The Effect of Age on the Structural Properties of Ribs in Dynamic Frontal Loading

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ABSTRACT

Few studies have looked at the structural properties of human bones across the entire age spectrum. The goal of this study is to define linear stiffness and other structural properties of human ribs across a wide range of ages. Ribs are of particular interest because they are often fractured during motor vehicle crashes and can lead to further injuries to internal organs such as the heart and lungs. Multiple rib fractures can also be linked to a high risk of mortality, particularly in elderly individuals and children. A total of 140 ribs from individuals with ages ranging from 6 to 99 years (mean = 56 years) were tested in a custom fixture simulating a dynamic frontal impact. Rib ends were potted and fixed in rotating cups for testing. Each rib had two strain gages applied on the pleural and cutaneous surfaces to determine time of fracture. A pendulum impacted the sternal end of each rib at 1 or 2 m/s. A 6-axis load cell measured forces and moments on the vertebral end and a linear string potentiometer measured displacement. The displacement at the time of fracture as a percentage of total span length of the rib was calculated and compared across ages. Percent displacement showed a distinct negative trend with increasing age. Force in the primary loading direction (X) at fracture was highest in the young adult range, which corresponds to the timing of peak bone mass acquisition. Structural stiffness (K) was calculated from the linear portion of the force-displacement curve. K-values indicate increased variation for younger subjects than older subjects, but a significant ($p<0.05$) relationship with age. Investigating the differences in the structural properties of ribs can contribute to the development of better physical and virtual models of the human thorax, which could ultimately lead to improved safety standards. Additionally, information from this study can provide insight into how bone structural properties are affected by the aging process and enhance approaches for clinically-based injury prevention and identification of fracture risk.

INTRODUCTION

The thorax has been an important and popular area of study for motor vehicle crash research due to the high incidence of fatalities from thoracic injury. The rib cage is the primary structure that protects the vital organs of the thorax. Injury to this structure reduces its ability to shield important organs such as the heart and lungs. In the realm of thoracic injury, rib fractures in particular lead to increased morbidity and mortality among multiple populations in the United

States (Bliss and Silen, 2002; Bulger, 2000; Garcia, 1990; Hanna and Hershman, 2009; Holcomb, 2003; Kent, 2008; Sirmali, 2003; etc.). Many studies focus on the middle-aged, 50th percentile individual when studying motor vehicle crash injury. However, the results do not represent pediatric or elderly subjects well.

The number of rib fractures that a child attains is related to the severity of injury and an increase in mortality rate (Garcia, 1990). In Garcia's (1990) study, motor vehicle occupants had the highest mortality rate of the pediatric groups examined, and this rate had a positive correlation with the number of rib fractures that a child sustained. Bliss and Silen (2002) also studied rib fractures in children and related soft tissue injuries. Fractured ribs can lead to severe organ and soft tissue damage to important structures such as the heart, lungs, and liver (Pattimore, 1992).

The elderly are also at a high risk of fractured ribs. Several studies have confirmed complications and increased mortality due to rib fractures from motor vehicle accidents (Bulger, 2000; Hanna and Hershman, 2009; Holcomb, 2003; Kent, 2008; Sirmali, 2003). As many studies have shown, older individuals have more brittle bone tissue, and therefore their ribs are more likely to break, and in multiple places, than younger ribs (Kent, 2005; Zioupos, 1998).

These two populations have different physical properties, and therefore need to be examined further. However, very few studies have focused on these extremes of the age spectrum despite their vulnerability to thoracic trauma. Even fewer studies have examined bone properties across the entire age spectrum using the same test methodology to provide a direct comparison. The purpose of this study is therefore to define the structural properties of whole human ribs across a wide range of ages, by testing them in a dynamic loading pattern that simulates a frontal impact.

METHODS

Sample and Specimen Prep

The test sample for this study was intended to test a wide range of ages (Figure 1). One-hundred-forty middle ribs from 70 individuals (58M, 12F) were tested in a custom fixture simulating a frontal impact. Individual ribs were acquired through the Body Donation Program of the Division of Anatomy at The Ohio State University and Lifeline of Ohio, and their procurement was exempted from review by an institutional review board. Specimens were removed from individuals immediately after or near time of death, wrapped in normal saline-soaked gauze, and stored at -20°C until the day of testing. Ribs were thawed and cleaned of all external soft tissue before being potted. Ends of each rib were potted in 4x4x3 cm^3 blocks of Bondo ® Body Filler (Bondo Corporation, Atlanta, GA) in single-plane orientation. To prevent ribs overheating, the amount of hardener used to cure the Bondo ® base was such that the maximum curing temperature was not greater than approximate body temperature. Using cyanoacrylate, four strain gauges (Vishay Micro-Measurement, Shelton, CT, CEA-06-062UW-350) were applied to the surface of each rib. The gauges were applied at 30% (SG1) and 60%

(SG2) of the curve length of the potted rib on both the pleural and cutaneous surfaces. Strain gauges were primarily used to detect time of fracture. Throughout preparation and testing, ribs were kept well-hydrated with normal saline, since several studies have shown that wet and dry bone properties are different (e.g., Evans, 1973; Özkaya, 2012; Zioupos, 1998).

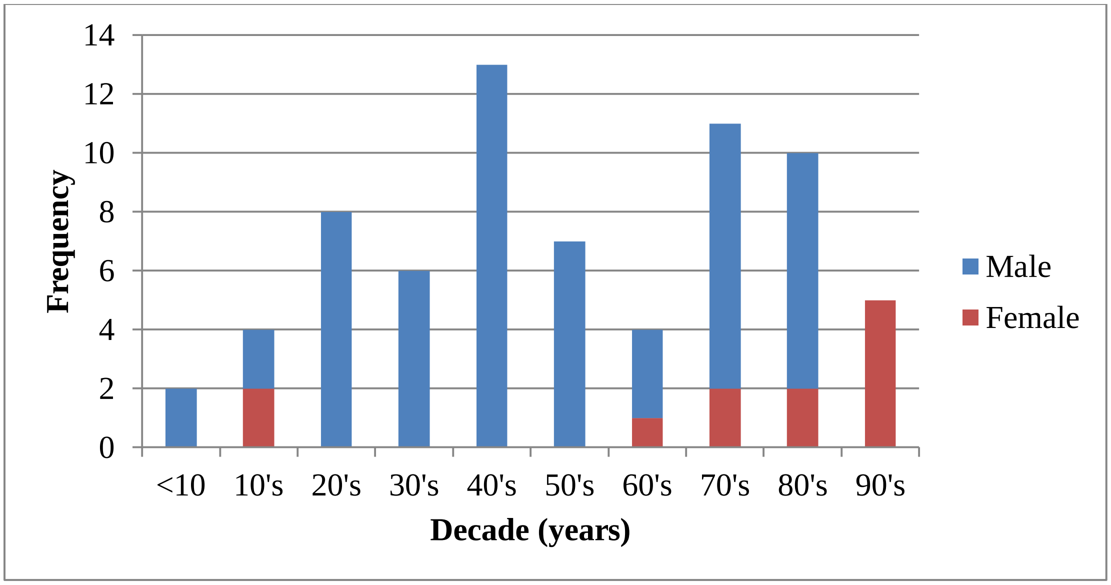

Figure 1. Number of subjects by decade. A wide spread of subject ages were tested in this study, with more male than female subjects represented.

Experimental Testing

Prior to testing, ribs were allowed to reach room temperature. The custom fixture used was built based on the design by Charpail, et al. (2005) and used by Kindig (2011) (Figure 2). The testing method simulated a dynamic frontal impact to the sternal end of the rib. The potted ends of the rib were fixed in freely rotating cups by screws. In order to reach velocities of 1 or 2 m/s (based on a random test matrix), a 54.4 kg pendulum impacted ribs at the sternal end. The sternal end was pushed in the direction of the vertebral end to produce a 2D bending scenario.

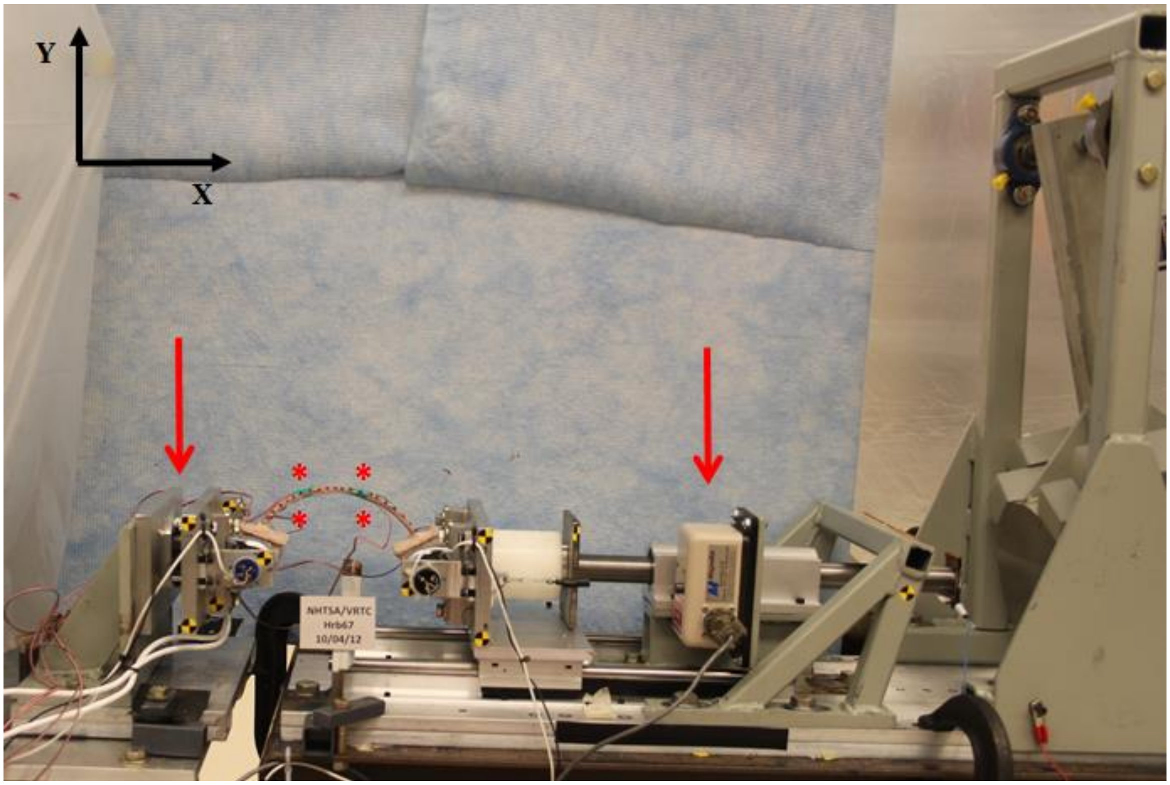

Figure 2. Experimental fixture and set-up. Instrumentation locations are indicated in red. Strain gauge locations on rib are marked by asterisks (*). Left and right red arrows indicate location of 6-axis load cell and linear string potentiometer, respectively. The pendulum can be seen to the right in the image. The fixed portion of the fixture (left) holds the vertebral end of the rib and the moving portion (right) holds the sternal end of the rib to mimic the frontal impact condition to the thorax.

The X-axis was defined along the axis of loading, with the Y-axis extending vertically, according to the SAE J211standard. Bending was almost entirely restricted to the X-Y plane during loading. A six-axis load cell (CRABI neck load cell, IF-954, Humanetics, Plymouth, MI) behind the fixed plate recorded forces and moments. Accelerometers (Endevco 7264G-2K, San Juan Capistrano, CA) were attached to both the fixed and moving plates. A linear string potentiometer (Rayelco P-20A, AMETEK, Inc. Berwyn, PA) measured displacement in the X-direction, which is analogous to sternal chest compression. Fracture location for the specimen was recorded after each test. The event was captured at 1000 frames per second by a high speed video camera (Phantom, Vision Research, Inc., Fort Wayne, IN) positioned perpendicular to the X-Y plane.

Data Processing and Analysis

Each separate fracture was tabulated as occurring in either the anterior, lateral, or posterior region. Regions were separated based on strain gauge location. Fractures posterior to SG1 were defined as posterior, and fractures anterior to SG2 were anterior (Figure 3). Fractures occurring between SG1 and SG2 were termed lateral. Ribs with multiple fractures had each fracture location tabulated individually.

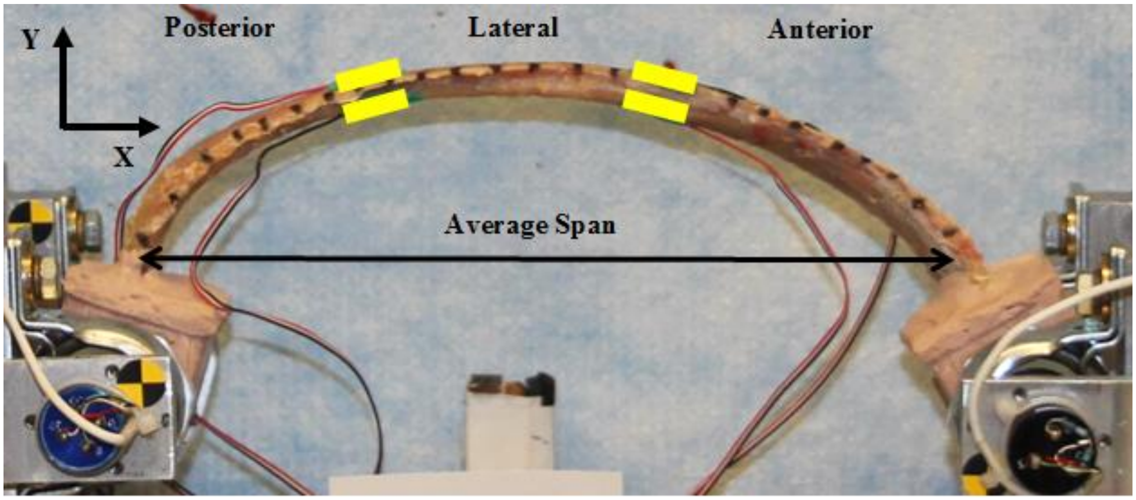

Figure 3. Fracture regions and span measurement. Strain gauge locations are indicated in yellow. Span measurement is shown by the black arrow.

Data were processed using a CFC180 filter before analysis. Displacement in the loading direction (X) was calculated as a percentage of the total rib span of each rib. The total rib span was defined as the average of the pleural (internal) and cutaneous (external) horizontal measurements.

For each specimen, a linear structural stiffness (K) was calculated. K was defined as the slope from 20-80% of yield of the force-displacement (F-D) curve. To define yield point for each rib, a method modified from unpublished work by Xavier was used (Xavier, 2006). Force and displacement data were first down-sampled to 1000 Hz. The linear slope of the F-D curve was calculated from the first point to every subsequent point. The cumulative rolling average and cumulative rolling standard deviation of these slopes was then calculated, and the yield point was defined as the point at which the cumulative rolling mean slope exited a ± 1 cumulative rolling standard deviation corridor from the mean. A linear regression line was fit to 20-80% of the linear region (Figure 4). This technique did not detect the end of the linear region for three of the 140 subjects, and these tests were therefore excluded from this part of the analysis.

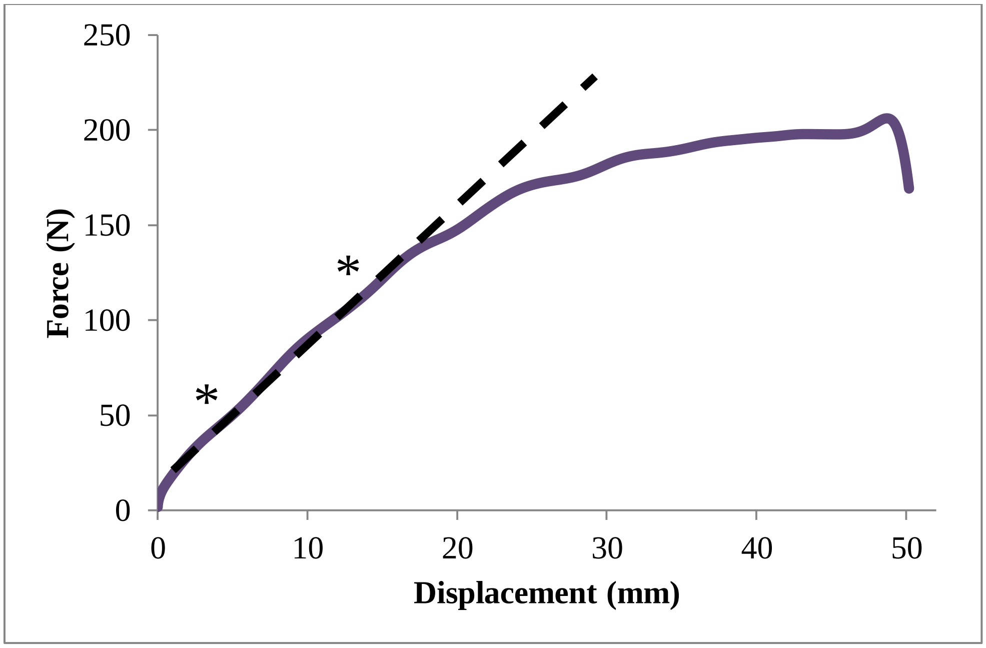

Figure 4. Representative force-displacement curve. Dashed line indicates linear regression line used for stiffness calculation. Approximate 20-80% of the linear region is indicated by asterisks (*). For this specimen, K = 7.16 N/mm with an $R^2 = 0.995$ for the linear fit.

Statistical Analysis

A multi-level mixed model was used to determine if a significant relationship existed between K and subject age. This model was chosen to account for possible dependence of some data points, since not all individuals had the same number of ribs available for testing. Level 1 analysis assumes a different mean stiffness for each individual and investigates degree of variation between and within subjects. Mean stiffness of ribs for a single individual was assumed to vary randomly. The level 2 model assumed a linear relationship between age and stiffness from all ribs. The model was tested at significance level $p<0.05$.

RESULTS

Fracture Location

Table 1 tabulates percentages and average ages of fracture locations for the test specimens. Most of the ribs fractured in the anterolateral region of the ribs. Average ages of ribs that fractured in the three regions are similar and standard deviations are large.

Table 1. Fracture locations, frequency, and average age of specimens

Fracture Locations		
Location	**Frequency (%)**	**Average Age (years)**
anterior	56.8	56 ± 25
lateral	34.8	64 ± 22
posterior	8.4	56 ± 27

Displacement Percentage

Percentage displacement in the loading direction has a clear decreasing trend with an increase in age (Figure 5). Qualitatively, younger subjects appeared to be more compliant and exhibit near-ideal bending during testing. Some of the ribs from elderly individuals deflected very little before fracturing. Maximum displacement in the loading direction also corresponds to the displacement at fracture.

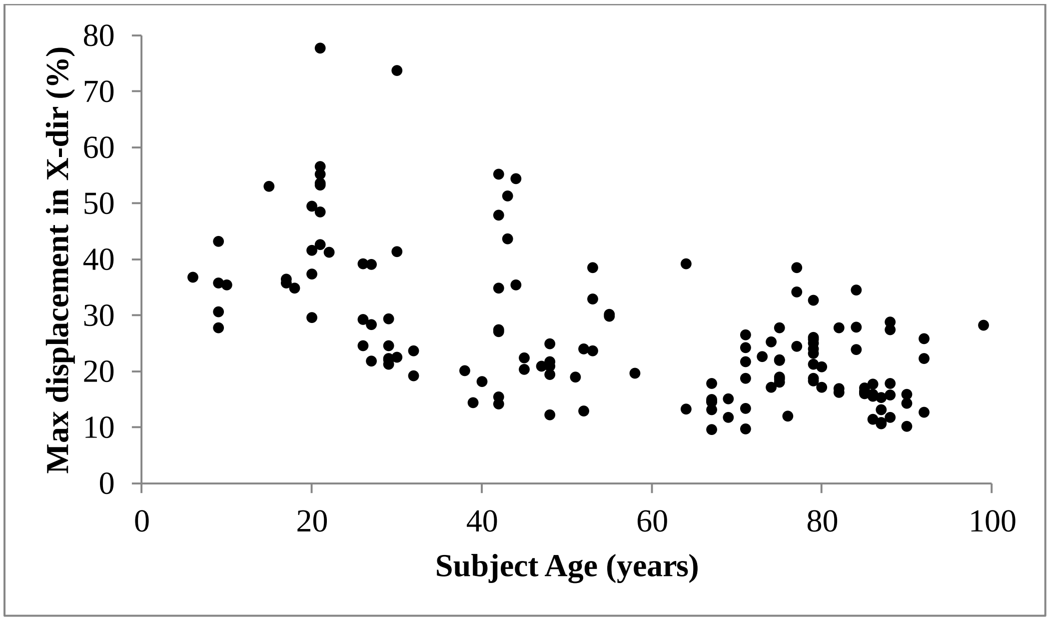

Figure 5. Maximum displacement percentage in the X-direction versus age. Age (years) is plotted on the x-axis and displacement (%) on the y-axis.

Forces at Fracture

Forces at fracture in the X-direction peaked in the young adult age range (Figure 6). Beyond the 25-40 year old range, forces at fracture decreased as age increased. Pediatric ribs also fractured at lower forces than young adults. Force at fracture did not always correspond to maximum force attained during the test, and was often at least slightly lower than peak force in the X-direction.

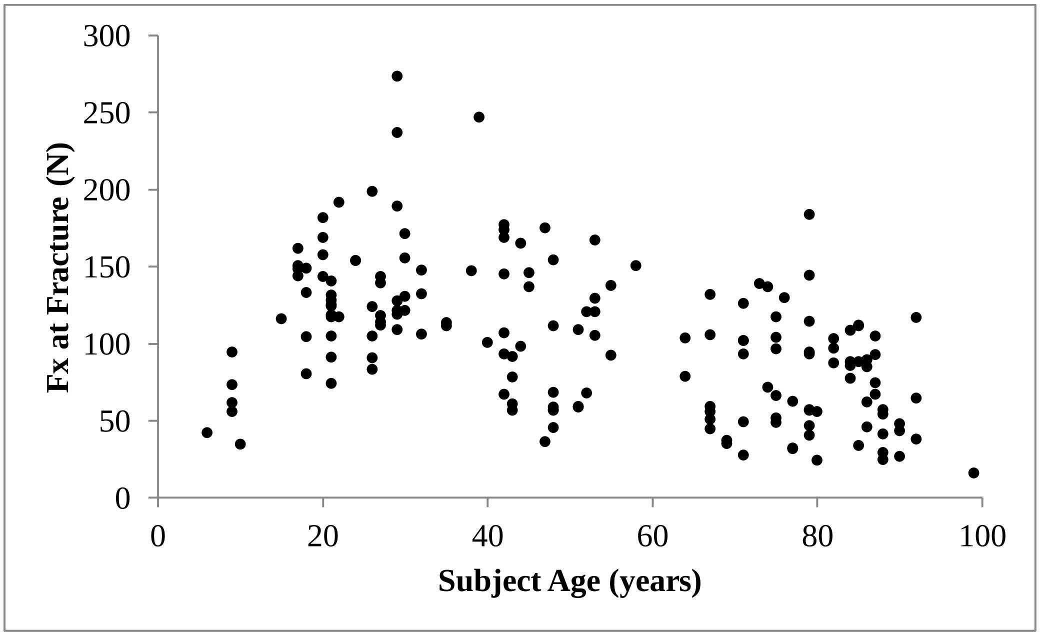

Figure 6. Force at fracture in the X-direction versus age. Age (years) is plotted on the x-axis and force at fracture (N) on the y-axis.

Linear Stiffness

Linear structural stiffness did not have an obvious trend upon first observation. However, level 1 model statistical tests revealed that approximately 68% of the total variance occurred between subjects, leaving the remaining 32% to be explained by intra-subject variation.

The level 2 tests revealed further details on how age is related to K. The fixed effect for age was considered significant ($p<0.0074$). Using a pseudo R^2 from regression to test variance explained by age, it was found that 13.8% of the variance in K was explained by age. However, a significant amount of variance can be described by factors other than age, since the estimate of residual covariance was significant ($p<0.001$). An implied marginal model line is shown with stiffness versus age data (Figure 7). The regression line illustrates that K significantly decreases with increasing age.

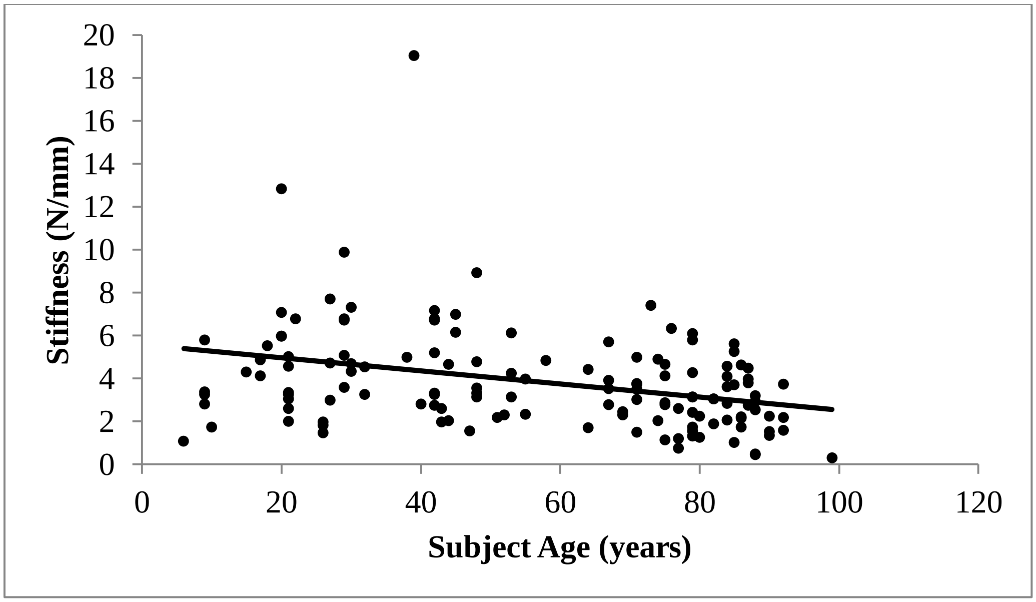

Figure 7. Linear structural stiffness (K) versus age. The line represents an implied marginal model based on the fixed effects estimate (an average regression for the subjects).

DISCUSSION

Fracture Location

Fracture locations seen in this study are similar to those in the literature for individual ribs and full thoraces, with the majority occurring in the anterolateral region (Crandall, 2000; Charpail, 2005; Daegling, 2008; Kindig, 2010). It should be noted, however, that the average ages of ribs with fractures occurring in each region were not different. One could conclude that the age-related changes in the material and structural properties of individual ribs may not play as large of a role in determining location of fracture. Structural properties of the entire thorax may also contribute to the most likely locations of rib fracture.

Of the 140 specimens tested, six ribs from five individuals did not fracture. The average age of these ribs was 21 ± 5 years, so they all occurred in subjects in the young adult or adolescent ages, and all with high displacement percentages. Multiple simultaneous rib fractures occurred for twenty-three ribs from 16 subjects. The average age of these ribs was 66 ± 15 years, and they often had lower displacement percentages. Younger ribs appear to be more likely to not fracture and displace more, while older ribs will exhibit multiple fractures.

Displacement Percentage

This study shows that there is a decrease in displacement percentage in the X-direction with increasing age. Several past studies support this observation, as it is well-known that bone material properties change with age. Bones from older individuals tend to be more brittle, and will therefore deflect less before fracture occurs (Evans, 1973; Özkaya, 2012; Zioupos, 1998).

A rib fracture in a child is a marker of severe trauma (Garcia, 1990). Unlike in older individuals, children are more likely to obtain severe soft tissue and organ damage even before a fracture occurs. Since the bones are more compliant, the rib cage can reach a depth of compression beyond that of an older individual. The young average age of the ribs that did not fracture is further evidence. Older ribs in this study were also more likely to fracture in multiple places and with less displacement, which is similar to past studies with full thoraces (Kent, 2005). These findings speak to the necessity of age-dependent injury risk curves based on chest compression, since rib fracture frequency changes with the age of the individual. Anthropomorphic Test Devices (ATDs) modeling the pediatric age group should be built with more compliant thoraces and injury standards appropriate to the structural and material properties of the younger population.

According to a model by Kent and Patrie (2005), rib fractures occur at different levels of chest compression for a 30-year-old versus a 70-year-old. After combining several studies, the model dictated that the 50% risk of a 30-year-old obtaining a single rib fracture from a frontal impact was at 35% chest compression, while a 70-year-old was at 13% chest compression. Comparing these values to our testing of single ribs appears to be similar (Figure 5). However, further investigation will be needed to compare the single-rib testing to full chest compression, and ultimately be able to create more specific injury criteria for ages not described by the model.

Forces at Fracture

During the young adult years (25-40), the forces at fracture in the X-direction exhibit a peak, and values are lower for younger and older subjects. Bone mass is highest during these years and probably able to resist fracture better than older and younger individuals. Results from this study were compared to maximum force results from two similar studies by Charpail (2005) and Kindig (2010) (Figure 8). Similar experimental set-ups were used, however slightly different rib numbers were analyzed. Charpail used ribs 4-9 from five separate subjects and loaded them dynamically. Kindig loaded ribs vertically at 0.5 or 1 m/s, and included an offset to account for removal of costal cartilage. Available ribs 4-9 from six subjects were tested dynamically in his study. Both studies used adults from a relatively small range of ages, but results correlate well with findings of the current study.

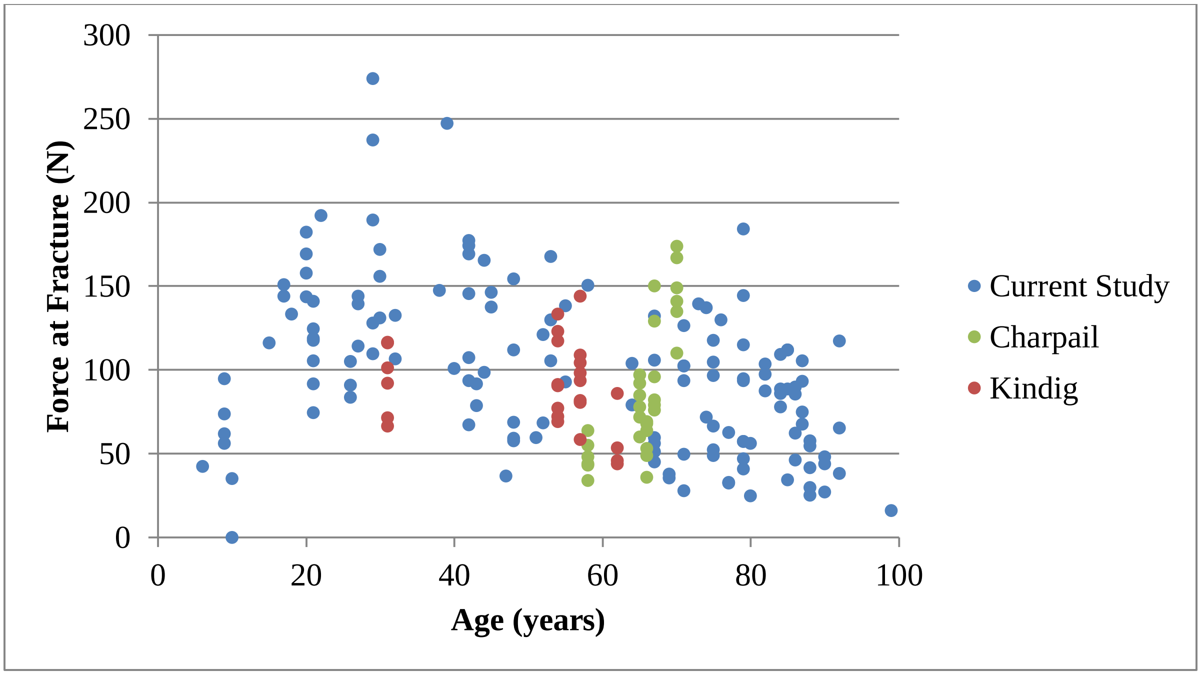

Figure 8. Comparison of force at fracture values versus age to previous studies by Charpail (2005) and Kindig (2010).

Linear Stiffness

The studies by Charpail and Kindig also looked at linear structural stiffness (Charpail, 2005; Kindig, 2010). Charpail determined the slope (K) of the linear force-displacement curve manually, while Kindig fit a line to the first 5% of total rib span displaced. All subjects analyzed by these studies were middle-aged, but the values of K agree with those from the current study (Figure 9). A linear elastic model was calculated in the current study to compare results to other literature. However, future studies will investigate other models such as elastic-plastic and viscoelastic.

Testing individual ribs is advantageous because it is possible to test a broader scope of subjects in a shorter amount of time. Since this study was not confined to whole intact thoraces, a wide range of subject ages could be analyzed. The next task is to then relate the findings back to a whole, intact thorax so as to develop injury criteria. The results of this study will be useful for both computational and analytical modeling purposes. One study in the past has looked at differences in stiffness between intact, denuded, and eviscerated thoraces (Kent, 2008). The thorax was found to retain about 30% of its intact stiffness after having been denuded and eviscerated. Studies like this could be combined with our results either analytically or in computational models.

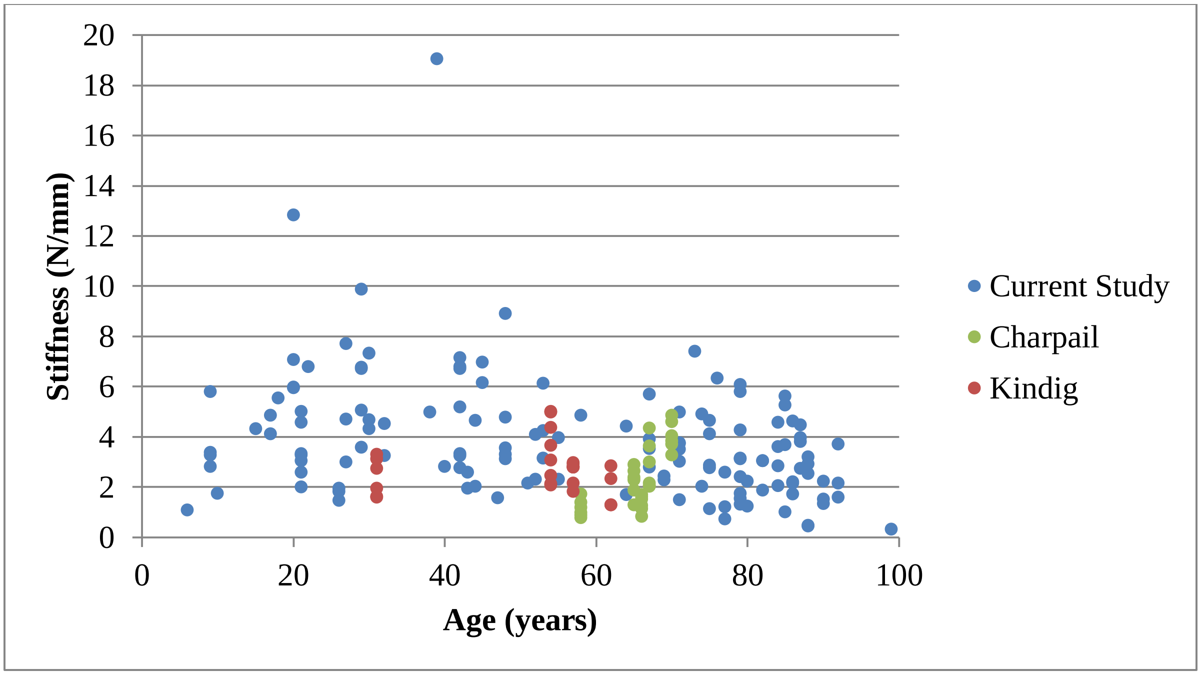

Figure 9. Comparison of linear structural stiffness values versus age to previous studies by Charpail (2005) and Kindig (2010).

Limitations

Despite the large range of ages that the study sample contained, there were still several limitations. It was not possible to obtain an equal amount of subjects for each age or group of ages. In particular, while several pediatric specimens were tested, there were far more ribs from elderly individuals in the sample. Additionally, the sample included more males than females, which could also skew the results.

Ribs were potted and prepped meticulously in an effort to constrain loading to pure bending. However, due to the natural curvature and variability in rib geometry, there may have been some torsional effects during loading. Additionally, further analysis may investigate comparative shear and bending stresses to determine if shearing failure is plausible.

The comparison of rib displacement values to that of chest compression of whole thoraces may not be appropriate. The 60% displacements that were seen for some of the pediatric ribs, for instance, seem somewhat unreasonable in the context of an intact thorax that contains soft tissues and organs that would resist compression. Rib angle with respect to the transverse plane of the intact thorax was also not taken into account in this test scenario. However, other avenues of analysis, such as the use of analytical and computational models, will be investigated to better understand the relationships. Past and future studies comparing structural properties of intact versus eviscerated thoraces will prove useful in this endeavor.

A linear relationship between stiffness and age was assumed in the statistical model, however nonlinearity in this relationship is possible. Trends shown in both stiffness and force at fracture suggest that these property values peak in the young adult, rather than the pediatric years. Nonlinear models are being considered, since there is a clear biological meaning for a peak during that time of life.

CONCLUSIONS

One-hundred-forty ribs from 70 individuals were tested in a custom fixture simulating a frontal loading pattern. Displacement percentages were highest in the younger subjects, and force at fracture peaked in the young adult years. Stiffness showed a significant relationship with age. Results of this study could improve ATD biofidelity and injury criteria, since it can help define the structural properties of ribs with age, although further analysis will be needed to fully define these relationships. The results of the study are important because the entire spectrum of ages was tested using the same repeatable method, and therefore values can be compared across ages in a straightforward manner.

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