Improved Predictions of Human Rib Structural Properties using Bone Mineral Content

Zac Haverfield MS RT(R), Randee Hunter PhD, Yun-Seok Kang PhD, Aditi Patel, Amanda Agnew PhD

Introduction
Motor vehicle crashes often result in rib fractures that are associated with high rates of morbidity and mortality, especially in older adults. Consequently, methods to assess rib bone quality are needed to increase the accuracy and sensitivity of identifying at-risk populations. Quantitative computed tomography (QCT) can identify variability in rib volumetric bone mineral density (vBMD) and may provide valuable information related to rib fracture risk. Further, incorporating the influence of bone size by utilizing bone mineral content (BMC) may improve predictions of rib structural properties. Therefore, the objective of this study is to determine if vBMD and BMC from QCT predict human rib structural properties and the influence of age and sex in these relationships.

Methodology
127 mid-level (5th-7th) ribs were obtained from post-mortem human subjects (PMHS) ranging in age from 22 to 108 years (59.2±19.9) and comprising of n=67 females (60.4±21.4 years) and n=60 males (57.8±18.2 years). QCT scans of each isolated rib were acquired at an in-plane resolution of 0.146mm and 0.671mm slice thickness. A true-axial 7.78mm³ volume of interest (VOI) at 50% of the rib curve length was segmented for subsequent analyses. vBMD was calculated from the VOI using a 960 Hounsfield unit threshold and the relative voxel area of each slice was then used to calculate BMC. Each rib was then dynamically tested (2m/s) to failure in a simulated frontal impact. Structural properties including peak force ($F_{\text{Peak}}$), percent displacement ($d_{\text{Peak}}$), linear structural stiffness (K), and total energy ($U_{\text{Tot}}$) were calculated.

Results
In the total sample, vBMD was a statistically significant predictor of $F_{\text{Peak}}$, $d_{\text{Peak}}$, K, and $U_{\text{Tot}}$ ($R^2 \leq 19.6\%$, $p<0.001$) but likely has little biomechanical or practical utility. However, BMC not only had a significant predictive relationship with all rib structural properties, but also explained a meaningful amount of variation ($R^2 \leq 68.7\%$, $p \leq 0.002$). While vBMD demonstrated no significant differences between sexes ($p>0.05$), males had a higher BMC than females ($p<0.001$). Age was found to have a significant relationship with both vBMD and BMC ($p<0.001$) for the total sample but only in females when separated by sex ($p<0.001$). In females and males, vBMD and BMC predicted all structural properties ($p<0.01$) with the exception of $d_{\text{Peak}}$ for males ($p>0.05$). Further, when controlling for sex and using age in the total sample, BMC better predicted all structural properties than vBMD except for $d_{\text{Peak}}$ where no differences were seen.

Conclusion
Accurate assessments of bone quality are crucial to distinguish factors that contribute to fracture resistance. Results from this study demonstrate that BMC better predicts rib structural properties than vBMD and isolates differences between sexes compared to vBMD. These findings are likely due to the normalization of bone size to the total volume of measured cortical bone in vBMD which may inhibit meaningful contributions when predicting of rib structural properties. Overall using BMC from QCT may improve assessments of rib fracture risk, compared to vBMD, and further aid rib fracture mitigation efforts within injury biomechanics research.