Contributions of Material and Geometric Properties to Structural Response in Anterior-Posterior Loading of Human Ribs

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Thorax injuries, e.g. rib fractures, are common in motor vehicle crashes (MVC), leading to high morbidity and mortality rates. Numerical simulations of occupants in MVCs require precise computational models of the thoracic skeleton to accurately simulate response and assess injury risk. The goal of this study was to quantify contributions of rib material and geometric properties to structural response.

One 6th rib from 29 post---mortem human subjects were tested in dynamic anterior---posterior bending simulating frontal thoracic impact. Prior to impact, uniaxial strain gages were attached at 30% and 60% of the total curve length (Cv.Le) of the rib. After impact, peak strain was defined as maximum strain recorded immediately before fracture. From force vs. displacement curves, the following properties were calculated: linear structural stiffness (K), %X---displacement at fracture (δX), force at yield (FYld) and peak (FPEAK), and total energy (Utot). After testing, a section was removed adjacent to fracture location from which high---resolution microscopic images were taken. Cross---sectional geometric properties were calculated using custom MATLAB or ImageJ codes. Robusticity was calculated as total area normalized by Cv.Le, Cortical Thickness (Ct.Th) was measured at the principal axes, and whole bone strength index (WBSI) was calculated as section modulus normalized by Cv.Le.

To make direct comparisons between structural and material properties, twenty---nine 6th ribs from the contralateral side were utilized for cortical bone coupon tension testing at a matched strain rate. After testing, material properties, e.g., modulus, yield stress, yield strain (using 0.1% offset), ultimate stress, ultimate strain and strain energy density were calculated from stress vs. strain curves. Previous analysis on this sample suggested that material properties explained only a small amount of variance in structural properties

(Albert et al., 2017), so this research was expanded to include geometric properties.

Strong correlations were found between all geometric predictors ($p<0.001$), so only one of each was included for analysis. Multiple linear regression analysis was used to explore relative contributions of a material and geometric property to an analogous structural property. Results included the following relationships: modulus and robusticity contributed 6% ($p=0.061$) and 65% ($p<0.0001$) respectively, to K; yield stress and Ct.Th contributed 8% ($p=0.537$) and 45% ($p<0.0001$) respectively, to FYld; ultimate stress and robusticity contributed 11% ($p=0.014$) and 50% ($p<0.0001$) respectively, to FPEAK; ultimate strain contributed 32% ($p=0.003$) while both robusticity and Ct.Th had minimal contributions to peak strain in structural tests. Finally, strain energy density and Ct.Th contributed 48% ($p<0.001$) and 6% ($p=0.085$) respectively, to Utot.

These data reveal that geometric properties play a larger role in determining structural response to loading than material properties, except in strain and energy analyses. The amount of variance explained by the models has a large range (R2 = 20---67%) suggesting that additional predictors should be sought to further understand variability in rib behavior. Results from this study are crucial to advancing finite element human body models by improving the accuracy by which the material and structural properties of ribs are modeled and how they contribute to overall thoracic response and injury tolerance during MVCs.