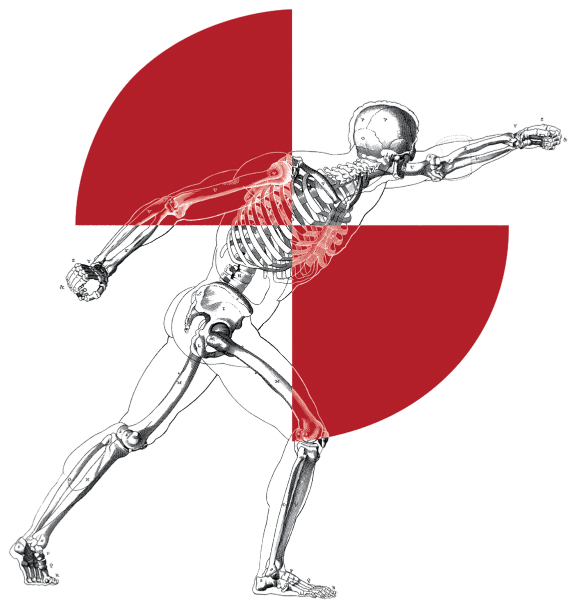

Robusticity in the Axial Skeleton: An example of the rib

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INTRODUCTION

- Skeletal robusticity, (total cross-sectional area relative to bone length) reflects the biological relationship between longitudinal growth and transverse expansion. Many have found robusticity to significantly covary with several morphological traits (e.g., cortical area) and tissue-level properties (e.g., porosity, cortical tissue mineral density) throughout the appendicular skeleton [1].
- These structural and material properties play a critical role in determining whole bone stiffness and strength, a direct reflection of the bone's ability to functionally adapt to its loading environment. However, the relationship among such traits has yet to be investigated in the axial skeleton.
- The goal of this study is to investigate the relationship between cortical area (Ct.Ar), section modulus (Z), and linear structural stiffness (K) and skeletal robusticity.

MATERIALS & METHODS

- 40 middle ribs (levels 5-8) from 40 fresh post-mortem human subjects 17-48 years of age (mean = 32.7, SD = 10.3 years) comprised of 9 females and 31 males were excised and measured to obtain Curve Length (Cv.Le) (Fig.1) and then impacted in a dynamic AP bending scenario. Linear structural stiffness (K) was calculated as the slope of the force-displacement curve for 20-80% of the elastic portion.

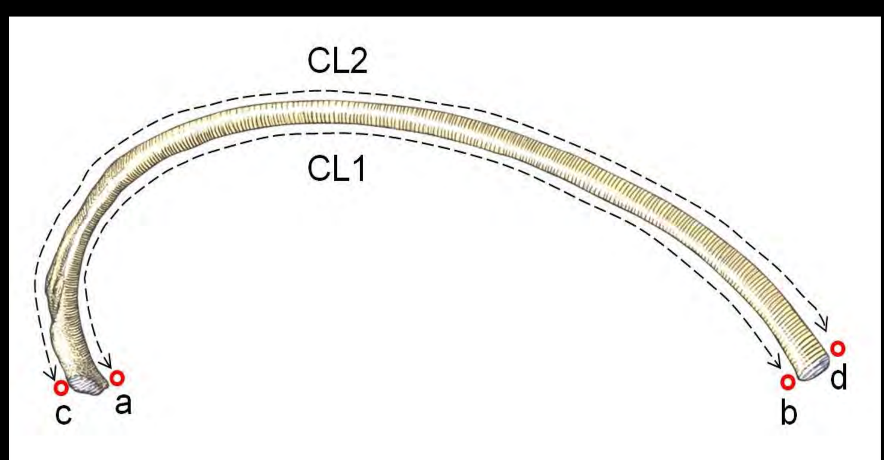
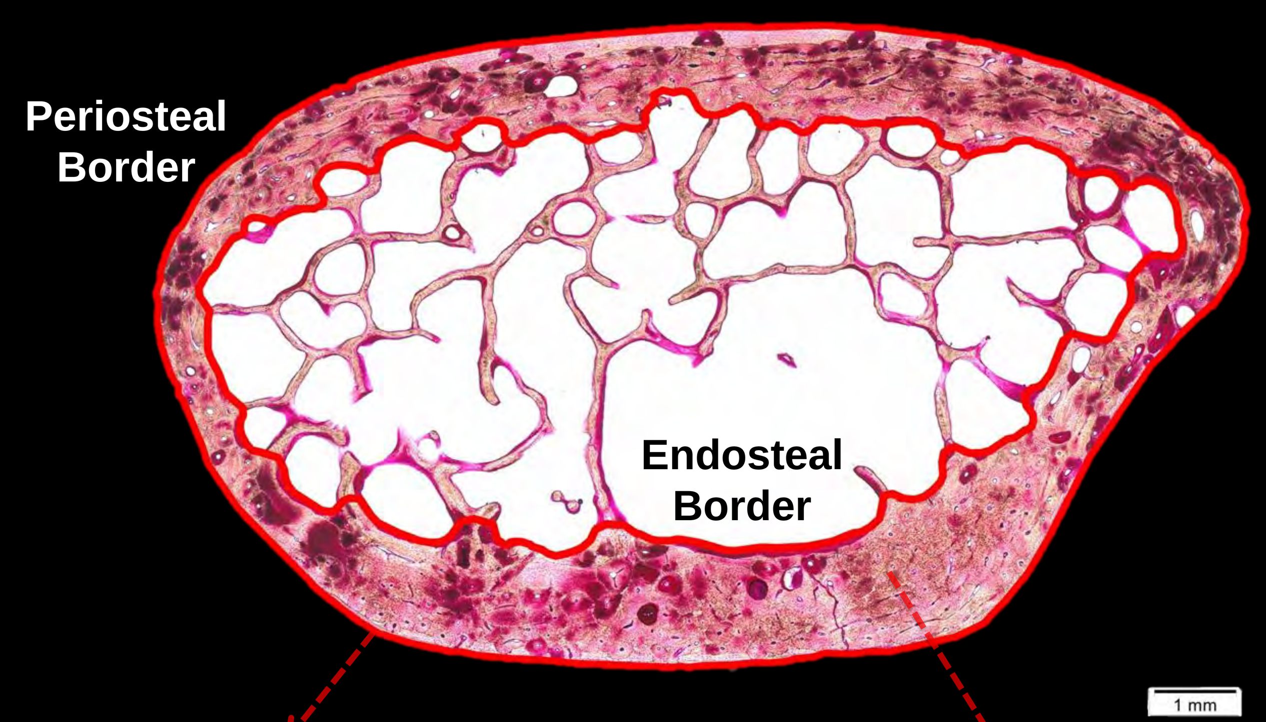


Fig. 1. CL1 (pleural Cv.Le) and CL2 (cutaneous Cv.Le) were measured and averaged to calculate Cv.Le.

- Sections were removed within the mid-shaft to explore cross-sectional properties, and rib thin-sections were prepared using standard histological procedures. Cross-sectional microscopic images were obtained at 40x magnification and measurements were taken in cellSens Dimension® imaging software and ImageJ (NIH) with a custom version of MomentMacro (Ruff, no date) to obtain Tt.Ar (total area), Ct.Ar, and Z, respectively (Fig. 2). Z values were calculated for the pleural (Z_{ple}) and cutaneous (Z_{cut}) cortices independently.
- Robusticity was calculated as Tt.Ar/Cv.Le. BM-Cv.Le was used as a proxy for body size and is defined as (Body Mass x Cv.Le)/100. All linear relationships were adjusted for Age and BM-Cv.Le via partial regression analysis.

Fig. 2a. Example of rib cross-section with cortical boundaries defined in red.



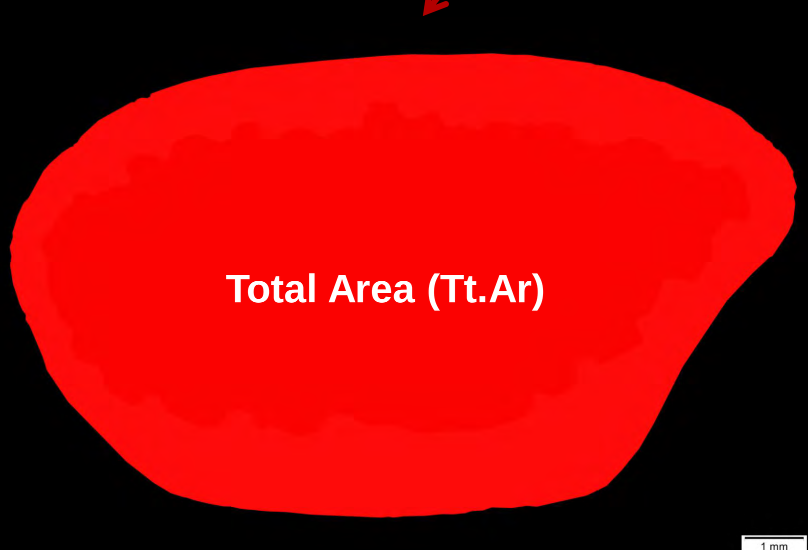


Fig. 2b. Tt.Ar of rib cross-section.

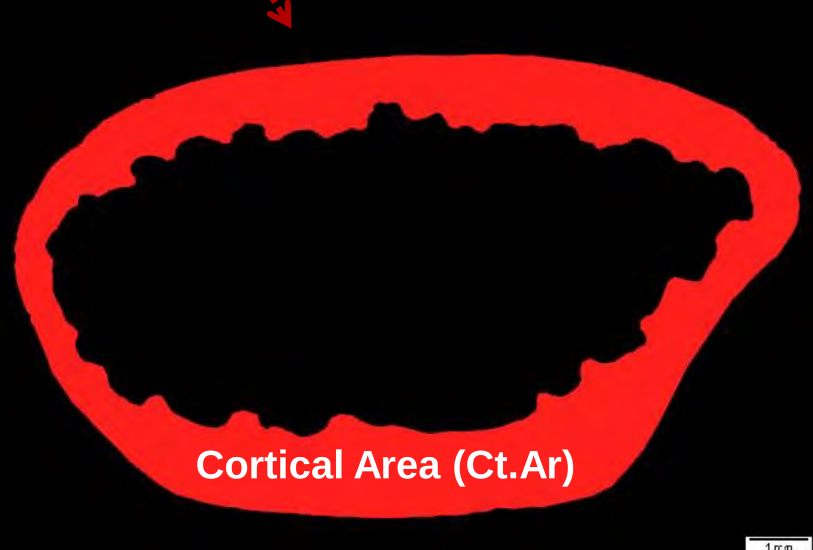


Fig. 2c. Ct.Ar of rib cross-section.

RESULTS & DISCUSSION

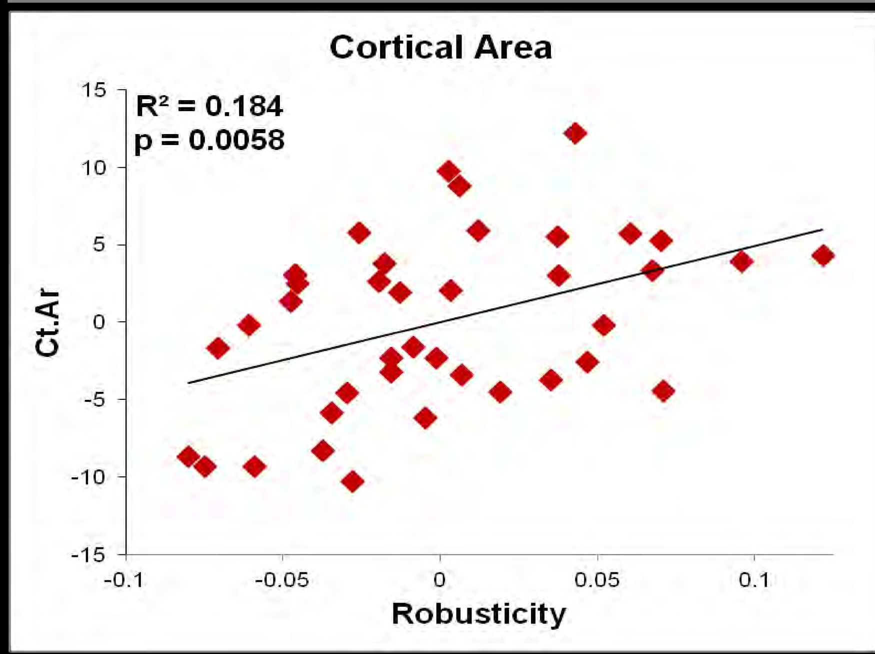


Fig. 3a. Robusticity v. Ct.Ar with the effects of BM-Cv.Le & Age removed.

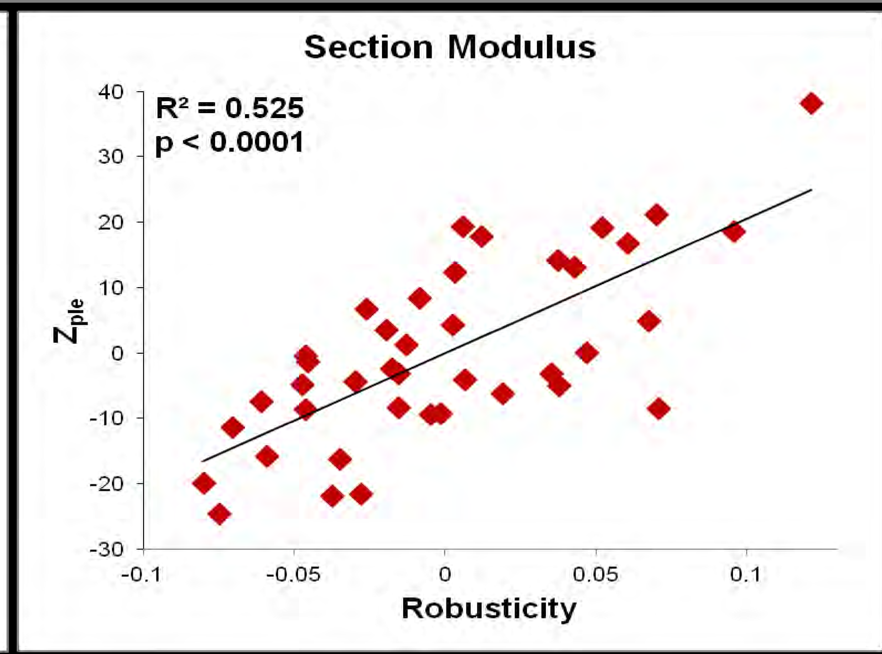


Fig. 3b. Robusticity v. Z_{ple} with the effects of BM-Cv.Le & Age removed. Z_{cut} has a similar result (R^2 = 0.432).

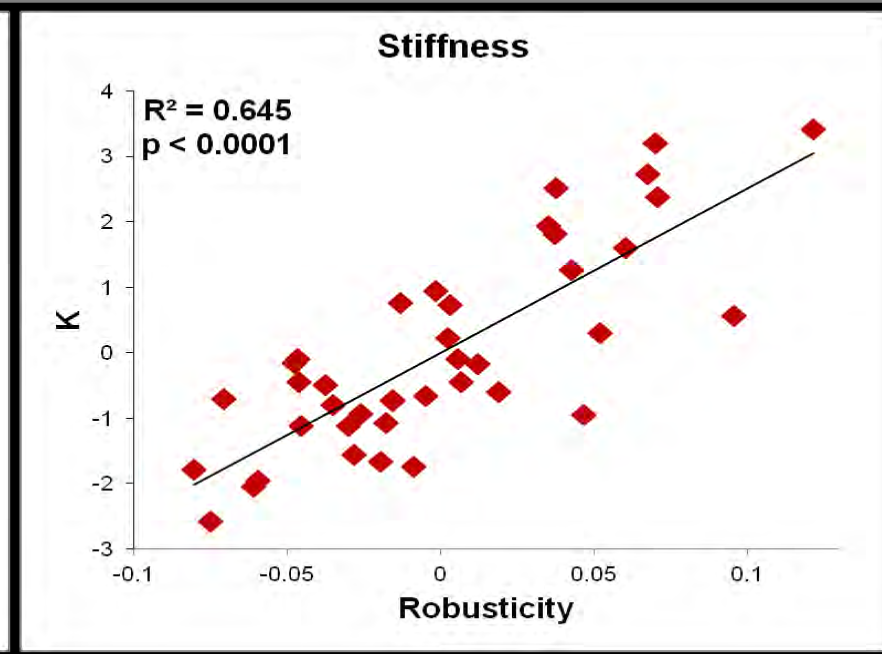


Fig. 3c. Robusticity v. K with the effects of BM-Cv.Le & Age removed.

- Fig. 3a highlights the positive relationship between Robusticity and Ct.Ar, which indicates that robust bones tend to have more tissue volume. Robusticity explains only 18.36% of the variation in Ct.Ar, indicating a large amount of inter-individual variation in Ct.Ar relative to Robusticity.
- Fig. 3b demonstrates the relationship between Robusticity and Z_{ple}. Section modulus has an inverse relationship with bending stress [2] and thus is an indicator of the ability of the bone to resist bending. The positive relationship indicates that robust bones have an increased resistance to bending, when compared to slender phenotypes.
- Fig. 3c shows the relationship between Robusticity v. K (measured directly from experimental testing). Robusticity was able to explain 64.53% of the variation in linear structural stiffness (K).
- The regressions in Fig. 3 were adjusted for Age and BM-Cv.Le to allow for comparison to previous analyses of the appendicular skeleton [1, 3], however the R^2-values for the rib only improve slightly with adjustment for Age and typically do not improve with adjustment for BM-Cv.Le. Since the calculation of BM-Cv.Le includes body mass, this variable should not have a large effect on the rib since it is not a weight-bearing bone. However, the long bones of the lower appendicular skeleton are weight-bearing and therefore have a strong dependence on body size index.
- For bones to be functional, they must maximize their stiffness while also minimizing their mass. The covariation of the skeletal traits shown here is largely responsible for this functional adaptation; however this process is not always perfect. With slender ribs being as much as 5 times less stiff than robust ribs, these data demonstrate a functional inequivalence.

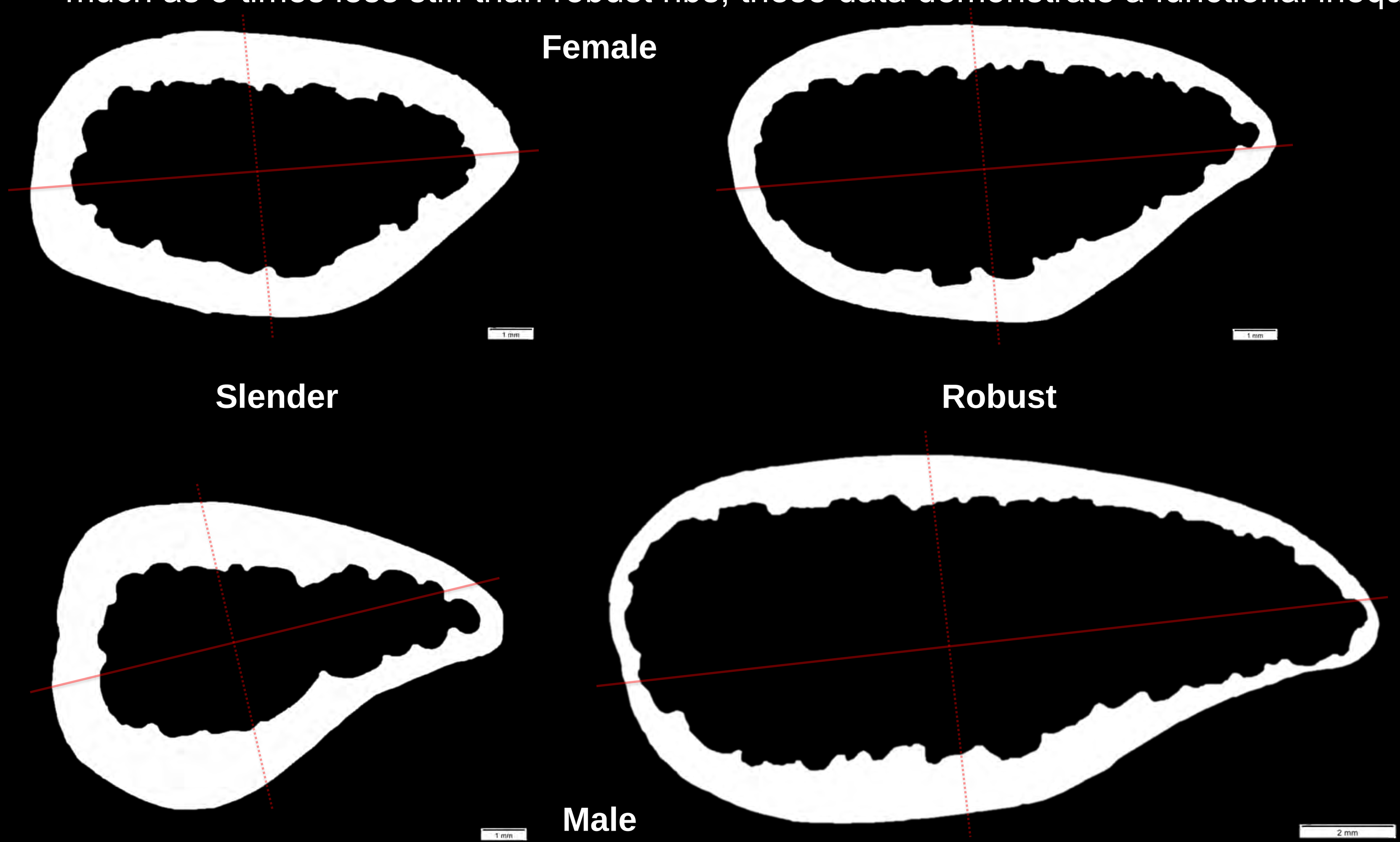


Fig. 4. Examples of the variation of traits of 4 individuals within the sample with principle bending axes in red.

- Visual differences in the cross-sectional properties of slender and robust ribs are shown in Fig. 4. Note the proportionally thicker cortices in the slender phenotypes versus the proportionally thinner cortices in the robust phenotypes. Fig. 4 demonstrates one example of functional compensation, as thicker cortices allow slender phenotypes to improve their resistance to bending. Robust phenotypes are able to have thinner cortices since the bone is distributed farther away from the centroid.
- These results indicate that slender ribs are constructed with less bone tissue and have less resistance to bending, as has been shown in long bones of the extremities [3]. This suggests that slender bones are at a functional disadvantage compared to robust bones and are therefore at a higher risk for fracture under extreme loading events (e.g. falls).

CONCLUSIONS

- This study is a critical preliminary step in understanding relations among skeletal traits as well as how these traits vary within an individual, which will improve the overall understanding of adaptation to functional demands in the human axial skeleton. The impact of these findings is important in anthropology and biomechanics and can also be useful in clinical studies for improved assessment of bone fragility and fracture risk. Future work will incorporate tissue-level properties into further analyses, since they could be a source of functional compensation.

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