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# THE FINITE ELEMENT MODEL OF THE HUMAN RIB CAGE

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In the paper, finite element analysis of the rib cage model is applied to recognize stress distributions and to determine the rate of bone fractures (especially for pathologically changed bones). Two thorax models are considered and the role of the implant is illustrated and discussed. The simulation result shows a good agreement with the cadaver test data.

*Key words:* finite element model, thorax, rib cage, Nuss implant, pectus excavatum, fail chest

## 1. Introduction

Generally, frontal impacts are considered to be the most common vehicle collisions causing injuries (Oshita *et al.*, 2001). This paper describes development and validation of a thorax finite element model of a 10-14 years old child. The thorax model is developed in order to perform more detailed investigation of the human rib cage responses and injuries subject to impact loads. Antropometric data of thorax is obtained from measurements and from drawings of crossections found in atlases of the human anatomy.

Let us begin first from a brief description of the rib cage anatomy. The skeleton of thorax or chest is an osseo-cartilaginous cage containing and protecting principal organs of respiration and circulation (Bochenek and Reicher, 1997). The *posterior surface* is formed by twelve thoracic vertebrae and posterior parts of the ribs. It is convex from the above downwards, 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 the above downwards and forwards. 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.

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 the costal cartilage. Ribs 5-12 are called FALSE, since the costal cartilage is not attached directly to the sternum. Cartilage of ribs 8, 9, 10 are attached to each other and then to the cartilage of 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 the sternum and posterior ends. The latter are attached to thoracic vertebrae (see Fig. 1). The ribs and the sternum contain red bone marrow capable of hematopoiesis (Sawicki, 1997).

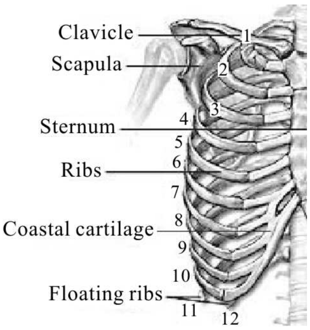

Fig. 1. Thorax anatomy

Let us now introduce description of joints of the thorax.

**Costovertebral joints:** head of each typical rib articulates with 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:** a joint between the costal cartilage and a rib. No movement normally occurs at these joints.

**Interchondral joints:** articulation between costal cartilages from adjacent ribs (Bochenek and Reicher, 1997).

## 2. Materials and methods

### 2.1. Thorax model

Antrophometric data of thorax is obtained from measurements and from drawings of crossections found in atlases of the human anatomy (Będziński, 1997; Bochenek and Reicher, 1977). Note that the rib cage is difficult to model due to complex curves of the ribs. After reviewing descriptions and diagrams of the ribs, when 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 ribs movement during breathing.

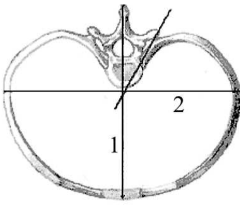

Fig. 2. Thorax joints

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

- the costochondral, intercostals, interchondral joints are neglected;
- natural complex curves of ribs are simplified;
- heterogeneous, anisotropic, non-linear material properties of bones and cartilage are approximated by a homogeneous, isotropic and linear elastic material.

### 2.2. Method

All computations are carried out using the commercial FEM (Finite Element Method) program ANSYS®. Static and linear strain-displacement relation analysis are performed. To create a finite element representation of a structure, it is first divided into simple parts called elements. Consider a single element: 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 a sum of all stiffness terms composed of the elements joined at that node. In this way, the global stiffness matrix for the whole structure is obtained by re-assemblement of individual elements (Łaczek, 1999).

### 2.3. 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 the internal surface of ribs and sternum a pressure of 0.04 MPa is applied in order to simulate interaction of internal organs. A force of 5000 N is applied to the sternum, which is generated by a car-to-car frontal collision (Kroell *et al.*, 1971; Oshita *et al.*, 2001).

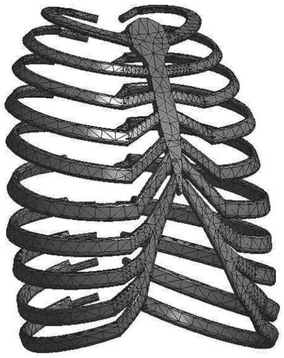

Fig. 3. Meshed model, applied loads and support

### 2.4. Model verification

The model is verified for correct movement of each rib in inhale and exhale periods (Bochenek and Reicher, 1997). Bochenek and Reicher (1997) found from measurements the range of displacement for each rib. Our simulation of the rib cage model is in a good agreement with Bochenek's observation. After that, the model was modified owing to the frontal impact cadaver test data conducted by Kroell *et al.* (1971), Łaczek (1999). Kroell *et al.* (1971) carried out a series of cadaver tests for the thoracic frontal impacts. Their test included cadavers of anthropometric data and was similar to our model. The simulation result showed 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.

## 3. Model

Two thorax models are considered. The first model is designed to investigate stress distribution in a healthy human rib cage. The second one taken into account is a numerical model of the chest after the Nuss pectus excavatum repair procedure. Pectus excavatum, or the funnel chest, is one of the

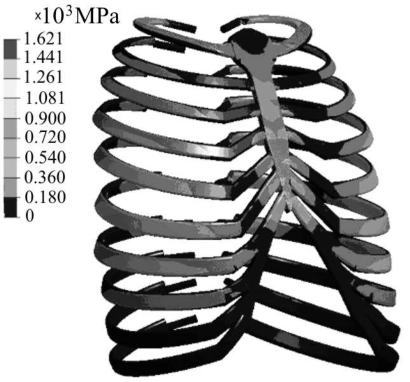

Fig. 4. Equivalent stress distribution without implant

most common major congenital anomalies occurring in approximately one in every 400 births (Correia De Matos *et al.*, 1997). The Nuss procedure is a new and minimally invasive technique of repair of 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 by turning it over to elevate the deformed sternum and costal cartilages to a desired position (Correia De Matos *et al.*, 1997). The bar is secured to the lateral chest wall muscles with heavy sutures. If the bar is unstable, a 2 up to 4 cm stabilizing cross bar is attached to one or both ends of the sternal bar. The bar is left in psuch a osition for two or more years, depending on patient's age and severity of deformation, when re-modeling of the deformed cartilages and sternum has occurred.

It is to be remembered that the nuss implant is left in the human organism for two or even more years. It can happened that during such a long period of time the patient may participate in a road accident. Therefore, investigation of the rib cage responses to impact loads is being carried out. Comparison of stress distributions in skeleton parts for these two cases is expected to be useful for further developments of appropriate implant designs (Prendergast, 2001).

## 4. Results

We got the following observations from our investigations referring to the cadaver test (Kroell *et al.*, 1971):

- the estimated number of bone fractures found by simulation (Fig. 4) was similar to the number obtained in the cadaver test,

- the time history of deformation is in good agreement with the cadaver test data.

## 5. Conclusion

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

- in the model with the implant, a fracture of the 5-th rib appears faster and is caused by a smaller force, and the implant may damage lungs or heart,
- it is easy to recognize that the stress distribution is violated by the implant,
- in healthy thorax, ribs (1-7) transfer a large majority of the load.

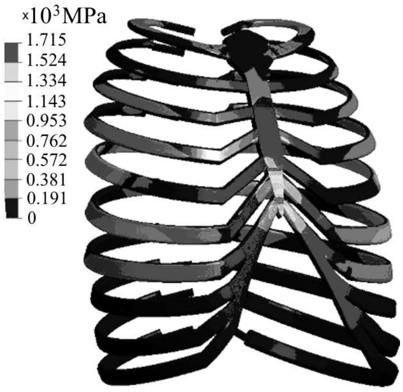

Fig. 5. Equivalent stress distribution with implant

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

When a human body is exposed to an impact load, soft tissues of internal organs can sustain large stress and strain rates (Kowalewski *et al.*, 1997). To investigate mechanical responses of the internal organs, further development of the model should include modelling of the organs as well.

Homogenous and linear elastic properties of incorporated materials are assigned to each part of the model, whereas the human cartilages and bones may exhibit different material properties. In order to create a more realistic representation, more complex tissue material properties should be reflected in the study (Harrigan and Hamilton, 1994).

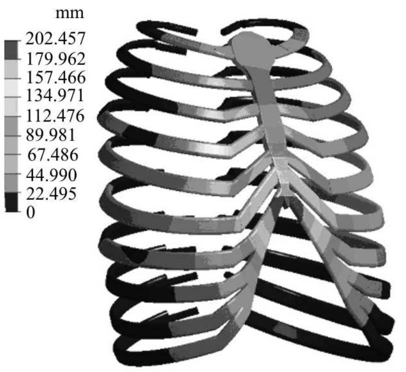

Fig. 6. Equivalent displacements distribution without implant

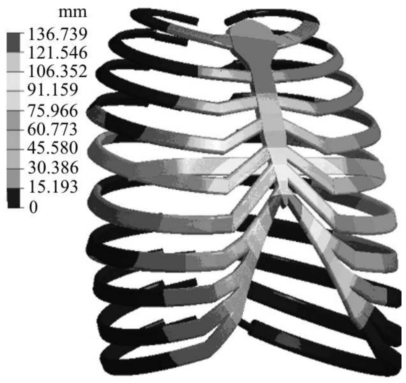

Fig. 7. Equivalent displacements distribution with implant

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## Numeryczny model klatki piersiowej

### Streszczenie

Artykuł przedstawia analizę wytrzymałościową klatki piersiowej metodą elementów skończonych. Przeprowadzone badania pozwalają na poznanie rozkładu naprężeń i odkształceń w klatce piersiowej oraz na ocenę miejsc najbardziej narażonych na złamania. Rozpatrzono dwa modele klatki piersiowej: pierwszy człowieka zdrowego oraz drugi człowieka po chirurgicznej operacji lejkowatej klatki piersiowej z zastosowaniem implantu. Opisano wpływ implantu na wytrzymałość klatki piersiowej.

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