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Rib Geometry Explains Variation in Dynamic Structural Response: Potential Implications for Frontal Impact Fracture Risk

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Abstract

The human thorax is commonly injured in motor vehicle crashes, and despite advancements in occupant safety rib fractures are highly prevalent. The objective of this study was to quantify the ability of gross and cross-sectional geometry, separately and in combination, to explain variation of human rib structural properties. One hundred and twenty-two whole mid-level ribs from 76 fresh post-mortem human subjects were tested in a dynamic frontal impact scenario. Structural properties (peak force and stiffness) were successfully predicted ($p < 0.001$) by rib cross-sectional geometry obtained *via* direct histological imaging (total area, cortical area, and section modulus) and were improved further when utilizing a combination of cross-sectional and gross geometry (robusticity, whole bone strength index). Additionally, preliminary application of a novel, adaptive thresholding technique, allowed for total area and robusticity to be measured on a subsample of standard clinical CT scans with varied success. These results can be used to understand variation in individual rib response to frontal loading as well as identify important geometric parameters, which could ultimately improve injury criteria as well as the biofidelity of anthropomorphic test devices (ATDs) and finite element (FE) models of the human thorax.

Keywords

Thorax; Rib; Cross-sectional geometry; Robusticity; Fracture risk; Stiffness

INTRODUCTION

The human thorax is commonly injured in motor vehicle crashes (MVCs), in which harmful loads can be applied to the chest resulting in rib fractures.^{20,26} Rib fractures are often

considered indicators of trauma severity, because the greater the number of fractured ribs, the higher the mortality and morbidity rates.^{10,20} Despite advancements in occupant safety, rib fractures are still highly prevalent in MVCs.^{18,26} In order to improve vehicle occupant protection against thoracic injuries, researchers are continually striving to make improvements to anthropomorphic test devices (ATDs) and finite element (FE) models of the human thorax. The biofidelity of these tools can be improved using specific data regarding the geometry, structural, and material properties of human ribs, as the ribs are the primary load bearing components of the thorax in a frontal collision. Many researchers have attributed variation in thorax and rib properties to age and sex, however these variables only explain a trivial amount of variation in individual rib properties and are poor predictors of rib response and injury.^{1,15,30}

Both cross-sectional and gross geometry of the rib may play a crucial role in determining the rib's response to loading.^{6,7,15} Charpail *et al.*⁶ tested whole mid-level ribs from five individuals in a dynamic bending scenario and found a relationship between mineral linear density (an index which represents rib bone quality and gross geometry by dividing ash weight by total curve length) and several mechanical properties: maximum displacement, peak force, stiffness, and work to fracture. Cormier *et al.*⁷ and Kemper *et al.*¹⁵ each conducted 3-point bending tests on variable locations of rib sections from four and six subjects, respectively, and found differences in structural properties to coincide with changes in cross-sectional geometry. Due to the limited number of subjects used in previous experimental studies, the applicability and predictive ability of rib geometry and structural properties could not be confidently quantified. However, many studies using FE models to investigate the mechanical response of human ribs have found that both cross-sectional and gross geometry are important determinants for how the model will behave.^{11,19,27}

Several indices that incorporate cross-sectional and gross geometry have been applied to long bones of the appendicular skeleton. Skeletal robusticity (total cross-sectional area relative to bone length) reflects the biological relationship between transverse expansion and longitudinal growth of bones.¹³ Robusticity varies along a biological continuum with individuals with bones tending to have a narrow cross-sectional diameter characterized as being slender and those with bones tending to have a wide cross-sectional diameter characterized as being robust. Robusticity has been shown to be sufficient in predicting whole bone stiffness and strength, and also has been shown to have a significant relationship with porosity, cortical tissue mineral density, and tissue modulus, which coordinately adjust in a predictable manner to mechanically offset variation in robusticity (external bone size).^{9,12,13,32} For example, slender bones have larger cortical thickness values and tissue mineral density with less intracortical porosity compared to more robust bones.^{31,32} Therefore, there appears to be a compensatory mechanism in place to maintain normal whole bone function.

Robusticity has also been widely investigated in terms of functional inequivalence; for bones to function, they must be sufficiently strong and stiff to tolerate repeated loading incurred on a daily basis. However, two individuals of similar body sizes can acquire different long bone morphologies, resulting in either slender or robust bones throughout their appendicular skeleton, leading to a disparity in the ability of bones to resist fracture.^{12,31} For example,

Schlecht *et al.*³¹ found that slender bones could be up to 2.8 times less stiff and strong for their body size when compared to robust bones.

Another index that incorporates cross-sectional and gross geometry, whole bone strength index (WBSI), is calculated using section modulus (Z) relative to bone length. A study by Armstrong *et al.*² used WBSI to investigate stress fractures in tibiae of a military population and found the WBSI of subjects that developed stress fractures to be significantly lower than that of the group that did not, suggesting that WBSI plays a role in determining fracture risk. Although both robusticity and WBSI have been shown to be useful in prediction of structural properties of long bones of the appendicular skeleton, applications of these mixed geometric variables have yet to be investigated in the axial skeleton, e.g., the rib.

The objective of this study was to quantify the ability of gross and cross-sectional geometry (as well as their combination) to explain variation on measured structural properties in whole human ribs. Furthermore, the possibility of obtaining such geometry from clinical computed tomography (clinCT) was explored.

MATERIALS AND METHODS

Experimental Sample and Specimen Preparation

One hundred twenty-two mid-level ribs from 76 fresh PMHS (20 females, 56 males) were experimentally impacted and analyzed in this study. Subject ages ranged from 15 to 99 years, with a mean age of 50.9 ± 24.5 years. All ribs were acquired through The Ohio State University's Body Donation Program or Lifeline of Ohio, and all ethical requirements were met, including informed consent for research. After procurement, ribs were wrapped in normal saline-soaked gauze and stored at -20°C until testing. Prior to testing, ribs were thawed, all external soft tissue was removed, and total curve length (Cv.Le) of each rib was manually measured from head to costochondral junction (Fig. 1) with a soft measuring tape. Rib ends were potted in Bondo® Body Filler (Bondo Corporation, Atlanta, GA) prepared such that the curing temperature was not greater than approximate body temperature to eliminate the risk of subsequent tissue damage. Four strain gages (Vishay Micro-Measurement, CEA-06-062UW-350, Shelton, CT) were applied to the cutaneous and pleural surfaces of each rib at 30 and 60% of Cv.Le to detect time of fracture. Special care was taken to ensure that ribs remained hydrated with normal saline throughout preparation and testing.

Experimental Testing

Ribs were tested in a custom-built pendulum fixture simulating a dynamic frontal impact to the thorax in which the sternal end of the rib was linearly translated toward the vertebral end, creating a two-dimensional (2D) bending scenario. A 54.4 kg pendulum impacted ribs at an average velocity of 1–2 m/s. The two potted ends of the ribs were allowed to rotate freely about the primary bending axis (Z) as defined by SAEJ211²⁹ (Fig. 1).

Displacement of the sternal end of the rib was measured by a linear string potentiometer (AMETEK, Rayelco P-20A, Inc. Berwyn, PA) attached to the moving plate of the fixture. Forces and moments were recorded by a 6-axis load cell (Humanetics, CRABI neck load

cell, IF-954, Plymouth, MI) located behind the fixed plate, however only forces in the primary loading direction (X) were analyzed in this study. Peak force (F_{PEAK}) 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.¹ Force and displacement data were filtered using a CFC180 filter,²⁹ and detailed descriptions of the test set-up, data treatment, and variable definitions can be found in Agnew *et al.*¹ and Schafman *et al.*³⁰

Post-Test Processing

After testing, a one cm segment was removed from mid-shaft of each rib (30–70% of Cv.Le) at fracture location, cleaned of soft tissue, and embedded in methylmethacrylate. One thick-section ($\sim 100 \mu m$) was cut and mounted on a slide according to standard histological procedures, and a cross-sectional image was obtained at $\times 40$ total magnification with an Olympus VS120 slide scanner, resulting in an image with a resolution > 580 pixels/mm. Periosteal and endosteal cortical borders were manually delineated in cellSens Dimension[®] imaging software (Olympus Corporation) and confirmed by an experienced histomorphologist (AMA) to obtain total subperiosteal area (Tt.Ar) and cortical area (Ct.Ar) (Fig. 1). Histological images are the gold standard for cross-sectional geometry because they have a very high image resolution compared to any other modalities and measurements are made *directly* (*D*) from the physical specimen, whereas other imaging modalities (e.g., computed tomography) require data reconstruction *via* linear interpolation between axial slices to create a meaningful image, and are therefore *indirect* (*I*) in nature. Rib robusticity was defined as:

$$\text{Robusticity} = \frac{\text{Tt. Ar}}{\text{Cv. Le}} \quad (1)$$

with the slender population defined as 10th percentile of the robusticity distribution and the robust population as 90th percentile.³¹

Cross-sectional images were oriented to replicate the rib orientation during testing, i.e., cutaneous cortex superior to pleural cortex (Figs. 1 and 2). Since the rib was confined to bending about the Z-axis of the cross section during the experiment (Fig. 2), a customized ImageJ macro was created in order to calculate the area moment of inertia with respect to the Z-axis of the cross-sectional image (I_z):

$$I_z = \int_A y^2 dA \quad (2)$$

where y is the distance of each differential area element (dA), i.e., pixel, to the z -axis (Fig. 2). The cutaneous section modulus (Z_{CUT}) was calculated using the distance from the neutral axis to the surface of the cutaneous cortex (CutRad):

$$Z_{\text{CUT}} = \frac{I_z}{\text{CutRad}} \quad (3)$$

The pleural section modulus (Z_{PLE}) was calculated using the distance from the neutral axis to the surface of the pleural cortex (PleRad):

$$Z_{\text{PLE}} = \frac{I_z}{\text{PleRad}} \quad (4)$$

Whole bone strength index (WBSI) was calculated using each of two cortex-specific formulations of Z :

$$\text{WBSI}_{\text{CUT}} = \frac{Z_{\text{CUT}}}{\text{Cv. Le}} \quad (5)$$

$$\text{WBSI}_{\text{PLE}} = \frac{Z_{\text{PLE}}}{\text{Cv. Le}} \quad (6)$$

Regression analysis on a larger dataset, which included the data from this study, found that age and sex did not capture a large amount of variation in the structural properties of human ribs.^{1,30} Previous work focusing on a subsample of the data presented here found that relationships between geometry and structural properties only slightly improved or did not improve when age and body size (body mass $\times$ Cv.Le) were controlled for.²³ Therefore, for this study all statistics were performed on data unadjusted for age, sex, or body size. A univariate multi-level mixed model was utilized to evaluate the ability of cross-sectional and gross geometry to explain variation in the structural properties of whole human ribs. This model was chosen to account for non-independence of data points, since a varying number of ribs from each subject were tested. A pseudo- R^2 ($p\text{-}R^2$) value was used to represent the ability of the independent variable to explain the amount of variance in the dependent variable.³³ For a detailed description of application of the statistical model to similar data, see Agnew *et al.*¹ and Schafman *et al.*³⁰

Clinical Computed Tomography

In order to investigate the possibility of measuring rib geometry (cross-sectional and the combination of gross and cross-sectional, i.e., mixed) from standard clinical computed tomography (clinCT), a sub-sample of ribs from the total sample ($n = 19$ ribs from 7 PMHS) was selected for which there existed both a midshaft histological cross-sectional image and clinCT images from the intact PMHS prior to rib removal. PMHS were scanned on a GE Medical Systems LightSpeed CT scanner, and scans were acquired and reconstructed at the minimum available slice thickness of 0.625 mm. OsiriX© MD, a commercial DICOM viewer and processing software, was used to make geometric measurements. A multi-plane

reconstruction (MPR) was rendered to view the rib in a single thick slab plane, since ribs are obliquely oriented to any standard anatomical view. MPR allowed for inclusion of the entire length of the curvature of the rib within a single oblique slice. Cv.Le was measured using the open polygon function to construct a smoothed contour along the medullary cavity of the rib from the costovertebral junction at the rib head to the costochondral joint (Fig. 3).

A cross-sectional viewing plane for each rib was rendered at the precise location along the Cv.Le where the histological section was taken, perpendicular to the local rib curvature. This plane view was exported to MATLAB as a single 16-bit DICOM image (pixel spacing 1.28 pixels/mm). A custom algorithm allowed for Tt.Ar to be measured at every Hounsfield unit (HU) threshold between 100 and 700 HU, which is used to determine a boundary between bone and soft tissue. Special attention was given to previously published HU threshold values for calculation of rib bone areas including 226 HU²⁷ and 452 HU,²⁷ as well as 500 HU.¹⁹

Additionally, a novel method of measuring cross-sectional geometry, hereafter referred to as the Adaptive Thresholding Technique (ATT), was created in order to overcome the pixel spacing limitation of clinCT, e.g., clinCT scans typically have an in-plane resolution of ~1 mm/pixel, whereas the cortical thickness of human ribs ranges from 0.5–2 mm.^{22,27} Grounded in the assumption that relatively large pixel spacing of clinCT systematically overestimates cortical thickness of human ribs,²⁷ this new approach was intended to produce the smallest possible cortical area while still retaining a complete cortical shell. Figure 4 illustrates how ATT utilizes the relationship of Tt.Ar values for each HU value to detect the maximum possible threshold at which the cortical shell remains continuous. The adaptive threshold (AT) can be observed qualitatively, where the unique HU threshold for any given sample occurs immediately prior to a distinct decline in measured area, which represents the value resulting from an incomplete cortical shell (Fig. 4).

ANOVA was used to evaluate five different methodologies used to calculate Tt.Ar (three different HU thresholds from literature, ATT, and histologically). Percent errors were calculated for indirect (*I*) measurements of rib geometry i.e., cross-sectional geometry measured from clinCT (*I*Tt.Ar., *I*Ct.Ar., *I*Z_{PLE}, and *I*Z_{CUT}), gross geometry measured using clinCT (*I*Cv.Le), and the combination of the two (*I*Robusticity, *I*WBSI_{PLE}, and *I*WBSI_{CUT}) compared to direct (*D*) measurements of rib geometry i.e., cross-sectional geometry measured histologically (*D*Tt.Ar., *D*Ct.Ar., *D*Z_{PLE}, and *D*Z_{CUT}), gross geometry measured manually during the experiment (*D*Cv.Le), and the combination of the two (*D*Robusticity, *D*WBSI_{PLE}, and *D*WBSI_{CUT}).

RESULTS

Table 1 contains descriptive statistics for the sample, while Table 4 (Appendix) provides rib-specific data, for directly measured geometric variables and structural properties of all 122 ribs tested in the experimental bending scenario. Because robusticity is a variable of considerable interest and is used extensively to predict mechanical properties in other bones,^{12,31,32} a normal probability distribution of rib robusticity is provided in Fig. 5 with examples of slender and robust cross sections.

The mixed model results for the prediction of peak force (F_{PEAK}) and structural stiffness (K) by *directly* measured geometric variables can be found in Table 2. The model indicates the fixed effect for each geometric variable on each structural variable is statistically significant ($p < 0.001$). Figure 6 includes scatterplots to highlight positive relationships between different geometric variables and F_{PEAK} . Tt.Ar explained 35% of the variance in F_{PEAK} (Fig. 6a), and calculations of Z (Fig. 6c) explained a similar amount of variation in F_{PEAK} to that of Ct.Ar ($p-R^2 = 0.67$ for Z_{PLE} and Ct.Ar, $p-R^2 = 0.66$ for Z_{CUT}). Figures 6b and 6d highlights the improvement in predictive ability when mixed geometry is used: the $p-R^2$ value increased from 0.35 for Tt.Ar alone to 0.38 for robusticity (Tt.Ar/Cv.Le), and from 0.67 for Z_{PLE} alone to 0.75 for $WBSI_{PLE}$. Both calculations of $WBSI$ were able to explain more of the variation in F_{PEAK} ($p-R^2 = 0.75$ and 0.74) than robusticity ($p-R^2 = 0.38$).

Figure 7 includes scatterplots to highlight positive relationships between geometric variables and structural stiffness, K . Tt.Ar explained more variation in K ($p-R^2 = 0.44$; Fig. 7a) than Ct.Ar ($p-R^2 = 0.26$). Both calculations of Z explained a similar amount of variation in K to that of Tt.Ar ($p-R^2 = 0.49$ for Z_{PLE} and $p-R^2 = 0.43$ for Z_{CUT}). Figures 7b and 7d highlights the large improvement in predictive ability when mixed geometry is used: the $p-R^2$ value increased from 0.44 for Tt.Ar alone to 0.68 for robusticity, and from 0.49 for Z_{PLE} alone to 0.64 for $WBSI_{PLE}$. Robusticity was able to explain more of the variation in K ($p-R^2 = 0.68$) when compared to both calculations of $WBSI$ ($p-R^2 = 0.64$ and 0.58). Overall, $WBSI$ is the best predictor of F_{PEAK} ($p-R^2 = 0.75$) and K is best predicted by robusticity ($p-R^2 = 0.68$).

Tt.Ar measurements from clinCT (I Tt.Ar) and histological images (D Tt.Ar) were compared for each rib in the subsample (Table 3). Significant differences were found between direct (D) and indirect (I) methodologies of calculating Tt.Ar (ANOVA, $p = 0.018$; Fig. 8). Figure 8 shows the clinCT (*Indirect*) methods, especially at 226 HU, overestimate Tt.Ar when compared to the histological image (*Direct*). Although 452 and 500 HU have similar means to D Tt.Ar, these thresholds often create incomplete cortical shells (Fig. 4), and therefore I Tt.Ar could not be calculated (Table 3). Since the ATT produced a mean I Tt.Ar that was closest to the mean of D Tt.Ar (considered the gold standard) and I Tt.Ar could be calculated for all the ribs in this subsample using ATT, I Tt.Ar from ATT was the only methodology further compared to D Tt.Ar. In making this comparison, percent errors ranged from -7.6 to 31.6 (absolute value mean = $7.4 \pm 7.7\%$). When incorporating Tt.Ar values into robusticity calculations and therefore comparing I Robusticity to D Robusticity, percent errors ranged from -17.4 to 19.2 (absolute value mean = $9.1 \pm 5.2\%$).

Of the four methodologies investigated for calculating Tt.Ar from clinCT, ATT produced the least amount of error (less than 10% when compared to D Ct.Ar), so an attempt was made to measure I Ct.Ar using the same method. The comparison between I Ct.Ar and D Ct.Ar yielded unacceptably large percent errors ranging from 6.5 to 202.4% (mean = $71.0 \pm 45.3\%$), indicating a consistent gross overestimation of Ct.Ar when utilizing ClinCT. Since calculation of D Z_{PLE} and D Z_{CUT} also require an accurate definition of cortical boundaries and any errors in their definition would only be further compounded (Eq. 2), I Z, and therefore I WBSI, calculations were not attempted from cross-sectional clinCT images.

DISCUSSION

Rib geometry, both cross-sectional and the combination of the gross and cross-sectional, was found to be important for explaining variation in experimentally measured structural properties. All variables investigated in this study successfully predicted peak force (F_{PEAK}) and linear structural stiffness (K) and all relationships were significant and positive, indicating that ribs with greater cross-sectional properties and those that are more robust or have a higher WBSI are stiffer and able to withstand higher forces (Figs. 6 and 7).

Despite all relationships being statistically significant, the ability to explain variation in structural properties varied, as evidenced by pseudo- R^2 values. When comparing simple cross-sectional geometry to the combination of gross and cross-sectional geometry, there is only a slight improvement in $p-R^2$ values for the prediction of F_{PEAK} (Fig. 6), indicating that cross-sectional geometric properties is most important for the prediction of the maximum force a rib can withstand prior to fracture. However, cross-sectional geometry alone may not be sufficient to describe the variability in K . Incorporating gross geometry into analyses with the calculation of robusticity and WBSI improved the ability to predict K compared to cross-sectional geometry by over 20% in some cases (Fig. 7), indicating K is highly dependent on the overall size and shape of the cross section of the rib.

Trends reported here for cross-sectional geometry and structural properties are comparable with those reported in other studies. Cormier *et al.*⁷ tested rib samples in three-point bending and found significant differences in mechanical properties with respect to cross-sectional area, moment of inertia, and distance from the centroid to the cortex. Results highlighted positive relationships between cross-sectional and mechanical properties similar to those shown here, but trends were weak. Kemper *et al.*¹⁵ also investigated geometric, material, and mechanical properties from tension and bending tests and found no significant differences with respect to material properties, but that changes in structural response were accompanied by significant changes in cross-sectional area, distance from the neutral axis to cortex (analogous to CutRad and PleRad), moment of inertia, inverse section modulus, and radius of gyration.

Mixed geometry (i.e., the incorporation of cross-sectional and gross geometry) had yet to be investigated in the rib and therefore presented the initial challenge of how it should be defined in the axial skeleton. The cross-sectional geometry used in the calculation of robusticity and WBSI (i.e., Tt.Ar, Ct.Ar, and Z) can be measured using the same methodologies for ribs as is commonly employed for long bones, however the same is not true for gross geometry. In long bones, a linear measurement is used to measure total bone length, reflecting the overall size of the bone. Because of the unique morphology of ribs, Cv.Le was chosen to best reflect their gross size (Fig. 1) in the calculation of robusticity (Eq. 1).

Although measured slightly differently, relationships between robusticity and WBSI and structural properties are similar to those seen in the appendicular long bones. Jepsen *et al.*¹² found that individuals with robust tibiae for their body size had a stiffer bone that was better able to resist fracture, which parallels the results found here indicating that robusticity is

important for predicting fracture risk for all bones and is not limited to the appendicular skeleton. Armstrong *et al.*² found that on average the WBSI of subjects that developed stress fractures was significantly lower than that of the group that did not develop stress fractures when examining a military cohort. The positive and strong relationships found between WBSI and structural properties in this study ($p\text{-}R^2 = 0.75$ & 0.64 for F_{PEAK} and K , respectively) compliment the results found by Armstrong *et al.*² and indicate that WBSI is also important for understanding variation in fracture risk.

For bones to be functional, they must maximize their stiffness while also minimizing their mass.³² *Post-hoc* Pearson correlation analysis revealed a positive relationship between robusticity and cortical area ($r = 0.40$), indicating that slender ribs are constructed with less bone tissue and are therefore at a functional disadvantage and may be indicative of higher fracture risk. Figure 5 shows the distribution of robusticity values found in this study, with slender ribs defined as those beneath the 10th percentile and robust ribs as those above the 90th percentile (also see Table 4). When averaging the stiffness within these two distinct groups, robust ribs were approximately 4.4 times as stiff as their slender counterparts, demonstrating the functional inequivalence of slender ribs. Schlecht and colleagues³¹ found that slender long bones (femur, tibia, humerus, radius, and 2nd metacarpal) ranged from 1.3 to 2.8 times less stiff when compared to robust long bones. The larger disparity found in this study compared to Schlecht *et al.*³¹ could potentially be attributed to differences in adaptation of the appendicular and axial skeleton to different loading environments, differences in mechanical testing protocols used, or the more extreme curvature of the rib compared to the appendicular long bones. Additional work is needed to explore these interpretations further to determine if the functional mechanism present in both the axial and appendicular skeleton are equivalent to one another.

Figure 5 includes two representative rib cross sections examined in this study: one from a slender rib (left) and one from a robust rib (right). Qualitative observation suggests there are proportionally thicker cortices in the cross section of the slender phenotype and proportionally thinner cortices in the cross section of the robust phenotype. *Post-hoc* Pearson correlation analysis revealed a negative relationship between robusticity and cortical thickness ($r = 0.45$), which demonstrates an example of slender ribs attempting to compensate for the functional disadvantage, as thicker cortices allow for slender phenotypes to improve their ability to resist loading. However, since slender ribs were approximately 4.4 times less stiff than robust ribs, it is evident that the proportionally thicker cortices are in themselves not enough to overcome the functional disadvantage and thus represent a population at a higher risk for fracture in the dynamic loading conditions imposed in this study. However, future work will aim to determine if tissue mineral density and associated material properties adjust to partially offset the structural disadvantage of slenderness, as others have shown to occur in the appendicular long bones.^{12,13,31,32}

Although histological analysis of cross-sections is considered the gold standard, the method for obtaining these images requires destructive processes. ClinCT is extremely low resolution compared to histology, but allows for reconstruction of cross-sectional images without destruction of bone. However, due to the small size of rib cross-sections, clinCT often grossly over-estimates their cross-sectional geometry when standard thresholding

techniques are used.²⁷ Furthermore, utilization of clinCT to obtain cross-sectional geometry of ribs presents the unique challenge of obtaining transverse images which are oblique to standard anatomical planes. Due to necessarily large slice thickness and pixel spacing, the resulting oblique images from MPR require linear interpolation in order to acquire a cross-sectional image, introducing further error into measurements.

Utilizing existing and standardized approaches for HU thresholding applied across the sample proved to be ineffective for accurate identification of the rib's periosteal border and therefore calculation of Tt.Ar from standard clinCT data (*I*Tt.Ar). Similarly, Perz *et al.*²⁷ found that clinCT overestimated Tt.Ar and Ct.Ar by over 100% when compared to microCT, which parallels percent errors found in this study. Calculating *I*Tt.Ar through the use of the adaptive threshold technique (ATT) was the most successful when the values were compared to *D*Tt.Ar because no data points were eliminated and it resulted in the least amount of error when compared to the other methodologies for calculating *I*Tt.Ar. Based on the poor (yet standard) resolution of clinCT scans, it was expected that Tt.Ar would be consistently overestimated by clinCT (even with ATT) when compared to *D*Tt.Ar, however this was not the case (Table 3). Although there was greater error in the positive direction, there were several ribs in which *I*Tt.Ar was less than *D*Tt.Ar. Although ATT holds promise, caution should be utilized when applying this method because the resolution of the scans utilized for this study were the highest that clinCT of the entire thorax can currently offer and still provided relatively erroneous results.

Future work will seek to increase the sample size in order to investigate the effects of rib angle with respect to standard anatomical and transverse image acquisition planes as well as explore causes for variation in scan resolution to better understand the source of error when measuring *I*Tt.Ar. The ability to confidently measure Tt.Ar and robusticity from standard clinCT could allow for estimation of an individual rib's ability to resist fracture independent of experimental testing, given the correlations obtained in this study. Future applications will involve screening of test subjects prior to testing to predict their vulnerability to rib fracture and therefore, thoracic injury risk. Additionally, if validated, this approach could allow investigation of these variables in a living population.

Overall, WBSI served as the best predictor of F_{PEAK} and a strong predictor of K. However, use of WBSI is limited in that it cannot be confidently calculated from clinCT scans due to the lack of resolution preventing the ability to obtain accurate cortical boundaries, particularly at the endosteal border. On the other hand, robusticity (which only utilizes Tt.Ar) was the best predictor of K ($p-R^2 = 0.68$), and may be able to be calculated from clinCT scans if ATT is used, but explains less than 50% of the variation in F_{PEAK} , and therefore should be utilized with caution for explaining force values.

The results of this study are a critical first step in the investigation of the influence of rib geometry on structural properties, but limitations exist. Geometric variables were not explored with respect to age or sex in the current study, nor were ages and sexes equally represented in the sample, so some bias may exist particularly when considering the differential remodeling rates between aging males and females. However, on a similar dataset Agnew *et al.*¹ and Schafman *et al.*³⁰ showed that age and sex explain only a small

amount of variation in F_{PEAK} or K , and suggested more biologically relevant variables be explored to identify the source of variation in structural properties. The remaining unexplained variance could be due to material property differences between individuals, which may be reflected in quantifiable changes in rib microstructure⁸ and will contribute to further work in a broader research effort by the authors.

Due to the large sample size of this study, the results presented here could aid in future efforts towards improving understanding of thoracic injury risk and thoracic response to loading. Thoracic injury risk is currently determined by chest deflection, and force–deflection corridors are currently used as biofidelity targets for ATD design.^{4,5,24,25} Future work will look to quantify the contribution of the individual rib to overall thoracic response. However, a significant challenge will be to account for the effects of rib angle when *in situ*, which is a limitation of the intentionally simplified experimental design used in this study and should be considered when interpreting the results presented here in a wider context. If a transfer function linking the two could be determined, it would be particularly useful to apply to populations on which full-thoracic testing is not typically conducted but for which individual rib data might be available (e.g., pediatric, elderly, subjects with poor bone quality, *etc.*) as the majority of full-thoracic injury research has been conducted on 50th percentile (for size) males.^{16,17,21,24,25} The large amount of variation seen in individual rib response in this study may reflect the degree of variation if thoracic impact tests were performed on a similar sample, and parallels the findings of epidemiologic studies focusing on thoracic injuries.^{18,28} Additionally, there is potential for current force–deflection corridors and thoracic injury risk curves^{3,14} to be modified to reflect the degree of human variability observed in this study. Of particular interest, will be one that captures the thoracic fracture risk of the slender (vulnerable) rib phenotype (Fig. 5) once it is known precisely how rib phenotype relates to overall thoracic response.

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APPENDIX

See Table 4 for specific rib data.

FIGURE 1.

A rib oriented in the SAEJ211 coordinate system consistent with experimental boundary conditions. The methodology for curve length (Cv.Le) measurement is depicted by a dashed line along the length of the rib. An exemplar histological cross section from the mid-shaft of a rib is shown (middle) with corresponding depictions of total area (Tt.Ar, left) and cortical area (Ct.Ar, right) measurements.

FIGURE 2.

A representative rib cross section indicating axes and measurements for the calculation of section modulus (Z) used in this study. The distance from the Z -axis (y) to each differential area element (dA), i.e., pixel, is used in the calculation of the area moment of inertia (I_Z). Cutaneous Radius (CutRad) and Pleural Radius (PleRad) are used in the calculation of cutaneous and pleural section modulus (Z_{CUT} and Z_{PLE} , respectively). See Eqs. (2)–(4).

FIGURE 3.
ClinCT scan of a rib with measurement of *I.Cv.Le* shown in red.

FIGURE 4.

Example of use of the adaptive thresholding technique (ATT). The cross-sectional images highlight HU thresholds investigated to obtain $I.Tt.Ar$ based on current literature and the histological image used to calculate $D.Tt.Ar$ for the same location on a single rib. The plot shows a rapid decrease in $I.Tt.Ar$ just after 295 HU, indicating the cortical shell is no longer complete, and is therefore used as the adaptive threshold (AT) for this particular cross section.

FIGURE 5.

Probability distribution of rib robusticity values in this study, with percentiles of interest emphasized. Representative rib cross-sections of cortical bone from the slender sample (10th percentile, left) and the robust sample (90th percentile, right) are shown to scale.

FIGURE 6.

Relationships between rib geometry and peak force (F_{PEAK}). Plots on the left (a, c) highlight the predictive ability of cross-sectional geometry alone. Plots on the right (b, d) show improvements in predictive ability when mixed geometry is utilized. All relationships are statistically significant ($p < 0.001$).

FIGURE 7.

Relationships between rib geometry and stiffness (K). Plots on the left (a, c) highlight the predictive ability of cross-sectional geometry alone. Plots on the right (b, d) show improvements in predictive ability when mixed geometry is utilized. All relationships are statistically significant ($p < 0.001$).

FIGURE 8.

Comparison of mean Tt.Ar values using five methodologies: clinCT scans at 226, 452, and 500 HU, the adaptive threshold technique (ATT) and the direct histological measurement. ANOVA indicates significant Tt.Ar differences between these methods ($p = 0.018$). Bars represent 95% confidence intervals.

TABLE 1

Descriptive statistics.

Variable type	Variable	Mean	SD	Min	Max
Gross geometry	Cv.Le (mm)	279.30	25.80	219.50	337.50
	Tl.Ar (mm ²)	70.19	14.63	33.03	105.81
	Ct.Ar (mm ²)	23.90	6.99	9.04	39.56
Cross-sectional geometry	Z _{PLE} (mm ³)	42.42	15.52	9.89	84.09
	Z _{CUT} (mm ³)	40.29	15.02	8.73	77.92
Mixed geometry	Robusticity (mm)	0.25	0.05	0.12	0.39
	WBSI _{PLE} (mm ²)	0.15	0.05	0.04	0.31
	WBSI _{CUT} (mm ²)	0.14	0.05	0.03	0.28
Structural properties	F _{PEAK} (N)	115.14	43.93	16.61	242.95
	K (N/mm)	3.52	1.67	0.36	9.42

All geometric variables reported here are those made from direct (*D*) measurements.

TABLE 2

Model parameters for geometry as predictors of F_{PEAK} and K .

Dependent variable	Independent variable	Estimate	Standard error	p value	p- R^2
F_{PEAK}	Intercept	-26.22	15.20	0.0885	0.35
	Tt.Ar	2.01	0.21	<0.0001	
	Intercept	-6.44	9.60	0.5044	0.67
	Ct.Ar	5.10	0.38	<0.0001	
	Intercept	15.49	7.06	0.0313	0.67
	Z_{PLE}	2.35	0.15	<0.0001	
	Intercept	20.90	7.69	0.0081	0.66
	Z_{CUT}	2.36	0.17	<0.0001	
	Intercept	-30.49	15.91	0.0592	0.38
	Robusticity	578.11	60.58	<0.0001	
	Intercept	6.16	6.74	<0.0001	0.75
	$WBSI_{PLE}$	719.89	40.52	<0.0001	
	Intercept	10.25	7.43	0.172	0.74
	$WBSI_{CUT}$	737.68	47.86	<0.0001	
K	Intercept	-1.07	0.67	0.1151	0.44
	Tt.Ar	0.07	0.01	<0.0001	
	Intercept	0.72	0.53	0.1827	0.26
	Ct.Ar	0.12	0.02	<0.0001	
	Intercept	0.70	0.39	0.0728	0.49
	Z_{PLE}	0.07	0.01	<0.0001	
	Intercept	1.05	0.40	0.0114	0.43
	Z_{CUT}	0.06	0.01	<0.0001	
	Intercept	-2.80	0.59	<0.0001	0.68
	Robusticity	25.13	2.28	<0.0001	
	Intercept	-0.01	0.36	0.984	0.64
	$WBSI_{PLE}$	23.44	2.21	<0.0001	
	Intercept	0.36	0.39	0.3526	0.58
	$WBSI_{CUT}$	22.33	2.52	<0.0001	

All geometric variables reported here are those made from direct (D) measurements. Cv,Le was not included because it had no statistically significant relationship with FPEAK or K ($p > 0.01$).

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TABLE 3

Geometry from direct (*D*) vs. indirect (*I*) measurement.

Tt.Ar (mm ²)		Robusticity (mm)			
		Indirect ^a		Indirect ^a	Direct ^b
		Direct ^b %		Error (ATT vs. Histo)	% Error (<i>I</i> .Robusticity vs. <i>D</i> .Robusticity)
226 HU	452 HU	500 HU	ATT	Histological	
124.0	-	-	106.8	94.2	13.38
106.2	-	-	100.3	76.2	31.63
45.4	-	-	42.3	43.1	-1.86
50.9	-	-	44.6	42.6	4.69
58.7	-	-	56.4	49.1	14.87
111.7	-	-	104.5	94.6	10.47
82.0	-	-	66.8	66.6	0.30
93.1	68.5	-	66.0	68.4	-3.51
90.7	66.9	-	63.8	66.7	-4.35
103.7	86.8	-	86.8	72.4	19.89
107.6	86.8	-	84.5	91.4	-7.55
59.1	50.5	-	48.6	50.3	-3.38
100.7	84.5	80.7	80.7	82.9	-2.65
117.6	99.1	95.3	95.3	96.5	-1.24
81.1	66.8	62.9	54.4	58.0	-6.21
88.7	73.4	71.5	62.9	63.7	-1.26
86.8	72.5	68.7	65.8	69.4	-5.19
95.4	82.0	80.1	69.6	71.5	0.29
80.1	63.9	62.9	50.5	54.5	-7.34
					0.30
					0.26
					0.18
					0.17
					0.21
					0.32
					0.23
					0.22
					0.23
					0.24
					0.28
					0.20
					0.28
					0.30
					0.23
					0.24
					0.24
					0.26
					0.20
					0.00
					-17.39
					-12.50
					-8.33
					-7.69
					-15.00

Each row represents individual rib measurements. Hyphens represent ribs which could not be measured using the indicated Indirect method.

^aIndirect robusticity (*I*.Robusticity) was calculated using ATT Tt.Ar (*I*Tt.Ar) and clinCT Cv.Le (*I*.Cv.Le).^bDirect robusticity (*D*.Robusticity) was calculated using histological Tt.Ar (*D*Tt.Ar) and manually measured Cv.Le (*D*Cv.Le).

TABLE 4

Rib data.

Test ID	Gross geometry			Cross-sectional geometry				Mixed geometry		Structural properties		
	CvLe (mm)	TtAr (mm ²)	CtAr (mm ²)	Z _{PLE} (mm ³)	Z _{CUT} (mm ³)	Robusticity (mm)	WBSI _{PLE} (mm ²)	WBSI _{CUT} (mm ²)	F _{PEAK} (N)	K (N/mm)		
Hrb137	272.50	33.03	9.04	9.89	9.74	0.121	0.036	0.036	16.61	0.36		
Hrb105	304.50	40.68	22.25	21.23	23.51	0.134	0.070	0.077	44.79	1.32		
Hrb170	249.50	39.65	11.74	17.42	12.50	0.159	0.070	0.050	53.66	1.48		
Hrb112	278.00	44.27	10.29	14.53	8.73	0.159	0.052	0.031	31.17	0.71		
Hrb08	253.00	42.63	13.66	18.96	18.76	0.168	0.075	0.074	54.67	0.77		
Hrb181	302.00	52.75	23.66	32.64	30.12	0.175	0.108	0.100	80.73	2.02		
Hrb16	241.00	43.11	11.65	18.15	15.55	0.179	0.075	0.065	56.21	1.19		
Hrb70	300.50	54.81	16.11	22.55	21.24	0.182	0.075	0.071	62.97	1.31		
Hrb150	297.50	54.49	28.01	37.64	35.65	0.183	0.127	0.120	96.74	1.64		
Hrb175	274.00	50.49	23.85	34.15	31.66	0.184	0.125	0.116	113.82	3.06		
Hrb191	276.50	52.22	19.80	25.44	26.57	0.189	0.092	0.096	78.99	1.46		
Hrb157	292.50	55.79	30.44	41.64	44.07	0.191	0.142	0.151	114.73	2.60		
Hrb160	272.00	52.33	21.92	35.32	31.95	0.192	0.130	0.117	109.38	2.46		
Hrb149	279.50	54.28	25.93	36.36	34.05	0.194	0.130	0.122	111.23	2.38		
Hrb83	279.50	54.54	26.51	33.69	35.85	0.195	0.121	0.128	113.92	2.54		
Hrb81	255.50	50.28	20.26	29.87	28.20	0.197	0.117	0.110	93.46	2.53		
Hrb176	281.00	55.38	27.18	37.53	42.67	0.197	0.134	0.152	122.99	2.68		
Hrb183	337.50	68.07	17.30	32.41	28.32	0.202	0.096	0.084	80.34	2.00		
Hrb102	292.00	59.46	34.98	37.07	36.40	0.204	0.127	0.125	94.02	1.86		
Hrb71	291.50	60.11	18.88	30.27	37.28	0.206	0.104	0.128	61.76	1.61		
Hrb167	307.00	63.32	29.86	41.24	43.73	0.206	0.134	0.142	154.08	3.56		
Hrb153	246.50	51.51	16.39	23.51	19.82	0.209	0.095	0.080	64.89	2.61		
Hrb113	228.00	47.75	10.26	14.95	13.24	0.209	0.066	0.058	36.70	1.64		
Hrb120	264.00	55.58	30.17	37.90	44.11	0.211	0.144	0.167	135.87	3.72		
Hrb128	297.50	62.69	32.74	47.41	47.50	0.211	0.159	0.160	149.09	3.37		
Hrb15	232.50	49.11	16.66	26.89	27.36	0.211	0.116	0.118	87.98	3.41		
Hrb56	238.00	50.31	13.11	18.63	13.13	0.211	0.078	0.055	39.02	1.41		

Test ID	Gross geometry		Cross-sectional geometry				Mixed geometry		Structural properties	
	Cv,Le (mm)	Tt,Ar (mm ²)	Ct,Ar (mm ²)	Z _{PLE} (mm ³)	Z _{CUT} (mm ³)	Robusticity (mm)	WBSI _{PLE} (mm ²)	WBSI _{CUT} (mm ²)	F _{PEAK} (N)	K (N/mm)
Hrb75	229.00	48.50	13.12	16.21	16.93	0.212	0.071	0.074	78.81	3.14
Hrb123	298.00	63.77	25.15	44.88	46.49	0.214	0.151	0.156	104.58	3.05
Hrb151	283.50	61.29	32.13	49.22	45.49	0.216	0.174	0.160	149.42	2.42
Hrb182	300.50	65.02	17.91	36.56	35.53	0.216	0.122	0.118	89.87	2.37
Hrb52	236.50	51.32	21.12	22.65	23.06	0.217	0.096	0.098	33.90	2.33
Hrb50	310.00	67.38	26.75	46.44	47.31	0.217	0.150	0.153	140.43	2.91
Hrb77	255.00	55.43	13.53	21.94	18.74	0.217	0.086	0.073	87.86	3.29
Hrb117	236.50	51.86	18.32	19.93	22.93	0.219	0.084	0.097	142.15	6.98
Hrb158	293.50	65.77	33.17	51.06	40.95	0.224	0.174	0.140	128.85	2.66
Hrb35	327.50	73.44	27.27	47.27	61.94	0.224	0.144	0.189	123.51	3.62
Hrb180	292.00	66.34	17.79	40.21	32.73	0.227	0.138	0.112	95.87	2.62
Hrb82	254.50	58.02	23.02	31.28	30.82	0.228	0.123	0.121	117.75	3.74
Hrb19	288.00	66.69	23.35	37.59	28.99	0.232	0.131	0.101	80.82	2.75
Hrb162	287.00	66.56	24.62	41.07	34.19	0.232	0.143	0.119	126.39	2.51
Hrb14	272.50	63.30	16.45	35.40	33.53	0.232	0.130	0.123	84.16	2.93
Hrb152	254.50	59.57	33.02	43.20	46.75	0.234	0.170	0.184	129.62	2.57
Hrb95	308.00	72.38	30.76	45.23	50.82	0.235	0.147	0.165	105.36	2.70
Hrb184	327.50	77.17	21.32	33.56	35.96	0.236	0.102	0.110	99.27	2.53
Hrb13	283.50	67.31	19.38	27.21	42.84	0.237	0.096	0.151	48.69	1.94
Hrb144	291.50	69.58	25.92	49.50	36.07	0.239	0.170	0.124	107.38	2.21
Hrb31	280.00	66.93	14.58	28.04	22.42	0.239	0.100	0.080	62.20	2.25
Hrb84	266.50	63.73	27.49	37.34	41.88	0.239	0.140	0.157	145.81	4.97
Hrb34	326.00	78.38	26.02	53.98	54.06	0.240	0.166	0.166	109.18	2.03
Hrb09	256.00	61.79	12.96	23.15	24.58	0.241	0.090	0.096	65.36	2.37
Hrb80	283.00	68.40	25.13	38.39	41.66	0.242	0.136	0.147	128.50	3.09
Hrb125	273.00	66.05	28.28	47.18	47.62	0.242	0.173	0.174	132.45	4.51
Hrb161	287.00	69.44	26.50	44.85	42.20	0.242	0.156	0.147	133.62	3.11
Hrb98	313.50	76.60	26.29	53.69	44.65	0.244	0.171	0.142	105.21	1.94
Hrb171	295.00	72.30	21.24	36.70	36.09	0.245	0.124	0.122	65.44	2.00
Hrb61	262.50	64.39	18.69	30.88	31.12	0.245	0.118	0.119	85.59	2.19

Test ID	Gross geometry		Cross-sectional geometry				Mixed geometry		Structural properties	
	Cv,Le (mm)	Tt.Ar (mm ²)	Ct.Ar (mm ²)	Z _{PLE} (mm ³)	Z _{CUT} (mm ³)	Robusticity (mm)	WBSI _{PLE} (mm ²)	WBSI _{CUT} (mm ²)	F _{PEAK} (N)	K (N/mm)
Hrb17	277.50	68.17	14.52	27.65	19.48	0.246	0.100	0.070	73.96	3.01
Hrb118	292.00	73.46	19.20	35.17	35.35	0.252	0.120	0.121	69.47	2.59
Hrb49	267.50	67.95	19.05	36.32	28.58	0.254	0.136	0.107	101.66	3.26
Hrb165	270.00	68.67	21.44	38.45	36.24	0.254	0.142	0.134	119.46	3.23
Hrb124	266.00	67.77	25.82	46.94	44.52	0.255	0.176	0.167	138.18	3.55
Hrb109	259.00	66.21	24.43	37.85	40.91	0.256	0.146	0.158	117.34	3.82
Hrb138	293.00	75.08	22.90	49.25	46.17	0.256	0.168	0.158	137.96	4.45
Hrb93	279.00	71.50	26.29	45.79	46.90	0.256	0.164	0.168	139.46	3.59
Hrb37	315.00	80.80	16.60	41.34	40.35	0.256	0.131	0.128	63.80	2.21
Hrb156	295.00	75.83	31.89	48.51	49.74	0.257	0.164	0.169	175.37	3.99
Hrb141	305.00	78.43	30.31	62.24	59.61	0.257	0.204	0.195	138.99	3.57
Hrb177	226.50	58.58	15.93	28.37	16.72	0.259	0.125	0.074	66.39	3.58
Hrb163	271.00	70.28	25.58	41.81	42.64	0.259	0.154	0.157	125.59	3.22
Hrb76	219.50	56.95	13.42	23.12	21.44	0.259	0.105	0.098	106.81	8.81
Hrb40	305.50	79.53	14.90	33.28	32.85	0.260	0.109	0.108	67.10	2.83
Hrb88	292.50	76.23	25.24	32.99	40.76	0.261	0.113	0.139	97.69	2.24
Hrb12	323.50	84.59	33.29	66.88	63.97	0.261	0.207	0.198	194.48	7.43
Hrb119	284.00	75.18	21.39	39.96	28.23	0.265	0.141	0.099	146.23	5.08
Hrb30	327.50	87.12	34.39	60.75	70.41	0.266	0.186	0.215	138.70	3.83
Hrb63	293.00	78.08	30.59	61.87	53.07	0.266	0.211	0.181	197.21	4.76
Hrb185	309.00	83.38	34.22	65.67	64.46	0.270	0.213	0.209	176.10	3.68
Hrb129	289.50	78.22	22.74	48.90	39.65	0.270	0.169	0.137	148.03	4.57
Hrb130	286.00	77.49	12.32	31.35	20.81	0.271	0.110	0.073	71.90	2.04
Hrb69	279.50	75.74	26.39	49.63	41.03	0.271	0.178	0.147	134.36	3.50
Hrb174	256.50	69.53	23.42	42.52	44.23	0.271	0.166	0.172	148.81	4.78
Hrb85	288.00	78.36	19.67	48.22	32.44	0.272	0.167	0.113	109.22	3.77
Hrb140	270.50	74.40	23.40	40.60	34.90	0.275	0.150	0.129	139.56	3.20
Hrb10	257.50	70.83	12.83	20.47	22.18	0.275	0.080	0.086	41.75	2.21
Hrb41	297.00	81.89	14.34	29.26	27.19	0.276	0.099	0.092	75.95	3.80
Hrb173	251.50	70.33	26.69	49.82	48.37	0.280	0.198	0.192	172.85	5.61

Test ID	Gross geometry			Cross-sectional geometry			Mixed geometry			Structural properties	
	Cv,Le (mm)	Tt,Ar (mm ²)	Cl,Ar (mm ²)	Z _{PLE} (mm ³)	Z _{CUT} (mm ³)	Robusticity (mm)	WBSI _{PLE} (mm ²)	WBSI _{CUT} (mm ²)	F _{PEAK} (N)	K (N/mm)	
Hrb07	291.00	81.45	17.05	43.53	31.86	0.280	0.150	0.109	49.95	2.95	
Hrb132	274.50	77.00	28.78	51.07	50.75	0.281	0.186	0.185	126.61	3.66	
Hrb139	253.50	71.45	31.60	51.38	51.11	0.282	0.203	0.202	131.15	5.32	
Hrb25	323.50	91.44	30.76	69.02	53.09	0.283	0.213	0.164	134.19	3.88	
Hrb33	314.00	88.77	39.56	66.08	70.92	0.283	0.210	0.226	159.94	3.97	
Hrb22	293.00	82.91	25.55	46.72	44.94	0.283	0.159	0.153	98.90	2.90	
Hrb164	259.50	74.12	25.07	40.97	43.31	0.286	0.158	0.167	121.88	2.81	
Hrb126	257.50	73.60	30.93	45.29	53.25	0.286	0.176	0.207	145.76	3.94	
Hrb11	265.50	75.96	13.40	30.76	28.34	0.286	0.116	0.107	38.28	1.70	
Hrb142	267.00	76.52	34.17	53.13	53.82	0.287	0.199	0.202	181.61	4.68	
Hrb43	280.00	80.27	14.74	32.80	29.24	0.287	0.117	0.104	85.16	3.57	
Hrb178	327.50	94.57	31.01	75.93	66.09	0.289	0.232	0.202	115.26	3.56	
Hrb168	304.00	88.94	25.66	55.36	48.39	0.293	0.182	0.159	134.56	3.25	
Hrb133	298.50	87.62	16.38	46.54	41.86	0.294	0.156	0.140	106.33	4.35	
Hrb127	254.00	74.74	27.22	45.93	49.00	0.294	0.181	0.193	155.02	5.80	
Hrb179	318.50	94.17	33.86	68.32	64.21	0.296	0.215	0.202	173.22	3.94	
Hrb145	230.50	68.70	33.82	44.57	51.00	0.298	0.193	0.221	136.04	6.44	
Hrb60	253.00	75.64	30.57	65.65	52.13	0.299	0.259	0.206	182.22	7.27	
Hrb73	294.50	88.46	36.03	64.34	62.04	0.300	0.218	0.211	190.84	5.82	
Hrb106	281.00	84.64	27.86	55.96	56.29	0.301	0.199	0.200	127.14	5.65	
Hrb26	318.00	96.55	32.12	65.06	69.25	0.304	0.205	0.218	165.93	4.68	
Hrb155	284.50	87.22	27.86	65.66	67.28	0.307	0.231	0.236	124.26	4.05	
Hrb116	284.50	87.92	24.44	49.01	49.71	0.309	0.172	0.175	106.65	3.05	
Hrb114	274.00	85.42	27.27	59.64	43.61	0.312	0.218	0.159	154.58	5.27	
Hrb99	263.50	82.36	22.89	48.07	45.44	0.313	0.182	0.172	100.01	3.73	
Hrb136	228.00	72.96	32.35	50.86	47.88	0.320	0.223	0.210	192.04	6.40	
Hrb115	272.00	87.39	24.66	48.11	47.28	0.321	0.177	0.174	130.03	6.37	
Hrb78	259.00	83.55	28.57	64.56	62.97	0.323	0.249	0.243	184.02	6.89	
Hrb134	302.50	99.20	32.40	73.87	73.35	0.328	0.244	0.242	150.73	4.58	
Hrb121	240.50	79.52	20.66	38.70	32.24	0.331	0.161	0.134	147.72	6.30	

Test ID	Gross geometry		Cross-sectional geometry				Mixed geometry		Structural properties	
	Cv.Le (mm)	Tt.Ar (mm ²)	Ct.Ar (mm ²)	Z _{PLE} (mm ³)	Z _{CUT} (mm ³)	Robusticity (mm)	WBSI _{PLE} (mm ²)	WBSI _{CUT} (mm ²)	F _{PEAK} (N)	K (N/mm)
<i>Hrb122</i>	231.50	80.13	21.88	45.39	35.86	0.346	0.196	0.155	167.62	6.34
<i>Hrb143</i>	288.00	102.29	31.25	66.72	62.78	0.355	0.232	0.218	172.18	4.47
<i>Hrb65</i>	277.00	100.11	34.74	84.09	77.92	0.361	0.304	0.281	242.95	6.31
<i>Hrb146</i>	283.00	105.81	27.59	82.28	59.20	0.374	0.291	0.209	206.19	7.10
<i>Hrb154</i>	266.00	103.86	35.35	83.05	66.14	0.390	0.312	0.249	205.31	9.42

Italicised rows indicate the 10th and 90th percentile groups for rib robusticity.