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INJURY BIOMECHANICS RESEARCH
Proceedings of the Thirty-First International Workshop

A 2-D Finite Element Model Representing the Human Thorax

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ABSTRACT

The purpose of this investigation was to create a finite element model of the thorax to study injury mechanisms and restraint conditions in an automotive environment. A two-dimensional (2-D) model was selected to achieve a fast run time on a standard PC, while still maintaining enough detail to represent the behavior of the full human thorax during impact. The model represents the thorax of a 50th percentile male and consists of six parts: rib, sternum, viscera, elastic spine, rigid spine, and spine/rib joint. A piecewise linear plasticity material model was used for the rib, sternum, viscera, and spine/rib joint. The stiffness and yield stress for each material were based on a review of the literature. Thoracic impact experiments by Kroell et al. were used as a benchmark of realistic thoracic response. Fourteen tests were simulated, including both fixed and free back conditions. The impactor mass varied from 1.6 to 23 kg and the initial velocity ranged from 15 to 48 km/h. For each simulation, the model was scaled to represent the size and mass of the cadaver used. The contact forces in both the 2-D slice model and the full thorax experiments were compared by scaling the simulation force by a factor based on the contact area between the chest and the impactor. Good agreement was found between the force – displacement curves for the simulations and experiments across all test conditions. The 2-D slice model is capable of representing the response of a full human thorax and can be used to study other impact conditions.

INTRODUCTION

Thoracic injuries are ranked second only to head injuries for automobile collisions in three categories: area most often injured (Ruan et al., 2003), overall number of fatalities and serious injuries (Cavanaugh, 1993), and overall societal harm (Malliaris, 1985). Injuries to the thorax were found to account for approximately 13% of all AIS 1-2 injuries and 29% of all AIS 3-6 injuries (Ruan et al., 2003). A better understanding of the mechanisms involved in these thoracic injuries will lead to improved restraint systems that have the ability to reduce injuries and save lives.

Thoracic injuries typically occur with numerous contributing factors, such as crash conditions like speed and intrusion, as well as the presence of restraint systems, including airbags, seatbelts, load limiters, and seatbelt pretensioners. While experimental research using cadavers and crash test dummies is an important step to understanding thoracic injury mechanisms, computer models offer increased flexibility at a lower cost. This paper presents a 2-D finite element model of the human thorax designed to study injury mechanisms and restraint conditions in an automotive crash environment.

METHODS

The purpose of this study was to create a finite element model of the human thorax with which to study injury mechanisms under different restraint conditions. The complexity of the model was determined by balancing computational issues, such as including enough complexity to accurately represent the response of the thorax while still maintaining a relatively fast run time on a PC. For this purpose, a 2D model was selected over a 3D model. After creating the mesh for the 2D thorax, the model's response was validated against thoracic impact experiments.

Model Description

The finite element model of the thorax was modeled using the LS-Dyna software package. The model represents a 50th percentile male thorax. As previously stated, it was created in two dimensions to allow simulation of the overall thorax response while dramatically reducing the solution time. The thorax model (Figure 1) contains six parts: rib, sternum, viscera, elastic spine, rigid spine, and spine/rib joint.

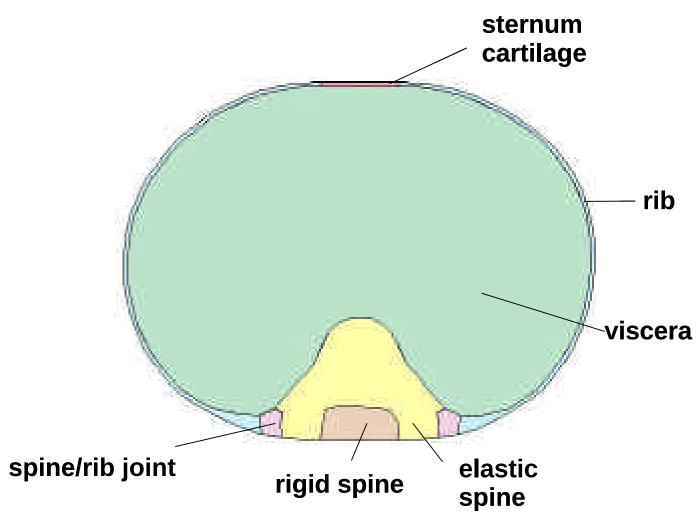

Figure 1: 2-D Thorax Finite Element Model

The material properties for the model are shown in Table 1 and were determined through a review of the literature. A variety of material models were considered and tested for the deformable parts in the model, including elastic, viscoelastic, and piecewise linear plasticity models. The piecewise linear plasticity material was used because it provided the most biofidelic behavior when tested. This material scales the yield stress based on the strain rate as shown in equation 1:

$$\sigma_y(\varepsilon^p_{eff}, \varepsilon'^p_{eff}) = \sigma^s_y(\varepsilon^p_{eff}) + SIGY*(\varepsilon'^p_{eff}/C)^{(1/p)}, \quad (1)$$

where $\sigma_y(\varepsilon^p_{eff}, \varepsilon'^p_{eff})$ = effective stress, $\sigma^s_y(\varepsilon^p_{eff})$ = static stress, SIGY = yield stress, ε'^p_{eff} = strain rate, and C and p are used defined coefficients (LS-Dyna User's Manual, 2003).

Table 1. Material Properties of the thorax finite element model (Granik and Stein, 1972, Deng, 2000).

Part Name	Density (kg/m^3)	Stiffness (kPa)	Yield Stress (kPa)
Sternum	2.5e-6	1200000	3445
Rib	1.1e-6	10335000	85284
Viscera	2.9e-6	207	0.69
Spine/Rib Joint	1.1e-6	1200000	3445
Elastic Spine	1.1e-6	25982190	N/A
Spine (rigid)	1.1e-6	25982190	N/A

The rib properties required some modification because the model is two-dimensional. Specifically, the space between the ribs in the full thorax cannot be directly modeled in two dimensions. The stiffness of the thorax is dependent on the total cross-sectional area of ribs in the thorax. An extruded 2-D thorax model would have one solid rib without any space between ribs, making the model too stiff. Therefore, to ensure the proper response of the model, the cross sectional area of the rib in the model was reduced to account for the space between the ribs, while the rib modulus was kept constant. First, an average rib cross sectional area was determined to be 0.73 cm^2 (Pintar & Yoganandan, 1998). A rectangular cross section was assumed with a height of 1.27 cm and a thickness of 0.58 cm. Next, the average sternum length, from rib 1 to rib 10, of a 50^{th} percentile male was found to be 29 cm (Robbins, 1983). Based on the average cross section, the ribs should take up 7.3 cm^2, leaving 9.52 cm^2 space between the ribs. Therefore, the ribs take up 44% of the area. To account for the space between the ribs, the cross sectional area of the rib in the 2-D model should be 44% of the average rib. The thickness of the rib in the 2-D model was reduced to a thickness of 0.25 cm; with a height of 1.27 cm, the rib has a cross sectional area of 0.32 cm^2.

The mass of the model was determined by comparing the mass and area of the full thorax to the mass and area of the 2-D thorax model. The mass of a 50^{th} percentile male is 76.3 kg, with a thorax mass of 23.6 kg (Robbins, 1983). The contact area on the 3-D thorax is 161 cm^2 (Kroell, 1974) and the contact area of the 2-D thorax is 18 cm^2. Therefore, the mass of the 2-D thorax was determined by multiplying the full thorax mass by the ratio of the thorax areas as shown in equation 2, resulting in a 2-D mass of 2.7 kg.

$$\text{2-D Mass} = \text{3-D Mass} * (\text{2-D Area} / \text{3-D Area}) \quad (2)$$

Model Validation

Fourteen experimental tests from Kroell et al., 1971 and 1974 (shown in Table 2) were simulated to validate the response of the thorax model under impact. These included ten free back tests and four fixed back tests. For the simulation of the fixed back tests, the rigid spine was restrained in all directions. Four of the free back tests had the skin on the thorax removed. For each simulation, the model was scaled based on the size and mass of the cadaver for that test. Each test was simulated using a 15.2 cm diameter impactor with the same initial velocity as in the experiments. The impactor was modeled as two-dimensional and its mass was scaled in the same manner as the mass of the model, based on the ratio of the 3-D and 2-D surface areas (Equation 2).

The results of each simulation were evaluated using force displacement curves, force time histories, and displacement time histories. Because the simulations used a 2-D model with scaled down masses, the forces in the simulation had to be scaled back up before they were compared to the experimental data. It should also be noted that a different scale factor was used for the tests that had the skin on the thorax removed than for the tests that did not. An assumption was made that the tests in which the skin on the thorax was intact would have a contact area that included the entire surface of the impactor (161 cm^2), due to the skin's distribution of the load to the underlying structures. In contrast, the tests with the skin removed will have a lower contact area (105 cm^2) because the impactor force will only be distributed over the ribs and sternum, and not the interstices. The force scale factors were calculated using the ratio of the 3-D contact area to the 2-D contact area (18 cm^2 in both cases). Therefore, the scale factor for the tests with the skin intact was 8.8 and the scale factor for the tests with skin removed was 5.8.

Table 2. List of Tests Simulated for Validation * = Fixed Back Test, ** = Skin Removed

Test No	Initial Velocity (kph)	Impactor Mass (kg)	Chest Depth (cm)	Cadaver Mass (kg)
92	48	1.6	18	41
96	30	19	24	59
99	26	19	23	75
104	35	23	25	74
171	18	23	22	55
177	18	23	25	64
182*	25	10	23	65
186*	26	10	23	60
187*	24	10	25	82
188*	26	10	22	52
7**	14	19	20	38
10**	18	19	19	43
6**	19	19	25	77
5**	19	19	26	86

RESULTS

Each simulation described above was compared to the experimental case based on force displacement curves, force time histories, and displacement time histories. A comparison between the simulations and the experiments for all tests is given for the peak displacements in Figure 2 and peak forces in Figure 3. Examples are given (Fig. 4 - Fig. 10) for each type of test: free back with skin, free back without skin, and fixed back. Time histories for the tests without skin are not shown because the experimental data was not available.

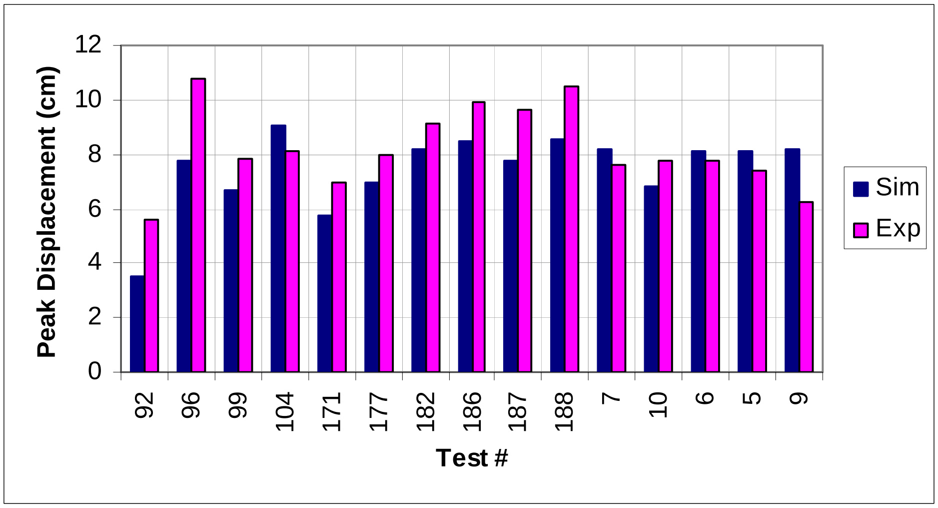

Figure 2: Comparison of Peak Displacements

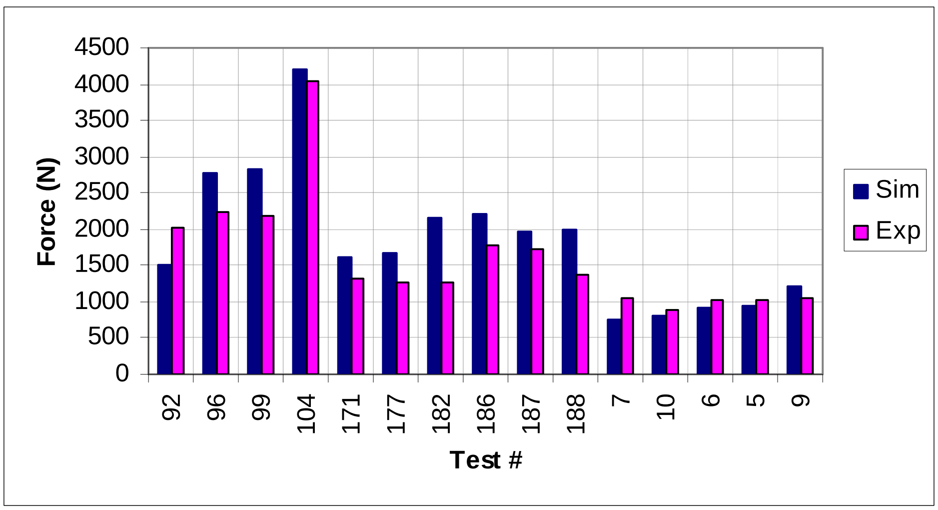

Figure 3: Comparison of Peak Forces

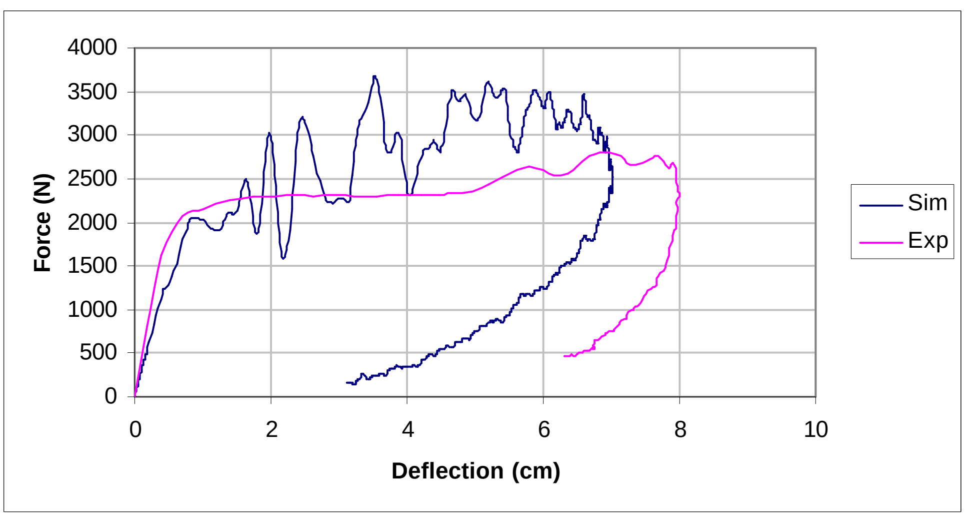

Figure 4: Force Displacement Curve, Test 177, Free Back With Skin

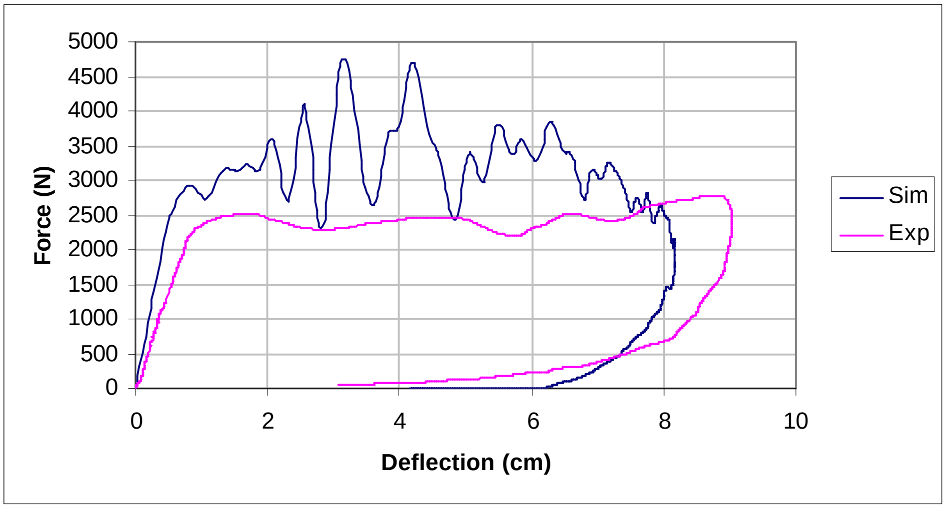

Figure 5: Force Displacement Curve, Test 182, Fixed Back With Skin

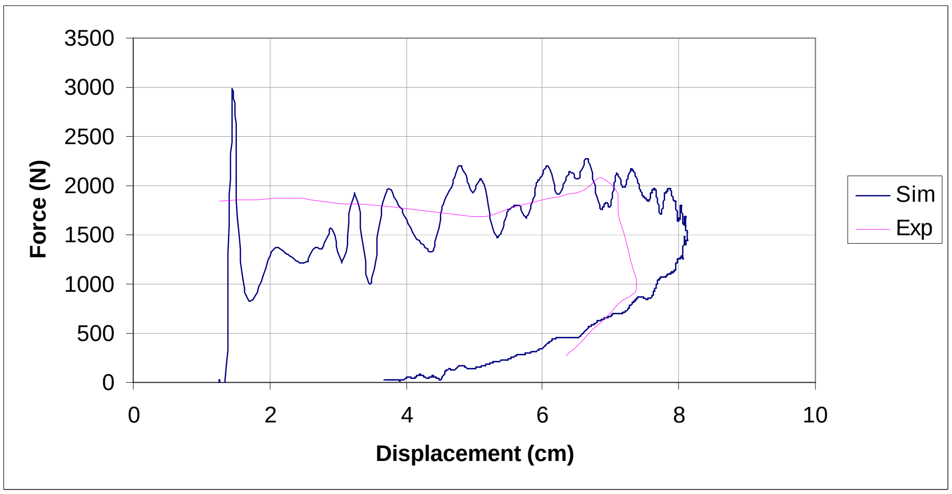

Figure 6: Force Displacement Curve, Test 7, Free Back Without Skin

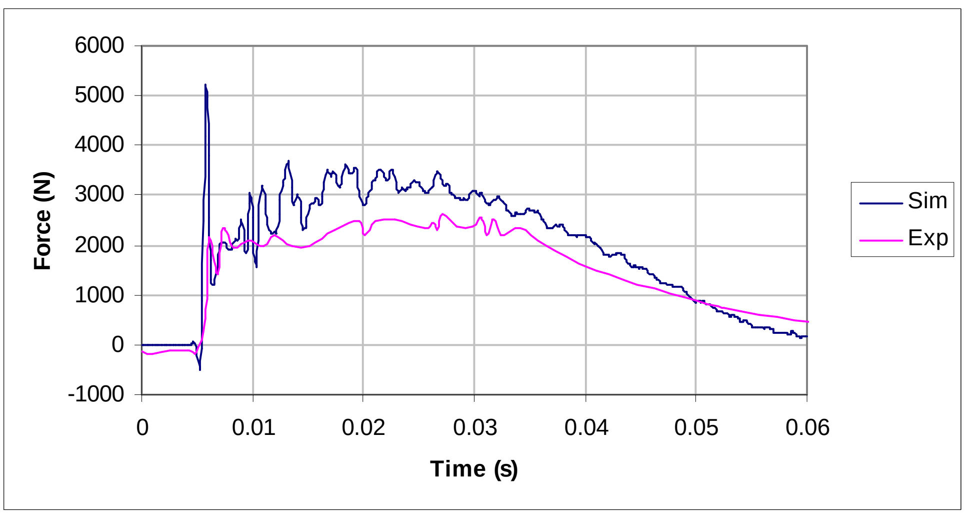

Figure 7: Force Time History, Test 177, Free Back With Skin

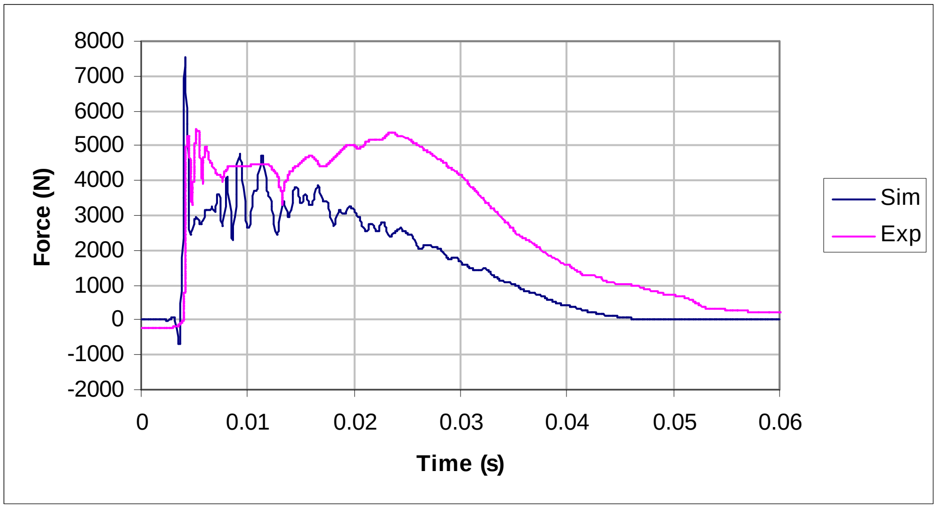

Figure 8: Force Time History, Test 182, Fixed Back With Skin

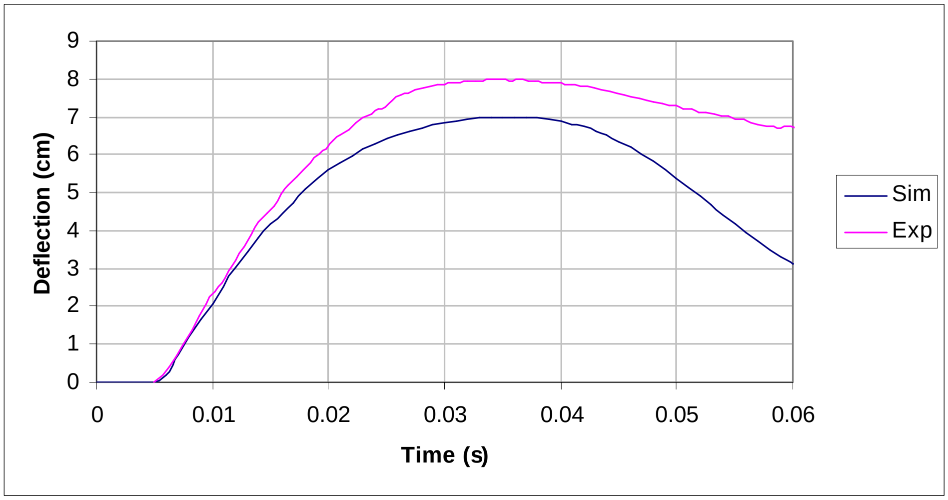

Figure 9: Displacement Time History, Test 177, Free Back With Skin

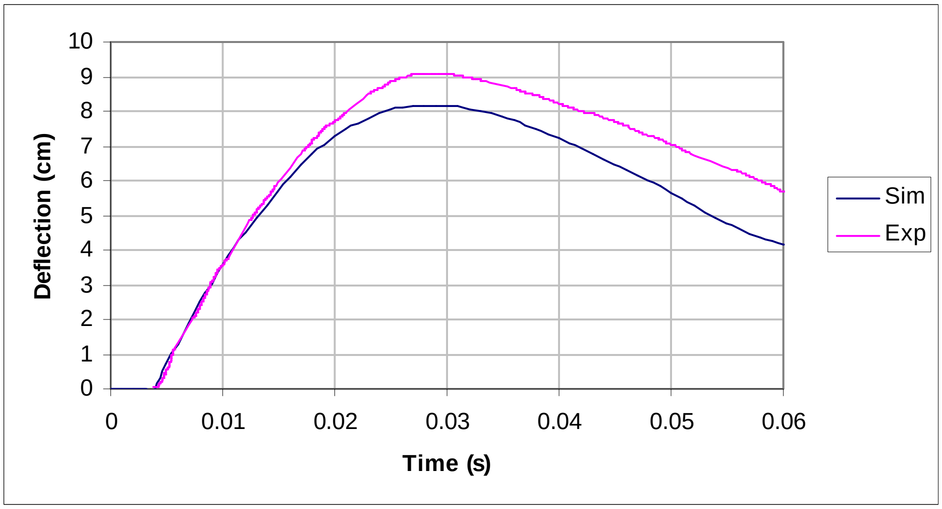

Figure 10: Displacement Time History, Test 182, Fixed Back With Skin

DISCUSSION

The 2-D finite element model of the thorax shows good correlation with the impact experiments of Kroell et al. The force displacement curves and time histories show that the model has a biofidelic response through the entire event, including at the peaks. The force scaling methods seem to allow accurate comparison of 3-D and 2-D force measurements. This is demonstrated in the accurate simulation of cases with and without skin. However, overall the results suggest that the model may be too stiff based on slightly higher forces and lower displacements seen throughout the simulations. It is possible that these results could be improved by altering the average rib cross section that was used, since the cross section of ribs varies greatly both along their length and at different levels within the thorax. Overall, the model performs relatively well in both fixed and free back conditions and the model can be used to evaluate restraint conditions with seatbelts and/or airbags.

CONCLUSIONS

- The 2-D finite element model of the thorax correlates well to the impact experiments of Kroell et al.
- The force scaling methods seem to allow accurate comparison of 3-D and 2-D force measurements.
- The model has a biofidelic response through the entire impact event, including at the peaks.
- The model performs relatively well in both fixed and free back conditions.
- The model can be used to evaluate restraint conditions with seatbelts and/or airbags.

ACKNOWLEDGMENTS

The authors would like to thank Lauren Shook for helping edit the paper.

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DISCUSSION

PAPER: **A 2-D Finite Element Model Representing the Human Thorax**

PRESENTER: ***Quinn Campbell, AASA, Inc.***

QUESTION: *Richard Kent, University of Virginia*
Nice presentation. One comment is: If you do want to apply this model to evaluating restraint loading, the Kroell tests are not a great tool for validation. The response in the Kroell test is about 80% inertial and only about 20% of it is due to any elastic or viscous characteristics of the thorax as opposed to restraint loading where it's about 90% elastic and viscous and the inertial contributions are quite small because there's never an impact. That's one issue. The second issue is that: What kind of injuries are you trying to predict with this? Rib fractures or other visceral injuries?

ANSWER: Mostly related to rib fractures.

Q: Now are you modeling superficial soft tissues? It looks like you have a ribcage with some stuff in the middle. Do you have that--?

A: We don't have the superficial soft tissues on the outside.

Q: Okay, because there was a paper a couple of years ago showing that there's potentially a quite large load distributing effect of those superficial soft tissues under belt loading. The deformation pattern of the exterior thorax doesn't really look much like the deformation pattern of the ribcage itself. So, you might want to consider putting something in between the ribcage and what you're loading with. So, thanks again.

A: Yeah, thank you.

Q: *Stewart Wang, University of Michigan*
Richard, kind of, in fact anticipated me in one of the questions, or one of the comments. We've been recently looking at the amount of subcutaneous fat depth and determining what the effect of the, you know, the volume or the depth of subcutaneous fat was with regard to torsal injuries, and this is done on a bunch of CIREN subjects who've had quantitative CT's. And, what we found was that subcutaneous fat depth is the biggest determinant in terms of both the injury to the chest region and to the abdominal region and just now recently that it has a significant affect on rib fractures. So, I guess the question was, as Richard mentioned, whether you might not want to consider putting, you know, something into the subcutaneous region between the impact the ribcage.

A: Yeah, I think that's a good point. We'll have to look at that, and it'll depend a lot on how we apply our impact conditions when we start looking at the restraints. So, I think that's a good point.

Q: *Jeff Crandall, University of Virginia*
Maybe just a question, then a comment. Well, let me do the comment first. On the free-back conditions, there's a paramount of spinal flexion in those tests. So, there's sort of an overall 3-dimensional affect and even on the fixed-back, there's a fair amount of 3-dimensional affect where you get the slanting of the ribs moving down. So with the planar approximation, you should be cautious and maybe do some investigations. You said you had some with skin removed. Maybe look at the kinematics of the rib and how that sensitivity might influence it.

And on the fixed-back, it's pretty complex motion. It might be difficult to go from the fixed-back to free-back. I had a question on some of your force scaling techniques in the--You looked at the area of the ribs versus the overall area of the anterior chest and you did some scaling based on that, sort of what percentage the ribs would occupy. But, you have a structure right in front which is the sternum which sort of bridges, imperially/superiorly, most in the anterior thorax. And, I can't see how you accounted for that in your force scaling.

A: You're right. I think we just accounted for the ribs in our scaling techniques.

Q: There'd be a tremendous amount of coupling. In fact, I think there's some static sort of looking at the coupling, but you can look at inferior, superior and lateral coupling due to pressing on certain points. There is definitely a coupling mechanism in the sternum...

A: And that mostly influenced the western move cast.

Q: Well, it would influence--I think you're using the scaling factor to determine some of your relative comparisons [Yeah] between the experiments, which have a whole chest. In yours, where you have to take one rib to the surface to extrapolate based on scaling factors. That whole scaling factor could be influenced by the sternum.

A: Right. Thank you.