Building Trust in HBM Injury Risk Predictions: Validations and Challenges

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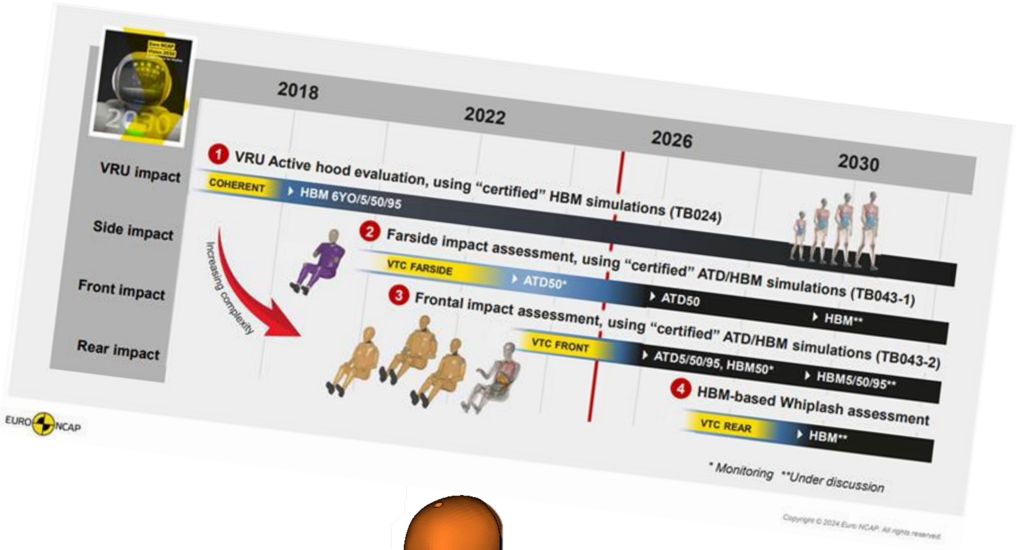
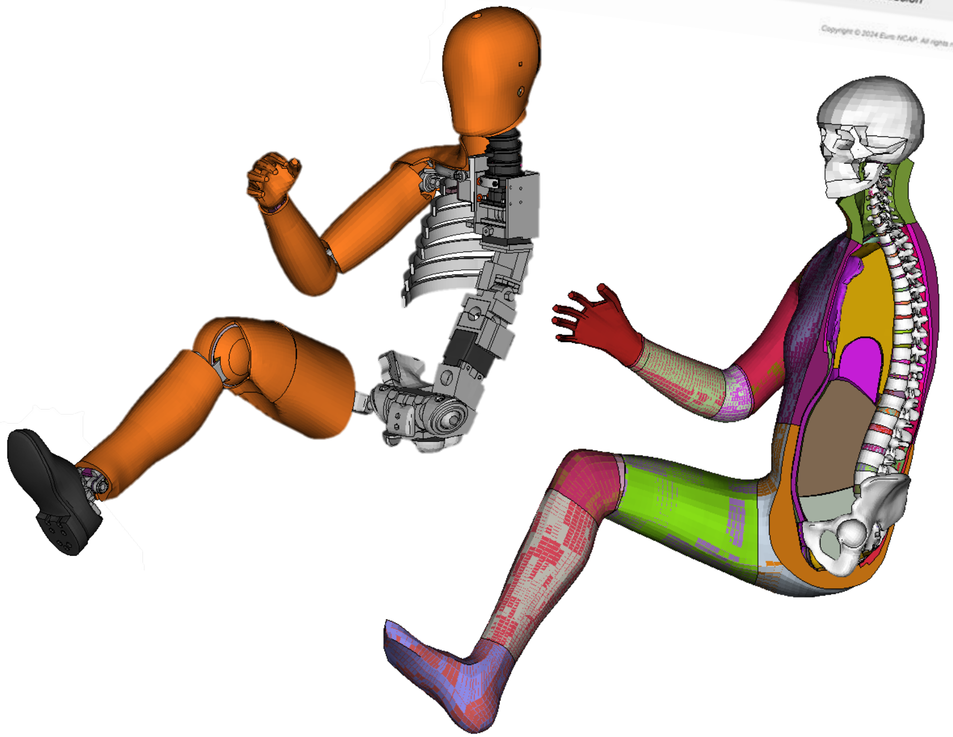
Introduction

- Human Body Models (HBMs) are being introduced in occupant safety rating assessments
  - E.g., Euro NCAP:
    - 2026: 50th – Male HBM in frontal impact sled simulation (monitoring)
    - 2029 (plans): 5th/50th/95th HBMs in Rating





- HBMs are different from crash test dummies (ATDs)
  - Which is why HBMs are introduced

- There can be situations where ATD and HBM injury risk predictions differ
  - i.e., HBMs favor one restraint system design, ATDs another

- Changing to HBM-based restraint designs requires trust

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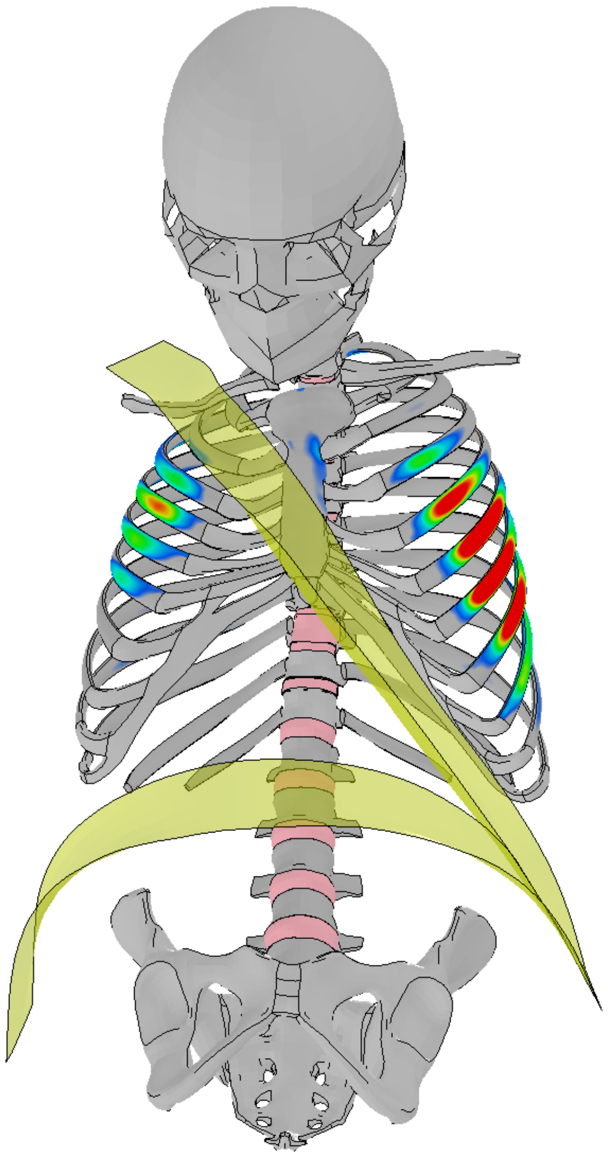
Aim

- Discuss how we can make HBM injury risk evaluations meaningful for real life safety
  - Demonstrate injury risk prediction validation status
    - SAFER HBM
    - Rib fracture risk – remains a prevalent injury
  - Discuss Challenges with risk predictions



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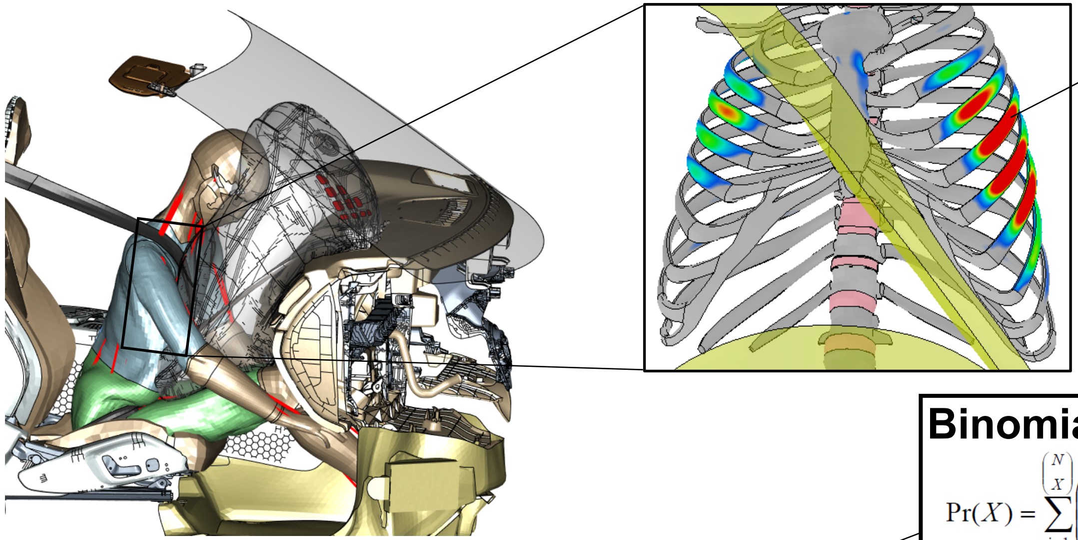
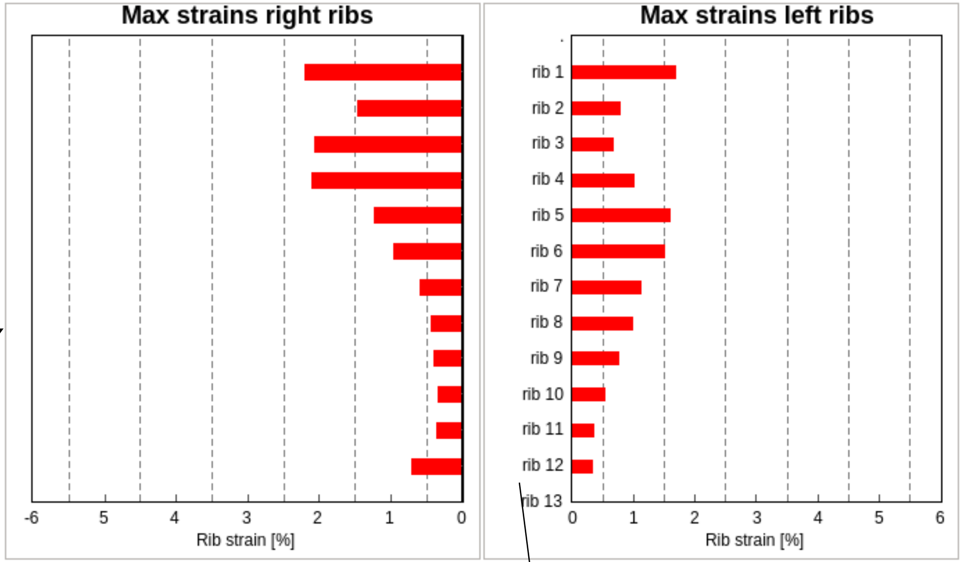
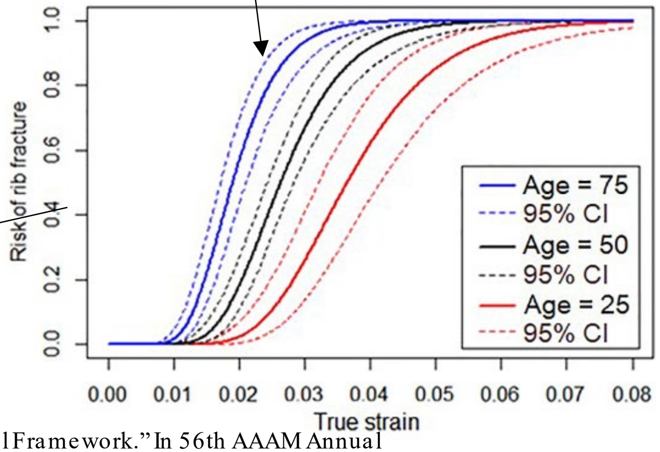
Rib Fracture Risk & Validation Status

Rib fracture risk prediction – probabilistic risk in rib cortical bone

- Risk based on predicted rib cortical bone strain
  - Probabilistic method (Forman et al. 2012)
    - Strain + Age-based risk function based on rib material testing (Larsson et. al 2021)







Binomial probability

$$\Pr(X)=\sum_{i=1}^{\binom{N}{X}}\left(\prod_{j\in C_i} p_j\right)\left(\prod_{k\in \bar{C}_i}(1-p_k)\right)$$

$$P_{\geq}(Y)=1-\sum_{X=1}^{Y-1}\Pr(X)$$

Probability of ≥X Fractures in the Rib cage (NFR X+)

Forman et al. (2012). "Predicting Rib Fracture Risk with Whole-Body Finite Element Models: Development and Preliminary Evaluation of a Probabilistic Analytical Framework." In 56th AAAM Annual Conference. Annals of Advances in Automotive Medicine., 56:109–24

Larsson et al. (2021). "Rib cortical bone fracture risk as a function of age and rib strain: Updated injury prediction using finite element human body models". Frontiers 9, 677768.

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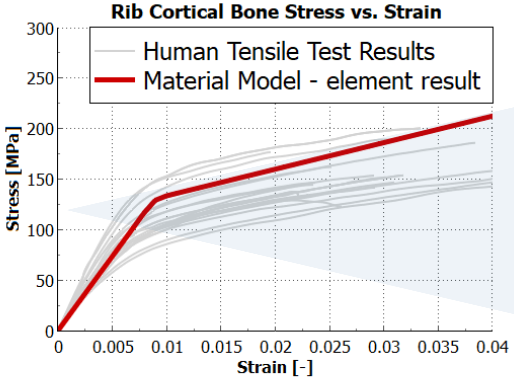
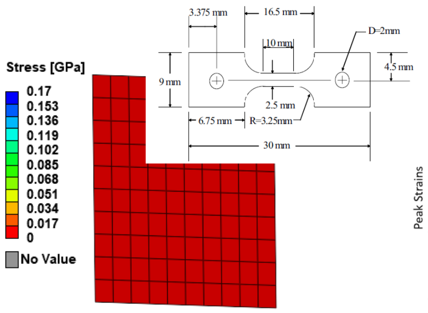
Validation of rib models and rib strain

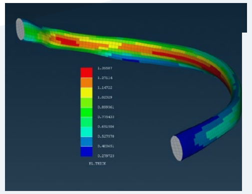
- Strain-based risk predictions requires validated strain predictions
  - Bottom-up validation of strain predictions in rib cage. * = Iraeus et al. 2019

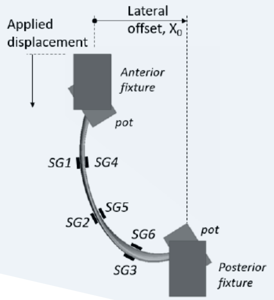
Material models
-Element Stress and strain

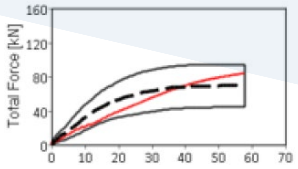


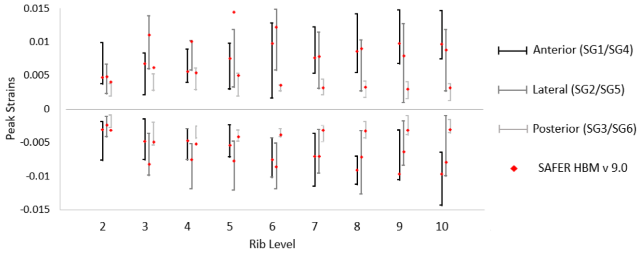


Single rib models*
-Shape, bone thickness
-Force-deflection
-Rib Strain

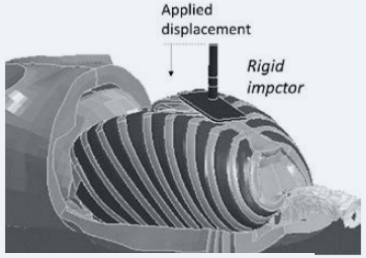


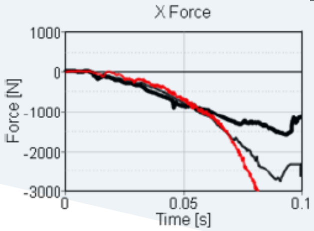


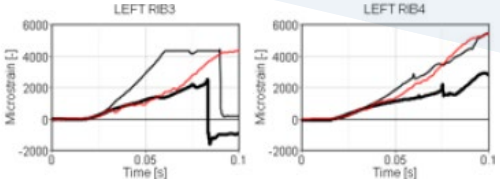




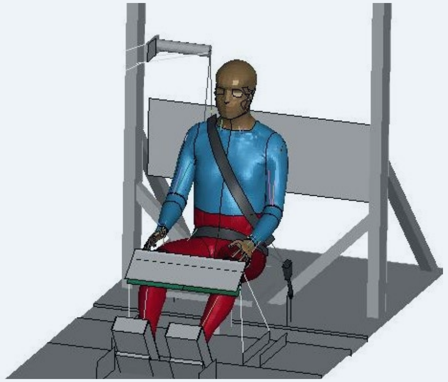
Thorax model*
-Force, rib deflection
-Rib Strains

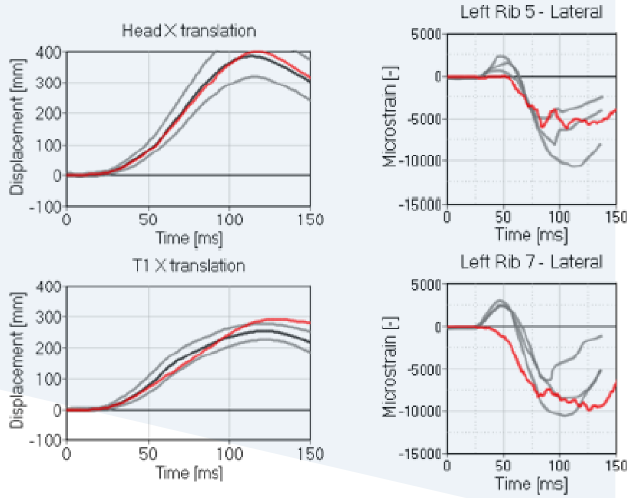






HBM model*
-Body kinematics
-Belt forces
-Rib strains





Iraeus et al.(2019). "Development and Validation of a Generic Finite Element Ribcage to Be Used for Strain-Based Fracture Prediction." In *Proceedings of IRCOBI Conference,* Italy

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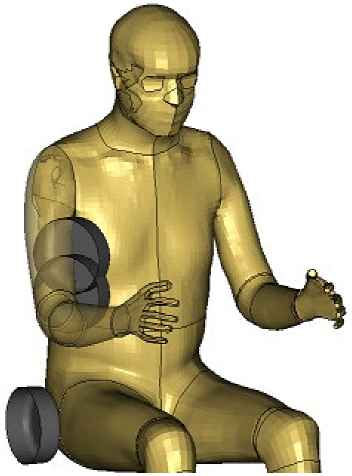
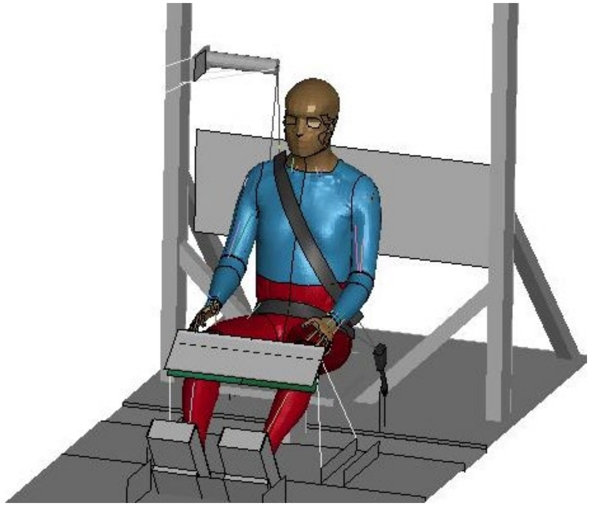
Validation of rib fracture risk predictions – PMHS tests



- Oblique hub impact (Viano 1989)

	PMHS (Males)		SAFER HBM
Speed	NFR	NFR 2+ [%]	Risk NFR2+ [%]
4.4 m/s	0-2	25%	11%
6.5 m/s	3-6	100%	97%



- 40 km/h Frontal Impact (Shaw et al. 2009)

PMHS (Males)		SAFER HBM
NFR	NFR 2+ [%]	Risk NFR2+ [%]
2-14	100%	97%

Viano, David C.(1989). "Biomechanical responses and injuries in blunt lateral impact." SAE transactions (1989): 1690-1719

Shaw et al. (2009). "Impact response of restrained PMHS in frontal sled tests: skeletal deformation patterns under seat belt loading." Stapp Car Crash J. 2009 Nov;53:1-48

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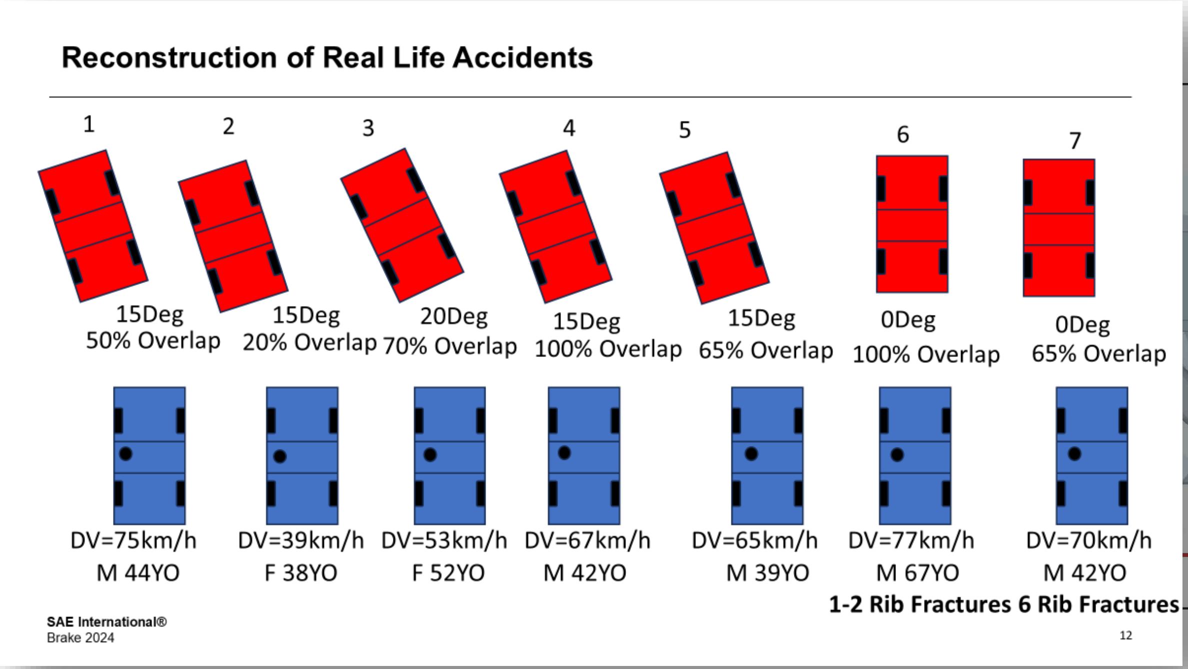
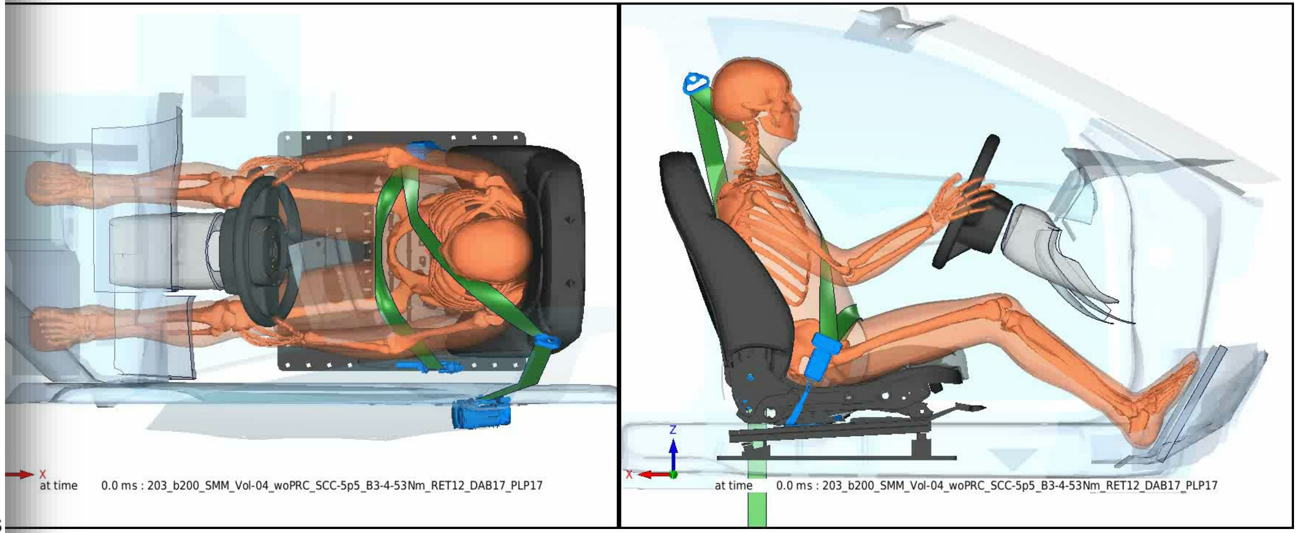
Validation of rib fracture risk predictions – Accident reconstructions

- Seven crashes reconstructed with 50th-M SAFER HBM (Pipkorn 2025)
  - Rib fractures in two cases
  - Generic vehicle sled, recorded crash pulses
  - Production models of seat, airbag and seatbelt





Pipkorn, B. (2025). "Insights Into Real World Chest Injury Causation in Frontal Crashes Using Human Population Models", Government/Industry Meeting, Washington, DC

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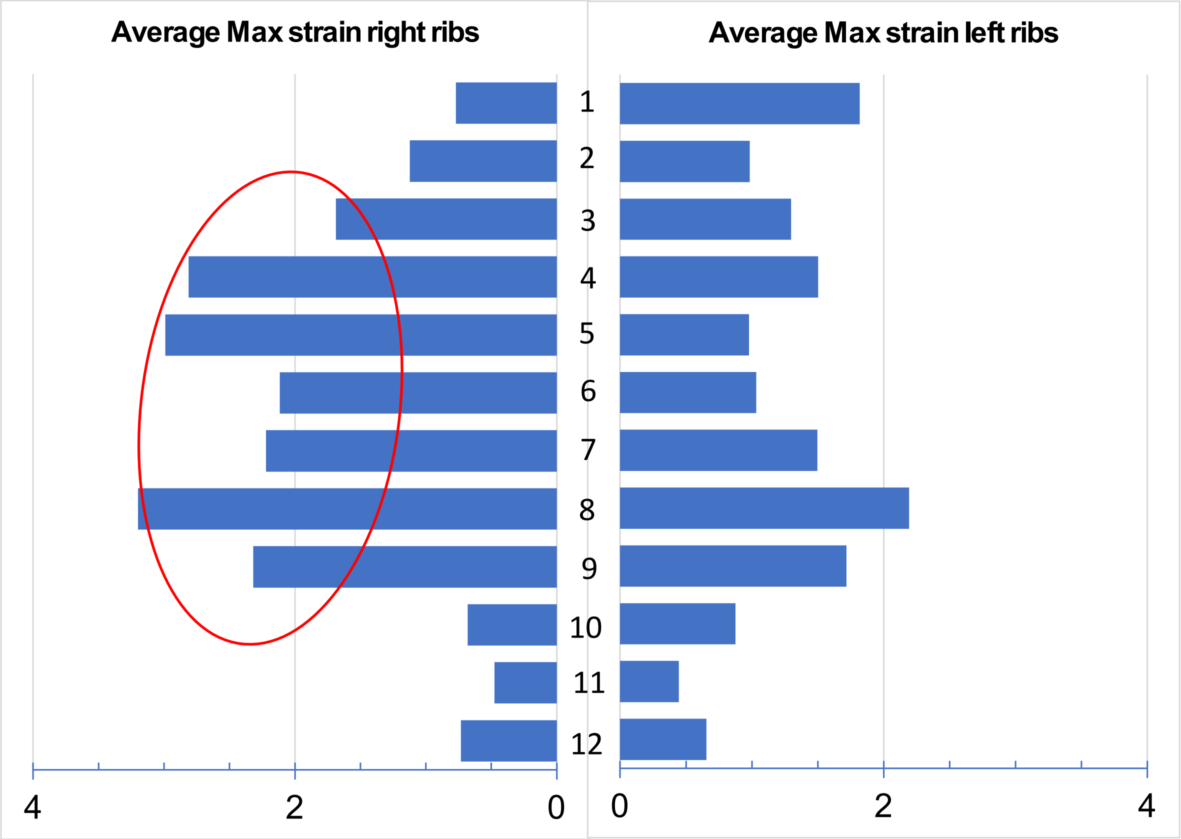
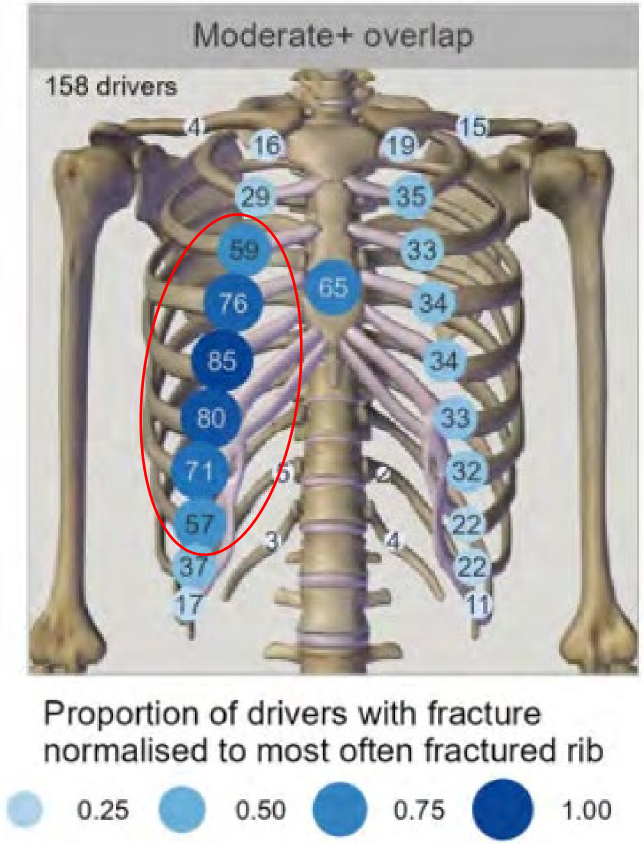
Validation of rib fracture risk predictions – Accident reconstructions

- Average rib strain results reconstructed crashes



Field Fractures (Brumbelow 2024)

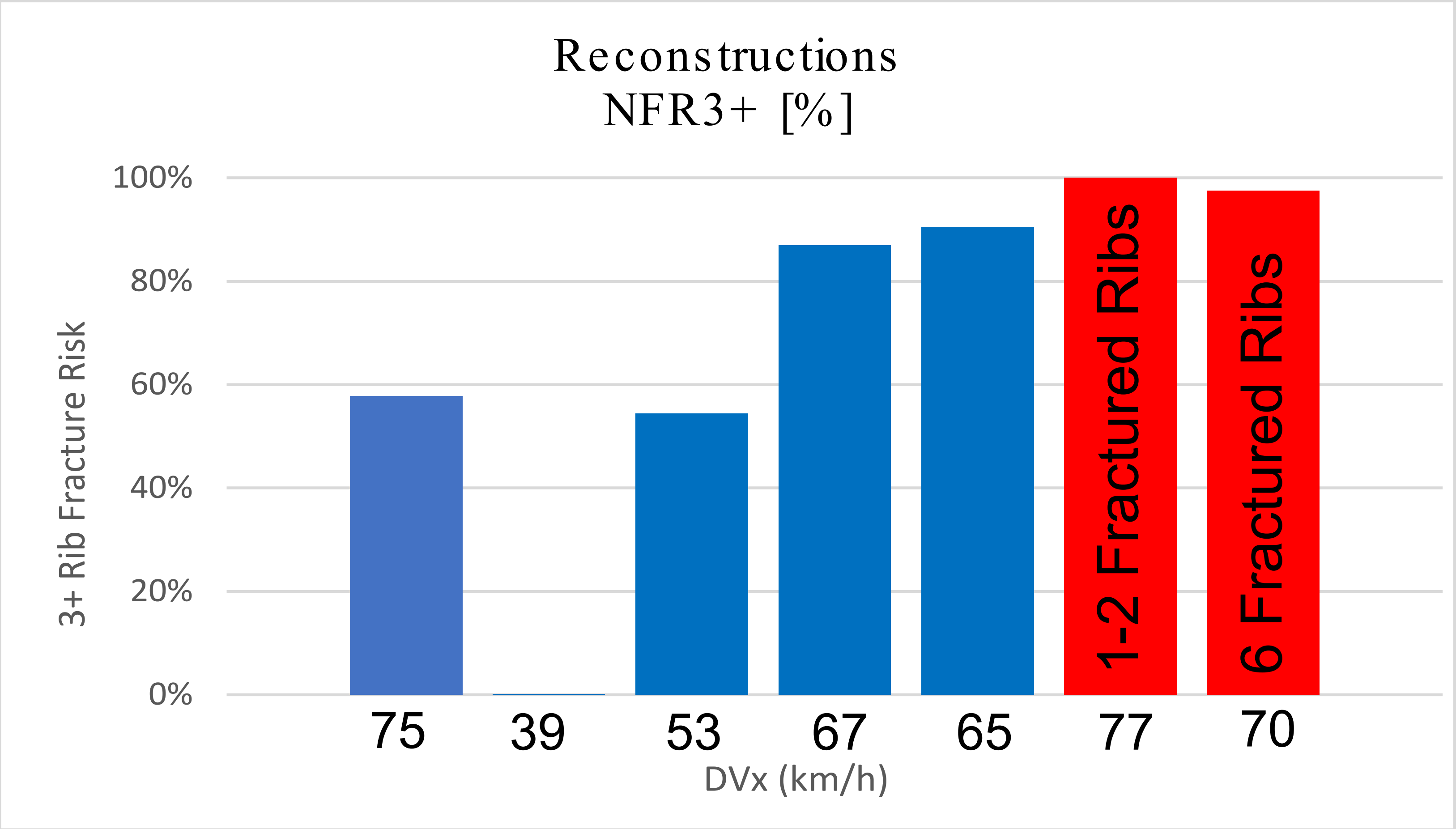


Pipkorn, B. (2025). "Insights Into Real World Chest Injury Causation in Frontal Crashes Using Human Population Models", Government/Industry Meeting, Washington, DC

Brumbelow, M. (2024). "Identifying Thoracic Injury Factors by Comparing Rib Fracture Patterns in Field Crashes and PMHS Tests", IRCOBI Conference Proceedings, Stockholm

Validation of rib fracture risk predictions – Accident reconstructions

- Rib fracture risk predictions
  - Overall, high risk levels predicted
    - Highest in fracture cases



Pipkorn, B. (2025). "Insights Into Real World Chest Injury Causation in Frontal Crashes Using Human Population Models", Government/Industry Meeting, Washington, DC

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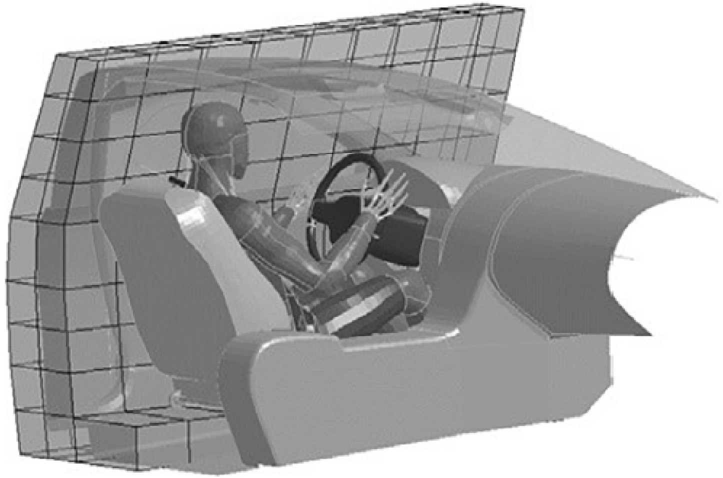
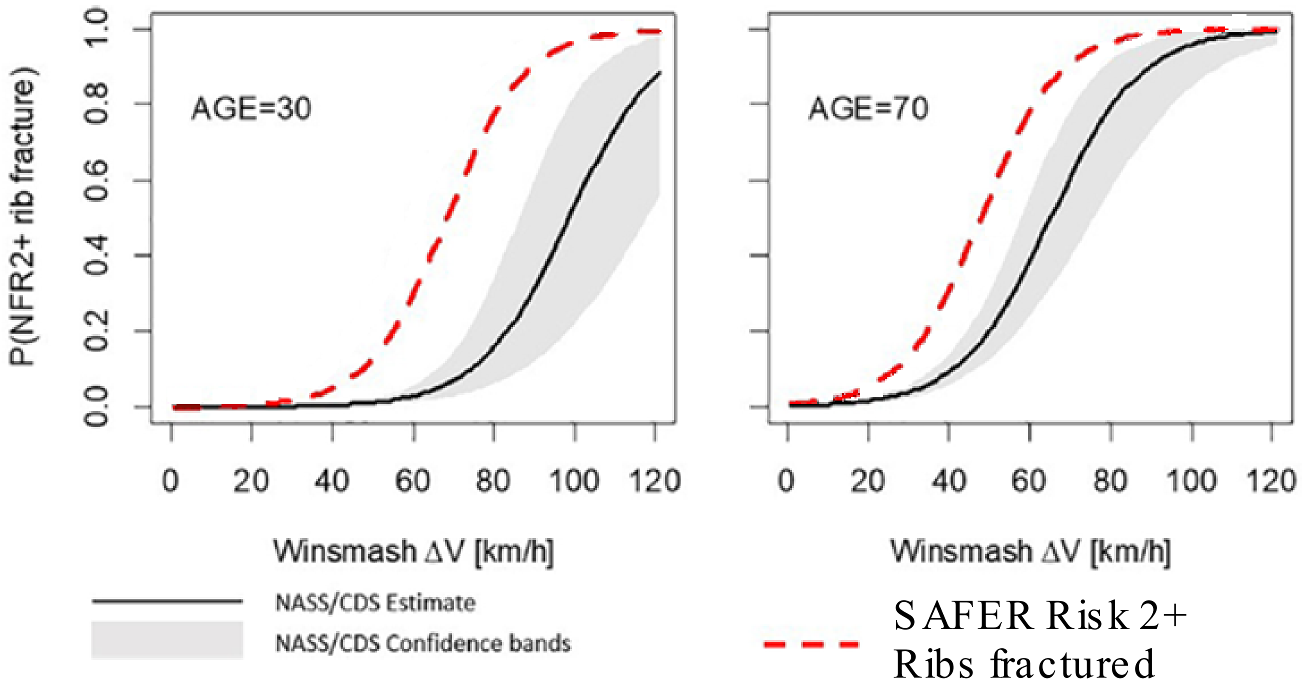
Validation of rib fracture risk predictions – Stochastic crashes

- 1000 simulations in parametric vehicle model (Larsson et al. 2021)
  - Variations of:
    - DV (from NASS/CDS)
    - Restraint system settings
    - Interior geometry



- HBM Risk vs. Delta-V compared to Field data estimate
  - Overall, high risk predictions for each crash speed



Larsson et al. (2021). "Rib cortical bone fracture risk as a function of age and rib strain: Updated injury prediction using finite element human body models". Frontiers 9, 677768.

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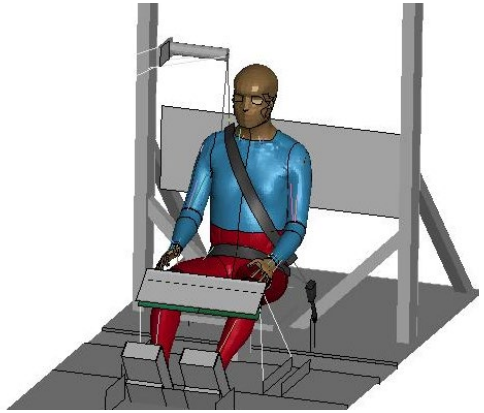
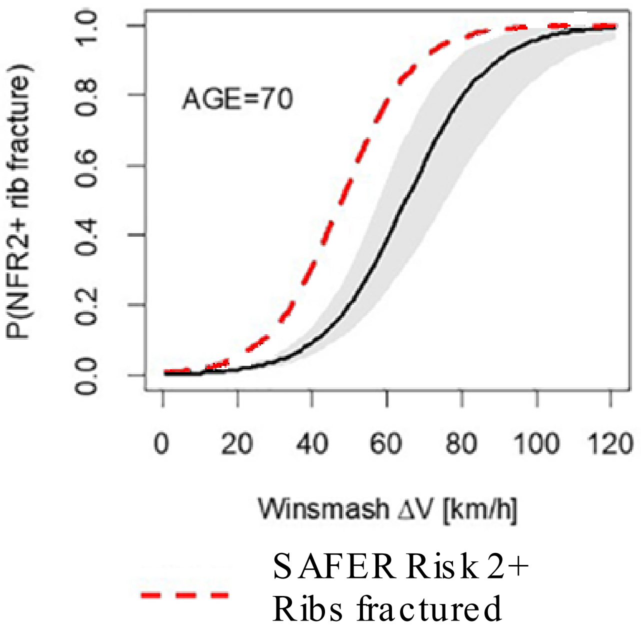
Validation of rib fracture risk predictions – Summary & Limitations

- Validations Summary:
- Generally inline with PMHS test fractures
  - Tendency to low risk
    - E.g. 97% risk of 2+, while subjects have 2-14 fractured ribs
- Compared to real-life occupants (reconstructions, field data)
  - Tendency towards high risks levels



PMHS (Males)		SAFER HBM
NFR	NFR 2+ [%]	Risk NFR2+ [%]
2-14	100%	97%



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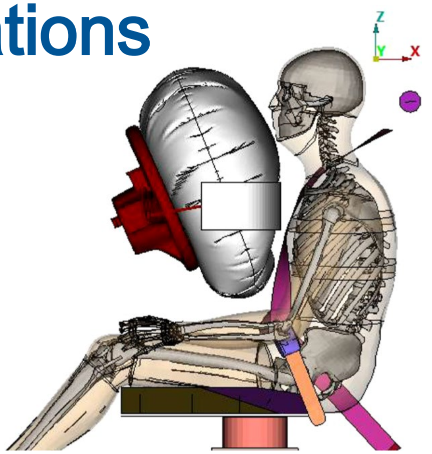
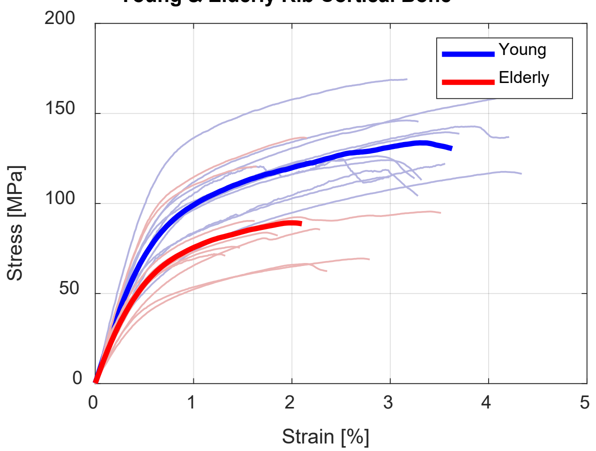
Validation of rib fracture risk predictions – Summary & Limitations



- Risk prediction limitations:
- Elderly PMHS rib fractures
  - Generally, around 65-70+ Years, PMHS rib fractures can increase a lot
  - HBM risk predictions generally low for elderly and fragile PMHS with many fractures
- Ageing is correlated with reduced rib material and structural properties
  - Nominal HBM does not model "aged" properties
  - Fracture risk function only considers age effect on failure strains
- "Elderly" HBMs can represent also reduced properties



- 35 km/h Frontal impact (Lopez-Valdez et al. 2018)
  - 3 Male PMHS. Ages 68-93 Years

PMHS		SAFER HBM
NFR	NFR 2+ [%]	Risk NFR2+ [%]
10-13	100%	19%

Lopez-Valdes, Francisco J. et al. (2018). "Chest Injuries of Elderly Postmortem Human Surrogates (PMHSs) under Seat Belt and Airbag Loading in Frontal Sled Impacts: Comparison to Matching THOR Tests." Traffic Injury Prevention 19 (sup2): S55–63.

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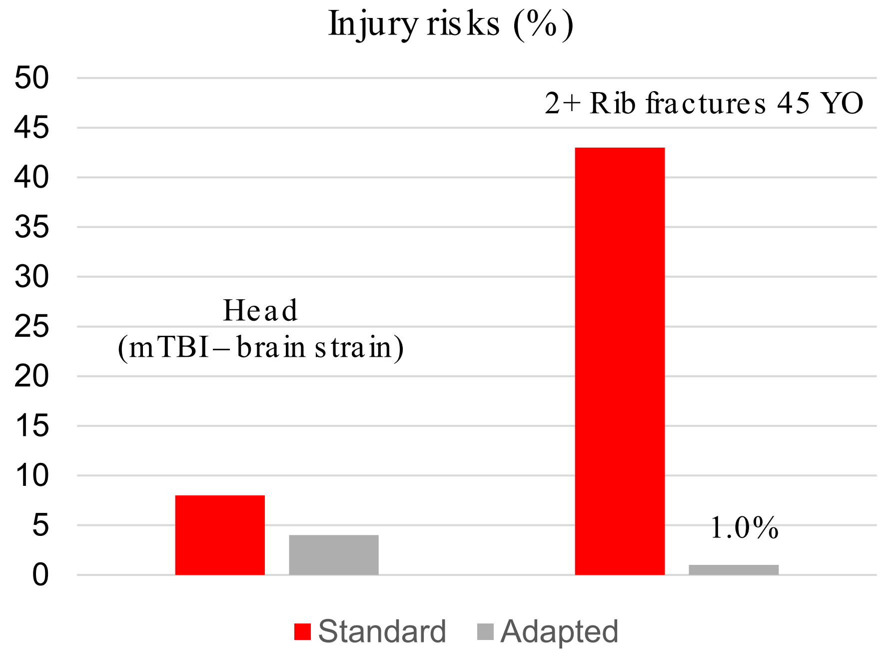
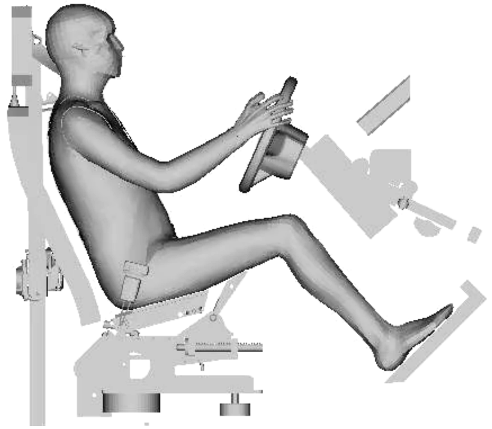
Challenges with risk predictions

What does the HBM risk prediction mean?

- Example: Low-speed adapted restraint system
  - Low-severity frontal crash (30km/h), generic environment
- An adapted system results in a 1% rib fracture risk
- Do I trust the 1% risk? – Yes
  - i.e., I would expect *similar* outcomes from PMHS testing
- Will all humans have this low risk? - No





Standard Restraints
Adapted Restraints

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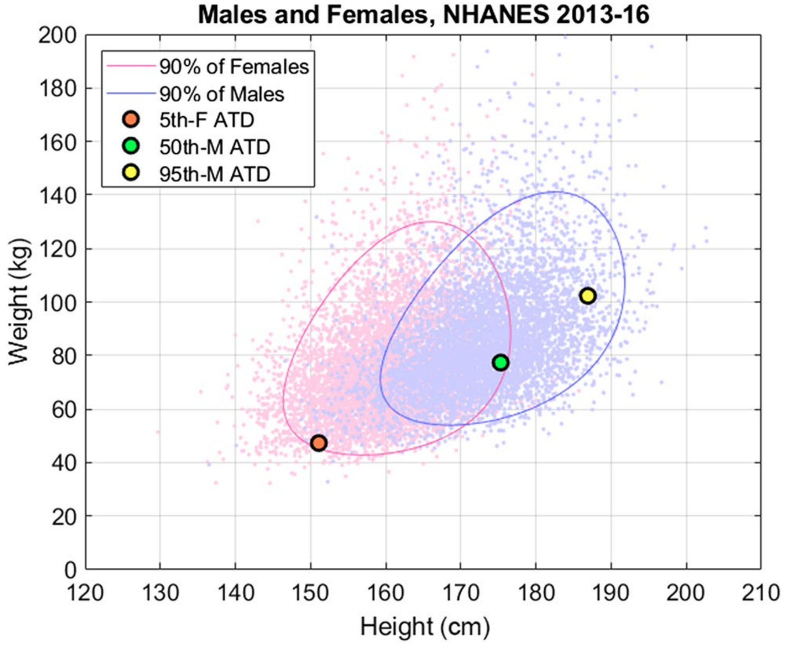
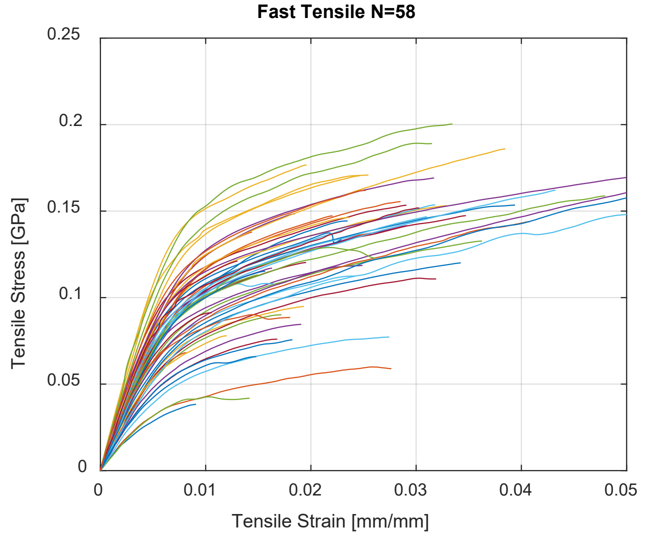
What are the challenges?

- Humans vary a lot
  - In "global" properties
    - Sex, Size, Age
  - Humans of the same sex, size and age still vary a lot in "local" properties important for rib fracture risk
    - Bone dimensions, thickness, material properties (Larsson et al. 2023)
  - → We should expect a range of injury outcomes in any particular crash
    - Just like we can have 2-14 fractured ribs in the same PMHS test
- The "1%-risk" system was obtained for the 50th- Male SAFER HBM
  - SAFER HBM is only ONE instance of possible humans to model
    - Average male size (50th-ATD size), average ribs, average materials…
  - THUMS, GHBMC, HANS 50th-M HBMs represent other individuals
    - Will likely predict some slightly different risk numbers…
- **#Challenge – An HBM models an Individual – need to understand what the risk prediction means for real-life outcomes.**





Larsson, Karl-Johan et al. (2023). "Influences of Human Thorax Variability on Population Rib Fracture Risk Prediction Using Human Body Models." Frontiers in Bioengineering and Biotechnology 11

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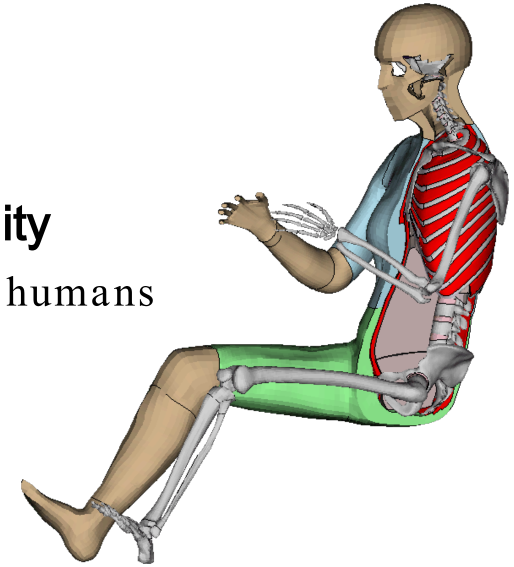
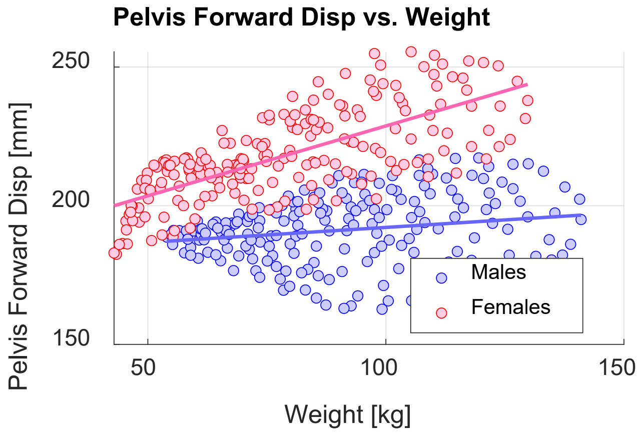
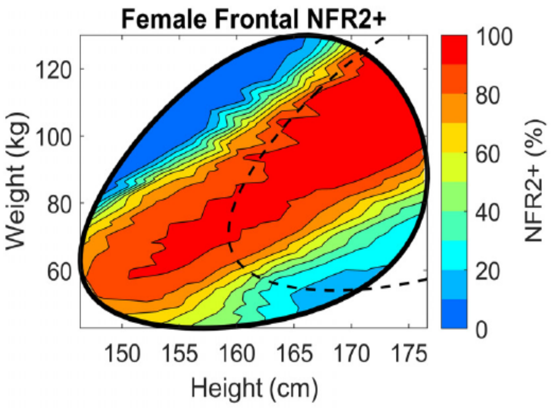
What are the challenges?

- **#Challenge: Occupant safety assessments that considers human and crash variability**
  - The potential of HBMs lies in the capability to represent the outcomes of the many different humans involved in many different crash scenarios
  - Example:
    - One crash: 400 SAFER HBMs of different sizes (Larsson et al. 2024)
    - Pelvis forward excursion and rib fracture risk varies a lot!







- However, current discussions around implementing HBMs in ratings focuses on ATD-sizes and streamlining different HBMs into predicting similar risks
  - We should not get stuck in trying to use HBMs as ATDs
  - Long term focus should be on enabling safety assessments for real-life crashes

Larsson, Karl-Johan et al. (2024). "A First Step Toward a Family of Morphed Human Body Models Enabling Prediction of Population Injury Outcomes." Journal of Biomechanical Engineering 146 (3)

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What to do?

- **Create safety evaluations that utilize the potential of HBMs to improve real-life safety**
  - Go beyond ATD sizes and test conditions
  - Consider crash and human variability: DV's & PDOFs, size distributions, injury tolerances
- **Methods to perform – and data to validate – real-life safety HBM predictions**
  - Leverage Machine Learning and AI to make it computationally feasible
  - PMHS test series, fixed boundary conditions – varied sex, ages, and sizes of PMHS
    - Validate predictions of Height, BMI, and Sex trends

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Saving More Lives