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

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INTRODUCTION

- Thorax injuries, specifically rib fractures, are common in motor vehicle crashes and can lead to high rates of morbidity and mortality (Kent *et al.* 2008). Creating biofidelic finite element models is important for improving thoracic injury countermeasures, but can only be achieved using accurate properties of human ribs in dynamic loading (Murach *et al*. 2017).
- Previous studies have identified relationships between structural response of ribs and material and geometric properties individually. However, these relationships only explained a small amount of variance in structural properties. Additionally, the combined contributions of these properties has yet to be investigated in regard to explaining variability in whole rib structural response.
- **The goal of this study was to quantify the contributions of human rib material and geometric properties to the variation in whole rib structural response.**

MATERIALS & METHODS

- Thirty-seven 6th level rib pairs from fresh post-mortem human subjects (16 female, 21 male, 24-99 years) were selected for direct comparison of properties.

Structural Dynamic Bending Testing

- One randomly selected left or right whole rib was tested in a 2D dynamic bending scenario, simulating a frontal impact to the thorax by translating the sternal end toward the fixed vertebral end (Figure 1). Structural properties were calculated from force vs. displacement curves (Figure 2).

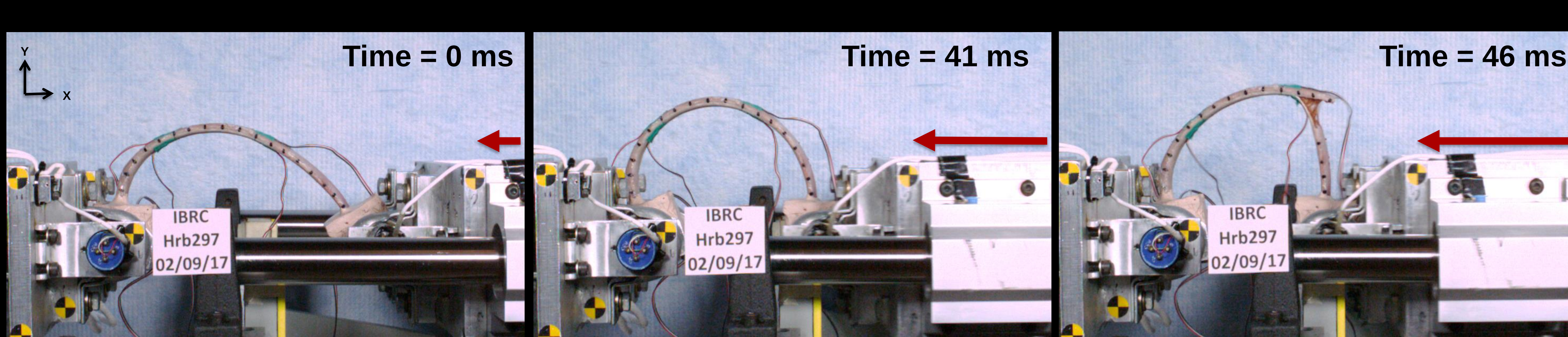

Figure 1: Dynamic bending test on whole human rib for structural properties

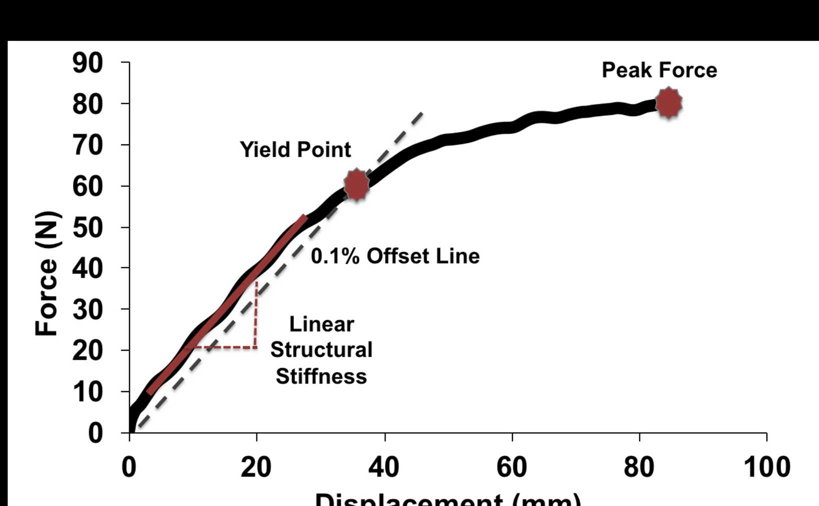

Figure 2: Typical force vs. displacement curve

Material Testing

- The contralateral rib was used to obtain cortical bone coupons (Figure 3) from the cutaneous cortex for uniaxial tensile tests on a high-rate servo-hydraulic 810 MTS. Material properties were calculated from the stress vs. strain curves analogous to structural properties.

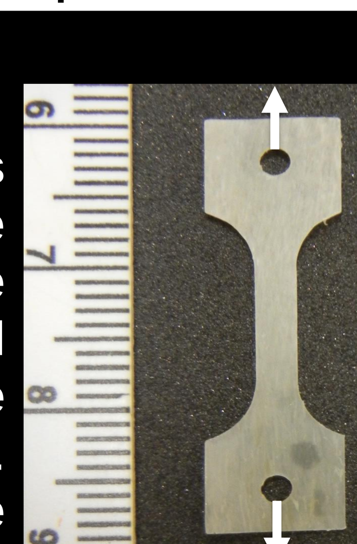

Figure 3. Rib Coupon

- For maximum comparability, all yield-dependent calculations were made using a 0.1% offset method in structural and material properties. All structural and material tests were conducted at ~0.5 strain/sec for direct comparison.

Geometric Properties

- After dynamic bending tests, high resolution (1446 pix/mm) microscopic images were obtained from a section adjacent to the fracture location (Figure 4). Cross-sectional geometric properties such as Whole Bone Strength Index (WBSI), Robusticity, and Cutaneous Cortical Thickness (Cut.Ct.Th) were calculated using MATLAB and ImageJ.

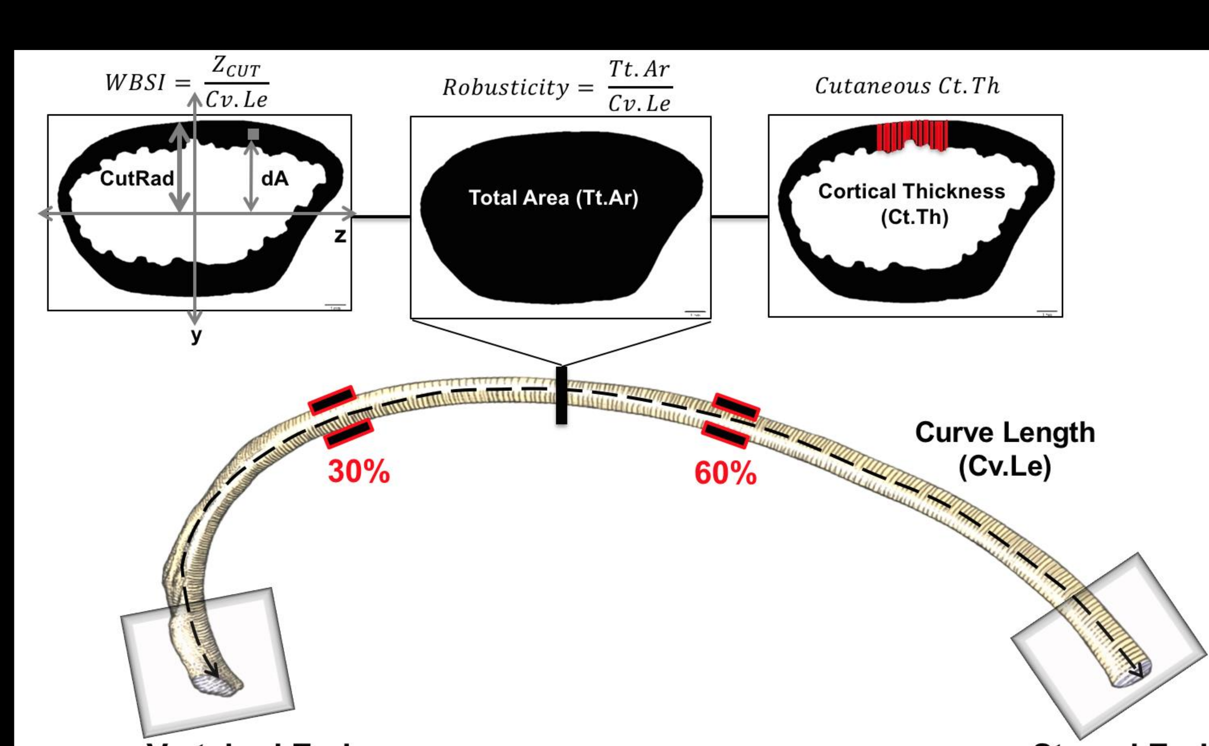

Figure 4: Cross-sectional property calculations

RESULTS & DISCUSSION

Table 1: Multiple Regression Results

Structural Property	Material Property			Geometric Property			Model	
			p-value			p-value	R^2	p-value
Stiffness	Modulus	1.20%	0.351	WBSI	**53.18%**	**<0.0001**	**54.38%**	**<0.0001**
Stiffness	Modulus	2.98%	0.119	Robusticity	**57.25%**	**<0.0001**	**60.23%**	**<0.0001**
Stiffness	Modulus	0.17%	0.794	Ct.Th	**15.63%**	**0.021**	15.80%	0.054
Displacement in X at Yield	Yield Strain	0.38%	0.713	WBSI	6.42%	0.127	6.80%	0.302
Displacement in X at Yield	Yield Strain	0.01%	0.953	Robusticity	**21.82%**	**0.004**	**21.83%**	**0.015**
Displacement in X at Yield	Yield Strain	0.05%	0.898	Ct.Th	6.31%	0.141	6.35%	0.328
Force in X at Yield	Yield Stress	**8.08%**	**0.04**	WBSI	**31.65%**	**<0.0001**	**39.73%**	**<0.0001**
Force in X at Yield	Yield Stress	**12.47%**	**0.02**	Robusticity	**15.85%**	**0.006**	**28.32%**	**0.003**
Force in X at Yield	Yield Stress	2.54%	0.193	Ct.Th	**48.58%**	**<0.0001**	**51.12%**	**<0.0001**
Peak Strain	Ultimate Strain	**19.70%**	**0.012**	WBSI	0.59%	0.881	**20.29%**	**0.037**
Peak Strain	Ultimate Strain	**21.86%**	**0.008**	Robusticity	0.39%	0.392	**22.25%**	**0.026**
Peak Strain	Ultimate Strain	6.16%	0.113	Ct.Th	**26.78%**	**0.026**	**32.94%**	**0.003**
Peak Force	Ultimate Stress	0.98%	0.434	WBSI	**47.78%**	**<0.0001**	**48.76%**	**<0.0001**
Peak Force	Ultimate Stress	0.10%	0.813	Robusticity	**41.12%**	**<0.0001**	**41.22%**	**<0.0001**
Peak Force	Ultimate Stress	1.66%	0.366	Ct.Th	**33.24%**	**<0.0001**	**34.90%**	**<0.0001**
Total Energy	Strain Energy Density	**27.19%**	**0.001**	WBSI	5.19%	0.287	**32.38%**	**0.002**
Total Energy	Strain Energy Density	**27.81%**	**0.001**	Robusticity	5.73%	0.193	**33.54%**	**0.001**
Total Energy	Strain Energy Density	**18.50%**	**0.006**	Ct.Th	11.80%	0.697	**30.30%**	**0.003**
Elastic Energy	Elastic Strain Energy Density	4.00%	0.216	WBSI	**12.87%**	**0.047**	**16.87%**	**0.047**
Elastic Energy	Elastic Strain Energy Density	2.41%	0.325	Robusticity	**17.82%**	**0.015**	**20.23%**	**0.024**
Elastic Energy	Elastic Strain Energy Density	2.67%	0.331	Ct.Th	6.65%	0.191	9.32%	0.199

- Using multiple regression models, results show the contribution of each predictor, an analogous material property and various geometric properties, in regard to explaining variation in each structural property (Table 1). Geometric properties had a larger role in determining structural response variables except for the total energy analyses. This was intuitive because energy absorption and resistance to deformation, prior to fracturing, are highly dependent on material composition.
- Structural properties have been found to be highly correlated with overall bone size and shape (Murach *et al*. 2017). This was evident in the stiffness relationships, where robusticity explained 57% of variance while modulus only explained 3%.
- The amount of variance explained by the models was relatively low (R^2=9-60%) suggesting additional predictors should be explored. Furthermore, utilizing alternate modeling techniques may improve our characterization of variability in whole rib response.

CONCLUSIONS

- Multiple regression models are useful tools to better understand sources of variation in rib structural properties. The current models revealed that geometric properties play a larger role in the structural response of human ribs than material properties.
- The results from this study and future work will be crucial to advancing finite element human body models by providing essential material and geometric properties of ribs and how they contribute to overall rib and thoracic response, with the ultimate goal of reducing thoracic injury risk from motor vehicle crashes.

REFERENCES CITED

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