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CAN THE FOAM MODEL SIMULATE THE BONE BEHAVIOUR?

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Abstract: *Dehiscence of median sternotomy wounds due to excessive forces caused by high pressure within the chest during coughing can lead to breaking closures sternotomy. This remains a clinical problem leading to significant risks of mortality and morbidity. The evaluation of the suture and the sternotomy biomechanical feedback is tested usually on the human cadaveric sternum or in some cases using suitable animal sternum. The foam sternal model was proposed as the alternative source that provides cheap, easily accessible sternum, without mentioning other advantages. The computational approach combined with experiment can provide more information about the foam behaviour and confirm the statement: "the foam model sternum behaves as a real bone" as advertised by supplier. The foam model sternum was scanned, and digitized geometry data was used to create the virtual computational model used to simulate the laboratory experiment by means of Finite Element Method. The data collected from the two experiments, the laboratory test and computational simulation, are compared and verified against the outcome of the experiment with the sternum from cadaver.*

Keywords: ***Sternum, finite element analysis, foam model.***

1. Introduction

The sternotomy incision is preferred path to access the heart and other vascular tissues in spite of the rising popularity of minimal invasive techniques. Dehiscence of the sternotomy closure represents a serious complication in the early post-operative period prior to start of significant bone healing. It is usually caused by sternal instability, disruption of the bone or the wire, and associated with wound infection. The rate of median sternotomy dehiscence falls between 0.5 to 2.5% with mortality ranging from 10 to 45%, which demands better understanding of the problem followed by improvement of the closure technique. To carry out the proper analysis of the situation after the surgery there is a need to conduct number of tests with application of different closure techniques. The number of suitable sternal plates from cadaver is limited therefore the alternative way or source has to be identified to be able to provide reliable results. The animal bone or artificial model made of polyurethane foam is offered as the alternative material to test techniques sternotomy. It is rather difficult to obtain an animal sternum that would have significant similarity to human sternum (Magovern, 1999). The model artificial sternum offers more or less uniform material properties, and shape thus seems to be the most suitable for the comparison studies. The first comparison between sternum cadaver and the artificial bone was carried by D. R. Trumble (2002). Even though the result supported the idea of similar behaviour between the foam model and human sternum the question mark related to biomechanical feedback and stress-strain response remained. The similarity of biomechanical response between sternum cadaver and the model from polyurethane foam has to be proved prior to further tests.

2. Methods

The similarity of biomechanical response between sternum cadaver, and the foam model can be proved via laboratory experiments or virtual simulation. In this paper we are going to discuss the virtual simulation of the sternum behaviour. Before we start the simulation of sternotomy closure, our

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task is to verify the identity or similarity of the behaviour of the sternum and the polyurethane model of sternum. The determination of the boundary conditions for computational model was subordinated to this goal thus the forces are applied at the points where the holder of the foam model will be clamped into the jaws of the tensile machine. Thus even though the loading conditions do not correspond to the reality we can conduct the comparative study under the same load condition for the foam model, computational model, and human cadaver.

2.1. Sternum

The sternum is a long flat bone that forms the anterior wall of the thorax whilst creating an anchor for the ribs meeting centrally along the midline of the body. The main function sternum that is anchored anteriorly to the rib cage and posteriorly in the vertebrae, is to protect vital organs against physical trauma. It is composed of three parts, which are the manubrium, the sternum, and the small irregular xiphoid process. The adjacent parts articulate via secondary cartilaginous joints that allow more movement between the bones than the fibrous joint.

Fig. 1: Artificial Model Sternum.

2.2. Computational model

The model consisting of the manubrium, sternum, and short cartilages attached to the sternum is moulded as one solid piece. The first goal was to create the geometry model therefore the data of the shape were obtained in form of a cloud point, using laser scan. The virtual model sternum made of solid polyurethane foam was created in drawing software Rhinoceros. The material properties of the foam were obtained from manufacturer with certification of the compliance with testing standards ASTM D-1621, D-1623, D-273. The type of foam with density 20pcf (pound per cubic foot) was proposed by medical person as the equivalent substitute they use for testing of the suture sternotomy.

2.3. Load during the cough

The mathematical model created for computation of the force load during the cough is based on the similarity between the shape of the chest and the pressure vessel. In both cases the internal pressure creates the load on the wall that encloses the pressurized space. This approach, proposed by Mr. Casha (1999, 2001) takes into account the pressure developed inside the chest during the cough without contribution from other structures such as intercostal or abdominal muscles. This simplified model of the chest is well accepted within the medical society even these days.

Thus the total force acting on the chest wall is modelled as uniformly distributed pressure over the projected chest area that is considered to form a cylinder

$$F = p \cdot D \cdot L \tag{1}$$

Considering the pressure p that can reach values 13 kPa to 40 kPa during the cough, and the average dimension of the human chest given as thickness D = 150 mm and length L = 300 mm measured in sagittal plane, based on the anthropometrics data available. The total force of 1350 N that was computed for given geometry and pressure of 30 kPa, is transferred through the adjacent structures to the sternum. This result is in agreement with an independent research that has been carried out by Losanoff (2004) by means of the experiment with cadavers.

2.4. Materials and simulation

Due to considerable difference between values of Young’s modulus in relation to the density we computed the density of our model that we have available, and together with the graph of Young's modulus, plotted from the data provided by the manufacturer, we evaluated correct Young’s modulus. The value of density for the polyurethane foam was 0.414 g/cm^3, which corresponds to 25.9 pcf and the extrapolated Young’s modulus reached 460MPa in tension, and 348 MPa in compression. The results of the computational simulation are going to serve as a benchmark for our future work utilising the foam model.

To identify the biomechanical differences in the response of the polyurethane foam model and the human sternum we need to simulate the material properties corresponding to the cortical and cancellous bone. The thickness of the sternum was measured at the valley, the position of the cartilage attachment, and at the ridge to be 9.5 ± 1.5 mm, and 13.15 ± 1.6 mm respectively while the thickness of the cortical bone at the valleys is around 1 mm, and at the ridges exceeds 2 mm. The effect of the cortical and cancellous bone on the magnitude and distribution of stress is investigated virtually, utilizing the geometry of the foam model that is coated with uniform layer of cortical bone 1mm, and 2 mm thick enclosing the cancellous bone of very low density. The given values of Young's modulus 5000 MPa and 50 MPa associated with cortical and cancellous bone respectively are based on the CT scans of six human cadaveric sternums. The data analysis was carried out at the Anatomy Department of University of Malta by evaluation of the average radio-density 1500 HU and 300 HU (Hounsfield Units) for cortical and cancellous bone respectively followed by the estimation of Young's modulus that corresponds to the radio-density related to the colour intensity of the CT scan image.

3. Results

The results of the three models were summarized in the following graphs recording the variation of stress and strain along the path as marked on the sternum in Fig. 2. The stress distribution for intact sternum indicates the areas that would be exposed to large force during the cough. Thus these would represent the potential sites of the sternotomy failure. Except of the stresses and strains investigated at the region of sternotomy the overall stress distribution was evaluated based on the Von Misses stress and strain.

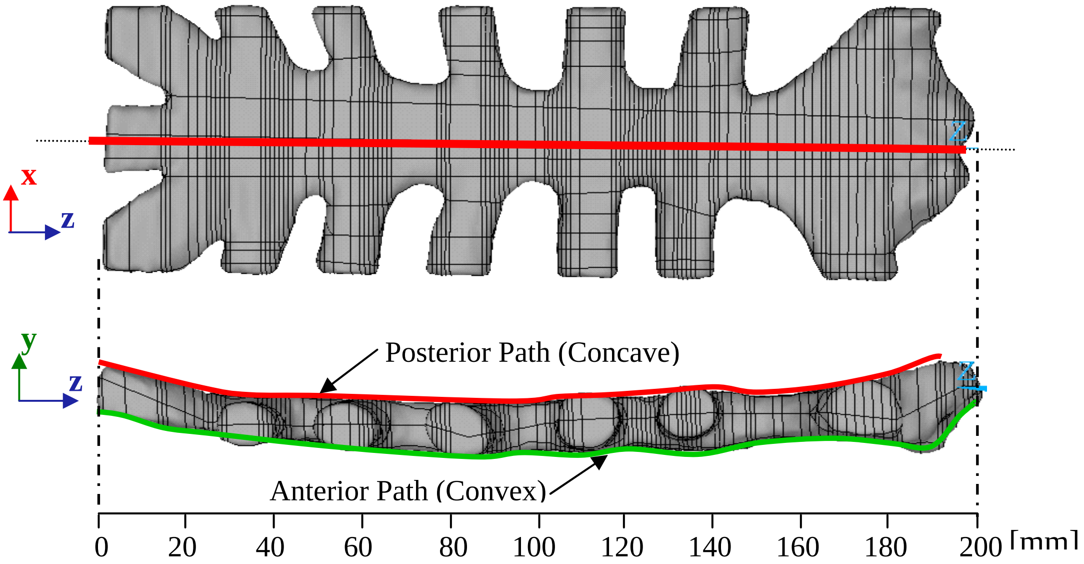

Fig. 2: The paths created along the sternum Finite Element Model to analyse the stress distribution within the sternum median plane.

Tab. 1: Summary of maximum equivalent stress and strain.

	Maximum Von Mises Stress (x10^6 Pa)	**Maximum Von Mises Strain** x10^{-3}
Foam Model	5.279	11.5
Bone 1 mm Cortical	18.867	4.16
Bone 2 mm Cortical	12.616	2.52
Bone 1 mm Cancellous	0.320	6.41
Bone 2 mm Cancellous	0.110	2.19

The maximum stress was developed at the region of the rib attachment near the xiphoid in case of the foam model. In other two cases simulating the human bone the maximum stress developed was at the region of attachment of 3rd and 4th rib. As indicated in Tab. 1 above the stress within the cortical bone increased its value compared to the result from foam model. The highest stresses encountered in case of 1 mm cortical shell model were reduced by approximately one third in case of 2 mm shell model that depicts more closely the real thickness of the cortical bone that supports better redistribution of the load within both types of bone that is confirmed by the resulting lower stress within the cancellous bone.

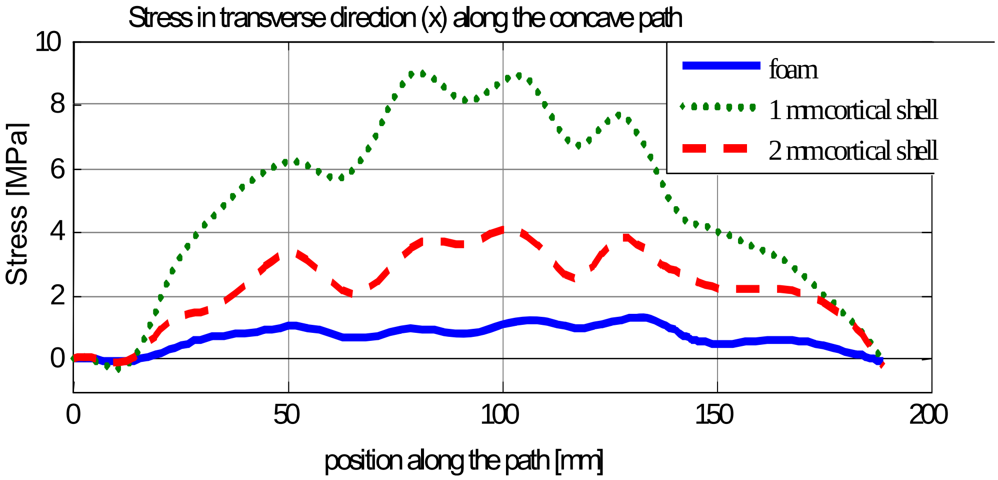

Fig. 3: Comparison of stress developed along the median path in coronal plane.

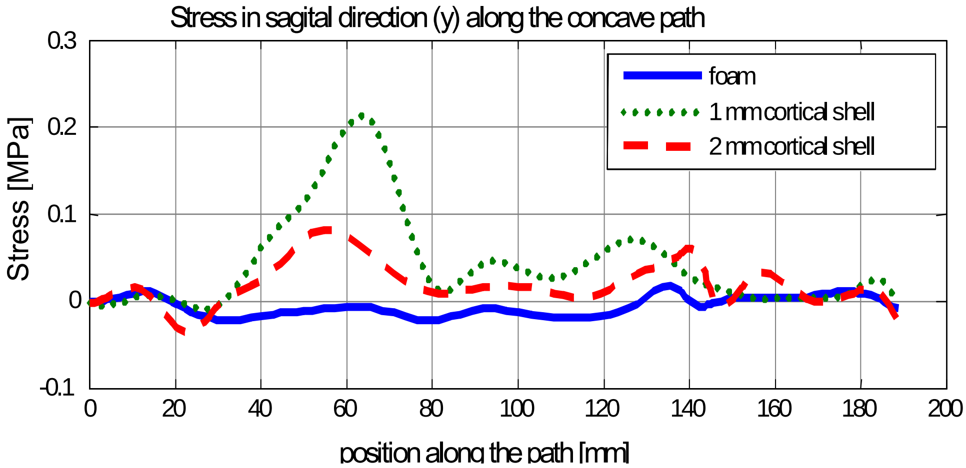

Fig. 4: Comparison of stress developed along the median path in sagital plane.

4. Conclusions

Our task was to answer the first question that crop out in our discussion about future tests of different closure techniques using the foam model of sternum. Based on the results from our simulation it can be concluded that there are considerable differences in the material response. The laboratory tests that are going to be carried in our laboratory in a very near future should verify our results and throw more light on the foam behaviour.

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