Finite Element Modeling of Chest Compressions in cardiopulmonary resuscitation

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Abstract

In cardiopulmonary resuscitation (CPR), the optimization of chest compression (CC) recommended by the American Heart Association (AHA) is 50mm to 60mm. Inappropriately performed CC can increase the risk of chest injury. In order to assess the reliability and accuracy of the AHA standard, mathematically reconstructed 3D human chest model using Finite Element Analysis (FEA) is used to determine how the human chest will react to physical stress. The optimized depth of CC can be obtained by analyzing chest information when the 3D chest model is subjected to different CC depths.

Literature Review

During manual CPR, force and acceleration are measured at the sternum. All transducer signals were recorded by digital computer. Real-time feedback was provided to the rescue team via chart recordings.	1990: System for Mechanical Measurements During Cardiopulmonary Resuscitation in Humans	This article is successful in establishing the relationship between the force and the effect of compression. But no standard has been made.
A dynamic mechanical model of the chest response and formulated. The elasticity, damping of the human chest were estimated with a constrained nonlinear least-mean square identification technique..	1990: Identification of Dynamic Mechanical Parameters of the Human Chest During Manual Cardiopulmonary Resuscitation	In the analysis of one human chest, a considerable amount of damping was found, but no significant difference between compression and release. The equivalent mass was too small to be determined accurately.
Sternal compressions were applied at a nominal rate of 90/min with a peak force near 400 N. From measurements of sternal force, displacement model, parameters were estimated. The elastic force and damping decreased with time and decreasing lung volume.	1999: Canine Sternal Force-Displacement Relationship During Cardiopulmonary Resuscitation	Use canine model parameters to simulate human despite the notable differences in thoracic anatomy between the species, supporting the continued use of canines as models for human CPR.
Dynamic injurious experiments were to record the structural behavior and fracture. Then, FE models for the three ribs were developed. Overall, the reaction force–displacement relationship in the offset middle-cortical surfaces compared well with those measured experimentally for all the three ribs.	2010: Rib fractures under anterior–posterior dynamic loads: Experimental and finite-element study	The results indicated that modeling strategies were applicable for simulating rib responses and bone fractures for the loading conditions considered, but these models were not computationally efficient.

Methodology

Experiment 1:

Commercially available human torso finite element model → Include torso flesh, rib, heart, lever and stomach, exclude rest parts of the model → Reassign 50%percentile material properties to elements → Fix bottom of model as boundary condition and simulate CC with a cuboid with certain initial velocity → Solve the model by LS-DYNA smp d R10.0.0 → Output deformation and pressure distribution of rib

Experiment 2:

Spiral computed tomography scan is performed to the chests of patients → Gather the images and reconstruct the 3D human chest model using MIMICS20 → Mesh the surface and the volume of the model using 3-MATIC → Assign the properties which are Young’s Modulus, Poisson Coefficients to the 3D human chest → Export the FEA file and analyze the model using ANSYS18 ✖ Experiments failed due to the failure of costicartilage reconstruction

Finite Element Analysis

The displacement vector u_3D of an element in three dimensions has three components $u_3D = [u\ v\ w]^T$. Given nodal degrees of freedom vector u_e and N_i, the shape function associated with node i, $i = 1 \dots n$, then the displacement vector function can be written as

$$u_{3D} = \begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{pmatrix} N_1 & 0 & 0 & N_2 & 0 & 0 & \dots & N_n & 0 & 0 \\ 0 & N_1 & 0 & 0 & N_2 & 0 & \dots & 0 & N_n & 0 \\ 0 & 0 & N_1 & 0 & 0 & N_2 & 0 & \dots & 0 & N_n \end{pmatrix} \begin{pmatrix} u_1 \\ v_1 \\ w_1 \\ u_2 \\ v_2 \\ w_2 \\ \vdots \\ u_n \\ v_n \\ w_n \end{pmatrix} = N u_e$$

For a general linear elastic material, one can show by principle of virtual work that the external virtual work EVW_e, of one particular element is:

$$EVW_e = u_e^{*T} \int_{\partial e} N^T t_n ds + u_e^{*T} \int_e N^T \rho b dx$$

where u^* stands is the virtual displacement, $t_n \in R^3$ is the traction vectors on the surface of the element, ρ is the mass density and $b \in R^3$ is the body force. The first integration is done over the element surface and the second in element volume. This leads to the local nodal forces vector,

$$f^e = \int_{\partial e} N^T t_n ds + \int_e N^T \rho b dx$$

Results

Experiment 1

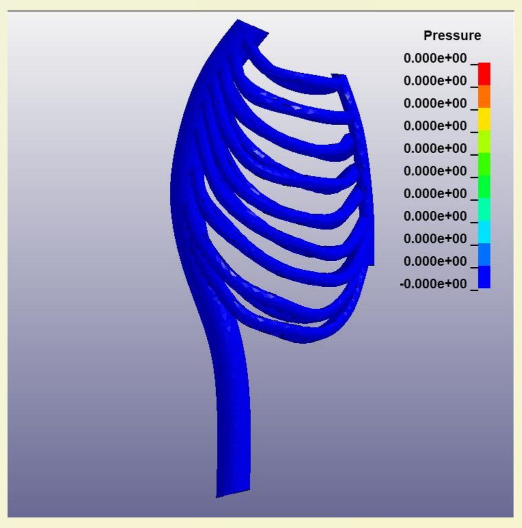


Figure 1

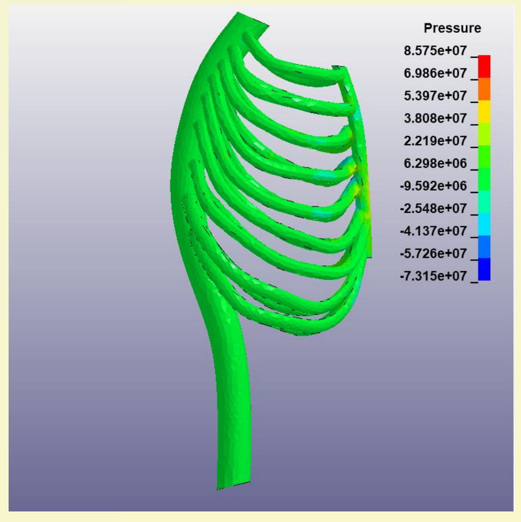


Figure 2

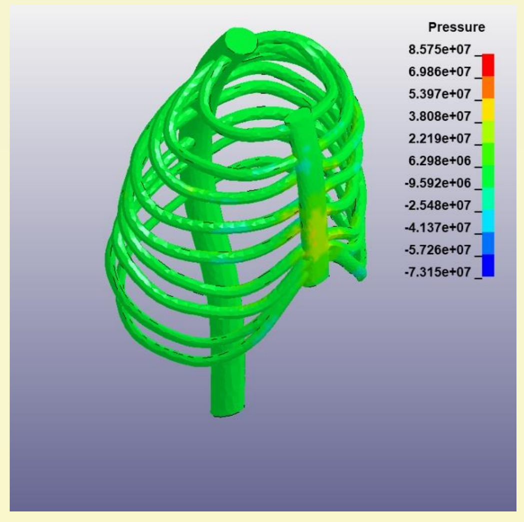
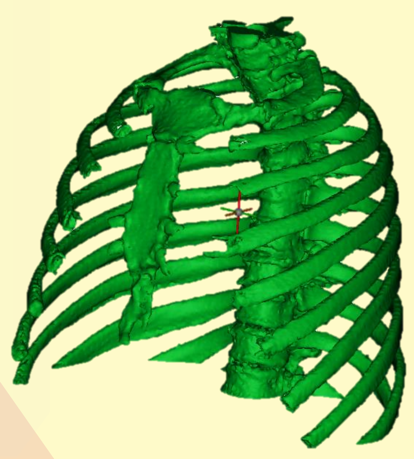


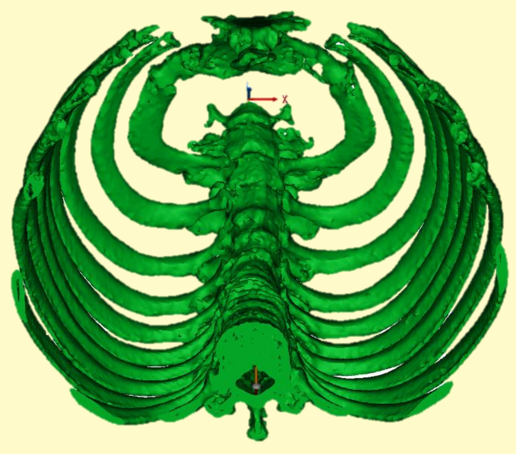
Figure 3

Figure 1-3 above represents the simulation results of experiment 1. ***Figure 1*** illustrates the initial state of the rib cage from right when no external force is added. ***Figure 2*** shows the pressure profile (in Pa) when the displacement of sternum is around 50mm, as a comparison to ***Figure 1***. ***Figure 3*** is at the same state of ***Figure 2*** from an isometric perspective. Note that the maximal pressure on rib cage is between 22.19MPa to 53.97MPa, which is smaller than the failure stress reported to be 124.6MPa. This suggests that rib fraction is not likely to occur in this setting.

Experiment 2:

In CPR, the optimization of CC recommended by the AHA is 50mm to 60mm. Inappropriately performed CC can increase the risk of chest injury. In order to assess the reliability and accuracy of the AHA standard, mathematically reconstructed 3D human chest model using FEA is used to determine how the human chest will react to physical stress. The optimized depth of CC can be obtained by analyzing chest information when the 3D chest model is subjected to different CC depths. Costicartilage cannot be constructed due to the high level of the similarity in grayscale. Following graphs are the 3D human chest model we ultimately reconstructed using the CT graphs displayed above.





In this experiment, the FEA part cannot be performed because of lacking costicartilage.

Conclusions and Future Work

The results of Experiment 1 show that, under our particular setting, rib fraction is not likely to occur under CC with depth 50mm. Given more time, it is necessary to study how stress profiles varies with different material properties since age and gender will affect material properties. For future work, refining the current rib cage finite element model will enable study on race, age and gender specified finite element model, hence answer the big question, whether 50mm CC is appropriate for Chinese in CPR.

However, for Experiment 2, due to the high level of similarity in greyscale, costicartilage cannot be reconstructed and the rest part of the experiment - FEA process - is undermined. We propose two ways to improve Experiment 2. First, we can acquire a new set of Spiral CT with higher clarity. Second, we shall perform regression analysis on two models of human chests with and without costicartilage using the results of Experiment 1. Based on this regression, the optimal depth of compression of Experiment 2 would be acquired.

Reference

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