REGIONAL VARIATION IN THE STRUCTURAL RESPONSE AND GEOMETRICAL PROPERTIES OF HUMAN RIBS

Joseph M. Cormier
Joel D. Stitzel
Stefan M. Duma
Virginia Tech – Wake Forest, Center for Injury Biomechanics
Blacksburg, Virginia

Fumio Matsuoka
Toyota Motor Corporation

ABSTRACT

By incorporating material and geometrical properties into a model of the human thorax one can develop an injury criterion that is a function of stress and strain of the material and not a function of the global response of the thorax. Previous research on the mechanical properties of ribs has focused on a limited set of specific ribs. For this study a total of 52 rib specimens were removed from four cadaver subjects. Variation in peak moment by thoracic region was significant ($p < 0.01$) with average values of 2, 2.9 and 3.9 N-m for the anterior, lateral and posterior regions respectively. Two geometrical properties, radius of gyration and distance from the neutral axis, showed significant variation by region ($p < 0.0001$) as well as by rib level ($p = < 0.01, 0.05$). The results of this study can be used to update current models of the human thorax to account for the variation in strength and geometrical properties throughout the rib cage. Accounting for the variation in rib properties by region will improve injury predictive measures and, therefore, the ability to design systems to prevent thoracic injury.

The human thorax is of particular importance due to its role in protecting life-essential organs of the human body. From an automotive safety standpoint, the thorax presents an essential load-bearing structure used to support the body against the vehicle restraint system. As a consequence of this dual role, the response of the thorax to external loading has been the focus of many previous investigations. The global response of the thorax has been investigated by subjecting restrained cadavers to a variety of sled test conditions (Cesari & Bouquet 1990, Eppinger *et al.* 1978, Eppinger *et al.* 1984, Kallieris *et al.* 1974, Kallieris *et al.* 1998, Kuppa & Eppinger 1998, Nahum *et al.* 1975, Viano *et al.* 1978, Walfisch *et al.* 1985). These sled tests are used to derive predictive measures of rib fracture based on measured responses such as chest acceleration, chest deflection and spine acceleration as well as the age of the subject. These tests are useful for developing criteria for thoracic injury such as the number of rib fractures, which can then be related to the threat to life of a living occupant using the Abbreviated Injury Scale (AIS). Computational modeling can be used by adjusting material properties to match the response of cadaver subjects. This method may produce accurate results when the model is used under similar loading conditions, however, in order to apply the same model to different loading conditions, another series of validation tests may be required to ensure accurate results. The purpose of this paper is to determine the structural and geometrical properties of human ribs and to examine the variation of these properties by region.

Research on the mechanical properties of ribs has focused on a limited set of specific ribs. Stein and Granik (1972) performed three-point bending tests on 52 rib sections taken from the 6th and 7th ribs. Their specimens were simply supported at a span of 10.2 cm. Using loading rates of 0.05, 0.25 and 1.3 cm/min they reported a statistically significant increase in failure stress with increasing loading rate. The values for failure stress were reported to be, 85.5, 87.6 and 97.9 MPa for the slowest to fastest loading rate respectively. The corresponding values for Young's modulus were 10.2, 9.79 and 9.24 GPa. Then in 1973, Granik and Stein performed additional three-point bending tests utilizing the same ribs and end conditions. They reported an average elastic modulus of 11.5 GPa and an average failure stress of 106 MPa for rib specimens tested without evident abnormality.

Considering a larger number of ribs, Schultz *et al.* (1974) determined the deformation characteristics of ribs 2, 4, 6, 8, 9 and 10 from five male thoraces. The ribs were loaded in a fixed-free condition by potting the head of the rib in acrylic bone cement and hanging a single weight from a metal pin pierced through the rib. The rib sections included the costal cartilage up to the sternum and therefore the deformations reported in the study include the contribution of the costal cartilage. The deflections produced as a result of the 7.5 N force were 3 cm for the upper ribs and 6 cm for the lower ribs, on average.

A more recent study by Yoganandan and Pintar (1998) performed three-point bending tests on 120 specimens from 30 subjects. Sections, 150 mm in length, were removed from the 7th and 8th ribs. The rib sections were simply supported at a span of 100 mm and loaded at a quasistatic rate of 2.5 mm/min. The results did not indicate a significant difference in mechanical properties between the two ribs considered. The average peak force was 153 N for the 7th and 137 N for the 8th rib, with corresponding average peak deflections of 0.3 cm and 0.32 cm. The average Young's modulus was 2.3 and 1.9 GPa for the 7th and 8th rib respectively. In their concluding remarks, the authors noted that if automotive applications are of interest, higher loading rates should be considered.

The previous research does provide insight into the mechanical properties of the human thorax. This knowledge is, however, limited in that it cannot address the variation in rib properties at different regions of the thorax. This issue has been addressed in a study by Stitzel *et al.* (2003) by obtaining material properties of cortical specimens from the anterior, lateral and posterior regions of the thorax. These specimens, comprised of cortical bone from the exterior rib surface, were subjected to three-point bending at an average loading rate of 356 mm/s. The results of the study indicated that there is a regional variation in the material properties of the human thorax which, when accounted for, altered the number and location of predicted rib fractures. Because AIS scores are dependent on the number of rib fractures, accurate models of the rib cage are necessary to predict the number of rib fractures for a given loading condition. The benefit of models based on geometrical and mechanical properties is their applicability to various loading conditions without the need to validate the model for each condition. The purpose of this study is to investigate the variation of mechanical and geometrical properties using whole rib specimens removed from the anterior, lateral and posterior regions of the thorax.

METHODOLOGY

A total of 52 rib specimens were removed from four cadaver subjects (2 male, 2 female) (Table 1). The cadavers were previously frozen and thawed at room temperature prior to removing test specimens. Test specimens were removed from ribs 2 through 12 on the right side of each thorax (Figure 1). The length of each specimen was determined by the longest section that could be removed and still produce a usable specimen. The lower ribs were more consistent in geometry and, therefore, specimens of similar lengths could be prepared from these ribs. The ribs were removed using an autopsy saw and were wrapped in saline-soaked gauze and stored in an air-tight container. The periosteum was left intact to minimize the invasiveness of the procedure and to mitigate bone deterioration. The bone mineral content of the cadaver subjects was determined by using the Osteogram® technique (Osteogram®, San Diego, CA). The BMD Index is not the actual bone mineral density, but rather an index number relative to other Osteogram® scans. More useful outputs from this technique are the BMD T-score, and BMD Z-score. The BMD T-score represents the number of standard deviations away from the average the subject's bone mineral content is compared to the average healthy individual between 25 and 50 years. The positive or negative T-score value denotes greater or lower bone mineral density respectively. T- scores at -1.0 or greater are considered normal, between -2.5 and -1.0 indicates a low bone mineral density, and below -3.0 is considered osteoporotic. The Z-score is the number of standard deviations away from the average bone mineral density of females at the subject's age. The Z-score is particularly important for females due to the decrease in bone mineral density after menopause and, therefore, is not reported for males.

Table 1: Cadaver data for specimens used during current work.

Subject	Gender	Age	Mass (kg)	BMD Index	T-score	Z-score
1	Male	71	71	90.3	-1.9	N/A
2	Female	61	54	77.9	-3.0	-1.2
3	Male	61	117	83.2	-2.5	N/A
4	Female	67	63	75.2	-3.3	-1.0

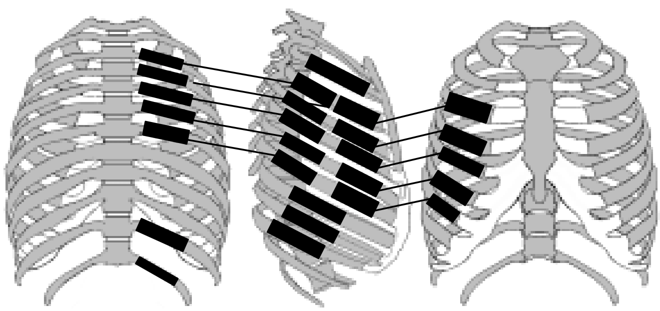


Figure 1: Location of rib specimens used for dynamic three-point bending analysis (posterior view on left, lateral and anterior at right; connecting lines represent same specimen).

The rib specimens removed from the anterior region of the thorax were loaded in the anterior-posterior direction. This placed the interior surface of the rib in tension, which would be expected when the thorax is exposed to seat belt loading during an automobile collision (Yoganandan *et al.* 1991, 1993). The lateral rib specimens were loaded in the medial-lateral direction, which placed the exterior surface of these specimens in tension. This loading state at the lateral region of the thorax is due to the compression of the thorax in the anterior-posterior direction during a frontal impact. The posterior rib specimens were loaded in the posterior-anterior direction, creating tensile forces on the internal surface of the rib specimen. This loading condition was shown in anterior-posterior chest compression of cadaver and case study investigations (Yoganandan *et al.* 1991, 1993, Kleinman *et al.* 1997). Tensile loading at the interior surface of the posterior region was shown to be a result of interaction with the transverse processes of the thoracic spine.

Before testing, a strain gage (Model CEA06062UW350, Vishay Measurements Group, Raleigh NC) was attached to the surface of the rib exposed to tensile strain. An area of periosteum, slightly larger than the strain gage was removed from the central region of each rib. The strain gage was positioned in the middle of the rib span and attached using the manufacturer's suggested procedure.

An MTS (Model 810, MTS, Raleigh, NC) servohydraulic test machine was used to apply the dynamic loading to the rib specimens (Figure 2). A load cell was attached to the impacting blade of the device to measure the load imposed on the rib specimen during the event (Model 1210AF, Interface, Scottsdale AZ). The MTS machine was equipped with a Microcontroller (Model 458, MTS, Raleigh, NC) and Microprofiler (Model 418.91, MTS, Raleigh, NC) that delivered the loading signal causing an average displacement rate of 500-1000 mm/sec. An Iotech Wavebook data acquisition system (Wavebook 516, Iotech, Cleveland, OH) was used to record data during the event at 10kHz. The motion occurring during each test was also recorded using high speed digital video (Phantom 5, Vision Research, Wayne, NJ) at 1000 fps.

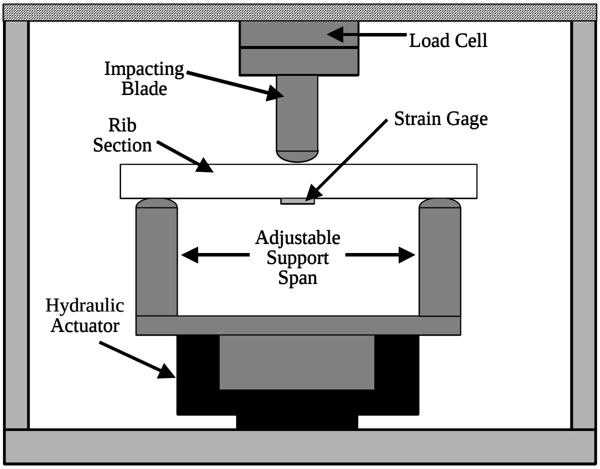


Figure 2: Apparatus used to evaluate human rib response to dynamic three-point bending.

Initial testing was performed using rib sections instrumented with a rectangular stain gage rosette. The center gage was oriented parallel to the rib axis at the center of the rib. The remaining two gages were offset 45 degrees from the center gage in either direction. Initial data using the stain gage rosettes was used to determine the orientation and magnitude of the principal strain in each rib during dynamic bending. The initial tests revealed that the principal strain direction deviated an insignificant amount from the axis of the rib and, therefore, the remaining tests were performed using a single axis strain gage configuration.

Cross sectional area of the ribs was determined using digitized photography of cross sections after testing. The sections were removed from an area near the fracture site. Area, moment of inertia (Ixx), distance to the neutral axis (c) and radius of gyration (kx) were determined for each cross section. Moment of inertia describes the cross section's ability to resist rotation and is an important property in defining the bending strength of a structural member. Generally, as moment of inertia increases, the bone's ability to resist bending also increases. The distance to neutral axis (c) is defined as the distance from the axis about which the bone is bending to the farthest surface of the bone, in this case it would be the distance to the strain gage. Radius of gyration (kx) is a relation that describes how far from the center of the cross section the area of the bone is located. This parameter will distinguish between a cross section with a wide area that is near the center and a cross section which has a thin strip of bone located farther away from the center. Each of these cross sections could have the same moment of inertia, but will exhibit a different radius of gyration.

Statistical variations as well as basic trends were examined between specimens from the three regions as well as between rib levels. To account for the dependence of region and level effects on the corresponding subject, a linear regression was performed on each response variable. The regression model was chosen within SAS (SAS Institute Inc., Cary, NC, USA.) to predict the response variable based on each region which was nested within each subject. This accounts for the interaction between region and subject and allows for F tests to be used to assess the significance of region effects. The ANOVA statistics produced using the same model were used to test the null hypothesis that there is no effect of region of rib level for the given response. The ANOVA p – values represent the probability that the effect of a given parameter is not zero.

RESULTS

The data collected during this study were used to examine the variation in rib strength and geometry between locations in the rib cage of four human subjects (Table 2). For clarity, the results will be reported using test number of the form i.j.k., where i is the subject number, j denotes the region the rib was removed from (A=anterior, L=lateral, P=posterior) and k denotes the rib level (2-12). For example, test specimen 1.A.3 would indicate a section removed from subject 1, in the anterior section of rib three. Due to the characteristics of the rib response, two strain values will be reported: strain at peak force (Pstrain) and overall maximum strain (Mstrain). All comments regarding statistical significance by region or rib level refer to the significance of the effect of the location by controlling for subject effects.

Table 2: Geometric and Strength Parameters

Test	Ixx mm^4	c mm	kx mm	Pmoment N - m	Pstrain µStrain	Mstrain µStrain
1.A.3	57.8	3.0	1.5	2.6	6824	15035
1.A.5	94.4	2.9	2.1	3.4	6164	6164
1.L.2	65.3	2.4	1.8	2.2	4554	10833
1.L.8	79.9	2.5	1.7	4.8	16546	16546
1.L.9	66.2	2.4	1.5	4.8	17754	17754
1.P.3	78.2	3.1	1.8	3.3	14438	17556
1.P.5	123.1	3.6	2.2	6.4	10092	10092
1.P.6	160.6	3.8	2.4	6.7	10271	11888
1.P.7	140.9	3.3	1.8	6.9	15873	25569
2.A.5	31.8	2.0	1.4	1.5	5196	6168
2.A.6	36.0	2.2	1.4	1.5	7541	7541
2.A.7	38.2	2.1	1.4	1.2	4058	5428
2.L.2	14.7	1.7	1.0	0.8	8671	17852
2.L.8	36.5	2.2	1.3	2.0	9129	9129
2.L.9	38.1	2.4	1.3	2.0	8866	8866
2.L.10	23.2	2.1	1.0	1.7	7596	7596
2.P.3	27.2	2.2	1.2	2.0	8739	8739
2.P.4	70.4	3.0	1.8	2.1	5680	6681
2.P.5	62.3	3.0	1.6	3.1	9254	12468
2.P.6	37.6	2.2	1.4	3.1	17667	21832
2.P.7	39.2	2.2	1.3	3.4	18716	18716
2.P.11	16.6	1.6	1.0	1.5	15408	15408
2.P.12	21.0	1.7	1.0	1.0	9393	12340
3.A.4	84.5	3.1	1.9	1.1	6240	7978
3.A.5	84.9	3.0	1.8	2.1	5675	6696
3.A.6	126.2	2.9	2.2	2.5	5651	5651
3.A.7	86.2	2.8	1.8	2.4	5441	10396
3.L.2	84.6	2.9	1.8	1.4	5556	5556
3.L.8	91.8	2.7	1.7	3.9	9186	10235
3.L.9	71.5	2.5	1.4	4.3	8816	12692
3.L.10	42.0	2.3	1.2	3.5	16993	21144
3.P.3	108.1	4.0	2.0	4.4	11893	11893
3.P.4	121.0	4.4	1.9	5.4	13254	15678
3.P.5	118.1	3.7	2.0	3.7	8002	9590
3.P.6	230.7	4.2	2.8	6.4	12686	21297
3.P.7	175.1	3.8	2.2	5.0	6010	13215
4.A.3	48.3	2.8	1.5	1.5	4598	8775
4.A.4	80.3	2.5	1.7	1.7	3976	18329
4.A.5	129.0	3.1	2.1	2.5	5656	19429
4.A.6	75.2	2.8	1.8	1.6	4026	18301
4.A.7	102.4	2.7	1.8	2.6	5941	15184
4.L.2	46.5	2.3	1.5	1.6	5869	10665
4.L.8	67.2	2.8	1.7	3.8	10459	10459
4.L.9	80.0	2.6	1.6	3.7	9487	9487
4.L.10	66.4	2.4	1.4	4.5	21635	29918
4.P.3	35.2	2.2	1.3	2.0	10191	17328
4.P.4	77.6	3.2	1.9	3.3	11133	34711
4.P.5	110.6	3.2	2.0	4.7	4553	4553
4.P.11	44.6	2.1	1.3	3.7	25327	25327

Structural Response

Peak moment was found to correlate with subject in the ANOVA analysis ($p < 0.01$). Comparing means by region did indicate significant differences between regions for peak moment (Pmoment) (Figure 3), strain at peak force (Pstrain) and maximum strain (Mstrain) (Table 3 and 4).

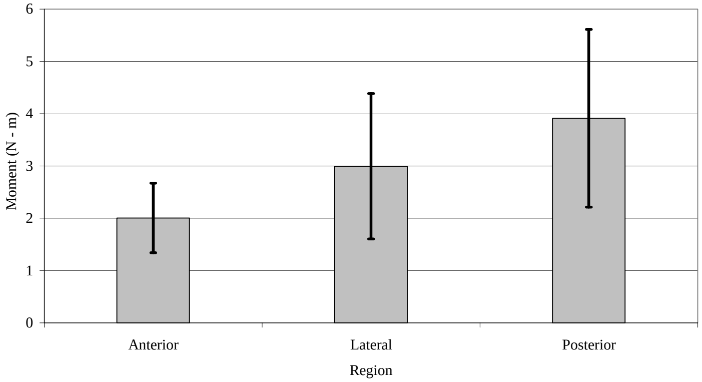


Figure 3: Mean peak moment by region with one standard deviation.

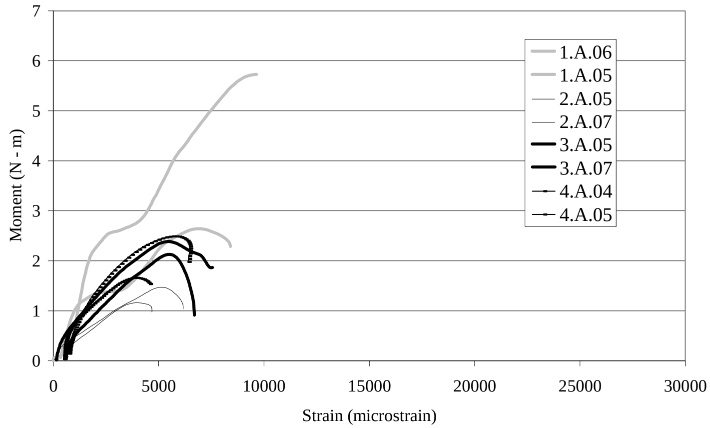
Table 3: Results from t-tests comparing means among mechanical and material properties.

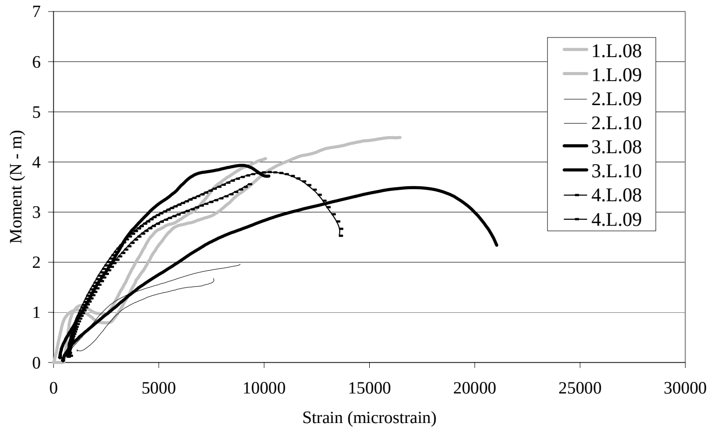
	Comparison	P value	Comparison	P value
P moment	Ant < Lat	0.02	Ant < Post	< .0001
	Lat < Post	0.0042		
Strain	Ant < Lat	0.0056	Ant < Post	0.0006
P Strain	Ant < Post	0.0141		

Table 4: Mean and standard deviation for structural response by region.

Mean	Strain	P moment	P Strain
Standard Deviation	microstrain	N m	microstrain
Anterior	5432	4.0	10552
	1056	1.3	5172
Lateral	10741	6.0	13249
	5054	2.8	6346
Posterior	11822	7.8	15847
	4756	3.4	7029

Strain at peak force was found to be related to rib level ($p = 0.01$). The trend indicated an increase in strain at ribs 10 (15,000) and 11 (20,000). The remaining ribs had peak strain values in the range of 6,000 to 11,200 microstrain. Maximum strain at the anterior region was found to be lower than that of the posterior specimens (p = 0.0141). Both trends in peak strain were evident when examining moment – strain traces for the various regions (Figure 4). The measured strain was assumed to be the maximum strain in all cases. This is a reasonable assumption due to the occurrence of fracture at the strain gage in 48 of the 54 specimens. In the other six cases, the strain values were not remarkably different from comparable tests, therefore, these values were assumed to be within the variation caused by the rib specimens and not location of the strain gage.





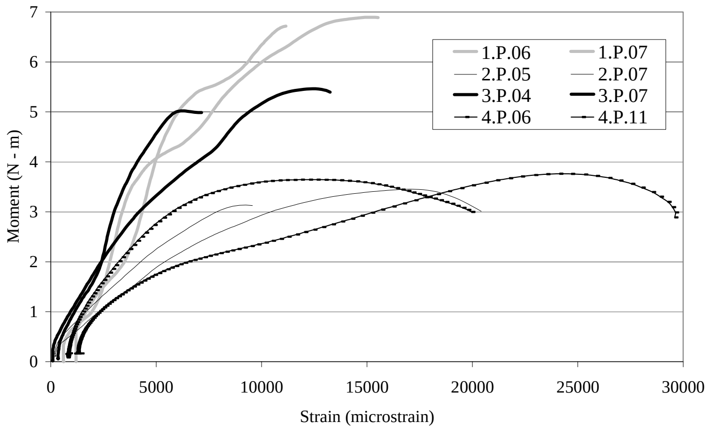


Figure 4: Representative moment - strain traces for specimens removed from the anterior, lateral and posterior thoracic regions.

Geometrical Properties

Subject and gender were statistically correlated with the four rib geometry parameters. Analysis of the means between subjects revealed that the geometrical parameters of subject two were statistically different from all other subjects (Figure 5).

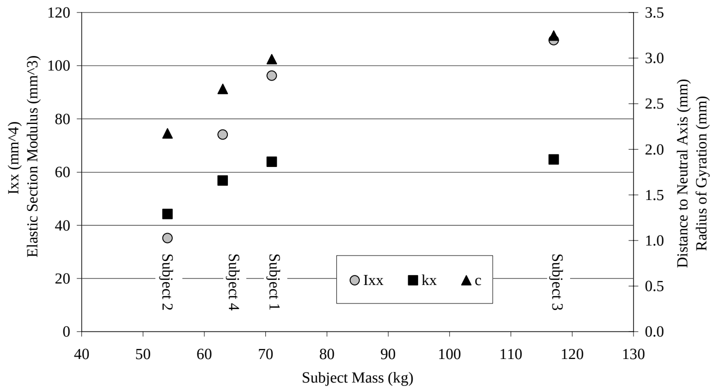


Figure 5: Mean geometrical properties by subject mass (Ixx – moment of inertia; kx – radius of gyration; c – distance to neutral axis).

Among the geometrical parameters, radius of gyration (kx) ($p < 0.0001$) distance to the neutral axis (c) ($p < 0.0001$) moment of inertia (Ixx) ($p < 0.0001$) and area ($p = 0.0012$) were statistically correlated with region. Statistically significant differences were found between means of various geometrical parameters by thoracic region (Table 5, 6; Figure 6). Radius of gyration ($p < 0.01$) and distance to neutral axis ($p = 0.05$) were also statistically related to rib level (Figure 7).

Table 5: Statistically significant variation in geometry by region.

	Comparison	**P value**	**Comparison**	**P value**
Ixx	Ant < Post	0.0354	Lat < Post	0.0005
kx	Ant > Lat	0.0189	Lat < Post	0.001
c	Ant < Post	0.0026	Lat < Post	< .0001

Table 6: Mean and standard deviation for geometrical parameters.

Mean	Ixx	c	kx
Standard Deviation	mm^4	mm	mm
Anterior	76.8	2.7	1.7
	31.3	0.4	0.3
Lateral	58.3	2.4	1.5
	23.3	0.3	0.3
Posterior	89.9	3.0	1.7
	58.1	0.8	0.5

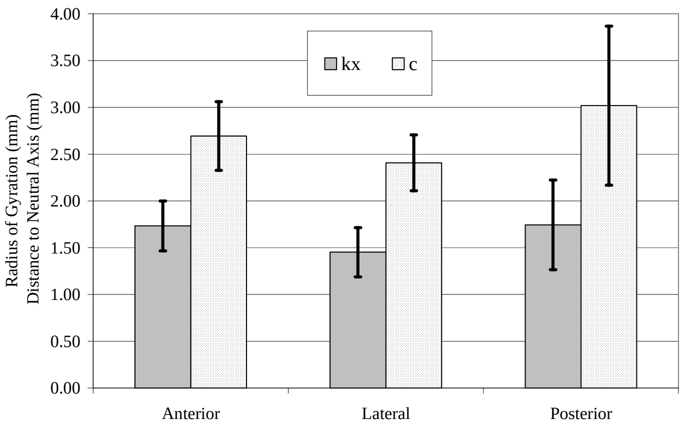


Figure 6: Mean values of Radius of Gyration and Distance to Neutral Axis by Region.

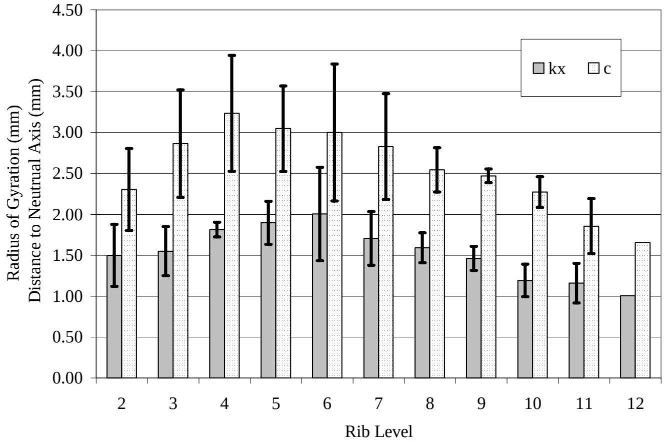


Figure 7: Radius of gyration and distance to neutral axis by rib level.

DISCUSSION

This study describes the regional variation in structural and geometrical properties of three regions in the thorax of four human subjects. For the comparable rib sections, the results are consistent with a previous study by Yoganandan and Pintar (1998) who reported peak moments of 3.8 and 3.4 N-m for the 7^{th} and 8^{th} ribs respectively. In the current study, the mean failure moment for all regions of the 7^{th} and 8^{th} ribs was 3.6 N-m and 3.2 N-m for the lateral region of the 8^{th} rib.

Although not statistically significant, there was a trend indicating an increase in moment of inertia (Ixx), distance to the neutral axis (c) and radius of gyration (kx) with an increase in subject mass. The geometrical parameters were statistically lower for the female subjects, which could also be related to subject mass. The correlation between gender and peak moment could also be a function of mass and bone quality since the female subjects had a lower BMD value than either of the male subjects. In contrast, subject 1, the oldest subject with the second highest mass and highest BMD, exhibited the highest peak moment and strain across all regions.

Examining the relationship between section modulus (I/c) and peak moment reveals interesting trends between regions and subjects (Figure 8). For all subjects, the relationship between section modulus and peak moment is weakest for the anterior region. In other words, for an increase in section modulus the expected increase in peak moment is lowest for the anterior regions, for all subjects. Also, the anterior regions generally failed at lower peak moments than rib sections from different regions with comparable values of section moduli. These trends and the fact that the anterior region failed at a lower strain than the remaining regions suggest that the variation in material properties may be altering the expected trends between geometrical properties and mechanical response.

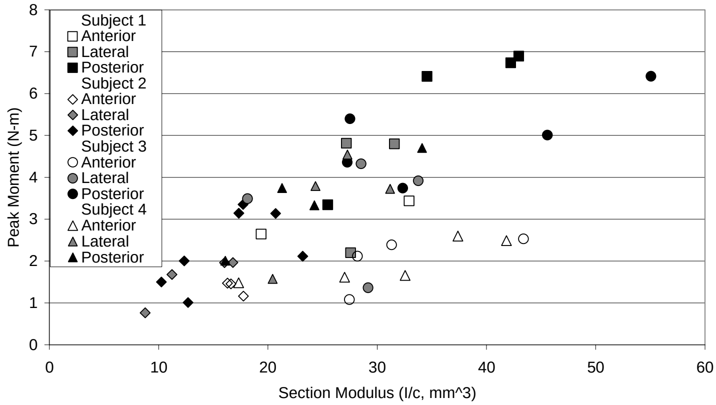


Figure 8: Peak moment related to section modulus by subject and region.

Another factor that may be contributing to the inconsistency among geometry and peak force is a compromise of the rib structure that occurs at the compressive side of the rib specimen. When the rib is loaded from above, it is possible for a local failure to occur, which would decrease the strength of the rib while maintaining integrity of the tensile side of the rib. This would allow the strain gage to continue to sense strain while the moment required to deform the rib would decrease due to the structural failure at the point of loading. Therefore, it is possible that during loading the geometry of the rib at the point of loading changes, causing a decrease in section modulus and a corresponding increase in bending stress. If structural failure at the loading site is the source of difference in the anterior specimens, it is a preferential difference which would still suggest a difference in rib property by region. The anterior ribs attach to the sternum via costal cartilage. Although this joint was not included in the test specimens, this may alter the material properties of the anterior region of the thorax. Finally, the inconsistency may be a result of variance which could be resolved with a larger sample size in future testing.

The fact that the statistical analyses demonstrate differences in moment of inertia by region as well as the presence of the same trend in moment of inertia by cadaver, indicates that such a trend does exist. However it is important to note that the test matrix does not include a full overlap of specimens from each region in each rib. For example, due to its length, only one lateral specimen could be removed from rib two. In some instances, anterior and posterior specimens were removed from a single rib, creating an improved comparison by controlling for rib level. As a result of the lack of complete comparisons for each rib, comparisons between anterior and posterior are the most significant as these are mostly made from rib sections from the same rib. This is a limitation of the study and a main source of variation that can be resolved with future testing.

The moment – strain plots demonstrate the large difference in strain at peak force and maximum strain. This trend is typically not seen in three-point bending tests of long bones. This may be attributed to a difference in composition between long bones and human ribs. Both bones are constructed of cancellous and cortical bone; however, in long bones the diaphysis is made up mostly of cortical bone. In rib specimens, cortical and cancellous bone is present throughout the length of the rib, creating a composite structure at the failure site. This difference in construction may partially explain the difference in loading behavior between long bones and rib specimens. Another factor that may be involved in this difference is the possibility of a structural failure at the compression region of the rib which will allow for an increase in strain with a decrease in stiffness. This is similar to the response seen in tensile tests in which the effect of necking or local shrinkage of the test specimen overcomes the effect of strain hardening which occurs after yielding. Once this occurs the ultimate force is reached and there is a negative slope to the force – strain curve.

The effects of rib curvature on the strength of the rib were found to be minimal. The change in stress values in a curved beam is a function of its radius of curvature (R) and its depth (d) in the plane of bending. These parameters were investigated for subject two and similar geometry was assumed to be present in the other subjects. The ratio R/d defines the significance of the curvature of a beam and was determined for all specimens removed from the subject. An R/d value of 8 or more represents the regime in which straight-beam theory applies with stress and strain errors that are on the order of 4% to 5% (Young 1989). The average depth for subjects 1 through 4 was: 6.1, 4.3, 5.1, and 6.6 mm respectively. The average radius of curvature (R) for subject two was 16 cm with an average R/d value of 38, therefore the influence of rib curvature was assumed to be negligible for all subjects because subject two represents the worst case for curvature effects.

Further support for the minimal effect of rib curvature on stress and strain measurements comes from an investigation by

Granik and Stein, (1973) who created plastic molds of rib specimens and of rectangular beams with a cross sectional area of 2 cm^2. They found that the calculated mechanical properties of the plastic ribs were not significantly different than those of the straight, rectangular beams.

CONCLUSIONS

This paper represents an introduction into the variation of rib geometry and strength throughout the rib cage. A total of 52 rib specimens were removed from four subjects from the anterior, lateral and posterior regions of the thorax. Statistically significant differences were found among region and rib level for both geometrical and structural properties; however, future testing may refine our knowledge of these relationships by reducing variance in the current dataset. Two geometry descriptors, radius of gyration (kx) and distance to the neutral axis (c), were statistically different across all three regions and among various levels within the rib cage. The trend among rib levels indicated an increase in these properties from rib 2 to 6, with a steady decrease to rib 12. The peak moment across rib levels followed the same trend, and was statistically different among all three regions. The current results indicate a difference in failure moment across the anterior, lateral and posterior regions of the thorax. However, the difference on average is an increase of 1 N-m from the anterior to the posterior regions with a similar variation of approximately 2 N-m among rib levels. Peak strain was also statistically lowest for the anterior region. The combined effect of these variations suggests a lower energy to failure for the anterior regions. This has important implications when considering frontal loading that is often encountered in automotive applications. Previous work by Stitzel *et al.* (2003) demonstrated that strain energy density values that are 47 % and 29 % lower for the anterior region than the lateral and posterior regions results in significant variation in fracture patterns over a homogenous rib model. The number of rib fractures predicted was also significantly different for the two models. This suggests that the variations observed in the current work could have implications in the prediction of rib fractures. Implementing the current results in future models should be performed to reveal their effect on the number of rib fractures predicted and fracture location.

ACKNOWLEDGEMENTS

The authors thank Toyota Motor Corporation for their funding and support of this study.

REFERENCES

Cesari D, Bouquet R: Behavior of Human Surrogates Thorax Under Belt Loading. Proceedings of the 34th Stapp Car Crash Conference, Society of Automotive Engineers. 73-81, 902310; 1990.

Eppinger RH, Augustyn K, Robbins DH: Development of a Promising Universal Thoracic Trauma Prediction Methodology. Proceedings of the 22nd Stapp Car Crash Conference, Society of Automotive Engineers, 780891; 1978.

Eppinger RH, Marcus JH, Morgan RM: Development of Dummy and Injury Index for NHTSA's Thoracic Side Impact Protection Research Program. Proceedings of the Gover./Industry Expo, Society of Automotive Engineers, 840885; 1984.

Granik G, Stein I: Human Ribs: Static Testing as a Promising Medical Application. J. Biomech., 6:237-240; 1973.

Kallieris D, Schmidt G, Barz J, Mattern R, Schulz F: Response and Vulnerability of the Human Body at Different Impact Velocities in Simulated Three-Point Belted Cadaver Tests. IRCOBI, 196-209; 1974.

Kallieris D, Zerial PD, Rizzetti A, Mattern R: Prediction of Thoracic Injuries in Frontal Collisions. Enhanced Safety of Vehicles, 98-S7-O-04: 1550-63; 1998.

Kleinman P.K., Schlesinger A.E.: Mechanical Factors Associated with Posterior Rib Fractures: Laboratory and Case Studies. *Pediatr. Radiol.*, 27: 87-91; 1997.

Kuppa S, Eppinger R: Development of an Improved Thoracic Injury Criterion. Proceedings of the 42nd Stapp Car Crash Conference, Society of Automotive Engineers, 983153; 1998.

Nahum AM, Schneider DC, Kroell CK: Cadaver Skeletal Response to Blunt Thoracic Impact. Proceedings of the 19th Stapp Car Crash Conference, Society of Automotive Engineers 259-277, 751150; 1975.

Schultz AB, Benson DR, Hirsch C: Force-Deformation Properties of Human Ribs. J Biomech., 7: 303-9; 1974.

Stein ID, Granik G: Mechanical Testing of Human Ribs: Effects of Strain Rate, Race and Age. Proceedings of the 25th Conference on Engineering in Medicine and Biology. 25.3; 1972.

Stitzel, JD, Cormier, JM, Barretta, JT, Kennedy, EA, Smith, EP, Rath, AL, Duma, SM. "Defining Regional Variation in the Material Properties of Human Rib Cortical Bone and its Effect on Fracture Prediction." The Proceedings of the 47th International Stapp Car Crash Conference, San Diego, California: 2003.

Viano DC, Warner CY, Hoopes K, Morenson C, White R, Artinian CG: Sensitivity of Porcine Thoracic Responses and Injuries to Various Frontal and A Lateral Impact Site. Proceedings of the 22th Stapp Car Crash Conference, Society of Automotive Engineers. 169-207, 780890; 1978.

Walfisch G, Chamouard F, Lestrelin D, Tarriere C, Cassan F, Mack P, Got C, Guillon F, Patel A, Hureau J: Predictive Functions for Thoracic Injuries to Belt Wearers in Frontal Collisions and Their Conversion into Protective Criteria. Proceedings of the 29th Stapp Car Crash Conference, Society of Automotive Engineers, 851722; 1985.

Yoganandan N, Skrade D, Pintar FA, Reinartz J, Sances A: Thoracic Deformation Contours in a Frontal Impact. Proceedings of the 35th Stapp Car Crash Conference, Society of Automotive Engineers, 912891; 1991.

Yoganandan N, Pintar FA, Skrade D, Chmiel W, Reinartz JM, Sances A: Thoracic Biomechanics with Air Bag Restraint. Proceedings of the 37th Stapp Car Crash Conference, Society of Automotive Engineers. 133-144, 933121; 1993.

Yoganandan N, Pintar FA: Biomechanics of Human Thoracic Ribs. J. Biomech. Eng., 120: 100-4; 1998.

Young W.C: Roark's Formulas for Stress & Strain, 6th Ed. McGraw Hill, Washington D.C.; 1989.