INTRODUCTION

As the human body ages, it becomes increasingly prone to the effects of which can be seen in the rib cage (Kent, 2005a) and osteoarthritis. An increased susceptibility to thoracic deformity, in particular, has been observed among older people (Morris et al., 2002 and Kent, 2005b). One of the most striking age-related changes that occur in the costal region is calcification of the cartilage layer, which connects the rib bones to the sternum. Local calcifications can start to develop in the costal cartilage around the age of 20. Severe calcifications of the cartilage can occur as early as age 60 (McCormick, 1984). Costal calcification also exhibits gender-dependent patterns (McCormick, 1980, Stewart, 1986, Tietjen, 1989). Because the costal cartilage provides a major load path between the rib and the sternum, calcifications can affect the load distribution through the ribs. 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 costal 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 selected 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 0.4. Bone elements (rib, sternum, calcifications) were modeled with Young’s modulus of 20 GPa and Poisson’s ratio of 0.3. Typical of cortical bone. The model characteristics are summarized in Table 1.

Boundary conditions were chosen to represent those generated by a posteriorly directed, concentric load applied to the rib-end. In this type of loading, any symmetry constraints that remain (such that no lateral displacement or rotation occurs). This was represented in the simulations with posterior displacement of the sternum, with the external boundary constrained to allow no rotation or displacement other than the loading direction. Similarly, stiffness in the rib constraint the movement and rotation of the costal-chondral junction (Shaw et al., 2007). This was represented in the simulations by being at all degrees of freedom of the costal boundary. During the simulations, the sternum 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.

DISCUSSION

Plots of resultant force at the costal border versus sternum displacement are shown in Figure 3. An increase of 28% was noted in the resultant force at 15 mm internal 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 greater 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 rib cage. The load distributing behavior may affect injury outcomes and precision increased rib-osteolysis coupling caused by ultimate cartilage failure and results in deformation of a greater number of ribs for a given anterior 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 decreases in cortical bone later, which 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 strain) to directly model cartilage calcifications in whole-animal FE models, (e.g. Knappe et al., 2005) the structural effects of these calcifications should be.

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- and female-pattern pattern may considerably increase the force generated by deformation of the cartilage under boundary conditions approximating those that occur from concentrated mid-axial, 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. Additional research is needed to determine 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 mechanical studies of the biomechanical properties and material factors with refined finite element geometries and material models.

REFERENCES


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

Figure 2: Resultant Force Plot

Table 1: Simulation Parameters

Table 2: Simulation Results

Table 3: Simulation Results

Figure 3: Displacement vs Time Plot

Figure 4: Stress Distribution