INJURY BIOMECHANICS RESEARCH
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Reconstructing and Assessing Confidence of Finite Element Simulations of CIREN Crashes

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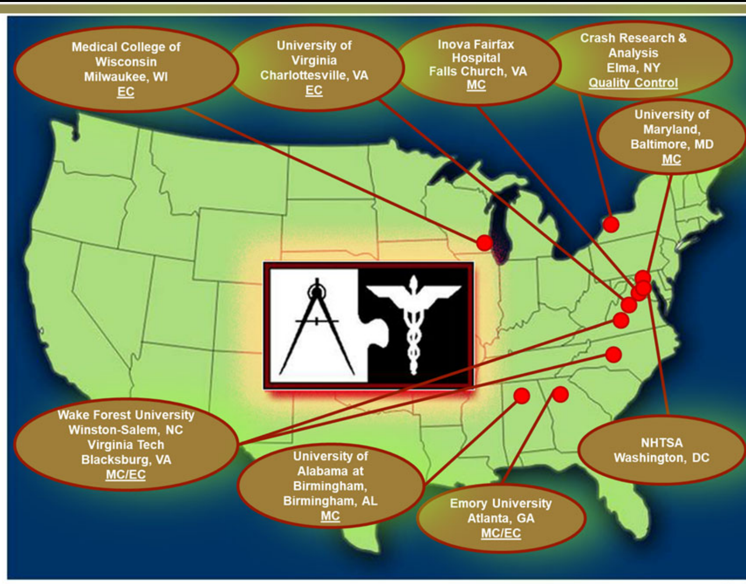
Crash Injury Research and Engineering Network (CIREN)



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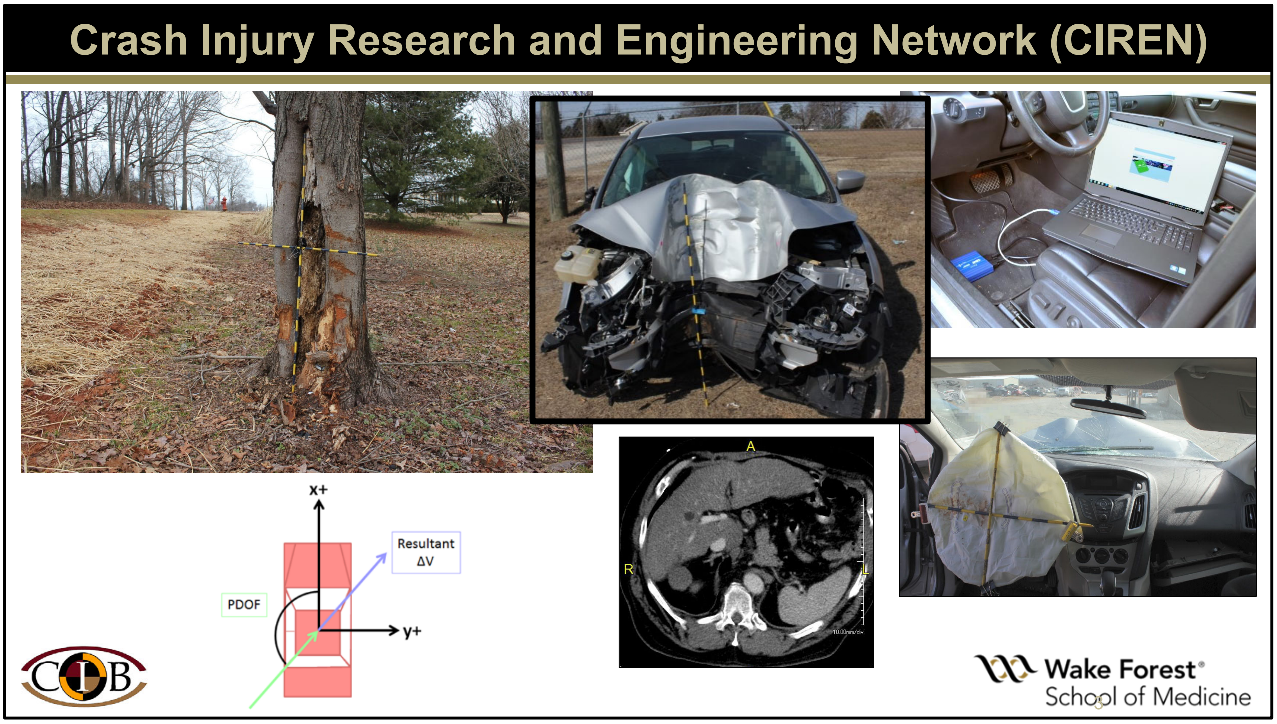
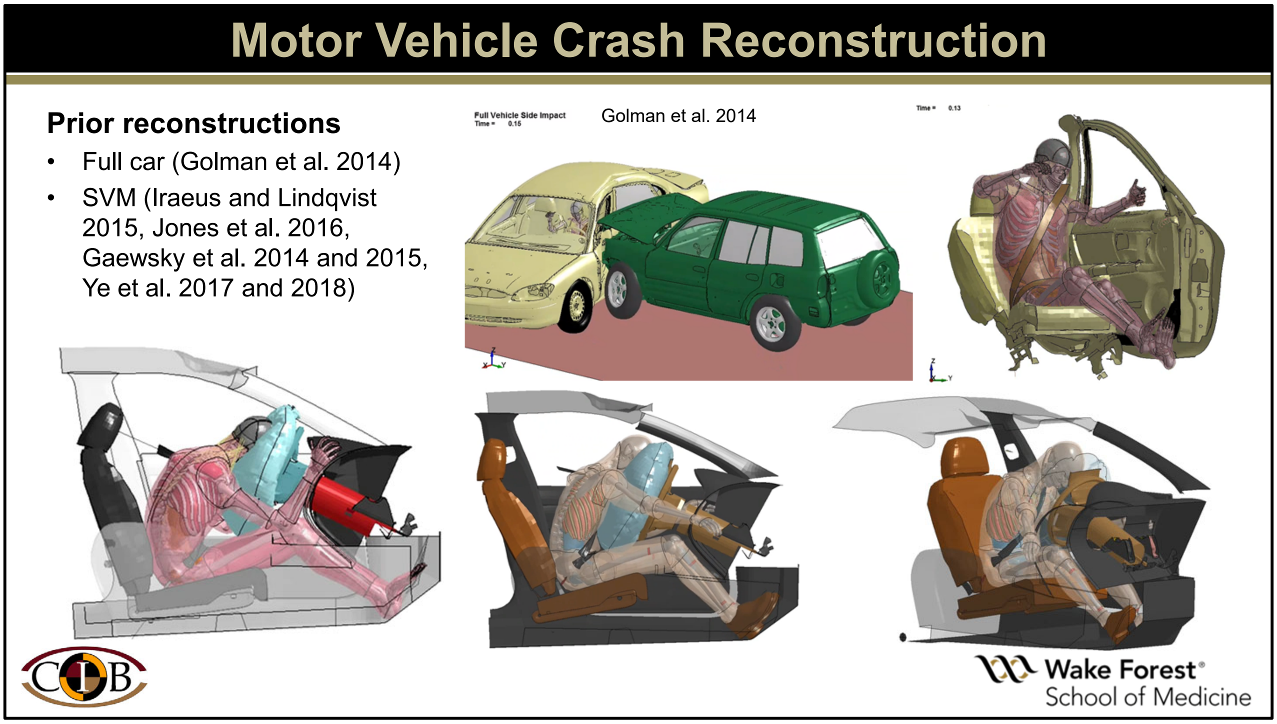
One of the databases ripe with crashes to reconstruct is the Crash Injury Research and Engineering Network, or CIREN. CIREN is a prospective cohort study focused on determining injury causation and mechanism in severely-injured crash occupants.



When a patient is enrolled as a CIREN occupant at the medical center they are treated at, a team at the medical center reviews police records, performs a field investigation of the vehicle and the scene, and compiles medical and radiology records to code the occupant's injuries using the abbreviated injury scale. The case is then sent to a team at an engineering center, where all aspects of the crash are analyzed to determine the causation and mechanism for each injury.



Finite element modeling using human body models can act as an additional supplement to CIREN investigations and many of the previously-mentioned studies reconstructed CIREN cases (As depicted in the figures). However, these studies implemented methodologies that are too time-consuming to integrate into CIREN because, generally, engineering centers only have around two weeks to review 2-4 cases. There is a need for a flexible reconstruction methodology that can be completed within the two-week time frame.

Motor Vehicle Crash Reconstruction

Objectives

1) Develop a flexible, time-efficient methodology for reconstructing CIREN crashes

2) Reconstruct a series of CIREN crashes and present them at monthly case reviews

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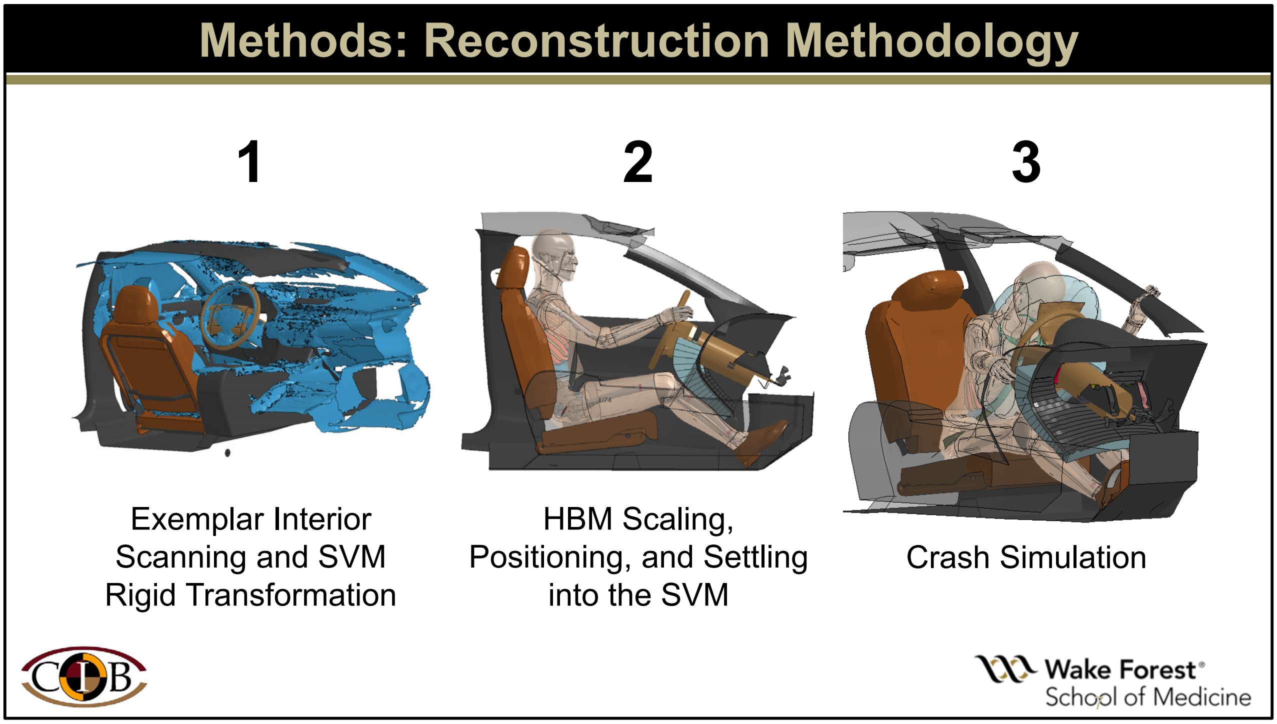
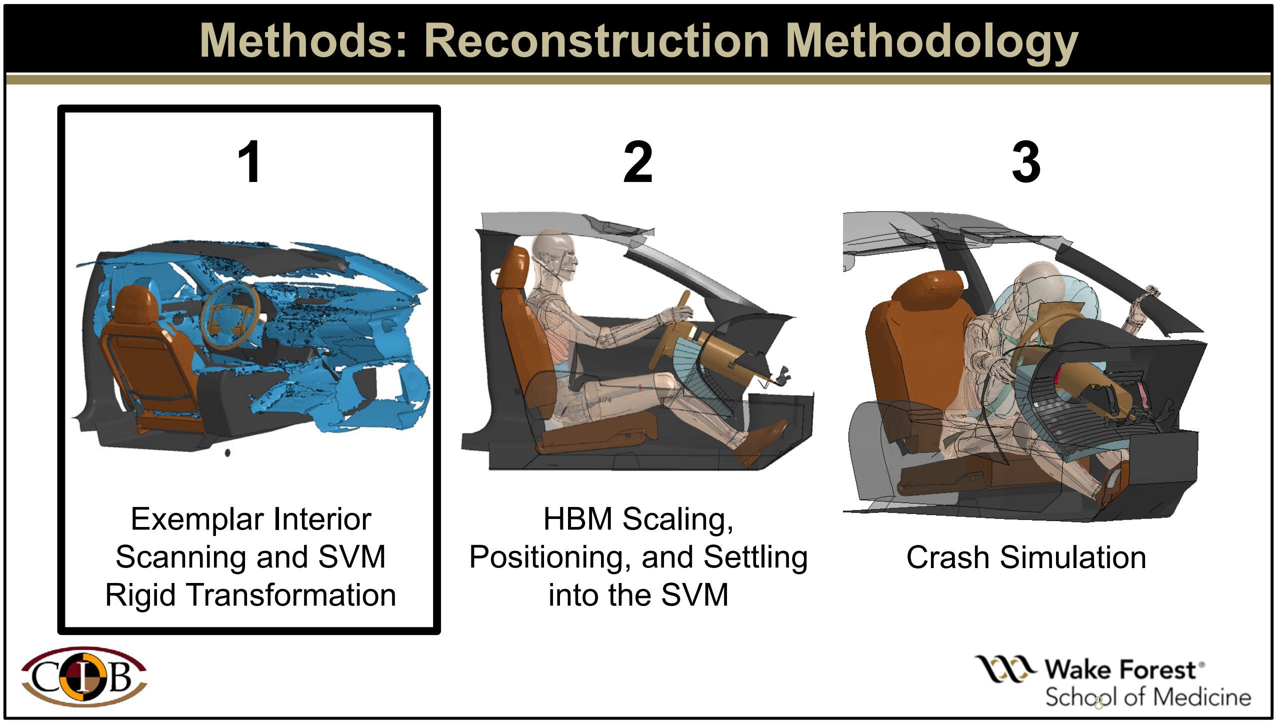
The primary objectives of this study were to develop a flexible, time-efficient methodology for reconstructing CIREN crashes and then reconstruct a series of CIREN crashes and present them at monthly case reviews.

METHODS

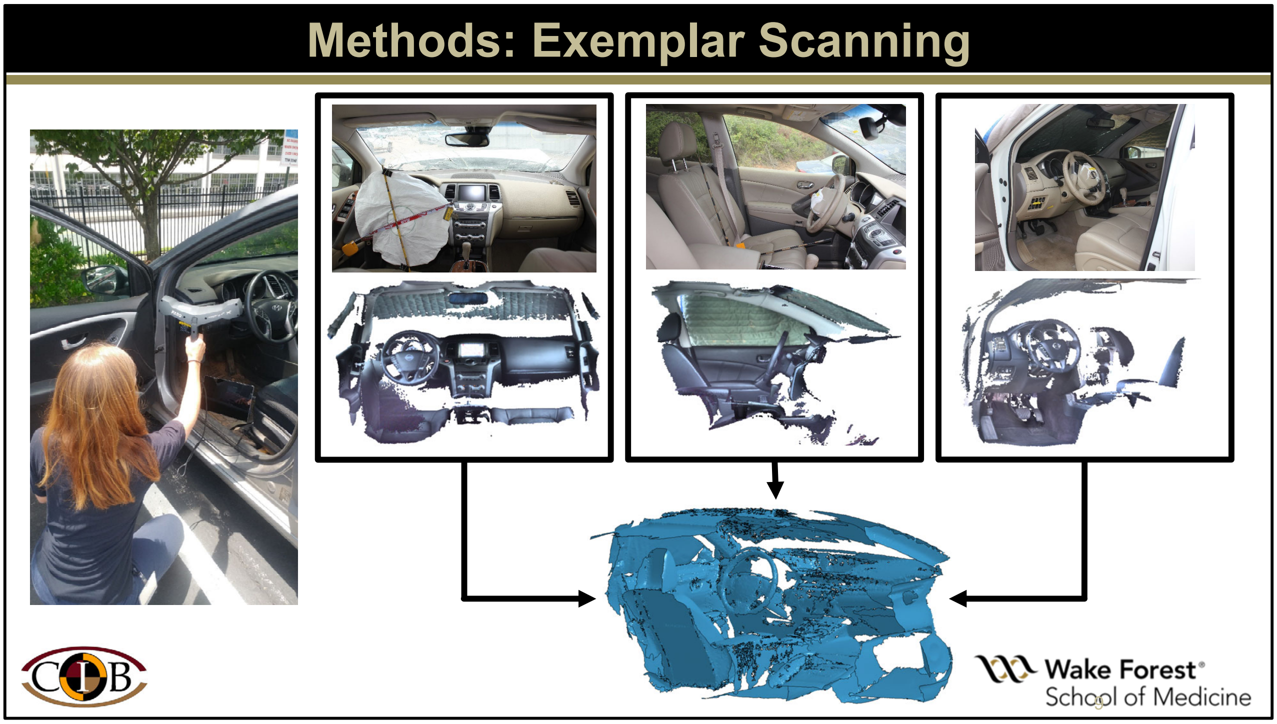


The reconstruction methodology in this study involved three parts

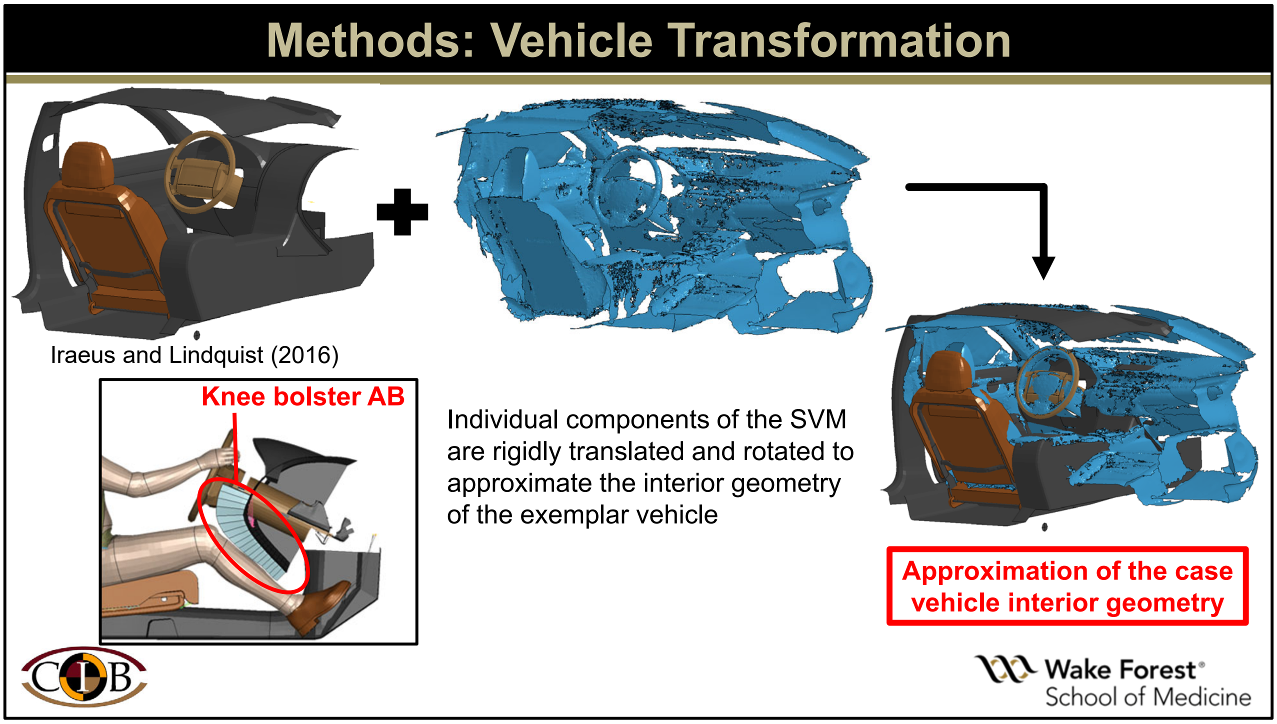
1. Exemplar vehicle scanning
2. Placing human body model in the simplified vehicle model
3. Simulating crash



The first of which involved rigid transformation of a simplified vehicle model to approximate the interior geometry of the crash vehicle.

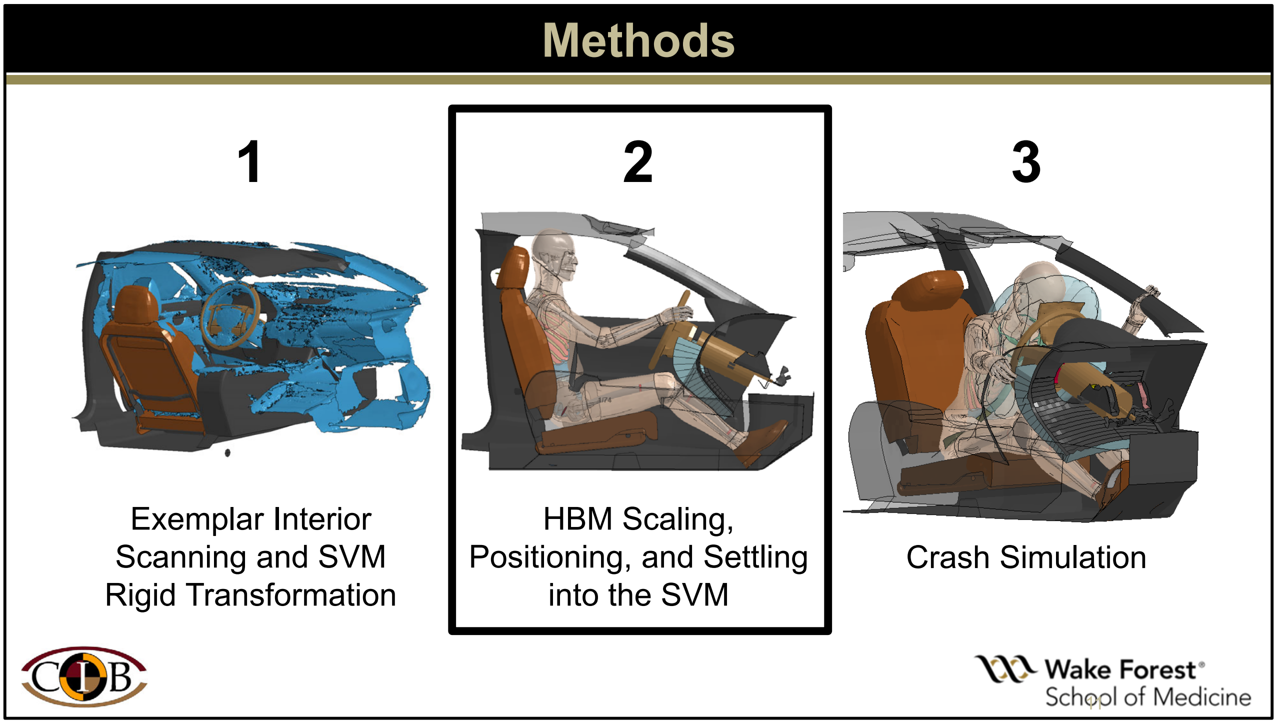


Once an exemplar (or undamaged) version of the crash vehicle had been found, a handheld Faro Freestyle 3D scanner was used to scan the interior of the vehicle as shown in the images on slide.

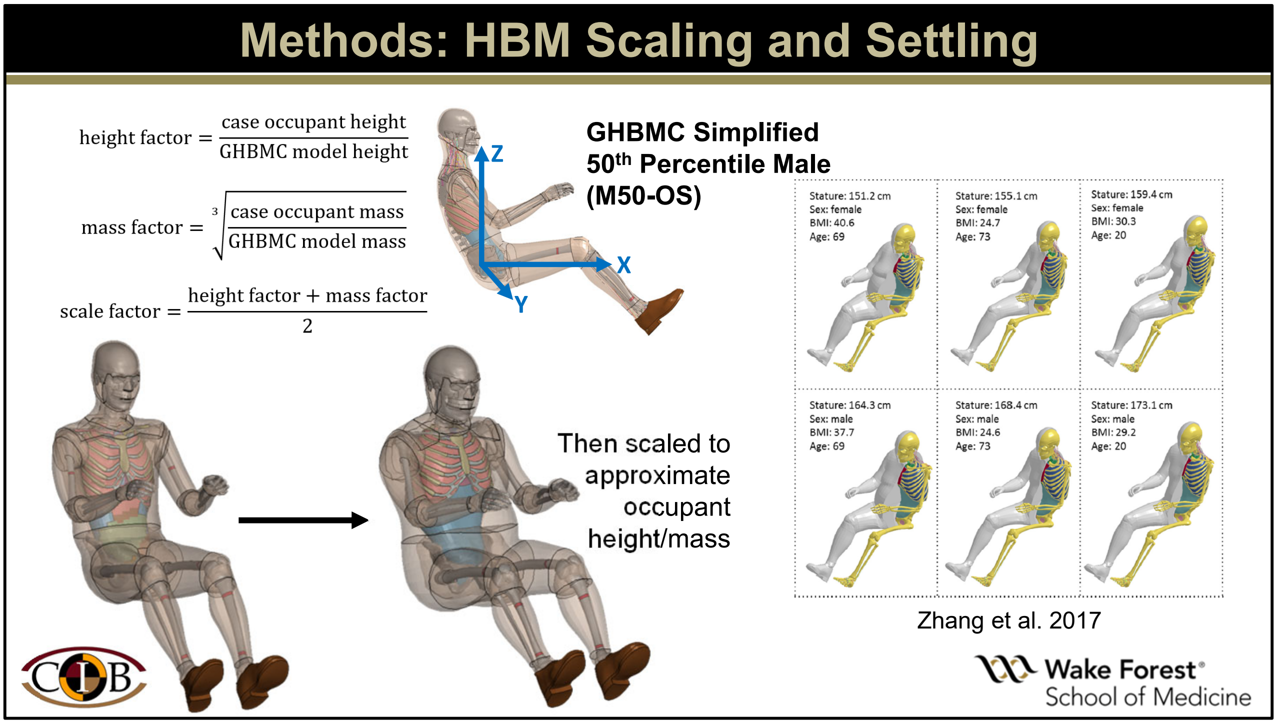


The resulting scans were used to develop a shell, which was imported into LS-PrePost with the augmented version of the simplified vehicle model developed by Iraeus and Lindquist.

Each of the individual parts of the SVM were rigidly translated and rotated to approximate the interior geometry of the exemplar shell.



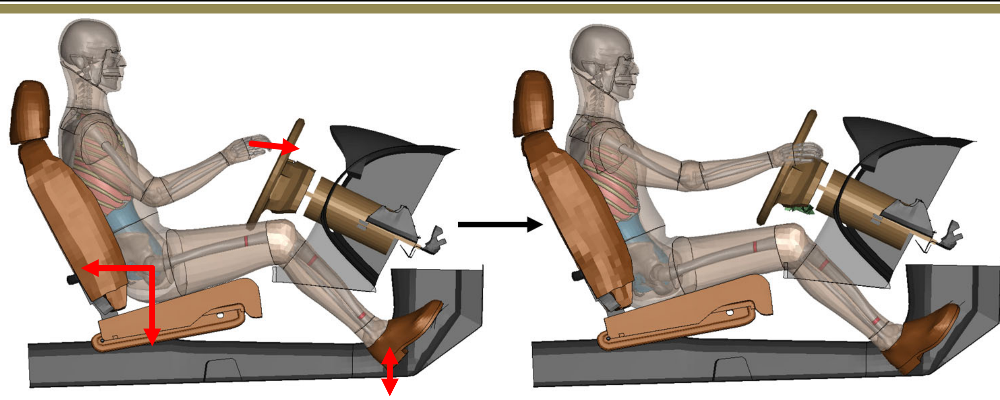
Step 2 involved settling of the human body model



This study implemented the GHBMC simplified 50th percentile male human body model due to it's computational efficiency and kinematic accuracy. The HBM was isometrically scaled in the x-, y-, and z-directions with respect to height and mass using a scale factor generated from the equations shown here.

In some cases, particularly those with high elevated BMI, a morphed version of the M50-OS that closely resembled the case occupant's height, weight, and age was used. Minor isometric scaling was then applied to the morphed model to provide and even more accurate representation of the case occupant.

Methods: HBM Scaling and Settling



Seat adjustments made, if necessary

Hands at 10 and 2 positions

Foot placed on accelerator or brake, if EDR evidence

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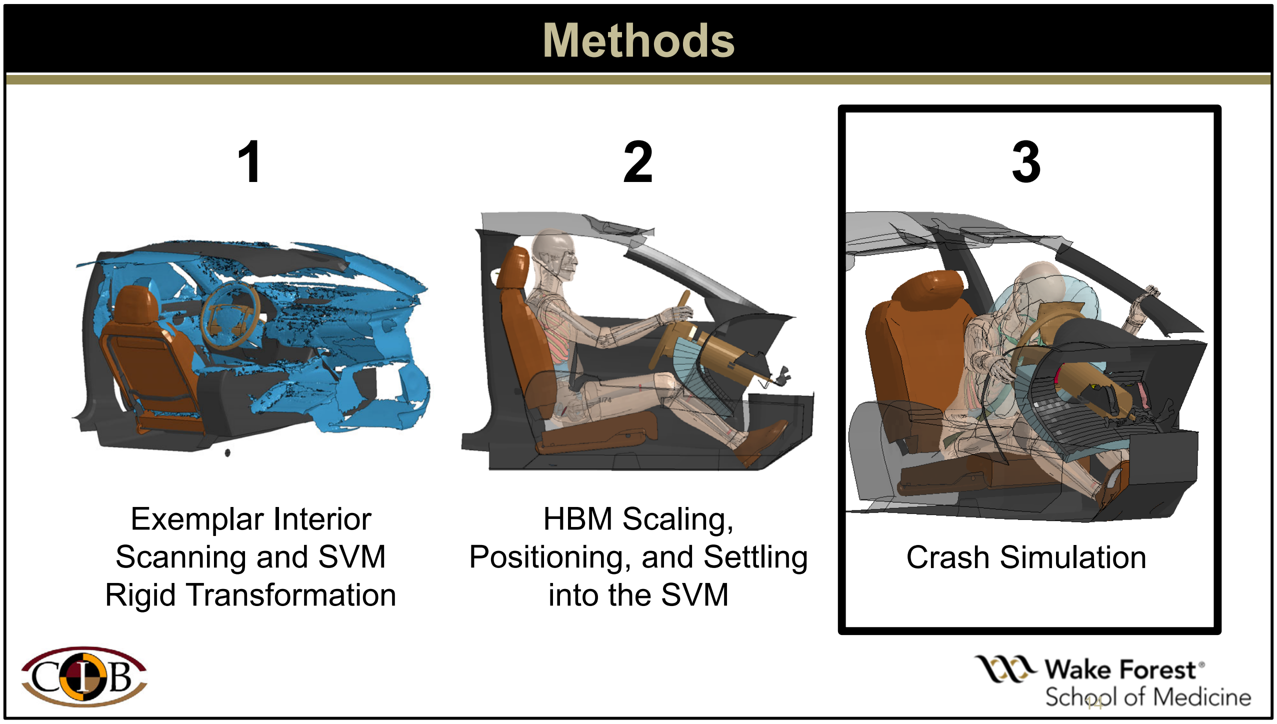
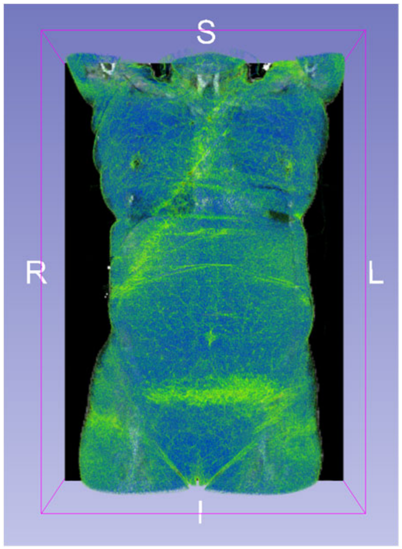
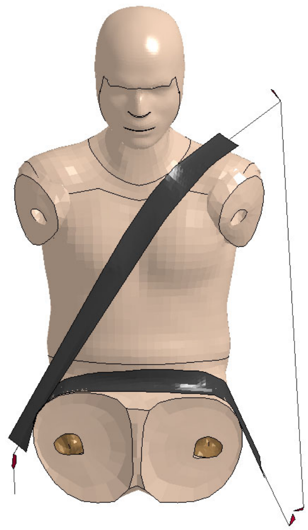
A global gravitational force was applied in the X and Z axes while holding the vehicle model in place and moving the extremities to the appropriate locations.



Step 3 involved execution of the crash simulation.

Methods: Seatbelt Application





Hartka et al. (2014): Visualization of subcutaneous adipose tissue beltmarks accurately predicted belt location in 19 out of 20 high-speed (>40 kph) frontal crash occupants

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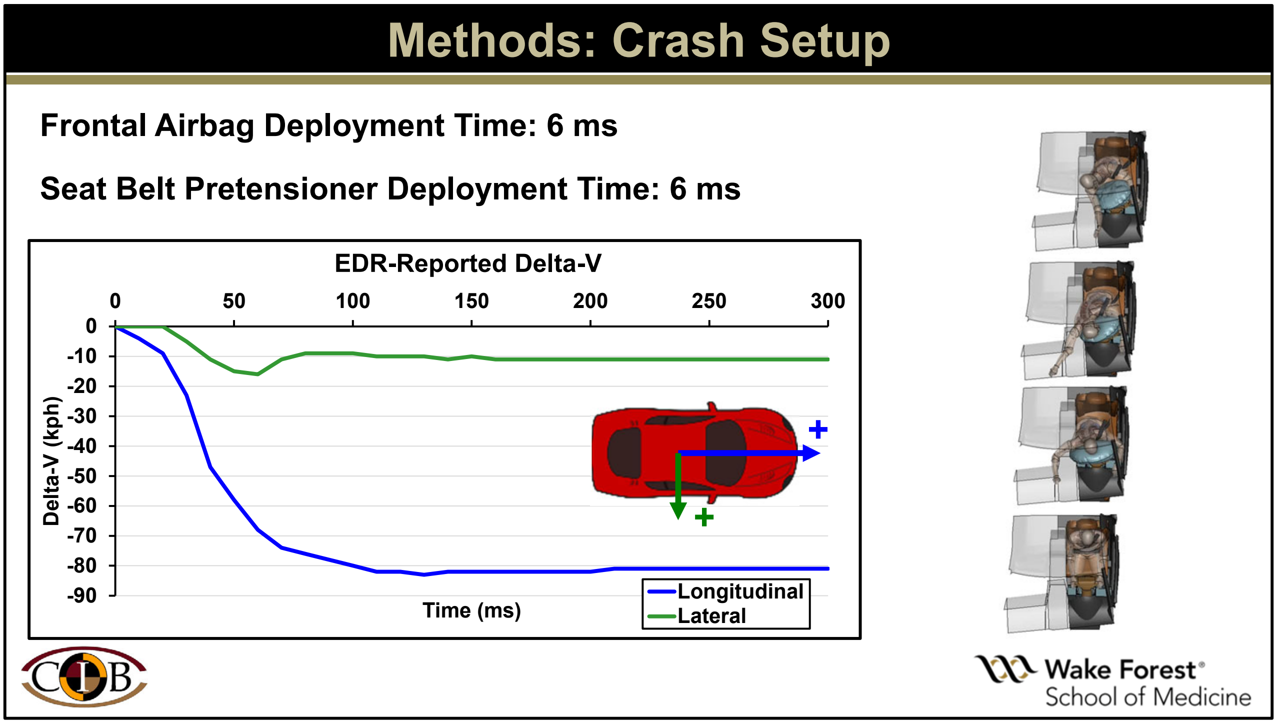
Belting was performed in LS-PrePost and subcutaneous fat renderings showing belt marks were used to assist in belt placement.



To simulate the crash, the EDR-reported delta-v (or change in velocity) was applied to the floor of the simplified vehicle model and the airbag deployment and pretensioner actuation times were implemented. If a case did not include an EDR crash pulse and it was a frontal crash with adequate engagement of the front bumper, the crash pulse was modeled using a spring-and-damper model developed from the NCAP frontal crash test data for the equivalent vehicle.

Methods: Kinematic Analysis

Contact Kinematic Score

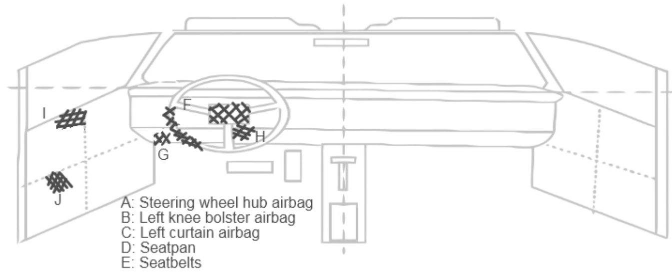
$$CKS = \frac{\sum(C_R \times CL)}{\sum(C_C \times CL)}$$

C_C – Case Contact

C_R – Reconstruction Contact

CL – Contact Confidence Level

Certain	3
Probable	2
Possible	1
Unknown	0



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Reconstructions were compared to corresponding CIREN cases for kinematics and injuries.

To assess kinematics, a contact kinematic score (CKS) was determined using the equation shown here. For every CIREN case, the crash investigator creates a list of potential occupant-to-interior contacts, with confidence levels indicating the certainty that it is truly a contact. Cr and Cc are binary variables that are equal to 1 if contact occurred and 0 if it did not occur. These variables are then multiplied by the weighting factor for the contact confidence level to give higher priority to contacts with higher confidence. The resulting score is a value between 0 (meaning the reconstruction satisfied no contacts) and 1 (meaning the reconstruction satisfied all contacts).

Methods: Contact Kinematic Score Example Calculation

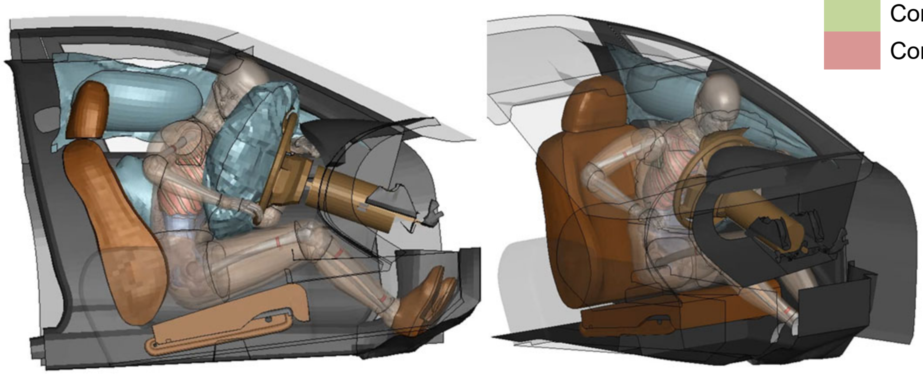
$$CKS = \frac{\sum(Reconstruction\ Contact\ * Confidence)}{\sum(Case\ Contact\ * Confidence)}$$

$$CKS = \frac{\mathbf{3} + \mathbf{3} + \mathbf{3} + \mathbf{2} + \mathbf{0} + \mathbf{3}}{3 + 3 + 3 + 2 + 2 + 3} = \mathbf{0.88}$$

CIREN Contact List	Confidence
Steering Wheel Hub	Certain
Rear Lower Quadrant	Certain
Forward Upper Quadrant	Certain
Forward Upper Quadrant	Probable
Steering Column	Probable
Left KB [R Knee]	Certain

Contact occurred in recon (green)
Contact did not occur in recon (red)

Possible: *Confidence* = 1
Probable: *Confidence* = 2
Certain: *Confidence* = 3



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Lets take an example of a CIREN case. There were 6 contacts listed in the case. 5 out of 6 contacts were occurred in reconstruction with confidence of each listed in the table. Based of this we get a contact kinematic score of 0.88.

Methods: Kinematic Analysis

Injury Kinematic Score

$$IKS = \frac{\sum\left[C_R\left(\frac{CL_C + CL_S}{2}\right)\right]}{\sum\left[C_C\left(\frac{CL_C + CL_S}{2}\right)\right]}$$

C_C – Case Contact
C_R – Reconstruction Contact
CL_C – IPC Confidence Level
CL_S – ICS Confidence Level

Certain	3
Probable	2
Possible	1
Unknown	0

IPC: Involved Physical Component (Contact that caused injury)
ICS: Injury Causation Scenario

Compared to CKS, IKS is weighted based on the case occupant injuries

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In addition to contact kinematic score, an injury kinematic score (IKS) was calculated, which differs in that it is also weighted based on the case occupant's injuries. Injury kinematic score is calculated similarly to contact kinematic score, with the contact that caused the injury acting in the same way as the contact for contact kinematic score

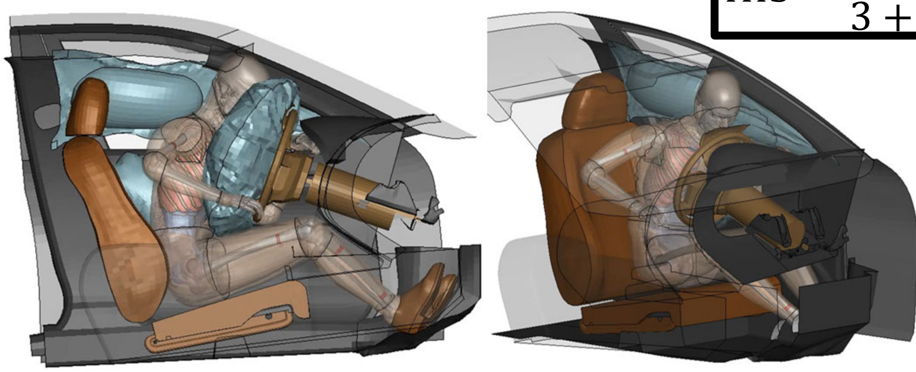
Methods: Injury Kinematic Score Example Calculation

Contact occurred in recon (green)
Contact did not occur in recon (red)

Possible: *Confidence* = *1*
Probable: *Confidence* = *2*
Certain: *Confidence* = *3*

CIREN Injury List	IPC	IPC Confidence	ICS Confidence
Right Femur Fracture	Knee Bolster	Certain	Certain
Right Tibia Fracture	Brake Pedal	Probable	Certain
Right Thigh Abrasion	Steering Column	Probable	Possible

$$IKS = \frac{\mathbf{3} + \mathbf{2.5} + \mathbf{0}}{3 + 2.5 + 1.5} = \mathbf{0.79}$$



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For example based three injuries listed in table and their IPC confidence and ICS confidence the injury kinematic score comes around 0.79.

Methods: Example Calculations

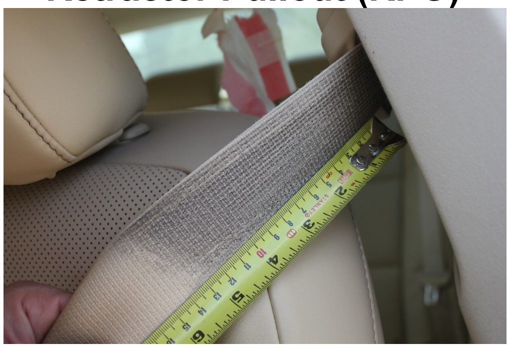
Total Kinematic Score

$$TKS = mean(CKS, IKS)$$

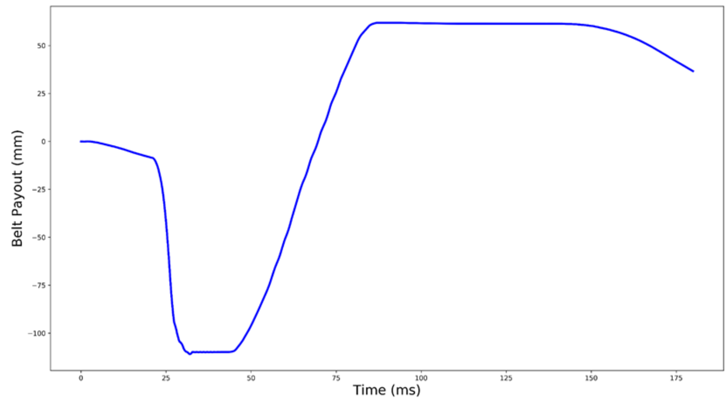
Total kinematic score, or TKS, was calculated from the average of these two scores (CKD and IKS).

Methods: Kinematic Analysis

Retractor Pullout (RPO)



Case



Reconstruction

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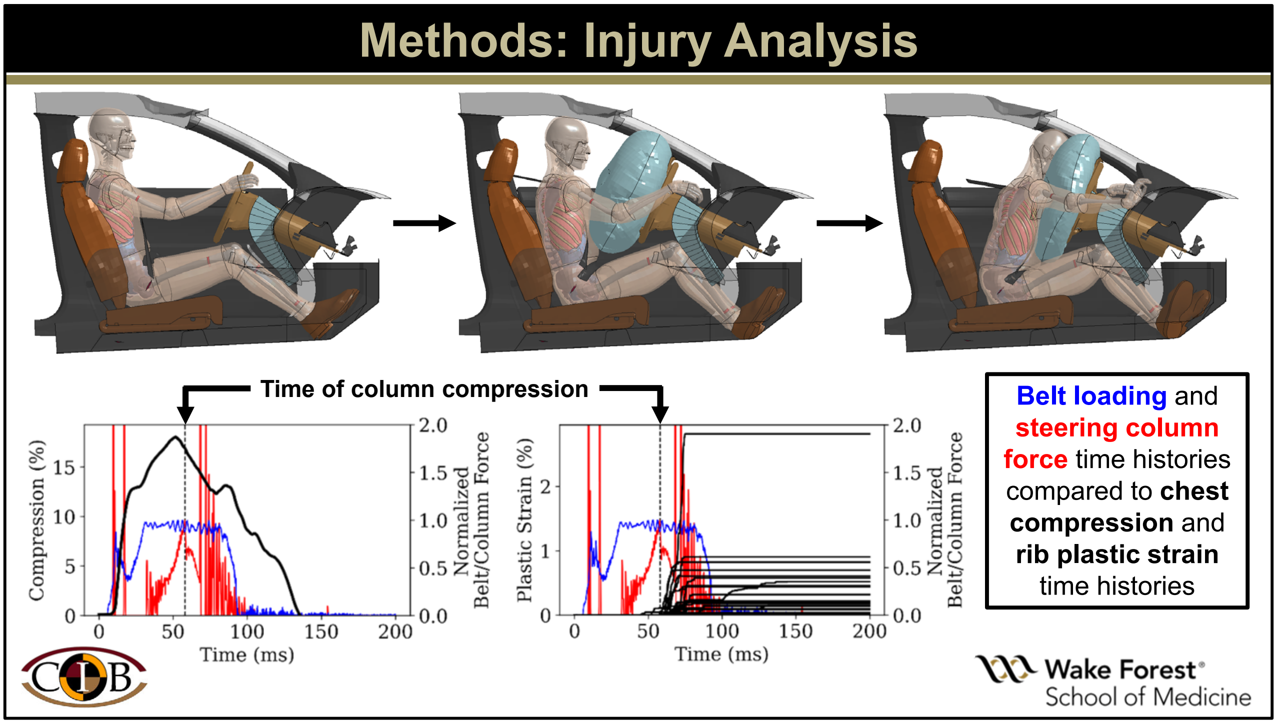
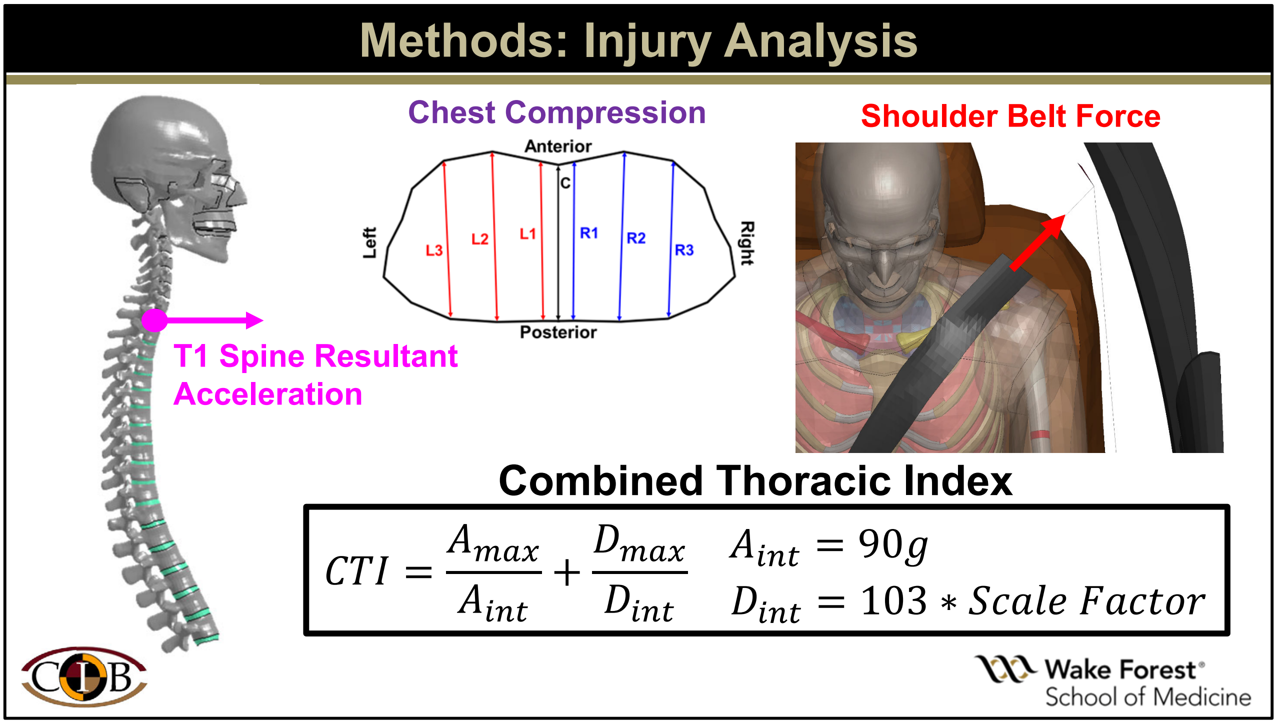
Lastly, for kinematics, the shoulder belt payout (or retractor pullout) between the reconstruction and the case was compared, if available.



In frontal crashes, the chest often loads multiple vehicle components (belt, airbag, steering wheel). In CIREN, it is important to determine which component contributes most to injury. To assess this in reconstructions, the chest compression and maximum rib plastic strain time histories were plotted against shoulder belt force and steering column axial compression force time histories. If the steering column collapsed during the simulation, the time of collapse was also included in the plot.



Injury was assessed using regional injury metrics and shoulder belt tensile force. The regional thoracic metrics included 3ms clip acceleration in the spine at T1, anterior-posterior chest compression along multiple cords of a chestband at the T8 level, and combined thoracic index (or CTI), which is a combined metric that accounts for both compression and acceleration.

Methods: Injury Analysis

Compared metrics in injured vs. non-injured case occupants:

- Parametric data – Student's t-tests
- Non-parametric data – Wilcoxon rank sum tests

α = 0.05

Student's t-tests and Wilcoxon rank sum tests were used for normally distributed and non-normally distributed data, respectively, to compare drivers with AIS 3+ thorax injury to those without AIS 3+ thorax injury. An alpha of 0.05 was used to determine statistical significance.

Methods: Injury Analysis

Area Under the Receiver Operating Curve (AUROC) calculated for each metric to determine predictive ability for AIS 3+ thorax injury.

Injury metrics were compared to:

- Literature-defined thresholds for AIS3+ chest injury
- Optimal thresholds determined from receiver operating curves

Univariate logistic regression between injury metric and outcomes (*AIS2+ injury*, *AIS3+ injury*, *lung/mediastinum injury*, and *AIS3+ rib fractures*).

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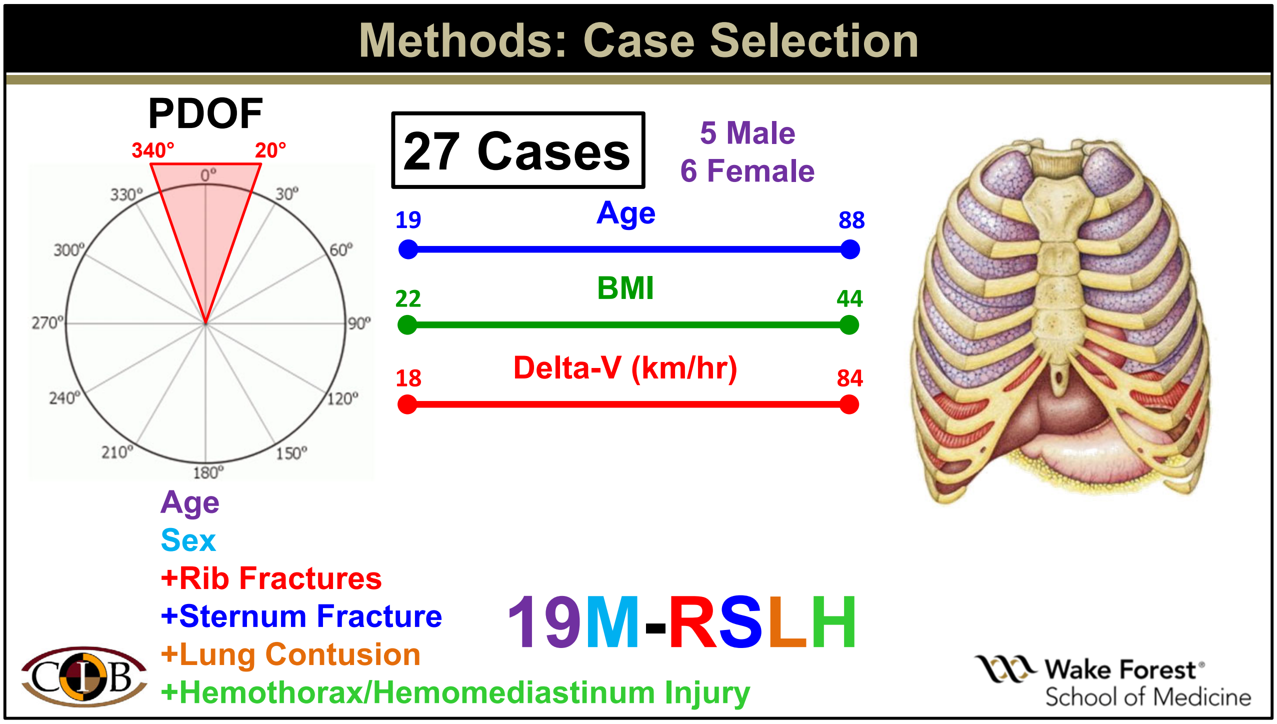
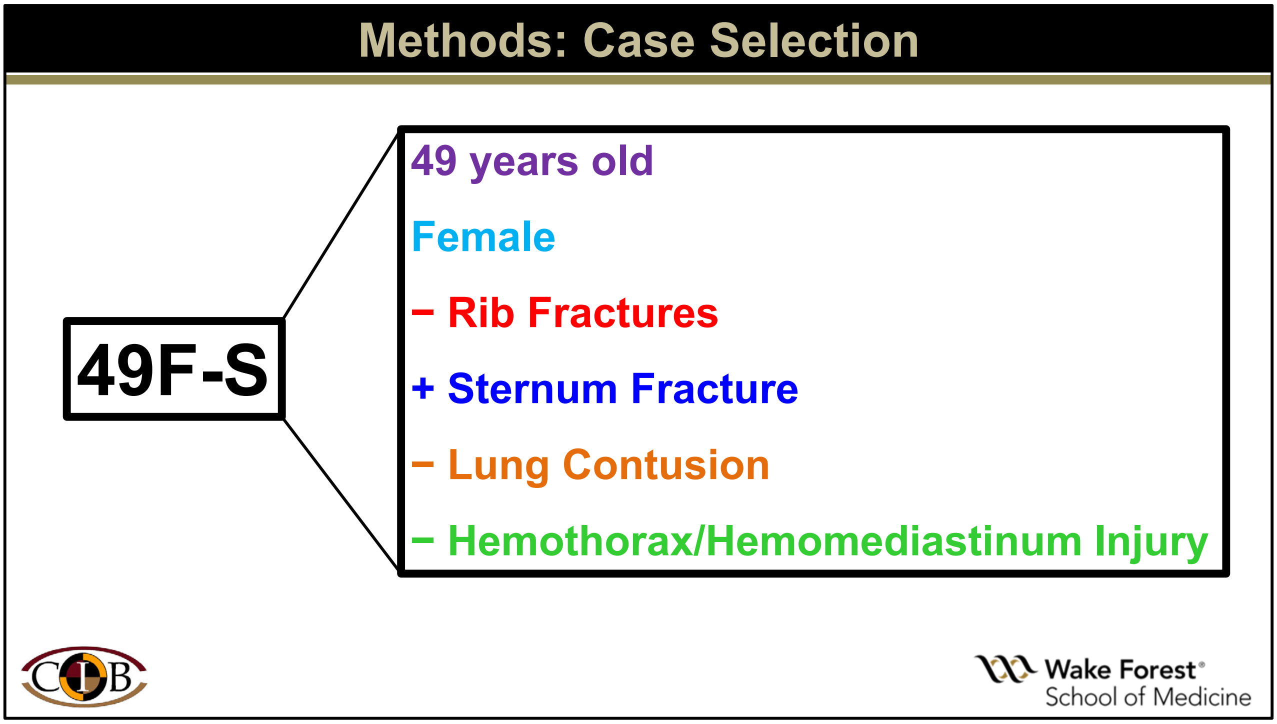
Injury metrics were compared to literature-defined thresholds. Additionally, for each metric, it's diagnostic ability and optimal injury threshold was determined by calculating its area under the receiver-operating curve. Univariate logistic regressions were performed with regional injury metrics and belt force used as independent variables and injury status for AIS 2+ thorax injury, AIS 3+ thorax injury, AIS 3+ lung and mediastinum injury, and AIS 3+ rib fractures used as dependent variables.

RESULTS

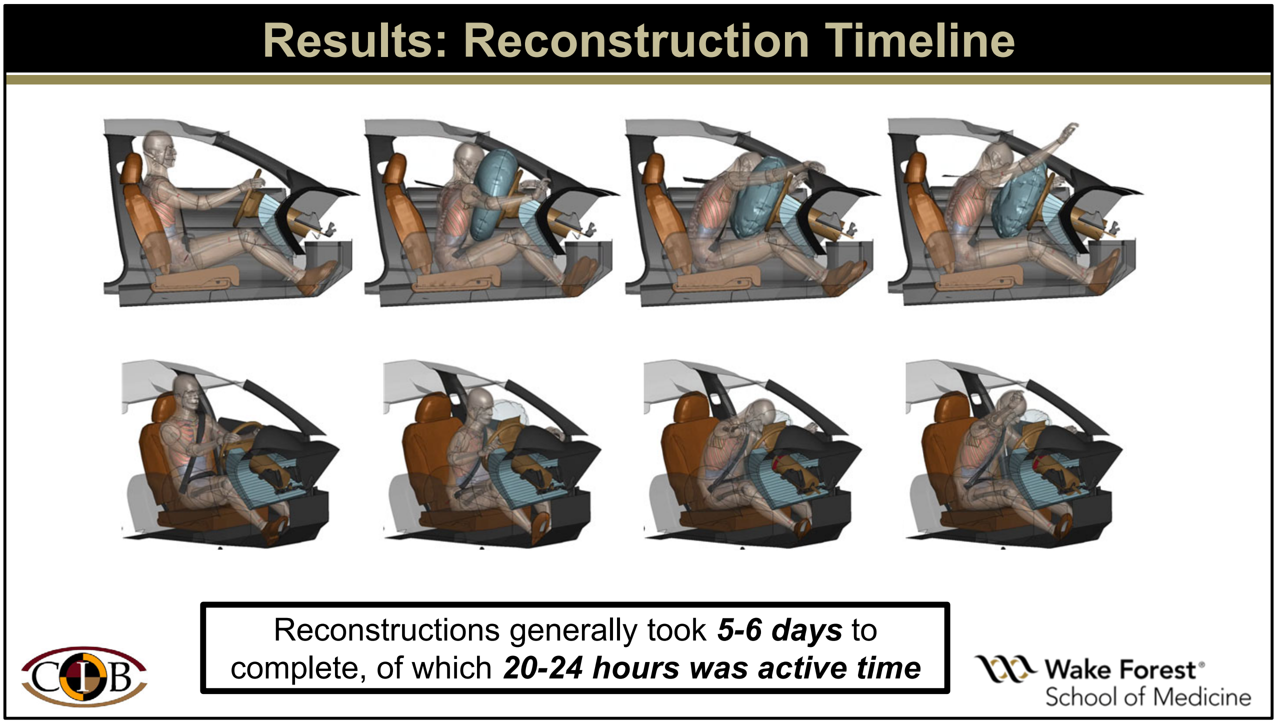


Twenty-seven frontal impact CIREN cases enrolled at Wake Forest between 2018-2021 were reconstructed.

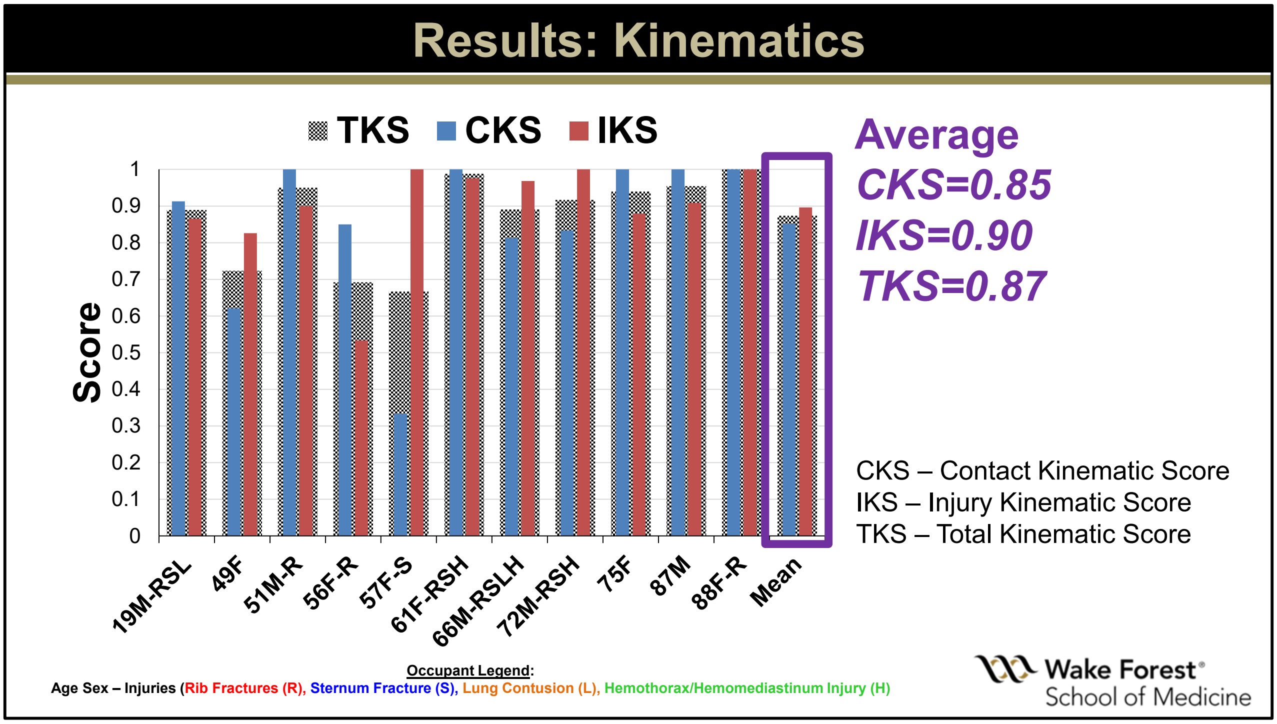
From this point forward, cases will be referred to by their age, sex, and injury status



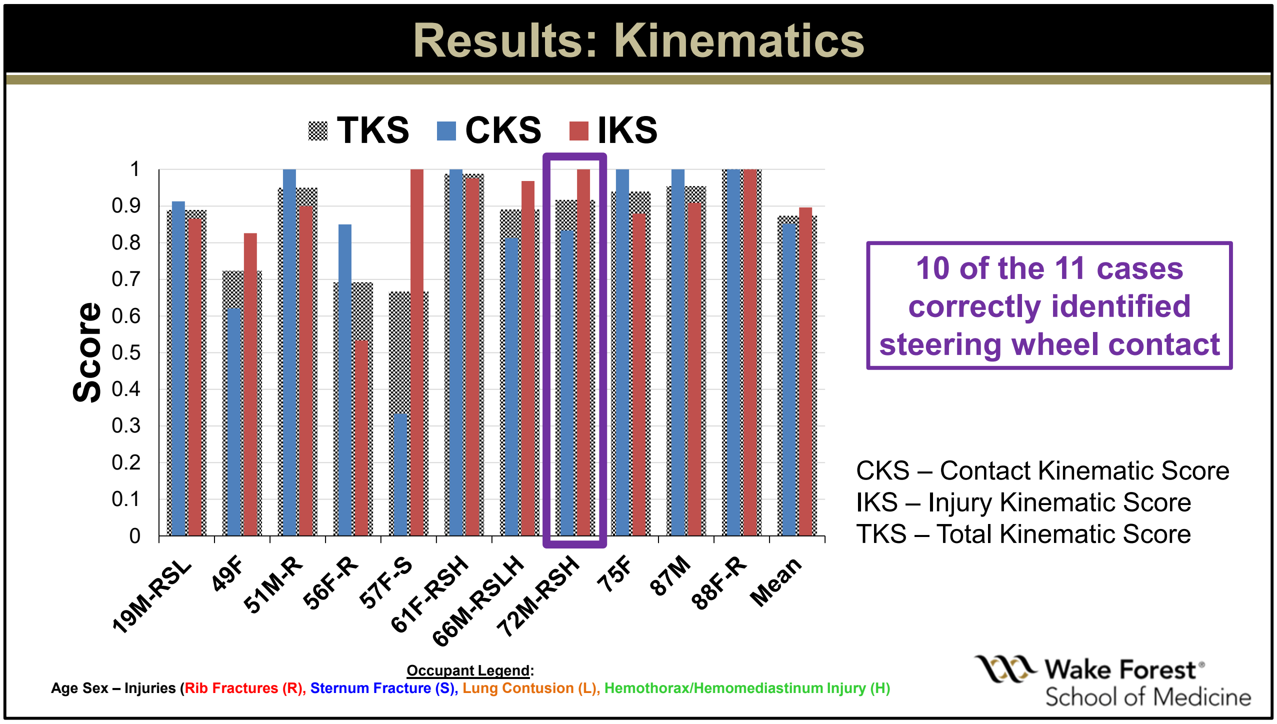
For example, 49F-S would refer to a 49-year-old female occupant that sustained a sternum fracture, but did not sustain a rib fracture, lung contusion, or hemothorax/hemomediastinum



Reconstructions generally took ***5-6 days*** to complete, of which ***20-24 hours was active time***

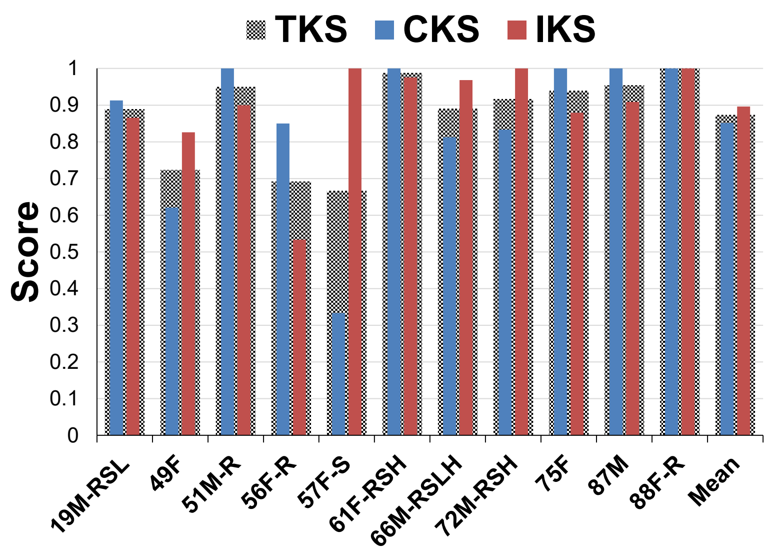


The bar chart on the slide shows all three scores for various reconstruction crashes. The average contact kinematic score was 0.85, the average injury kinematic score was 0.90, and the average total kinematic score was 0.87.



10 of the 11 cases correctly identified steering wheel contact, with only 72M identifying incorrectly. The case reported steering wheel contact, but the reconstruction did not.

Results: Kinematics



Case	RPO (mm) CIREN	Sim.
19M-RSL	Indeterminate	311
49F	180	155
51M-R	Indeterminate	330
56F-R	150	87
57F-S	120	67
61F-RSH	Indeterminate	160
66M-RSLH	170	171
72M-RSH	Indeterminate	156
75F	Indeterminate	28
87M	220	57
88F-R	Indeterminate	98

CKS – Contact Kinematic Score
IKS – Injury Kinematic Score
TKS – Total Kinematic Score

Occupant Legend:
Age Sex – Injuries (Rib Fractures (R), Sternum Fracture (S), Lung Contusion (L), Hemothorax/Hemomediastinum Injury (H)

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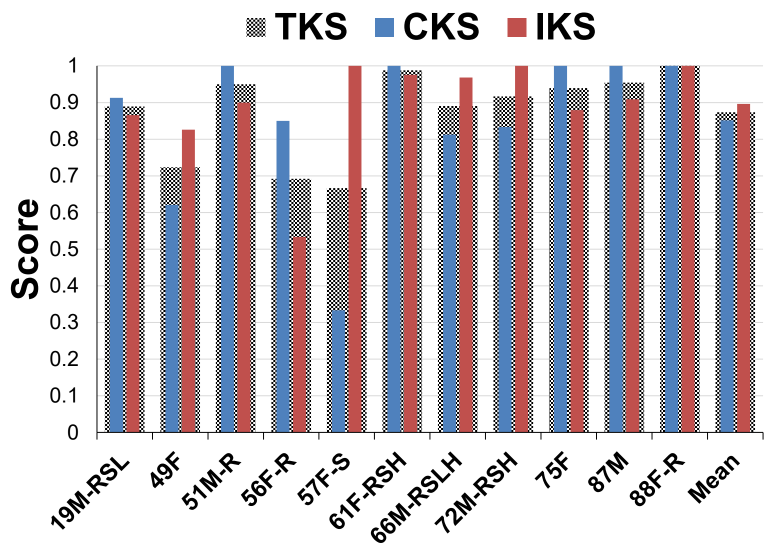
Retractor pullout was available for 5 cases which are reported in the table.

Results: Kinematics



	RPO (mm)	
Case	CIREN	Sim.
19M-RSL	Indeterminate	311
49F	180	155
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57F-S	120	67
61F-RSH	Indeterminate	160
66M-RSLH	170	171
72M-RSH	Indeterminate	156
75F	Indeterminate	28
87M	220	57
88F-R	Indeterminate	98

Belt payout **underpredicted** in 4 cases and **overpredicted** in 1 case

Occupant Legend:
Age Sex – Injuries (Rib Fractures (R), Sternum Fracture (S), Lung Contusion (L), Hemothorax/Hemomediastinum Injury (H)

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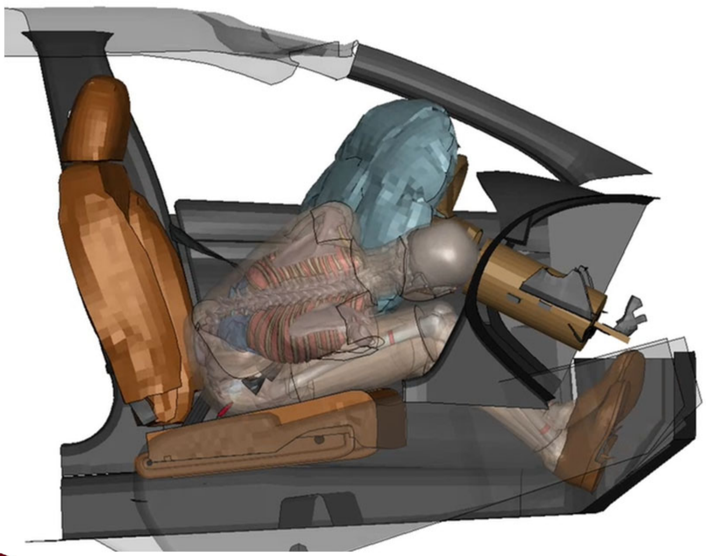
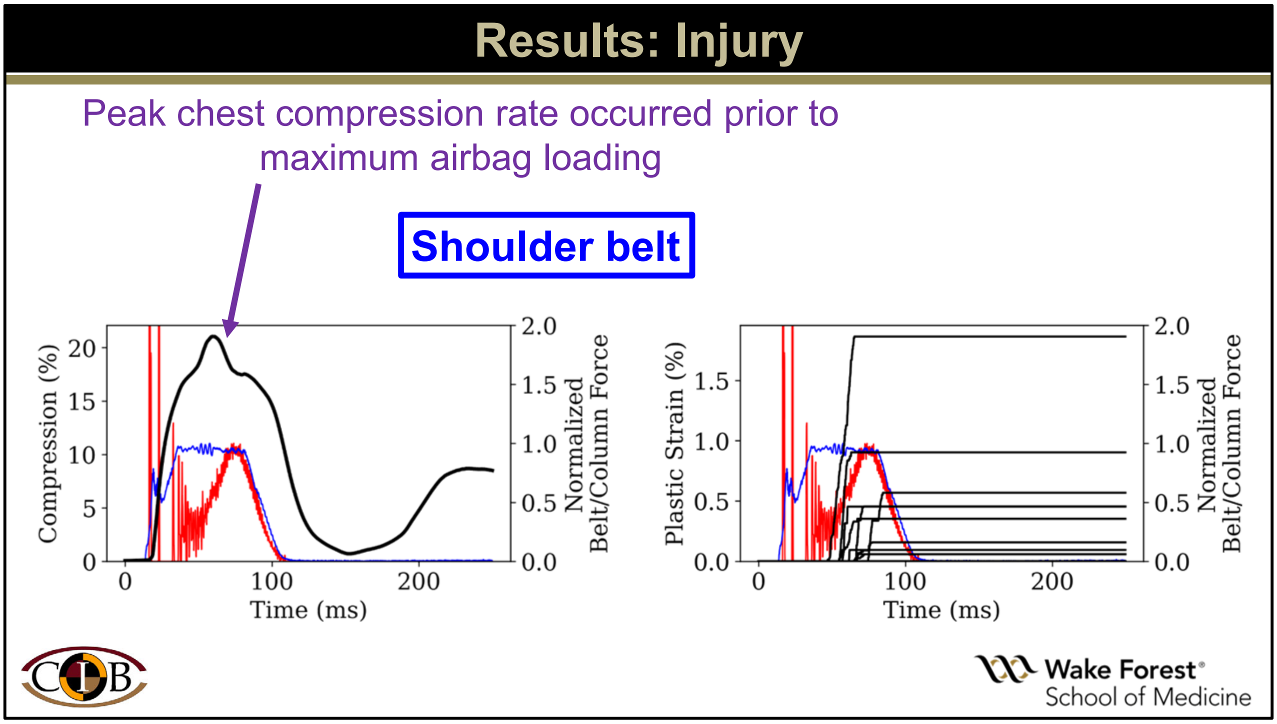
4 of the 5 reconstructions under predicted the amount of pullout. The exception is Case 66M, which over predicted by 1 mm. it becomes apparent that, reconstructions tended to under predict forward motion.

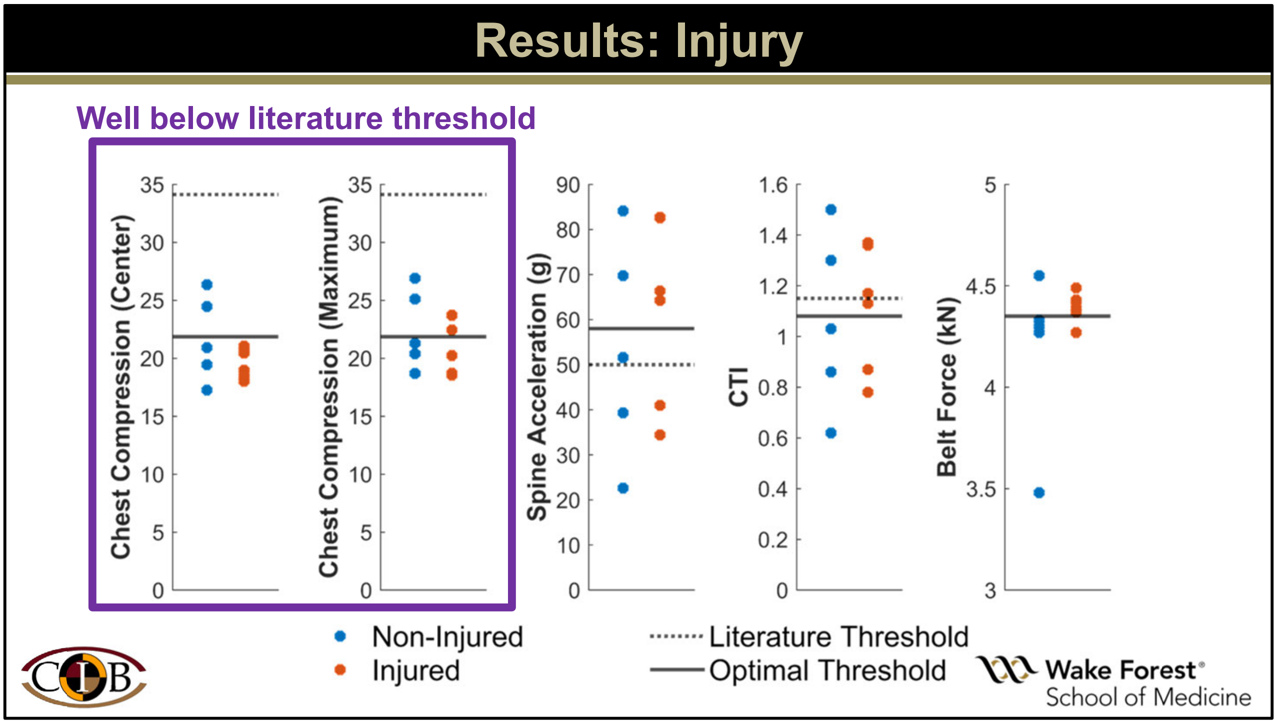
Results: Kinematics



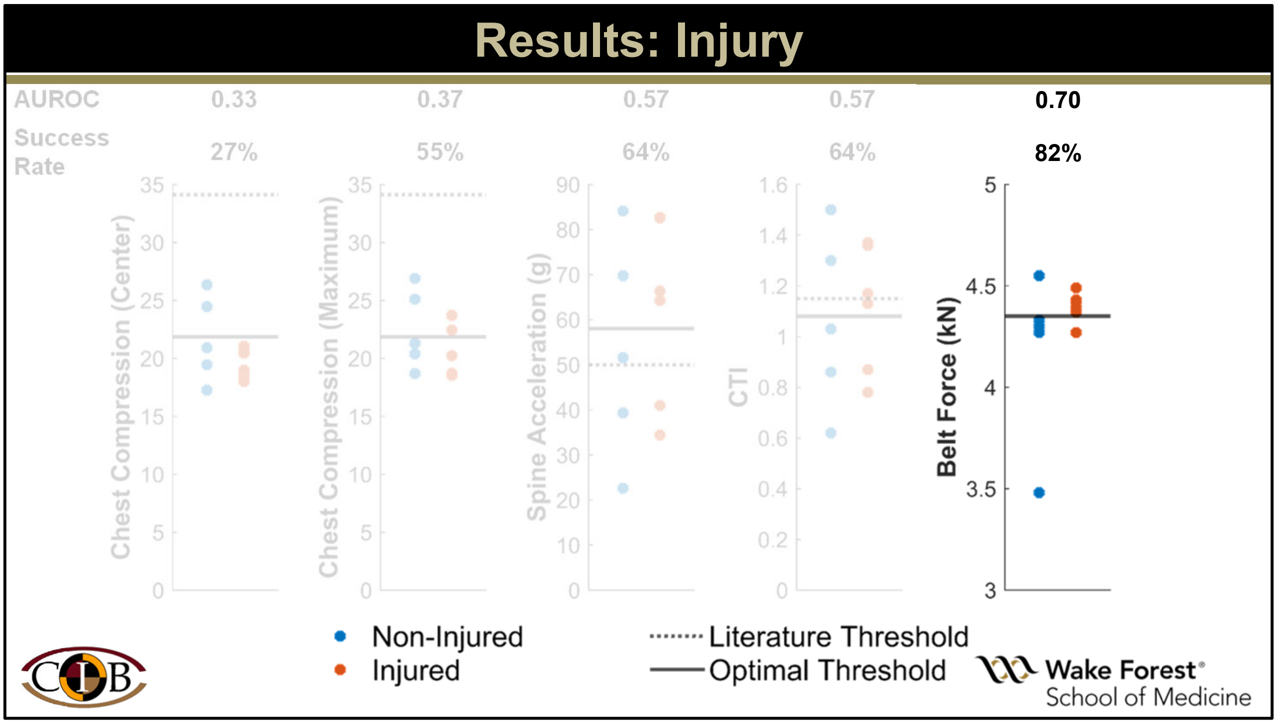
There were also instances where reconstructions explained contacts or injuries that were either unknown or uncertain from the CIREN case details. One of the best examples of that is shown here for Case 19M. The driver sustained a head abrasion in this case that was ultimately attributed to an unknown contact and the contact to the center console was attributed to the arm. However, as can be seen here, the driver's head impacts the center console in the same location from the CIREN case details.



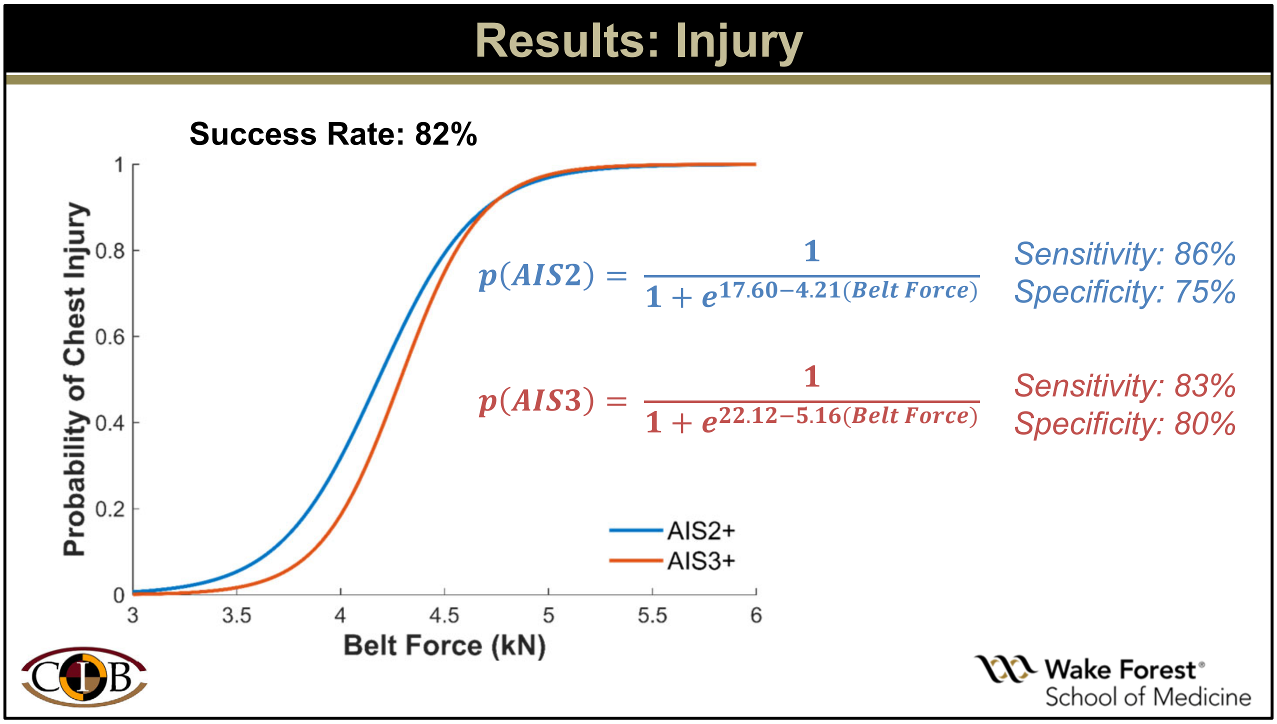
In all reconstructions, peak chest compression and rate of compression occurred prior to the time of maximum column compression force,
Indicating that the shoulder belt was the greater contributor to compression than the airbag.
Similar trends were observed in most cases for rib strain, but there were some interesting exceptions, which will be discussed later.



Spine acceleration and CTI predicted AIS3+ thorax injury with 55% success when using literature thresholds, but chest compression was well below the literature thresholds.

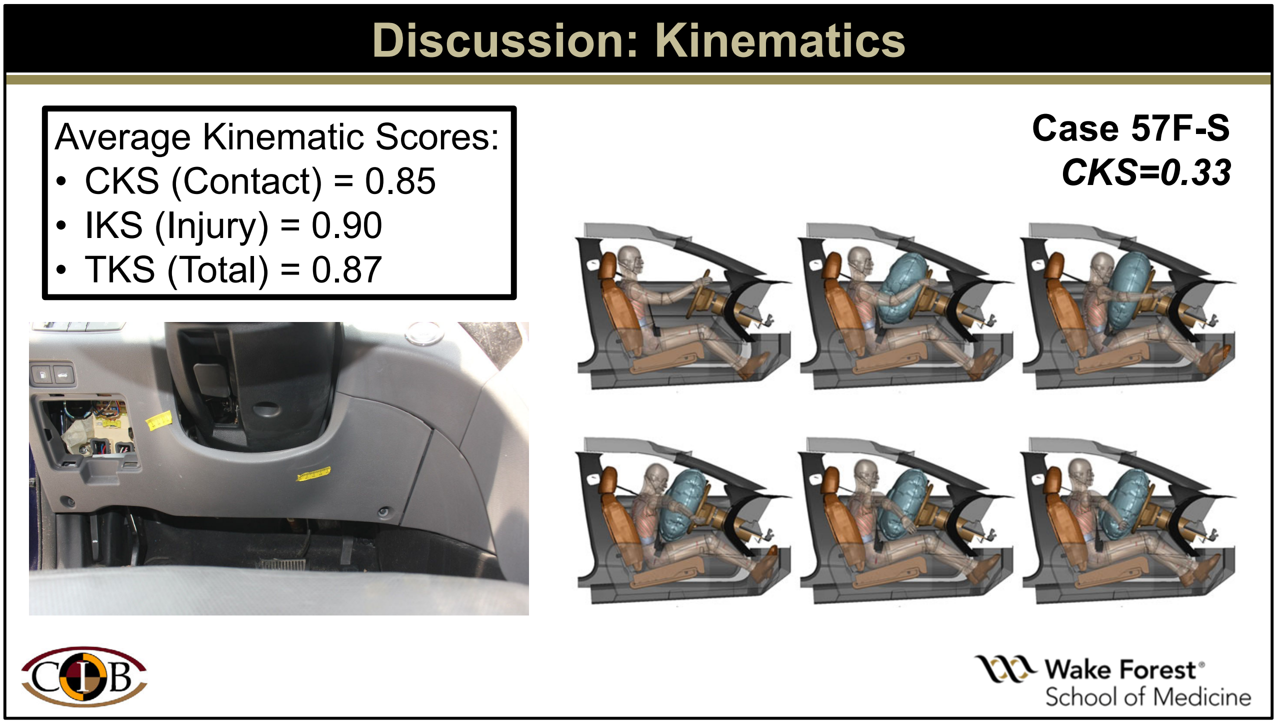


Optimal injury thresholds were better for determining injury, as expected, but only belt force was an effective predictor of injury, as can be seen by the area under the receiver-operating curve, which is 0.7. For reference, a value of 1 indicates perfect diagnostic ability and 0.5 indicates no diagnostic ability. Belt force predicted AIS3+ thorax injury with 82% success.



Belt force was used to develop injury risk functions for likelihood of sustaining AIS2+ and AIS3+ injury, both of which had 82% success rates, with sensitivities and specificities shown here.

DISCUSSION

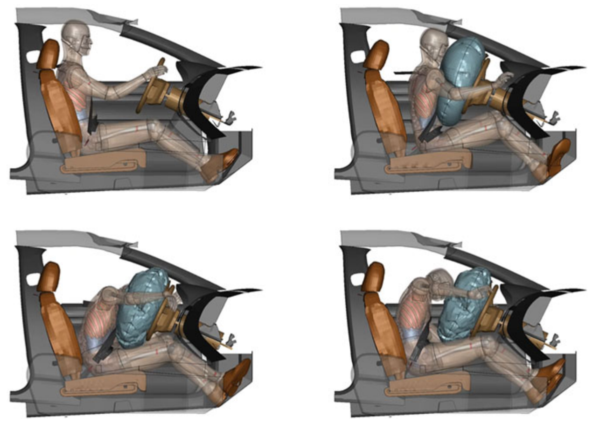


The average kinematic scores obtained in this study suggest that there was at least good agreement between CIREN cases and reconstructions. The lowest contact kinematic score was in Case 57F-S, which only had three contacts documented. 2 of the three contact were to the knee bolster, which the simulation did not satisfy.

Discussion: Kinematics

Average Kinematic Scores:
- CKS (Contact) = 0.85
- IKS (Injury) = 0.90
- TKS (Total) = 0.87

Case 49F
CKS=0.62



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Case 49F had the second-lowest contact kinematic score, which was primarily due to missed contacts on the A-pillar and windshield.

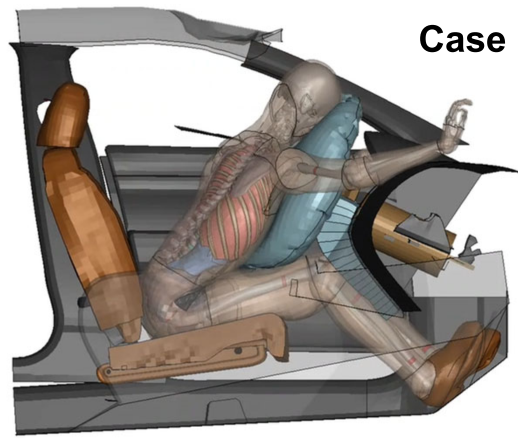
Discussion: Kinematics

Case	CIREN	Recon.
19M-RSL	X	X
49F	X	X
51M	X	X
56F-R	X	X
57F-S	O	O
61F-RSH	O	O
66M-RSLH	X	X
72M-RSH	X	O
75F-R	O	O
87M	O	O
88F-R	O	O

X – Positive for steering contact
O – Negative for steering contact

10 / 11 reconstructions accurately identified steering assembly contact

Case 51M



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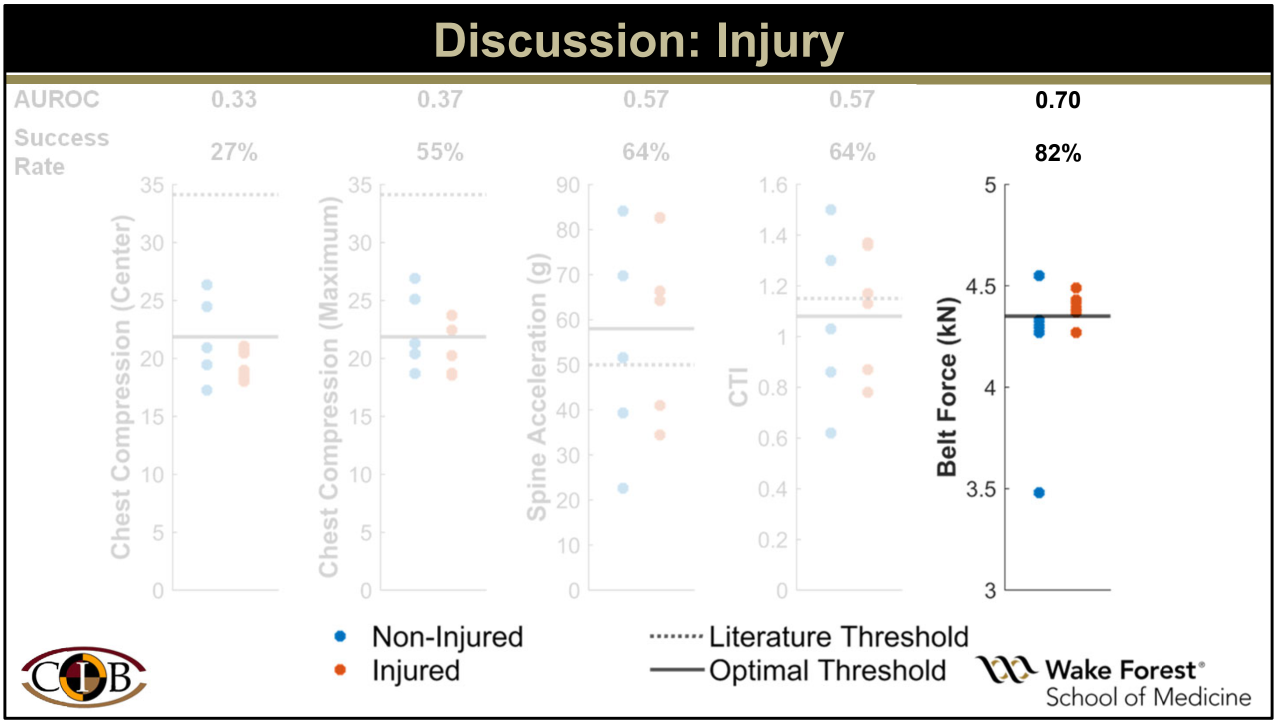
However, even though they under predicted forward motion, 10 of the 11 reconstructions accurately identified steering wheel contact, which is impressive



When looking at injury prediction, only belt force was an effective predictor.

Discussion: Injury

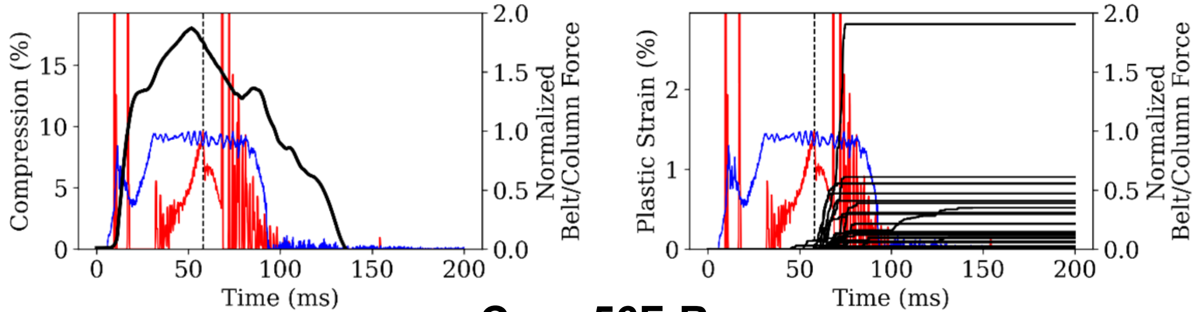
CIREN

Injury ***causation***, not injury ***prediction***

However, it is important to again emphasize that the focus of CIREN is injury causation, not injury prediction.

Discussion: Injury

Reconstructions successfully identified injury causation and, in some cases, suggested that the airbag may be just as significant as the shoulder belt



Case 56F-R

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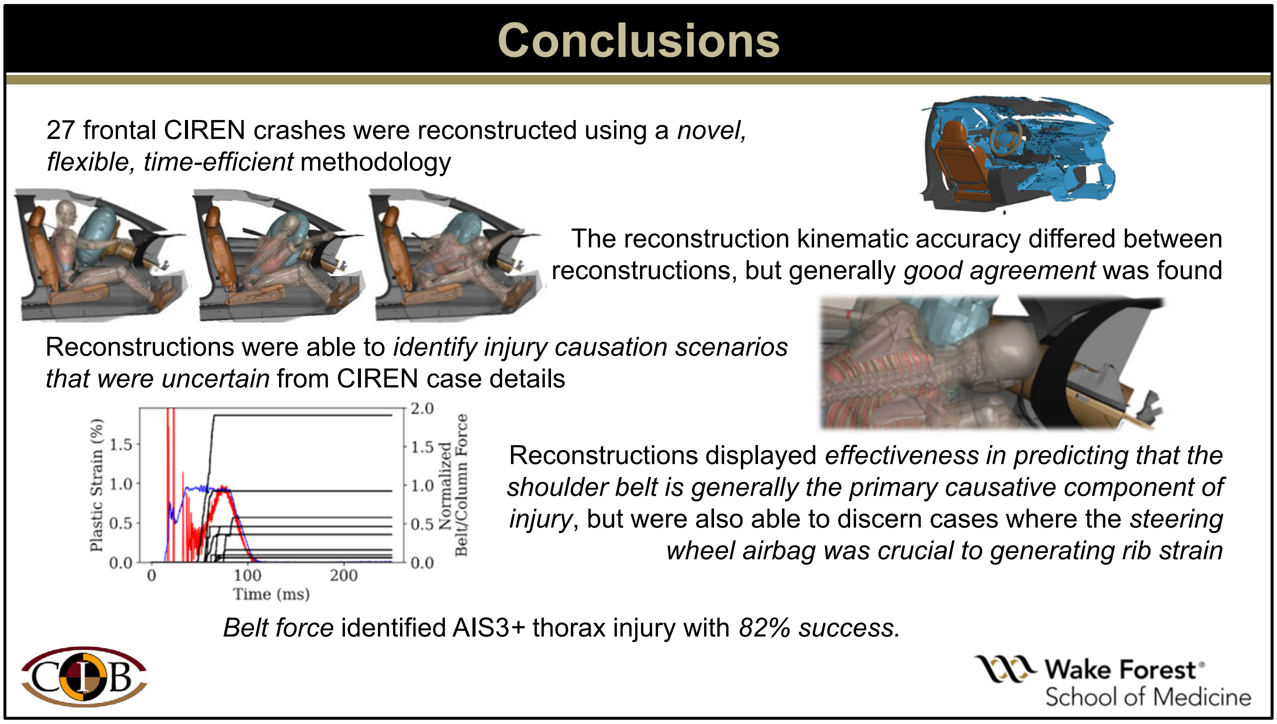
For injury causation purposes, reconstructions appeared to be effective. All reconstructions displayed sharp and significant elevations in chest compression during belt loading, followed by sustained or increased chest compression during airbag and steering assembly loading, indicating that the belt was the primary component causing chest compression. However, this was not always true for rib fracture. In three cases, rib plastic strain did not develop until the model loaded the steering wheel airbag and assembly, indicating that these components may have played a crucial role in generating fracture, contrary to the CIREN case injury coding.



To conclude,
27 frontal CIREN crashes were reconstructed using a novel, flexible, time-efficient methodology. The reconstruction kinematic accuracy differed between reconstructions, but generally good agreement was found. Reconstructions were able to identify injury causation scenarios that were uncertain from CIREN case details. Reconstructions displayed effectiveness in predicting that the shoulder belt is generally the primary causative component of injury, but were also able to discern cases where the steering wheel airbag was crucial to generating rib strain. Belt force identified AIS3+ thorax injury with 82% success.

Conclusions

This reconstruction methodology can be applied to reconstruct a variety of crashes (frontal, near-side, far-side, and rear) across the CIREN network, as well as to conduct parametric studies to examine the influence of input conditions on MVC occupant response.

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Crash Injury Research & Engineering Network

NHTSA
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DEAC Cluster

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Q&A

Last Name	First Name	Question Asked	Answer Given
Takhounts	Erik	How did you address uncertainties? Specifically, the airbag shape, mass flow rate, steering wheel braking force, etc.? And the human uncertainties, such as chest geometry (if different from 50M OS model), femur length, etc.?	These are excellent questions that address one of the future areas of growth for the project. For the crashes presented, uncertainties regarding vehicle safety parameters were addressed by using the average parameter values obtained from eleven previous reverse-engineered crash tests using this vehicle model. This was done consciously to prevent the need to reverse-engineer additional crash tests for each case, which can lengthen the reconstruction timeline to unpredictable and unrealistic lengths for the goals of the project. Regarding the M50-OS model, changes in occupant geometry were addressed by either isometrically scaling the model, which is quick but extremely limited, or using morphed versions of the M50-OS, which is more accurate. When using morphed models, selection was prioritized based on accurately representing height and weight, but more detailed components, such as femur length or chest geometry, were not directly prioritized. As a result, there were differences between occupant and model for each case, but the hope was to obtain the "average" occupant geometry corresponding to the occupant's height and weight. These are both areas that may be addressed in future studies by also including more probabilistic modeling by varying some parameters to generate a design of experiments as opposed to one simulation. For example, in cases where safety parameters are uncertain, airbag and belt parameters may be adjusted across a range of values to obtain a larger number of possibilities for each crash.
Morris	Russ	How do you account for differences in restraint components - seatbelt load limiter, steering column stroke, seat stiffness, airbag stiffness?	
Marini	Giacomo	Was the belt system adapted to the specific vehicle? E.g., Load limiter, pretensioner, etc.	

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Q&A

Last Name	First Name	Question Asked	Answer Given
Draper	Dustin	can you play the movies again? playback was a bit delayed (for me at least)	The movies were replayed in the live session.
Nusholtz	Guy	How do you know that the airbag is as important as seat belt for chest injury?	This is a fantastic question. Simulations found that the airbag may be more critical to generating rib fractures than was originally attributed in some of the CIREN case injury coding. The reason for this is because plastic strain in the ribs for three of the cases did not develop significantly until the occupant impacted the airbag, which often occured after the load limit on the belt was reached. As a result, it appeared that the airbag impact was necessary to generate fracture in the ribs.

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Q&A

Last Name	First Name	Question Asked	Answer Given
Seyedi Marghaki	Mohammad Reza	How you extract the initial position of the occupant right before the crashes? and is this analysis only for a driver or the most injured person in crashes?	Great questions. Pre-crash occupant positioning can be incredibly challenging to both predict and model. Often, the initial position in CIREN cases must be assumed. When hard evidence was available, it was used. This included EDR evidence regarding right foot position (brake, accelerator), and belt location on the chest/abdomen from CT scan fat rendering. Sometimes, patient interviews revealed more information, but implementing this information was difficult due to the minimal details provided (i.e. right arm outstretched over the right passenger seat). As a result, most occupants were modeled similarly with the pelvis positioned in the seat, chest upright, hands at the 10 and 2 positions on the steering wheel, and right foot on the appropriate pedal unless hard evidence specified otherwise. If there were pre-crash events, such vehicle tilting or pitching, two simulations were conducted: one using normal occupant positioning and one incorporating pre-crash information. These analyses were only conducted for drivers, but the vehicle model is being adapted for reconstruction of right front passengers.
Nusholtz	Guy	Do you have enough data to determine confidence intervals for the results and what are they.	This study was conducted as a pilot study to determine the effectiveness of the methodology. As a result, confidence intervals were obtained for the results obtained, but they require additional results in order to be implemented effectively for future injury prediction in crash reconstructions.

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