#### 5.2.3.1 First step

In Kemper et al. [20], the geometrical properties were analysed to discover differences between the ribs in two locations (anterior or lateral, therefore the location near the costal cartilage or the location in the middle respectively, as reported in the figure 39). For this reason, in the article, the specimen was taken in these two positions.



Figure 39 - Costal cartilage in orange while a representative rib in light brown

In this way, it was discovered that the thickness in the anterior specimen is significantly less than lateral in three points, inferior, superior and interior (these parts are shown better in the following image, figure 40).

In the figure 40, you can note the results found in the article.

## Changes in the THUMS

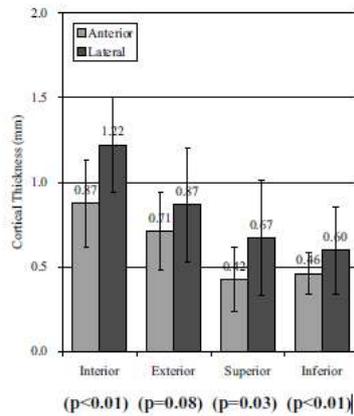


Figure 40 - Kemper et al [20]'s results

As you can see in the image (figure 40), the values of the thickness in the four parts (interior, exterior, superior and inferior) and, also, in lateral and anterior locations, are different. Instead, in the human body model, the value of thickness is uniform along the rib and in all the ribs.

For this reason, according to the values, just reported, the thickness in the THUMS models is changed. In the figure 41, it is shown a figure to better demonstrate how the changes are made.

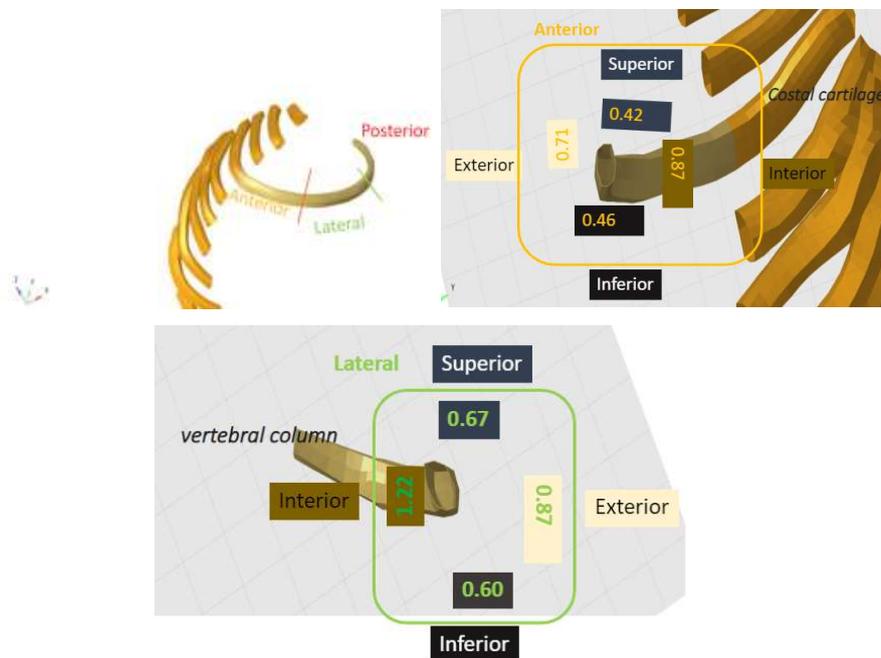


Figure 41 - Cortical thickness for anterior and lateral specimen

In the THUMS, the thickness is 0.7 mm, therefore there is a difference between the model and the values reported in the previous figure. In the anterior specimen, the difference, between

the THUMS and the article's value, is more or less of -0.28%, +17%, -24% and +0.01% respectively for superior, interior, inferior, and exterior, while in the lateral specimen is of -3%, +17%, -10% and +52%.

Through the tool, present on Ls-Dyna, 'shell thickness', the thickness in the model is changed according to Kemper et al.'s values and then the model is revalidated.

In this case, when the re-validation test is performed, no differences between the curves are shown, even for the problematic nodes. For this reason, to note how thickness changes the behaviour in the human body model, also stress and strain are analysed. Therefore, a comparison between the model before and after the changes in thickness is made, using the values, reported in Kemper et al.'s article, as basis. In particular, the values, which represent the stress and the strain when the fracture occurs for the bending or tensile coupon, are used as limits.

Analysing the comparison between the THUMS before and after the changes, it is noted that the values, for von mises stress and equivalent principal strain, are greater in the left side than the right ribs. For this reason, it is reported, in the pictures 42, only the behaviour of ribs located in the left side.

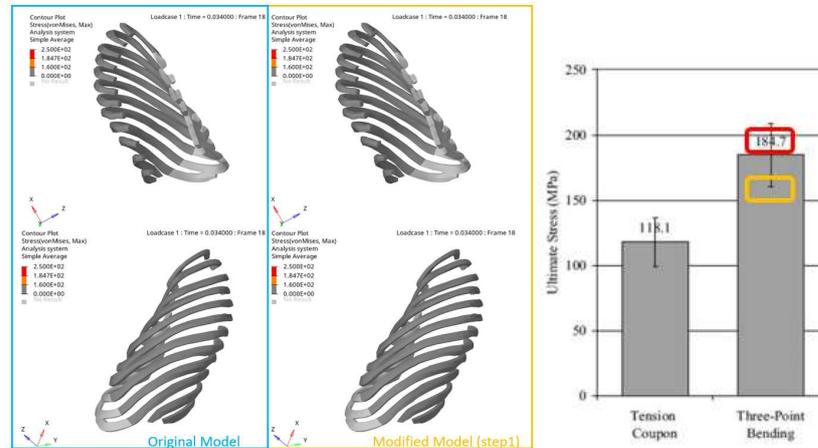


Figure 42 - von mises stress

In the figure 42, you can note the value of von mises stress on a greyscale. The elements of the ribs in red represent the elements that have a value greater than 184.7 MPa, namely the value after which there is the fracture of the three-point bending. While in orange are reported the elements with a value between 160 MPa and 184.7 MPa to consider also the standard deviation. The values are based on three-point bending because this test represents better the behaviour of the ribs, when they are loaded.

As you can note in the picture 42, in the ribs there aren't any elements in red, therefore the ribs, stressed in the thorax with the belt, don't reach the fracture. The same thing can be noted for elements in orange.

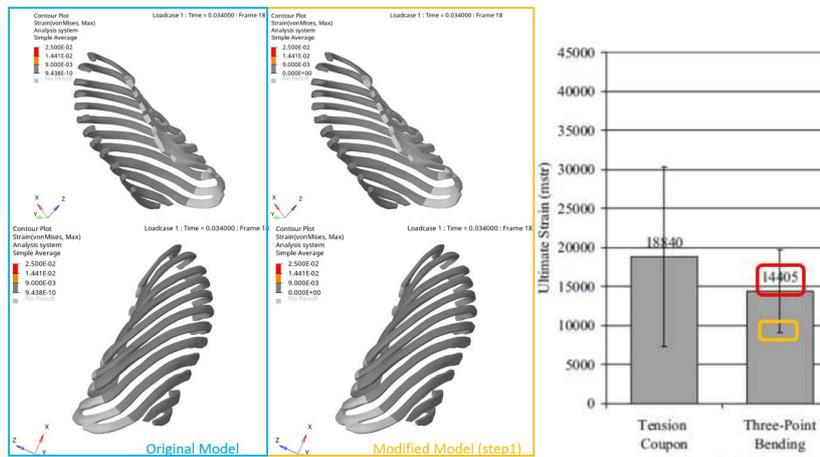


Figure 43 - Equivalent strain

In the figure 43, the strain is represented in a scale of grey, where in red there are the elements with a strain greater than 14405 microstrains, while in orange with a value major than 9000 microstrains, respectively the average value after which a specimen breaks and the value, looking also at the standard deviation for the three-point bending.

Also in this case, there aren't elements with red or orange colour. For this reason, also the colorimetric maps are represented. In these, the maximum value is the value of stress or strain at which the fracture occurs for the bending test.

Therefore, in the colorimetric maps (figures 44 and 45), respectively for stress and strain, the behaviour of the ribs can be noted. In the case of the stress, greater values are reported for the 3<sup>rd</sup> and the 4<sup>th</sup> ribs, in both studies. For the un-modified ribs, more elements in the third rib are stressed than the fourth, while with the modified ribs it's the opposite. The same behaviour can be noted for the strain.

Changes in the THUMS

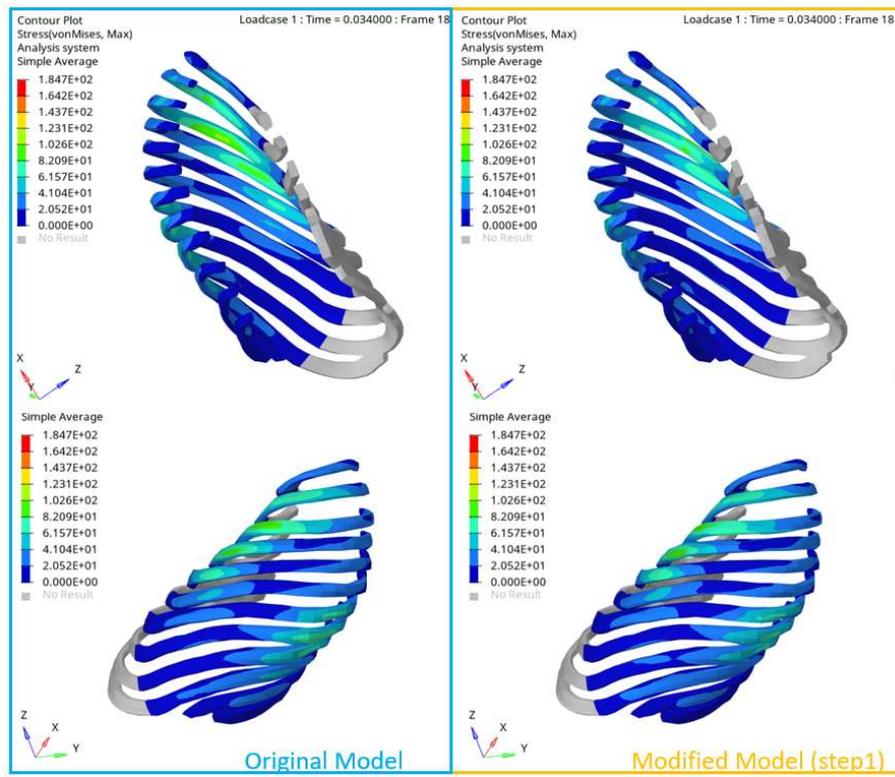


Figure 44 - Colorimetric Map (Stress)

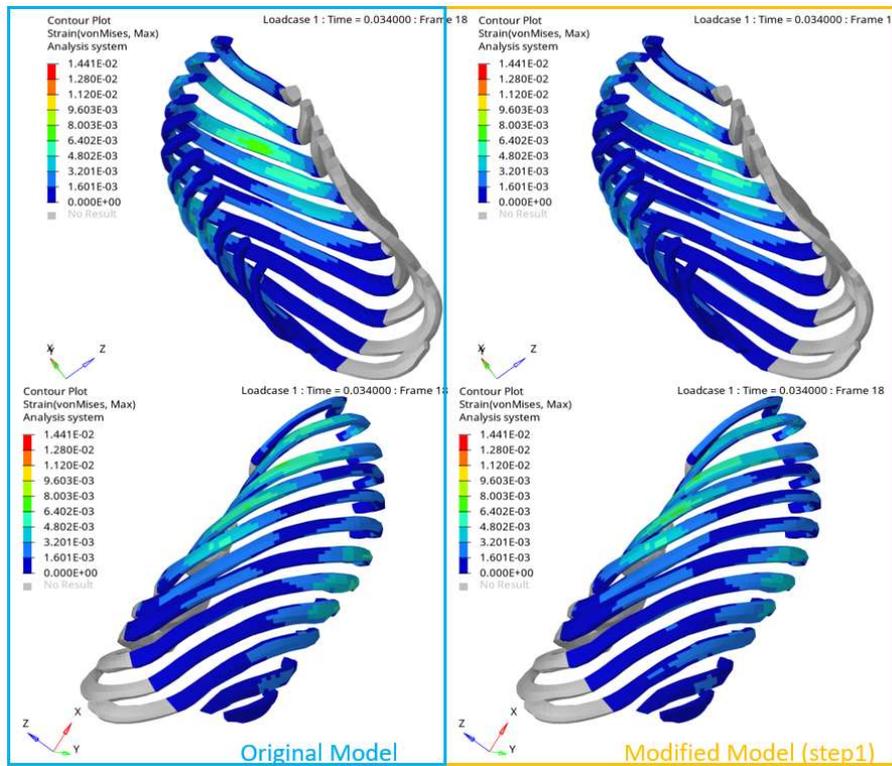


Figure 45 - Colorimetric Map (Strain)

In conclusion, after the first step the differences between original, THUMS with the original thickness, and modified model are noted. About the stress the original model has a higher value than modified while for the strain the modified value has some problematic elements. Anyways there are few elements with a problematic value and no one, in both cases, has a value comparable with the fracture, for this reason we can assume that the ribs, with this test, don't reach the fracture.

### 5.2.3.2 Second step

After the first step, another change is made. To make these modifications Kemper et al.'s article is used as the basis, as in the previous one. Differently by the first step, in this case, the thickness is modified only in 4 ribs and not in all, in particular in the fourth, the fifth, the sixth and the seventh rib.

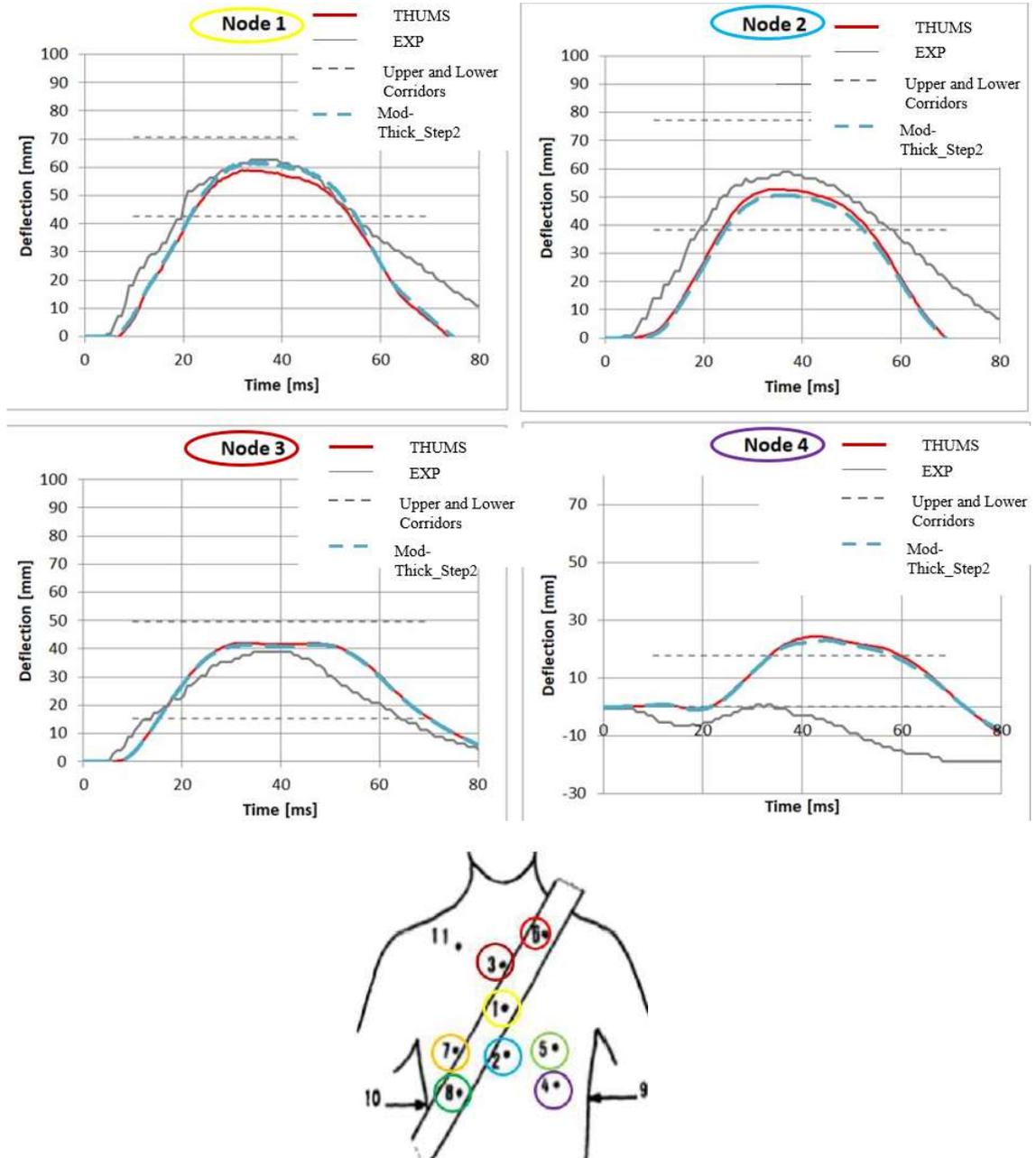
In the article, there are two final tables: one for values in anterior position and one for values in lateral position. In both the tables, the thickness is reported for every analysed subject in the four ribs in the interior, exterior, superior and inferior parts. Analysing the tables of the article, the average values are calculated and reported in the table 11. Near all values of thickness, the difference, in percentage, between the new values and the original THUMS values is presented.

N° rib	Location	Interior (mm)		Exterior (mm)		Superior (mm)		Inferior (mm)	
4	Anterior	0,55	-15%	0,6	-10%	0,45	-25%	0,46	-24%
4	Lateral	1,05	35%	0,71	1%	0,91	21%	0,63	-7%
5	Anterior	0,91	21%	0,62	-8%	0,51	-19%	0,47	-23%
5	Lateral	1,15	45%	0,7	0%	0,63	-7%	0,57	-13%
6	Anterior	1,06	36%	0,69	-1%	0,35	-35%	0,45	-25%
6	Lateral	1,3	60%	0,99	29%	0,58	-12%	0,72	2%
7	Anterior	0,97	27%	0,84	14%	0,37	-33%	0,46	-24%
7	Lateral	1,39	69%	1,06	36%	0,57	-13%	0,49	-21%

The difference between the new and the old values are, in some cases, significant. This problem is accentuated in the interior position, where the percentage often exceeds 35%. In the other three locations, the difference is minor, but it is also important.

Basing on these average values, the changes are made to the model. Following this phase, the validation test is remade to discover if these changes are correlated with different behaviour in the thorax.

In the figure 46, there are the results of the validation test for the thorax when it is loaded with the belt and for the lateral impact, because these two impacts give a different behaviour than the original model.



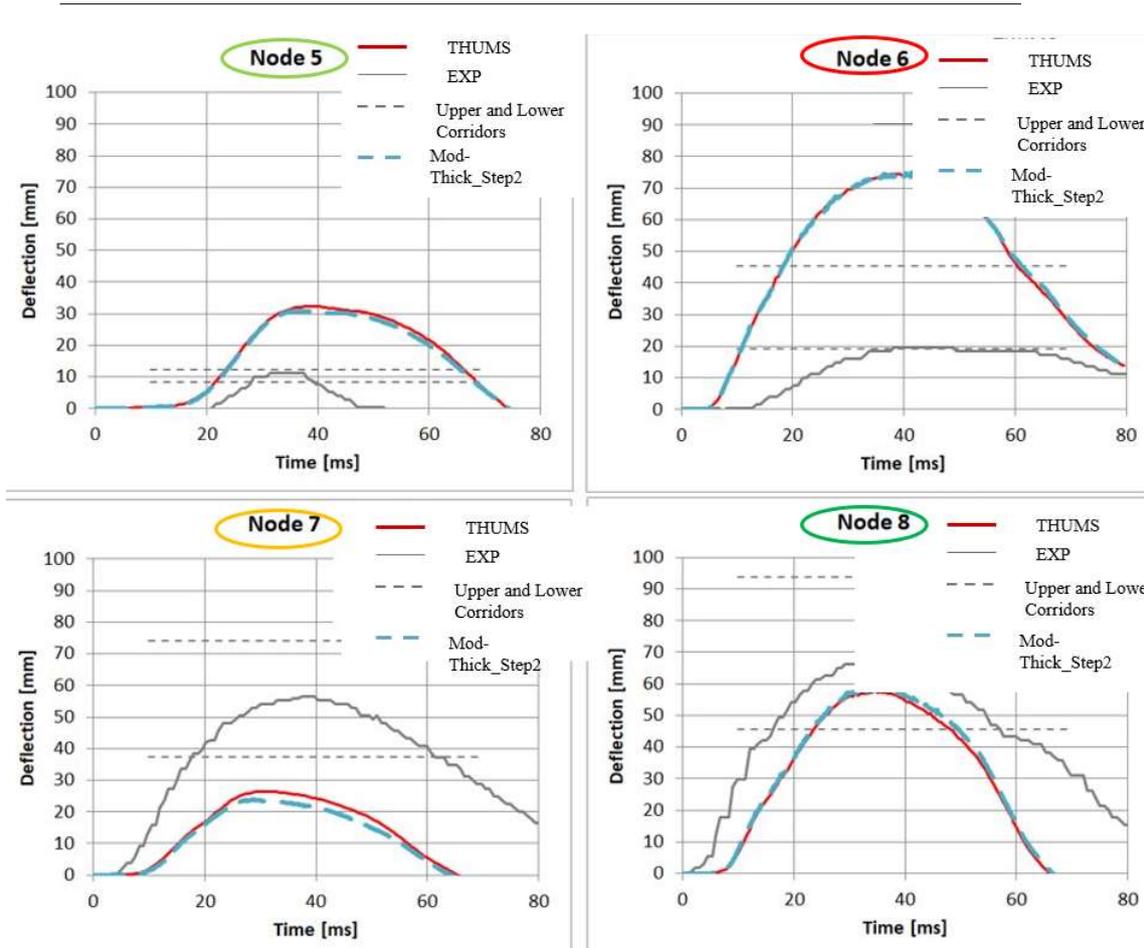


Figure 46 - Validation test (Belt loading)

In these figures, the curves for the belt loading are shown, in red the original model while in light blue the model with the thickness changed. With these changes, a similar behaviour has emerged with some exceptions. For the node 1, the curve is again in the corridors but, in this case, the behaviour is more or less the same as the experimental curve (exp.). For the node 4, the curve is slightly lower than the previous one, so the one of the problematic curves is nearly to be into the corridors. In the case of the node 5, the curve is lower than the original, but it is still distant to have an acceptable behaviour. Even if there are some little improvements, the node 7 presents a worse behaviour than the original model.

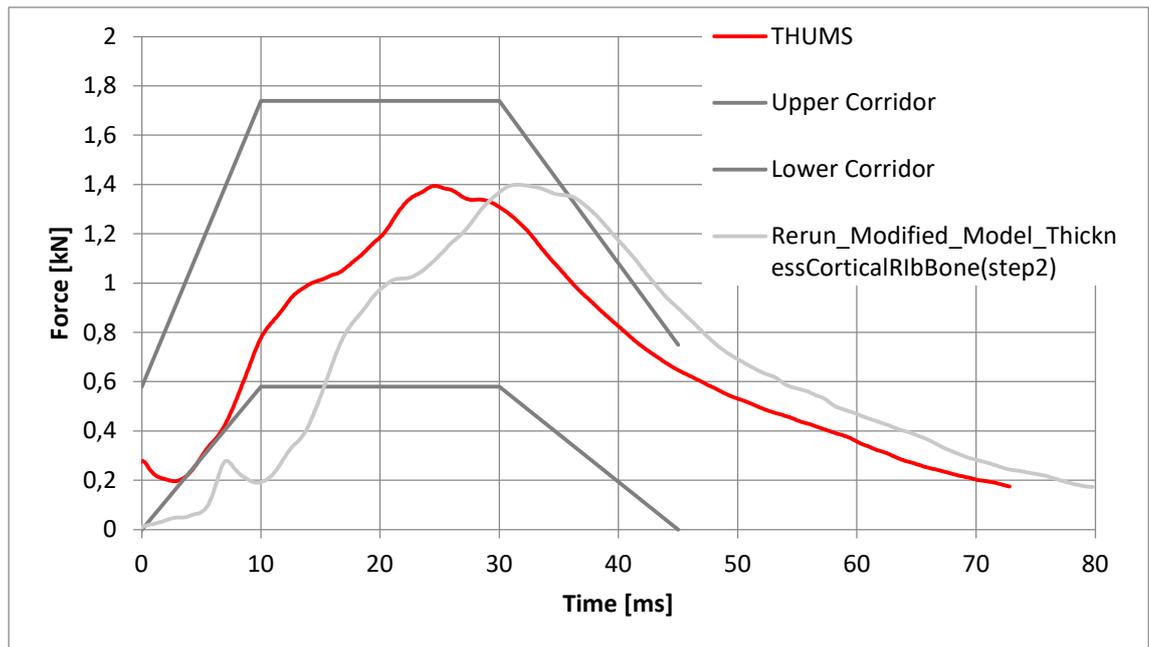


Figure 47 - Validation test (lateral impact -Thorax)

In this case, also the response for the lateral impact for the thorax is shown, because the modified THUMS has a different behaviour than the original THUMS for this impact. The analysis of the deflection-force curve presents the same result to the original (for this reason it is no shown), so it is in the corridors. In the case of the force-time curve (figure 47), instead, different behaviour is shown. In the second curve, the model with a new thickness for the ribs' cortical bone gives a curve shifted than the previous. For this reason, in the beginning, the curve is not in the corridors.

The other tests of the validation are not reported because there are no differences in the answer. Indeed, the model, with thickness changed, give the same response as the original THUMS when it is loaded with the other impact.

After the validation, the Von Mises stress and the equivalent principal strain are re-analysed, to understand if the ribs should go to fracture or not. In the figure 48, it is reported only the values for the left side, because, as in the first step, the left ribs have major values than the right ribs.

## Changes in the THUMS

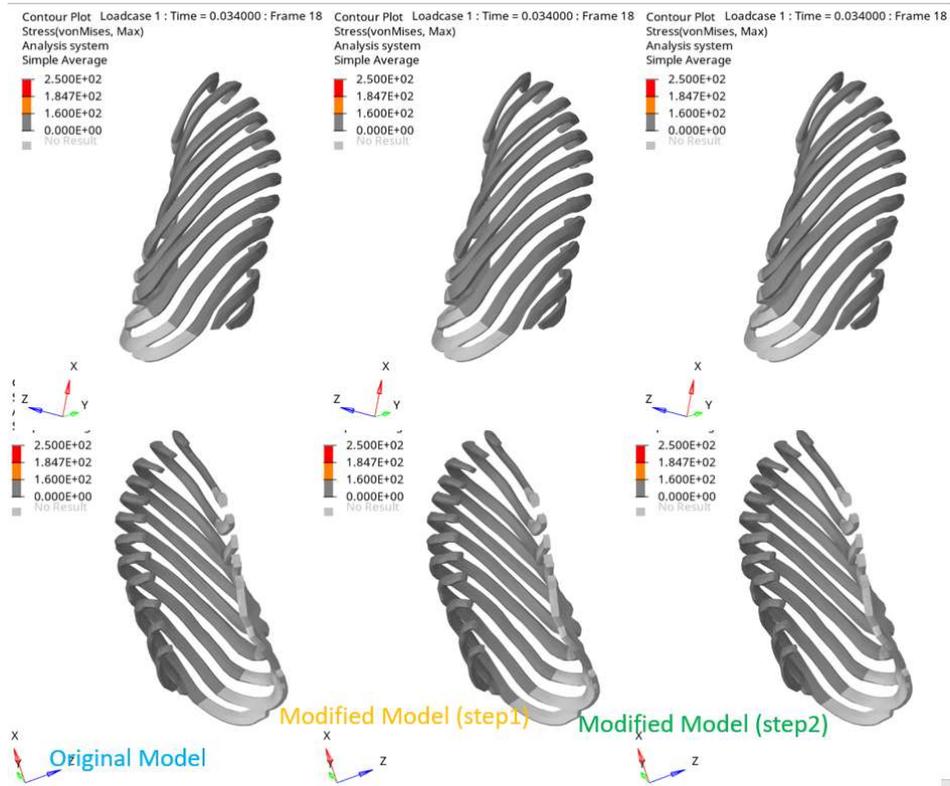


Figure 48 - Comparison With von Mises Stress

In these figures, there is the comparison between three models: the original model, the modified model with the thickness modified as in the step 1 and the modified model with the changes of the step 2. The figures have presented a pair: exterior view above and interior view below. The comparison is made on a grey scale as in the step 1. Not interesting values have emerged, so the colorimetric map is shown (figure 49).

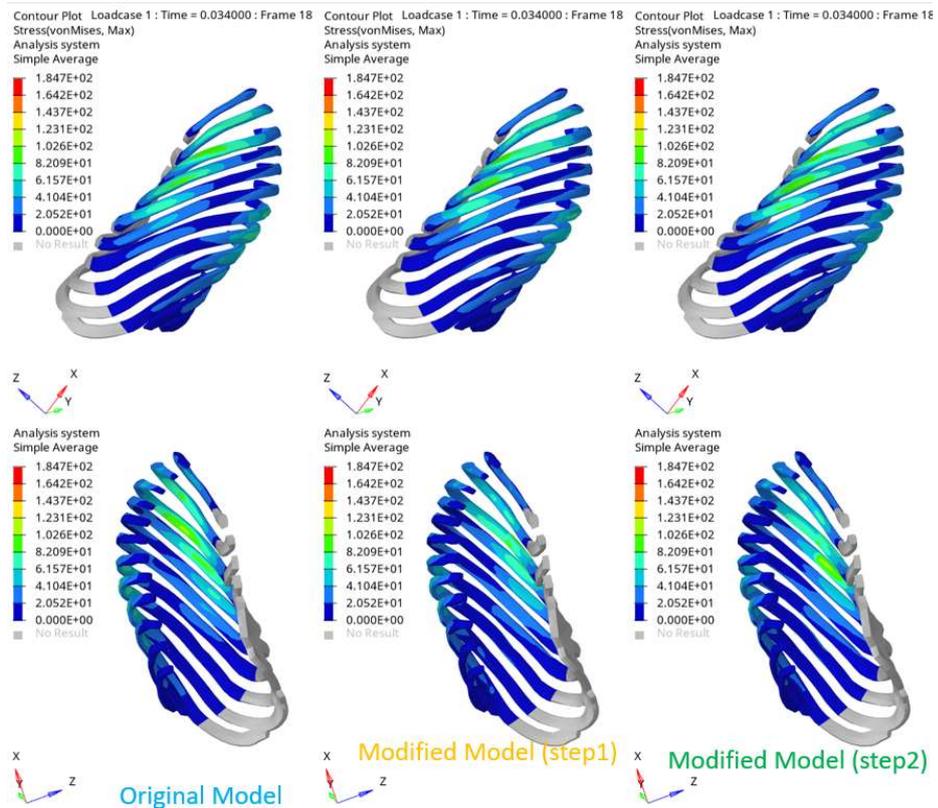


Figure 49 - Colorimetric map (stress)

The stress is lower in the step 1 while, in the step 2 and in the original model the values are similar. These values are not so critical because they are not major than the ultimate stress reported in Kemper et al.

In the figures 50, the values of strain are reported at the same method, as just described.

Analysing the figures, the lack of element with values major than the lower limit of standard deviation and the ultimate strain is noted. For this reason, as previously, also the colorimetric map is shown. With this, a similar behaviour for the original model and the modified model for step 2 can be noted. Indeed, they have a green region but for two different ribs, in the first case for the 3<sup>rd</sup> while in the second case for the 4<sup>th</sup>.

## Changes in the THUMS

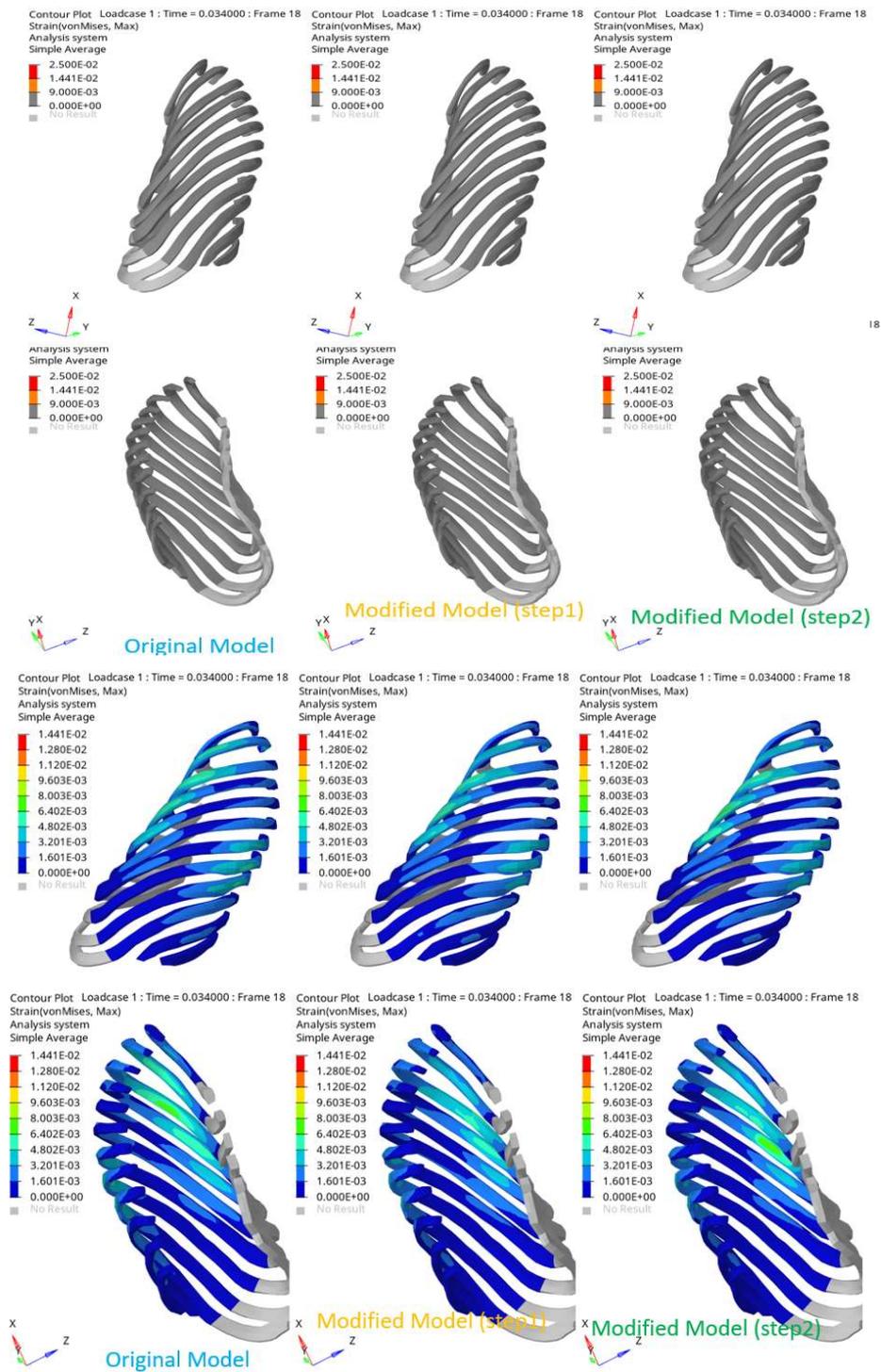


Figure 50 – Comparison with strain

The values of stress and strain are lower than the ultimate values, but to be sure about their no-breakage, another type of analysis is followed.

To make the last analysis another article is used as basis. In the Iraeus et al. [18], the ribs are analysed and studied, especially the geometry. To understand better if these changes give an acceptable result some parameters are calculated and compared with other articles. In the figure 51, there is the comparison made using the ultimate strain before the fracture. The black lines represent the average experimental data before the fracture with a standard deviation of  $\pm 1$ . The red dots are the values of strain found in the article with the simulation at the same condition as the experimental model. The green dots are the values, given by the model with the modified thickness, in the simulation with the belt loading. The conditions around the simulations are different because in this case the purpose is to discover if the maximum strain is lower or not than the strain after which the fracture occurs.

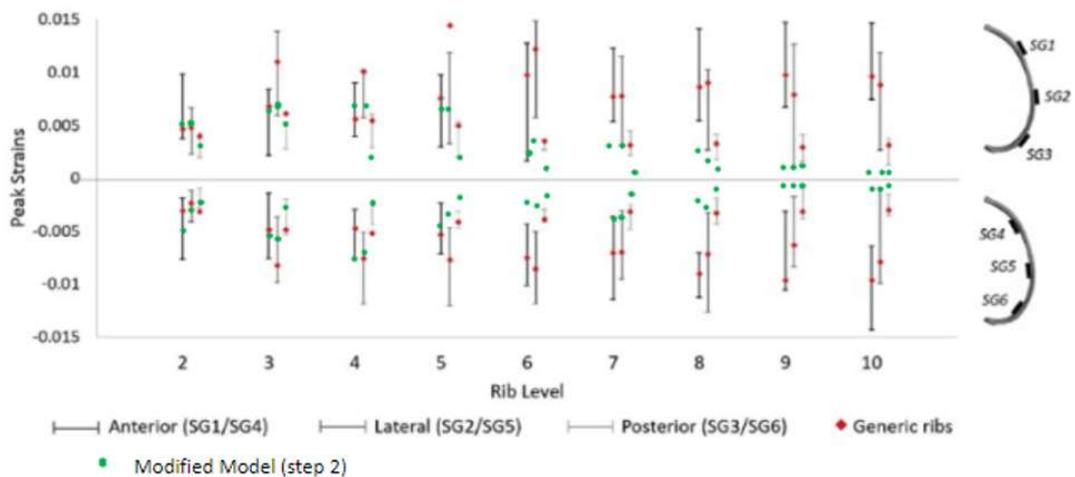


Figure 51 - Comparison of strain (by Iraeus et al)

Thank this comparison, the lack of fracture is confirmed. Indeed, in all ribs, the green dots are or lower or within the experimental range.

In conclusion, after the thickness changed, some problematic curves have an improvement, even if it is minimal, but there are two worsening: the node 7 when the thorax is loaded with a belt and the force-time curves in lateral impact of thorax. With these changes, the stress and strain are modified than the original model and no rupture any cases are predicted.

#### 5.2.4 Fracture

With the comparison of stress and strain, reported in the previous paragraph, an absence of fracture is noted for the analysed impacts. To underline this fact, the fracture is added to the

material to investigate if the validation test change or not with it. To do it, the plastic strain, at which the material breaks, is put in the material cards of ribs' cortical bone. The value is decided basing on the ultimate strain, as explained by Kemper et al. [20]. For this reason, the EPPFR value, the corresponding parameter to this in the material card, is put equal to 0.02 strain.

To study this parameter, first of all, the tensile test with the original material (Thums\_Original), the modified material, as explained in the paragraph 5.2.2 (Thums\_Modified\_material), and these two with the fracture are compared. In the figure 52, the materials with fracture are reported with the name 'Original\_Thums\_WithDamage' and 'Thums\_Modified\_materialWithDamage'.

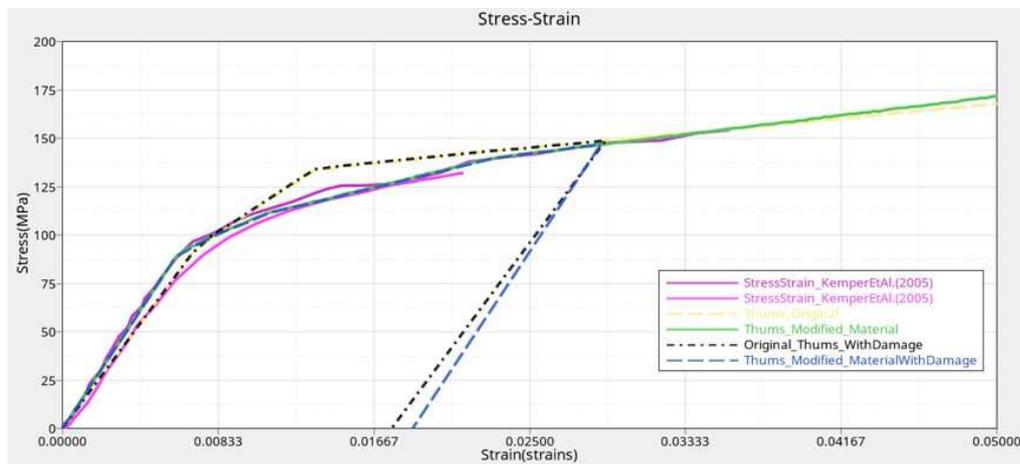


Figure 52 - Tensile Test

In the figure 52, the comparison can be analysed. The fracture, as it is shown, is comparable with article's values. Indeed, in the article, all the ribs have a different value of rupture, and, with this parameter, the breakage is inside the range of these values.

After this, the validation tests are remade, adding the fracture to the cortical bone of the ribs. Analysing the results, a lack of differences is noted, but, also, with different impacts this value could be interesting.

### 5.3 Analysis of the clavicle

After the study of the ribs, the clavicles are analysed. Their position and their role are crucial in the human body, especially in the thorax. For these reasons, it is important have a FE model with an acceptable geometry of the clavicle, a similar answer than the clavicle in the human body

and, also, it is important their fracture. Indeed, this bone often breaks, so it is important to study its behaviour.

### 5.3.1 Geometry of the clavicles

The first step is to discover if the geometry is similar to reality. To make this, this article [21] is used as a basis. In this article, few clavicles were analysed, in particular 263 pairs of clavicles, 195 of males and the others of females. In this case, the purpose was to find the difference between clavicles of female or male and, also, between the right and the left clavicle. Through this analysis, a sexual difference was discovered, confirmed by other articles, the only exception was the angles. In addition, different values between the right clavicle and the left clavicle were found. In particular, the right has a larger sagittal diameter than the left. Furthermore, the length of the left clavicle is longer than the other one.

In this thesis, the values of the geometry, found in the article, was used to make a comparison between the shape of a real clavicle and the clavicle of the THUMS.

To can do this, the different length and angles, analysed on the article, are measured in the FE model and then a comparison is made. The most of measurements are reported in the figure 53.

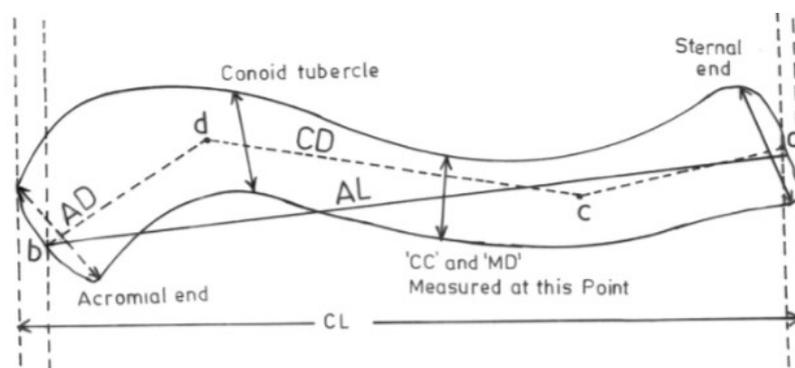


Figure 53 - Measurements of the clavicle [21]

All these measurements are re-taken in the FE model and compared with the mean values of clavicles. In the article the average values are reported for the right and left clavicle. In this case, these two values are averaged and, using the standard deviation, the maximum and minimum value are calculated to have the range.

In the table 12, the measurement and the respective values are reported.

*Changes in the THUMS*

Name	Mean	Max	Min	THUMS' values	Error (%)
<b>CL</b> <b>Clavicle Length</b>	150.195 mm	160.85 mm	139.64 mm	156.582 mm	4.25%
<b>AL</b> <b>Articular Length of Clavicle</b>	145.3 mm	156.01 mm	134.92 mm	153.041 mm	5.33%
<b>CC</b> <b>Mid-point Circumference</b>	37.88 mm	41.8 mm	33.86 mm	45.805 mm	20.92 %
<b>WC</b> <b>Weight of clavicle</b>	32.535 g	38.85 g	26.18 g	47.3 g	-
<b>AD</b> <b>Acromial Diameter</b>	23.63 mm	27.26 mm	20.04 mm	15.589 mm	34.03 %
<b>MD</b> <b>Middle Diameter</b>	12.15 mm	13.83 mm	10.75 mm	12.378 mm	5.18 %
<b>SD</b> <b>Sternal Diameter</b>	21.705 mm	25.39 mm	18.39 mm	22.6225 mm	4.23 %
<b>CD</b> <b>Conoid Diameter</b>	16.95 mm	19.37 mm	14.44 mm	17.9969 mm	6.17 %
<b>LA</b> <b>Lateral Angle</b>	142.32	145.18	139.37	144.987	1.87 %
<b>MA</b> <b>Medial Angle MA</b>	152.38	154.71	149.98	153.313	0.62 %

*Table 12 - Comparison between real and FE model's measures*

In particular, the CL is the length between the points more distant, located in the acromial end and the sternal end. This value has a little error and, indeed, it is within the range.

In the range, there is also the articular length of the clavicle. It is measured as the distance between the point located in the middle, respectively, of the sternal and the acromial end.

The mid-point circumference is the circumference, measured at the middle of the clavicle. At the same point, the diameter is measured and it is called the middle diameter. The first one is not within the range, but the second one is in it.

Also, the weight of the clavicle is analysed, but in this case a large error is discovered.

After this, three diameters are calculated, the diameter in the acromial, sternal end and in the conoid area. Measuring these three values, only of them is noted to be smaller than the real one: the acromial diameter. The other two value are, so, inside the range.

In addition, the angles are also analysed. The first one, shown in the table 12, is the lateral diameter, in the picture 53, denominated as 'cdb'. The second one, instead, is the medial angle, shown as 'acd' in the picture 53. These two values represent the curvature of the clavicle and they are inside the range of the real angles. In the same way, the total angle, given by the sum of these two values, is similar to the reality, in the article it is 296.7 while the THUMS has a total angle of 298.3, therefore the error is very little.

In conclusion, the geometry between the THUMS' clavicle and the real one is similar. The only exceptions are: the mid-point circumference, the diameter of the acromial end, which is too little than the real, the weight, maybe it is correlated to the mass density of the clavicle. For these reasons, the shape of the clavicle could be considered as well modelled.

### *5.3.2 Axial compression test*

After the comparison for the geometry, it is important to understand if the properties of the clavicle are similar to reality or not. To make this, another study is used as basis, the 'Development and validation of a subject-specific finite element model of a human clavicle' [22]. In this article, a clavicle was analysed and then it was recreated using the FE analysis. The purpose of the study was to validate a model of the clavicle to obtain one similar to reality. For this reason, two tests are made: compression test and bending test. In both the analysis, the behaviour of a human clavicle and its model, made in the same conditions, are studied and compared. To be sure to find the better model, in the article, not only one was created but several numbers, with different characteristics for the cortical thickness or for the material properties of the cortical bone. In particular, four models are created, for each test, one with all-hexahedral and the properties of the material based on the density variable, one with a cortical shell thickness variable and variable properties, one with cortical shell thickness constant and variable properties and one with both

these parameters variable. The values, of the material properties or of the thickness, were extracted by a CT scanner. The trabecular bone was the same in all the models.

In this thesis, first of all, the axial compression test was recreated. The results, obtained with the simulation, are compared with the experimental data and with the tests with constant material properties and the one with constant cortical thickness. It is decided to make a comparison only with these two models because the clavicle of the THUMS has a uniform thickness and uniform material properties.

To compare the results, the test has to be recreated at the same way of the experimental method. For this reason, the blocks are made in resin and put in the acromial and sternal end. The top, acromial end, is put into motion with a low velocity, 0.1 mm/s to translate the lateral end in the medial-lateral direction. Indeed, the test is a quasi-static one and, for this reason, an implicit analysis is made. The other block, instead, is linked in a rotation pin joint, so it can't move along the direction of the velocity but it can rotate about the axis perpendicular to the direction of the velocity. The blocks are attached to the bone, as in the experimental one, with a tied contact.

For the resin, an elastic material is used with a Poisson ratio of 0.4 and a young's modulus of 293MPa, while for the aluminium the Poisson ratio is 0.3 and the young's modulus is 69GPa.

The clavicle, in this thesis, is made as in the THUMS, as shown in the chapter 3. Instead, in the article, the geometry and the thickness of the trabecular, cortical bone and the resin are found, with a manual segmentation on CT data. Using a solid phantom, the data, found with the CT scanner, was correlated with the bone density. Basing on this correlation, the bone material properties were calculated, giving different values of young's modulus for the trabecular bone for the acromial and the sternal end. The cards were an elastic-plastic material for cortical and trabecular bone.

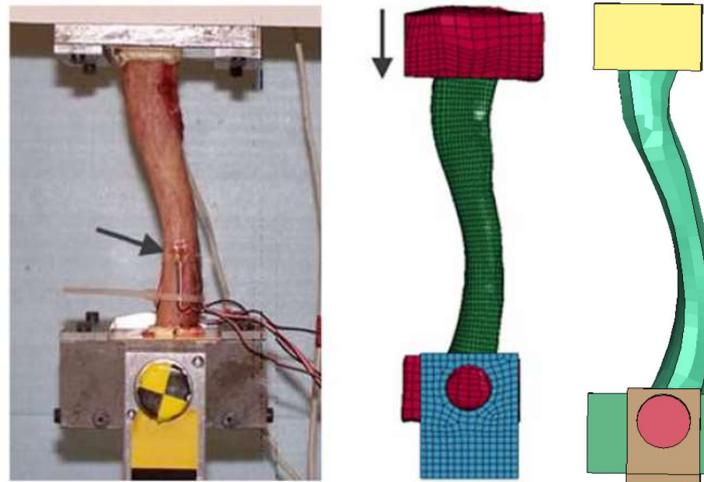


Figure 54 - Experimental and FE models

(A- EXPERIMENTAL MODEL; B FE MODEL OF ARTICLE e C NEW MODEL)

In the picture 54, the models are shown, in particular the experimental model on the left, the FE model, made in the article, on the centre and the final FE model created in this thesis on the right.

After the simulation, the results are analysed at the same way of the article, so with a curve force-displacement. Therefore, the displacement of a node, in the centre of the top block, is taken and, also, the reaction force, between the bottom block and the cortical bone, is studied. In this way, the graph with displacement and force is made and compared with the results of the article.

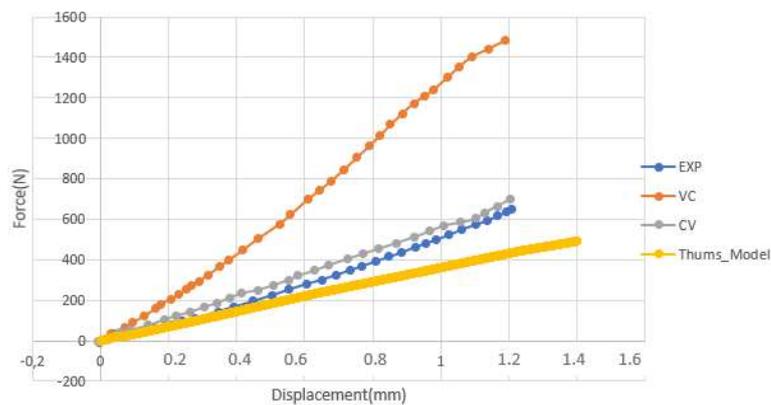


Figure 55 - Force-Displacement (Axial Compression Test)

In the figure 55, the comparison is shown. The ‘EXP’ curve is the behaviour of the clavicle given in the experimental data for the uniaxial compression test, while the ‘VC’ one is the answer of an article’s model with a cortical thickness variable and a material property constant. The ‘CV’

curve is the opposite of the 'VC' one, because it is the behaviour of the model with a constant thickness for the cortical bone but variable material properties (so the young's modulus changes according to the location). Finally, there is the Thums\_model curve, which represents the model created in this thesis with the clavicle of the THUMS model.

Studying the picture 55, a different answer for these curves is shown. In particular, the orange one has a very different slope than the experimental one, so the clavicle applies, on the block, a force bigger than the real one. Instead, the grey curve has more or less the same behaviour as the experimental curve, so a variation of the young's modulus, for the compression test, gives a more reliable answer. The last curve, the yellow one, shows the behaviour of the clavicle of the THUMS. It is similar to the blue one, but it exerts a lower force. Indeed, when the displacement is over 0.6 mm, the two curves start to diverge, because their slope is different.

For this reason, the behaviour of the clavicle has to be more investigated to improve its answer to have a clavicle in the THUMS similar to the reality.

### *5.3.3 Three point bending test*

After the study of the compression test, also the bending test is analysed. To make this, a model with the same condition of the experimental one is re-created. Therefore, there are 2 blocks in resin, one for each end, acromial and sternal. The model of the clavicle is created as in the axial test. Therefore, with a variable thickness and constant material properties for the cortical bone or with a constant thickness and variable material properties for the cortical bone for the article, while a clavicle taken by the THUMS for this thesis.

Unlike the first test, the velocity is applied on a loader and not on a block. This loader is in aluminium as the support. In addition, all the two blocks are linked in rotation pin joints, while in the axial only one is in it.

The velocity is the same of the first simulation, with 0.1 mm/s, so also this test is a quasi-static simulation.

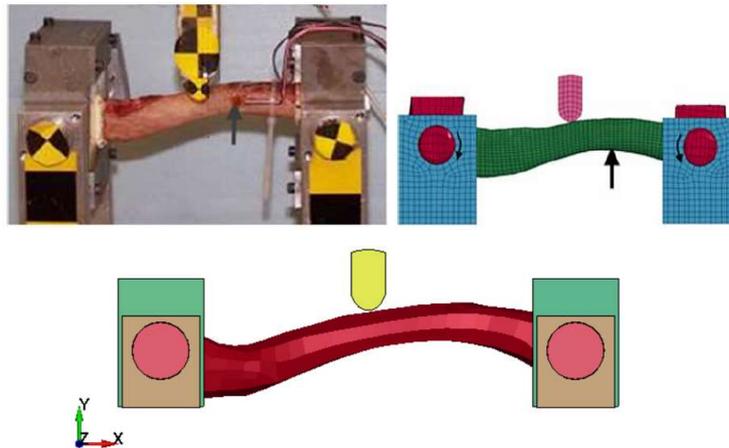


Figure 56 - Experimental and FE models (in the line above, there are the tests of the article, in the line below the model made in this thesis)

In the picture 56, the models are shown, in particular the experimental model (the first picture) and the FE models (the second picture is the model of the article, the second one is the model created in this thesis).

Also, this test is an implicit simulation, because it is a quasi-static one.

After the simulation, the force is calculated as the sum of the reaction forces. These are obtained for the contact between the block and the end of the bone, attached to it. Then, also, the displacement, as a node of the loader, is analysed. Created the curve force-displacement, it is compared with the article's curves.

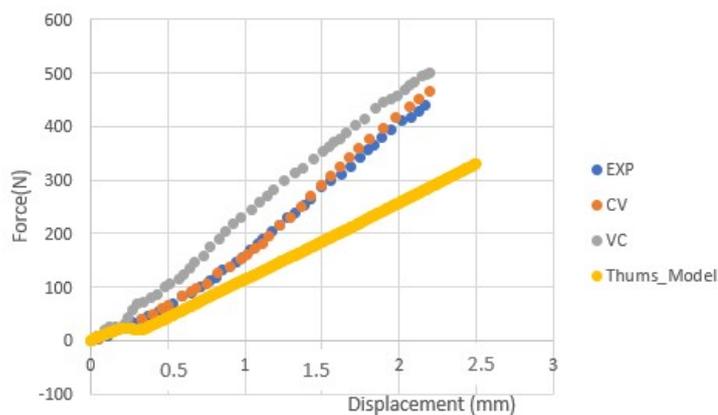


Figure 57 - Force-Displacement (Bending Three-Point Test)

In the figure 57, it is shown the comparison between 4 curves: the experimental ('EXP'), the model with a not uniform thickness but uniform material properties for the cortical bone ('VC'),

the model with a value of thickness constant but variable material properties ('CV') and the model with the clavicle of the THUMS ('Thums\_Model').

As shown in the figure 57, a better behaviour of the VC curve than the behaviour, shown in the axial test, can be seen. Again, the CV curve is similar to the real one, so the variability of the material properties gives a behaviour as the experimental in both the tests, the axial one and the bending three point one. Finally, the Thums\_Model curve, created in this thesis, has a behaviour not so similar to the real one. Indeed, as for the axial compression test, a lower force, than the experimental curve, is shown.

After the studies of the two tests for the collar bone, it is possible to note an answer not so accurate for the clavicle with the material of the THUMS than the FE model presented in the article. For this reason, more analyses of this bone are important to obtain a behaviour similar to the human clavicle. In addition, after the study to have better behaviour, the fracture has to add because the collarbone is a bone, which often breaks. Therefore, the probability of its rupture during a crash test is high. The lack of this event in the model can compromise the answer of the thorax.

## Conclusions and future developments

The Human Body Models are very important to evaluate the injuries of people after a crash test. Therefore, an accurate model can give more detailed information, which allows applying some improvements in cars and, so, to decrease the chance to incur serious injuries during an accident.

The purpose of this thesis is to change the THUMS to have a more accurate answer similar to reality. In particular, it is noted that the thorax has a different behaviour when it is stressed with a belt.

For this reason, some parts of the thorax are analysed.

First of all, some changes in the cortical bone of the ribs are proposed:

- A tensile test is made to understand if the material is similar to reality and a different behaviour, between experimental data and THUMS' material, is noted. Some changes are made on it to obtain a result more similar to experimental.
- The thickness of the ribs' cortical bone is studied. In particular, a variability, not present in the human model, is discovered. For this reason, a no uniform thickness is added in the model. In this way, there is a slightly change in the response of the thorax.

After, the collarbones are analysed:

- The shape of the collarbones is studied. Therefore, lengths and angles are studied and it was noted a similar shape to the reality. The only exceptions were: the circumference in the middle, the diameter at the acromial end and its weight.
- The material properties are investigated, using two tests: the uniaxial compression test and the bending test. With these two simulations, a not so accurate response can be seen. Indeed, in both the simulations, the THUMS has a behaviour different to experimental data. Therefore, some improvements have to be made.

Generally, all the changes, put in the validation phase, not give a big variation in the response of the thorax.

In conclusion, the changes of ribs don't solve the problem, associated with the validation phase, but give a model similar to reality. This aspect is important to obtain, in the future, a model which can simulate better the human body. For the same reason, the studies of clavicle are important. In addition, it is important to underline that the body is very complicated, because it is made by several number of parts interconnected with each other. For this reason, the changes of

few organs make the Human Body Model more accurate, but it can't give a variation of the response in the THUMS in the impact or in the validation phase.

In the next future, as concerns the ribs, the trabecular bone can be also investigated to understand its behaviour. Then, also the shape of the ribs has to be studied and some changes can be made. For the collarbone, instead, in this thesis, only the comparisons are made, so this is a first step that has to be continued. In particular, it can be important to improve the material properties to have a model like the real one and, then, change also the shape, because the acromial end is shorter than the reality. Another crucial thing to improve is the failure/rupture of this bone, because, as said in chapter 3, this bone often breaks. For this reason, also, another test has to be made, the bending test in a dynamic way to evaluate the fracture and to see if it occurs at the same point as the real clavicle. It is important to underline that, before the analysis of the fracture, some changes to the material have to be done.

After the analysis of these changes, the model has to be improved with them and the validation must be done to understand if these modifications give a better behaviour. After this phase, the impact of the THUMS, during a crash test in a sled model, has to be re-analysed to understand the type of injury which the human model can undergo. For this reason, a criterion for the lesion has to be made. In chapter 4, the PVP is explained, because the purpose of this model was to modify the THUMS, to improve its biomechanical answer, for spleen and liver.

## Bibliography

- [1] Corporation e T. Motor, «Total human model for safety (thums): revolutionizing crash simulation to support safe mobility for all,» 2021.
- [2] T. Xu, X. Sheng, T. Zhang, H. Liu, X. Liang e a. A. Ding, «Development and Validation of Dummies and Human Models Used in Crash Test,» 2018.
- [3] J. Zhao e G. Narwani, «DEVELOPMENT OF A HUMAN BODY FINITE ELEMENT MODEL FOR RESTRAINT SYSTEM R&D APPLICATIONS,» *TAKATA – Automotive Systems Laboratory, Inc.*, 2005.
- [4] C. Kroell, D. Schneider e A. Nahum, «Impact tolerance and response of the human thorax,» *SAE International*, 1971.
- [5] Schneider, C. K. Kroell e D. C. Schneider, «Impact Tolerance and Response of The Human Thorax II,» *SAE International*, 1974.
- [6] R. Bouquet e C. Dominique, «Behaviour of Human Surrogates Thorax under Belt Loading».
- [7] J. Shaw, R. Herriott, J. McFadden, B. Donnelly e J. and Bolte, «Oblique and lateral impact response of the PMHS thorax».
- [8] J. Cavanaugh, G. Nyquist, S. Goldberg e a. A. King, «Lower Abdominal Tolerance and Response».
- [9] W. Hardy e L. a. S. Rouhana, «Abdominal Impact Response to Rigid-Bar, Seatbelt, and Airbag Loading».
- [10] J. D. Rupp, C. S. Miller, M. P. Reed, N. H. Madura, K. D. Klinich e L. W. Schneider, «Characterization of Knee-Thigh-Hip Response in Frontal Impacts Using Biomechanical Testing and Computational Simulations».
- [11] H. Guillemot, B. Besnault, S. Robin, C. Got, J. Y. L. Coz e F. L. a. J.-P. Lassau, «Pelvic Injuries in Side Impact Collisions: A Field Accident Analysis and Dynamic Tests on Isolated Pelvic Bones».

- [12] F. Brittany, «The anatomy of the sternum».
- [13] G. Antonio, «Costole o Coste,» *My personal trainer*.
- [14] Hyland, Charlick e Varacallo, *Anatomy, Shoulder and Upper Limb, Clavicle*.
- [15] C. Bastien, C. Neal-Sturgess e L. W. J. Christensen, «A Deterministic Method to Calculate the AIS Trauma Score from a Finite Element Organ Trauma Model (OTM)».
- [16] C. Bastien, C. Neal-Sturgess e H. D. a. X. Cheng, «Computing Brain White and Grey Matter Injury Severity in a Traumatic Fall».
- [17] H. Kimpara, J. B. Lee, K. H. Yang, A. I. King e e. al, «Development of a Three-Dimensional Finite Element Chest Model for the 5th Percentile Female,» 2005.
- [18] J. Iraeus, K. Brodin e B. Pipkorn, «Generic finite element models of human ribs, developed and validated for stiffness and strain prediction – To be used in rib fracture risk evaluation for the human population in vehicle crashes,» 2020.
- [19] A. R. Kemper, C. McNally, E. A. Kennedy, S. J. Manoogian, A. L. Rath, T. P. Ng, J. D. Stitzel e E. P. S. a. S. M. Duma, «Material Properties of Human Rib Cortical Bone,» 2005.
- [20] A. R. Kemper, C. McNally, C. A. Pullins, L. J. Freeman e a. S. M. Duma, «The Biomechanics of Human Ribs: Material and Structural Properties from Dynamic Tension and Bending Tests,» 2007.
- [21] J. S. Sehwata e R. Pathak, «Variability in anatomical features of human clavicle: Its forensic anthropological and clinical significance,» 2016.
- [22] Z. Li, M. W. Kindig, J. R. Kerrigan, R. W. Kent e J. R. Crandall, «Development and validation of a subject-specific finite element model of a human clavicle».

## Software

Some different software is used.

- Pre-processor =LS-PrePost (version 4.7)
- Solver = Ls-Dyna (version 11.1 double precision)
- Post- processor = Ls-PrePost and Hyperview
- To recreate the graphs = WebPlotDigitizer

## Acknowledgements

Vorrei ringraziare coloro che, con il loro supporto, hanno contribuito alla stesura e alla realizzazione di questo lavoro.

Per questo motivo vorrei ringraziare il mio relatore, Professor Alessandro Scattina, per avermi aiutato ad entrare in un'ottica diversa da quella a cui ero abituata ma che mi ha permesso di migliorare.

Vorrei, inoltre, ringraziare il Professor Christoph Bastien, della Coventry University, per i preziosi consigli e per il tempo che ci ha sempre donato.

Ringrazio la mia famiglia, i miei amici (in particolare Laura) e il mio ragazzo che mi hanno sempre supportato e sopportato.

Vorrei inoltre ringraziare Giulia per aver condiviso con me l'esperienza.

Computational resources provided by [hpc@polito](mailto:hpc@polito) (<http://hpc.polito.it>)