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Numerical Anthropometry Comparison between the THOMO PMHS and GHBMC Model

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ABSTRACT

Various models of the human chest have been developed to evaluate injury risks or to assess innovative safety systems. In the frame of the EU FP7th project THOMO, a protocol has been established to determine relevant parameters of the human ribcage. This original method has been developed by combining CT-scan, 3D laser scan and µCT-scan to determine precisely the internal rib architecture. The main advantage of this approach is to provide a refined analysis of the bone distribution on the whole thorax. The different results will be compared in this paper with the Global Human Body Model data, based on its FE model. Global parameters are computed such as the rib length from 3D spline for each rib, cross section dimensions, volume measurement from 3D outer spline and global dimensions (lateral-medial-lateral and antero-posterior measurements). GHBMC is then compared to the 50 percentile male class, defined from THOMO data. For the local scale, a µCT-scan is used to investigate accurately the rib geometry and the cortical bone thickness. This µCT-scan method was applied on 2 hemi thorax of THOMO subjects. Through a cross section representation, different calculated parameters are considered (i.e. section area, trabecular bone area, cortical bone thicknesses). In order to compute the cortical bone ratio, the cortical bone area is generated using the inner and outer B-spline curves. A cortical bone thickness distribution map is made along the rib. GHBMC thorax FE model was investigated using the same local analysis to compare results with THOMO database.

INTRODUCTION

Numerical human body models could be used to assess injury risks in different scenarios, to improve safety in vehicles, regulations, and anthropomorphic dummies. Many models have been published during the past decade (Lizee et al., 1998; Iwamoto et al., 2002; Behr et al., 2003).

The thorax is the one of the segments frequently injured in road accidents (Foret-Bruno et al., 2001). This anatomical part has a complex geometry defined on a global scale, by rib curvature, orientation and shape, and on a local scale, by its internal structure composed by thin cortical thickness, spongy bone variability and marrow. The global shape depends particularly on the percentile class of the body. The inter-individual difference makes the characterization task even more difficult on this geometrical aspect. Furthermore, on a local scale, the ribs that present a thin cortical thickness influence the thorax response. This parameter is rarely investigated and few studies have been focused on the definition and evolution of the cortical bone thickness along the rib length (Roberts et al., 1972; Trosseille et al., 2009; Li et al., 2010). This cortical bone characterization is needed on this constitutive part to develop more biofidelic FE models. For a better assessment of injury criterion during crash simulations the numerical model of the thorax should be refined in terms of accurate geometry and material properties.

The FE model improvement is sustained internationally by recent initiatives like the Global Human Body Model Consortium (GHBMC). The principal goal of GHBMC is to deliver a more realistic model of the whole body taking into account the geometrical and mechanical aspects. The principal interest of this model is that geometry of its thorax considered global and local characteristics. This worldwide project interacts with the European project THOMO. One of the principal objectives of THOMO is the improvement of the knowledge of the geometrical and mechanical properties of the ribcage. This project is focused on the thoracic segment and upper extremities and leads to a biomechanical database, built from Post-Mortem Human Subjects (PMHS).

The following study is based on the geometrical analysis of the 18 PMHS tested in THOMO. The objective was to compare the geometrical characteristics of the GHBMC thorax model to that of the THOMO subjects, at both the global and local scales. The different parameters for global scale are the thorax volume, the width and depth of the thorax and rib length. For each rib level, the local parameters are also investigated with the total cross-sectional area along the rib, the ratio with the areas cortical and trabecular bones within each cross-section and the thickness distribution along the rib. The different results are plotted using a box-plot representation. Each parameter was normalized by the mean value of the subject in order to highlight the inter-individual dispersion.

METHODS

In the frame of THOMO project, a protocol has been developed to analyze the anthropometric properties of each subject. All subjects were supplied to the project by the Body Donation program of the University of Paris with respect to ethical rules and a scientific committee approval. The body was frozen in an upright position to fix the ribs, the spine, and the internal organs in an anatomical position close to live beings. The GHBMC model was developed based on MRI and CT images, along with external anthropometry measurements, obtained from a 25 year old living male subject in a seated position. In order to compare the THOMO subjects to the GHBM, different percentile classes are established. The THOMO project used 12 males and 6 females referred on the next table. The 50th percentile class corresponds to 4 male subjects named 606, 609, 619 and 621. The global geometry comparison was made between these 4 THOMO cadavers and the GHBM. For the local comparison, 2 THOMO cadavers (605 and 609) have been totally scanned with a µCT device and results are analyzed in terms of cortical bone thickness and cross section areas.

Table 1: Main characteristic of the GHBM and THOMO subjects

		50th Percentile				Others THOMO cadavers													
Subjects	**GHBM**	**606**	**609**	**619**	**621**	**605**	**607**	**610**	**612**	**613**	**614**	**616**	**620**	**622**	**623**	**627**	**628**	**629**	**630**
Gender	M	M	M	M	M	M	M	M	M	M	M	M	M	F	F	F	F	F	F
Age		87	69	83	82	73	84	70	82	65	80	55	79	77	63	85	71	67	62
Weight *(Kg)*	78.6	71	71.5	73.5	78	61	56	60	62	73	56.5	63	63.5	45	43	43	39.5	49	38.5
Height *(m)*	1.75	1.71	1.7	1.69	1.71	1.71	1.75	1.7	1.61	1.6	1.78	1.75	1.67	1.53	1.65	1.66	1.55	1.57	1.54
BMI *(Kg/m²)*	25.67	24.28	24.74	25.73	26.67	20.86	18.29	20.76	23.92	2/8.52	17.83	20.57	22.77	19.22	15.79	15.60	16.44	19.88	16.23

Global parameters

The first step consists of obtaining, prior to testing at macroscopic level, the global geometry of the thorax using a medical CT scan obtained thanks to collaboration between CEESAR, Cochin Hospital, ENSAM and LAB. Digital Imaging and Communications in Medicine (DICOM) slices were acquired on a CT-Scan Siemens Sensation 16 (120 kV, 155 mA) with a 512 x 512 matrix of 0.934 mm pixels. The interval between slices was defined as 0.8 mm without overlap, and the field of view was limited to 47.80 cm. The image reconstruction was done with a B70f algorithm (Convolution Kernel) corresponding to bone tissues. The first step is the build a 3D model of each subject. MIMICS software is used since it can convert easily DICOM data to 3D STL models. Since the desired selection here is the thorax, a special threshold is applied on grey level data. MIMICS software proposes an automatic thresholding procedure, to distinguish the bones from soft tissues, based on density variation.

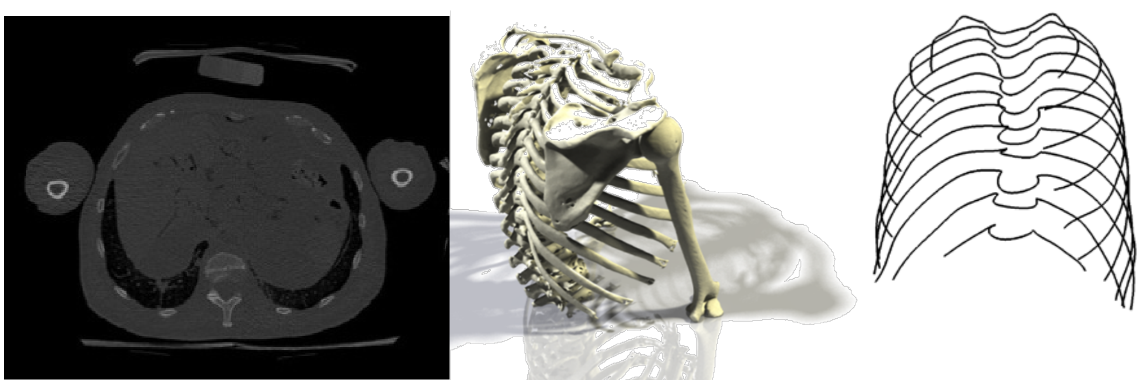

Figure 1: CT-scan data in MIMICS software, STL file and wireframe model used to compute the geometrical properties.

This numerical reconstruction is efficient but leaves some imperfections (skin, muscles, ghosting and other imaging artifacts) in the final STL model. This file should be cleaned before it can be used. After treatment, the STL model is imported in CAD software to measure the different anthropometric parameters. In order to avoid the operator influence during the measurements and to handle a lighter model, the thorax is first simplified in a wireframe model, where the ribs are represented by spline lines. From the 3D wireframe model of the thorax built with CAD software, different parameters can be measured and extracted. The major difficulty is to identify the most relevant ones. These parameters should also be objective and operator-independent. After a pre-study protocol, 4 parameters were defined and have been measured for all the subjects: Length and orientation of each rib, length and width of each pair of ribs and the thorax global volume. The rib length is measured from the outer guideline. This 3D spline starts at spine-rib junction (0%) and ends at the costo-condral junction (100%). The antero-posterior parameter (AP) is the global depth of the thorax on each pair of ribs. This parameter gives an idea on the evolution of thorax depth. The AP parameter is measured by projecting each pair of ribs on a reference transverse plane. The lateral-median-lateral (LML) parameter is measured in a same way to study the evolution of thorax width. Finally, the thorax volume is obtained by interpolating the wireframe model of the ribs with a spline surface. This surface is then closed at the rib 10 level and the total volume is thus computed. The volume is measured in liters (L).

In order to compare the same parameters, the THOMO protocol described above is applied on GHBM global geometry given by the University of Virginia. The global measurement parameters are established on the GHBM, with respect of the wireframe model definition.

Local parameters

The local parameter investigation is based on the THOMO protocol. The microstructure analyses are made thanks to a µCT-scan device. The µCT parameters used for this task should be adapted for this kind of structure (enough contrast for both cortical and trabecular bones). They have been chosen in accordance with previous reported works: (Bayraktar et al., 2004; Halgrin et al., 2012). The accurate local geometry is merged later with the global model obtained previously. This study has applied on 2 THOMO subjects (S605 and S609) according to the following protocol summarized by 3 steps (Mayeur et al., 2010). The first step is the acquisition and reconstruction method using successively CT-scan, Laser scan and µCT-scan. The laser scan is applied on each harvested rib of the 2 subjects and µCT-scan on 40mm long sections of the rib. The second step allows having the whole precise geometry by combining the previous reconstruction on the same reference system. The merged model gives the local geometry of each rib with respect of internal structure composed by cortical and trabecular bone. The last step, which is more time consuming, consisted of distinguishing the cortical from trabecular bone with B-spline curves. These curves are defined in cross section (normal plane of the rib curvature coming from global wireframe model) and located every 2% gap of the rib length. Then, the 3D model composed by outer and inner B-splines is used to investigate the local analysis (Figure 2).

Figure 2: µCT section, total section area, cortical bone area and thickness illustrations

In this study, the total section and cortical bone section areas are computed for each rib. The evolutions of cortical bone thickness are also analyzed on the THOMO cadavers. The same method was used to extract the value of these parameters from the GHBMC thorax FE model. Results of the THOMO protocol applied on 2 PMHS have been compared to GHBMC data in terms of total section area, cortical bone and trabecular bone area and cortical bone thickness variation along rib length.

RESULTS

Volume

The thorax volume is obtained by interpolating the wireframe model of the ribs with a spline surface. This surface is then closed at the rib 10 level and the total volume is thus computed (Figure 3).

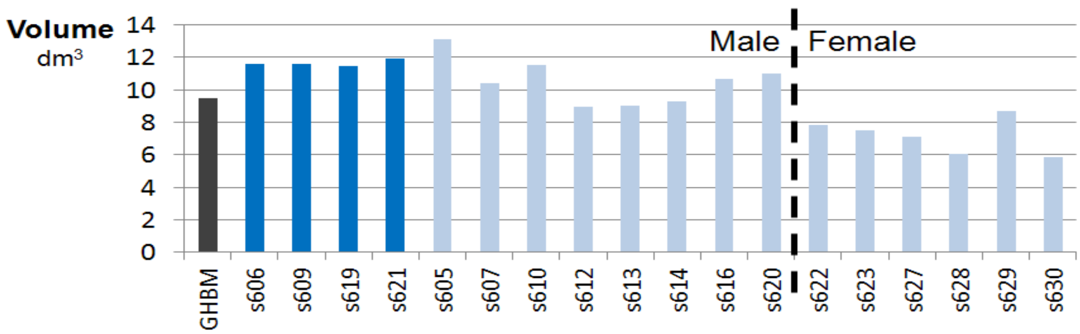

Figure 3: Volume distribution of the considered subjects (blue) and GHBM

The volume of GHBM is 9.5 L against an average of 11.5 L for the 4 considered THOMO subjects. Application of the global parameters protocol gives differences in terms of volume. This difference can be explained by the general shape of the THOMO cadavers against the GHBM geometry. This global shape measurement is presented in the global parameter analysis section and discussed on the conclusion.

Global analysis

In order to study the inter-individual variability, each rib is considered separately. The next figure shows the rib length distribution (mean value of right and left ribs) of the 4 THOMO subjects and GHBM. Since the inter-individual dispersions are important, and in order to compare the ribs from the same positions, a normalization procedure is applied systematically. The reference value for each subject is taken as the mean measurement on the 24 constitutive ribs. For the following study, the rib lengths as well as the different anthropometrical parameters will be considered with this normalization.

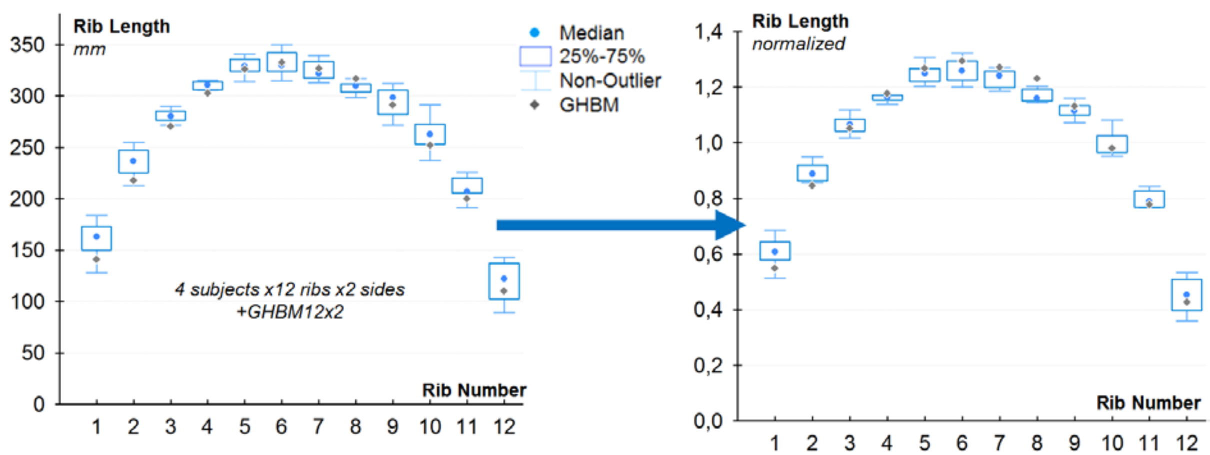

Figure 4: Rib length distribution for the 4 THOMO subjects and GHBM: comparison according to the rib number.

A parabolic curve is obtained with an increasing length from the first to the 6th rib and a decreasing length from the 7th rib to the last one. Comparison between THOMO and GHBMC highlights the same rib length distribution with the 6th rib being the longest. The normalization of the rib length of each subject by the mean value of the 24 ribs allows –evaluation of the difference between cadavers and GHBMC. The difference between cadavers and GHBMC is more important on the 2 first ribs with difference about 5%.

Lateral-medial-lateral (LML) and antero-posterior (AP) parameters are measured in millimeters. As previously explained, the results are normalised by the mean value of each subject before plotting it according to the rib number.

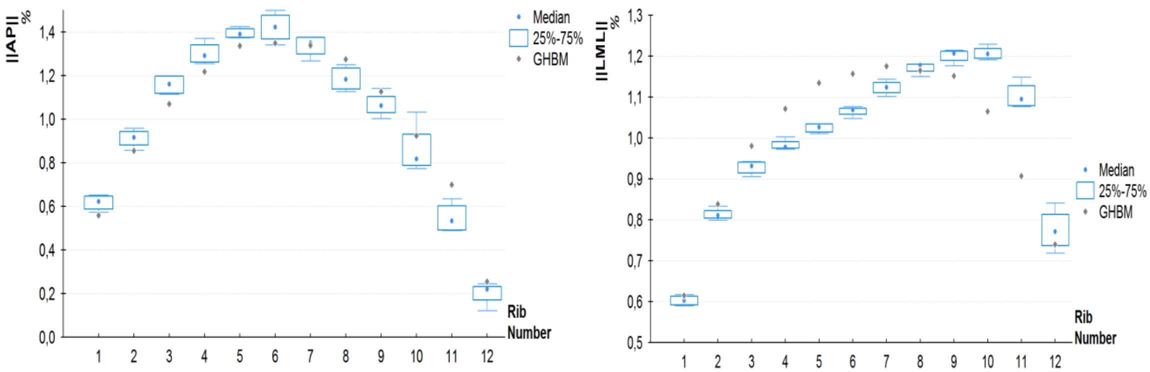

Figure 5: AP and LML distribution for the 4 cadavers and GHBM: comparison according to the rib number

Considering the rib number, AP values present the same evolution with a maximum value on the 6th rib. Despite this analysis, GHBMC evolution is out of the THOMO range. The GHBMC AP dimension is less important on the first ribs but higher after the 7th one. This difference is more significant on the LML parameter. THOMO cadavers have a LML dimension rising on the 10 first ribs and decrease on the floating ones. The GHBM have a more regular shape, with a horizontal asymptote on the 7th rib.

The difference between cadavers and GHBMC is more pronounced on the 11th ribs. The mean difference is about 7% for AP dimension with a standard deviation at 3.5%. The LML dimensions present equivalent evolution with a mean value at 7.19% and 5.6% standard deviation.

Local analysis

In order to highlight the difference between THOMO and GHBMC, data of the 4th rib are chosen to illustrate the area variations (Figure 6). The abscissa axis refers to the ratio position on the rib length. This position is computed on each rib from the head rib (0%) to the costochondral junction (100%). The ordinate axis gives each section area normalised by the mean total section area value of the considered rib.

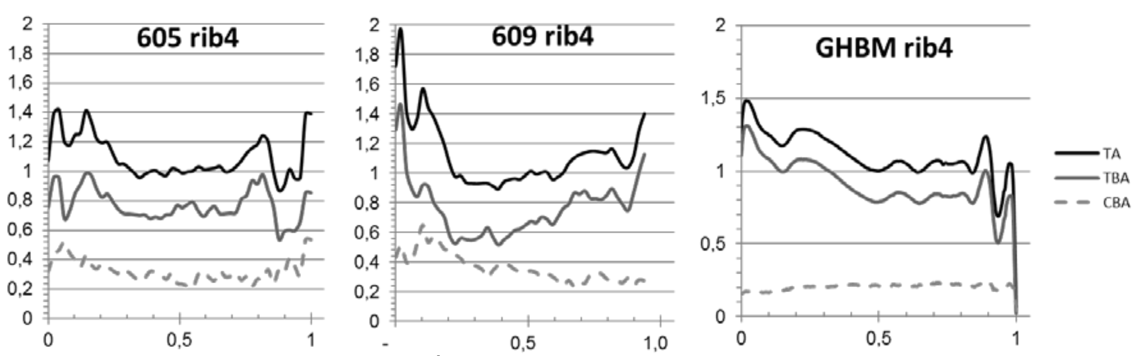

Figure 6: 3 area parameters along the 4th rib (TA: Total Area, TBA: Trabecular Bone Area, CBA: Cortical Bone Area).

Overall, the areas measured from the GHBMC ribs are smoother. This observation is explained by the fact that analysis of THOMO subjects is based on a CAD reconstruction. This model leads to more information on each cross section (unfiltered data), whereas GHBMC results are established on thorax FE model and are controlled by the meshing points (interpolation). Another underlined result concerns the cortical bone area evolution which is constant on GHBM when THOMO subjects follow the others areas tendency.

The mean thickness values are also computed for the 3 area parameters on each rib. The different areas measurements are normalized by the mean value of the whole data from the considered subject. The variations are similar between each rib for the cortical bone area and total cross-section area. S605 and S609 have the same tendency also on the trabecular bone area but the GHBMC model presents other variations for the 2 first ribs. Due to this observation, the mean GHBM areas of each rib have been also represented on the box-plot curve established on THOMO subject. Figure 7 and Figure 8 present these dispersion results.

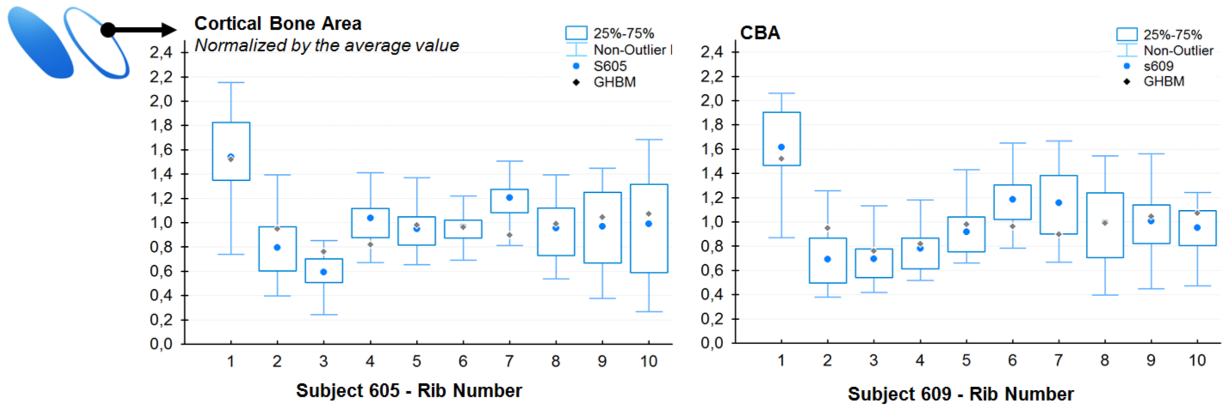

Figure 7: Cortical bone area dispersion on THOMO and GHBM subjects

On a global way, the cortical bone areas of GHBMC follow the trend documented for the 2 THOMO. The maximum difference is observed for the 7th rib of the subject 605 and on the 2nd one of subject 609.

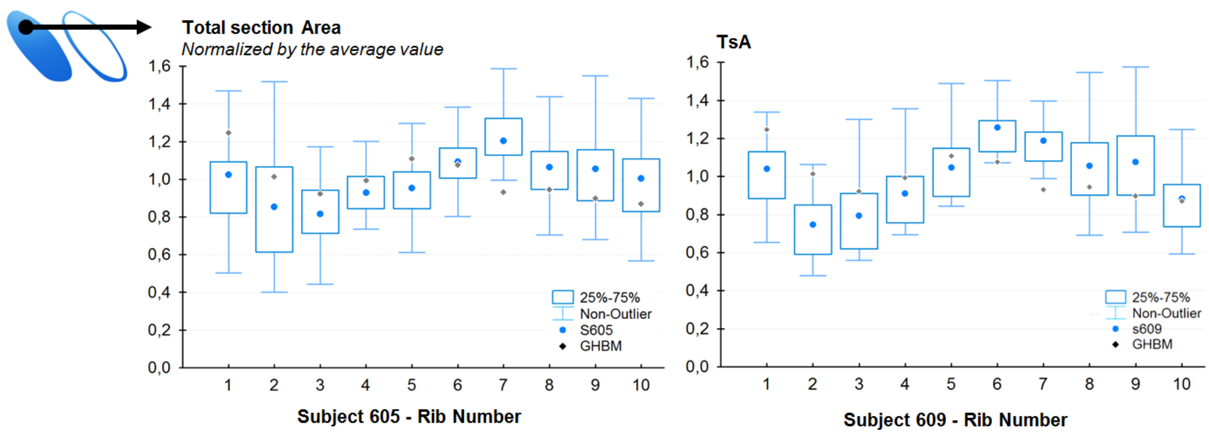

Figure 8: Total cross-section area dispersion on THOMO and GHBM subjects

On the total cross-section area, the same trends are observed in spite of gaps between GHBM and THOMO median value. Results on the 2 THOMO cadavers are averaged in order to compute the differences with GHBM. The percentage differences are plotted on the 3 histograms (Figure 9) taking into account the rib number and 3 area parameters.

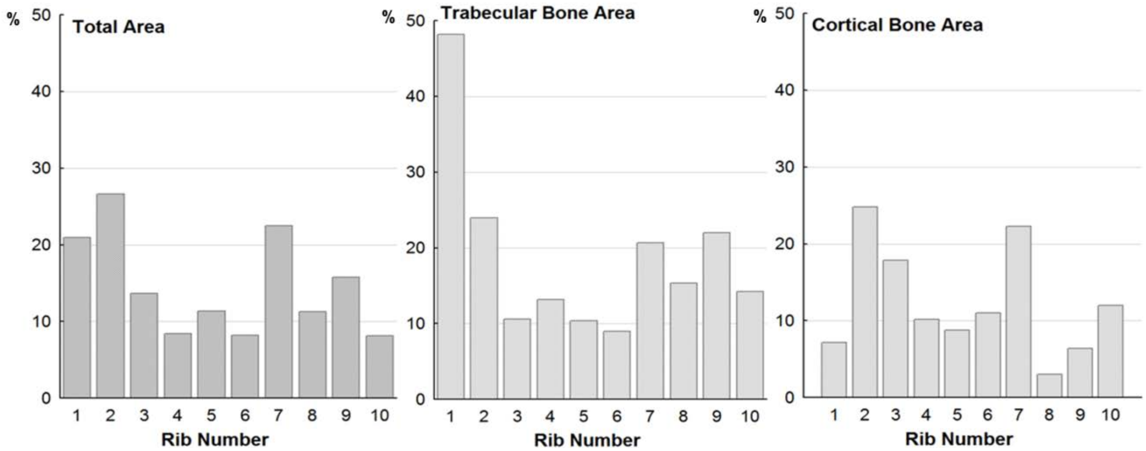

Figure 9: Difference between mean values of THOMO and GHBM subjects for the 3 cross section parameters.

The difference between cadavers and GHBM is about 13% for the total and cortical bone area with a standard deviation at 7% on the 2 cases. The trabecular bone area is more dispersive (standard deviation at 11.5%) and has a mean value at 18.7% due to the 48% maximal difference on the first rib.

Cortical bone thickness along the rib

The following study is focused on the cortical bone thickness comparison between THOMO subjects and the GHBMC models. In order to illustrate the cortical bone thickness variation along the rib length, Figure 10 presents the variation of the mean cortical thickness calculated for each cross-section along the rib length for the 4th and 5th ribs.

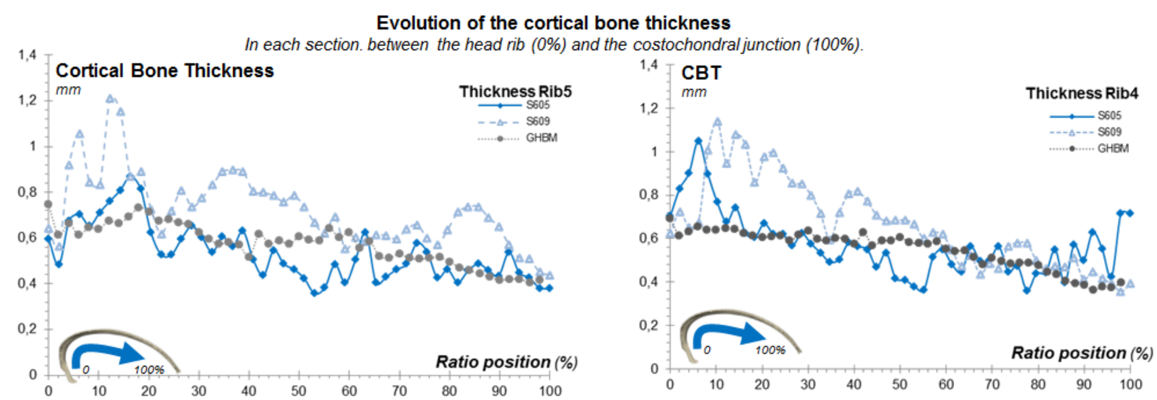

Figure 10: evolution of the cortical bone thickness along the rib.

The GHBMC thickness evolution is smoother than that of the THOMO subjects. The main observation is the decrease of mean cortical bone thickness along the rib. The analysis of THOMO subjects is based on a CAD reconstruction that leads to more information on each cross section (unfiltered data). GHBMC results are established on thorax FE model and are controlled by the meshing points (interpolation, smoothing, etc).

The following study is based on this decrease of the cortical bone thickness from the head of the rib to the costochondral junction. The evolution of the GHBMC thicknesses is plotted on Figure 11. The studied data are the mean cortical bone thickness from the 2nd to 10th rib on the 2 THOMO cadavers S605 and S609. The 1st rib cortical bone presents a different evolution due to its curved and flattened geometry. The floating rib is also excluded because it was not investigated in the THOMO thickness analysis.

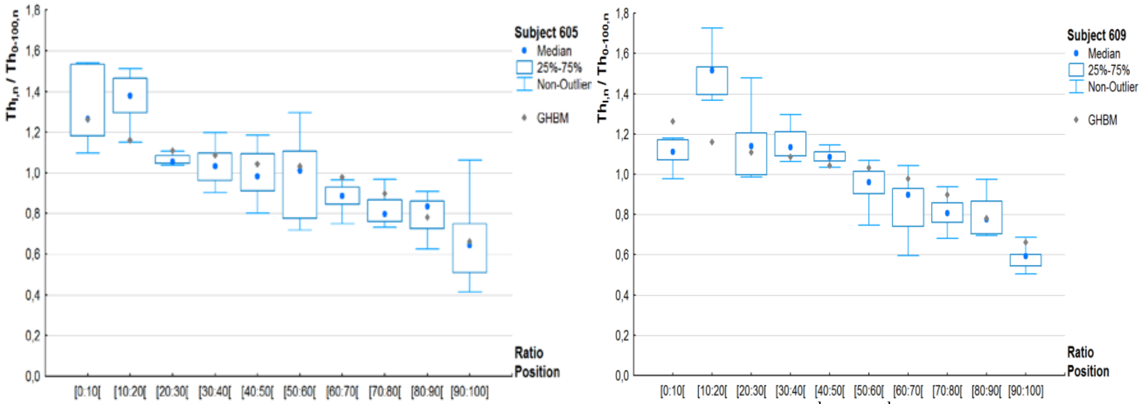

Figure 11: (a) Dispersion of the cortical bone thickness along 9 S605 ribs (2nd to 10th) - (b) Dispersion of the cortical bone thickness along 9 S609 ribs (2nd to 10th) - Values are normalized by the mean cortical bone thickness of the considered rib.

Observation made on subject 605 and GHBMC comparison is that same evolution is observed except for the 10-20% bin. The THOMO subjects increase on the first 20% where GHBMC presents a continuous decrease along the rib. The same observation is made on subject 609. In order to compare the thickness evolution along the rib length between the THOMO and GHBMC, Figure 13 illustrates the difference of median value. The mean difference is about 6% with a standard deviation at 8%. Like the previous observation, the maximum difference is observed on the 10-20% ratio position section with a 27.5% gap.

Cortical bone thickness of each rib

After studying the cortical bone evolution along the rib length, a complementary comparison was made considering the mean thickness value of GHBMC and THOMO cadavers.

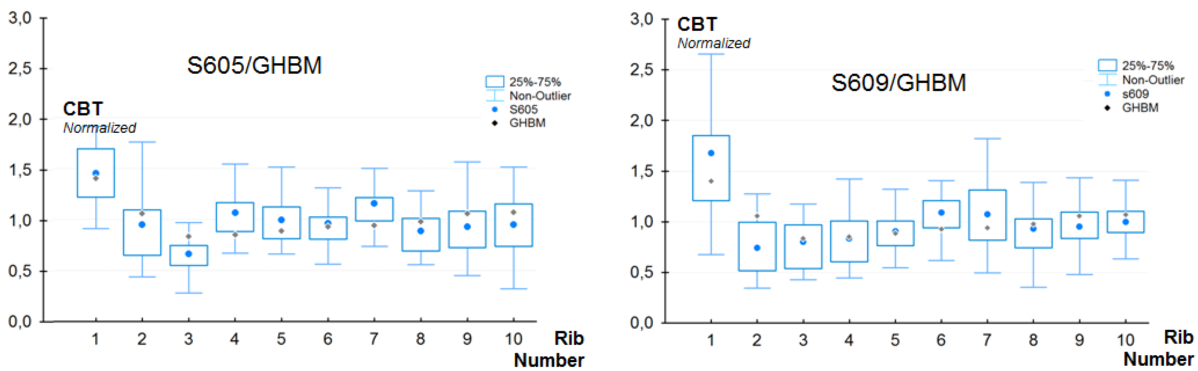

Figure 12: Mean cortical bone thickness of GHBMC and THOMO dispersion for each rib

The mean cortical bone thickness of GHBMC follows the 2 THOMO cadavers' tendencies when rib number is considered. The maximum difference is observed on the 7th rib of the subject 605 and on the 2nd one of subject 609. These results were also observed on the cortical bone area results.

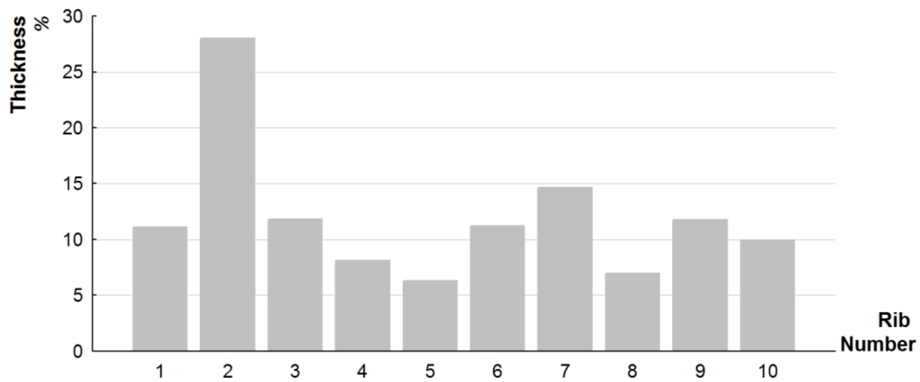

Figure 13: Difference (%) of the thickness between THOMO and GHBMC values

Considering the mean cortical bone thickness value of each rib, the difference between the mean value of 2 THOMO cadavers and GHBMC is more important on the 2nd ribs (27%). The mean difference is about 12% for the whole thorax with a standard deviation at 6.17%.

CONCLUSION

The global geometry analysis revealed a comparable rib length between THOMO 50th percentile subjects and the GHBMC model. The rib length varies between 100 and 350mm with the maximum of the parabolic curve on the 6th rib on each considered subjects. The difference between the GHBMC model and the PMHS is greater for the AP and LML dimensions. This difference is likely due to the trapezoidal form of the THOMO cadavers that influences the LML and AP dimensions (Figure 14). The LML dimensions increased on THOMO subjects, except for floating ribs, contrary to the GHBMC form where the maximum LML dimension is located on the 6th rib. This shape difference also explains the larger thorax volume of the THOMO subjects due to the higher result observed on the LML dimension.

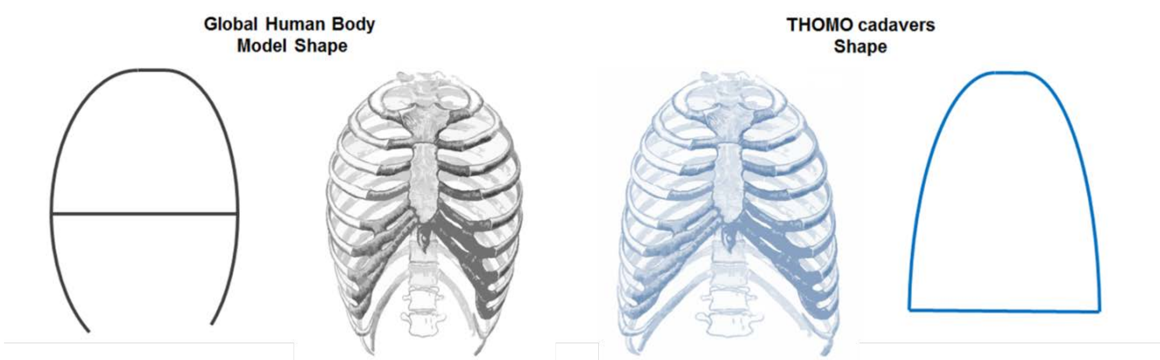

Figure 14: Illustration of GHBM and THOMO cadavers shapes

The geometrical measurements included in this study show some differences between the THOMO subjects and the GHBMC model. However, the data presented here do not allow determining whether these variations are inter-individual variations or age-related, as the shape of the rib cage changes with age because of a change in rib orientation and pulmonary activity. Also, the effect of the global and local variability on the biomechanical response of the thorax, in particular for the prediction of injury, has yet to be established. A recent study (Li et al, 2010) showed that detailed cortical thickness information is required but not sufficient to properly predict rib fractures. The next step to better characterize the injury mechanisms and determine the injury threshold would be to perform a parametric analysis using a computational model which takes into account the variability of the global and local parameters.

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