A Preliminary Investigation of Costal Cartilage and the Costochondral Junction in Three-Point Bending

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ABSTRACT – Thoracic skeletal trauma is a common result from motor vehicle collisions. This includes fractures to the ribs, costal cartilage, and costochondral junction (CCJ). Obtaining accurate material and mechanical properties for these structures is important for the development and validation of human body models. Consequently, the objective of this preliminary study was to quantify and compare the mechanical properties of costal cartilage and the CCJ during three-point bending. Samples of isolated cartilage (CC only) and costal cartilage with the rib still attached at the CCJ (Rib+CC) were loaded to failure during three-point bending tests. The stiffness, ultimate properties, and failure properties were analyzed with respect to sample type, age, and sex. Ultimate displacement and failure displacement were the only properties that were significantly different with respect to sample type, with CC only samples displacing more than the Rib+CC samples, but a larger sample size is needed to further the analysis and confirm the results.

INTRODUCTION

The thorax is frequently seriously injured during motor vehicle collisions. Serious skeletal thoracic injuries, as defined by the 2015 Abbreviated Injury Scale, consist of three fractures to the ribs, costal cartilage, or costochondral junction (CCJ). Previous studies have sought to characterize the material properties of the ribs and costal cartilage to aid in the development of human body models, which rely on such properties to accurately predict thoracic injury when evaluating vehicles and their safety systems (Katzenberger et al., 2020; Albert et al., 2021; Albert et al., 2023; Nowinski 2022; Damron 2024). However, the material property data for costal cartilage is limited for older adults due to difficulties in fabricating samples as the cartilage becomes more fragile with increasing age. Previous studies have investigated the bending properties of isolated costal cartilage and ribs (Forman et al., 2010; Goh and Anderson, 2024; Agnew et al., 2018). However, the mechanical properties of the CCJ have not yet been studied.

The CCJ is a cartilaginous joint between the costal cartilage and rib without a clear boundary where they meet. The rib cups the end of the cartilage, and the depth of this cup varies between individuals. Calcifications in the cartilage, which are often observed with increased age, can also obfuscate the boundary between cartilage and bone materials. Discontinuities in both materials where they integrate together could result in decreased mechanical strength of the joint relative to the isolated materials. If the CCJ is weaker than the surrounding ribs and cartilage, human body models could be underpredicting thoracic injuries. Therefore, the purpose of this preliminary study was to quantify and compare the mechanical properties of the costal cartilage and CCJ during bending.

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METHODS

Thirty (n=30) total samples were ethically obtained from nineteen (n=19) donors (M=9, F=10) via informed consent tissue donation programs. The donor ages ranged from 21 to 98 years (62.9 ± 23.0 years). Sixteen (n=16) isolated costal cartilage samples (CC only) and fourteen (n=14) costal cartilage samples attached to ribs at the CCJ (Rib+CC) were prepared. Both CC only and Rib+CC samples were obtained from the same donor at either the same or different rib levels for 11 of the 19 donors. Tissue from rib levels 3 through 6 were used for this study.

Sample Preparation

Samples were wrapped in saline soaked gauze and kept frozen until use. After thawing, soft tissue was removed from the samples, while keeping the fiber layer of the perichondrium intact. Then, the medial end of each sample was potted using a two-part polyurethane resin (EasyFlo 60 Liquid Plastic, PolyTek Development Corp., Easton, PA). Prior to potting, a carbon fiber pin was inserted into the medial end of each sample to serve as an anchor in the potting compound. A custom potting rig was used to center the samples within the potting cup and ensure the portion of the sample within the testing span length was as straight as possible. For the Rib+CC samples, the CCJ was positioned at the anticipated midpoint of the span length. A fiberglass rod spanned the width of the potting cups with excess material on each side to serve as a pin interface with the three-point bending fixture.

Test Fixture and Procedure

The three-point bending fixture consisted of a T-slotted base (G238, Test Resources, Shakopee, MN), one non-articulating roller support, a custom pin support, and a custom aluminum impactor. The impactor and roller support had diameters of 6-mm. The span length from the pin to roller support was 54 mm with the impactor placed at the middle of the span length. Therefore, the impactor was positioned to directly load the CCJ at initial contact for the Rib+CC samples. All samples were positioned in the setup such that the impactor loaded the pleural surface of the sample in compression, resulting in tension on the cutaneous surface (Figure 1). A single-axis load cell (12010ACK-300-B, Interface, Scottsdale, AZ) below the base of the fixture recorded the reaction force, and a string potentiometer (150-0121, Firstmark Controls, Creedmoor, NC) recorded impactor displacement.

Testing was conducted using an electronic material testing system (800LE4, Test Resources Inc., Shakopee, MN). The target impactor displacement rate was 30-mm/s. This was estimated to correspond to a strain rate of approximately 0.5 strain/s on the outer surface of the material, which is representative of dynamic seat belt loading (Kemper et al., 2007). Force and displacement data were collected at 20 kHz, and high-speed video was collected at 1000 fps (Phantom v9.1m, Vision Research, Wayne, NJ).

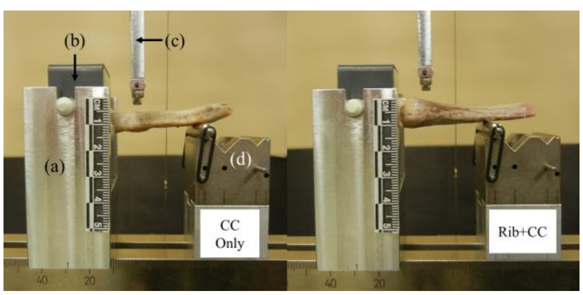

Figure 1. Three-point bending test setup for CC only (left) and Rib+CC (right) samples. (a) pin support, (b) potting cup with pin, (c) impactor, (d) roller support structure.

Data Analysis

Force and displacement data were filtered using an SAE J211 lowpass filter at a channel frequency class of 60 (SAE 2014). Stiffness, ultimate force, ultimate displacement, failure force, and failure displacement were calculated from the force and displacement time histories. Stiffness was defined as the slope of a linear regression line fit to the linear portion of the force-displacement curve. Failure timing was determined by analyzing the force data in conjunction with the synced high-speed video data. An ANOVA was used to evaluate any mechanical property differences between sample types (CC only and Rib+CC). Additional factors of age, sex, and the interaction of age and sex were included to account for possible effects on the mechanical properties. A p-value less than 0.05 was considered significant.

RESULTS

Four (n=4) CC only and one (n=1) Rib+CC sample did not fail or failed within the potting cup. The stiffnesses of these samples were included in the data analysis. but, the ultimate and failure properties were not included. On average, the CC only samples had greater ultimate and failure properties than the Rib+CC samples, while the Rib+CC samples had greater stiffnesses (Table 1). The ANOVA indicated that the ultimate displacement (p=0.0026) and failure displacement (p=0.0031) were statistically significantly different between sample types. Increasing age was associated with a significant decrease in failure displacement (p=0.0408), but age did not have a significant effect on any other mechanical properties. Sex and the interaction of age and sex did not have a significant effect on any mechanical properties.

Table 1. Average (standard deviation) mechanical properties for all CC Only and Rib+CC samples. Bold values indicate a significant difference in sample type.

Property	CC Only	Rib+CC
Stiffness (N/mm)	18.4 (14.7)	23.6 (24.8)
Ultimate Force (N)	93.8 (59.1)	83.2 (71.1)
Ultimate Displacement (mm)	**7.9** (2.4)	**5.0** (1.8)
Failure Force (N)	88.1 (61.3)	82.1 (71.4)
Failure Displacement (mm)	**9.1** (3.8)	**5.2** (1.8)

DISCUSSION

The results of this preliminary study showed that the CC only samples experienced greater displacement prior to failure than the Rib+CC samples. This finding could be attributed to greater deformation of the cartilage before failure and less cartilage being present in the Rib+CC samples. A previous study comparing whole ribs with and without the costal cartilage intact during anterior-posterior loading reported greater displacement of the specimens containing costal cartilage prior to failure, agreeing with the results of this study (Schaffer et al., 2024). When compared to a previous study that tested isolated rib sections in three-point bending (Kemper et al., 2007), the peak bending moment of the CC only (1.27 Nm) and Rib+CC samples (1.12 Nm) were lower than those of the anterior ribs (3.5 Nm). Therefore, both the CC only and Rib+CC samples were mechanically weaker than isolated rib samples.

The results of this preliminary study are limited by sample size. It is possible that a larger sample size could reveal more statistical differences between CC only and Rib+CC samples, but the variance for some properties could be too large to achieve statistical significance. Some outliers in terms of stiffness, failure force, and failure displacement were observed (Figure 2), which contributed to the large standard deviations observed for some properties (Table 1). Given the small sample size of the study, it is unclear if these are true outliers or if they approximate the outer bounds of the population response. Therefore, they were not excluded from any analyses. It is not known to what degree the observed variance derives from the material properties of the cartilage or the geometric properties. Differences in cross-sectional area between subjects and sample types could contribute to increased variance and lack of statistical significance. For example, the cartilage had a larger cross-sectional area than the anterior ribs for some samples (Figure 1-right), which could bias differences between CC only and Rib+CC samples. The ANOVA used for this analysis is limited due to the presence of outliers and because it did not account for the geometry of the samples. Future work can include accounting for the effect of cross-sectional area in statistical analyses with a larger sample size. The effect of inter-subject variability, whether from material or geometric properties, on the sample type statistical analysis could be decreased by using a matched-pair analysis once a larger sample size of matched pairs is obtained. This analysis would have more statistical power to reveal any differences between sample types.

The current sample size could also be too small to identify differences in mechanical properties with respect to age and sex. Material property testing of costal cartilage and rib bone have shown changes with advancing age (Katzenberger et al., 2020; Albert et al., 2021; Albert et al., 2023; Nowinski 2022; Damron 2024). However, bending tests on whole ribs have demonstrated weak correlations between age and structural properties (Agnew et al., 2018). While the material properties of these tissues typically decrease with increasing age, a larger stiffness and failure force were observed for some CCJ samples from subjects aged 90 years and above. It is anticipated that calcification of the cartilage could be confounding age trends. Additionally, there were few subjects available below 50 years of age, and failure properties were not available for any subjects aged 20-29 years. If there are large mechanical differences between younger and older subjects but not within older subjects, the absence of the younger subjects could contribute to age having no significant effect on the mechanical properties. Future work will increase the sample size of this study and aim to more evenly distribute samples between decades to strengthen analyses with respect to sample type, age, and sex. Additionally, samples will be tested at a lower loading rate to evaluate whether rate affects any of these relationships.

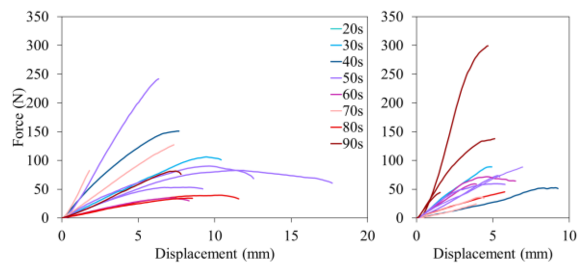

Figure 2. Force-displacement curves for the CC only (left) and Rib+CC (right) samples colored by decade. Only samples with successful failures were included.

CONCLUSION

This study was a preliminary investigation of the mechanical properties of costal cartilage and the costochondral junction in three-point bending. No significant differences in stiffness, ultimate force, and failure force were observed between sample types. However, greater ultimate and failure displacements were observed in the isolated costal cartilage compared to the samples that included the CCJ. The results of the current study suggest that differentiation of the costal cartilage and the costochondral junction could be necessary for optimizing the ability of HBMs to predict thoracic response and injury when designing and evaluating vehicle safety features.

ACKNOWLEDGMENTS

The authors thank the anatomical tissue donors of this study, for without their contributions, this study would not have been possible. We thank Autoliv Research for funding this study. We also thank David Boyle, Jada Czesnakowski, Brock Palm, and Eugene Legaspi for their valuable contributions to this project.

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