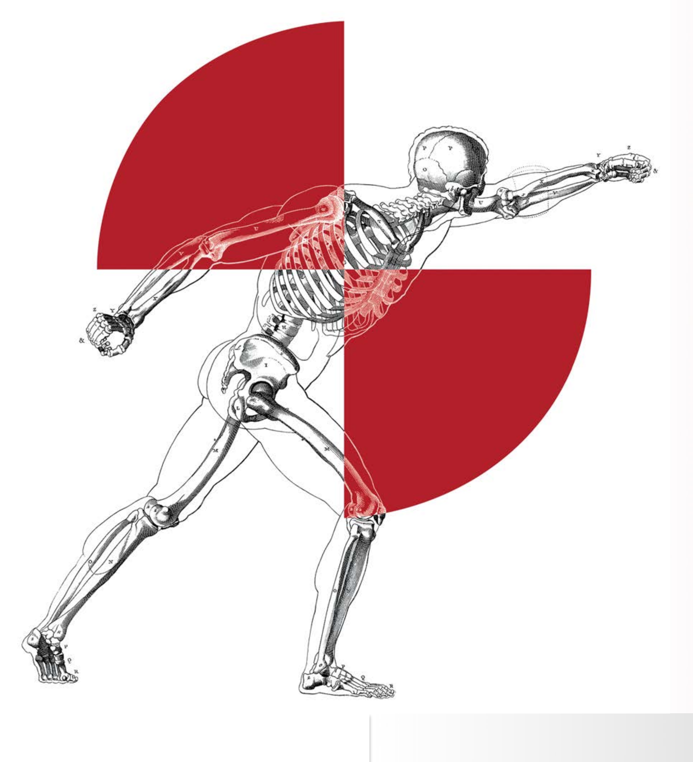

Investigation of Repeat Anterior-Posterior Loading of Human Ribs

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INTRODUCTION

- Thorax injuries, specifically rib fractures, are common in motor vehicle crashes and can lead to high rates of morbidity and mortality (Kent *et al.* 2008). In order to ultimately improve thoracic injury prevention measures, quantifying variation in rib response for all occupants is crucial.
- Many studies have been conducted on single impacts of ribs in dynamic testing (Agnew *et al.* 2018) and on non-injurious quasi-static fatigue loading (Li *et al.* 2010). However, repeated dynamic test data for whole human ribs are lacking.
- **The goal of this study was to explore why some ribs did not fail during a dynamic impact to better understand differential fracture risk. Additionally, we investigated changes in structural properties between multiple impacts.**

MATERIALS & METHODS

- Three-hundred and seventy-two ribs from 204 post-mortem human subjects (72 females, 132 males, 4 - 108 years) were dynamically impacted in anterior to posterior loading (Fig. 1). Displacement was measured by a linear string potentiometer attached to the moving plate of the fixture. Force was measured in the direction of impact (X) by a 6-axis load cell behind the vertebral end of the rib. Strain gages attached at 30% and 60% of whole rib curve length on the cutaneous and pleural surfaces measured strain. Structural properties were calculated from force vs. displacement (F-D) curves (Fig. 2).
- Eleven ribs did not fracture during initial impact and were subsequently impacted again. These ribs fell into three distinct cases according to impact velocity (1 m/s or 2 m/s) and failure or not during the second impact (Fig. 2).

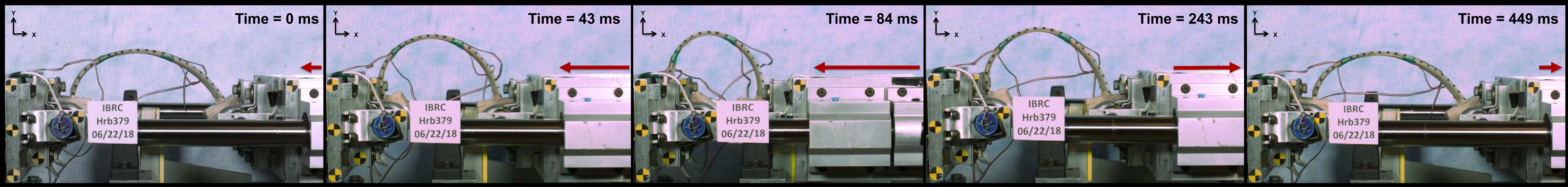

Figure 1. Dynamic A-P rib bending test that did not fail on first impact through loading and "unloading"

RESULTS & DISCUSSION

11 ribs did not fail on first impact and were impacted again

Case 1	Case 2	Case 3
Same velocity (2m/s→2m/s)	Different velocity (1m/s→2m/s)	Different velocity (1m/s→2m/s)
No failure during second impact (n=4)	Failure during second impact (n=3)	No failure during second impact (n=4)

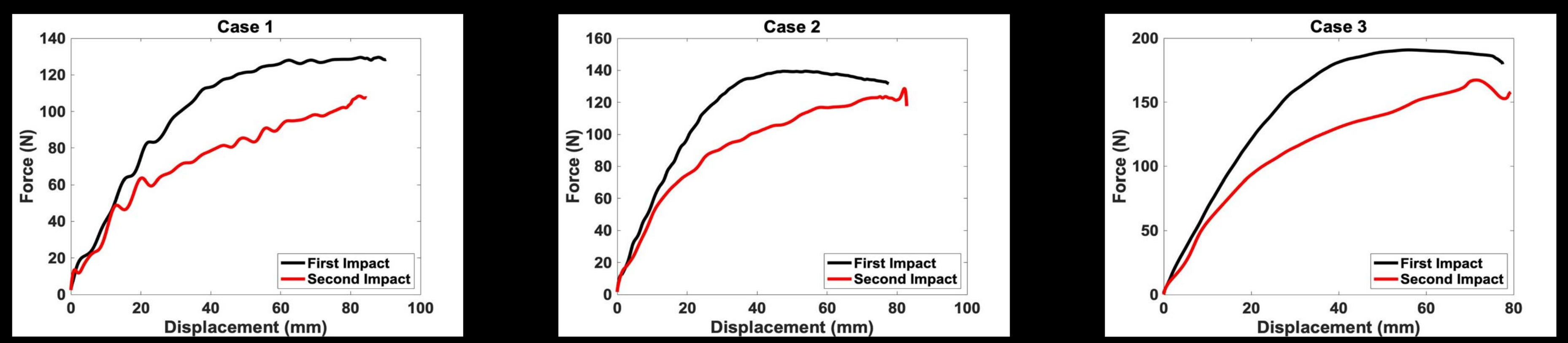

Figure 2. Schematic of rib responses for each impact organized by case scenarios. Data are cut at the time of peak strain for calculation of structural properties.

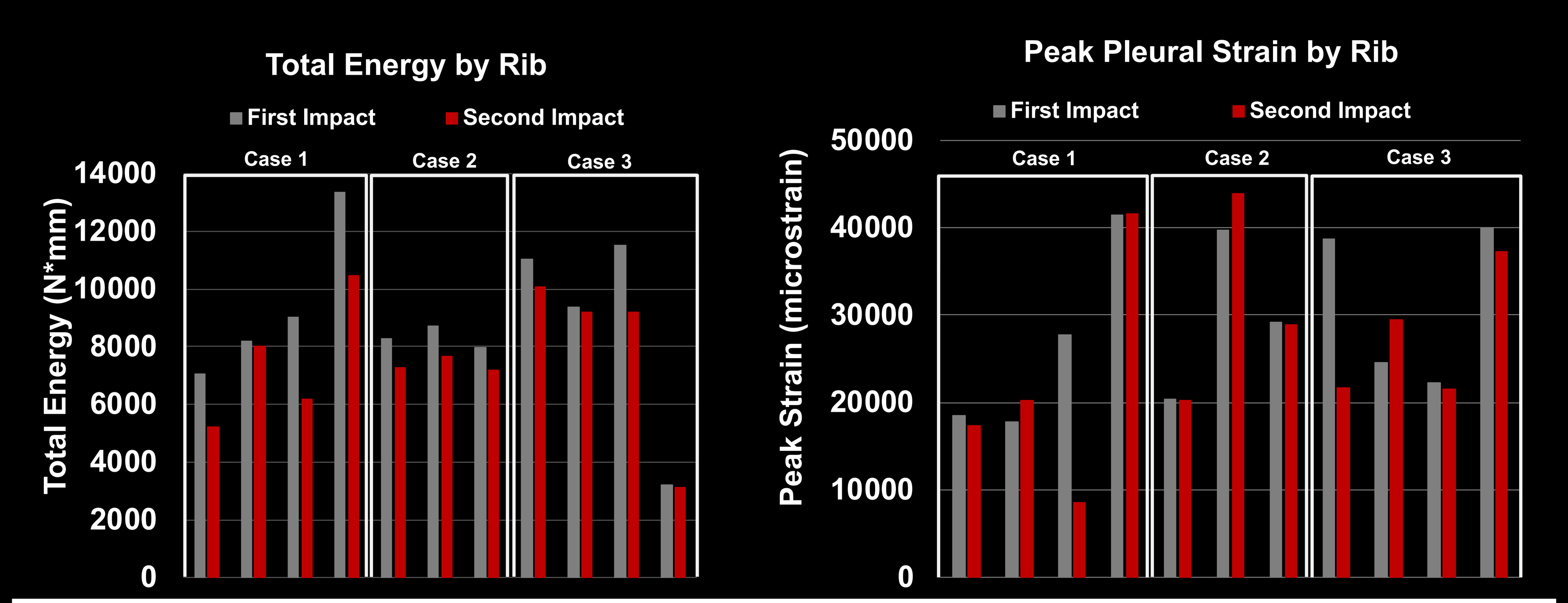

Figure 3. Total energy (left) and peak strain (right) comparisons by rib and impact number

- Total energy, force (peak and yield), and linear structural stiffness were generally lower for the 2nd impact than the 1st.
- Total energy (Fig. 3) decreased after the first impact regardless of varied impact velocities. The second rib in Case 1 shows only a small difference in total energy between impacts. During the second impact, the displacement was greater than that of the first impact contributing to similar energy values despite lower peak forces.
- No trend in peak strain (Fig. 3) was observed. For ribs in Case 1 strain rates were decreased by 0.1 strain/s during the 2nd impact despite the same impact velocity.
- Fig. 4 shows the complete loading and "unloading" cycle of both impacts corresponding to Fig. 1. The end of the loading cycle was determined by the peak strain. The loading behavior between impacts is different but shows similar "unloading" response for both impacts.
- Fig. 5 explores the differences in these 11 ribs compared to the 362 fractured ribs. Microdamage accumulation may explain decreased structural properties during subsequent impacts. Despite potential microdamage, ribs in Cases 1 and 3 did not fracture during a 2nd impact and therefore these individuals could be at lower risk for thoracic injuries in frontal impacts.

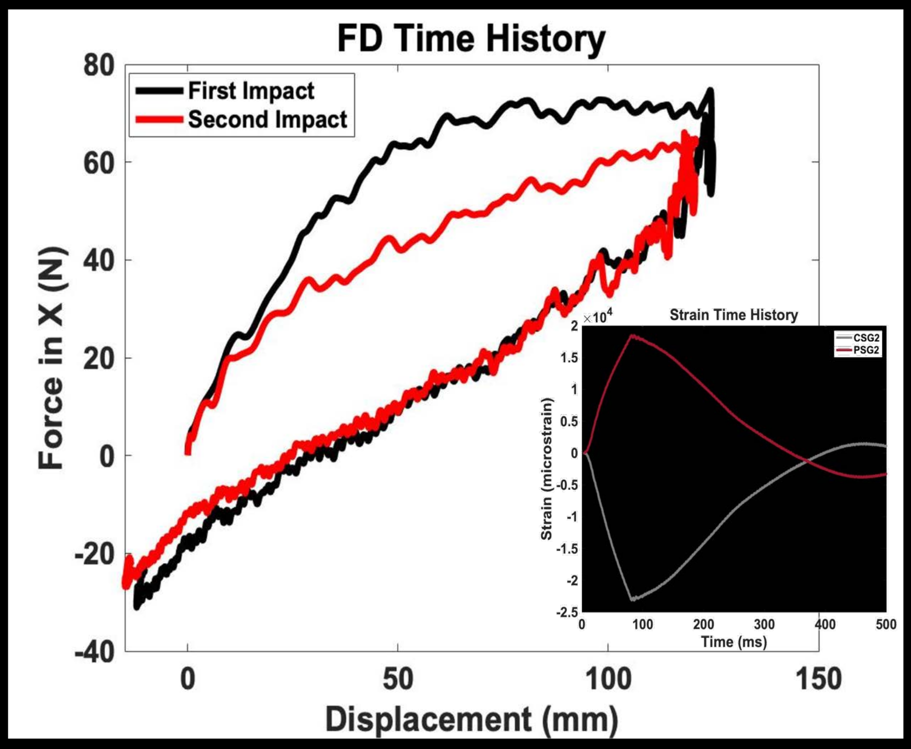

Figure 4. F-D and strain time history for rib in Fig. 1 showing loading and "unloading"

Between Subjects

- Age was lower (4 - 30 years) than the fractured sample
- Both sexes: 7 Males, 2 Females

Structural Properties

- Average structural properties in all cases for these 11 ribs were greater than the average of the sample of fractured ribs.

Cross-Sectional Geometric Properties

- Larger Ct.Th and Ct.Ar (Fig. 6) in these 11 ribs were found when compared to age- and sex-matched ribs from the fractured sample, and likely contributed to increased fracture resistance.

Figure 5. Hierarchical exploration of why ribs did not fail

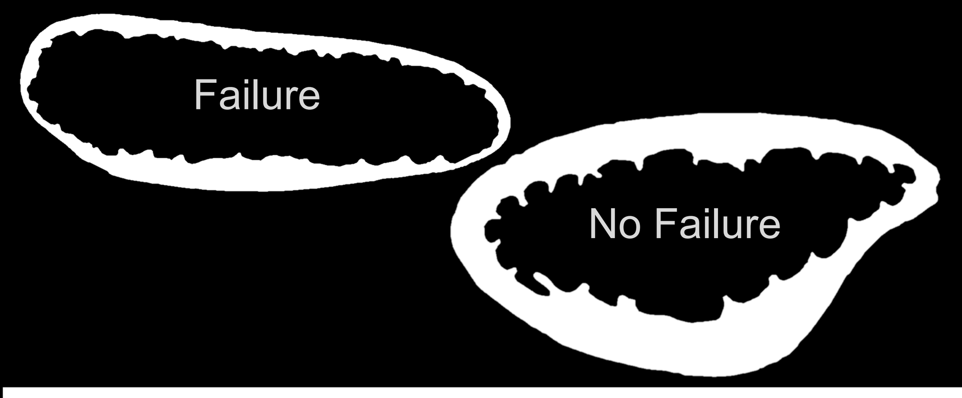

Figure 6. Ex: Ct.Ar and Ct.Th comparison

CONCLUSIONS

- Results from this study and future work in exploring complex loading mechanisms will be crucial in quantifying variation in rib response for a large population with the overall goal of identifying differential injury thresholds and preventing thoracic injuries in motor vehicle crashes.

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