The Effect of Body Size on Adult Human Rib Structural Properties

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Abstract

Rib fractures sustained during motor vehicle crashes are a common cause of increased mortality, and their causes within and between individuals is not fully understood. This study aimed to identify the effect of body height, body weight, and body mass index (BMI) on measured structural properties of human ribs. Two-hundred sixty one ribs from one-hundred forty seven individuals were impacted in a dynamic (2.0 m/s) bending scenario representing a frontal thoracic impact. Linear regression revealed body height and weight each had a significant positive relationship with peak force and stiffness ($p<0.001$ for all), and weaker relationships with total energy ($p=0.003$ and 0.015, respectively), although explanatory power remained low for all relationships (R^2=10-12%). The introduction of age as an additional variable in multiple regressions increased the ability to predict structural properties: R^2=33%, 17%, and 41% for peak force, stiffness and total energy, respectively. Body size parameters have a measurable effect on rib properties, but should be used with caution to understand variance in dynamic whole rib response because the source of the majority of variation remains unaccounted for in all models explored here. Future work will incorporate rib-specific variables and explore the utility of these relationships on scaling and normalization techniques.

Keywords Energy, Force, Fracture, Stiffness, Thorax injury

I. INTRODUCTION

The thorax, and especially ribs, are commonly injured in motor vehicle crashes (MVC) and this trauma represents a significant threat to life [1]. Understanding rib response is crucial to elucidate specific mechanisms of fracture and develop accurate tools (e.g., anthropomorphic test devices and computational models) designed to assist in measuring thoracic response in an MVC and ultimately to mitigate fracture risk.

Human rib structural properties have previously been reported as to how they relate to individual characteristics such as chronological age and sex with limited success [2]. However, the influence of body size on structural properties is relatively unexplored, and these parameters have potential to explain additional variation in properties that age and sex alone do not. There have been only a few studies exploring human body size and its effects on dynamic rib properties representative of loading in a car crash scenario [2,3].

Furthermore, many researchers rely on scaling techniques which utilize height and weight to normalize impact response data obtained from experimental testing [4-6]. Several normalization techniques utilize other more complex anthropometric variables beyond height and weight but still operate under the assumption that the human body behaves as a simple mechanical system and therefore the relationship between impact response and body size parameters can be obtained through linear scale factor ratios [7-10]. However, whereas these normalization techniques are effective when applied to response data from test subjects that have small variations in size/weight about a central population (i.e., approximate 50^{th} male test subjects normalized to a precise 50^{th} male anthropometry), the techniques tend to perform worse when adjusting one population to a vastly different one (e.g., 50^{th} male to child), likely due to anatomical variation and differences in skeletal geometric or material properties (tissue quality) that are too complex to be accounted for using linear scaling ratios. For example, [11] explored variation in both rib cross-sectional geometry and the combination of cross-sectional and gross geometry and found these parameters could successfully predict impact response. Furthermore, the authors noted these relationships were independent of body size (defined simply as weight multiplied by bone length), indicating there is potential for using specific bone geometry to improve existing scaling techniques.

Nonetheless, it is important to first understand the effects of subject-level variables, such as body height and weight, on the response and fracture risk of components of the human body which are at a high risk of injury during motor vehicle accidents such as the human thorax. For example, [12] conducted a finite element (FE) study in which body weight and height as well as area moments of inertia of the rib cage and ribs alone were varied to investigate their effects on the response of the thorax. Although the authors concluded that the area moments of inertia were the most important parameters, they also found that weight and height were significant predictors of the maximum force and maximum chest deflection, respectively.

As these FE models become increasingly utilized in the field of injury biomechanics, it is important that the load-bearing component of the human thorax, the ribs, be scaled and modeled appropriately. Several studies have focused on the relationship between body size and gross rib geometry and found in general that increases in body size resulted in increases in rib geometry [1,3,13]. However, the influence of body size on the structural response of individual ribs to dynamic loading that is representative of a car crash scenario has yet to be investigated. Identifying parameters that can be readily quantified such as body size that are important for understanding fracture risk will allow for improvements to scaling techniques and injury countermeasures. Therefore, the objective of this study is to identify the effect of total body height, body weight, and body mass index (BMI) on rib structural stiffness, peak force, and total energy.

II. METHODS

Sample

Two-hundred sixty-one mid-level ribs (4-7) from 147 adult post-mortem human subjects (PMHS) were analyzed in this sample, including 67 females and 194 males. Ribs were acquired ethically via the Ohio State University's Body Donation Program and Lifeline of Ohio. Total body height and body weight were recorded at the time of death, and body mass index (BMI) was calculated as: [weight(kg)/height(m)^2]. BMI was further categorized according to the World Health Organization (WHO) standards: <18.5=underweight, 18.5-24.9=normal weight, 25.0-29.9=overweight, and 30.0+=obese [14]. Height was not recorded for one individual for which one rib was tested, so the total sample size is reduced by one for height and BMI. Table 1 includes descriptive statistics for the sample.

TABLE I
SAMPLE

	Height *(cm)*	**Weight** *(kg)*	**BMI** *(kg/cm^2)*	**Underweight**	**Normal**	**Overweight**	**Obese**	**Age** *(yrs)*
n (ribs)	260	261	260	23	113	79	45	261
Mean	174.7	76.6	25.1	16.6	21.8	27.0	34.5	56.6
SD	9.5	18.6	5.8	1.6	1.73	1.4	4.64	23.3
Min	142.2	32.2	12.5	-*	18.5*	25.0*	>30.0*	15
Max	199.4	136.0	48.4	<18.5*	24.9*	29.9*	-*	108

*WHO defined corridors

Experimental Testing

Complete ribs from costovertebral to costochondral junction were excised from individuals immediately near the time of death, wrapped in normal saline-soaked gauze, and stored at -20°C. To prepare for testing, ribs were thawed and cleaned of all external soft tissue, and the ends were potted in 4x4x3 cm3 blocks of Bondo® Body Filler (Bondo Corporation, Atlanta, GA) in single-plane orientation. Two strain gauges (CEA-06-062UW-350, Vishay Micro-Measurement, Shelton, CT,) each were applied to the pleural and cutaneous surfaces at 30% and 60% of the total curve length (Cv.Le) of the rib from vertebral to sternal end. Span length (Sp.Le), a linear measurement between rib ends, was also documented. Ribs were kept well-hydrated with normal saline throughout preparation and testing.

All ribs were impacted in a dynamic (average 2.0 m/s and 0.5 strain/s) bending scenario representing a frontal thoracic impact with the sternal rib end translated towards the vertebral end. This was accomplished in a custom pendulum (54kg) fixture. The experimental coordinate system was constructed such that the primary loading axis was defined as the X-axis, with the Y-axis extending vertically according to the SAE J211 standard (Fig. 1). In this configuration, bending was restricted to the X-Y plane almost entirely. Displacement of the sternal rib end was measured by a linear string potentiometer (Rayelco P-20A, AMETEK, Inc. Berwyn, PA) fixed to the moving plate of the fixture. Forces and moments were recorded by a 6-axis load cell (CRABI neck load cell, IF-954, Humanetics, Plymouth, MI) behind the fixed plate.

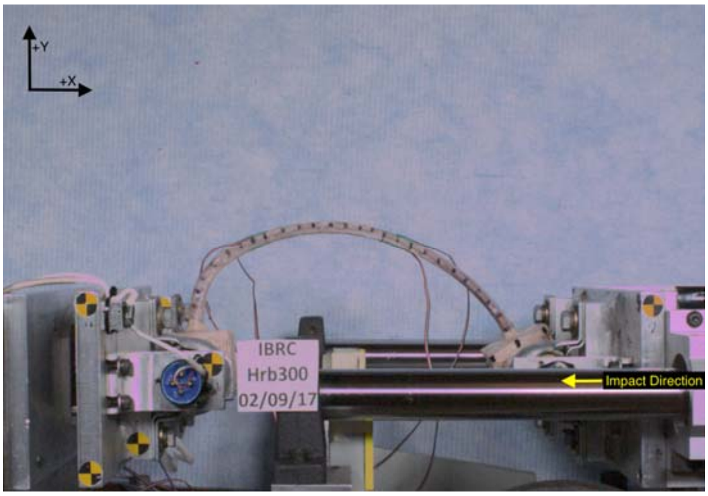


Fig. 1. Bending experiment showing a rib in the test fixture

Data Analysis

Force and displacement data were filtered using a CFC180 filter [15]. Utilizing the force-displacement (F-D) curve from each impact, structural stiffness was calculated as the slope of 20-80% of the linear elastic portion [16], peak force was defined as the maximum force in the X (primary) loading direction prior to fracture, and total energy was calculated as the area beneath the F-D curve from time zero to time of failure. The structural properties of linear structural stiffness (K), peak force (F_{peak}), and total energy (U_{tot}) are treated as dependent variables in this study. Height, weight, and BMI were treated as independent variables and were all assessed as continuous data points to investigate predictive relationships with structural properties. This was accomplished using both univariate and multiple regression models. Additionally, differences in means of BMI classifications were compared using analysis of variance (ANOVA) for all structural properties. An α value of <0.05 was considered significant for all statistical tests.

III. RESULTS

Descriptive statistics for each structural property for the entire sample and when divided by BMI category can be found in Table II. Univariate regression results are presented in Table III and Figure 2. Body height had a significant positive relationship with peak force ($p<0.001$), stiffness ($p<0.001$), and total energy ($p=0.003$). Body weight had a significant positive relationship with peak force ($p<0.0001$) and stiffness ($p<0.0001$), and a slightly weaker relationship with total energy ($p=0.015$). Body mass index (BMI) assessed as discrete values had a significant positive relationship with peak force ($p=0.005$) and stiffness ($p=0.003$), but not total energy ($p=0.200$). Height and weight predicted peak force and stiffness best, explaining approximately 10-12% of variance in the data.

Since previous analysis on a subsample has shown age to have a statistically significant influence on the structural properties presented here [2], age was included along with height and weight as a predictor variable in multiple regression analysis. These data were standardized and centered prior to application in the models, and the results can be found in Table IV. In short, age, height and weight together explained around 33% of variance in peak force, 17% in stiffness, and 41% in total energy ($p<0.0001$ for all three models), but age contributes to explaining the majority of variance in each case.

Table II
DESCRIPTIVE STATISTICS

	Total Sample	BMI Classification			
		Underweight	***Normal***	***Overweight***	***Obese***
Peak Force *(N)*	110.7 (±49.3)	86.2 (±35.6)	100.4 (±46.2)	130.5 (±53.0)	114.3 (±44.1)
Stiffness *(N/mm)*	3.33 (±1.69)	2.48 (±1.25)	3.01 (±1.58)	3.85 (±1.60)	3.66 (±1.95)
Total Energy *(N*mm)*	3714 (±2934)	2710 (±2551)	3535 (±2989)	4329 (±3169)	3598 (±2360)

Table III
UNIVARIATE REGRESSION RESULTS

	Peak Force		Stiffness		Total Energy	
	R^2 (%)	*P-value*	*R^2 (%)*	*P-value*	*R^2 (%)*	*P-value*
Age	19.3	**<0.0001**	7.4	**<0.0001**	36.9	**<0.0001**
Height	12.9	**<0.0001**	9.8	**<0.0001**	3.4	**0.003**
Weight	10.3	**<0.0001**	10.5	**<0.0001**	2.3	**0.015**
BMI	3.0	**0.005**	3.5	**0.003**	0.6	0.200

Note: bolded values are statistically significant

Table IV
MULTIPLE REGRESSION RESULTS

	Peak Force		Stiffness		Total Energy	
	Contribution (%)	*p-value*	*Contribution (%)*	*p-value*	*Contribution (%)*	*p-value*
Age	18.4	**<0.0001**	6.49	**<0.0001**	37.19	**<0.0001**
Height	7.55	**<0.0001**	3.90	**0.024**	2.14	**0.002**
Weight	6.07	**0.004**	5.20	**0.002**	0.23	0.972
Age*Height	0.06	0.540	0.19	0.299	0.65	0.099
Age*Weight	1.23	**0.044**	1.07	0.184	0.10	0.092
Height*Weight	0.06	0.654	0.04	0.854	0.37	0.153
Age*Height*Weight	0.00	0.992	0.44	0.256	0.55	0.133
Total	R^2 = 33.36	**<0.0001**	R^2 = 17.33	**<0.0001**	R^2 = 41.22	**<0.0001**

Note: bolded values are statistically significant

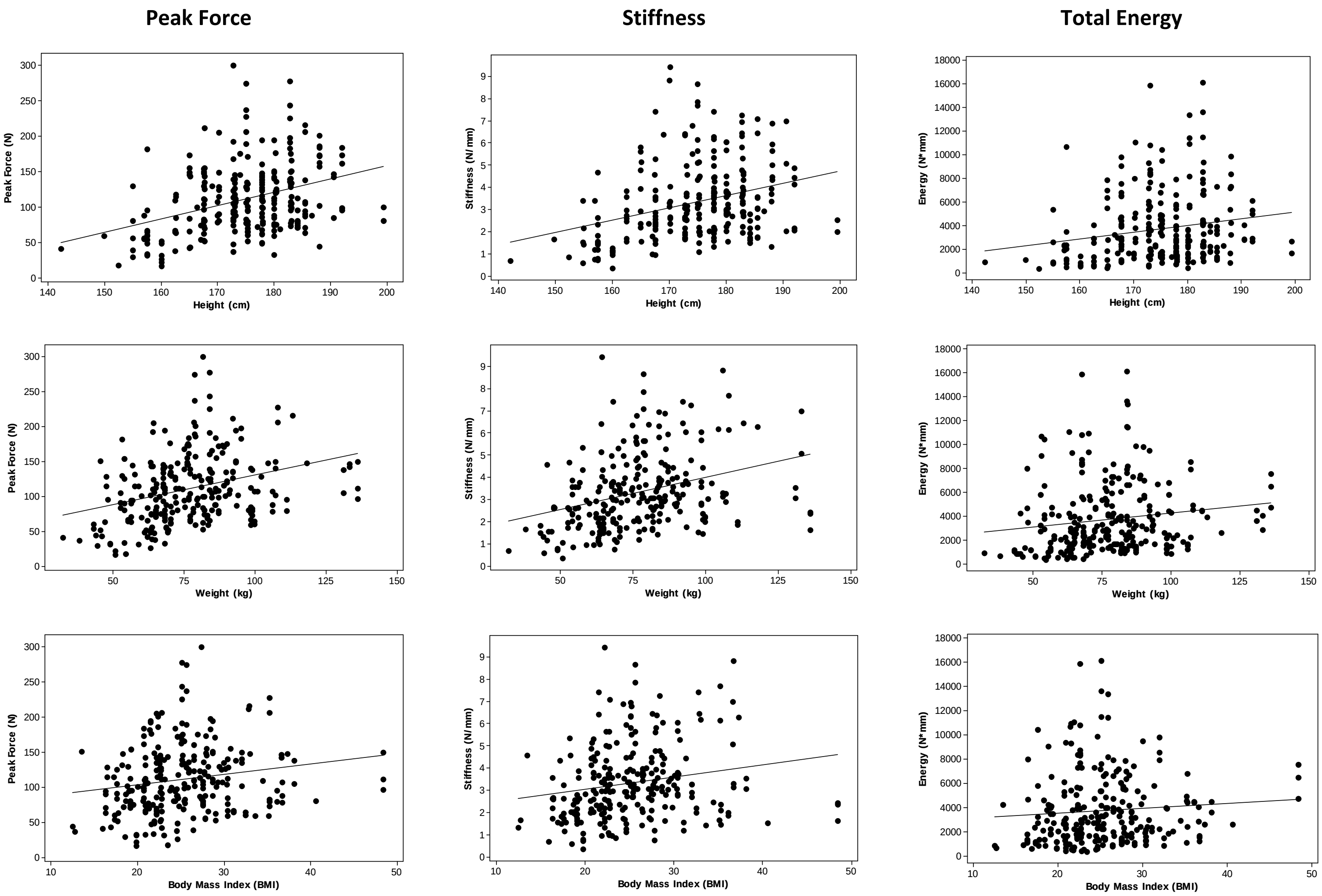
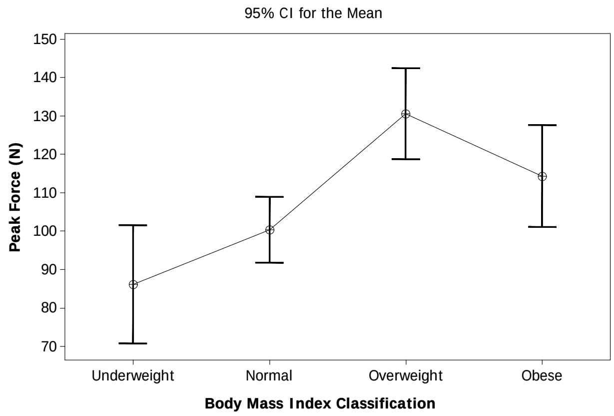


Fig. 2. Scatterplots showing independent relationships of peak force (left), stiffness (center), and total energy (right) with height (top), weight (middle), and BMI (bottom)

When BMI was assessed categorically, a clear trend for all structural properties emerged of increasing with mean BMI from the underweight to normal to overweight categories and then decreasing from the overweight to obese categories (Fig. 3). ANOVA results reveal significant differences in BMI groups ($p<0.0001$) for peak force and stiffness, while no statistically significant differences were found between groups for total energy ($p=0.083$) despite the same distinct trend. To identify where the differences lie between groups, *post hoc* Tukey tests were performed. No significant differences were found between underweight and normal groups or between overweight and obese groups, but a difference was found between normal and overweight groups for peak force and stiffness.



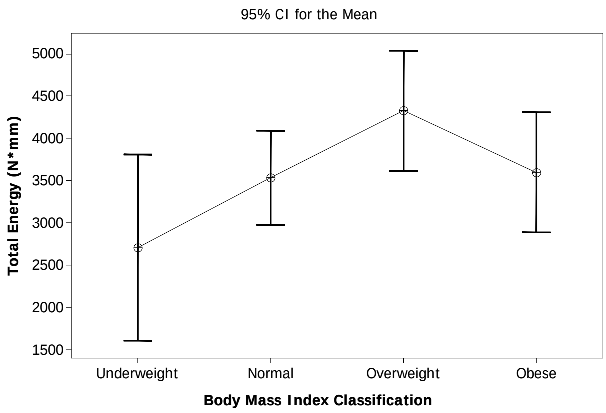


Fig. 3. Interval plots showing mean and 95% confidence intervals of each BMI classification for Peak Force (left) and Total Energy (right). Stiffness results are not shown, but the trend appears similar with an increase in structural properties accompanying an increase in BMI, except for in the obese category.

IV. DISCUSSION

This research found that body size parameters play a role in the determination of individual dynamic rib response in a frontal loading scenario. Few other studies have explored the effects of body size on rib or thoracic properties, although there has been research conducted to explore the ranges of variation seen in rib or thorax geometry related to size parameters. For example, [13] used Computed Tomography (CT) data to develop a statistical rib cage geometry model and found a significant influence of height, BMI, and sex, in addition to a weaker effect of age. Similarly, [1] found a larger effect of BMI than age on rib angle. Despite these findings, there have been few attempts to link thoracic geometry changes with skeletal mechanical properties.

Kalra *et al* [17] performed 3-point bending on adult rib segments at a quasi-static rate and found no height or weight effect on equivalent measures of moment and stiffness. Since this experiment was point loading on a small section of rib and did not take the overall size of the bone into account, it is reasonable to conclude that the rib cross-section (presumably providing the most resistance to bending in this test) would be less influenced by total body size. Although in a similar quasi-static 3-point bending rib test as [17], a significant relationship between moment and height in children was found [18]. To further explore the effect of total rib size on properties, a *post hoc* analysis on the sample in the current study was conducted utilizing the following measures of rib size: total length along the curvature of the rib (Cv.Le) and minimum linear length between the vertebral and sternal rib ends (Sp.Le). A significant ($p<0.0001$) correlation was found between total rib size, curve length (Cv.Le) and span length (Sp.Le), with body height (Pearson's $r = 0.447$ and 0.319, respectively), but not with body weight ($p = 0.624$ and 0.185, respectively). This is consistent with previous studies which found rib curve length to be associated with total body height [3,19]. However, in our study an additional *post hoc* analysis utilizing a linear regression reveals no relationship between Cv.Le or Sp.Le and any of the structural properties, suggesting more work needs to be done in this area. It is anticipated that rib cross-sectional geometry or microstructural variables will help provide additional understanding. For instance, in a simulation study, [12] found body height and weight to influence thoracic injuries, but that rib-specific measurements (e.g., area moment of inertia) could better account for overall thoracic responses and injuries.

Interestingly, [11] found that rib cross-sectional geometry (total cross-sectional area, cortical bone area, and section modulus) as well the combination of cross-sectional and gross geometry (robusticity and whole bone strength index) were all significant predictors of measured peak force and stiffness and can account for as much as 75% of the variation seen in these structural properties. Although skeletal morphology (i.e. gross geometry) is related to body size, the cross-sectional geometry is dependent on a variety of factors such as specific loading environment and genetics [20], and therefore may provide a way to account for these differences between individuals. This work provides preliminary evidence that inclusion of skeletal geometry may improve existing scaling techniques and allow for predictable adjustments to various populations (pediatric or elderly), however more research needs to be done in this area.

The trend in structural properties across discrete BMI classifications where each property increases from underweight to normal weight, continues to increase and peaks in the overweight category, but then is reduced in obesity, presents an interesting discussion topic. The described pattern, which is observable for all three structural properties, suggests a functional advantage in the form of higher resistance to bending as more body size is gained (taller and heavier), until a threshold where these benefits are then outweighed by the deleterious effects of obesity. The effect of obesity (i.e., excessive adipose tissue) on fracture risk is widely debated in the literature [21]. However, there is evidence that the trend observed in the current study is representative of fracture risk variations across BMI classifications seen in the clinical environment [22] suggesting that advanced obesity has negative impacts on bone quality [23]. These results should be approached with caution as there is great variation in the BMI data as seen in Figure 2, and there are unequal numbers of subjects in each BMI category.

Displacement was not included as a dependent variable in this study, because potential relationships with body size may be confounded by its typical presentation as a variable normalized by rib span length [2,16]. This complicated interaction will be explored in future work in conjunction with thoracic anthropometry (e.g., chest depth) to better understand how the size and shape of the thorax, is influenced by individual rib response. Additionally, it will be crucial to learn the specific role that individual rib response plays in overall thoracic response. This added layer of complexity will aid our understanding of thoracic injury risk, as this is based mostly on chest compression.

Sex was not included in the models presented here. Past work on a subset of this sample found sex to influence peak force, stiffness, and total energy [2]. However, these differences may have been due to sexual dimorphism, in which case including sex herein would confound the model using body size parameters. In fact, a *post hoc* analysis revealed significant differences in height and weight between males and females (student t-test, $p<0.0001$ for both), supporting the use of a pooled sample for this preliminary work. Future research aims to utilize a more complex statistical model able to tease out sex-differentiated structural properties while controlling for body size. Furthermore, a possible sampling bias could be influencing results as not all ages or body sizes are equally represented in the sample.

It was assumed here that linear regression models were appropriate for analysis of this dataset. While previous rib data analysis has utilized different and more complex modeling techniques [2,16], those results are very consistent with simple regression models as provided here, and therefore the analysis was simplified for this preliminary work. Future studies can further explore more complicated models and possibly non-linear fits.

V. CONCLUSIONS

Body size parameters have an effect on structural properties of human ribs, but even when included with age, predictive models still do not explain the majority of variation in peak force, stiffness, or total energy. Future work will investigate the relationship between thoracic anthropometry and rib size and properties. Additionally, more biologically-relevant variables related to the specific geometry, cross-sectional geometry, and microstructure of ribs will be explored as predictors of rib structural response to loading. These data can ultimately be advantageous to aid in improving size-based scaling techniques.

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