Subject-Specific Variation in Injury Response of the Thorax.

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I. INTRODUCTION

Thoracic injury remains one of the most frequent and severe outcomes in motor vehicle crashes. Human body models (HBMs) are a useful tool in studying thoracic injuries as they enable granular detection of rib fractures. Typically, HBMs are developed using detailed medical imaging of a single subject which limits their ability to represent natural anatomical variability. Recent studies have introduced parametric methods to account for population variability [1–2]. However, these approaches generate a single predicted geometry for a given set of demographic inputs even though demographics explain only about half of the variance in rib cage shape. This is notable given that rib cage shape is thought to influence injury risk [3–5]. The variability observed in reported data suggests that relying solely on average anatomy may not adequately reflect subject-specific outcomes. To address this limitation, this study aims to develop a pipeline to integrate subject-specific rib cages into existing HBMs and to assess the influence of isolated geometric features on injury risk predictions during simulated crash scenarios.

II. METHODS

Subject rib cages from Robinson *et al.* [6] were integrated into the GHBMC M50-O v6.2 using radial basis function interpolation with a thin-plate spline as the basis function (RBF-TPS). Homologous landmarks on the ribs and sternum were collected on each subject (target) and the baseline HBM (reference) in an automated fashion. Principal Components Analysis (PCA) was used to define local coordinate systems for landmark collection. MATLAB code was used to perform the morphs in an automated fashion. Morph success was evaluated quantitatively via 3D surface deviations between morphed and target rib cage geometries. Additionally, the 10 rib cage measures from Robinson *et al.* were collected on the morphed rib cages and cross plot against their original measurements to quantify correspondence. Morphed models were simulated in a 6.7 m/s frontal thoracic hub impact, and peak force, peak deflection, and rib fracture probability were collected. Fracture probability was calculated using Metriks v0.10.1 (Elemance, Winston-Salem, NC, USA) and evaluated in anterior, lateral, and posterior sections of each rib. Peak force and deflection were related back to rib cage measurements via univariate linear regression and multivariate multiple linear regression. Rib fracture probability was related back to rib cage measurements via a linear mixed effects model, and rib cage measurements were standardised prior to analysis to allow for direct comparisons. All statistical testing was performed at a significance of $\alpha = 0.05$.

III. INITIAL FINDINGS

Morphed models (n = 1,049) deviated from their targets by 3.6 mm on average. Rib cage measurements taken on the morphed and target rib cages were highly linearly correlated ($R^2 = 0.97$) and the average deviation was less than 1% across all 10 measurements. Eighty percent of simulations terminated normally. Average peak force and peak deflection were 3.78 ± 0.20 kN and 92.66 ± 7.75 mm, respectively. In univariate analysis, all shape measurements, except height, showed weak negative correlations with peak force, while all shape measures showed weak positive correlations with peak deflection. In multivariate regression, shape measures accounted for 49% of variance in peak force and 73% of variance in peak deflection. Increasing rib 1 or rib 7 angle increased peak force. Conversely, increasing sternum angle decreased peak force. For peak deflection, every measure except depth and rib 1 angle were significant, however the direction of the effect differed depending on the measurement. For example, linear rib cage measurements were negatively associated with peak deflection, but areal measurements were positively associated.

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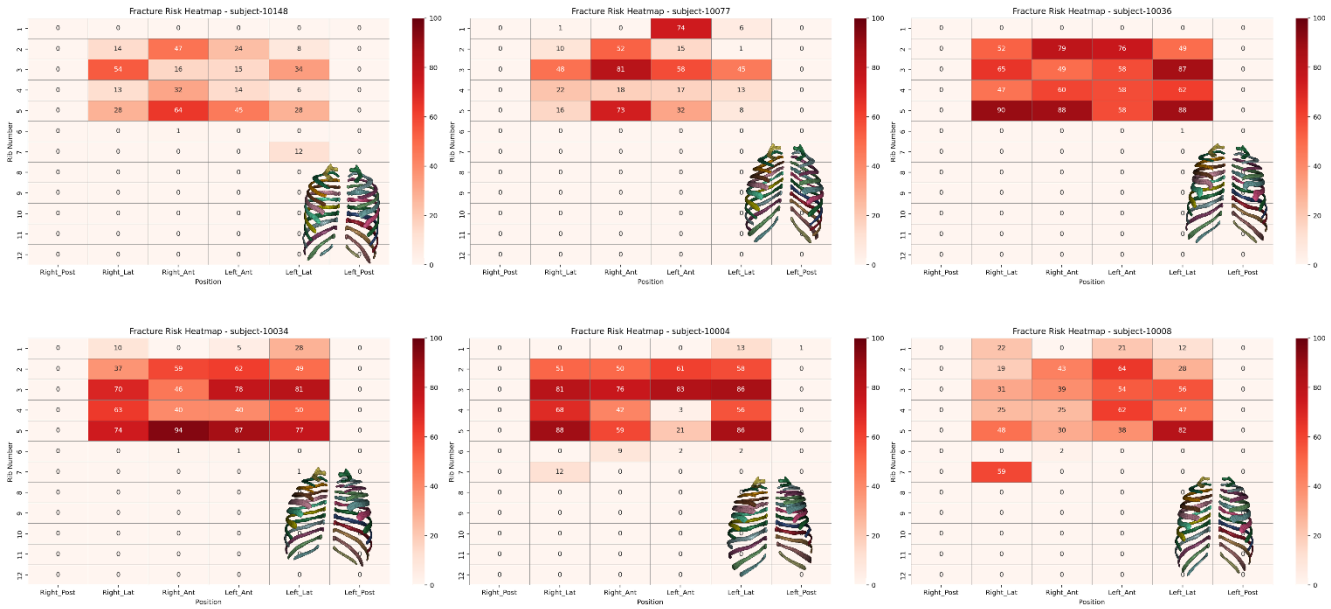

Fig. 1. Exemplar rib fracture risk heat maps for six different rib cages shown in the bottom right.

In general, rib fractures were isolated to the anterior and lateral sections of ribs 2–5. As demonstrated in Fig. 1, fracture risk varied across subjects. Each shape measure was significantly associated with fracture probability in at least one rib location for which the average fracture risk across all subjects exceeded 10%. Increases in coronal and sagittal area were associated with decreased fracture risk while increased height, volume, and rib 1 angle were associated with increased fracture risk. Overall, 10.4 ± 4.4 rib fractures were predicted across all morphed models.

IV. DISCUSSION

Subject-specific rib cages were integrated into a HBM and simulated in a frontal hub impact to evaluate how individual rib cage morphology influences model response. While prior studies have used representative population averages, this work takes a step towards individualised risk assessment.

Angular orientation primarily influenced force while size and shape influenced deflection. For rib fracture, these findings demonstrate that multiple morphological features jointly influence fracture risk, and these relationships are location dependent. Assigning a single “most influential” shape measurement is difficult because measures vary in both effect magnitude and the number of fracture locations affected. For example, rib 1 angle was significant for 17 locations, whereas volume was significant for 12 locations. However, the effect sizes for rib 1 angle were smaller, and summing the magnitudes of significant effects would suggest that volume was approximately ten times more influential. Coronal area and height were also significant at 12 locations but had lower summed effect sizes (917 and 474, respectively) compared to volume (1254).

These findings highlight that importance depends on both the strength and spatial extent of each shape feature’s influence. Developing a metric that simultaneously captures magnitude and scope may provide a more comprehensive understanding of how rib cage morphology affects model response and fracture risk.

V. REFERENCES

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