Human Rib Fracture Characteristics and Relationships with Structural Properties

Angela L. Harden, Yun-Seok Kang, Kevin Moorhouse, Jason Stammen, Amanda M. Agnew

Abstract Thoracic injuries, specifically rib fractures, are prevalent in motor vehicle crashes and are a significant source of morbidity and mortality. Rib fractures present in a variety of patterns, ranging in severity from minor to severe. The number of fractures also contributes to the injury assessment; as fracture number increases, severity increases. Research regarding relationships between a rib's structural properties and fracture characteristics is lacking; therefore, the objective of this study was to identify relationships of fracture characteristics with structural properties in human ribs subjected to anterior-posterior loading to contribute to a comprehensive understanding of thoracic injury and improving injury risk assessment. Ribs (n=347) were impacted in a dynamic bending scenario representing a frontal thoracic impact. Fracture characteristics (location, classification, number, and severity) were analyzed utilizing a new classification system. Structural properties (peak and yield force, %peak and yield displacement, linear structural stiffness, total energy, plastic energy, and ductility/brittleness) were calculated from test data for each rib and their relationships with fracture characteristics were assessed. Three structural properties (%peak displacement, total energy, and plastic energy) were found to have significant differences with all fracture characteristics except fracture location. However, the significant differences were only found in specific comparisons within each fracture characteristic. Fracture location was only found to have a significant relationship with %peak displacement.

Keywords Fracture classification, injury risk, rib fractures, structural properties, thoracic injury.

I. INTRODUCTION

Thoracic injuries, specifically rib fractures, are one of the most common injuries in motor vehicle crashes (MVCs) in the United States [1-2] and are associated with high morbidity and mortality rates [3-5]. However, rib fractures are often overlooked or are oversimplified in clinical [6-8], forensic [9-10], and biomechanical [11-12] evaluations. Rib fractures, in clinical and forensic applications, are often described as simply being present and may or may not include any further descriptions of the fracture, e.g., location. Scientific methods utilized to evaluate skeletal trauma often exclude rib trauma entirely [6][8] or focus on specific injury patterns [9] and do not provide an interdisciplinary, quantifiable method to evaluate rib fractures. The AO/OTA Fracture and Dislocation Classification System [7] and the Abbreviated Injury Scale (AIS) [11] both address rib fractures, but neither of these evaluation methods addresses the complexity, precise location, or knowledge of variation in fracture characteristics required for an in-depth thoracic trauma assessment. A comprehensive understanding of thoracic injury severity and variation is integral to thoracic injury risk assessment. In order to identify and assess thoracic injury risk, the dynamic response of the thorax and variations in fracture characteristics should be more thoroughly understood.

Previous studies have demonstrated that specific fracture characteristics vary, even within the same controlled loading conditions [13-16]. However, investigations into the source of these variations are lacking. Previous studies have linked variation in rib mechanical response and failure to differences in cross-sectional geometry [17-19]. More recent studies have demonstrated the ability to predict rib peak force and structural stiffness from cross-sectional variables, e.g., total area, cortical area [20]. Reference [14] explored sources of variation in rib structural properties to better understand variation in rib response and injury risk. The authors found that generally, cross-sectional geometry was the most important factor in predicting structural properties [14]. However, a gap still remains in the research investigating and identifying sources of variation in fracture characteristics and evaluating the roles of rib structural and cross-sectional properties in the fracture characteristic variation. Previous studies have identified trends in frequencies of rib fracture locations [13-14][21-22]; however, trends in fracture types, number, and severity in human ribs have not been evaluated.

The aim of this study was to identify relationships between fracture characteristics and structural properties in human ribs subjected to anterior-posterior loading. It was anticipated that rib behavior during dynamic loading will correlate with resulting fracture patterns.

II. METHODS

Materials

Human rib specimens (n=347) were ethically obtained from 182 individuals (59 female, 123 male) through The Ohio State Whole Body Donation Program and tissue donors from Ohio and Wisconsin following compliance protocols established by research ethics advisory committees. Mid-level (3–8) thoracic ribs were selected for this research as previous studies [5][22-23] have established that mid-level ribs are most often fractured during traumatic thoracic events and are the most morphologically similar within the thorax [24-25]. Previous research has established that side (left or right) has no influence on rib structural properties [19], therefore side was not a consideration within this research and right and/or left ribs were randomly included in the sample. The sample was compiled to represent the U.S. population and capture biological diversity; however, ribs with pre-existing trauma, established through visual inspection, were excluded. The age and sex distribution of the entire rib sample is provided in Figure 1.

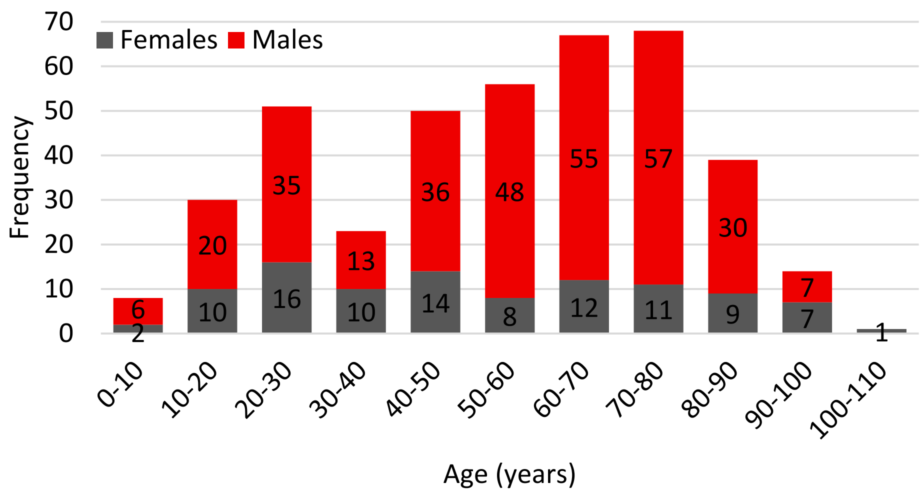


Fig. 1. Rib sample by age and sex.

Experimental Testing

Three-hundred forty-seven ribs were impacted in a dynamic bending scenario, representing a frontal thoracic impact. Vertebral and sternal ends of each rib were potted into 3x3x4 cups of Bondo (Bondo Corporation, Atlanta, Georgia) and four uniaxial strain gages were attached to the cutaneous and pleural surfaces. A 54kg pendulum was dropped to displace the sternal end of the rib towards the vertebral end in a dynamic (1-2m/s) impact, creating a simplified 2D bending scenario. The testing fixture was equipped with a six-axis load cell behind the fixed rib end, and an accelerometer and linear string potentiometer were attached to the moving rib end. For further experimental details see [14]. Bending is the most common mechanism leading to fracture in the clinical and forensic setting [26] and the test design utilized in this research is similar to previous biomechanical studies [27-28] allowing for comparisons across investigations. Structural properties (peak force [F_{Peak}], yield force [F_{Yld}], %peak displacement [δ_{Peak}], %yield displacement [δ_{Yld}], linear structural stiffness [K], total energy [U_{Tot}], plastic energy [U_{Plas}], and rib behavior [ductile or brittle]) were calculated from test data for each rib according to [14] and are defined in Table I. Ribs with calculated plastic energy values above zero were classified as ductile and ribs with the value of zero were classified as brittle.

TABLE I
STRUCTURAL PROPERTY DEFINITIONS AND CALCULATIONS

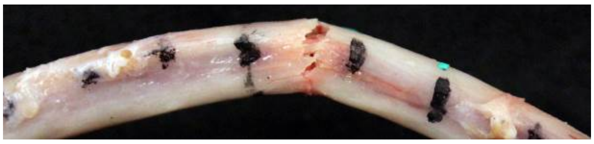
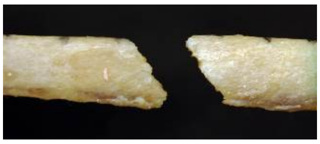
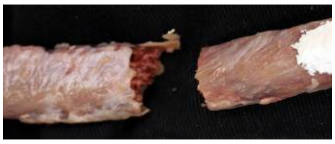
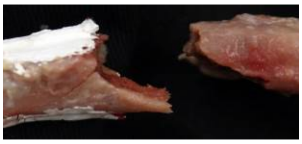
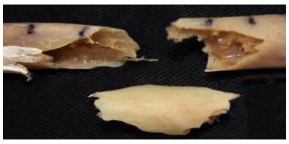
Property Type	Property Name	Abbreviation (*units*)	Description
Force	Peak Force	F_{Peak} (*N*)	Maximum force in X direction
	Yield Force	F_{Yld} (*N*)	Force in X direction at time of yield
Displacement	% Peak Displacement	δ_{Peak} (*%*)	Maximum displacement in X normalized by initial span length of the rib
	% Yield Displacement	δ_{Yld} (*%*)	Displacement in X at time of yield normalized by initial span length of the rib
Stiffness	Linear Stiffness	K (*N/mm*)	Slope of 20%–80% of linear portion of F-D curve
Energy	Total Energy	U_{Tot} (*N*mm*)	Total area under the F-D curve to fracture
	Plastic Energy	U_{Plas} (*N*mm*)	Area under the F-D curve post yield
Behavior	Ductile	Ductile	Plastic energy values of 0
	Brittle	Brittle	Plastic energy values > 0

Rib Fracture Classification

Rib fractures were classified utilizing a rib fracture classification system developed by the Injury Biomechanics Research Center (IBRC) at The Ohio State University, USA. This new classification system incorporates multiple fracture characteristics (location, type and group, and number), along with injury severity, to provide a comprehensive framework for rib fracture classification. Fracture location was defined as a percentage and was calculated by measuring the distance from the vertebral end to the fracture and dividing by the curve length (Cv.Le) of the rib. Fractures were classified utilizing a two-part system, which was modified from the AO/OTA Fracture and Dislocation Classification [6-7] (Table II). First, the fracture was assigned to one of the following types: Incomplete (A), Simple (B), Wedge (C), or Multifragmentary (D). Then, if applicable, the fracture was assigned to a group, e.g., oblique, transverse, intact, to complete the classification, e.g., simple oblique. After the fracture classification was determined, the number of fractures per rib was recorded. Rib fracture severity was categorized according to the following: minor (Incomplete fractures), moderate (Simple fractures), serious (Wedge Incomplete and Wedge Intact fractures), and severe (Wedge Multifragmentary and Multifragmentary fractures). The severity assessment of each rib was determined from the fracture classification and the number of fractures per rib; as fracture number increases, severity increases. This results in an injury severity for each fracture and for each rib. For example, if a single rib has two simple fractures, each fracture would be assigned an injury severity of moderate, but the whole rib would be assigned an injury severity of serious due to the number of fractures present. Relationships were explored between fracture location, types, groups, and severity with all structural properties, and statistical significance was set at $p<0.005$.

TABLE II

OBSERVED FRACTURE CLASSIFICATIONS

Fracture Types	Fracture Group	
Incomplete (A)	 *Incomplete (A)*	
Simple (B)	 *Oblique (B1)*	 *Transverse (B2)*
Wedge (C)	 *Incomplete (C1)*	 *Intact (C2)*
Multi-fragmentary (D)	 *Multifragmentary (D)*	

III. RESULTS

The 347 ribs tested in the dynamic anterior-posterior bending scenario resulted in 391 fractures. Eleven ribs did not fracture and were not included in further analyses. Of the 391 fractures, three could not be classified. Fracture locations ranged from 11%–89% of the curved rib length (mean = 63% from the vertebral end of the rib) (Figure 2). Six different fracture types were observed: Incomplete (A), Simple Oblique (B1), Simple Transverse (B2), Wedge Incomplete (C1), Wedge Intact (C2), and Multifragmentary (D) (Figure 3). The distribution of the number of fractures observed per rib were: one (n=280), two (n=52), and three (n=4). The severity for each fracture and each rib ranged from minor to severe and is shown in Figure 4.

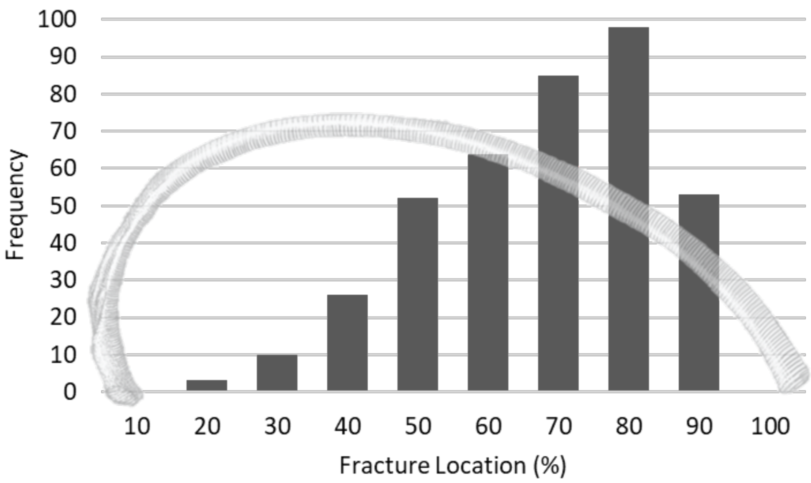


Fig. 2. Frequency of fracture locations.

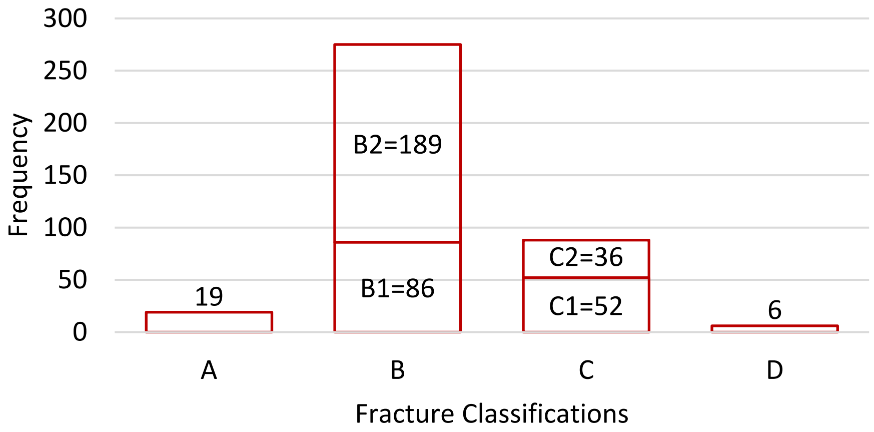


Fig. 3. Frequency of fracture types observed.

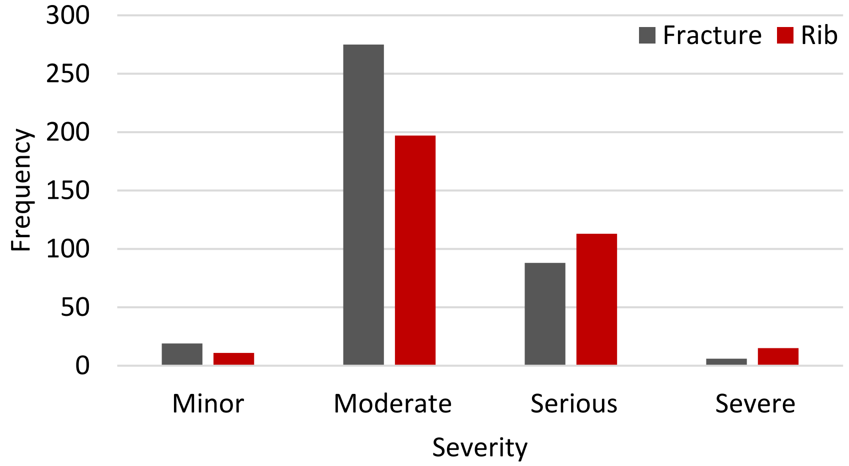


Fig. 4. Injury severity frequency by fracture and rib. Each individual fracture was assigned an injury severity and the frequency of fracture severity is shown in grey. Additionally, each rib was assigned an injury severity, calculated from the fracture injury severity and the number of fractures per rib, and the frequency of rib severity is shown in red.

Relationships between fracture characteristics (location, type, number, and severity) and structural properties (F_{Peak}, F_{Yld}, δ_{Peak}, δ_{Yld}, K, U_{Tot}, U_{Plas}, and rib behavior) were assessed using Pearson's Correlation, Kruskal-Wallis, and Chi Square tests as appropriate. Descriptive statistics of the structural property variables (excluding rib behavior) are listed in Table III. Rib behavior was only compared to fracture location and fracture number due to insufficient expected counts in the Chi Square tests with other fracture characteristics. Ribs that fractured in three locations were not included in these analyses due to the small sample size (n=4).

TABLE III
DESCRIPTIVE STATISTICS OF STRUCTURAL PROPERTIES

	F_{Peak} (N)	F_{Yld} (N)	δ_{Peak} (%)	δ_{Yld} (%)	K (N/mm)	U_{Tot} (N*mm)	U_{Plas} (N*mm)
Mean	108.05	73.01	23.29	11.13	3.60	3428	2454
SE Mean	2.42	1.69	0.51	0.21	0.10	123	116
SD	47.80	33.37	10.07	4.23	2.03	2442	2293
Minimum	16.61	12.00	6.49	2.66	0.33	350	0
Maximum	299.84	292.38	67.21	32.74	19.14	16154	13466

Fracture location only had a statistically significant relationship with δ_{Peak} (Pearson's correlation, $p<0.001$) (Table IV) but no statistically significant relationship with all other structural properties examined. However, this was a weak negative relationship, where δ_{Peak} decreased as fracture location moved anteriorly (Figure 5). Relationships between fracture type, group, number, and severity and δ_{Peak}, U_{Tot}, and U_{Plas} were all significant ($p<0.005$) (Table V). Kruskal-Wallis *post hoc* tests demonstrated that only specific comparisons within fracture type, group, and severity were significant. Significant differences in fracture type and δ_{Peak}, U_{Tot}, and U_{Plas} were found in the following type: B vs. C ($p<0.001$) (Figure 6). The same trends were observed in U_{Tot} and U_{Plas}; so, only the relationships with U_{Tot} are depicted in the figures. Fracture type and δ_{Peak} also demonstrated a significant difference in type B vs. A ($p=0.005$) (Figure 6). Fracture group had significant differences with δ_{Peak} in the following groups: B2 vs. C1, B1 vs. C1, and B2 vs. C2 ($p<0.003$) (Figure 6). Significant differences were found in fracture groups: B2 vs. C1, B1 vs. C1, and B2 vs. C2 ($p<0.005$) for both U_{Tot} and U_{Plas} (Figure 6). Fracture severity demonstrated significant differences in Moderate vs. Serious categories for δ_{Peak}, U_{Tot}, and U_{Plas} ($p<0.001$) (Figure 7). Additionally, Moderate vs. Minor also showed significant differences in δ_{Peak} (Figure 7).

TABLE IV
PEARSON'S CORRELATION *(R)VALUES AND P-VALUES (PEARSON'S CORRELATION AND KRUSKAL-WALLIS)*

		F_{Peak}	F_{Yld}	δ_{Peak}	δ_{Yld}	K	U_{Tot}	U_{Plas}	Rib Behavior
Fracture Location	*r*	0.036	0.035	-0.196	-0.112	0.107	-0.130	-0.131	
	p	0.482	0.489	**<0.001**	0.027	0.035	0.010	0.009	0.037

*significant p-values are shown in **bold**

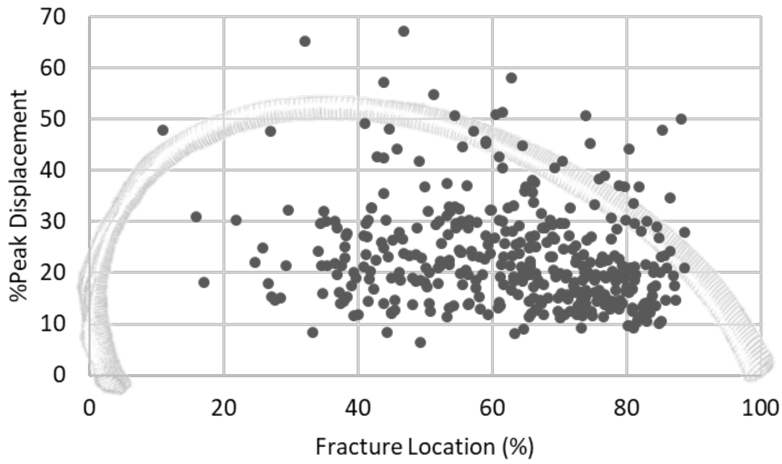


Fig. 5. Scatterplot for fracture location with δ_{Peak}.

TABLE V
KRUSKAL-WALLIS AND CHI SQUARE *P-VALUES*

		F_{Peak}	F_{Yld}	δ_{Peak}	δ_{Yld}	K	U_{Tot}	U_{Plas}	Rib Behavior
Fracture Type	*p*	0.013	0.072	**<0.001**	0.122	0.495	**<0.001**	**<0.001**	
Fracture Group	*p*	0.018	0.158	**<0.001**	0.267	0.547	**<0.001**	**<0.001**	
Number of Fractures	*p*	0.302	0.945	**0.005**	0.599	0.818	**0.004**	**0.004**	0.021
Fracture Severity	*p*	0.026	0.070	**<0.001**	0.078	0.614	**<0.001**	**<0.001**	

*significant p-values are shown in **bold**

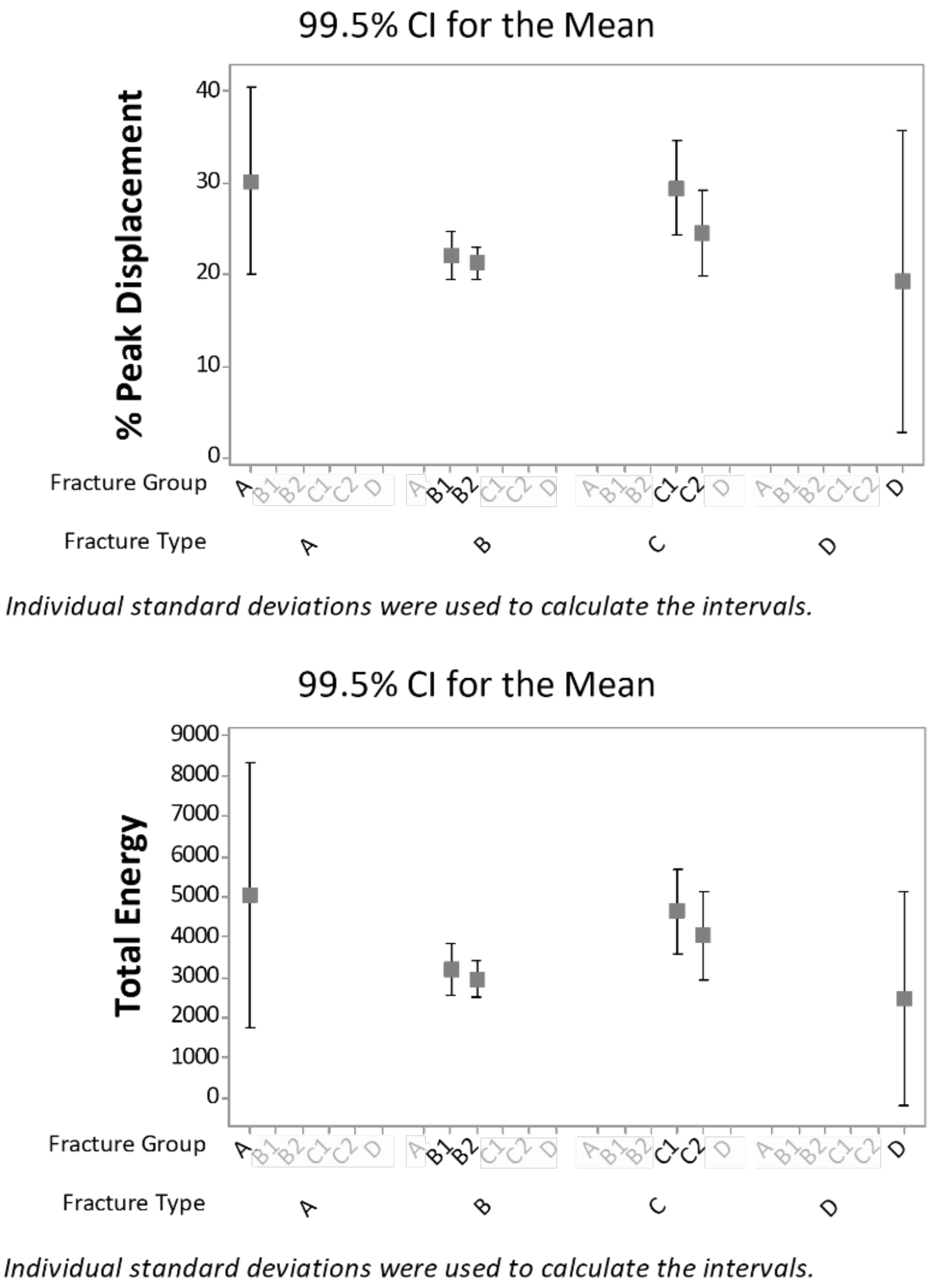


Fig. 6. Interval plots of fracture type and group and δ_{Peak} (%) (top) and U_{Tot} (N*mm) (bottom).

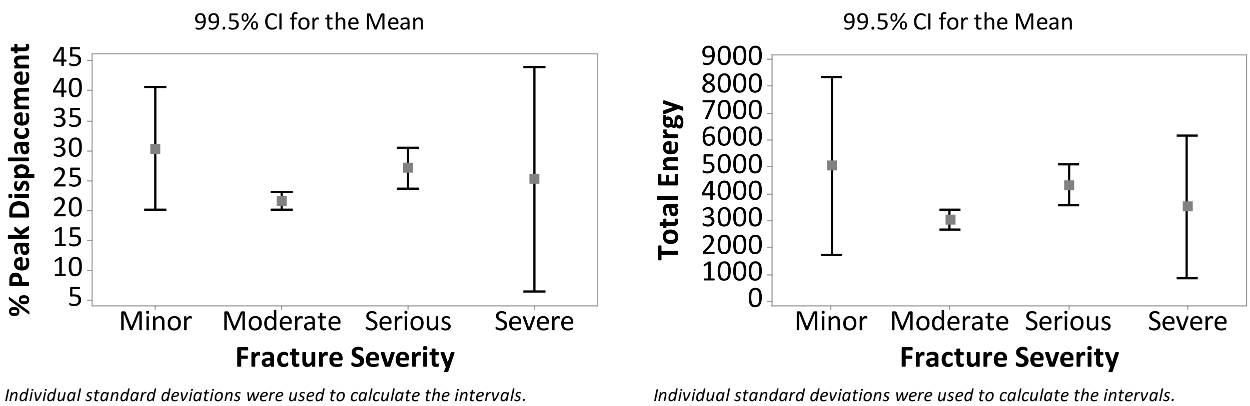


Fig. 7. Interval plots of fracture severity and δ_{Peak} (%) (left) and U_{Tot} (N*mm) (right).

IV. Discussion

The data from this research (specific fracture location, type, group, fracture severity, and rib injury severity) cannot be compared to any results from other studies, as these data have not been previously collected. This lack of fracture characteristic and rib injury severity data highlights the critical need of the developed rib specific classification system and controlled experimental thoracic trauma research. Previous research and general assumptions regarding fracture mechanics in other long bones, e.g., femur, tibia, are most likely not applicable to the ribs, which are unique in their overall and cross-sectional geometry. Previous studies have suggested that the wedge fracture is most typical in bending scenarios [6][29]. However, it has also been suggested that the fracture mechanics of ribs differ from those of other long bones due to differences in the amount of cortical bone and overall rib geometry [9][23]. In order to accurately assess thoracic injuries and conduct valid rib trauma analyses, the variation in rib fractures needs to be analyzed. To understand what is normal or expected with specific loading events, researchers should identify the sources and range of variation. Without identifying the source of the variation, we cannot control for it and explore how differences in extrinsic variables, e.g., input velocity, affect fracture characteristics.

The fracture location frequencies observed in this study are consistent with frontal impact crash event data and previous research [12][15][22][30]. For example, reference [22] found the highest frequency of rib fractures was in the anterolateral region in frontal crashes, as was found in this study. There is a paucity of data to link additional fracture characteristics (specifically fracture type and group) to the real-world, as this level of detail has not been previously recorded for rib fractures. Fracture location had a weak negative relationship with δ_{Peak}; fractures were located more sternally with less displacement. This could be due to a relationship between fracture location and cross-sectional variables, e.g., cortical thickness, which could affect the bending behavior of the rib during impact. Future work will investigate the relationships between fracture characteristics and cross-sectional variables.

While there were significant relationships between fracture type and δ_{Peak}, U_{Tot}, and U_{Plas}, the specific relationships between types that were significant are most interesting. Evaluating only incomplete vs. simple vs. wedge vs. multifragmentary found the only significant differences in δ_{Peak} were between simple and wedge and between simple and incomplete fracture types. Incomplete and wedge fractures had higher δ_{Peak} values than simple fracture types. This is intuitive for incomplete fractures, as they are expected to occur in more ductile ribs, which would allow for higher δ_{Peak}. The complexity of the wedge fracture (multiple fracture propagation paths) may allow for or require more displacement to occur for the fracture to complete. Whereas with the simple fracture pattern, the fracture propagates directly through the rib and less displacement is exhibited. Significant differences in U_{Tot} and U_{Plas} within fracture types were only found between simple and wedge fractures. The means of U_{Tot} and U_{Plas} were lower for simple fractures compared to wedge fractures, indicating a relationship between energy and fracture types. Ribs that resulted in wedge fractures demonstrated higher values of U_{Tot} and U_{Plas} compared to simple fractures. This indicates that ribs that sustain wedge fractures may be more ductile, resulting in higher values of U_{Plas}, than ribs that sustain simple fractures. However, the comparison of the mean values of δ_{Peak}, U_{Tot}, and U_{Plas} and fracture types comes with a caveat. The variance, specifically in types A and D, are likely a product of sample size, which is addressed as a limitation of this study. Number of fractures also had a significant relationship with δ_{Peak}, U_{Tot}, and U_{Plas}. Ribs that sustained one fracture demonstrated less displacement and less total and plastic energy in an anterior-posterior bending scenario than ribs with multiple fractures. This is logical as more energy would be stored in ribs that resulted in multiple fractures vs. one fracture. Relationships between fracture severity and rib structural properties mimic the results found with fracture types and structural properties, as types were used to determine severity.

The assessment of fracture severity has both clinical and forensic implications. Clinically, fracture severity has the potential to affect the assessment of treatment options and the determination of healing time. Minor severity rib fractures would require less treatment and result in quicker healing times while severe fractures could have implications for organ trauma, surgical treatment, and extensive healing times [5][31-33]. In a forensic context, the severity of the rib fractures has the potential to affect the determination of cause of death. If severe rib fractures are present in a forensic case, the likelihood of internal organ damage is greatly increased vs. a case involving minor rib fractures.

Five of the eight rib structural properties were unrelated to fracture characteristics and did not demonstrate any significant trends or sources of fracture variation. All fracture characteristics were found to have significant relationships with δ_{Peak}, U_{Tot}, and U_{Plas}, except for fracture location which had a significant relationship only with δ_{Peak}. While these relationships were not significant with all comparisons within each characteristic, this does indicate that differences in structural properties do correlate with variation in fracture characteristics. However, the lack of significance in all comparisons within each fracture characteristic indicates that other variables, e.g., cortical thickness, porosity, may have more significant relationships with fracture characteristics. While these data provide insight into the relationships between the selected structural properties and fracture characteristics, they do not reveal the source of variation observed in fracture characteristics. Other rib geometry and cross-sectional variables may prove to have stronger relationships with fracture types.

Limitations of this study include the lack of inter- and intra-observer error rates in regards to identification of fracture type and group, small sample size for fracture types A and D, and the simplified 2D boundary conditions of the ribs in the testing design. Inter- and intra-observer error rates will be calculated in future research utilizing the rib fracture classification system. The testing boundary conditions do not mimic *in situ* rib boundary conditions; however, while this is a limitation, it is also a strength of the testing design. By not accounting for *in situ* boundary conditions of each rib, this allowed for all of the ribs to be tested in the same way with a repeatable controlled set-up.

V. CONCLUSIONS

This is the first known study to quantify relationships between rib structural properties and multiple fracture characteristics. Of the structural properties explored within this research, only δ_{Peak} had statistically significant relationships with all of the defined fracture characteristics (location, type, group, number, and severity). Additionally, U_{Tot} and U_{Plas} demonstrated statistically significant relationships with fracture type, group, number, and severity. Simple fractures demonstrated less displacement, less total energy, and less plastic energy than wedge fractures. Lastly, ribs that fractured once exhibited less displacement, and less total and plastic energy than ribs that fractured in two discrete locations. Understanding fracture characteristics and their relationships with rib structural properties and rib level-variables may assist with reconstructing traumatic loading events and identifying injury risk. Future work will investigate relationships between fracture characteristics (location, type, and number) and rib-level variables, e.g., rib geometry and cross-sectional variables, to determine whether they account for a significant amount of variation in fracture characteristics.

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