Geometric Properties of Human Ribs as Predictors of Structural Properties

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Abstract

Classification of structural properties of human bones is essential for understanding differential response to loading and fracture risk. Ribs, in particular, are frequently fractured during motor vehicle crashes and are linked to high mortality rates, especially in elderly individuals. While many studies describe variation of bone properties with respect to age and sex differences, these parameters explain only a small amount of variability in rib properties. Geometric properties can also have a significant effect on how a bone will respond to loading. The goal of this study is to investigate the ability of gross and cross-sectional geometric properties of human ribs to predict experimental structural properties.

A total of 122 complete mid-level ribs from 76 fresh post-mortem human subjects (15-99 years of age, 20 females, 56 males) were excised and their straight length (St.Le) and curve length (Cv.Le) were measured from head to costochondral junction. The ribs were tested in a custom-built pendulum fixture simulating a dynamic frontal impact to the thorax. Peak force (F) was defined as the maximum force in the primary loading direction prior to failure. Linear structural stiffness (K) was calculated as the slope of 20-80% of the elastic portion of the force-displacement curve. Sections were removed from mid-shaft of the rib and thin-sections were prepared. Cross-sectional microscopic images were obtained at 40x magnification with an Olympus VS120 slide scanner. Measurements were manually made in cellSens Dimension® imaging software to obtain total subperiosteal area (Tt.Ar) and cortical area (Ct.Ar). Section modulus was calculated for the pleural and cutaneous cortices independently (ZP and ZC, respectively) in ImageJ software using a customized macro.

Tt.Ar, Ct.Ar, and Z all have positive relationships with F and K. When considering only cross-sectional geometric values, F was best predicted by Ct.Ar (R2 = 0.63) and ZP (R2 = 0.65) and K was best predicted by Tt.Ar (R2 = 0.29) and ZP (R2 = 0.34). Robusticity, an index used to establish the relationship between longitudinal growth and transverse expansion, allows for the combination of gross and cross-sectional geometric parameters. This index was calculated in four ways: Tt.Ar/St.Le, Tt.Ar/Cv.Le, Ct.Ar/St.Le, and Ct.Ar/Cv.Le, and these variations were

individually evaluated in terms of their ability to predict F and K. Preliminary findings indicate that F is best predicted by Ct.Ar/Cv.Le (R2=0.65), but K is best predicted by Tt.Ar/Cv.Le (R2=0.52). Since linear structural stiffness takes overall geometry into account, the ability of Tt.Ar/Cv.Le to predict K could be attributed to Tt.Ar providing a better representation of the overall size and geometry of the rib. On the other hand, F, which is best predicted by Ct.Ar/Cv.Le, is more dependent on the area of bone bearing the majority of the load. By comparison, the variables utilizing St.Le were not as successful at predicting structural properties as those using Cv.Le.

Identifying accurate predictors of structural properties of ribs may improve the ability to assess fracture risk. Additionally, detailed cross-sectional properties can contribute to improved physical and computational models, injury criteria, and clinical assessments of bone fragility.