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Establishing a Hierarchical Approach to Explore Biological Contributors to Dynamic Response and Failure in the Human Thorax

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ABSTRACT

Establishing thoracic response targets and injury thresholds are important for design and validation of biofidelic Anthropomorphic Test Devices (ATDs) and computational models utilized to mitigate injury risk of vehicle occupants. This is done through extensive exploration of post-mortem human subject (PMHS) whole thoracic and rib properties, which has occurred for many decades with considerable success. However, the majority of research has focused on the 50th percentile male and relies heavily on population means or a select few individuals thought to best represent those population means. Little attempt has been made to understand the full breadth of human variation, mostly because of test sample limitations. Ultimately, a significant gap in knowledge remains; the biological mechanisms and anatomical variability that determines an individual's thoracic response and injury risk are not fully understood. It is therefore important to explore innovative ways to fully expand our understanding of thoracic variation to improve the tools used to decrease injury risk and protect ALL vehicle occupants. The objective of this study is to explore contributions to thoracic response and injury risk using a multi-phase, hierarchical approach to experimental testing and data analysis to elucidate mechanistic explanations.

Dynamic (2 m/s) experiments simulating a frontal impact conducted in the laboratory on ribs from donors of all ages (4-108 years) form the basis of this work (n=272). From individual ribs tests, structural properties are assessed (e.g., linear structural stiffness), and explanatory variables collected or calculated include curve length of the entire rib (global geometry) and total subperiosteal area (cross-sectional geometry). Novel cross-sectional geometric assessment provides highly precise variables from varied locations along the rib. At each location, and on a smaller anatomical scale yet, the rib cortex can be

assessed for its individual contributions utilizing histomorphometry (e.g., intracortical porosity). Subject-level variables are also included as explanatory variables, including demographics (e.g., chronological age).

The question remains of how individual rib properties contribute to whole thorax properties. The next phase of research is focused on answering this question through a similar hierarchical approach to testing as is used for data analysis. Some tested ribs are from individuals from which non-injurious thoracic tests are conducted, allowing a direct comparison between rib properties and thoracic properties. Ultimately, the established relationships will provide the basis for transfer functions to estimate thoracic properties from rib properties, which will be particularly useful to apply to the pediatric population since approval for pediatric PMHS testing is rare and difficult, but access and approval for testing pediatric rib specimens has been obtained for this study. This complex approach to finding mechanistic biological explanations for rib and thoracic properties will form a thorough understanding of why and how thoracic injuries occur, with the goal of identifying injury risk in all vehicle occupants, especially children and others farther from population means (i.e., more or less vulnerable).

INTRODUCTION

The thorax is frequently injured in motor vehicle crashes, with rib fractures occurring most commonly. Rib fractures are associated with increased morbidity and mortality, especially because of their relationship with internal organ injury (Lee et al. 2015). Establishing thoracic response targets and injury thresholds are important for design and validation of biofidelic Anthropomorphic Test Devices (ATDs) and computational models utilized to mitigate injury risk of vehicle occupants. Extensive testing has been conducted over the past decades to elucidate thoracic response in a variety of loading conditions. The majority of this work has been focused on the 50th percentile male post-mortem human subject (PMHS) and anthropomorphic test device (ATD). The injury biomechanics community has made significant advances in automotive safety based on this work to protect this main portion of the population. However, those individuals that represent the extremes (e.g., pediatric or elderly individuals) remain at high risk as less is understood about their thoracic response to loading. It is therefore important to explore innovative ways to fully expand our understanding of thoracic variation to improve the tools used to decrease injury risk and protect ALL vehicle occupants. The objective of this study is to explore contributions to thoracic response and injury risk using a multi-phase, hierarchical approach to experimental testing and data analysis to elucidate mechanistic explanations.

METHODS

This study is framed around identifying variation in rib properties and utilizing the measured individual rib response as common ground to 1) explain mechanisms for rib response and failure, and 2) characterize the relationship between individual rib and whole thoracic response.

Individual Rib Testing

Two hundred seventy two (272) mid-level (4-7) ribs from one hundred fifty two (152) PMHS have been tested to date. Sex and age of individuals from which ribs were acquired from the Body Donor Program of The Ohio State University or Lifeline of Ohio are shown in Figure 1. This includes 47 females and 105 males ranging in age from 4 to 108 years at the time of death. After procurement, ribs were immediately 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. Total curve length (Cv.Le) of the rib was measured from head to costochondral junction and the ends potted in Bondo ® Body Filler (Bondo Corporation, Atlanta, GA). Bondo ® was prepared such that the temperature of curation was not greater than approximate body temperature. Four strain gages (CEA-06-062UW-350, Vishay Micro-Measurement, 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.

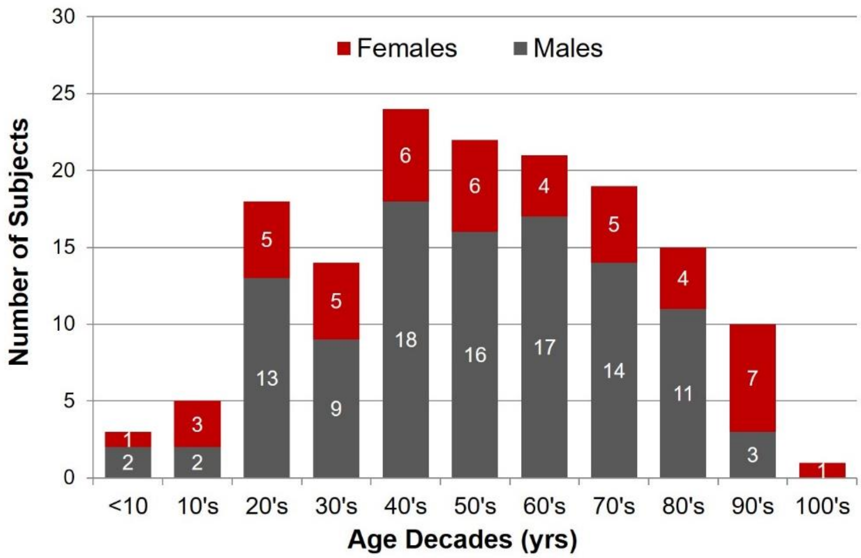

Figure 1: Subject demographics divided by sex (F = red, M = gray) and age decades from which ribs were tested.

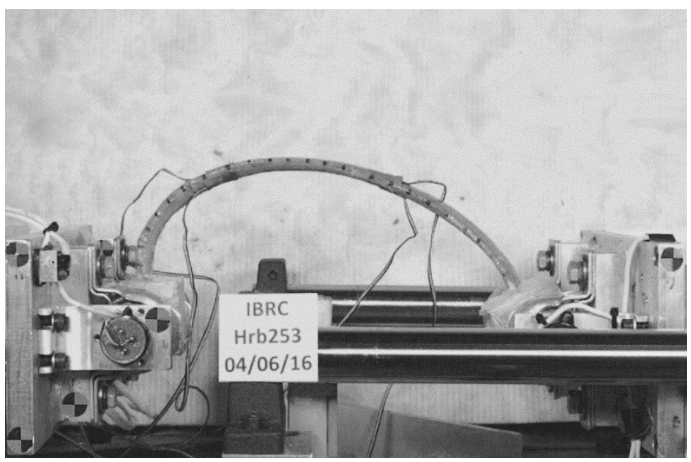

Figure 2: Exemplar human rib in the test fixture prior to testing

Ribs were dynamically tested in a custom-built pendulum fixture. The experiment simulated a 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. Both potted ends of the ribs were fixed in freely rotating cups during the event. A 54.4 kg pendulum impacted ribs at 1-2 m/s. Displacement of the sternal end of the rib was measured by a linear string potentiometer (Rayelco P-20A, AMETEK, Inc. Berwyn, PA) attached to the moving plate of the fixture. Forces were recorded by a 6-axis load cell (CRABI neck load cell, IF-954, Humanetics, Plymouth, MI) located behind the fixed plate. Peak force (F_{PEAK}) was defined as the maximum force in the primary loading direction, X, prior to failure. Linear structural stiffness (K) was calculated as the slope of 20–80% of the elastic portion of the force-displacement curve (see Agnew et al. 2015).

Sections were removed from the fracture location after testing, cleaned of all soft tissue, and embedded in methymethacrylate. Thin-sections (~70 µm) were cut and mounted on slides according to standard histological procedures, and then cross-sectional images were obtained at 40x magnification with an

Olympus VS120 slide scanner. Measurements were manually made in cellSens Dimension® imaging software (Olympus Corporation) to obtain total subperiosteal area (Tt.Ar) and cortical area (Ct.Ar). Rib robusticity was calculated as Tt.Ar/Cv.Le. The area of porous spaces (Po.Ar) within the cortical boundaries was manually measured and subtracted from Ct.Ar to establish an absolute area of the amount of bone within the rib cortex, bone area (B.Ar).

Thoracic Hierarchy Testing

In order to better understand the results of individual rib testing in the context of the intact thorax, a series of non-injurious frontal impacts (<20% chest deflection) were conducted on one male PMHS (79 years). Prior to impact, the subject was instrumented with strain gages at 30% and 60% of the Cv.Le for rib levels three through eight, allowing for direct comparisons between thoracic and individual rib testing. The impacts were delivered using a pneumatic ram at a speed of 2.7m/s, resulting in an approximate strain rate of 0.5/s. The ram face was a 6.0 x 12.0 x 0.5" rectangle with an impactor mass of 23kg and was centered vertically and horizontally on the center of the subject's sternum. The subject was tested in a fixed-back scenario for all impacts and chest deflection was then calculated from the linear displacement potentiometer (Celesco CLWG-600-MC4, TE Connectivity Co., Berwyn, PA) attached to the impactor face. A 6-axis load cell (Denton 2944JFL, Humanetics, Plymouth, MI) attached to the impactor face was used to measure forces at impact location. To quantify the effect of all thoracic components, each subject was tested in three subsequent tissue states: intact, denuded (superficial tissue removed), and eviscerated (superficial tissue and viscera removed). Force-deflection curves from each impact were generated for each tissue state. Following eviscerated testing, ribs four through seven were removed and tested to failure in the dynamic bending scenario described above (Figure 2).

RESULTS

Individual Rib Testing Results

The approach to data analysis for the larger rib properties project can be summarized as a map of biological hierarchical levels (Figure 3). An example from each level of data analysis is provided here as compared to measured structural properties situated near the center of the hierarchy.

An example of rib variation being predicting by subject level variables was explored using calculated linear structural stiffness (structural property) and chronological age (subject level variables). Figure 4 depicts the large amount of variability in linear structural stiffness observed in this sample, ranging from 0.5 – 9.5 N/mm. Furthermore, almost this entire range of stiffness is seen across all decades of life. With the large sample size, the 95% confidence interval for stiffness when regressed against age is narrow, however the 95% prediction interval is so wide that it becomes essentially meaningless. In other words, rib stiffness cannot be accurately predicted by the chronological age of an individual, as age explains merely 5% of the variance in stiffness.

Moving down the hierarchical levels, an additional example is provided utilizing rib geometry to once again predict linear structural stiffness. Robusticity is frequently applied to long bones of the appendicular skeleton to predict material and mechanical properties (Jepsen et al. 2011). However, the unusual geometry of the rib makes traditional measures of robusticity, a simple relationship between transverse expansion and longitudinal growth, difficult to define. Figure 5 indicates the combination of the overall geometry and cross-sectional geometry of the rib is a valuable tool for explaining variation in linear structural stiffness, with an R^2 of 0.68. Robusticity has added value due to the potential ability of obtaining the required variables from a clinical CT.

When incorporating a smaller hierarchical level into analyses, the effect of histomorphometry can be assessed, specifically intracortical porosity in this example. The preliminary findings reported here indicate that B.Ar is a better predictor of peak force than Ct.Ar, and accounting for intracortical porosity marginally improves regressions (Fig 6). Furthermore, while a reduction in bone due to increased intracortical porosity by itself may not meaningfully influence structural response to loading, these results do indicate that even microstructural differences in bone structure can alter the rib resistance to loading as measured by peak force.

Future research will incorporate other histomorphometric variables into analyses of structural and material rib properties.

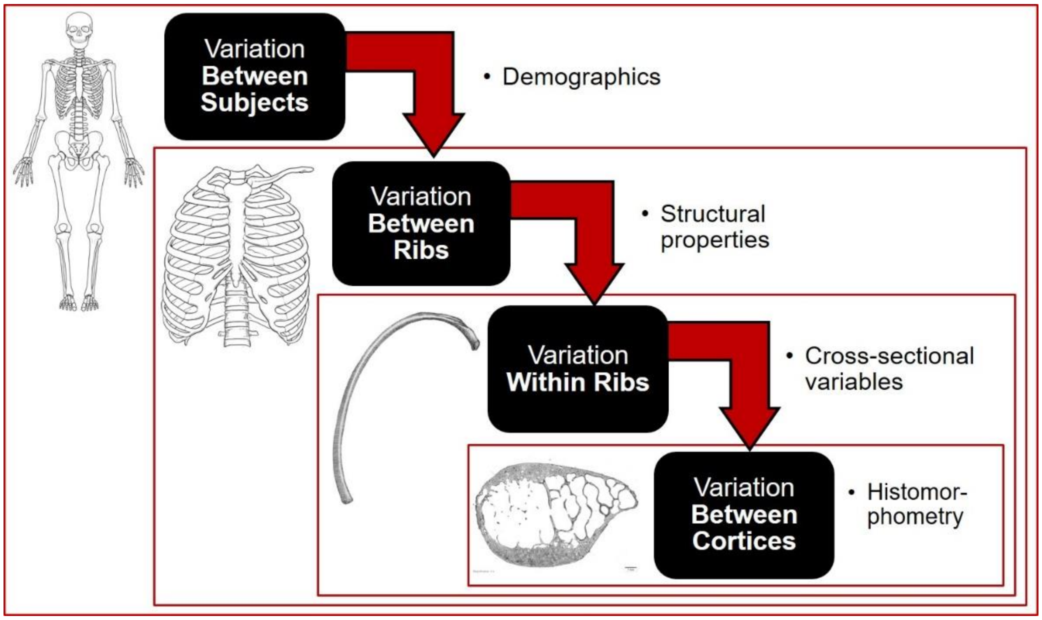

Figure 3: Schematic of approach to data analysis

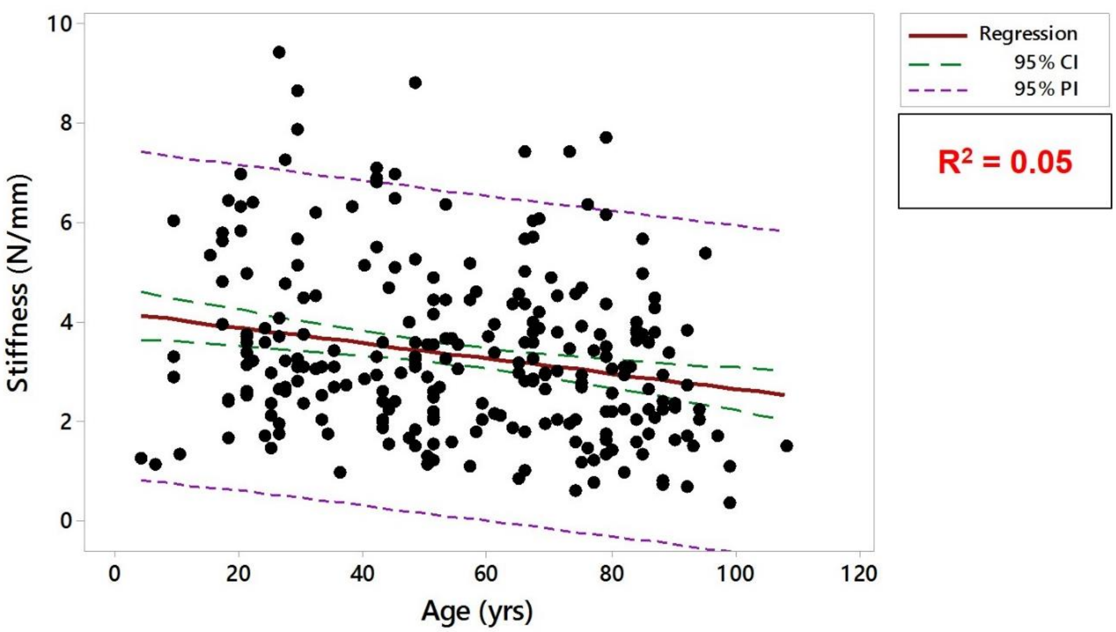

Figure 4: Scatterplot of age and linear structural stiffness indicating a narrow confidence interval and the wide prediction interval, strongly showing that age is a poor predictor of rib stiffness.

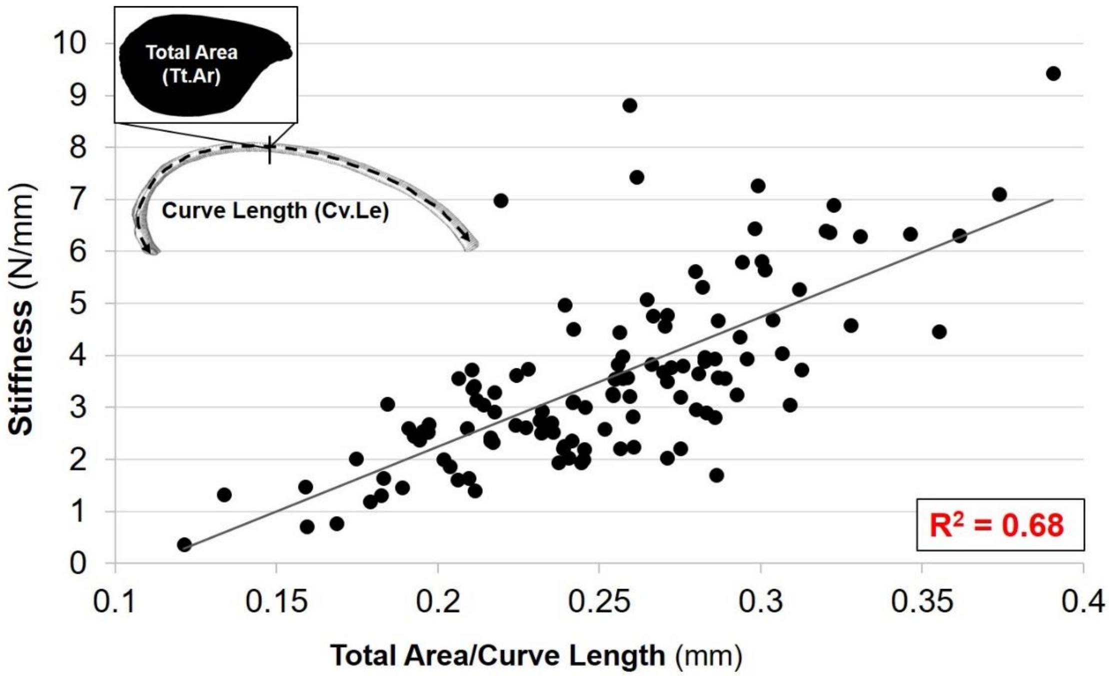

Figure 5: Scatterplot of robusticity (Total Area/Curve Length) and linear structural stiffness indicating a strong relationship and the successful ability of robusticity to explain variance in stiffness (68%).

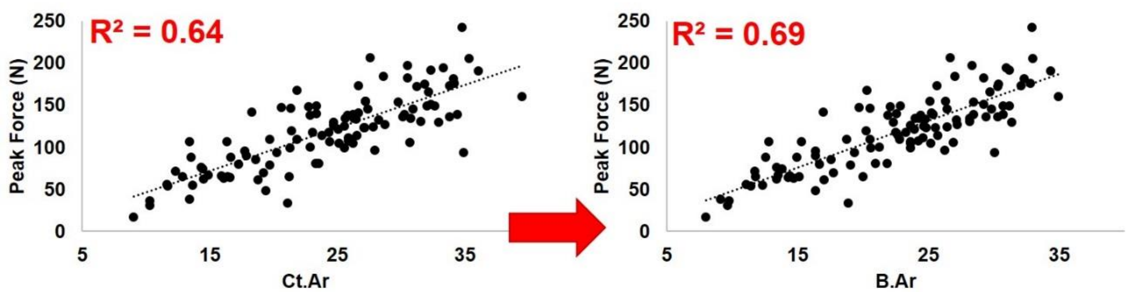

Figure 6: Scatterplots indicating the strong linear relationship of cortical area (Ct.Ar) and peak force of ribs (left) and the improved relationship when porosity is accounted for in cortical area measures, more appropriately called a true bone area (B.Ar) and peak force (right).

Thoracic Hierarchy Results

Force-deflection curves for the intact, denuded, and eviscerated test conditions can be found in Figure 7. Due to concerns about causing fracture, the deflection allowed for the denuded and eviscerated conditions was much less than that of the intact condition. However, the response data still show a linear portion following the initial inertial response, allowing for a comparison of stiffness to eventually be made across all tests.

Additionally, strain gage data as well as examination at autopsy revealed no ribs fractures, validating that the impacts were non-injurious as designed.

Focusing on the inertial response portion of the force-deflection curves in Figure 7, one can see a distinct incremental change in the inertial response as superficial tissue and viscera was removed. Also, when looking at the overall force-deflection response, it is evident that the removal of tissue, whether it was superficial tissue or viscera, resulted in a decrease in the force-deflection response. Visual inspection reveals that the largest effect on thoracic response can be attributed to removal of the viscera, as the eviscerated force-deflection response is much lower than that of the intact and denuded. These results parallel the findings of Kent 2008, as he found that denuded thoraces retained approximately 60% and eviscerated thoraces only retained 30% of their intact stiffness when tested under similar loading environments as the one presented in this study.

A cumulative force-deflection response for the eight individual ribs tested following eviscerated testing can also be found in Figure 7. This cumulative rib response was calculated by summing the force data generated during each individual rib test and averaging the displacement data according to Equations 1 and 2, respectively. This method of analysis essentially treats each individual as a spring acting in parallel with the remaining ribs in the thorax, similar to the analysis presented by Kindig et al. 2010. Although this cumulative model lacks the initial inertial response, it is evident that the slope of the cumulative rib model is very similar to the linear portion of the eviscerated response curve, indicating the potential usefulness of a parallel spring model for bridging the gap between the individual rib and thoracic response.

$$Force = \sum_{i=1}^{n} F_n(t) \quad (1)$$

$$Displacement = \frac{1}{n}\sum_{i=1}^{n} D_n(t) \quad (2)$$

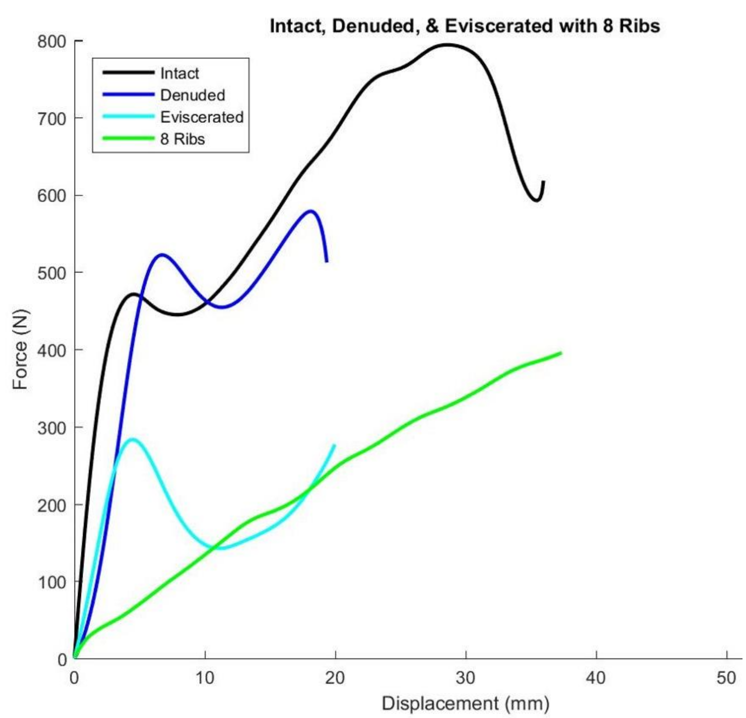

Figure 7: Force-displacement curves for various test conditions to one PMHS thorax

CONCLUSIONS

We have successfully established that subject-level variables (e.g., age) play only a small role in predicting rib response to loading on an unprecedented large sample size. Furthermore, we have shown that more localized variables occurring at the rib level are more appropriate for explaining variation in structural properties. These findings highlight the need to explore more biologically relevant explanatory variables to gain a more comprehensive understanding of variation in rib response between and within individuals. The preliminary findings explaining the differences in thoracic response in different tissue-states is a first step towards understanding the role the individual rib response plays in the overall response of the thorax.

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REFERENCES

AGNEW, A.M., SCHAFMAN, M., MOORHOUSE, K. WHITE, S.E, and KANG, Y-S. (2015). The effect of age on the structural properties of human ribs. J. Mech. Behav. Biomed. Mater., 41, 302-314.

JEPSEN, K.J., CENTI, A. DUARTE, G.F., GALLOWAY, K., GOLDMAN, H., HAMPSON, N., LAPPE, JOAN M., CULLEN, D.M., GREEVES, J., IZARD, R., NINDL, B.C., KRAEMER, W. J., NEGUS, C.H., EVANS, R.K., (2011). Biological Constraints That Limit Compensation of a Common Skeletal Trait Variant Lead to Inequivalence of Tibial Function Among Healthy Young Adults. J. Bone Miner. Res. 26, 2872–2885.

KENT, R., (2008). Frontal thoracic response to dynamic loading: the role of superficial tissues, viscera and the ribcage. Int. J. Crashworthiness, 13, 289-300.

KINDIG, M.W., LAU, A.G., FORMAN, J.L., KENT, R.W., (2010). Structural Response of Cadaveric Ribcages under a Localized Loading: Stiffness and Kinematic Trends. Stapp Car Crash J., 54, 337-380.

LEE, E.L., CRAIG, M., SCARBORO, M., (2015). Real-World Rib Fracture Patterns in Frontal Crashes in Different Restraint Conditions. Traffic Inj. Prev., 16, S115-S123.

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