Probabilistic Analysis of Injury Risk Using Human Body Finite Element Models

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I. INTRODUCTION

Computational modelling is a powerful and widely implemented tool for the analysis of biomechanical systems. Advancements in computational power and software capabilities have allowed researchers to create high fidelity models of the human body capable of modelling the body's response to complex dynamic boundary conditions. These models provide advantages when compared to more traditional experimental methodologies, as it is often difficult and costly to perform post-mortem human subject (PMHS) experiments for all potential boundary conditions of interest. With all of their advantages however, computational models still have their caveats. One of these is the fact that a deterministic model only represents a single individual and cannot accurately predict risk of injury across a specific population group.

Across the human population, there exists a great deal of natural variation both in mechanical properties as well as musculoskeletal geometry. Material properties for example can have coefficients of variation (COV) of 80% or higher and these material properties play a critical role in determining if a response was injurious or not. Additionally, overall size of the subject as well as less obvious geometrical differences can have significant effects on the response and corresponding injury prediction. Exercising a computational model within a probabilistic framework helps to overcome these deficits and allows the model to account for these inherent variabilities. Rather than reporting an injury vs. no injury response as with a deterministic model, the probabilistic model will directly return a probability of injury relevant to the population of study.

II. METHODS

In this study we utilised a provided human torso model [1] (Advanced Total Body Model, ATBM) (figure 1) within a probabilistic framework as a proof of concept for quantifying risk of injury due to behind armor blunt trauma. Boundary conditions consisted of 100 gram impactor with an initial velocity of 65.2 m/s centred over the heart. Boundary conditions directly replicated the experimental setup of a whole body PMHS experimental setup. Rib cortical bone strains were output and compared to a threshold [2] for definition of fracture.

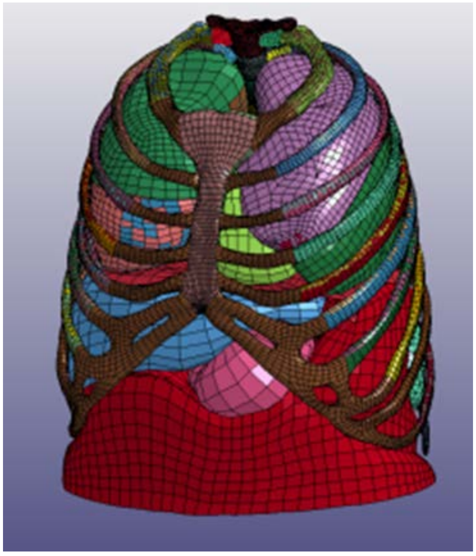

Figure 1: 95% Male ATBM with skin, muscle, and adipose tissue hidden to expose ribs and organ detail

Probabilistic analyses were performed for three versions of the model representing a 5th percentile female, 50th percentile male, and 95th percentile male. Material properties of the major structures in the models as well as the boundary conditions were all included in the probabilistic analysis. Distributions were defined for each model parameter to replace the individual values typically defined for a deterministic model. A Latin Hypercube sampling technique was then used to generate 300 random samples of each model size, each with a unique set of material properties and boundary conditions sampled from their respective distributions. Each sample was then run and post processed to export the element by element strains of the rib cortical bone. Combining these responses allows the calculation of the response distribution at each individual element, capturing the response variability that would be expected across a population.

Custom code was written to process the response distributions and calculate the probability of injury on an element by element basis and produce a probability of injury contour plot (Figure 2). In order to accomplish this, strain results for each element of interest in the model were output for every timestep, for every model sample resulting in nearly 1 billion data points. At each element and timestep a deterministic injury prediction was made for a sample. Then, the positive injury predictions were summed across the 300 samples. The percentage of models that predicted an injury for that element at that timestep defines the probability of injury. Rib fracture analysis was completed for all three subject sizes and compared quantitatively as well as qualitatively with the probability of failure contours.

III. INITIAL FINDINGS

Figure 2 shows a comparison of the predicted rib fracture probabilities for the 5th percentile female and 95th percentile male. The female model had a 34% probability of at least one rib fracture, 17% chance of between 2 and 5 fractures, and an 8% chance of 6 or greater rib fractures. Conversely, the 95th percentile male had a 10% chance of at least 1 rib fracture, a 5% chance of between 2 and 5 rib fractures, and a 0% chance of 6 or more fractures.

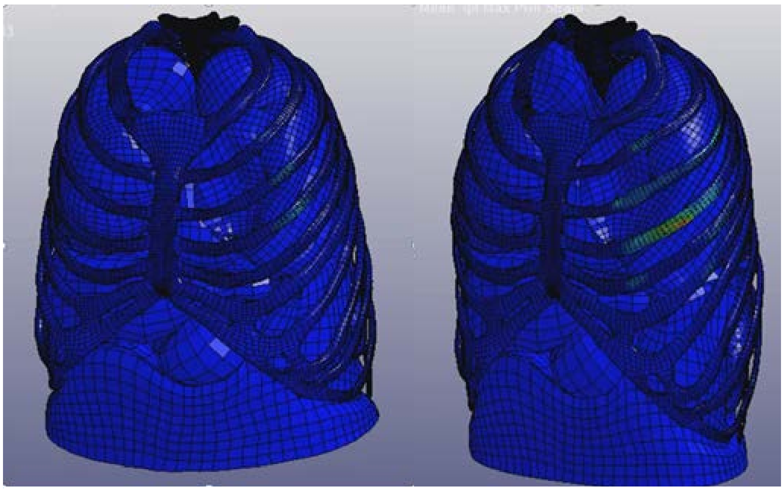

Fig. 2. Example probability of injury contour for rib fracture. Contour colors represent the probability of fracture at each element. 95th percentile male results are on the left with 5th percentile female results on the right.

IV. DISCUSSION

While time consuming and technically challenging, we believe that this probabilistic approach to injury prediction gives significant advantages to the traditional deterministic approach. Typically, a deterministic model is used along with a safety factor to determine if a piece of equipment or loading environment is safe. This approach while useful is a blunt tool that ignores the complex interaction human variability has on responses. In order to be sure something is safe, large safety factors must be used which result in non-optimal designs which could be improved with a more complete understanding of their interaction with the human system. Additionally, probability of injury prediction results can be directly correlated to military incapacitation scales to convert the probability of injury into an incapacitation level probability. For example, the 5th percentile female results shown in Figure 2 correspond to a 34% chance of a Military combat injury scale (MCIS) score of 1 injury, 17% chance of a MCIS 2 injury, and an 8% chance of a MCIS 3 injury. These injury codes offer an actionable interpretation of model results for military decision makers to use. A MCIS score of 1 corresponds to a minor injury with no loss to the mission, MCIS 2 is a moderate injury which leads to slight functional incapacitation but is not life threatening, and MCIS 3 is a serious injury that takes a solider out of a mission but is recoverable [3].

By moving away from the blunt application of safety factors and deterministic models, a more refined understanding of how the human body interacts with the environment can be achieved. This will lead to optimised equipment designs that work across the variability of the human population, that are safer, lighter, and more comfortable. While the work done in this study is a proof of concept, when applied along with rigorous model development, verification, and validation methodologies the probabilistic approach to injury prediction will help better explain the *so what* of modelling results and help users make actionable decisions from those results.

V. REFERENCES

[1] Shen, W, et al., Journal of Biomechanical Engineering 130-2, 021022, 2008.
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[3] LwnickM., et al, Trauma and Acute Care Surgery, 75-4:572-581, 2013