Preliminary Study of the Effects of Calcification on the Structural Behavior of Costal Cartilage

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INTRODUCTION

As the human body ages it becomes considerably more fragile, the effects of which can be seen in the ribcage (Kent, 2005a) and other osseous structures. An increased susceptibility to thoracic injury, rib fractures in particular, has been observed among older drivers (Morris et al. 2002 and Kent, 2005b). One of the most striking age-related changes that occur in the osseous thorax is calcification of the costal cartilage, which connects the rib bones to the sternum. Local calcifications can start to develop in the costal cartilage around the age of 26; severe calcification of the cartilage can occur as early as age 60 (McCormick 1980). Costal cartilage calcification also exhibits gender-dependent magnitudes and patterns (McCormick 1980, Stewart 1984, Teale 1989, Retjarova 2004). Because the costal cartilage provides a major load path between the ribs and the sternum, stiffening caused by calcification may affect the load distribution throughout the ribcage. The objective of this analysis was to use a simple finite element model to determine if moderate calcification can affect the structural behavior of a costal cartilage segment enough to warrant further investigation.

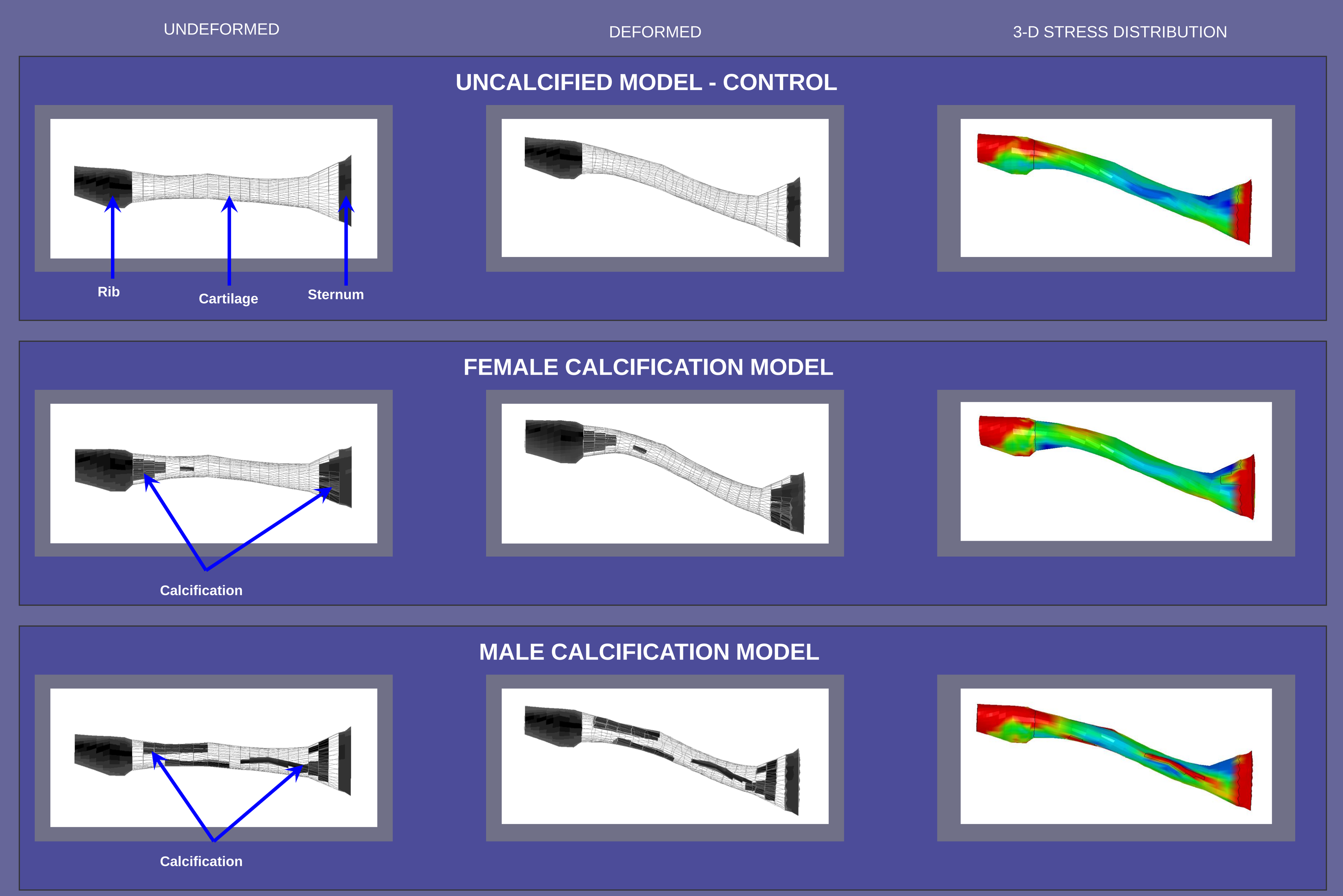
METHODS

Three different models (control, female calcified, male calcified) of a single costal cartilage segment were constructed in HyperMesh and then imported to LS-DYNA for simulation and analysis. The rib, sternum, and exterior cartilage geometries were identical for each of the models, and were constructed via digitization of a micro-CT scan of the costal cartilage from the right fourth rib of a 23 year old male. All elements were fully integrated eight-node solid elements.

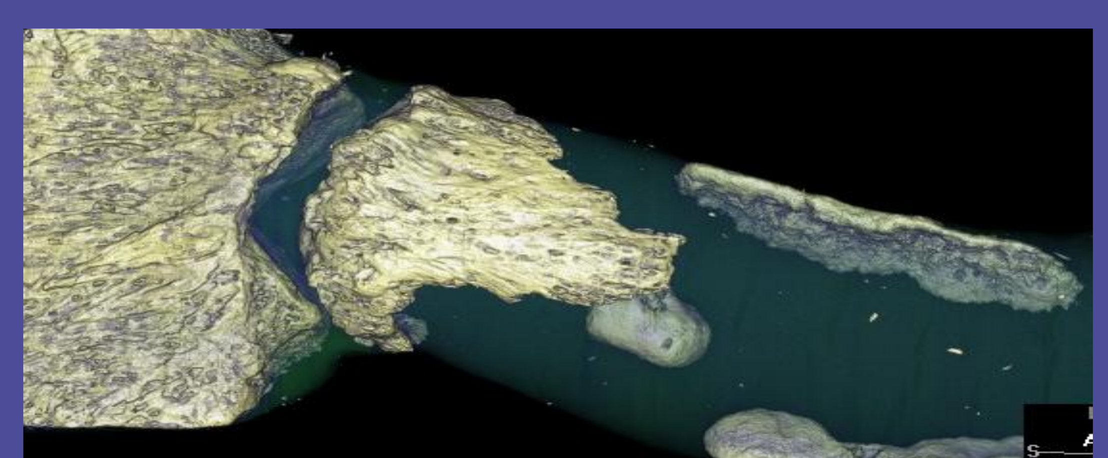
In the control model, the entire cartilage region was modeled homogeneously as cartilage. In the male and female calcified models, calcified regions were added within the cartilage (by changing the material properties of select elements) to represent the patterns typical of moderately calcified male and female costal cartilages. For simplification, all elements were modeled as isotropic and linear elastic; cartilage elements were modeled with a Young's modulus of 20 MPa and Poisson's ratio of .4. and bone elements (rib, sternum, calcifications) were modeled with a Young's modulus of 20 GPa and Poisson's ratio of .3, typical of cortical bone. The model characteristics are summarized in Table 1.

Boundary conditions were chosen to represent those generated by a posteriorly directed, concentrated load applied to the mid-sternum. In this type of loading, symmetry constrains the sternum such that no lateral displacement or rotation occurs. This was represented in the simulations with posterior displacement of the sternum, with the sternal boundary constrained to allow no rotation or displacement other than in the loading direction. Similarly, stiffness in the rib constrains the lateral movement and rotation of the costo-chondral junction (Shaw et al. 2007). This was represented in the simulations by fixing all degrees of freedom of the costal boundary. During the simulations, the sternal boundary was displaced posteriorly at a rate of 15 mm/sec up to 15 mm total displacement. The resultant force across the face of the costal boundary was then observed, representing the force transmitted from the sternum to the rib throughout the deformation.

Figure 1: Wire-mesh images of un-deformed and deformed costal cartilage illustrating calcification patterns



CT Scan Display of Male Pattern Calcification



CT Scan Display of Female Pattern Calcification

Table 1: Simulation Parameters

	Control	Female	Male
Number of elements	3194	3194	3194
Total volume (mm^3)	5885	5885	5885
Cartilage volume (mm^3)	3379	3063	3116
Calcification volume (mm^3)	0	316	263
Calcification percentage*	0	10.32	8.44
Sternum displacement (mm)	15	15	15

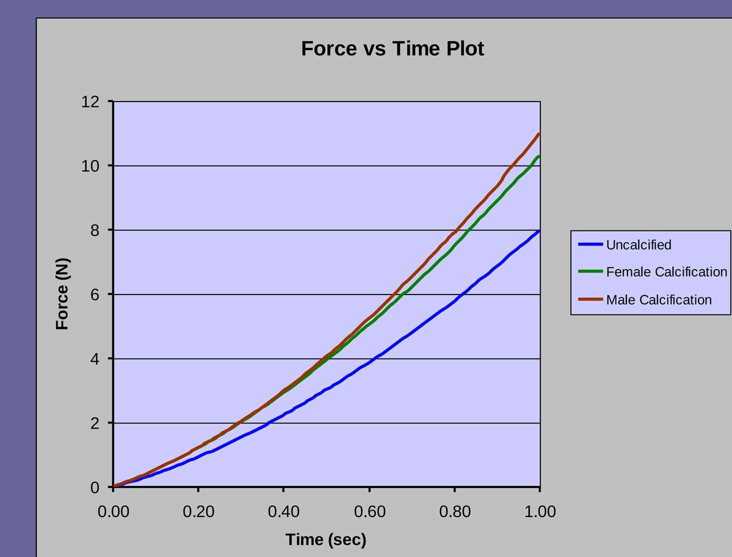
* Calcified cartilage volume divided by total original cartilage volume.

Table 2: Simulation Results

Maximum force (N)*	8	10.3	11

* Resultant force at the rib end after sternum displacement

Figure 2: Resultant Force Plot



DISCUSSION

Plots of resultant force at the costal border versus sternum displacement are shown in Figure 2. An increase of 28.8% was noted in the resultant force at 15 mm sternal displacement (compared to the control) when a female-pattern calcification was added to the model (Table 1). The male model showed a 37.5% increase in resultant force at 15 mm displacement despite containing a slightly smaller volume fraction of cartilage calcification than the female model. These simulations suggest that moderate degrees of calcification of both the male and female pattern have a stiffening effect on the structural behavior of the cartilage under this type of load. These results also suggest a possible gender-related dependence in the stiffening effect of calcification.

The stiffness of the costal cartilage influences the distribution of stress and strain throughout the ribcage. This load-distributing behavior may affect injury outcomes and prediction. Increased rib-sternum coupling caused by stiffer cartilage likely results in deformation of a greater number of ribs for a given exterior load. This may cause injuries in regions of the ribcage where none would otherwise occur. These effects may be exacerbated in an aging ribcage, where thinning of the rib bone cortical shell and a decrease in cortical bone failure strain may decrease the tolerance of the ribs to moderate deformations (Kent et al. 2005a).

The results presented here suggest that even moderate calcification of the costal cartilage may have an effect on the structural behavior of the costal cartilage. Although it may not be reasonable (due to limitations in mesh size) to distinctly model cartilage calcifications in whole-thorax FE models, (e.g., Kimpara et al. 2005) the structural effects of these calcifications should be considered when developing an aged model of the thorax. This may be accomplished by altering the material properties or the geometries of the model cartilages to attain a target effective cartilage structural behavior, determined either experimentally or with detailed FE modeling.

The study presented here uses a simplified representation of the costal cartilage, particularly in the material model utilized. Healthy costal cartilage is, however, believed to be relatively isotropic due to a random orientation of collagen fibrils (Hough et al. 1973, Hukins et al. 1976). Different cartilage geometries (e.g. different lengths of cartilage from the various ribs), different magnitudes of calcification, and variations in the patterns of calcification also likely affect the relationship between calcification and the structural behavior of the cartilage. This study suggests that further investigations into the structural effects of costal cartilage calcifications are warranted. Such further investigations may include parametric studies of the aforementioned geometric and material factors with refined finite element geometries and material models.

CONCLUSIONS

This study investigated the potential effects of moderate calcification on the structural behavior of a segment of fourth rib costal cartilage using a simple finite element model. The results suggest that moderate calcification of both a male-typical and female-typical pattern may considerably increase the force generated by deformation of the cartilage under boundary conditions approximating those that occur from concentrated mid-sternum, posteriorly-directed loading. These results suggest that computational models of the aging thorax should include provisions to model the structural effects of moderately calcified costal cartilage, and that further investigations into the structural effects of costal cartilage calcification are warranted.

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