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Multi-Scale Characterization of Human Internal Organs

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ABSTRACT

The purpose of this paper is to present a multi-scale approach for the biomechanical characterization of the human liver, spleen, lung and heart. A four step study is presented to quantify the injury mechanism, biomechanical response, and rate dependent constitutive model for each tissue. First, the CIREN and NASS databases were examined in order to determine crash characteristics for injuries for each of the four organs. From this step, the injury mechanism relative to loading directions and loading rates could be approximated. Second, whole fresh human organs were tested within 36 hours of death using multiple rates of indenter style tests up to 50% compression. Third, fresh human organs were processed into either dog-bone tension coupons or cylindrical compression coupons and tested at multiple strain rates to the point of failure within 48 hours of death. Fourth, each whole organ and tissue test was recreated using FEM with scanned geometry. An optimization routine was used to develop the best constitutive model for each organ tissue. The full test matrix consists of 860 individual experiments. The overall methodology and preliminary results of the whole body, organ, tissue and modeling are presented. It is anticipated these results will provide the foundation for human FEM tissue properties.

INTRODUCTION

In a study of the NASS data base from 1988 – 1994 performed by Elhagediab and Rouhanna it was determined the injuries to the chest and abdomen account for 37.6% and 8% of AIS 3+ injuries, 46.3% and 16.5% of AIS 4+ injuries, and 43.3% and 20.5% of AIS 5+ injuries respectively (Elhagediab and Rouhana 1998). Although it was demonstrated that these injuries account for a significant portion of injuries in automotive crashes, there is limited data post 1998 for the epidemiology of injuries in automotive crashes. Finite element models are becoming increasingly useful to understanding these injuries; however, material properties need to be obtained for the models to be accurate and effective. Therefore, the purpose of the study was to use a multi-scale approach to characterize injuries and material properties of the heart, lungs, liver and spleen. This approach consists of four parts: 1) Determine the incidence of injuries in automotive crashes, 2) Perform impacts to intact whole organs, 3) Perform tissue level tension and compression tests, and 4) Develop accurate computational models from the tissue level tests (Figure 1).

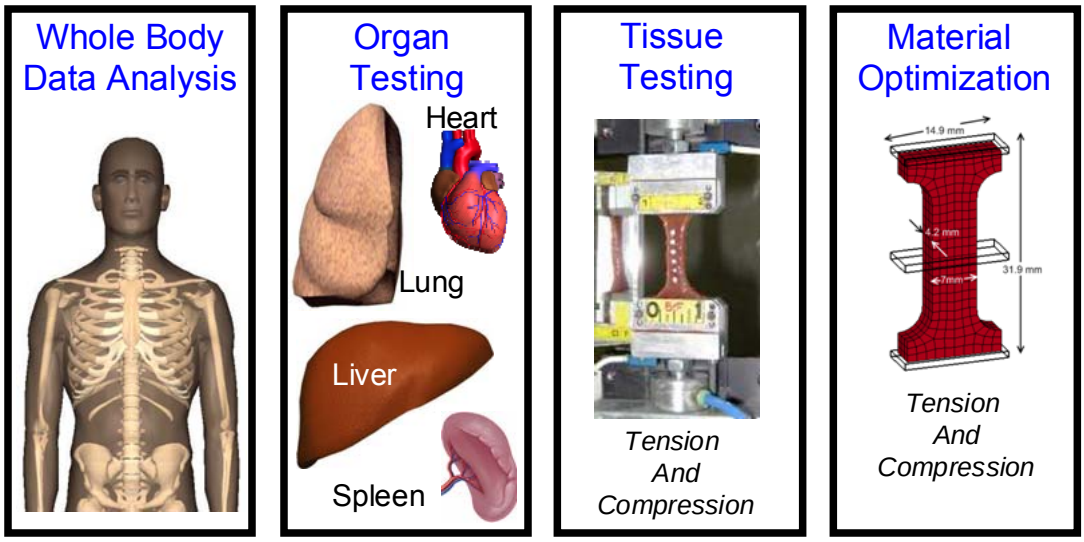

Figure 1: A multi-scale characterization approach to determining the incidence of injury and material properties of human internal organs.

METHODS AND PRELIMINARY RESULTS

Whole Body Data Analysis

Multiple resources were utilized to perform data-driven analyses of injuries to the heart and great vessels, lungs, liver, and spleen. The NASS/CDS database was utilized to determine the distribution and mechanisms of thoracic organ injury. The liver and spleen were included as thoracic organs because they are at least partially protected by the rib cage and they are among the most frequently injured internal organs. For this analysis, only buckled, front seat occupants in vehicles of model year 1998 or later were included. Crash modes were limited to frontal crashes and rollovers were excluded. The distributions in Figures 2-3 were published in Thor (2008). The CIREN database was utilized to determine injury mechanisms, crash characteristics, and involved physical components; while, the NHTSA Biomechanics database was used primarily to ascertain appropriate injury indices for predicting injuries.

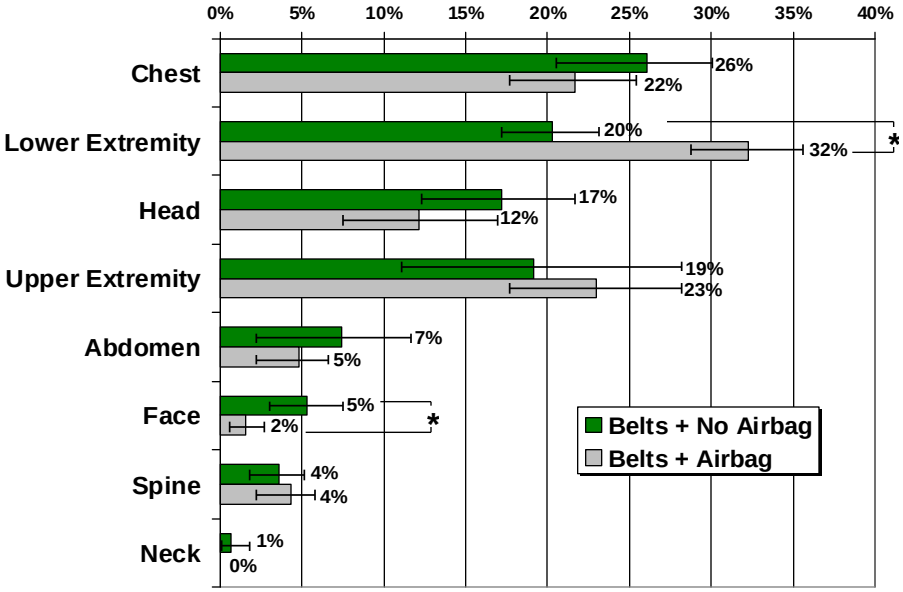

Figure 2: Distribution of MAIS3+ injured body regions for buckled occupants in frontal crashes (weighted).

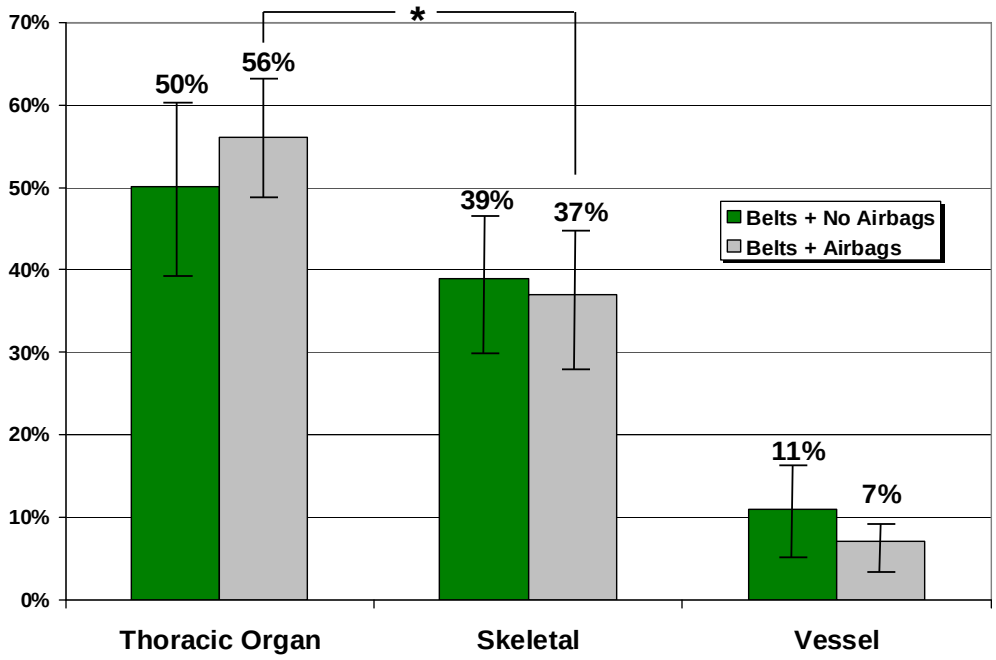

Figure 3: Distribution of AIS3+ thoracic injuries by tissue type for buckled occupants in frontal crashes (weighted).

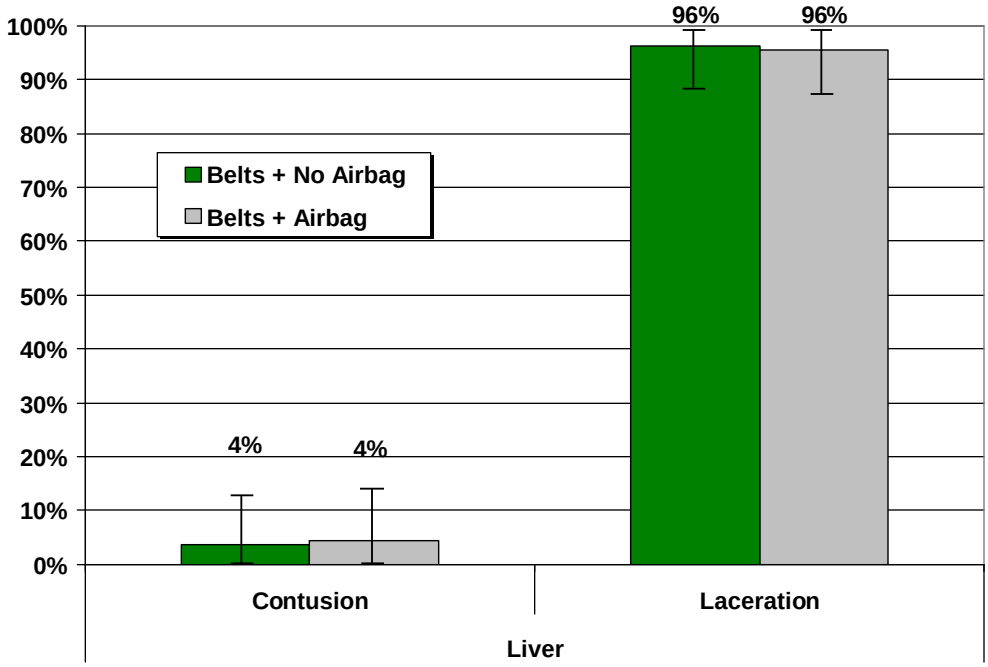

Figure 4: Distribution of AIS3+ liver injuries by lesion type for buckled occupants in frontal crashes (weighted).

Whole Organ Impact Testing

In order to obtain accurate material properties it is imperative to test the organs as quickly as possible after subject death. A procurement protocol was developed in order to limit degradation to the organs (Figure 5). An age limit of 80 was set for the each subject. It has been previously determined that freezing affects the biomechanical response of the bovine liver tissue; therefore, the organs arrived fresh and never frozen (Santago et al. 2009b).

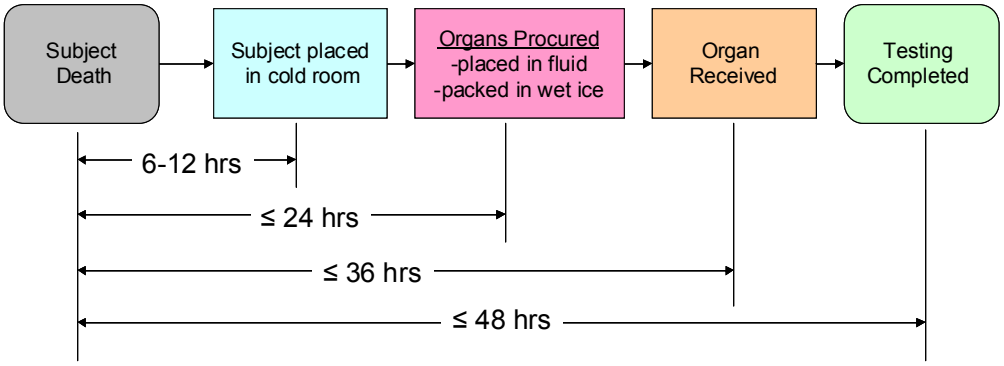

Figure 5: Organ procurement testing time-line.

To begin the whole organ tests, each organ was heated in DMEM (Dulbecco's Modified Eagle's Medium) bath in approximately 98°F to simulate physiological conditions. It was previously determined that biomechanical properties of bovine tissue tested at 98°F had less scatter than tissue tested at 75°F (Santago et al. 2009a). Each organ was then placed on the testing apparatus and aligned underneath the impactor (Figure 6). If the organ was to be perfused prior to testing, the perfusion system was attached to organs vessels. A static pressure was used to simulate the physiological conditions similarly to the system utilized by Sparks and Kerdok (Kerdok et al. 2006; Sparks et al. 2007). For the liver a static pressure of 100mmHg was utilized for the hepatic artery while a static pressure of 9mmHg was utilized for the hepatic vein (Sparks et al. 2007). Each organ was then scanned using a Faro Arm (FARO Switzerland) to obtain the three dimensional geometry of the organ (Figure 7). A series of impacts were then performed on each organ. For the liver, preconditioning cycles were performed using a maximum deflection of 20% of the organ height at 0.2Hz to simulate normal breathing (Figure 8). A series of three impacts were then performed at 2mm/sec, 20mm/sec, and 200mm/sec to a depth of 20% of the organ height. Finally, a failure impact was performed at 2000mm/sec. Each organ was allowed to sit for approximately 10min in between each test to allow time for the organ to recover after the impacts (Figure 9).

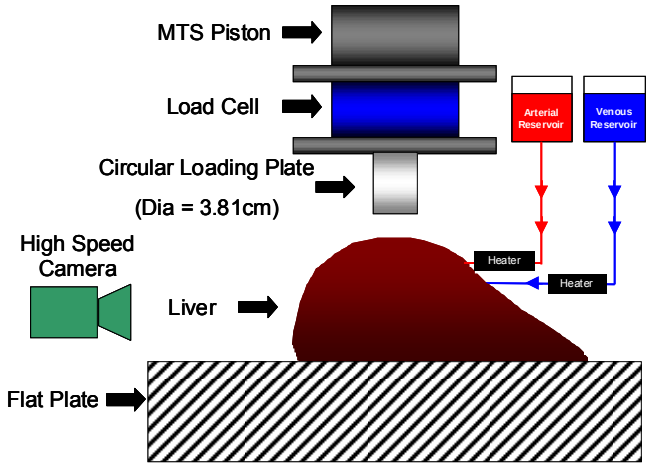

Figure 6: Whole organ test apparatus for the liver. A perfusion was utilized to simulate physiological pressures inside the organ.

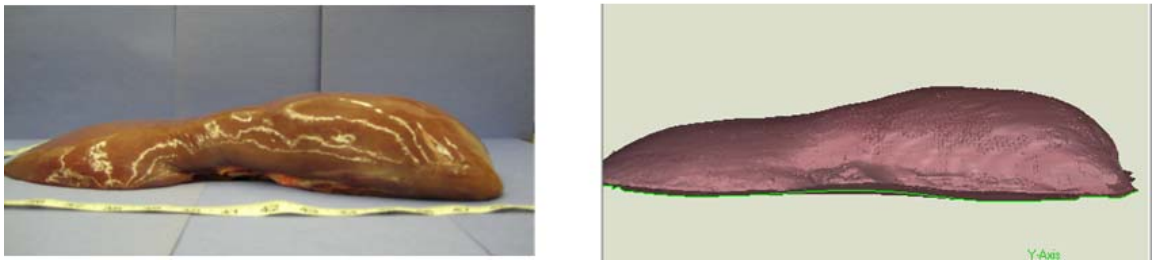

Figure 7: Lateral view of a liver with the corresponding 3D geometry obtained from the faro arm.

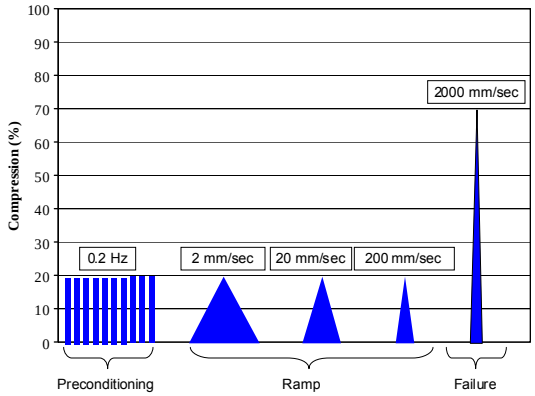

Figure 8: Impacts a compression distances for whole liver impacts.

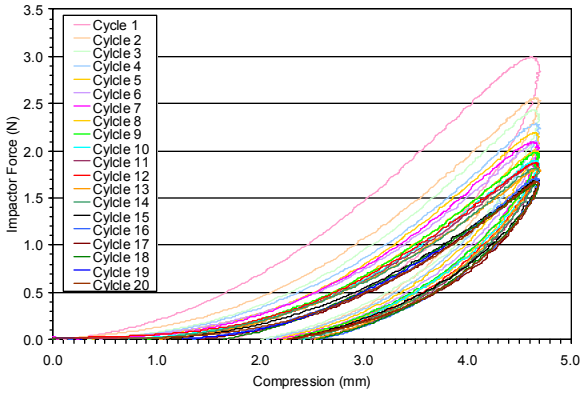

Figure 9: Example of liver preconditioning.

Tissue Level Testing

Whole organ tests are limited by their ability to calculate localized stress and strain; therefore, tissue level tension and compression tests need to be performed (Figure 10). The procedure for organ procurement was identical to that of the whole organ tests. In order to test the organs in uni-axial tension and compression, dog boned shaped tension samples and cylindrical shaped compression samples must be constructed.

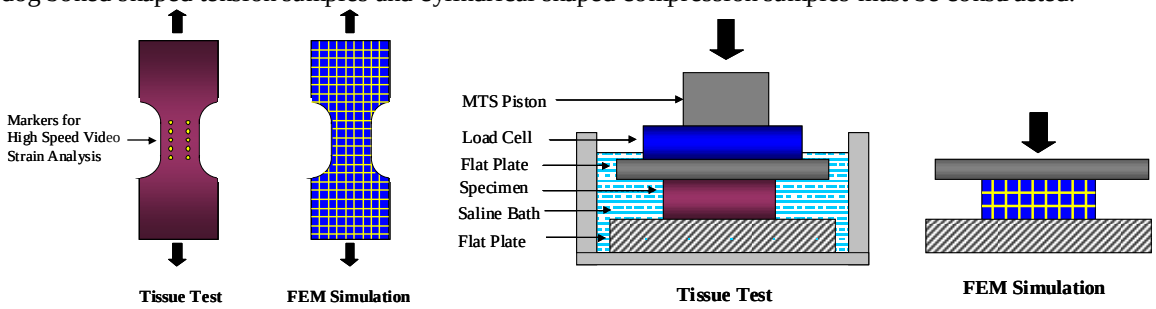

Figure 10: Tissue level tension and compression tests and corresponding Finite Element Model simulations.

To create the samples, a constant thickness slice of the parenchyma needed to be obtained. A custom blade assembly and slicing jig was developed and utilized to create the slice (Figure 11). The spacing of the blades on the blade assembly and blade guides on the slicing jig were designed to obtain multiple slices of tissue with a constant thickness. A block of tissue was first cut from the parenchyma of the liver and placed in the slicing jig and the slicing was performed in one smooth pass of the blades through the tissue block. Downward force was minimized in order to avoid damaging or deforming the tissue. After slicing, the tissue samples were then immersed in DMEM to maintain specimen hydration. It should be noted that in between each step of sample preparation the tissue was immersed in the DMEM bath to maintain specimen hydration.

Figure 11: Custom designed slicing jig (left) and blade assembly (right). Gaps between the blades could be changed so that thickness of the tissue slice could go from 5mm to 10mm.

In order to create consistent tension samples, a "dog bone" shaped stamp was utilized (Figure 12). A slice of tissue (5mm thick) was placed on the stamping base and positioned with the help of a cut out jig in order to obtain a specimen devoid of any vasculature or defects. Once the tissue sample was positioned, the stamp was placed on top of the tissue using guide rods. Finally, a plastic block was then placed on top of the stamp and lightly struck several times so that the stamp would cut the tissue into the desired shape.

Figure 12: Specimen stamping methodology.

In order to create consistent compression samples a sharpened hollow tube was utilized (Figure 13). A slice of tissue (10mm thick) was placed on a base and the pipe was aligned perpendicular to the tissue in an area that was void of vasculature and other deformities. The tube was then slowly rotated while applying minimal downward force in order to avoid tearing and sample inconsistencies.

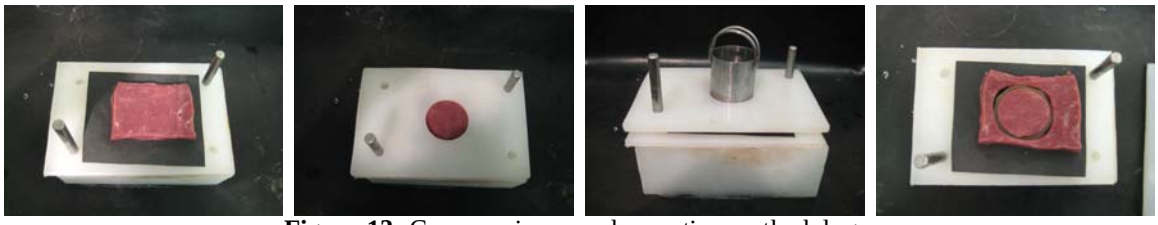

Figure 13: Compression sample creation methodology.

Once the samples had been created they were heated a bath of DMEM, placed in their appropriate testing apparatus, and then pre tests pictures were taken (Figure 14). Pre test pictures were utilized to calculate initial width and thickness in the tension samples at the failure locations and initial area and height in the compression samples. Failure tests were then performed on the samples at four different rate loading rates 0.007^{-1}, 0.07^{-1}, 0.7^{-1}, and $7.0s^{-1}$. All tests were performed in a heated test chamber at approximately 38°C (100°F) to simulate *in vivo* conditions.

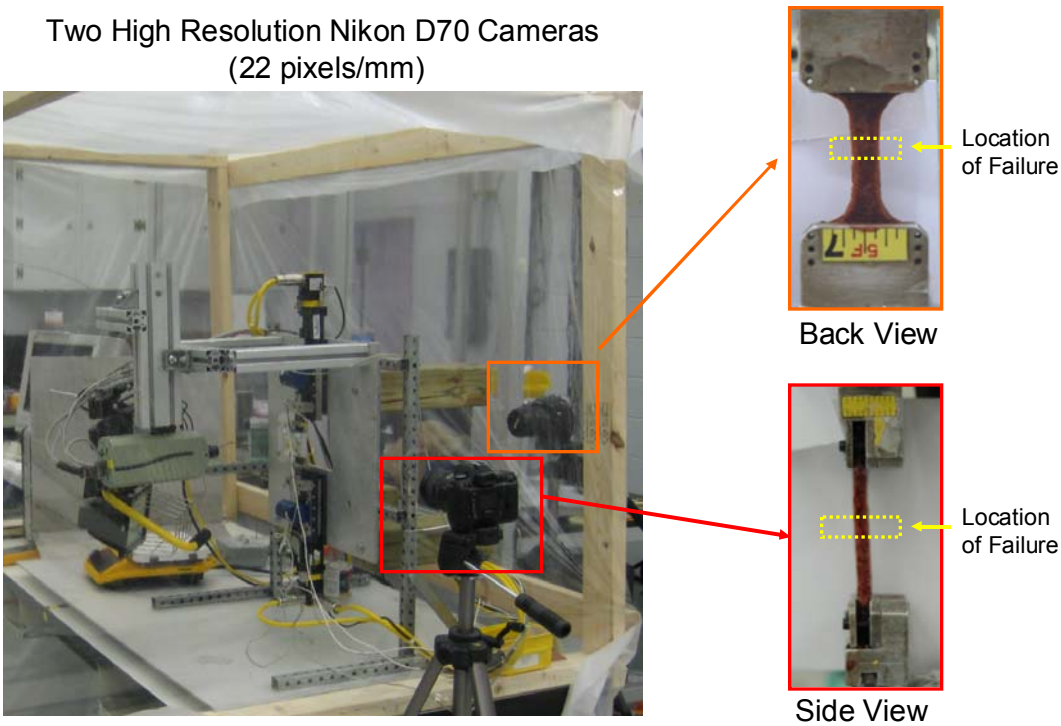

Figure 14: Pre test width and thickness images for the tissue level tension tests.

Characteristic averages were developed for each loading rate in tension and compression (Lessley et al. 2004). Preliminary results from the liver tension and compression tests demonstrate rate dependence with strain decreasing and stress increasing with each increasing strain rate (Figures 15 and 16).

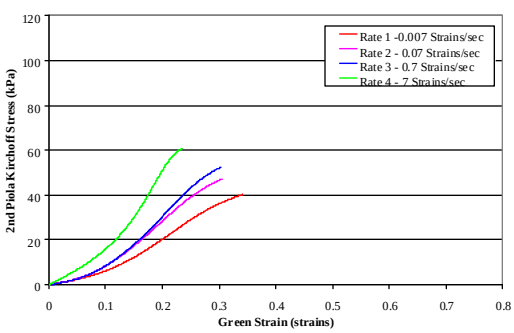

Figure 15: Characteristic Averages for Human Liver Tested in Uni-axial Tension.

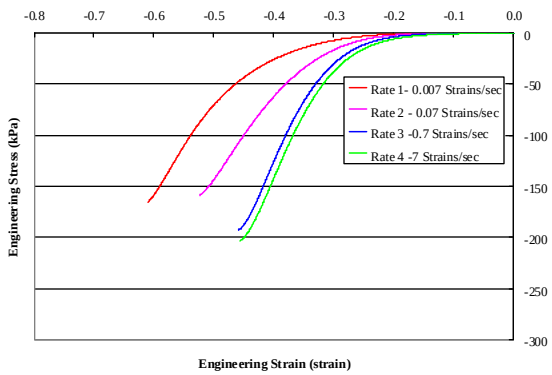

Figure 16: Characteristic Averages for Human Liver Tested in Uni-axial Compression.

Material Model Optimization

The overall approach to model development and optimization is shown in Figure 17. It involves experimental data interpretation and conditioning, simulation, and optimization steps outlined here. Raw data processing - Raw data from the tensile tests are loaded and separated into different strain rate categories. Each strain rate has multiple series that consist of data from individual tests. Two graphs are produced for each series: displacement versus time and force versus time. Data before t=0 is truncated, and then

normalization of the data is performed. The displacements are normalized by initial gauge length into stretches and the forces are normalized by initial cross-sectional area into stress. The initial cross sectional area for each series is calculated by multiplying the thickness by the gauge width. By normalizing both the displacement and the force, the series can then be combined to get an average characteristic for each strain rate. In addition to an average characteristic for each strain rate, a global average characteristic can be acquired to estimate initial material parameters.

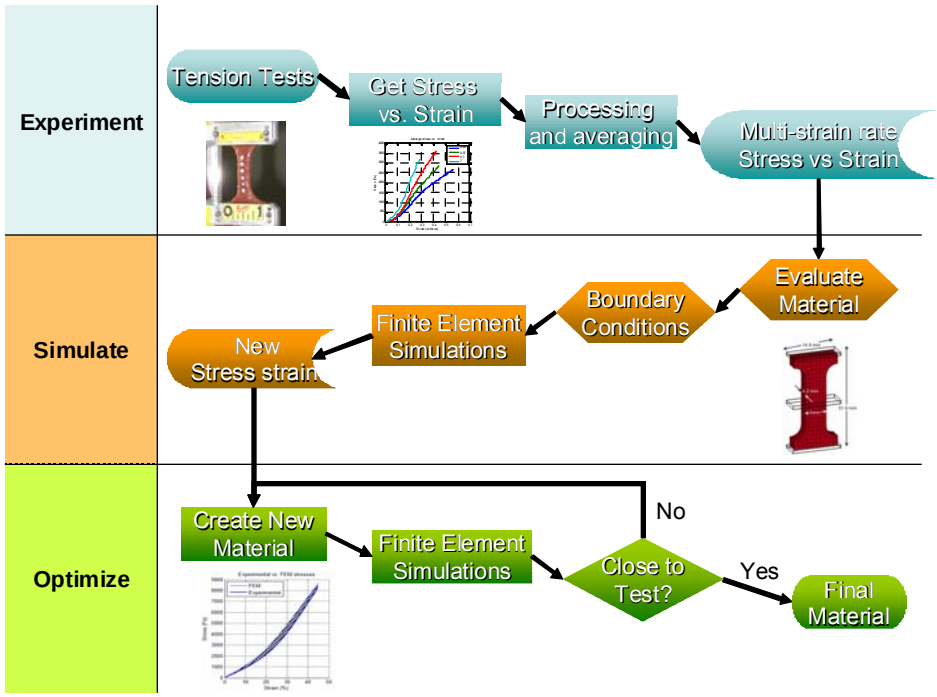

Figure17: Optimization for Finite Element Material Constants.

Stretch averaging: To get an average stretch versus time characteristic knowing that the tests are done at a constant displacement rate, the stretch versus time data is differentiated to get the stretch rate versus time for each series. This plot can then be compared to a constant displacement rate to see deviations from the defined displacement rate. The time for each series is scaled by the max time so that all the data have x-values between 0 and 1. Then y-values can be averaged to get a characteristic curve that is the combined average for the full range of the data. The final average for each strain rate can then be scaled by the average end time to add back the temporal aspect. After the average for each strain rate is computed, the global average is computed for all strain rates.

Stress averaging: The stretch versus time defines the displacement of the top grip with respect to the bottom; in addition, the stress versus strain characteristic must be defined for the material model. The method used here is similar to the method used for the stretch versus time averaging, in which the strains are normalized by the maximum strain for each series, and the stresses are normalized by the maximum stress for each series. The averaged stress versus strain curves for each strain rate can then be regressed to a polynomial (order depends on fit) enabling them to be scaled by the average end strain and end stress. In addition, the global stress versus strain curve can be calculated similarly by a regression of the series. The average can then be scaled back by the average end strain and average end stress.

Material selection: After the global stretch versus time and global stress versus strain relationships are found, the curves are inputted into a standard FE coupon model with varying material models to find the material model that best matches the shape of the global averages. Any material model that is deemed a possibility for this model is run with the input curves. All hyperelastic material models in LS-Dyna are considered as

candidates. The different material models are compared with the target stress versus strain curve to find one that best matching behavior of the experiments (Figure 18).

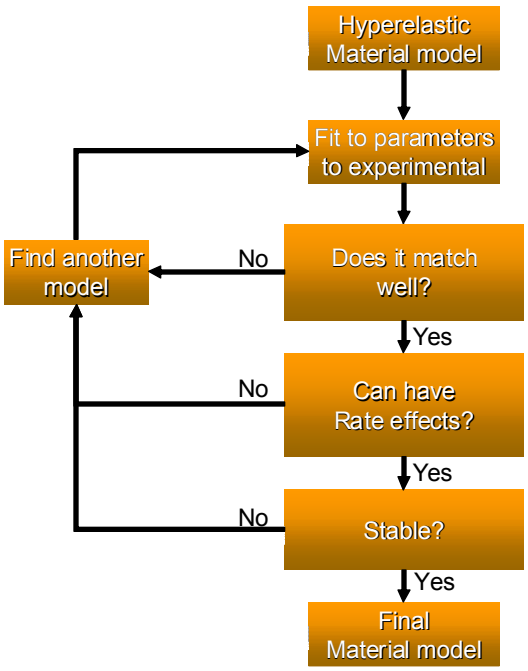

Figure 18: Methodology for Selecting the Appropriate Material Model for the Biological Tissue.

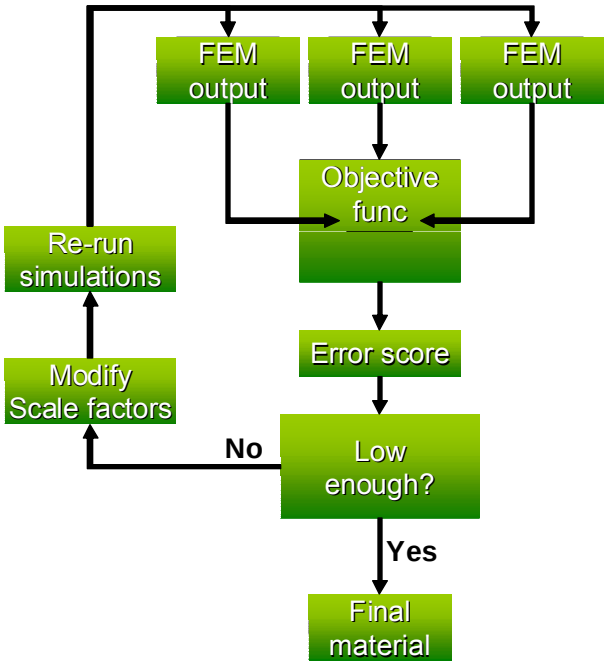

Figure 19: Methodology for Optimizing the Final Material Model.

Material parameter optimization: One best shape describing a material model is formulated using a polynomial from stretch and stress normalized data. Scaling parameters are defined to modify the input curve. The scaling factor approach is needed because of the need to optimize three separate loading rates, one for each strain rate, and the factors are optimized with a multi-island genetic algorithm to minimize the least square error between the model output and the target stress versus strain curve for all 3 strain rates (Figure 19).

SUMMARY

A multi-scale four step approach was utilized to characterize human heart, lung, liver, and spleen tissue. Whole body injury analysis was performed by using NASS/CDS, CIREN, and NHTSA databases. Whole organ impacts were then performed. Sub failure impacts and failure tests at multiple rates were performed on each organ. Tissue level tension and compression failure tests were then performed on each organ at four different loading rates. Finally, finite element modeling was utilized to obtain an optimum model of the different tissue level tests. It is anticipated that the data from this research will enhance the understanding of internal organ injuries and provide a foundation for future human internal organs finite element models.

ACKNOWLEDGEMENTS

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