Effects of Strain Rate and Age on the Tensile Material Properties of Rib Cortical Bone

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INTRODUCTION

Finite element models of the human body are frequently used to evaluate thoracic injury risk in motor vehicle collisions. However, the accuracy of these models is dependent on the biomechanical data available to validate them. While it is well established in the literature that cortical bone is viscoelastic, previous studies have only evaluated the tensile material properties of rib cortical bone at 0.5 s^{-1}, which was the average strain rate in cadaveric ribs due to seat belt loading that simulated a 48 kph sled test [1-4]. In addition, previous studies have been limited to a small number of subjects. Therefore, the purpose of this study was to evaluate the effects of age and loading rate on the tensile material properties of rib cortical bone over a wide range of subject demographics.

METHODS

A total of sixty-one (n=61) subjects (M=32, F=29) ranging in age from 17-99 yrs. (Avg.=56.4 $\pm$ 26.2 yrs.) were used in this study. Rib cortical bone coupons were tested to failure in tension on a servo-hydraulic material testing system. The test setup consisted of a load cell to measure axial load and an extensometer to measure displacement within the gage length (Figure 1).

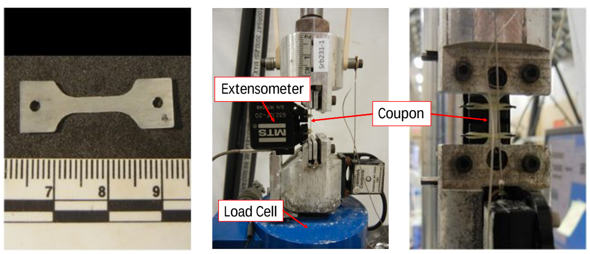


Figure 1. Final dog-bone coupon (left), frontal view of experimental set-up with clamped coupon (center), and side view of experimental set-up (right).

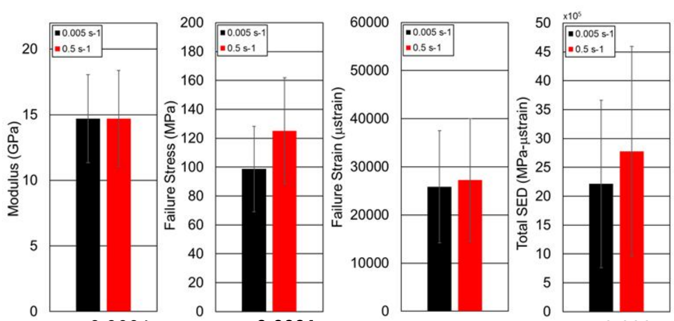
Two samples were taken from each subject. One coupon was tested at 0.005 s^{-1} and the other was tested at 0.5 s^{-1}. The modulus, yield stress, yield strain, failure stress, failure strain, ultimate stress, and elastic, plastic, and total strain energy density (SED) were calculated for each test and compared between loading rates. Spearman correlation analyses were conducted to determine whether there were significant relationships between material properties and age (Table 1). Paired t-tests or Wilcoxon signed rank tests were conducted to evaluate the effect of loading rate.

Table 1. Correlation analysis for the effect of age on material properties.

Material Property Variable	0.005 strain/s tests			0.5 strain/s tests		
	ρ	R^2	p-value	ρ	R^2	p-value
Modulus	-0.188	0.041	0.1569	-0.445	0.241	**0.0005**
Yield Stress	-0.389	0.145	**0.0025**	-0.462	0.237	**0.0003**
Yield Strain	-0.527	0.226	**<.0001**	-0.197	0.041	0.1375
Failure Stress	-0.594	0.358	**<.0001**	-0.785	**0.556**	**<.0001**
Failure Strain	-0.703	**0.527**	**<.0001**	-0.697	**0.490**	**<.0001**
Ultimate Stress	-0.624	0.397	**<.0001**	-0.787	**0.559**	**<.0001**
Elastic SED	-0.451	0.178	**0.0004**	-0.424	0.194	**0.0009**
Plastic SED	-0.744	**0.547**	**<.0001**	-0.791	**0.611**	**<.0001**
Total SED	-0.745	**0.551**	**<.0001**	-0.792	**0.623**	**<.0001**

RESULTS – EFFECTS OF STRAIN RATE

The effects of strain rate were analyzed for fifty-five (n=55) subjects that had a successful test at both strain rates. While the modulus and failure strain did not show any significant differences with respect to strain rate, failure stress and total SED were significantly lower at 0.005 s^{-1} than 0.5 s^{-1} (Figure 2). The trends in the current study are consistent with previous experiments that tested femoral and tibial cortical samples at similar loading rates [5, 6].



p = 0.9664 p **< 0.0001** p = 0.2582 p **< 0.0001**

Figure 2. Comparison of modulus (left), failure stress (left-center), failure strain (right-center) and total SED (right) between 0.005 strain/s and 0.5 strain/s.

RESULTS – EFFECTS OF AGE

Fifty-eight (n=58, M=32, F=26, Avg.=56.9 yrs.) coupons were successfully tested at 0.005 s^{-1} and fifty-eight (n=58, M=31, F=27, Avg.=57.3 yrs.) coupons were successfully tested at 0.5 s^{-1}. All material properties decreased significantly with increased age at both loading rates except modulus at 0.005 s^{-1} and yield strain at 0.5 s^{-1}. The R^2 values were highest for total and plastic SED with respect to age for both loading rates (Figures 3-4). The corresponding trends in plastic stress and strain and the weakness in trends in yield stress and strain with age indicate that post-yield behavior drove the correlation between SED and age (Figure 5).

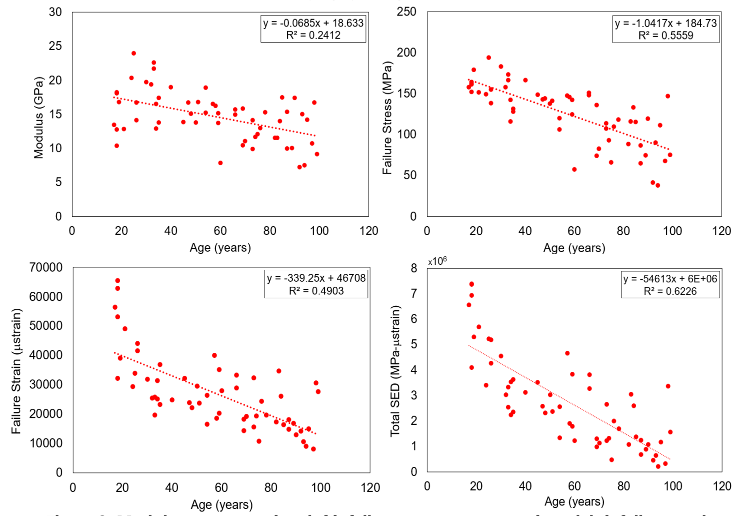


Figure 3. Modulus versus age (top left), failure stress versus age (top right), failure strain versus age (bottom left), and total SED versus age (bottom right) at 0.5 s^{-1}.

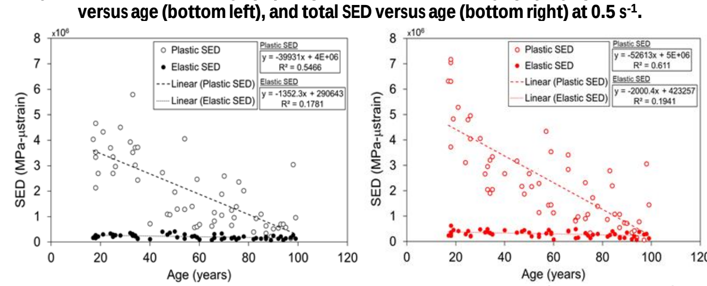


Figure 4. Plastic and elastic strain energy density versus age at 0.005 s^{-1} (left) and 0.5 s^{-1} (right).

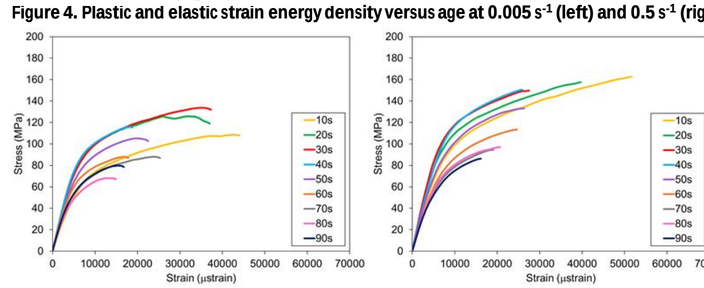


Figure 5. Characteristic average curves for 0.005 s^{-1} tests (left), and 0.5 s^{-1} tests (right) for each decade.

DISCUSSION & CONCLUSIONS

The results showed that the material properties of human rib cortical bone varied significantly with respect to both loading rate and age. However, the R^2 values for the material property data with respect to age only ranged from 0.24-0.62, indicating that there may be other variables that better account for the variance within a given population. Overall, this is the first study to analyze the effects of loading rate and age on tensile material properties of human rib cortical bone using a reasonably large sample size. Although a number of studies have analyzed the effects of strain rate and age on cortical bone, the majority of these studies evaluated samples from the femur, tibia, or fibula. Due to the fact that the ribs withstand different types of loading in everyday life than long bones in the lower extremity, and bone is known to remodel in response to the stresses that are placed upon it, the microstructure of the ribs is inherently different than long bones. Consequently, the magnitudes of the material properties for rib cortical bone are likely different as well. Therefore, the data from this study should be utilized when modeling the biomechanical response of the ribs.

REFERENCES

[1] Kemper AR et al., The Biomechanics of Human Ribs: Material and Structural Properties from Dynamic Tension and Bending Tests. Stapp Car Crash J., 51, 2007.

[2] Kemper AR et al., Material Properties of Human Rib Cortical Bone from Dynamic Tension Coupon Testing. Stapp Car Crash Journal, 49, 2005.

[3] Albert DL et al., A Comparison of Rib Structural and Material Properties from Matched Whole Rib Bending and Tension Coupon Tests. IRCOBI, IRC-17-71, 2017.

[4] Duma SM et al., Rib Fracture Timing in Dynamic Belt Tests with Human Cadavers. Clinical Anatomy, 24(3), 2011.

[5] McElhaney, JH and Byars, EF., Dynamic response of biological materials. ASME, Publ. 65- WA/Huf-9, 1965.

[6] Crowninshield RD and Pope MH., The response of compact bone in tension at various strain rates. Annals of Biomedical Engineering, 2(2):217-25, 1974.

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