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NUMERICAL MODEL OF A THORAX

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Abstract. Finite element analysis of the rib cage model is applied to recognize the stress distributions and to determine a rate of bone fractures (especially for pathologically changed bones). Two thorax models are considered and a role of an implant is illustrated and discussed.

1. Introduction

Generally, frontal impacts are considered to be the most common vehicle collision and causing an injury [9]. This paper describes development and validation of a thorax finite element model of a 10-14 years old child. Thorax model is developed in order to perform more details investigation of the human rib cage responses and injuries subject to impact loads. Antrophometric data of thorax is obtained from measurements and from drawings of crossections found in atlases of the human anatomy.

Rib cage anatomy: The skeleton of a thorax or a chest is an osseo-cartilaginous cage, containing and protecting the principal organs of respiration and circulation [2]. The *posterior surface* is formed by the twelve thoracic vertebrae and the posterior parts of the ribs. It is convex from above downward, and presents (on either side of the middle line) a deep groove, in consequence of the lateral and backward direction taken by the ribs from their vertebral extremities to their angles. The *anterior surface***,** formed by the sternum and costal cartilages, is flattened or slightly convex, and inclined from above downward and forward. The *lateral surfaces* are convex. They are formed by the ribs, separated from each other by the intercostal spaces, eleven in number, which are occupied by the intercostal muscles and membranes.

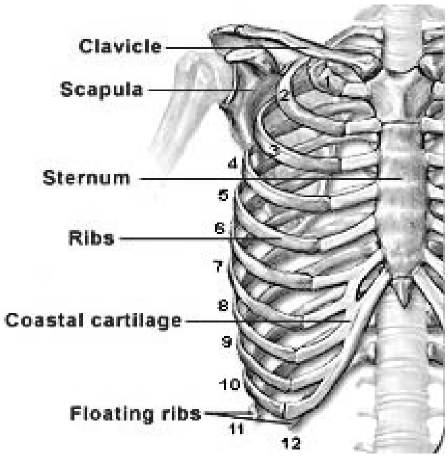

Fig. 1. Thorax anatomy

Ribs (1-7) either increase in length or decrease (7-12). Ribs 1-7 (called TRUE) are attached directly to sternum (sternal joints or interchondral joints) via strips or bars of hyaline cartilage, called a costal cartilage. Ribs 5-12 are called FALSE, since costal cartilage is not attached directly to sternum. Cartilage of the ribs 8, 9, 10 are attached to each other and then to cartilage of the rib 7, and they form the costal margins.

The left and right costal margins form costal arch. Ribs 11 and 12 are called FLOATING, because anterior ends are not attached to sternum and posterior ends. The latter are attached to thoracic vertebrae (see Fig. 1). The ribs and the sternum contain red bone narrow capable of hematopoiesis [11].

Joints of the thorax: *Costovertebral joints*: head of each typical rib articulates with the demifacets of two adjacent vertebrae and the crest of the head is attached by a ligament to the intervertebral disk. *Costotransverse joint*: the tubercle of a typical rib articulates with the facet on the tip of the transverse process of its own vertebra to form a synovial joint. *Sternocostal joints*: the point of articulation between the costal cartilages and the sternum (costal notches). The lower joints are strengthened anteriorly and posteriorly by radiate sternocostal ligaments. *Costochondral joints*: joint between a costal cartilage and a rib. No movement normally occurs at these joints. *Interchondral joints*: articulation between costal cartilages from adjacent ribs [2].

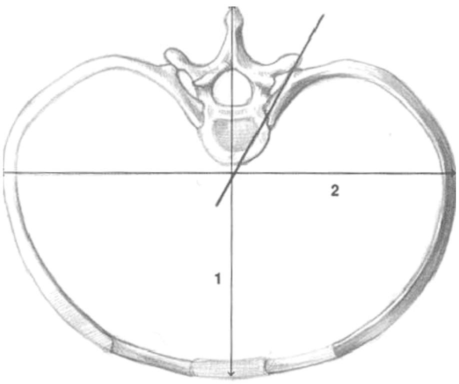

Fig. 2. Thorax joints

2. Materials and methods

Thorax model: Antrophometric data of thorax is obtained from measurements and from drawings of crossections found in atlases of the human anatomy [1, 2]. Note that the rib cage is difficult to model due to the complex curves of the ribs. After reviewing text and diagrams of the ribs, when the lungs inhale and exhale, it had been discovered that they are rotated around the costovertebral joints (the joints that are attached to the spine). The pivot points are moved into this position and the ribs are rotated to test their movement. The root bones are placed in the centre of the spine where the pivot points are placed. Figure 2 shows the axis which the ribs rotate around. The root bones are placed to get an accurate representation of the ribs' movement during breathing.

The created FE model of a thorax has a few important simplifications:

- The costochondral, intercostals, interchondral joints are neglected;
- The natural complex curves of the rib are simplified;
- Heterogeneous, anisotropic, non-linear material properties of bone and cartilage are approximated by an homogeneous, isotropic and linear elastic material.

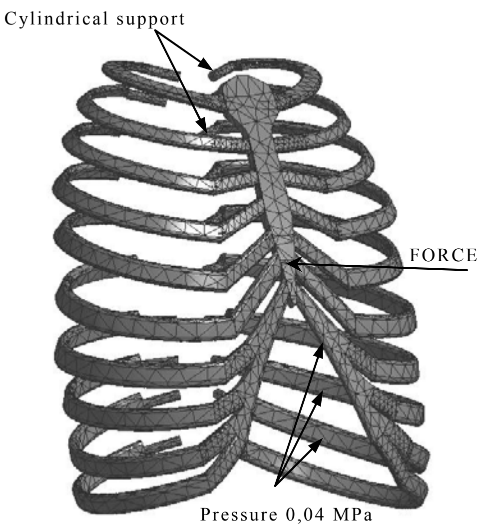

Fig. 3. Meshed model, applied loads and support.

Tab. 1. Implant material properties [1].

Material Steel AISI 316L	Young's modul E [MPa]	Rm [MPa]	Ro [MPa]	Zgo [MPa]
Saturation	$2{,}0*10^5$	480	170	-
Cold rework	$2{,}0*10^5$	860	690	240

Tab. 2. Tissue material properties [1].

Material	Young's modul E [GPa]	Density ρ [g/mm^3]	Poisson ratio ν
Bone	11,5	0,0013	0,3
Cartilage	1,1	0,0013	0,3

Method: All computation are carried out using the commercial FEM (Finite Element Method) program ANSYS. To create a finite element representation of a structure, it is first divided into simple parts called elements. Consider a single element: the forces and displacements at the nodes are linked by the stiffness matrix for the element. Each element has nodes which are joined by the nodes of adjacent elements to re-create the total structure. The stiffness terms for a node are then sum up of all the stiffness terms composed of the elements joined at that node. In this way, a global stiffness matrix for the whole structure is obtained by re-assembly of the individual elements [7].

Model environment: The thorax model is cylindrically supported in place, where in a real rib cage the costovertebral joints are placed [see Fig. 3]. In internal surface of ribs and sternum the pressure 0,04 MPa is applied in order to simulate an internal organs interaction. The force 5000 N is applied to the sternum, which is generated by a car-to-car frontal collision [9, 6].

Model verification: The model is verified for a correct movement of each of the ribs in an inhale and exhale times [2]. Bochenek et al. [2] obtained from measurements a range of displacement for each rib. Our simulation of the rib cage model is in a good agreement with the Bochenek's observation. After that the model is modified owing to the for frontal impact cadaver test data conducted by Kroell et al. [6]. Kroell et al. carried out a series of cadaver tests for the thoracic frontal impacts. Their test included cadavers of the anthropometric data and is similar to our model. The simulation result shows a good agreement with the test data. Figure 4 demonstrates that the model can predict a bone fracture in the ribs and sternum, which is in agreement with observation in the cadaver tests.

Model: Two thorax models are considered first model is designed to investigate stress distribution in a healthy human rib cage. The second one taken into account is the numerical model of a chest after Nuss pectus excavatum repair procedure. Pectus excavatum, or a funnel chest, is one of the most common major congenital anomalies, occurring in approximately one in every 400 births [3]. The Nuss procedure is a new and minimally invasive technique to repair pectus excavatum. The Nuss procedure avoids any cartilage resection and sternal osteotomy by placing a carefully preformed convex steel bar under the sternum through bilateral thoracic incisions, and then the bar is turning over to elevate the deformed sternum and costal cartilages to a desired position [3]. The bar is secured to the lateral chest wall muscles with heavy sutures. If the bar is unstable, a 2 to 4 cm stabilizing cross bar is attached to one or both ends of the sternal bar. The bar is left in position for two or more years, depending on the age of a patient and a severity of the deformity, when re-modeling of the deformed cartilages and sternum has occurred.

Recall that Nuss implant is left in a human organism for two or even more years. It can happened that during such a long period of time a patient may participate in a road accident. Therefore, an investigation of a rib cage responses to impact loads is carried out. Comparison of stress distribution in skeleton parts for these two cases is expected to be useful for an appropriate further implants design [10].

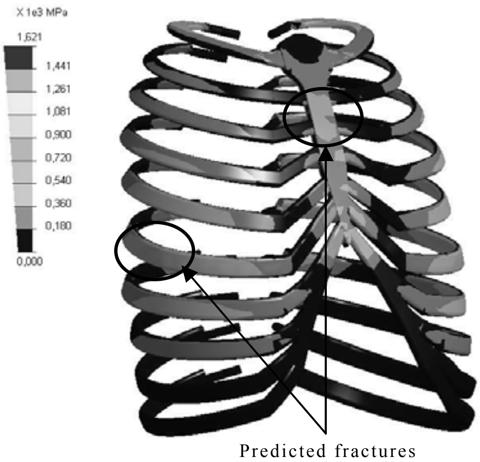

Fig. 4. Equivalent stress distribution without implant

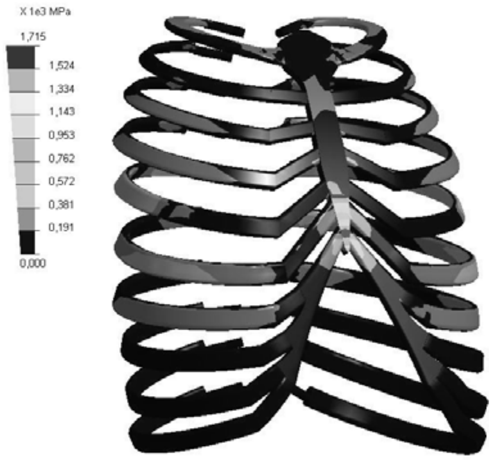

Fig. 5. Equivalent stress distribution with implant

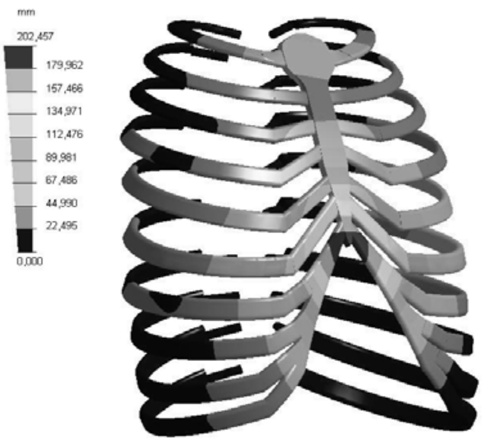

Fig. 6. Equivalent displacements distribution without implant

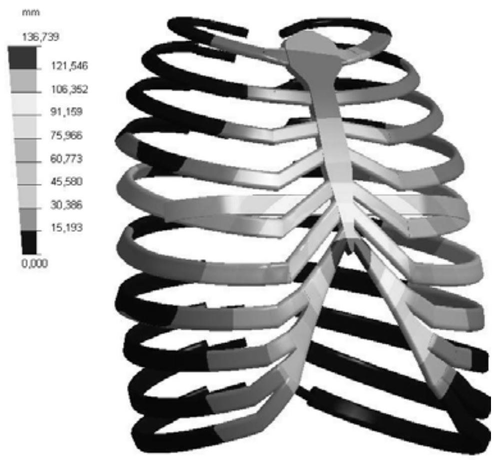

Fig. 7. Equivalent displacements distribution with implant

3. Results and conclusion

Careful analysis of Fig. 4 and Fig. 5 leads to the following conclusions:

- In the model with implant a fracture of the 5-th rib will appear faster and it is caused by a smaller force, and the implant may damage lungs or heart;
- It is easy to recognize that stress distribution is violated by the implant;
- In the health thorax ribs (1-7) transfers a large majority of the load;

Comparing Fig. 6 and Fig. 7, one can be conclude that the sternum displacement in the model with implant is smaller. However, it could be an illusion since the implant causes faster fracture of the 5-th rib, and the thorax stiffness becomes weaker.

4. Further development of the thorax model

When a human body is exposed to an impact load, soft tissues of the internal organs can sustain large stress and strain rate [5]. To investigate the mechanical responses of the internal organs, further model development should include modelling of the organs.

Homogenous and linear elasticity material properties are assigned to each part of the model, whereas the human cartilages and bones may have different material properties. In order to have more realistic representation, more complex tissue material properties should be applied [4].

5. References

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