A new method to determine rib geometry for a personalized FEM of the thorax

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ABSTRACT

The thorax is one of the segments frequently involved in road accidents. Various models of the human chest have been published over the past decades to evaluate injury risks in a car accident and to access innovative safety systems. However, they are limited in their biofidelity due to simplification needed for global testing or computer limitations. The purpose of this study is to propose a method to determine relevant parameters of the human ribcage to be incorporated in a refine FE model.An original method has been developed by combining medical CT images, 3D laser scan acquisitions, and micro-CT techniques for acquiring the whole geometry of the bone structure of human chest. From these 3 acquiring systems, a surfacic model was generated including the whole geometry modelled by 2 surfaces: an external one defined by the external border of the cortical bone; an internal one obtained by the determination of the limit between the cortical and the trabecular bone. An automatic routine was also developed to generate a neutral surface by calculating distances between these two surfaces with a precision of about one micron. The final step was the generation of a finite element model, characterized by personalized and optimized shell meshing and localized real cortical thicknesses.All these data were merged to define a geometrical thorax model at a multilevel scale (thorax, rib, bone structure). From this complete geometrical acquisition, a finite element model was obtained. The main advantages of this approach is to provide a FE model which is personalized, biofidelic, CPU-time efficient, and which takes into account the entire geometry and bone distribution. This paper highlights an original and innovative link between medical imaging, 3D reconstruction and FE modelling.

INTRODUCTION

Despite recent road safety improvements in developed countries, this health issue remains a concern in developing countries and at a worldwide scale. To make more progress in this field, research is still needed to provide advanced numerical tools for future evaluations of new cars and to develop innovative safety designs. This approach globally known as Virtual Testing (VT) is sustained internationally and many projects have been developed to characterize the geometry of the human body, not only at a global level, but also at a microscopic scale. The main objective of those projects is to define parameters as inputs for new generation finite element models.

Numerous human models have already been populated: Thums (Iwamoto, 2002), Humos 2 (Behr, 2003). Although the geometry of all these projects came from CT images, they suffered from a lack of precision regarding the microscopic description of the constitutive parts. Due to simplification needed for global testing, element number limitations, or computer capabilities, these models needed parameter identification to fit available experimental datasets.

As the thorax is one of the segments frequently involved in road accidents (Foret-Bruno, 1998), experimental investigations have been conducted to access detailed characteristics of the human ribcage. The main motivation was to provide models an accurate description of the cortical bone thickness of the ribs, as this factor influences the thorax response submitted to an impact (Kemper, 2007). Previous studies investigated this parameter by using physical measurements (Roberts, 1972), photographs (Kallieris, 2000), medical CT-scans (Kent, 2005) or vet CT-scans (Charpail, 2005). An original work, conducted thanks to a micro CT, has also been proposed by Li (Li, 2009). Particularly, it has been demonstrated that CT images issued from clinical acquisitions are not sufficient to measure precisely the cortical bone thickness. Thus, the characterization of the thorax geometry, in the frame of THOMO project, is carried out at a multilevel scale with multiple acquisition devices in order to build a complete model.

THOMO is a European project funded under the 7th Framework Program. It focuses on the research, development, and validation of the human thorax region models, which include the body components of the thorax, the shoulder complex and the upper extremities for the 5th, 50th, and 95th percentile of each gender. This project fits into a worldwide project, called Global Human Body Model, which aims to create and maintain the world's most biofidelic human body models.

METHODS

This study is a part of THOMO project and it aims to propose a new method to build a more biofidelic FE model of thorax. This original method has been developed by combining medical CT images, 3D laser scan acquisitions, and micro-CT techniques to determine precisely the internal rib architecture within the entire ribcage geometry. All these data were merged to define a geometrical thorax model at a multilevel scale (thorax, rib, bone structure). At the end, a finite element model was built from this complete geometrical acquisition as a feasibility step to access the quality of the meshing obtained.

Data acquisition

The geometry of the whole thorax was obtained precisely at 3 different scales, by using successively 3 acquisition systems: first, the whole geometry of the thorax was acquired with a medical CT scanner; at a lower level, the external geometry of all ribs was recorded with a contactless 3D laser scanner; finally, the structural geometry of ribs (i.e. spongy and cortical bone) was defined on 35 mm samples scanned with a micro CT device (μCT).

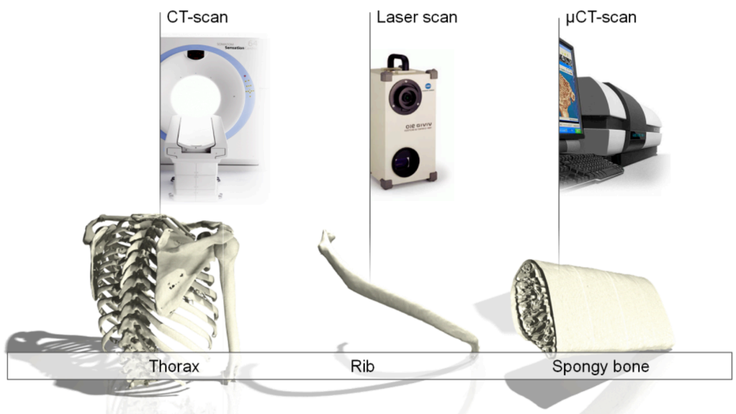

Fig. 1 - Acquisition devices and corresponding imaging scales.

The first step consists of obtaining, prior to testing, at macroscopic level, the entire ribcage geometry using a medical CT scan, thanks to collaboration between CEESAR, Hôpital Cochin Radiologie B, ENSAM and LAB. 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. After the lateral impact imposed on the left side of the thorax, right ribs were harvested for the second imaging step. Each rib was scanned with a Konica Minolta (VIVID 910) laser device. Solid lines were drawn with a surgical marker every 35 mm along the rib to define section cuts to be done for step 3. These markers were visible on the 3D laser acquisition and thus allow repositioning afterward the 3D models from the μCT scanner (step 3) in the medical imaging model (step 1). At microscopic level, the third step consists of scanning the samples with μCT scanner in order to differentiate the cortical bone from the spongy bone. μCT scanning was performed thanks to a 1172 SKYSCAN system, with 80 kV and 100 μA settings. The voxel size was 20.8 μm. This choice was conditioned by the complexity of the whole 3D model and the acquiring time: the duration of acquisition is about 2 hours for a sample of 35mm height.

Once these acquisition steps completed, a set of data with different resolutions and geometrical references have to be merged in the whole geometrical model of human thorax. The reconstruction and the repositioning are key-steps in the elaboration of a 3D model since they affect strongly the accuracy of the final model.

Model reconstruction

The reconstruction of a 3D model from the medical imaging (figure 1) was realized under MIMICS software by Materialise™. The grey scale DICOM data were binarised with constant threshold of 224 (default level for osseous tissues in the software). Thanks to the marching cube algorithm, the surface model of the thorax is built in a stereo lithography format (STL, triangles edges coordinates and directing facets). The 3D laser acquisition and the global geometry file from CT-Scan are then imported under RAPIDFORM™ software in the same STL format. All the geometrical data are repositioned regarding the CT-scan reconstruction reference. The repositioning of all reconstructions is based on an optimization loop where the target function consists of minimizing the gap between the 3D models.

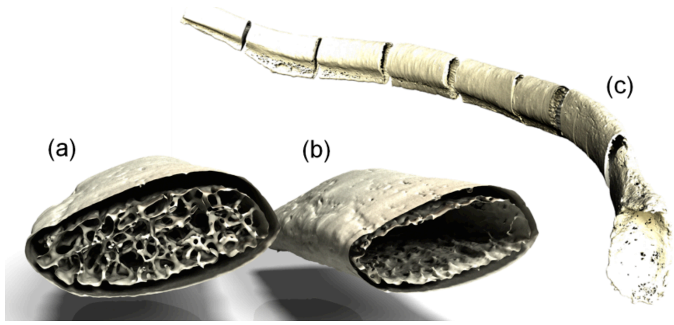

Fig.2 - 3D Reconstructions of µCT samples - (a) Total reconstruction with spongy and cortical bone of the 7th µCT sample, (b) Reconstruction of cortical bone of the same sample, (c) Repositioning of the 8 µCT samples of 7th rib.

Since the target is the cortical bone thickness characterization, considering the spongy bone leads to heavy files with no useful information for our application. One way to simplify the procedure and to reduce the 3D model numerical size and treatment is to overlook the spongy bone in µCT slices. Figure 2 illustrates the 3D models of the same sample with considering the spongy bone (a: 2 359 256 faces) and only the cortical bone skins (b: 486 610 faces).

Surface generation

The 8 samples assembly (Figure 2c) leads to an STL surface model with discontinuities due to the cutting edges. This problem was corrected with interpolated surfaces generated in CATIA software. The first surface defines the external rib geometry from the µCT sample and a second one is created to determine a limit between the cortical and spongy bone.

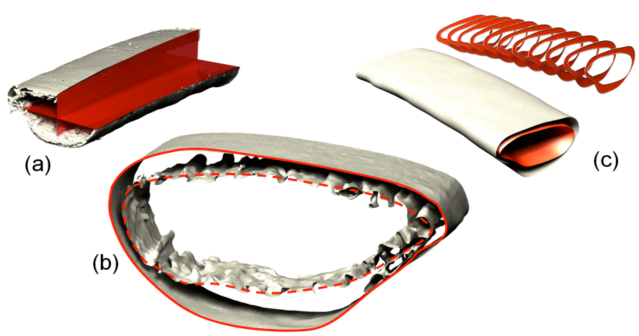

Fig. 3 - Surface reconstruction for 1 µCT sample - (a) Generation of the guide line from 4 B-spline curves, (b) B-Spline curve delimitations for inner and outer surface, (c) Delimited surface and sectional area for 1 sample.

After defining the neutral rib line, normal cutting planes are configured with a constant gap equal to 2% of the rib length. Along these planes, 2 B-spline curves (internal and external) are created. The external curve is perfectly obtained by the border detection of the rib. The internal one is manually defined to follow the variation of cortical bone thickness along the rib. These B-spline curves on normal sections are interpolated with continuous surfaces and are used to generate a 3D model (figure 3c) that will be used for building the FEM.

RESULT

THOMO project goal is to build a biofidelic model for industrial use. Consequently shell element representation is the optimal option. The project originality is to describe as well as possible the real thickness distribution of the cortical bone in every part of the thorax. Generating such a model needs the definition of a neutral surface from the previous results.

A new method has been developed allowing creating a neutral surface from the two complex surfaces of the rib. From the CAD file, MATLAB routine analyses the distances between each meshing point of the internal surface to the other points in the external one. At the end of the loop, the minimum distance is identified. By repeating this loop for all the points, the neutral surface can be generated by connecting all the middle points. The generated neutral surface (Figure 4a) is meshed and imported in a second routine in order to assign the thickness of each shell element. This thickness is obtained by measuring the distance between the centroid of the element and the 2 rib skins (from CAD file). The result matrix includes the nodal coordinates, the shell references and the thicknesses for each element. This matrix is transformed to PAM-Crash format for this application (Figure 4b).

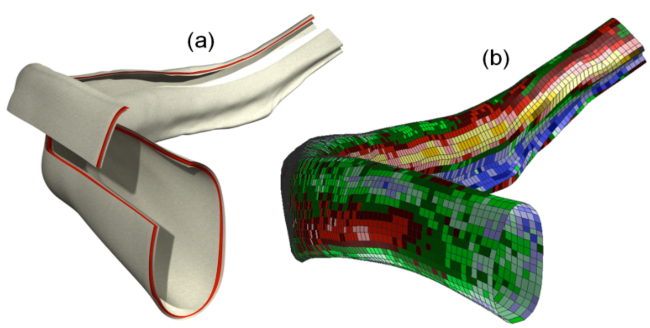

Fig. 4 - (a) Representation of the rib neutral surface, (b) FEM of the rib (neutral surface meshing with 20 average thicknesses).

These automatic routines generate a FE model of the rib with a parametric configuration to determine material card (thicknesses and bone material properties). Thickness distribution in different ribs will be combined with shell elements size in order to study mesh dependency.

DISCUSSION AND CONCLUSION

The purpose of this study is to develop a new protocol from geometry acquisition to FE modeling of the human thorax with a better precision compared to existing models.

The geometry acquisition strategy is based on a combination of imaging techniques at 3 different scales: a medical CT-scan, a 3D laser scan and a µCT-scan. The use of different imaging techniques is necessary to obtain a biofidelic FE model with an optimal computing time. The work presented in this paper describes the protocol applied on one rib as a feasibility step to be extended to a whole thorax. In medical imaging, the voxel size resolution is not precise enough to detect the real cortical thickness, whereas µCT-scan is the optimal one to achieve it and to differentiate a border between cortical and spongy bones. An automatic detection of this inner skin is possible but it leads to heavy models which will be anyway simplified in FE modeling. In this intent, manual B-spline definition is the most suitable solution because it gives continuous surfaces to optimize meshing. The part of the protocol regarding µCT contour definition can be discussed because it is time demanding and operator dependant since it is manual. The ideal validation of this approach is to estimate the dispersion induced by a set of different operators and compare them to the protocol's global precision. Another main advance of this study is to use parametric CAD modeling to generate the cutting plans normal to the rib curvature. The sections of the rib located between 2 correctly defined B-splines can be used to analyze thickness and inertia (centre of gravity and moments) variations. The next step is to apply this kind of analysis to a large number of ribs coming from different subjects and to identify an average variation law.

From the complete geometrical acquisition, a Finite Element model of the rib was built taking into account the entire geometry and bone distribution. Since the model should be adapted for crash application, shell elements were preferred and their size can be adjusted depending on the required accuracy. The distribution of thickness intervals is a parametric value that can be adjusted according to the intended accuracy. The model built is now under validation in order to estimate the advantages of more realistic thickness distribution of the cortical bone. A simple bending load configuration is applied on the rib with the explicit PAM-Crash code. The first aspect of validation will be based on the comparison of global forces either in case of a constant or a variable thickness. Moreover, the fracture location and shape of these 2 simulations will be compared to experimental observations from THOMO project partners.

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