Predicting Small Stature Young Female Rib Response with an Isolated Rib Finite Element Model

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ABSTRACT

Thorax injuries are a significant cause of mortality in automotive crashes, with varying susceptibility across sex and age demographics. Finite Element (FE) Human Body Models (HBMs) offer potential for injury outcome analysis by incorporating anthropometric variations. Recent advancements in material constitutive models, Cortical Bone Fracture and Continuum Damage Mechanics Model (CFraC) and an orthotropic trabecular bone model (OrthoT), offer the opportunity to further improve rib models. In this study, the CFraC and OrthoT material modes, coupled with age-specific material properties, were progressively implemented to the Global Human Body Model Consortium small female 6th rib. Four distinct 6^{ths} rib models were developed and compared against sex and age-specific experimental data. The updated material models notably refined the predictions of force-displacement responses, aligning them more closely with the experimental averages. The CFraC model significantly improved the prediction of displacement at fracture, suggesting that incorporating stress-triaxiality criteria can better account for the complex loading conditions ribs face in crashes, such as combined cortical tension and shear due to rib bending and torque. The study highlights the importance of using biofidelic material models and sex and age-specific data to simulate hard tissue fractures. The improved rib model demonstrates the effectiveness of integrating updated material properties and constitutive models to enhance injury prediction accuracy, which can inform better automotive safety designs and reduce mortality rates. Further research is recommended to extend these models across different demographic groups to fully capture population variability in rib fracture risk.

INTRODUCTION

Thorax injuries continue to be one of the primary contributors to mortality in car crash scenarios, with rib fractures being a predominant cause of fatal injuries in frontal and side impacts (Forman et al., 2019). Notably, incidence rates vary across different sex and age groups, reflecting a sensitivity to anthropometry on the injury outcome (Forman et al., 2019). It has been reported that small stature females exhibit a higher risk of thoracic injuries compared to males, highlighting the need for sex-specific biomechanical research (Forman et al., 2019).

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Finite Element (FE) Human Body Models (HBMs) can be used to evaluate injury outcomes with varying anthropometric features. These models are particularly valuable for exploring the effect of geometry and material properties on the structural response in isolation (Corrales & Cronin, 2021). Despite considerable progress, existing rib FE models have encountered difficulties in accurately predicting rib force and displacement to fracture under anterior-posterior (AP) loading, and most models have not been validated against age and sex-specific experimental data.

Recent advancements in constitutive modeling, such as the Cortical Bone Fracture and Continuum Damage Mechanics Model (CFraC) and the orthotropic trabecular bone model (OrthoT), have shown improved prediction accuracy of rib response (Corrales et al., 2024; Cronin et al., 2022; Khor, 2018; Ngan et al., 2024). The CFraC model, which incorporates a continuum damage mechanics approach, has demonstrated improved predictions in fracture initiation, location, and patterns under AP loading conditions (Cronin et al., 2022).

Additionally, significant changes in the mechanical properties of cortical and trabecular bone with age have been observed (Albert et al., 2021; Katzenberger et al., 2020). It was shown that the Young's modulus, strength (ultimate stress) and the strain to failure all decrease with increasing age.

However, despite these methodological advances, no rib model has yet successfully predicted the population force-displacement response. Extensive testing of individual ribs under AP loading, considering various ages and statures for both male and female subjects, has shown that the rib response is sensitive to these factors (Agnew et al., 2018; Kang et al., 2021). This sensitivity underscores the ongoing need for further refinement and validation of HBMs to ensure they accurately represent the diverse characteristics of the human population, ultimately leading to more effective automotive safety systems and reduced mortality in car crashes.

The present study aimed to refine an isolated small female 6th rib finite element model (F05), enhancing it with improved constitutive models for the cortical and trabecular bone using material population data targeting 26-Year-Old. By progressively integrating these enhancements, the study focuses on quantifying the isolated effects on rib force and displacement to fracture.

METHODS

Four distinct isolated rib models were assessed: 1) The baseline isolated rib model extracted from the GHBMC F05-O v6.0 (F05) (Figure 1a), 2) the F05 model enhanced with rib cortical material model featuring age-specific material properties (Cronin et al., 2022; Katzenberger et al., 2020) ($F05_{CFraC}$), 3) the F05 model enhanced with rib trabecular material model featuring age-specific material properties (Ngan et al., 2024; Albert et al., 2023) ($F05_{OrthoT}$) and 4) combined cortical and trabecular material enhancements targeting a small female of 26 years of age ($F05_{26}$). These models were tested in an AP isolated rib loading configuration (Figure 1d) (Agnew et al., 2018), previously established computationally by Rampersadh et al., (2022) and compared against age and sex-specific experimental data (Kang et al., 2021).

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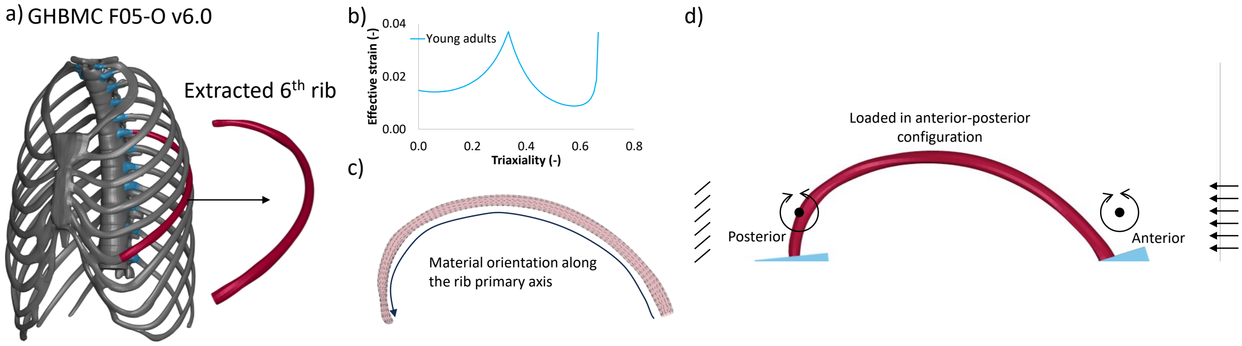

Figure 1: Schematic demonstrating the development of the age and sex-specific 6th rib model from the a) baseline GHBMC F05-O v6.0. b) enhancement of the cortical and trabecular constitutive models populated with age-specific material properties, c) element orientation along the osteon direction, and d) evaluation of the developed rib models in an anterior-posterior configuration.

Experimental Data Selection

From a comprehensive dataset at the Injury Biomechanics Research Centre (IBRC) at The Ohio State University, response data for the 6th rib from young and middle-aged females was selected to be compared to the developed models.

Improving Material Models and Material Properties

The rib cortical bone material model in the F05 model was updated to the CFraC model (Cronin et al., 2022), incorporating inputs such as Young's modulus, ultimate strength, and the modified Mohr Coulomb model fracture parameter 'C2'. The model was populated with age-specific rib cortical bone material properties (Katzenberger et al., 2020). The orientation of the cortical bone elements was set along the long axis of the rib, generally corresponding to the osteon direction (Cormier J., 1998). Additionally, the trabecular bone model was enhanced to an orthotropic model (Ngan et al., 2024) with age-adjusted rib trabecular bone properties (Albert et al., 2023).

RESULTS

The baseline 6th rib model (GHBMC F05) response overpredicted the displacement at failure by 105% while underpredicting the force at failure by 2% when compared to the experimental average (Figure 2).

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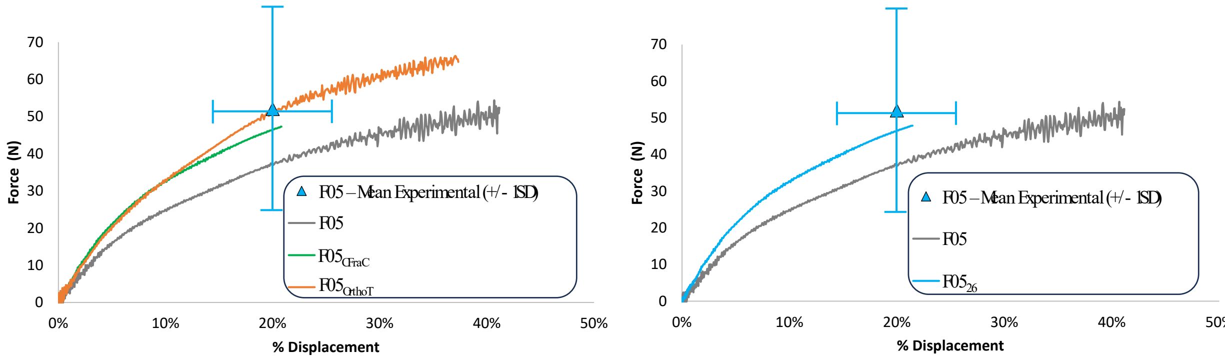

Figure 2: Force-displacement response of the progressive development of the $F05_{26}$ model.

Implementing the CFraC model populated with age-specific material properties improved the displacement to fracture (4% higher than the experimental average) to be closer to the experimental average with a modest effect on the force to failure (9% lower than the experimental average). The implementation of the OrthoT model populated with age-specific material properties increased the force to failure (26% higher than the experimental average) and reduced the displacement to failure (87% higher than the experimental average) (Figure 2a) with respect to the F05 model. The $F05_{26}$ model predicted both the displacement (4% higher than the experimental average) and force (7% lower than the experimental average) to failure close to the experimental data (Figure 2b).

DISCUSSION

The influence of the enhanced constitutive models coupled with age-specific material properties can be observed mainly in the displacement to failure. When including the CFraC model and OrthoT material models with age-specific properties, the displacement to failure was reduced substantially bringing the overall rib response within one standard deviation of the population average. The reduction of displacement to failure was attributed to the effective strain vs. stress triaxiality criteria used in the CFraC model. Including stress-triaxiality for the failure criteria in a geometrically non-linear structure, such as the rib, captures the reduced strain to failure when the material is loaded outside of pure tension. In contrast, the GHBMC metal plasticity cortical bone material model fails when the plastic strain reaches the specified threshold (usually defined from uniaxial tension tests) in the model. Previous studies (Corrales et al., 2024) have found that ribs under a side impact, experience rib torque in addition to rib bending. Rib global torque loading translates into local shear stress load in the cortical bone. Under combined loading (bending and torque), the cortical bone triaxiality deviates from uniaxial tension (triaxiality of 1/3), which ultimately leads to a reduced strain to failure. More than the material properties, the CFraC model failure criterion was identified in this work as the main contributor to the improved predicted rib displacement to failure.

CONCLUSIONS

The present study suggests that using biofidelic constitutive models is critical when studying the contributing factors to a biological system response, such as in ribs. Another important contribution of including the CFraC material model was the reduction of the displacement to failure. Given that the rib cortical bone exhibited combined loading (tension and shear) under rib AP loading (due to rib bending and torque), including a stress-triaxiality fracture criteria effectively reduced the displacement to fracture when compared to the baseline model, with a tension-based failure criterion.

The developed rib model, using sex and age-specific population data, predicted age and sex-specific overall response. It was demonstrated that the constitutive model and age-specific material properties are important factors when developing age and sex-specific rib models. Other studies that investigate population variability may benefit from these findings. Future work includes the development of male, female, young, and aged rib models evaluated using sex and age-specific experimental data.

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