

Age-Related Changes in Stiffness in Human Ribs

Amanda M. Agnew¹, Yun-Seok Kang¹, Kevin Moorhouse², Rod Herriott³, John H. Bolte IV¹

Abstract The risk of rib fracture significantly increases with age with compounding deleterious effects. Previous research identifying rib properties has provided useful information for application in car safety. However, no study to-date has included a comprehensive sample including pediatric and elderly ribs tested in the same repeatable set-up. The goal of this study is to characterize the differences in rib response across the age spectrum. Seventy-one excised ribs from 26 individuals were experimentally tested in a custom fixture simulating a dynamic frontal impact. Four strain gages on each rib were used to determine time of failure. Ages ranged from nine to 92 years old, with a mean age of 61 years and with the exception of the 50's, all age decades are represented. Effective stiffness (K) was calculated as the slope of the linear portion of the force-deflection curve. Rib pairs were tested at different rates (1.0 and 2.0 m/s) to assess the rate-dependency of stiffness. Results indicate a significant difference in effective stiffness by age (evaluated by ANOVA, $p < 0.001$) and no difference by rate within rib pairs (evaluated by paired t-test, $p = 0.125$).

Keywords elderly, fracture, pediatric, rib, stiffness

I. INTRODUCTION

Traumatic injury from motor vehicle crashes is a major cause of death in children [1]. The thorax is an important region of study because it is an area often injured in motor vehicle crashes [2]. Few studies exist that explore the mechanical properties and behavior within immature human bone specimens, (e.g., [3],[4]) which are necessary to help understand injury mechanisms in children. Thorax injuries are not only common in children, but are also highly prevalent in the elderly. In fact, rib fractures are one of the most common injuries in the elderly, especially in motor vehicle crashes. Age-related fragility fractures are a continually growing problem worldwide, especially as the proportion of older adults in the population increases. Rib fractures can greatly affect morbidity, mortality, and quality of life in elderly individuals [5].

Many researchers have evaluated rib properties through experimental testing (e.g., [6-9]), but no study exists that includes an age-comprehensive dataset tested under the same repeatable loading conditions. The goals of this study are to identify trends in rib stiffness from early childhood through old

A.M. Agnew, PhD, is an assistant professor of Anatomy at The Ohio State University in Columbus, OH USA. (email: amanda.agnew@osumc.edu, phone: 1.614.366.2005, fax: 1.614.292.7659)

Author affiliations: ¹Injury Biomechanics Research Center (IBRC), The Ohio State University; ²National Highway Traffic Safety Administration (NHTSA), Vehicle Research & Test Center (VRTC), ³Transportation Research Center, Inc.

age and evaluate the rate-dependency of stiffness from ribs of all ages. It is expected that age-related trends in stiffness will emerge and that the rib will exhibit a higher stiffness when tested at a higher dynamic rate. Additionally, fracture patterns are characterized and compared to existing frontal impact data to validate these tests.

II. METHODS

Sample

Seventy-one ribs were obtained from 26 post-mortem human subjects (PMHS) through the Division of Anatomy's Body Donation Program at The Ohio State University and Lifeline of Ohio. All ethics review requirements were met for this research. Complete ribs, from the head to the costo-chondral joint, were excised from individuals at or near the time of death. Fresh specimens were wrapped in saline-soaked gauze and frozen at -20°C until the time of testing. Subjects included in the sample are of both sexes and range in age from 9 to 92 years old. Age phases were created to categorize groups based on established biological changes to the skeleton. Phase '1' includes subadults (0-18 years) in which skeletal development is occurring throughout, Phase '2' includes young adults (19-39 years) in which bone mass is still being accrued and peak bone mass is reached, Phase '3' includes middle adults (40-60 years) in which degeneration and loss of bone mass is beginning, and Phase '4' includes older adult (61+ years) in which age-associated bone loss and osteoporotic changes are likely. The only exclusion criterion employed was that thoracic trauma was not documented. Ribs in the sample were limited to anatomical levels between 3 and 8 to maximize geometric consistency. See Table 1 for subject demographics.

Ribs were thawed and cleaned of all excess soft tissue (muscles, ligaments, etc.) prior to testing. The vertebral and sternal ends were then potted in 4x4x3 cm³ blocks of Bondo® Body Filler (Bondo Corporation, Atlanta, GA). During potting, a ratio of hardener to base was used such that the exothermic reaction of the Bondo® was controlled to not exceed 37.7°C (i.e., approximate body temperature). In this way, the rib did not experience any extreme heat that could damage it and potentially affect the response of the bone to impact. Ribs were oriented in the pots in a single plane to reduce torsional effects during the event. Four strain gages (Vishay Micro-Measurement, Shelton, CT, CEA-06-062UW-350) were adhered to each rib for documentation of fracture timing. Gages were placed on the pleural (inside) surface at 30% and 60% of the curve length of the potted rib, and two more were placed at corresponding locations on the cutaneous (outside) surface.

Ribs were allowed to reach room temperature (~21.1°C) prior to testing. Special care was taken to ensure the specimens remained hydrated throughout the duration of the testing process by leaving them wrapped in saline-soaked gauze whenever possible and spraying them continually with fresh saline. Proper hydration is necessary to measure realistic bone properties [10].

TABLE 1
Subject information

Subject ID	Sex	Age (yrs)	BMI [^] (kg/m ²)	Age Phase [*]	n [†]
A5730	M	73	21.5	4	1
A5894	F	92	24.5	4	1
A5998	M	71	20.9	4	4
A6011	M	88	22.8	4	3
A6024	M	87	27.5	4	4
A6034	F	80	26.4	4	2
A6035	M	79	22.2	4	6
A6090	F	77	27.8	4	3
A6169	M	67	30.4	4	6
A6172	M	75	25.4	4	4
A6236	M	69	21.9	4	2
A6281	F	90	21.8	4	1
A6367	M	84	26.5	4	4
A6369	F	90	29.0	4	2
A6390	M	86	16.3	4	4
A6444	M	79	35.2	4	2
L0100	F	10	15.1	1	2
L0108	M	42	32.0	3	3
L0132	M	30	24.6	2	1
L0213	M	39	27.4	2	1
L0214	M	27	28.4	2	2
L0216	M	20	25.1	2	4
L0221	M	43	36.1	3	2
L0247	M	48	36.7	3	3
L0252	M	42	24.3	3	1
L0418	M	9	21.1	1	3

[^]BMI (body mass index) = weight/stature². ^{*}Phase 1 = subadult, 0-18 years; Phase 2 = young adult, 19-39 years; Phase 3 = middle adult, 40-60 years; Phase 4 = older adult, 61+ years. [†]n = number of ribs tested from each subject.

Experimental Testing

A custom pendulum fixture was constructed based on the concept introduced by [11] and modified by [12] to load whole ribs horizontally (Fig. 1). The mass of the pendulum impactor is 54.4 kg. Each end of the fixture is separated to minimize vibration effects. The two ends of the potted rib were secured firmly in rotating cups with screws to each portion of the fixture. These cups allow for freely rotating pivot joints at each rib end. A rotary potentiometer (14CB1, Servo Instrument Corporation, Baraboo, WI) is incorporated at each of these joints to measure rotation during the event. A 6-axis load cell (CRABI neck load cell, IF-954, Humanetics, Plymouth, MI) is situated behind the stationary plate and is

positioned to align with the center of the vertebral rib-end pot. The stroke of the moving plate was controlled according to the span length of each rib to create a consistent test condition with varying rib sizes.

A linear displacement string-potentiometer (Rayelco P-20A, AMETEK, Inc. Berwyn, PA) was attached to the moving plate to measure the displacement of the sternal end of the rib (comparable to A-P compression of the thorax in a whole-body test scenario). An accelerometer (Endevco 7264G-2K, San Juan Capistrano, CA) was also attached to the moving plate to measure acceleration and velocity of the moving plate. These test conditions are meant to simulate a dynamic frontal impact in a simplified scenario. The primary loading axis was defined as the x-axis according to the SAE J211 coordinate system (Fig. 1).

A randomized test matrix was constructed to include impacts at two different dynamic speeds: 1.0 m/s and 2.0 m/s. In instances where bilateral rib pairs were available, one rib was selected at random to be impacted at one speed while the other was tested at the other speed. This approach is based on the assumption that left and right ribs in a pair are not anatomically different [6],[13].

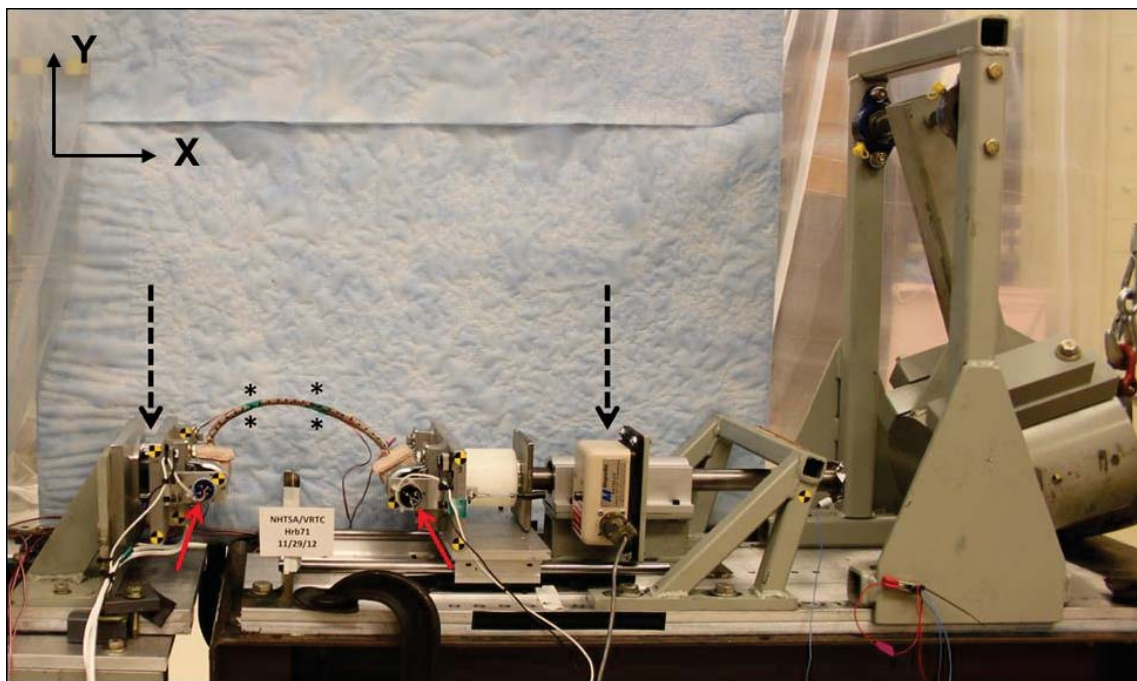


Fig. 1. Experimental test set-up. The 54.4 kg pendulum can be seen on the right side of the image. Asterisks (*) represent the location of strain gages on the rib. Left and right dashed arrows (black) show the location of the 6-axis load cell and displacement pot, respectively. Solid arrows (red) show the rotary potentiometers. The stationary end of the fixture (left) holds the vertebral rib end, while the moving end (right) holds the sternal end (i.e., a frontal impact scenario).

Data Analysis

Fracture patterns were assessed by identifying their location. Location was recorded as a percentage of the curved length from the vertebral (posterior) end. In instances where fractures occurred in two distinct locations, both locations were included. Accelerometer and linear potentiometer data were filtered at 300 Hz using a 4-pole Butterworth filter. Low frequency oscillations observed in the force signals due to structural vibrations in the test fixture were filtered with a 120 Hz cut-off frequency. This threshold was determined through a Fast Fourier Transform (FFT) analysis that revealed an oscillation frequency on the order of 120 Hz. Only force and displacement in the x direction (i.e., primary loading direction) are considered in this manuscript, while a complete analysis utilizing rotational moment, displacement at fracture location, and combined loading (including F_y , F_z , M_x , M_y and M_z) will be reported in a future study.

Effective stiffness was defined as the slope of the linear portion of the force-displacement curve (Fig. 2). The linear portion was defined as the displacement from time zero to 5% of the span length. This method is consistent with [12] and appeared appropriate for the data since they became less linear as force and displacement increased. An analysis of variance (ANOVA) was used to assess differences in stiffness between age groups. Rate-dependency in rib pairs was assessed with a paired t-test.

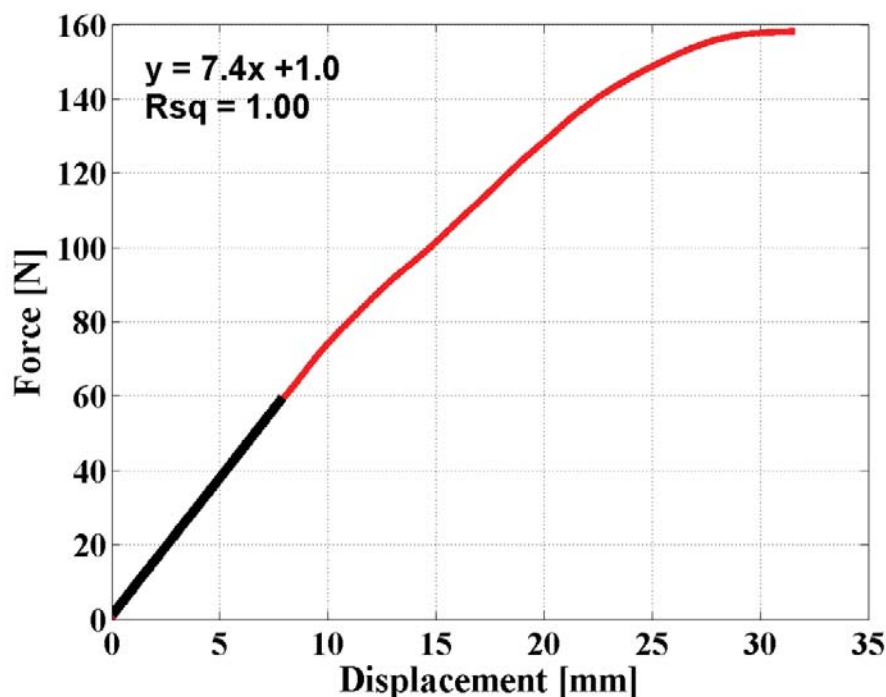


Fig. 2. Representative force and displacement curve (red line) (Subject L0132, right 3rd rib) illustrating the defined linear portion used to calculate stiffness (black line).

III. RESULTS

Frequency of fracture location is presented in Figure 3. Most fractures occurred in the anterolateral section of the rib (mean= 63.29%, 95% CI= 57.36 - 69.22).

A summary of the stiffness results for each rib tested within subjects can be found in Table 2. ANOVA results reveal a statistically significant difference ($p < 0.0001$) in stiffness between age groups in phases 1-4 as shown in Figure 4. Phase 1 ($n=5$) has a mean stiffness of 4.07 N/mm, phase 2 ($n=8$) is 9.05 N/mm, phase 3 ($n=9$) is 4.36, and phase 4 ($n=49$) is 3.41. When phase 2 data points are removed from the analysis, no significant stiffness differences exist between phases 1, 3, and 4 ($p=0.259$).

Paired t-tests reveal no significant difference in stiffness within rib pairs tested at different velocities ($p=0.125$) (Fig. 5). The mean stiffness at 1.0 m/s is 3.8 N/mm, while the mean stiffness at 2.0 m/s is 3.3 N/mm.

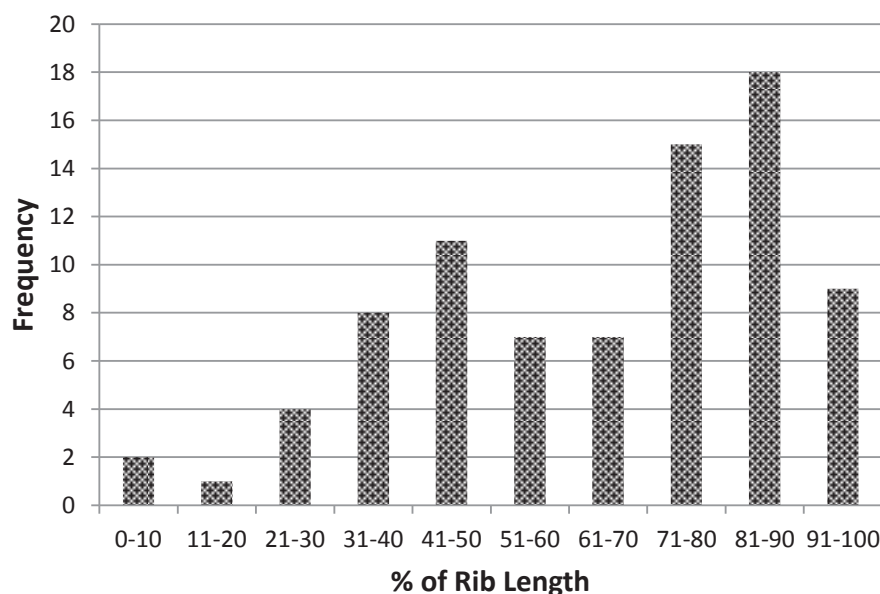


Fig. 3. Frequency of fracture location. Values given are percentages of the rib curved length where fracture occurred (0% = vertebral end; 100% = sternal end). Note: some ribs experienced more than one fracture, so the number of fractures is greater than the number of ribs tested.

TABLE 2
Summary of Stiffness Results

Subject	Age (years)	Rib #	Left (m/s)	K (N/mm)	Right (m/s)	K (N/mm)
A5730	73	7	1.0	7.443	-	-
A5894	92	5	-	-	1.0	1.735
A5998	71	4	1.0	3.441	2.0	3.498
		7	1.0	1.811	2.0	5.375
A6011	88	4	-	-	1.0	2.310
		5	-	-	1.0	3.367
		6	-	-	2.0	2.993
A6024	87	4	2.0	3.251	1.0	4.531
		7	1.0	4.785	2.0	4.556
A6034	80	4	2.0	1.089	1.0	2.758
A6035	79	4	1.0	2.600	2.0	2.333
		5	1.0	1.516	2.0	1.620
		7	2.0	1.835	1.0	2.640
A6090	77	4	2.0	2.496	-	-
		5	2.0	2.423	-	-
		6	2.0	3.511	-	-
A6169	67	4	1.0	3.286	2.0	3.701
		5	2.0	3.459	1.0	3.003
		7	2.0	6.232	1.0	6.435
A6172	75	4	1.0	3.243	2.0	3.081
		7	2.0	4.388	1.0	4.839
A6236	69	4	-	-	1.0	2.182
		5	-	-	2.0	2.553
A6281	90	7	2.0	3.060	-	-
A6367	84	5	2.0	2.760	1.0	3.880
		7	2.0	3.232	1.0	4.083
A6369	90	7	1.0	2.476	2.0	1.683
A6390	86	5	1.0	2.413	2.0	1.845
		7	1.0	3.711	2.0	2.500
A6444	79	7	2.0	6.869	1.0	8.157
L0100	10	6	1.0	1.937	2.0	2.325
L0108	42	3	-	-	2.0	3.430
		4	-	-	1.0	3.758
		5	-	-	2.0	3.237
L0132	30	3	-	-	1.0	7.406
L0213	39	5	-	-	2.0	19.571
L0214	27	5	2.0	6.879	-	-
		6	1.0	6.015	-	-

L0216	20	4	-	-	1.0	13.592
		5	-	-	2.0	6.032
		6	1.0	6.471	-	-
		7	2.0	6.466	-	-
L0221	43	4	-	-	2.0	2.393
		5	-	-	1.0	2.789
L0247	48	4	2.0	3.534	-	-
		6	1.0	8.755	2.0	3.602
L0252	42	6	1.0	7.752	-	-
L0418	9	4	-	-	1.0	3.853
		6	-	-	1.0	7.025
		8	-	-	2.0	5.193

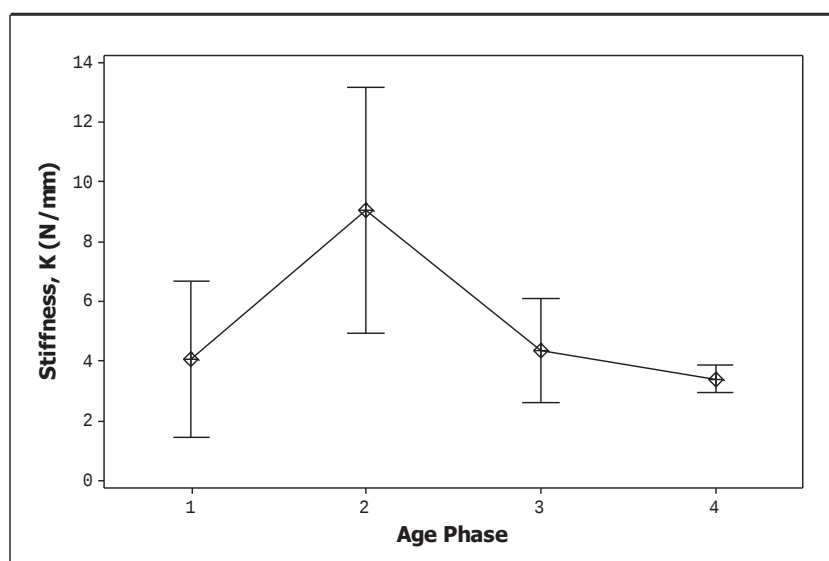


Fig. 4. Interval plot for effective stiffness (K) by age phases. Phase 1 = 0-18 years; Phase 2 = 19-39 years; Phase 3 = 40-60 years; Phase 4 = 61+ years.

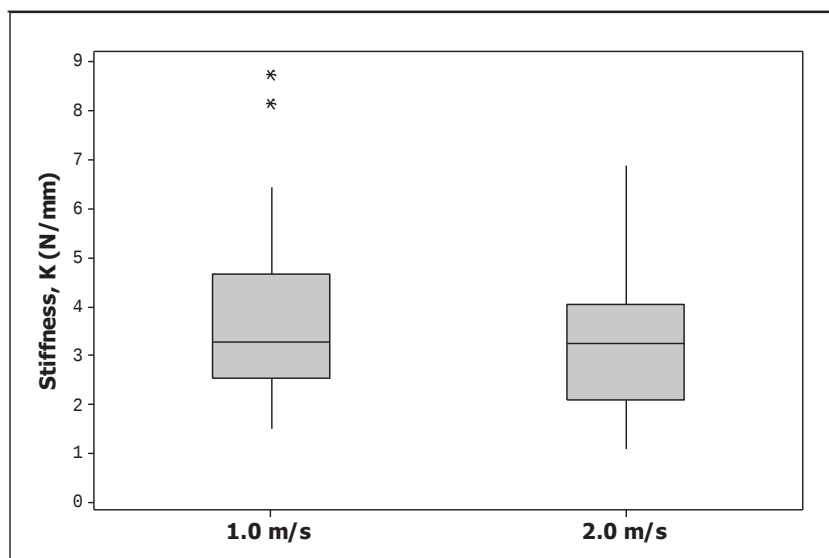


Fig. 5. Boxplot showing the lack of stiffness differences between rib pairs tested at two different dynamic rates.

IV. DISCUSSION

Fractures were most commonly located in the anterolateral region of the ribs. This fracture site is consistent with experimental whole-body results in a frontal crash scenario [14][15] as well as other isolated rib testing [11][12][16], providing some validation that our test set-up does in fact represent the chest compression experienced in a frontal impact. This study resulted in two other similar findings to [12]: 1) in 16 of the 71 tests, two distinct fractures occurred simultaneously causing a large portion of the rib to become fully separated (Fig. 6), and 2) fracture location was found to be the same within rib pairs tested at different rates ($p=0.972$).

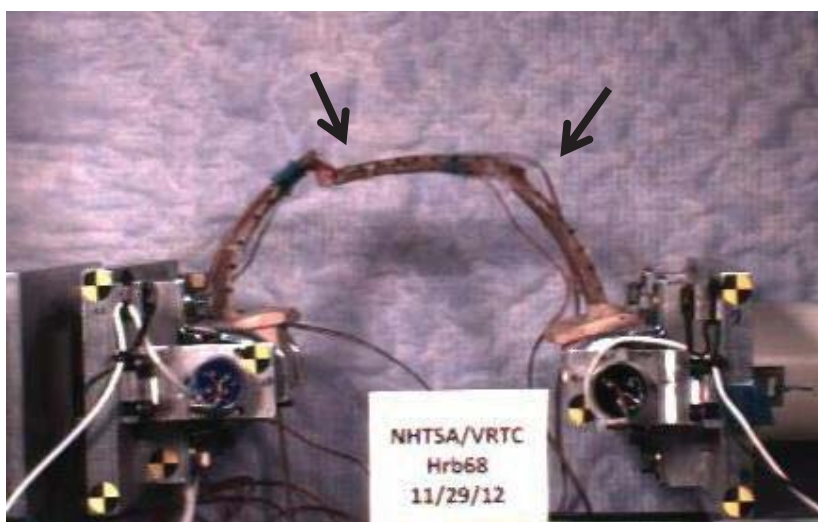


Fig. 6. Representative test illustrating the phenomenon of two simultaneous fractures (arrows) occurring at 71.25 msec.

The Charpail study [11] provides the most relevant comparison to the current study because a similar test set-up and comparable velocities were used. Our stiffness values ($n=71$, mean= 4.21 N/mm) varied significantly from [11] ($n=30$, mean=2.34 N/mm) when comparing all individuals in the sample (t-test, $p<0.0001$). Since their [11] sample contained only individuals in age phases 3 and 4 (as defined here) only those individuals that fell into these categories between the samples were compared, and a significant difference was still found (t-test, $p<0.0001$) between their sample ($n=30$, mean=2.34) and ours ($n=58$, mean=3.56 N/mm). Furthermore, this significant difference (t-test, $p=0.022$) persisted (although not as pronounced) even when a comparison of only those individuals in age phase 4 were compared between the current study and [11] ($n=49$, mean=3.41; $n=24$, mean= 2.63, respectively). This approach was taken for comparison to [12]'s data as well, and significant differences in stiffness were found in comparable age groups between our study and [12] (t-test, $p<0.0001$). Similarly, [12] compared stiffness means to [11] and found no significant differences. These differences could be reflective of the larger sample size and potential larger range of variation in the current study which represents 26 different individuals, rather than the 5 and 9 that [12] and [11] included in their samples, respectively. Differences in test set-up, boundary conditions, or specimen preparation could also contribute. Future studies should focus on characterizing the range of variation in stiffness and other properties independent of age, as these data are not fully understood and could assist in explaining the differences between comparative samples here.

The current study shows a distinct trend for stiffness with increasing age (Fig. 4). Stiffness starts low during the developmental phase (Phase 1) and then increases significantly for Phase 2. After this point, stiffness begins to drop with increasing age (Phases 3 and 4). Similar trends have been found in other experimental test series in which a broad age range is included in the sample. Maltese and colleagues [17] report the stiffness of child thoraces based on cardiopulmonary resuscitation techniques. They present a compilation of data from their study, from [18] and [19], that depicts an age-associated trend in thorax stiffness in which an increase in peak force is observed until the end of the young adult period, at which point the force declines. Figure 7 provides comparable data from the current study, showing this trend in force. Similar findings for femur bending moments have recently been presented [4]. This trend of increasing properties with a subsequent decline is not surprising as the peak values coincide with the expected timing of peak bone mass acquisition.

Bone is viscoelastic and therefore may behave differently as loading rates (i.e., strain rates) change [20], although this theory was not supported by the current study for stiffness (Fig 5). Kindig [12] also found no difference in stiffness between loading rates (quasi-static versus dynamic) on the same ribs. However, if comparing maximum force between 1.0 and 2.0 m/s tests in the current study, while there is still no significant difference ($p=0.212$), there is an increase in the mean peak force with increasing speed (1.0 m/s = 91.97 N, 2.0 m/s = 100.01 N). Sandoz et al. [21] report this same trend of increasing force with speeds (2 mm/min, 0.1 m/s, and 0.25 m/s) without significance for 3-point bending of rib specimens. The lack of differences between rates may be the result of the impact velocities chosen. While they are different at 1.0 and 2.0 m/s, the range of dynamic speeds may not be large enough to elucidate significantly different stiffness values. Also, the nature of the test set-up cannot ensure that the velocity stays consistent throughout the duration of the test, making it difficult to identify trends in velocity without a larger dataset.

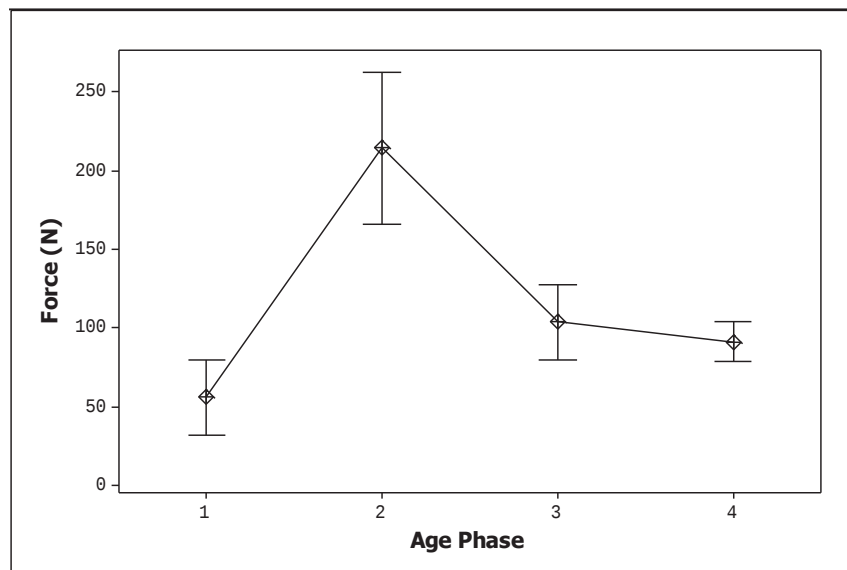


Figure 7. Interval plot for maximum force by age phases. Phase 1 = 0-18 years; Phase 2 = 19-39 years; Phase 3 = 40-60 years; Phase 4 = 61+ years.

Limitations and Future Work

All ribs were tested in a horizontal plane to maximize repeatability and reduce the number of variables. This is not unrealistic in a child because their ribs are oriented fairly horizontal in the thorax. However, this orientation is not a true representation after early childhood as the ribs become more angled relative to the spine with increasing age [22]. This approach was meant to create pure bending loads on the rib to aid our understanding of bone properties. In reality, the rib likely experiences some bending, torsion, and shear forces.

Stiffness according to rib level was not assessed as very little of the variance (13%), as assessed by ANOVA, could be attributed to this variable. Although [12] found no difference, [8] did find significant differences in many properties by rib level. This will be evaluated fully in future work in which the sample size is greatly increased.

This study presents only preliminary data which is part of a much larger project investigating the properties of human ribs. The number of ribs evaluated in each age category is not equal here, especially within the early phases, so interpretation should be approached with caution. Additionally, sex-differentiated stiffness values were not analyzed here because females are grossly underrepresented across this sample. As a larger sample is obtained, future work will include such analysis, in addition to incorporating more rib samples from a variety of ages, ethnicities, body sizes, and health conditions.

V. CONCLUSIONS

- This study summarizes the stiffness results of 71 whole rib tests from 26 pediatric through elderly subjects.
- Effective stiffness was found to vary significantly between age phases (1-4). A trend was revealed in which stiffness and peak force values increase throughout childhood and early adulthood, peak at about the time when peak bone mass is reached, and subsequently decline thereafter.
- A rate-dependency stiffness (1.0 m/s vs 2.0 m/s) was not supported in this sample.

VI. ACKNOWLEDGEMENTS

This research would not be possible without the selfless gifts that the donors and their families have shared with us, and it is only through their donations that progress is made in saving the lives of others. Donations were made through the Body Donation Program at The Ohio State University and Lifeline of Ohio. Thank you to NHTSA for sponsoring this research, and especially Bruce Donnelly and Jason Stammen for their continued support. The Transportation Research Center, Inc. and Jim Stricklin contributed as well. IBRC associates and students to thank include: Julie Bing, Kyle Icke, Rakshit Ramachandra, Laura Boucher, Amie Draper, Alexis Dzubak, Colleen Mismas, and Matt Reynolds.

VII. REFERENCES

- [1] NHTSA. Children. Traffic Safety Facts DOT HS 811 387, 2009.
- [2] Kent R, Henary B, Matsuoka F. 2005a. On the fatal crash experience of older drivers. *Annals of Advances in Automotive Medicine*, 49, 2005.
- [3] Sturtz G. Biomechanical data of children. *Stapp Car Crash Journal*, 24, 511-549, 1980.
- [4] Forman J, de Dios E, Symeonidis I, Duart J, Kerrigan J, Salzar R, Balasubramanian S, Segui-Gomez M, Kent R. Fracture tolerance related to skeletal development and aging throughout life: 3-point bending of human femurs. *IRCOBI Conference Proceedings*, Dublin, Ireland, 529-539, 2012.
- [5] Kent R, Woods W, Bostrom O. Fatality risk and the presence of rib fractures. *Annals of Advances in Automotive Medicine*, 52, 73-84, 2008.
- [6] Yoganandan N, Pintar F. Biomechanics of human thoracic ribs. *Journal of Biomechanical Engineering*, 120, 100-104, 1998.
- [7] Stitzel J, Cormier JM, Barretta JT, Kennedy E, Smith EP, Rath AL, Duma S, Matsuoka F. Defining regional variation in the material properties of human rib cortical bone and its effect on fracture prediction. *Stapp Car Crash Journal*, 47, 243-265, 2003.
- [8] Kemper A, McNally C, Pullins C, Freeman L, Duma SM, Rouhana S. The biomechanics of human ribs: Material and structural properties from dynamic tension and bending tests. *Stapp Car Crash Journal*, 51, 1-39, 2007.
- [9] Kindig MW, Lau AG, Forman J, Kent R. Structural response of cadaveric ribcages under localized loading: stiffness and kinematic trends. *SAE International*, 2010.
- [10] Reilly D, Burstein A, Frankel V. The elastic modulus for bone. *Journal of Biomechanics*, 7, 271-275, 1974.
- [11] Charpail E, Trosseille X, Petit P, Laporte S, Lavaste F, Vallencien G. Characterization of PMHS ribs: A

- new test methodology. *Stapp Car Crash Journal*, 49, 183-198, 2005.
- [12] Kindig MW. Tolerance to failure and geometric influences on the stiffness of human ribs under anterior-posterior loading: Master's thesis, University of Virginia, 2010.
- [13] Agnew A, Stout S. Reevaluating osteoporosis in human ribs: The role of intracortical porosity. *American Journal of Physical Anthropology*, 148, 462-466, 2012.
- [14] Kent R, Crandall J, Patrie J, Fertile J. Radiographic detection of rib fractures: a restraint-based study of occupants in car crashes. *Traffic Injury Prevention*, 3, 49-57, 2002.
- [15] Trosseille X, Baudrit P, Leport T, Vallancien G. Rib cage strain pattern as a function of chest loading configuration. *Stapp Car Crash Journal*, 52, 205-231, 2008.
- [16] Daegling DJ, Warren MW, Hotzman JL, Self CJ. Structural analysis of human rib fracture and implications for forensic interpretation. *Journal of Forensic Sciences*, 53, 1301-1307, 2008.
- [17] Maltese M, Castner T, Niles D, Nishisaki A, Balasubramanian S, Nysaether J, Sutton R, Nadkarni V, Arbogast KB. Methods for determining pediatric thoracic force-deflection characteristics from cardiopulmonary resuscitation. *Stapp Car Crash Journal*, 52, 83-105, 2008.
- [18] Tsitlik J, Weisfeldt M, Chandra N, Effron M, Halperin H, Levin H. Elastic properties of the human chest during cardiopulmonary resuscitation. *Critical Care in Medicine*, 11, 685-692, 1983.
- [19] Arbogast KB, Maltese M, Nadkarni V, Steen P, Nysaether J. Anterior-posterior thoracic force-deflection characteristics measured during cardiopulmonary resuscitation: Comparison to post-mortem human subject data. *Stapp Car Crash Journal*, 50, 131-145, 2006.
- [20] Wu Z, Ovaert T, Niebur GL. Viscoelastic properties of human cortical bone tissue depend on gender and elastic modulus. *Journal of Orthopaedic Research*, 30, 693-699, 2012.
- [21] Sandoz B, Laporte S, Charpail E, Trosseille X, Lavaste F. Influence of the velocity in human ribs response. *Journal of Biomechanics*, 40, Suppl 2, S215, 2007.
- [22] Openshaw P, Edwards S, Helms P. Changes in rib cage geometry during childhood. *Thorax*, 39, 624-627, 1984.