

IRCOBI

pre-conference workshop

**Human Body Models (HBMs) used in standardised virtual testing –
Progress and Visions**



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Session 1: Visions of rating agencies –
how will future assessments using
HBMs look like?

IIHS vision for advancing human surrogates used in safety evaluations

IRCOBI pre-conference workshop
Human Body Models (HBM) for Standardized Virtual Testing –
Progress and Visions

September 9, 2025

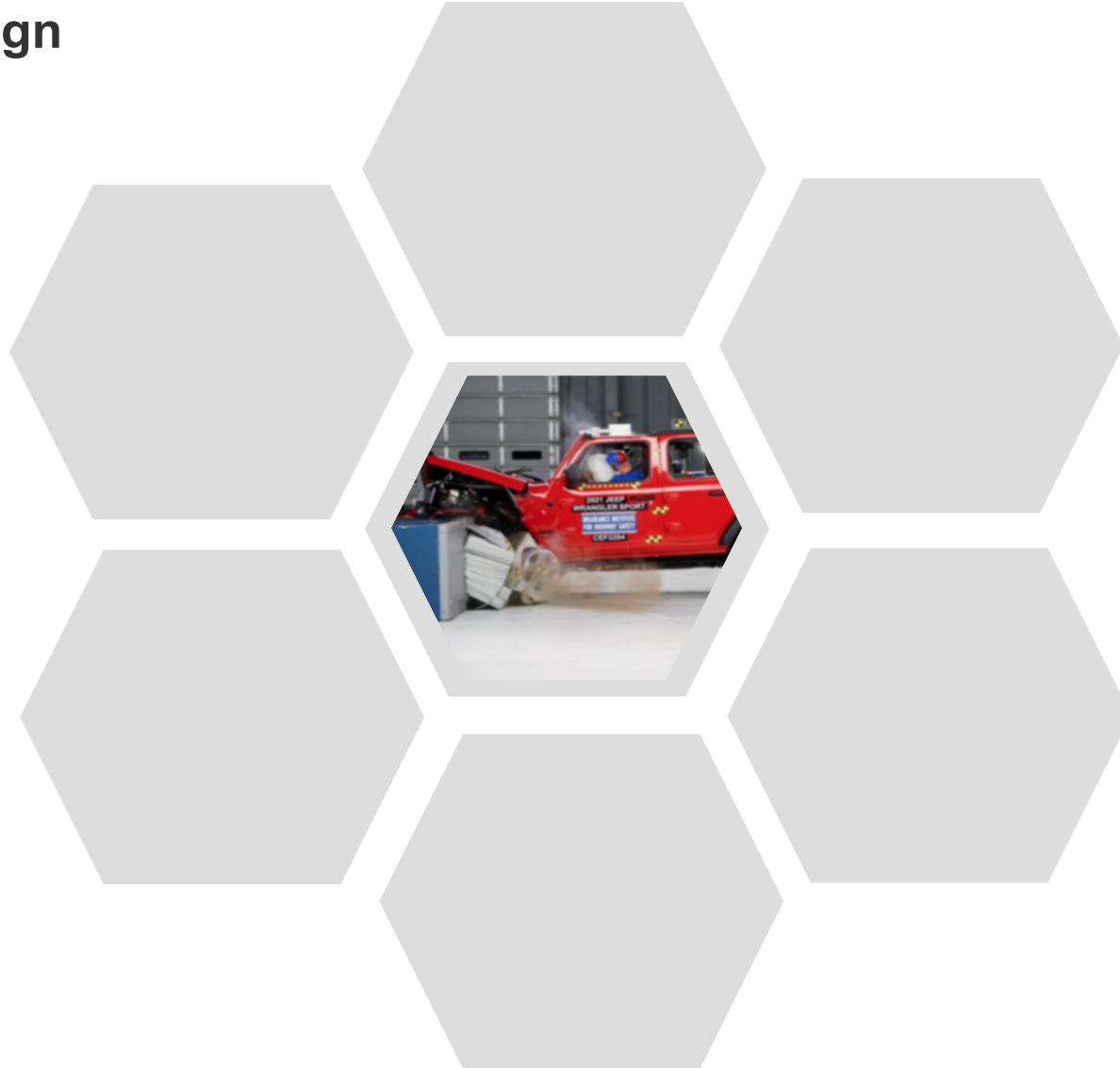


Marcy Edwards
Senior Research Engineer



Virtual testing

building safety design
robustness



Virtual testing

building safety design
robustness



Virtual testing

building safety design
robustness

Injuries



Occupant diversity



Virtual testing

building safety design
robustness

Injuries



Kinematics



Occupant diversity



Virtual testing

building safety design
robustness

Injuries



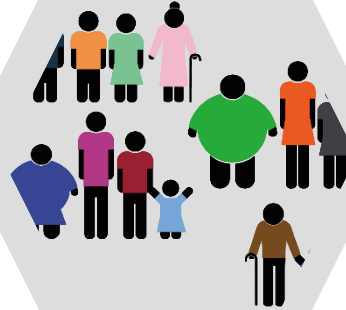
Kinematics



Occupant position



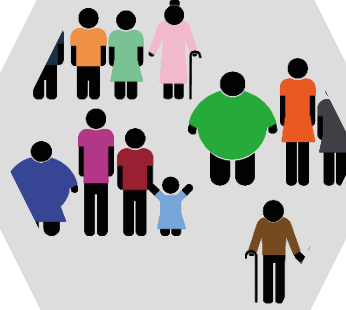
Occupant diversity



Virtual testing

building safety design
robustness

Injuries



Occupant diversity



Kinematics



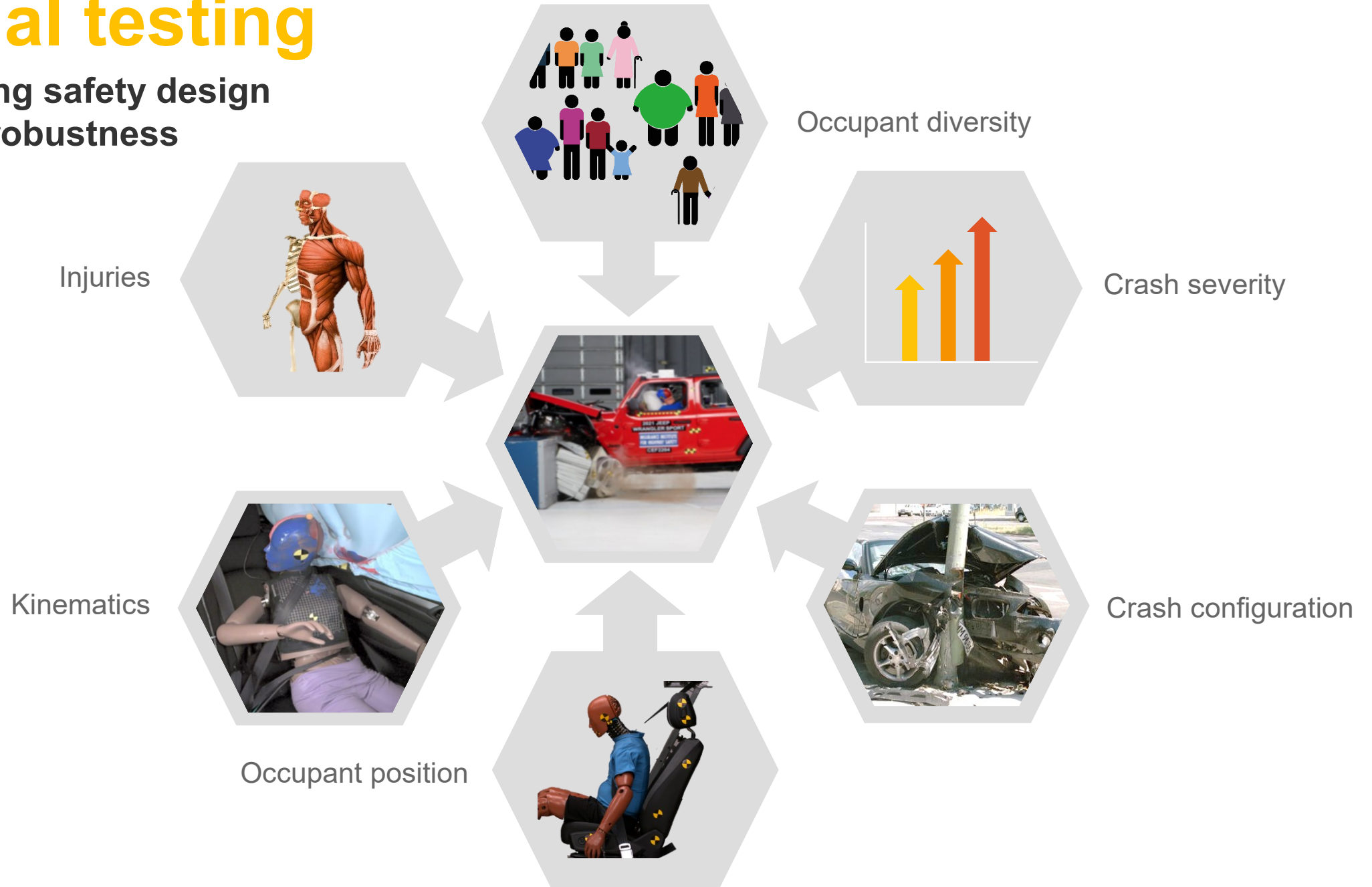
Occupant position



Crash configuration

Virtual testing

building safety design
robustness





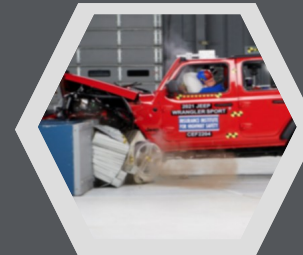
IIHS VT strategy



Implementation of the most basic path (FE ATDs) to test and build expertise and workflow



Development of workflow, tools and model prediction to use HBMs



Explore opportunities for using HBMs to build robustness in existing safety assessments

IIHS activity – building virtual testing



Implementation of the most basic path to test and build expertise and workflow

IIHS activity – building virtual testing



June 2025

Rear impact 2.0 draft test protocol allowing submission of ATD simulation results

December 2025

Rear impact 2.0 rating protocol with auditing procedures to ensure validity of automaker submitted physical or simulation results

February 2027

Rear impact 2.0 (with simulation option) included in IIHS Top Safety pick awards

IIHS activity – building virtual testing



Development of workflow, tools and model prediction to use HBMs

IHS activity – building virtual testing



Parametric study on seat design to identify important test scenarios for rear impact (occupant size, position etc.)

Tools and workflow for ensuring data and model traceability

Developing work to understand the process and scope for vehicle, ATD and HBM model validations

Male/female injury risk research to understand types of injuries HBMs need to predict

Identify where HBMs in safety assessments will provide significant real-world impact beyond physical tests

IIHS activity – building virtual testing



Explore opportunities for using HBMs to build robustness in existing safety assessments

IIHS activity – building virtual testing

Under consideration



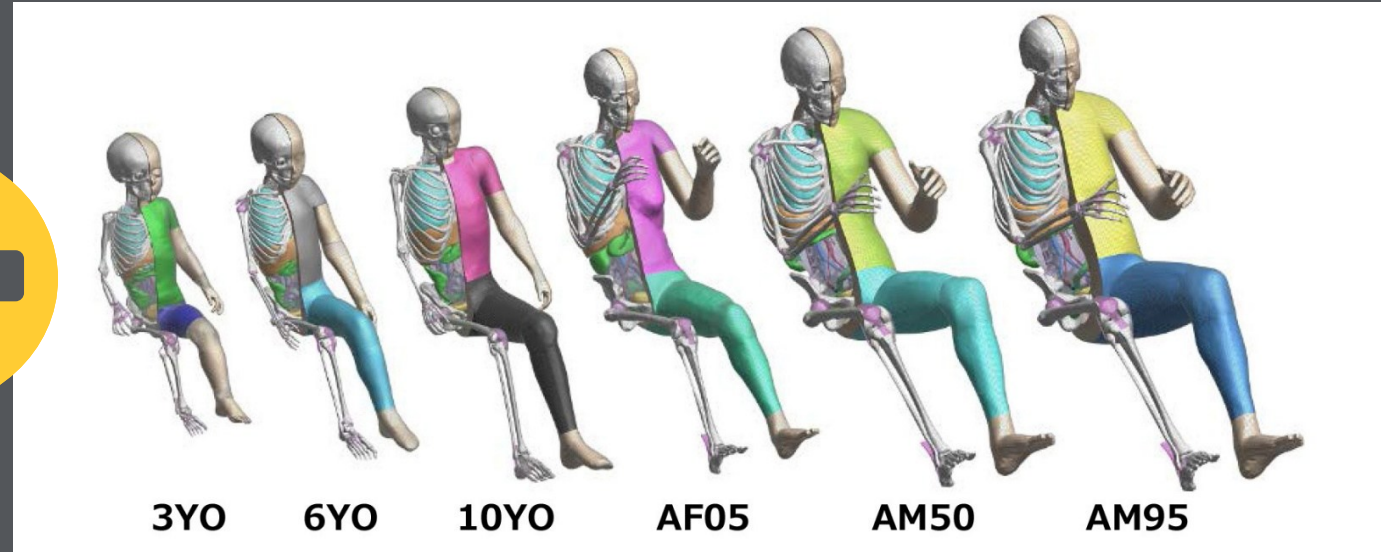
Rear impact



Front and rear
occupants in
frontal crashes



IIHS move toward HBMs



Use HBMs to complement to existing ATD safety assessments and encourage safety design robustness with information about kinematics, injuries, sex and anthropometry that ATDs can't provide

VT framework development

Building trust in simulation



VT building blocks to reach safety robustness

VT framework development

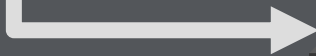
Building trust in simulation



Injury prediction

What are meaningful injuries that HBMs can predict?

What can HBMs tell us that ATDs cannot?



VT building blocks to reach safety robustness

VT framework development

Building trust in simulation



Trust in simulation

Injury prediction

What is appropriate validation for models?

How do we define the scope for validations?

VT building blocks to reach safety robustness

VT framework development

Building trust in simulation



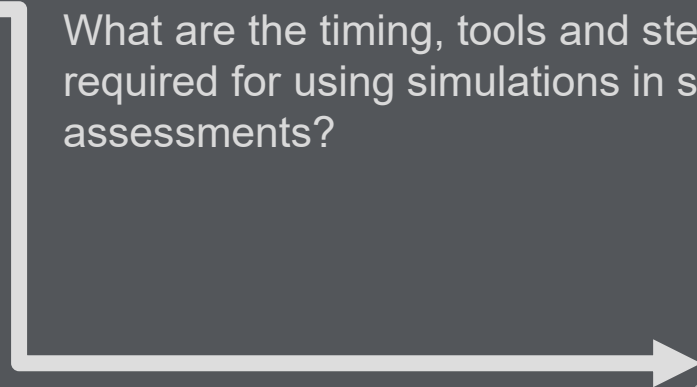
Workflow

Trust in simulation

Injury prediction

Who is running simulations?

What are the timing, tools and steps required for using simulations in safety assessments?



VT building blocks to reach safety robustness

VT framework development

Building trust in simulation



Trust in data

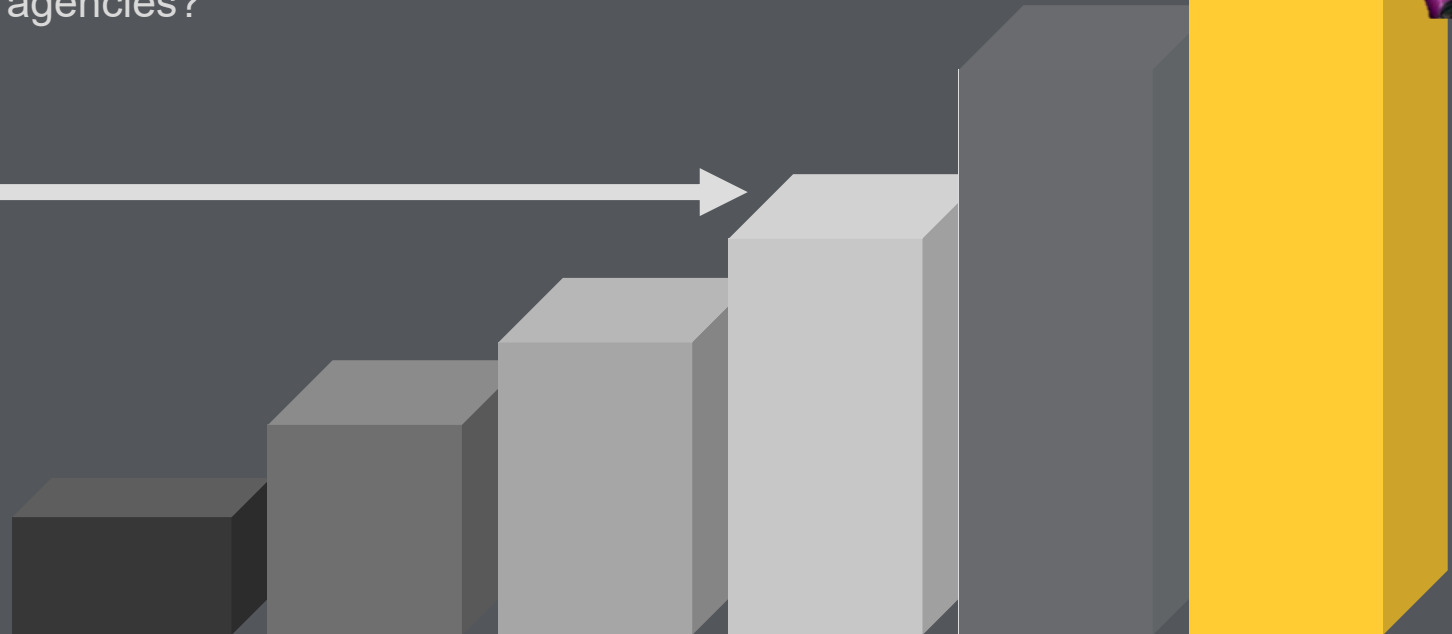
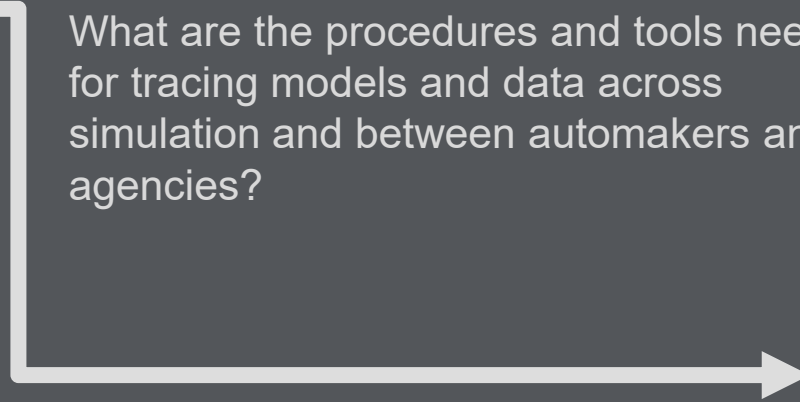
Workflow

Trust in simulation

Injury prediction

What level of confidence do we need?

What are the procedures and tools needed for tracing models and data across simulation and between automakers and agencies?



VT building blocks to reach safety robustness

VT framework development

Building trust in simulation

Information sharing

Trust in data

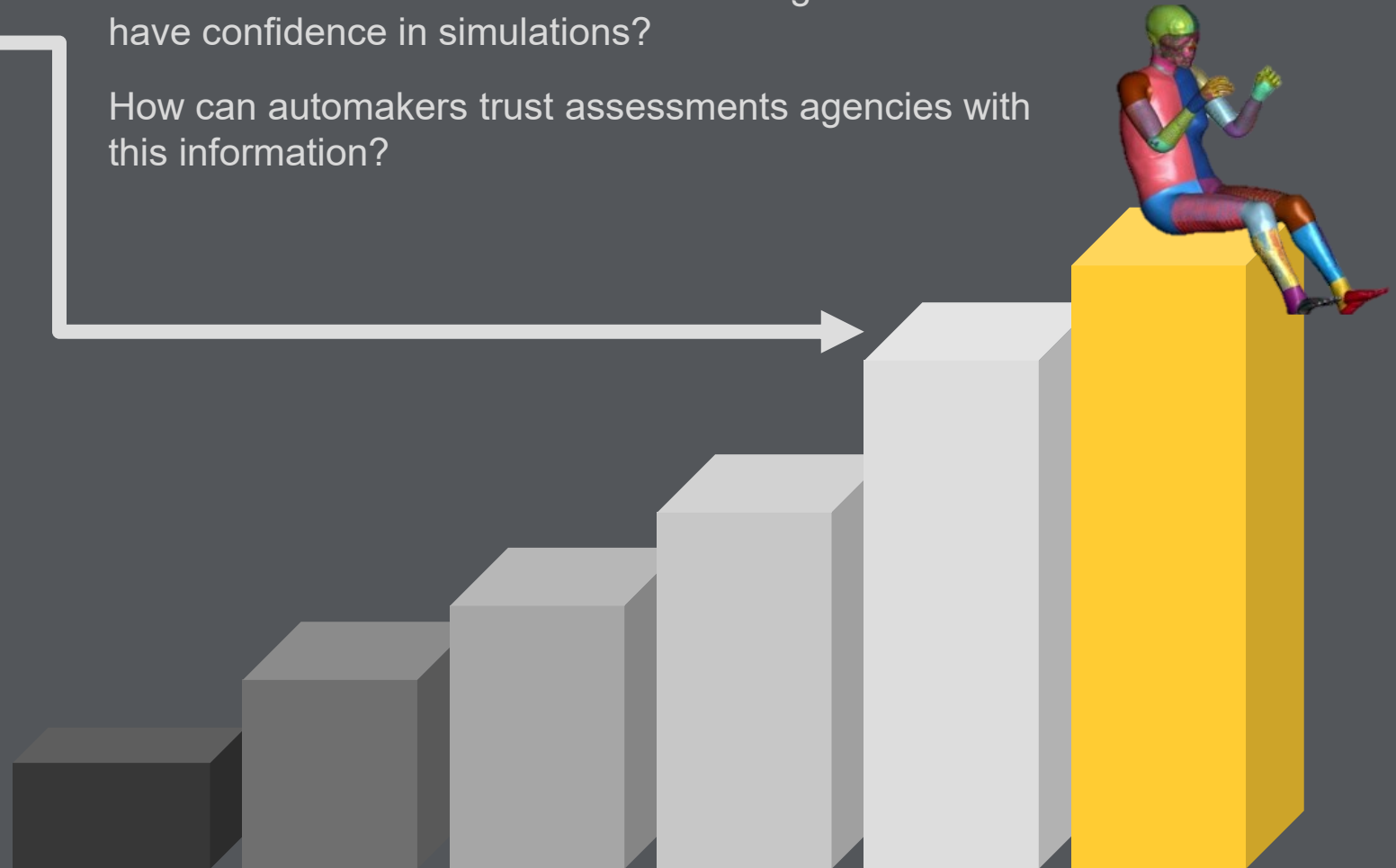
Workflow

Trust in simulation

Injury prediction

How much information do assessment agencies need to have confidence in simulations?

How can automakers trust assessments agencies with this information?



VT building blocks to reach safety robustness

VT framework development

Building trust in simulation

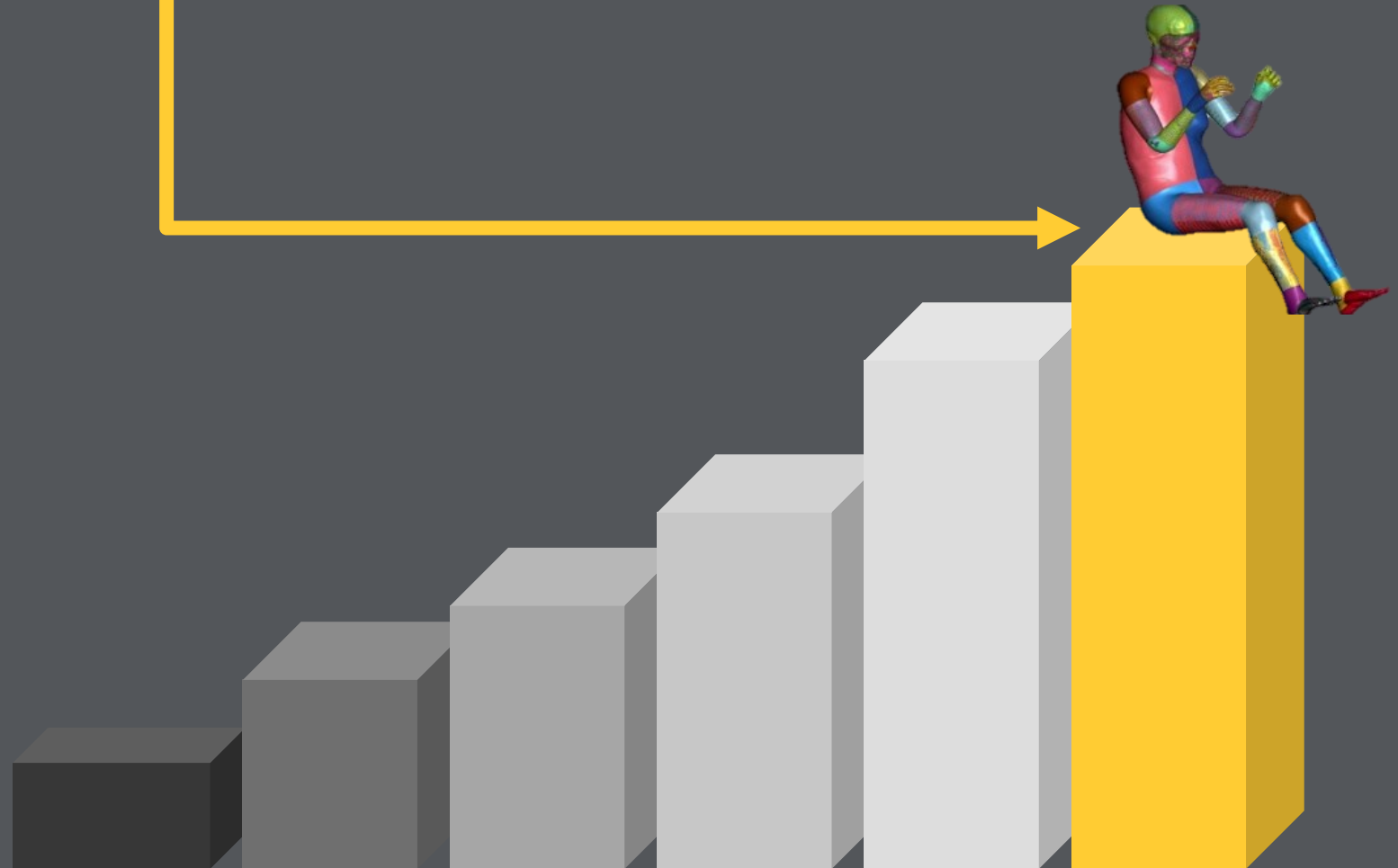
Information sharing

Trust in data

Workflow

Trust in simulation

Injury prediction



VT building blocks to reach safety robustness

How do we get on the same page

- ▶ Collaborating and building communication with other NCAPS, industry and academia
- ▶ Working with solver developers to address industry feedback
- ▶ Initiating virtual testing programs to build expertise
- ▶ Designing initial VT programs with reasonable expectations of automakers
- ▶ Working with FE model developers and physical human surrogate developers to develop the appropriate validation tools

Insurance Institute for Highway Safety
Highway Loss Data Institute

iihs.org



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IIHS



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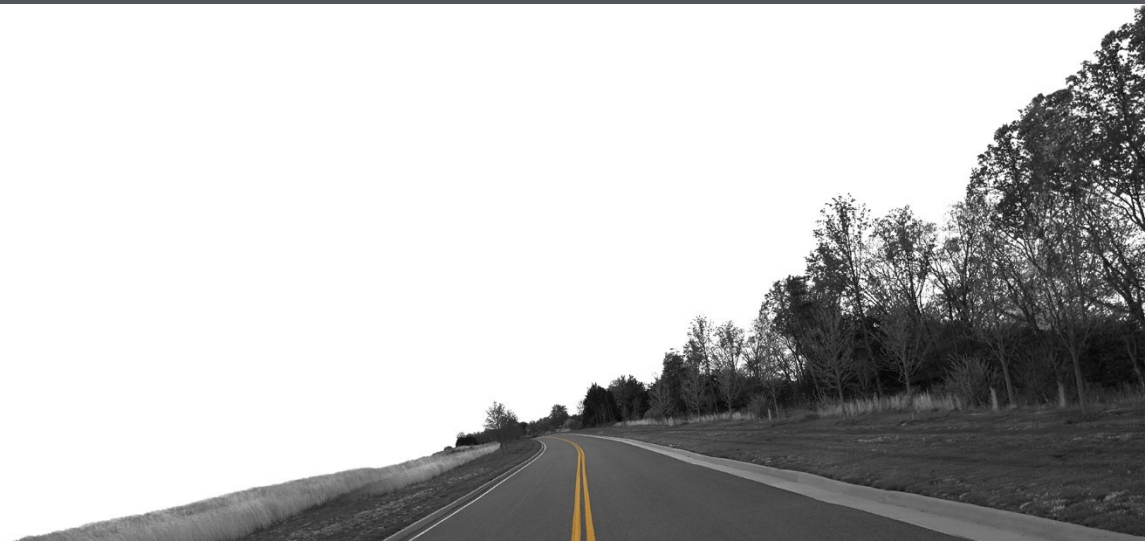


@iihs_autosafety

THANK YOU



Marcy Edwards
Senior research engineer
medwards@iihs.org



Industry Perspectives

Aditya Belwadi, Philipp Wernicke and Hiroaki Imai



Advantages

1. Better consideration of diversity
 - population-based morphing
 - overcome hardware limitations
2. Enhanced outputs and biofidelity
 - localised injury outputs
 - Overcome hardware limitations
3. Real-world robustness
 - more Scenarios (oblique, reclined)
 - humanlike postures
 - enhanced interaction with restraint systems

Challenges

1. Tooling / Handling
 - Pre/post-processing
 - Robustness, stability; time-efficiency
 - How to connect ATD and HBM world?
2. Outputs
 - How can the results from different HBM be evaluated fairly?
 - Consistency before/after HBM update
 - Which outputs to use for assessment or internal product development?
3. Harmonisation / Collaboration
 - Growing number of HBMs
 - Growing number of rating agencies using HBMs
 - No established standardization institution (e.g. ISO, SAE, ...)

Session 2: Qualification of Human Body Models – when is a model good enough to be used for virtual testing



Validation vs. Qualification vs. Certification of HBMs - which terms and requirements need to be defined?

Steffen Peldschus

Certification / qualification of an HBM in VT procedure

Validation requirements

Comparability requirements

Further requirements

- Challenge:
 - How close does a validation LC need to match the conditions of the assessment LC (especially for non-testable HBM load cases)?
- 2 Purposes of Comparability LCs:
 - Bridge gap Validation LCs → Application LCs
 - Self-comparison
- Number of Comparability LCs
 - Robustness/sensitivity analysis/assessment needed
 - Re-running a large qualification catalogue for small HBM changes is inefficient
 - Rather 4 than 20 comparability LCs
 - Extra need in case of use of Injury Risk Functions

Anthropometry prescription in validation ?

- In first stages of VT, different views on benefits
 - Focus on single application LC: Benefit of same/comparable results between HBMs
 - Focus on Robustness evaluation of protection system: equal validation quality of different HBMs sufficient
- Future VT:
 - Different needs when population protection is addressed
- Some problems may already deserve particular attention in early stages:
 - Spine curvature prescription in Validation LCs, then
 - what does a validation result mean for application LCs ?
 - how to ensure realistic spine curvature in different seat environments ?
 - Pelvis angle...
- Appreciate human diversity, remove sources of user errors (e.g. CoG head definition...)

- **Acceptance criteria**

- How to define acceptable level of “cosmetic errors”?
- What performance/score to reach with HBM? Not average of HBMs, not current lowest performance. How to be tightened in the future?

- **Tool Agnostic Approaches**

- No prescription of tools, rather methods

- **Harmonisation of Validation Protocols**

- Not unnecessarily diversify validation protocols around the globe (validation needs should not be too different)
→ As in today’s workshop: Efforts on harmonization of basic validation methodology, load cases and criteria



Contact Details

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Qualification of HBMs for Euro NCAP

Current status of CP550 and outlook



Speaker: Felix Ressi

Graz University of Technology, Austria

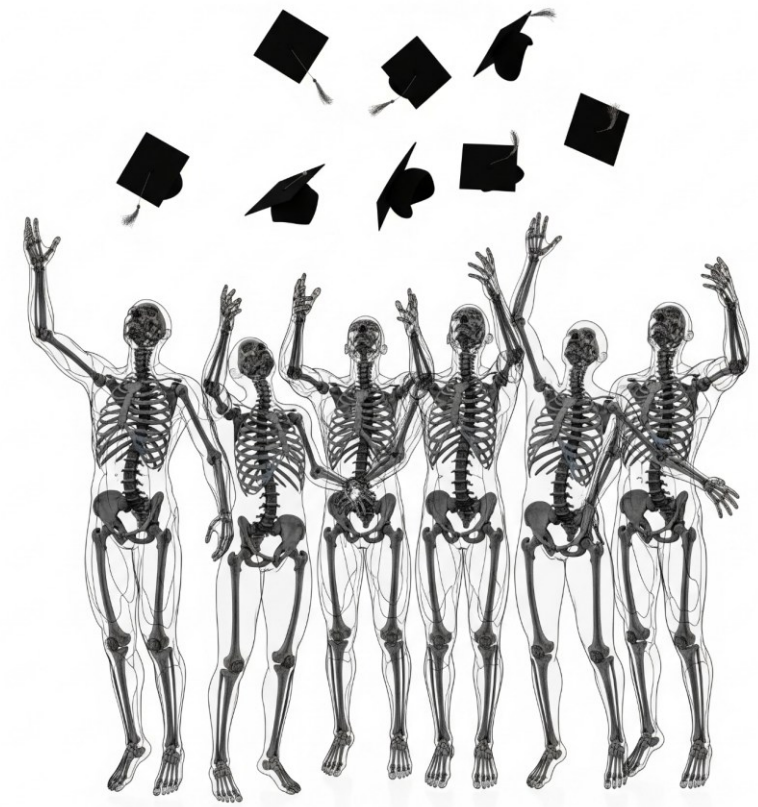


Image generated by Google Gemini

Background

- Need for standardised qualification was determined within HBM4VT
 - HBM-neutral validation setups (far-side and frontal)
 - Harmonised post-processing and biofidelity scoring
 - First implementation: Euro NCAP (frontal impact)
- Setups are **not** designed for **model tuning**, but to check whether an HBM is suitable for virtual testing or not.
- Hence, the setups were not designed for perfect replication, but to provide consistent results (reproducibility) and enable hashing in the future.

HBM4VT Validation Catalogue

- HBM4VT validation setups are publically available at openvt.eu:
<https://openvt.eu/EuroNCAP/hbm4vt-validation-catalogue>

EuroNCAP / HBM4VT Validation Catalogue

H

HBM4VT Validation Catalogue

New subgroup

New project

Subgroups and projects

Shared projects

Shared groups

Inactive

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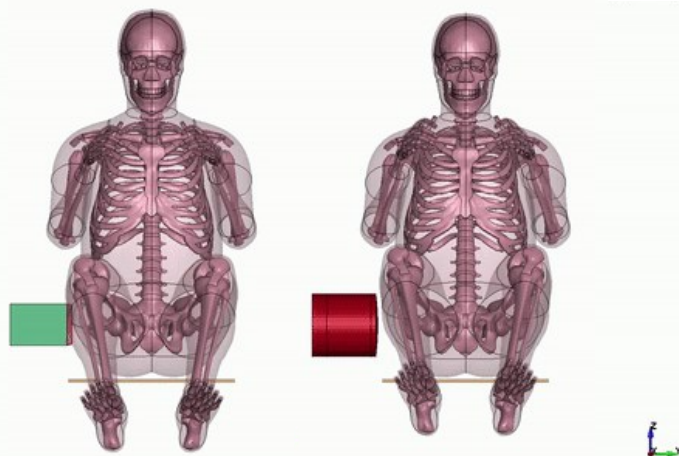
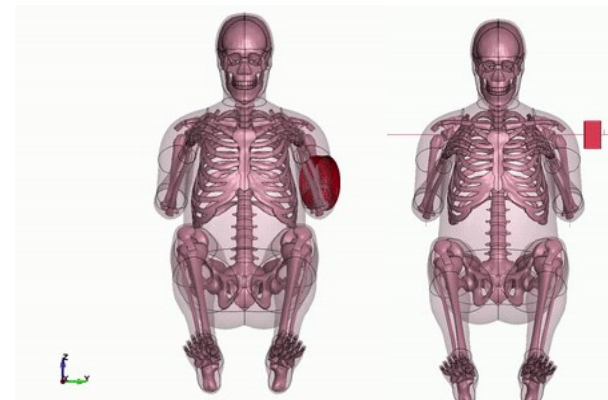
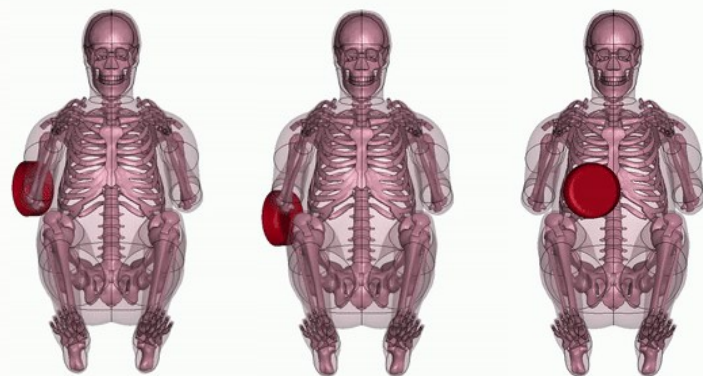
General Instructions

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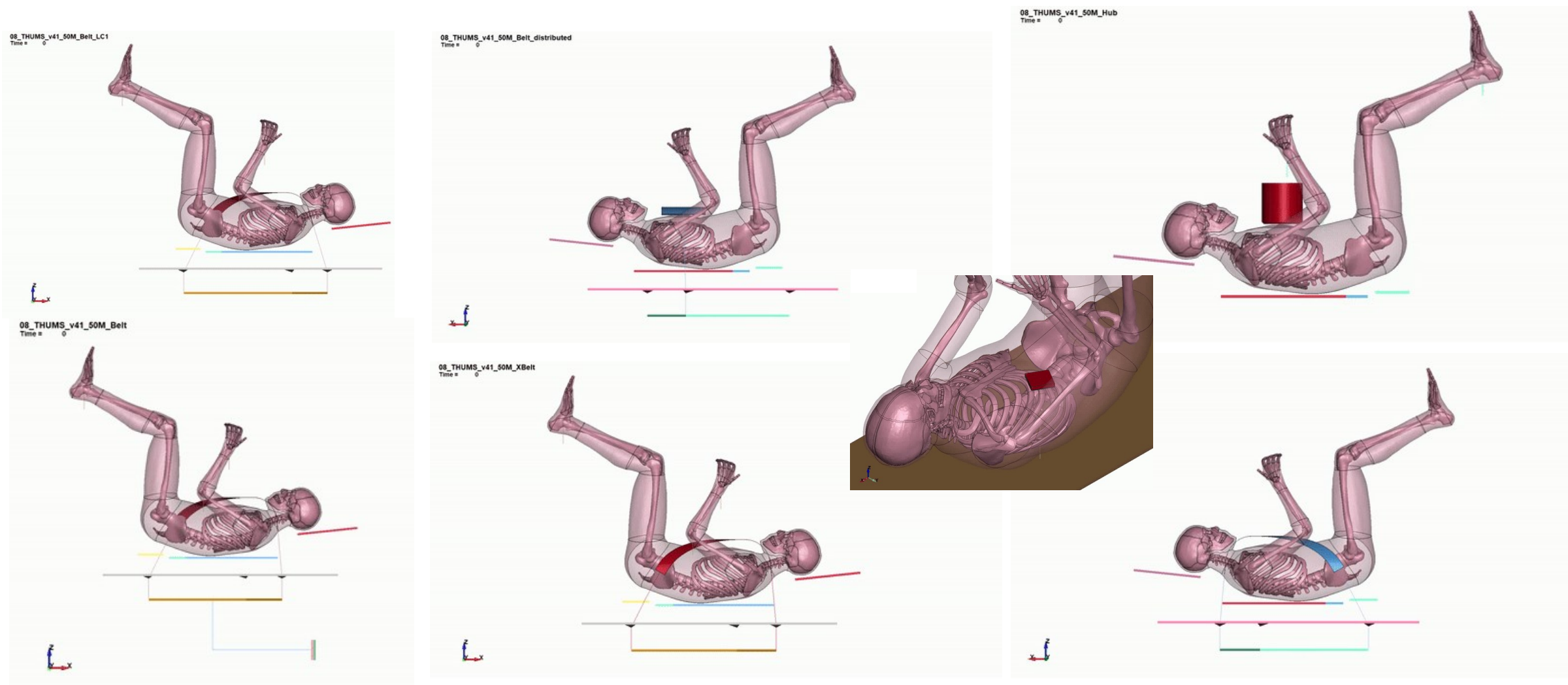
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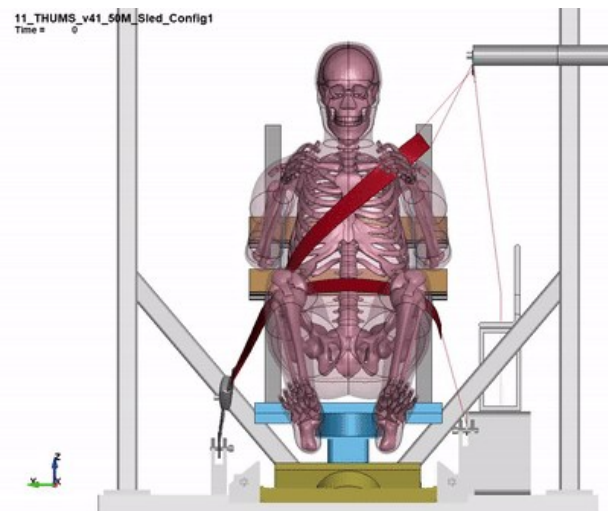
Setup overview: Impactor setup animations



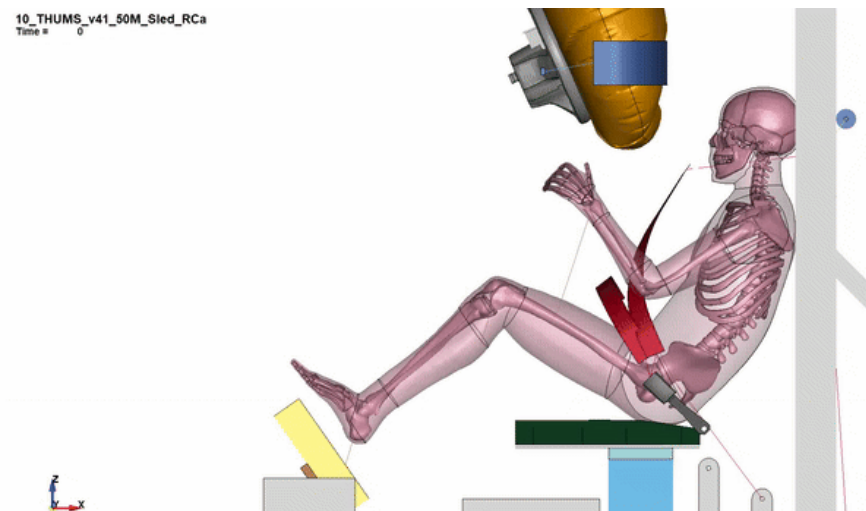
Setup overview: Tabletop setup animations



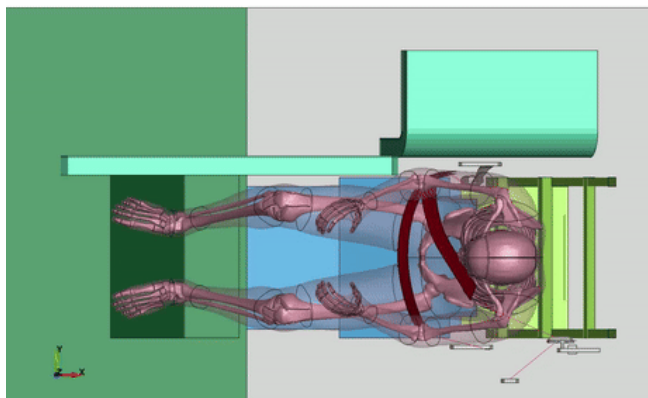
Setup overview: Sled setup animations



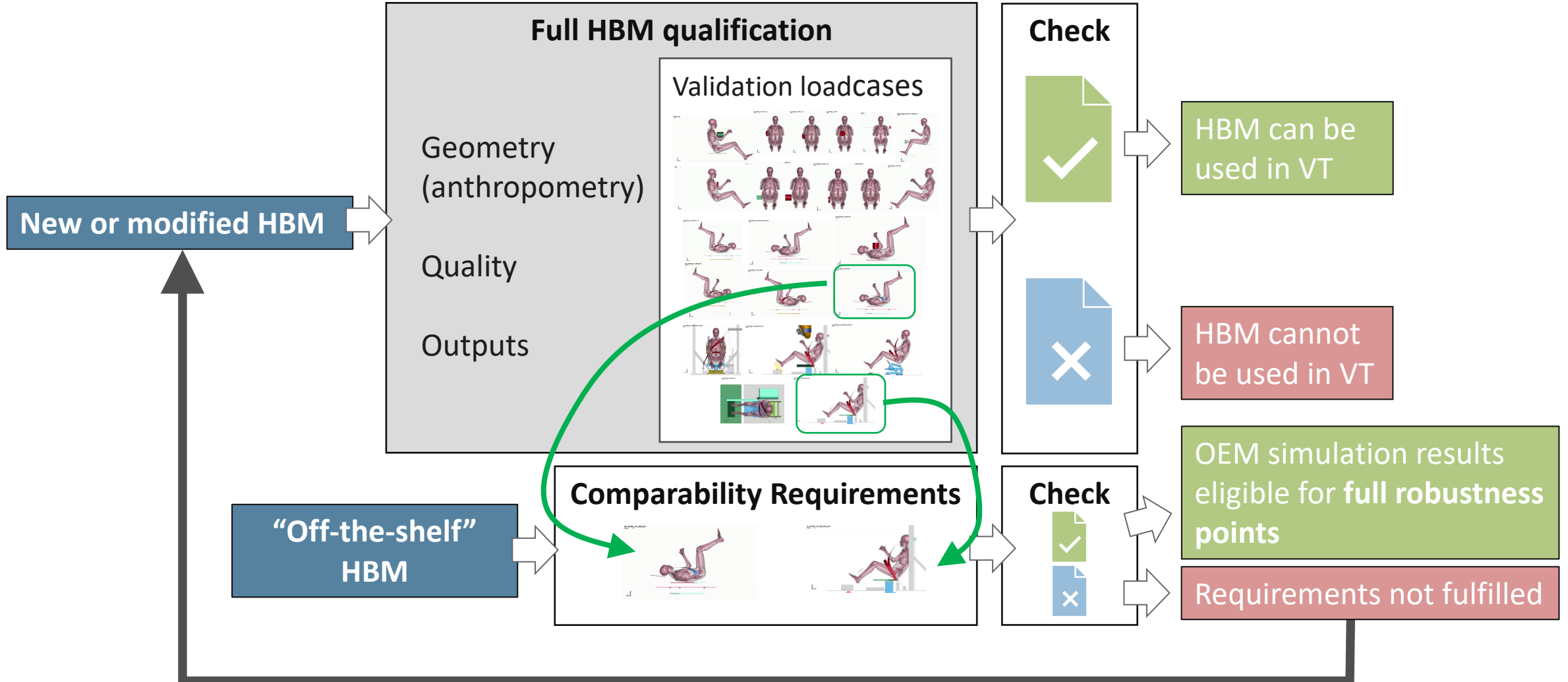
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10_THUMS_v41_50M_Sled_GS1
Time = 0



Qualification overview



HBM4VT Validation Catalogue

 EuroNCAP / HBM4VT Validation Catalogue

HBM4VT Validation Catalogue



New subgroup

New project



Subgroups and projects

Shared projects

Shared groups

Inactive



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Name



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General Instructions 

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Workflow from an OEM perspective

LS-Dyna

Subgroups and projects Shared projects Shared groups Inactive

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C	Cesari_1990	★ 0	1 month ago
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K	Kroell_1971	★ 0	1 month ago
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T	Tabletop-Kent-2004	★ 2	1 week ago
U	Uriot_2015	★ 0	1 month ago
Y	Yoganandan-1997	★ 0	1 month ago

Comparability loadcases



Requirement:
Scores within ± 0.1 of
full HBM qualification

Workflow from an OEM perspective

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Find file Code

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Update version number
 desi_kofler authored 2 weeks ago

Name	Last commit	Last update
.gitlab/issue_templates	Initial beta version release	1 year ago
_HBM	First model upload	1 year ago
_env	Implement a parameter to increase posi...	1 month ago
data	Update assessment notebook	1 month ago
sim_results	Add sim_results folder	1 year ago
00_Master_Sled.k	Update values z_DR and y_DR	2 weeks ago
Documentation_Sled.pdf	Specify the description of measuremen...	2 weeks ago
LICENSE	Initial commit	1 year ago
README.md	Update references	1 month ago
Shaw_2009_assessment.ipynb	Update version number	2 weeks ago
Shaw_2009_assessment_csv_input.i...	Add assessment notebooks which proc...	1 month ago
Version_v1.0.1.md	Update version number	2 weeks ago

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Project information

 99 Commits

 2 Branches

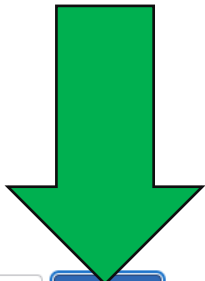
 21 Tags

 README

 Apache License 2.0

Created on
 April 23, 2024

Workflow from an OEM perspective



S Shaw_2009 🌐

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Name	Last commit	
📁 .gitlab/issue_templates	Initial beta version release	
📁 _HBM	First model upload	
📁 _env	Implement a parameter to increa	
📁 data	Update assessment notebook	1 month ago
📁 sim_results	Add sim_results folder	1 year ago
📄 00_Master_Sled.k	Update values z_DR and y_DR	2 weeks ago
📄 Documentation_Sled.pdf	Specify the description of measuremen...	2 weeks ago
📄 LICENSE	Initial commit	1 year ago
📄 README.md	Update references	1 month ago
📄 Shaw_2009_assessment.ipynb	Update version number	2 weeks ago
📄 Shaw_2009_assessment_csv_input.i...	Add assessment notebooks which proc...	1 month ago
📄 Version_v1.0.1.md	Update version number	2 weeks ago

Clone with HTTPS

<https://openvt.eu/EuroNCAP/hbm4v> 

Open with

Visual Studio Code HTTPS

IntelliJ IDEA HTTPS

Download source code

zip tar.gz tar.bz2 tar

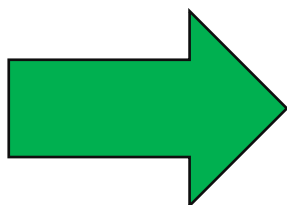
Workflow from an OEM perspective

S Shaw_2009 

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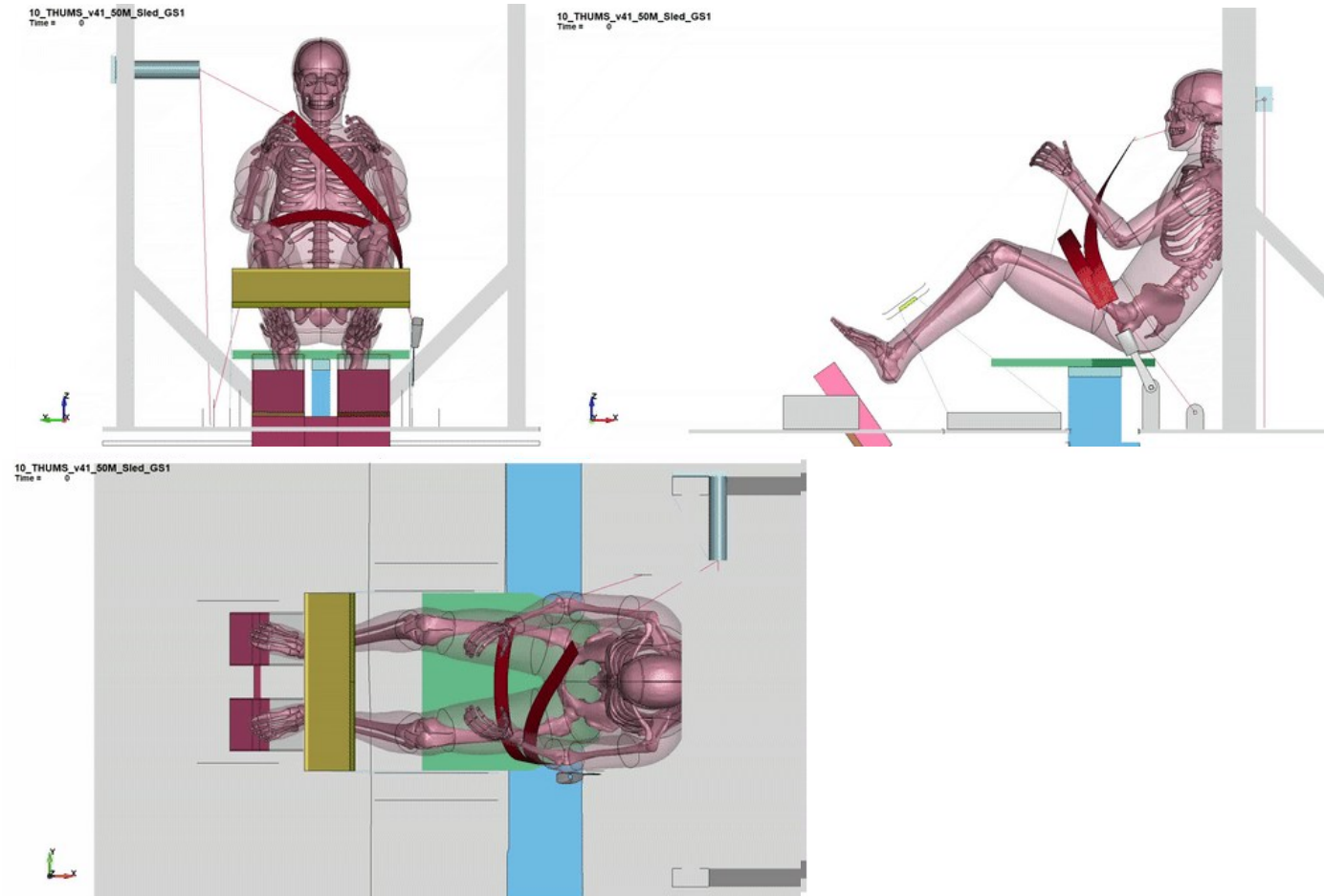
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Name	Last commit	Last update
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 _HBM	First model upload	1 year ago
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 Shaw_2009_assessment_csv_input.i...	Add assessment notebooks which proc...	1 month ago
 Version_v1.0.1.md	Update version number	2 weeks ago



Workflow from an OEM perspective

Example animations illustrating the sled test in a simulation with VIVA+ 50F are provided below. Note that while the sled moves in the simulations, a viewpoint moving with the sled was chosen for the animations.



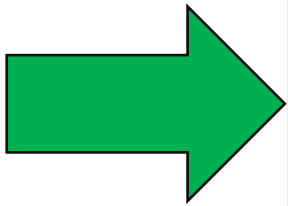
Workflow from an OEM perspective

Shaw_2009 

main shaw_2009 Find file Code ⋮

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desi_kofler authored 2 weeks ago 7038adc8  History

Name	Last commit	Last update
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 _HBM	First model upload	1 year ago
 _env	Implement a parameter to increase posi...	1 month ago
 data	Update assessment notebook	1 month ago
 sim_results	Add sim_results folder	1 year ago
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 Documentation_Sled.pdf	Specify the description of measuremen...	2 weeks ago
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 Version_v1.0.1.md	Update version number	2 weeks ago



Workflow from an OEM perspective

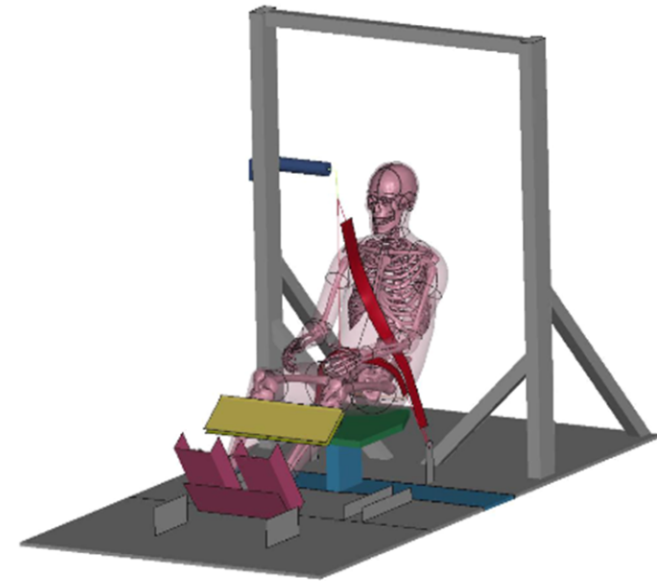
→ Step-by-step guide

3

Frontal sled tests by Shaw et al. 2009

Key factors to replicate from PMHS tests:

- HBM seated on rigid seat
 - Seat belt fitted
 - Hands on lap
 - Lower extremities fixed
- Sled acceleration in x direction
- Head trajectory measured
- Seat forces, footrest forces and knee support forces measured
- Belt forces in shoulder and lap belt measured



Workflow from an OEM perspective

→ Step-by-step guide

6

Simulation phases

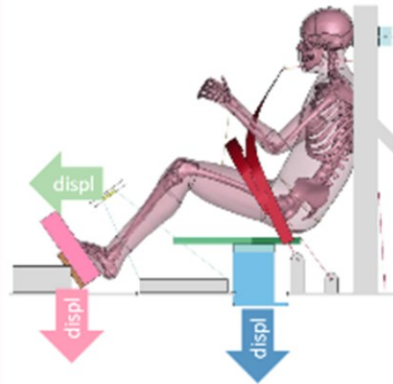
Initial model

HBM positioned in target position

- HBM in standard driver posture



Testbed transformations



Position

- HBM is rotated to reach target sternum angle for AM50 or AF05 anthropometry

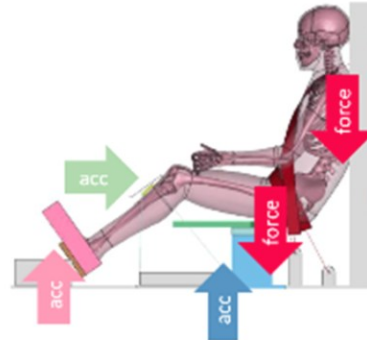
Testbed

- Seat is moved downwards
 - Footrest is moved downwards
 - Knee support is moved away from HBM

Settling phase

Testbed settling and belt fit

- HBM pelvis and spine constraint
- No gravity

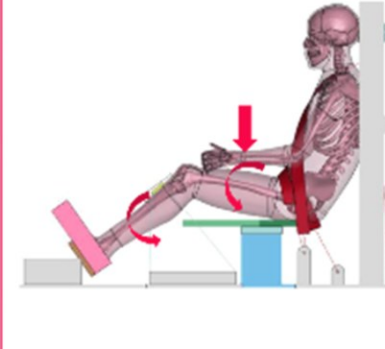


Testbed

- Seat is accelerated upwards with 1g
- Footrest is accelerated upwards with 1g
- Knee support is accelerated towards HBM with 1g
- Belt fit**
- Pretension force is applied to fit belt to HBM

Hand positioning

- HBM pelvis and spine constraint
- No gravity



Hands

- Hands move to target position

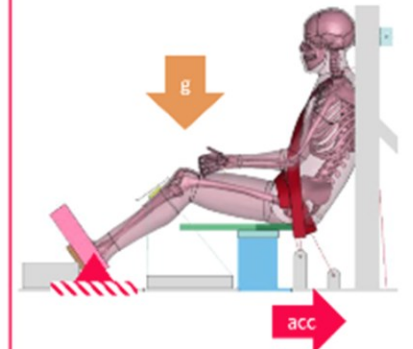
Legs

- Femur is rotated to reach target angle
- Tibia is rotated to reach target angle

Loading phase

Load application

- HBM constraints released
 - Gravity applied
 - Sled loading applied



Load

- Sled velocity applied in x direction
 - Gravity applied
 - Ankles constrained to footrest

Workflow from an OEM perspective

→ Step-by-step guide

10

Set the include file

- 1) Put the main HBM file in the folder directory "_HBM"
- 2) Open the main HBM file in a pre-processor
- 3) Open the file 00_Master_Sled.k in a text editor
- 4) Define the main HBM file in the I N C L U D E S section
- 5) Follow the instructions from STEP 1 to STEP 8
 - Note: If you need to change previously defined parameters, walk through the subsequent steps again and check if parameters need to be updated. E.g. the coordinates of the landmarks need to be updated, if the position of the HBM changes.

Workflow from an OEM perspective

- Run simulation and copy results (binouts) in the respective folder
- Run assessment notebook (with python environment → see Gl...)
- Check your results
 - Error messages in the notebook
 - Plausibility
- Share results with Euro NCAP
 - Binouts/HDF5 and csv files from assessment
 - Comparison to results from full HBM qualification

Note: validation setups are publically available – anyone can run them!

Status/next steps

- All setups are available (at least) as v1.0.0
- Publication of **v1.0 of TB CP550** by end of September
 - This allows for VPS results to be considered in the thresholds as well
 - Comments received for v0.9 were considered
 - Thresholds updated to include all state-of-the-art HBMs

Outlook for next Euro NCAP protocol update (2029)

- Qualification in general
 - Create template for qualification report (for model providers/developers)
 - Improve definition of average male anthropometry
 - Update qualification to include small female, average female, and large male
 - Integrate traceability (hashing of HBM, boundary condition models and results)
- Validation loadcases & biofidelity scoring:
 - Critical review of contribution/added value of all loadcases
 - Review scoring methodology
 - Increase biofidelity requirements
 - Integrate harmonised strain-based (rib fracture) assessment

Acknowledgements

We would like to acknowledge and thank all **HBM4VT participants** for their valuable feedback and contributions to this project and the **QualiPro HBM4VT sponsors** for funding the work on the public setups and methodology:

- DYNAmore
- GHBMC
- Elemance
- Humanetics
- Autoliv
- Volvo
- Toyota Motor Europe

Disclaimer:

All claims expressed in this presentation are solely those of the presenter and do not necessarily represent those of all HBM4VT participants.

Qualification of HBMs for Euro NCAP

Current status of CP 550 and outlook



Speaker: Felix Ressi
Graz University of Technology, Austria



<https://openvt.eu/EuroNCAP/hbm4vt-validation-catalogue>

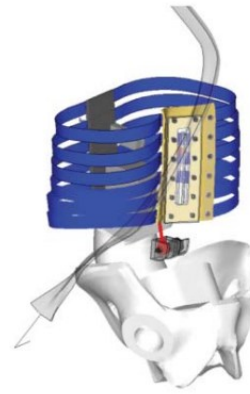
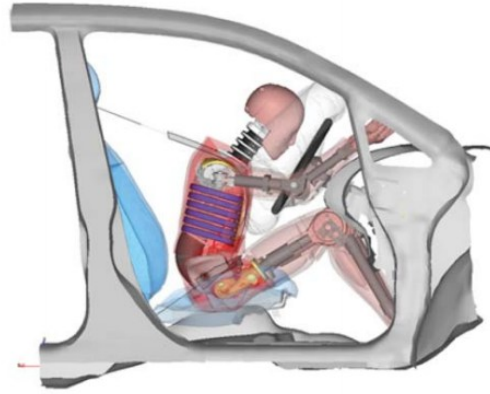
Session 3: Injury predictions –
which outputs are useful and
how can we get more of them?

Strain-based Probabilistic Rib Fracture Prediction

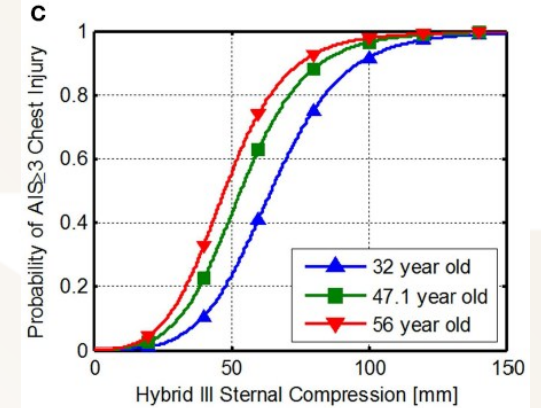
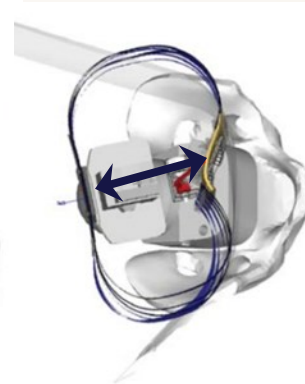
Jason Forman

University of Virginia Center for Applied Biomechanics

Thoracic Injury Prediction with Human Body Models

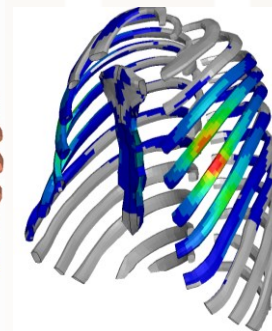
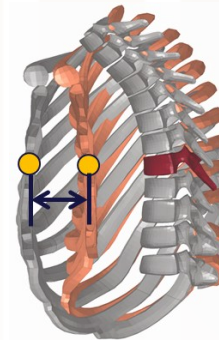
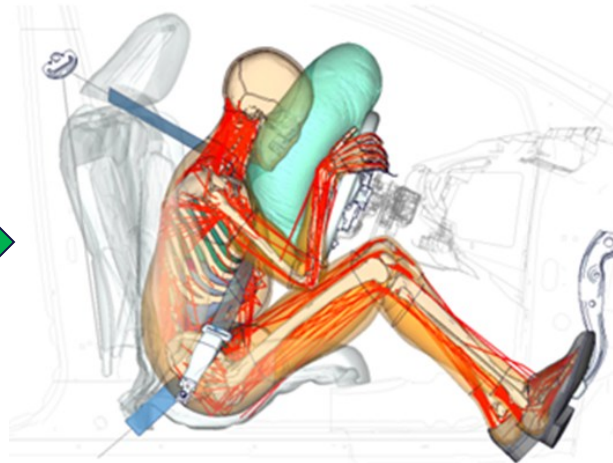


ATD Sensor Measurement



$$P(HIII | AIS3+) = \frac{1}{1 + e^{-(12.597 + 0.05861 * Age + 1.568 * Delta^{0.4612})}}$$

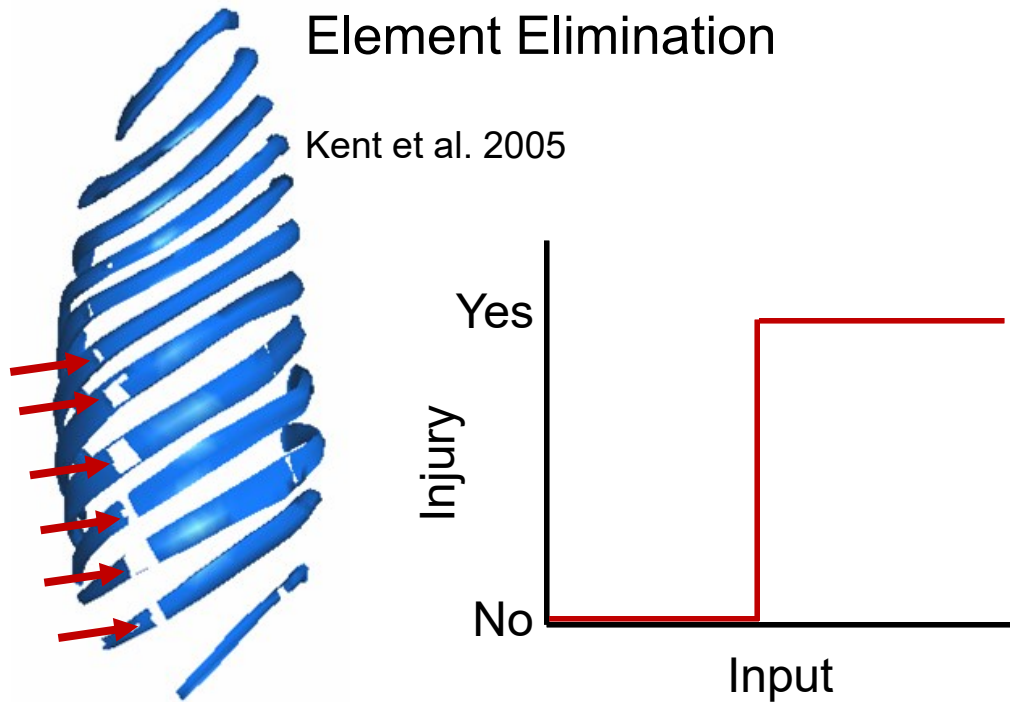
Where,
 Age = occupant age in years
 Delta = Hybrid-III sternal chest deflection in mm



HBM Simulation Outputs

Deterministic Injury Prediction Methods

Definition: Predict a single output (injury or no injury) for a given input.



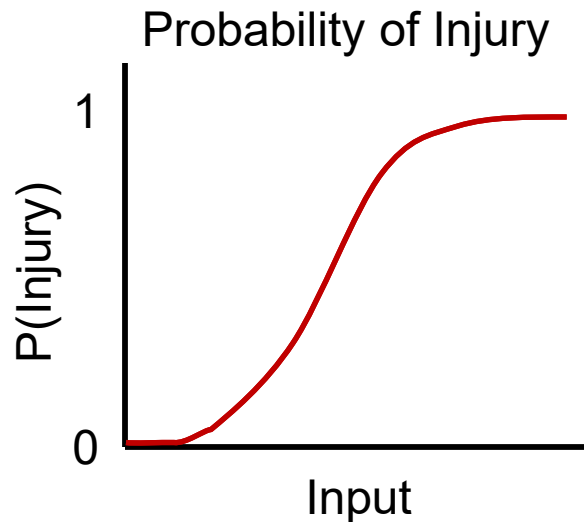
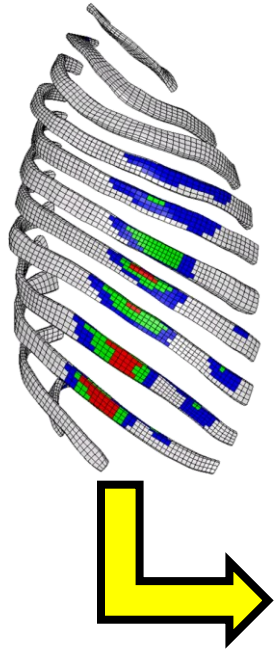
Softening Fracture Model,
Strain Threshold, etc.

Limitations

- Binary output (yes or no)
- Threshold
- Single subject

Probabilistic Injury Prediction Methods

Determine a probability of failure (i.e., a risk of injury) affected by variations in the population, exposure, etc.

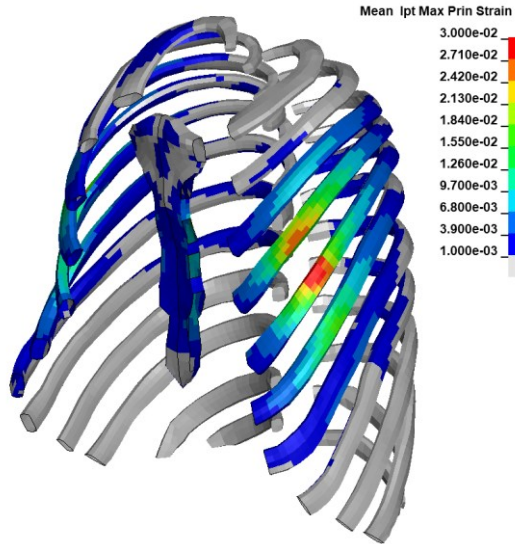


- Used to predict mechanical failure in other engineering disciplines
- Explored on a limited basis in injury biomechanics (e.g., Thacker et al. 1999, Francis et al. 2005)

Probabilistic Rib Fracture Prediction using Strain

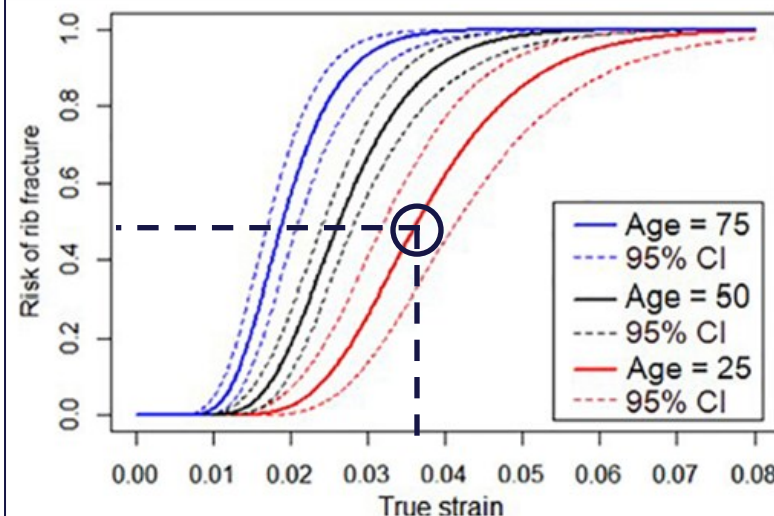
Probabilistic Rib Fracture Risk Prediction Framework (Forman et al. 2012)

Simulation Data



Rib #	Peak Strain	Prob. Of Fracture
1	0.005	0.00
2	0.025	0.10
3	0.015	0.06
4	0.040	0.62
5	0.052	0.83
...	...	...
N	ϵ_N	p_N

Rib Fracture Risk Function (Larsson et al. 2021)



Generalized Binomial Model:

- Probability of X fractures within the ribcage

$$\text{Probability of X fractures} \rightarrow P(X) = \sum_{i=1}^N \left(\prod_{j \in C_i} p_j \right) \left(\prod_{k \in \bar{C}_i} (1 - p_k) \right)$$

Where: $\binom{N}{X}$ is the binomial coefficient $\binom{N}{X} = \frac{N!}{X!(N-X)!}$

C_i is a vector containing the i^{th} combination of X site indices

$\bar{C}_i$ is a vector containing the set exclusive or values between the index vector [1...N] and the combination vector C_i

Probability of $\geq Y$ fractures within the ribcage

$$P_{\geq}(Y) = 1 - \sum_{X=0}^{Y-1} P(X)$$

Probability of 1+ Rib Fx

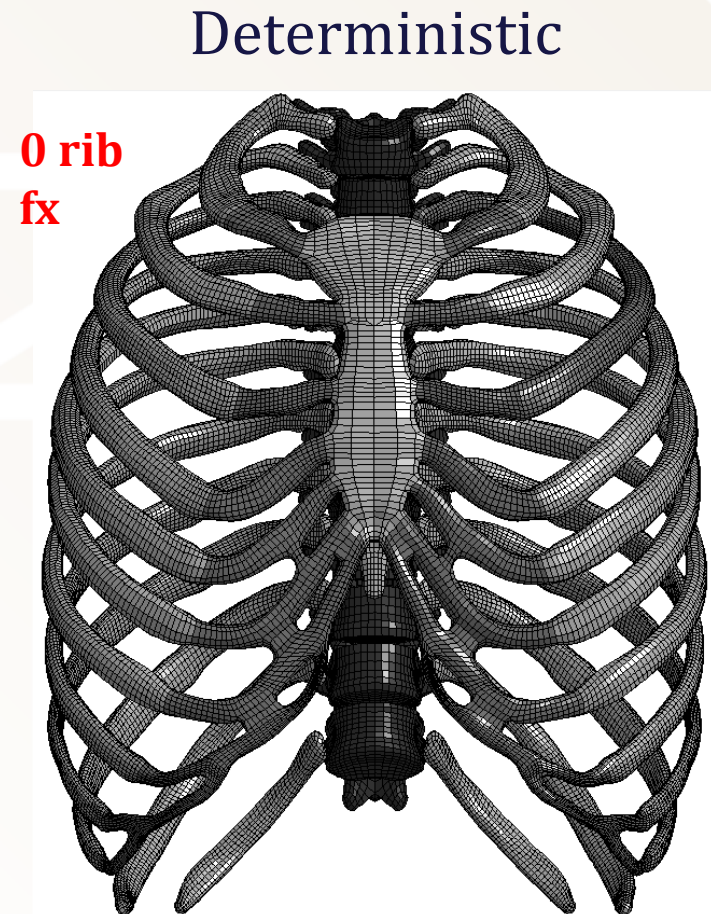
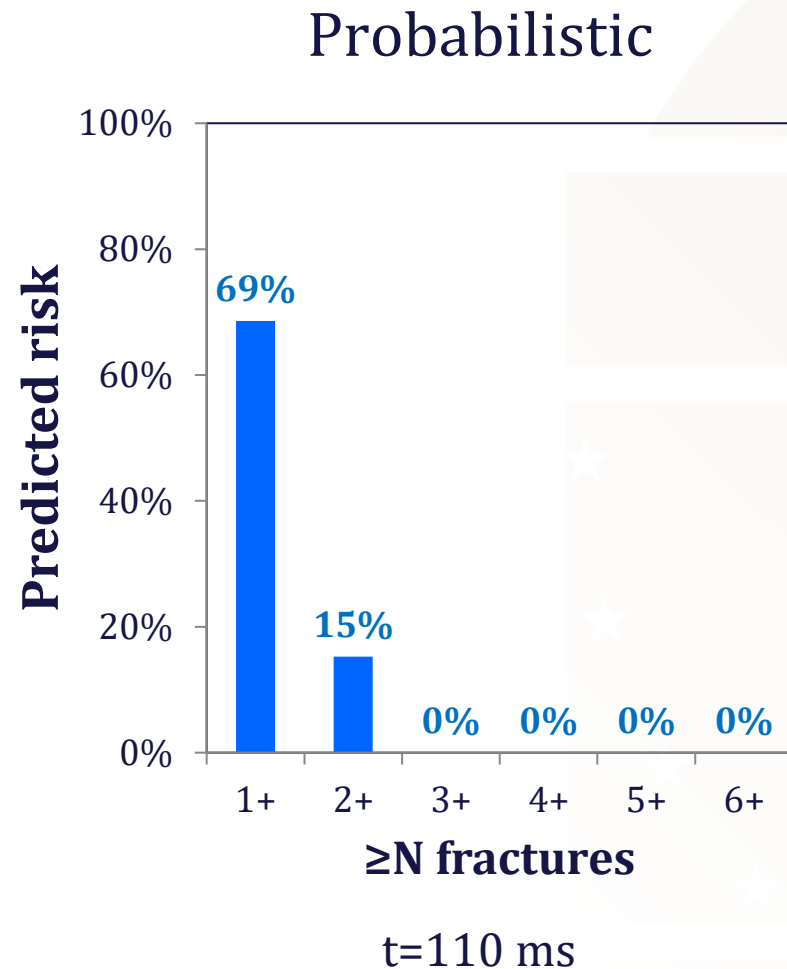
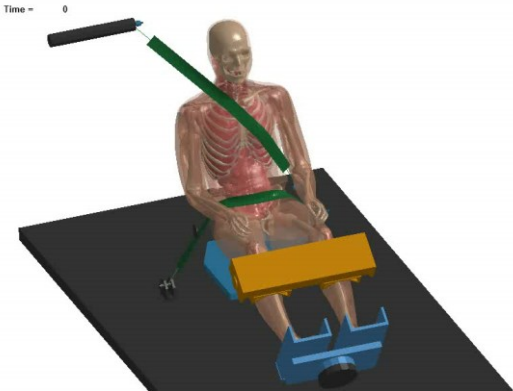
Probability of 2+ Rib Fx

Probability of 3+ Rib Fx

Probability of 4+ Rib Fx

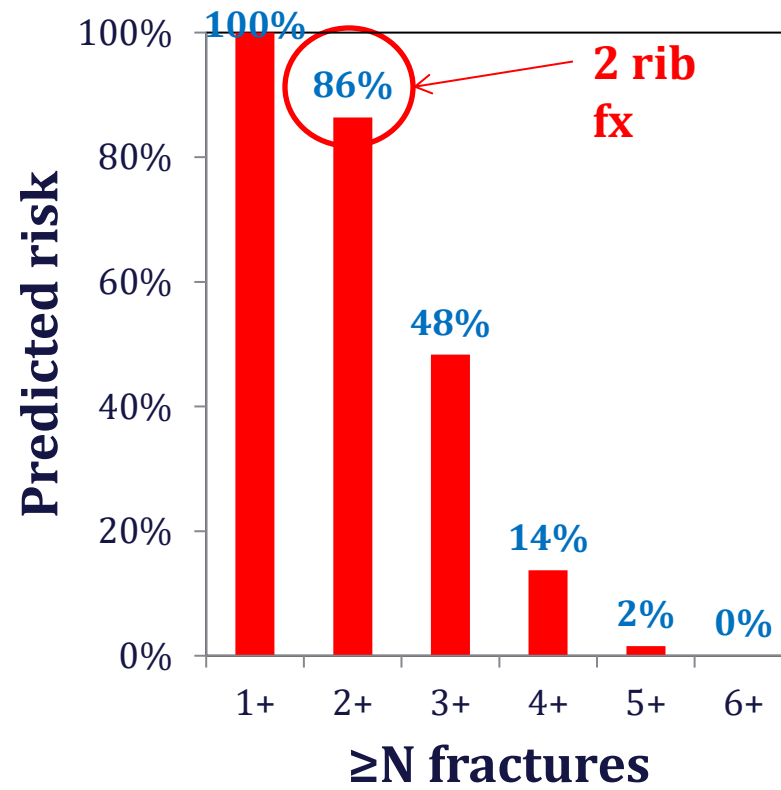
...

Example - 20 km/h Frontal Sled Simulation



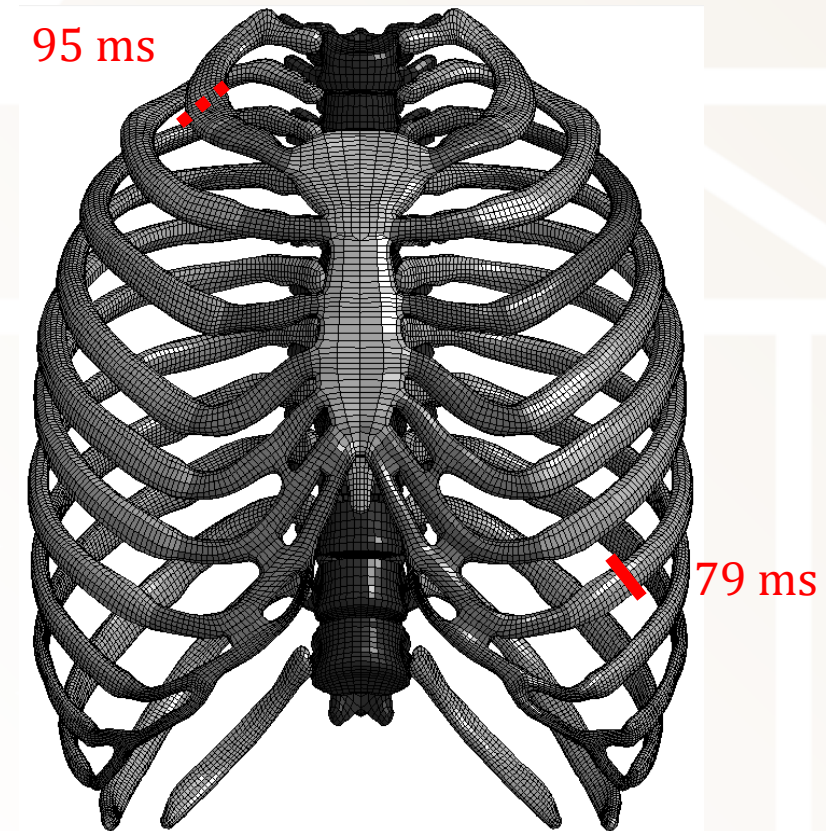
30 km/h

Probabilistic



t=93 ms
(time of max. probability)

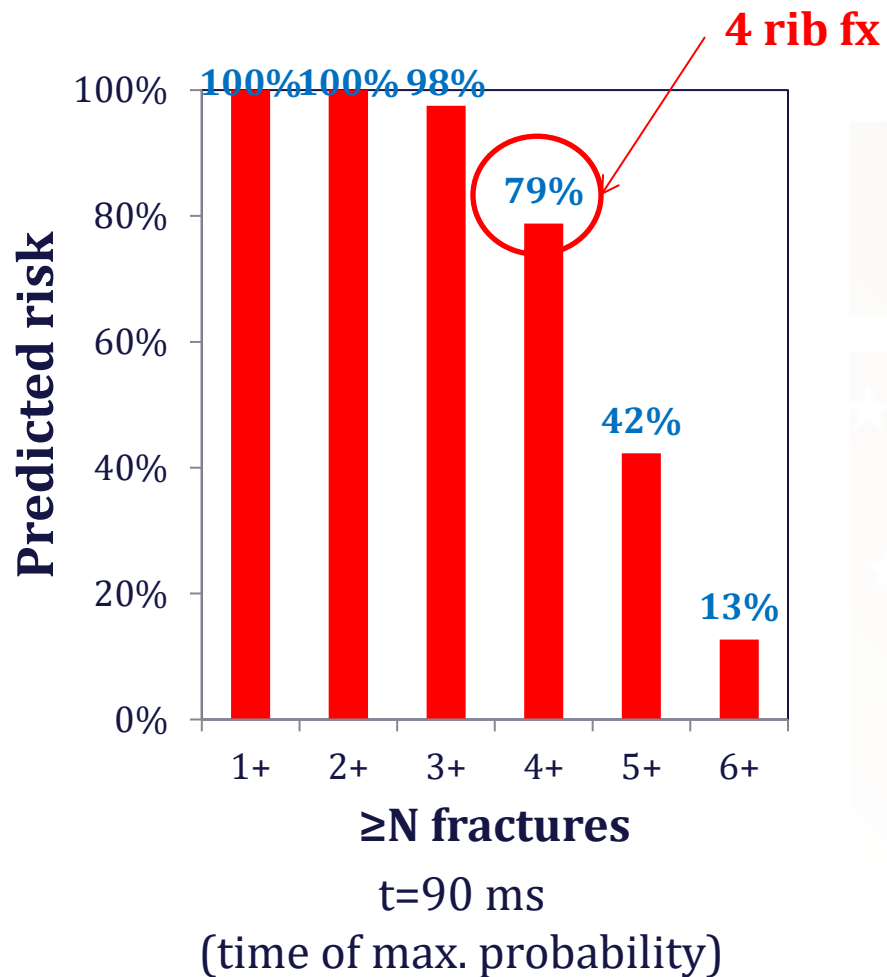
Deterministic



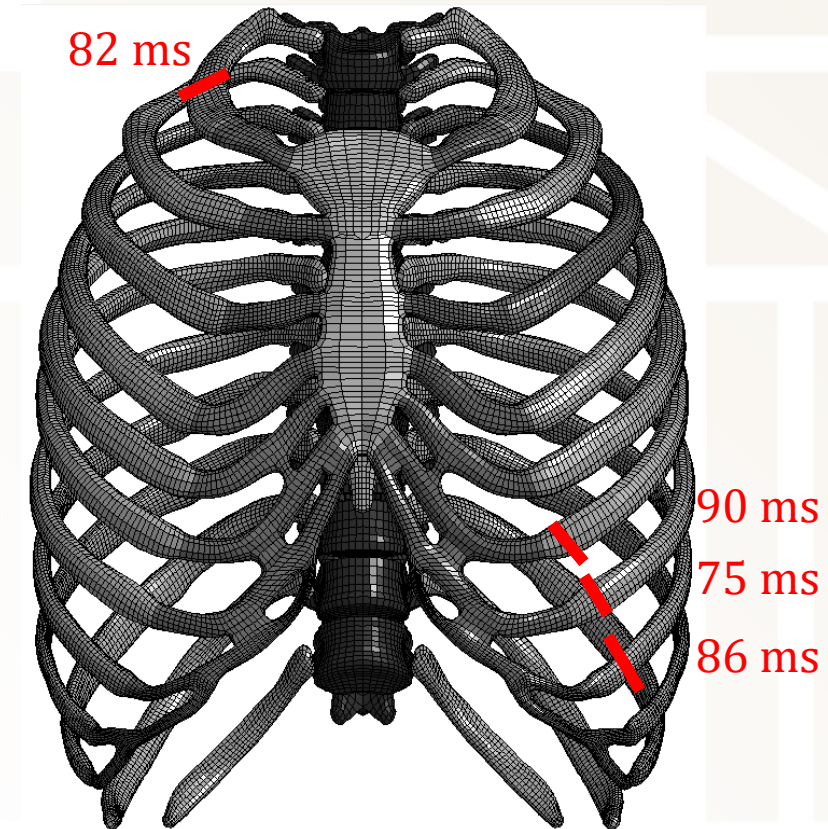
--- Incomplete fx
— Complete fx

40 km/h

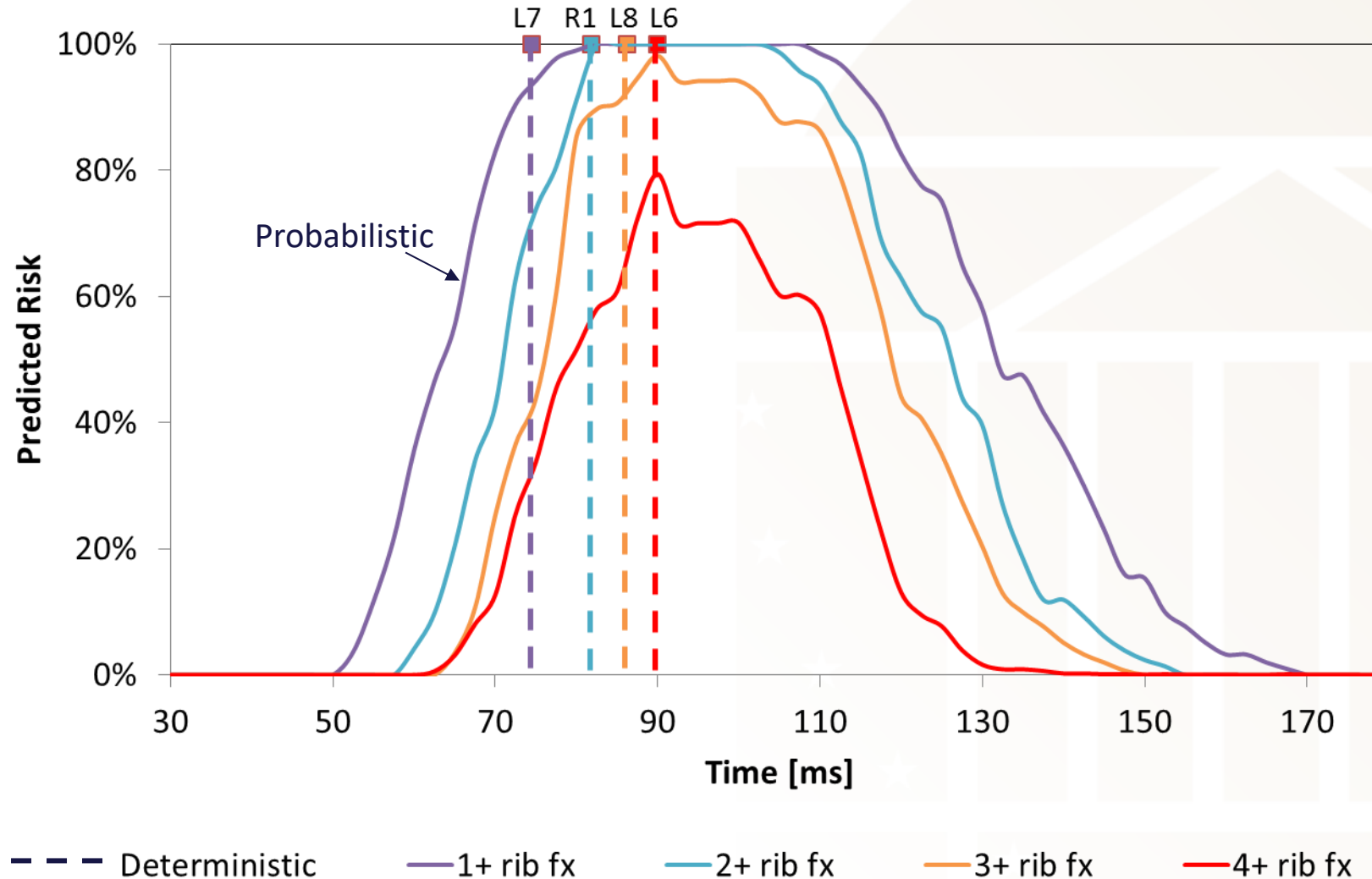
Probabilistic



Deterministic



40 km/h: Rib Fracture Risk vs. Time



Challenge: Every Model is Different

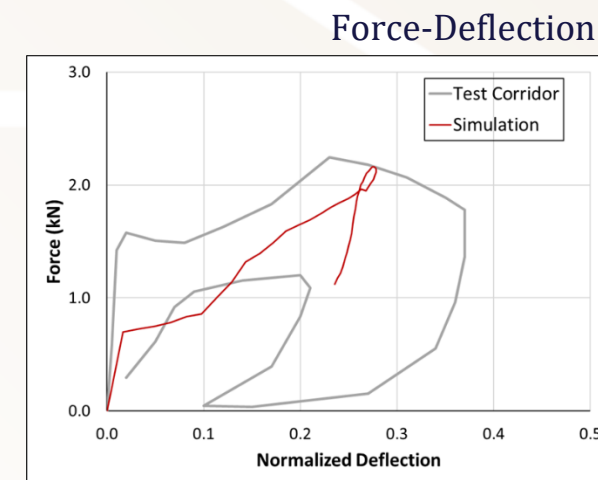
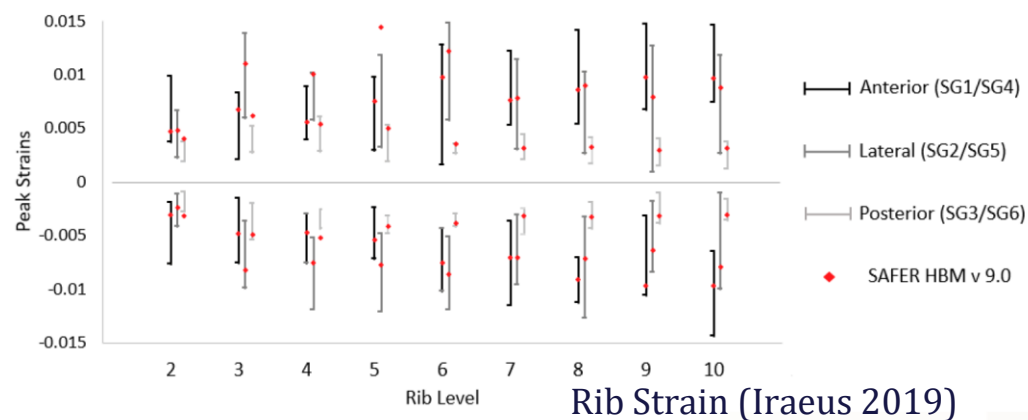
Mesh

Material

Anatomy / Geometry

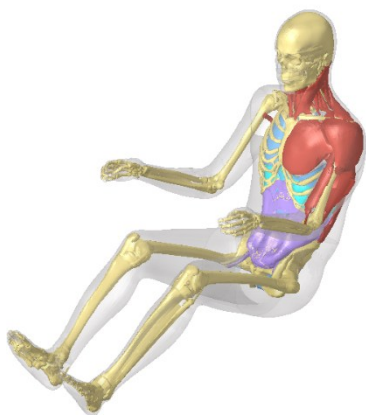
Purpose

Validation

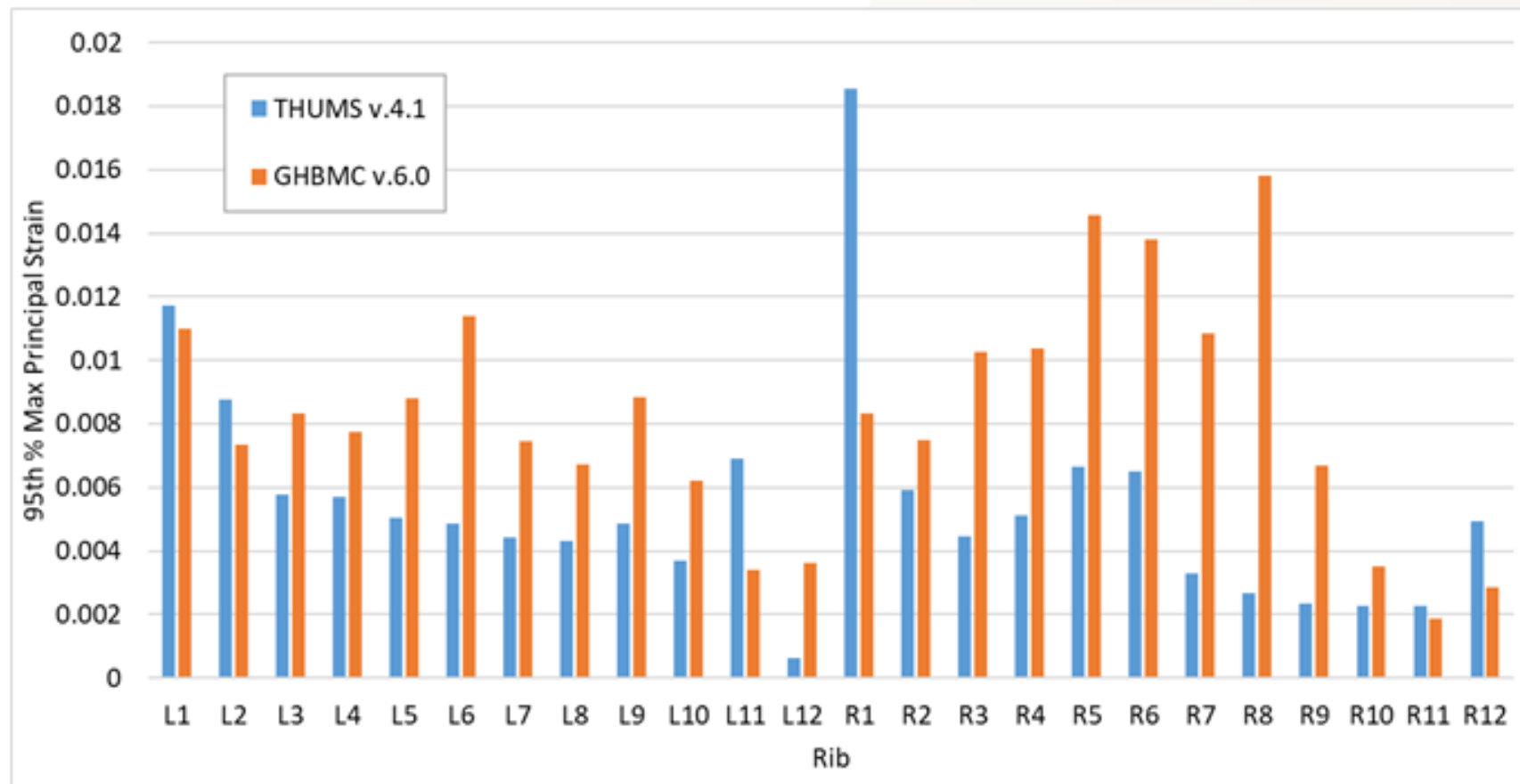
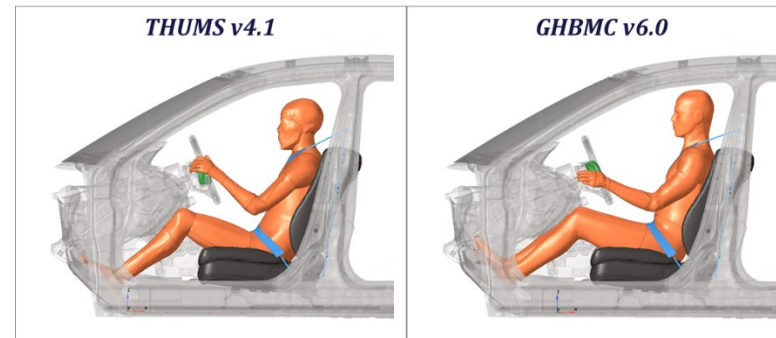


Biofidelity corridors are quite wide

↳ Two models can be judged biofidelic, while still being quite different



THUMS V GHBMC Rib Strain Comparison



Maximum Principal Strain

Effect on Injury Risk Prediction

Differences in:

Mesh

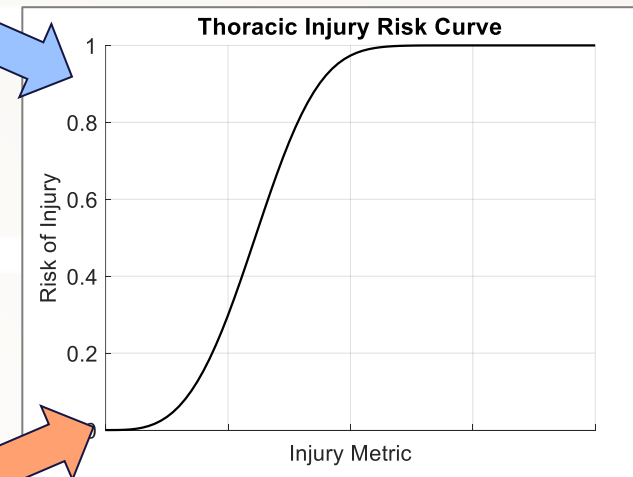
Material

Anatomy /
Geometry

Purpose

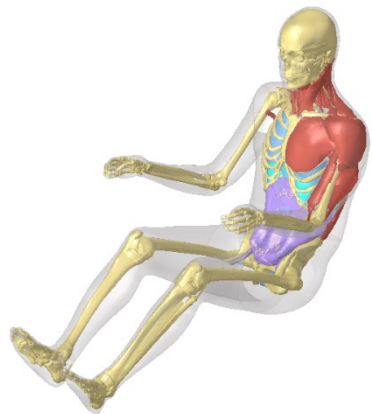
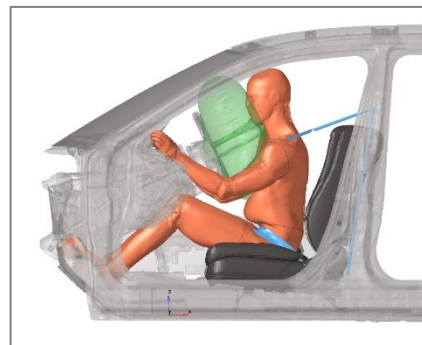
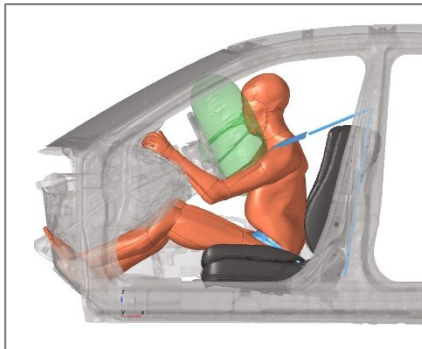
Validation

Outcome
Measures

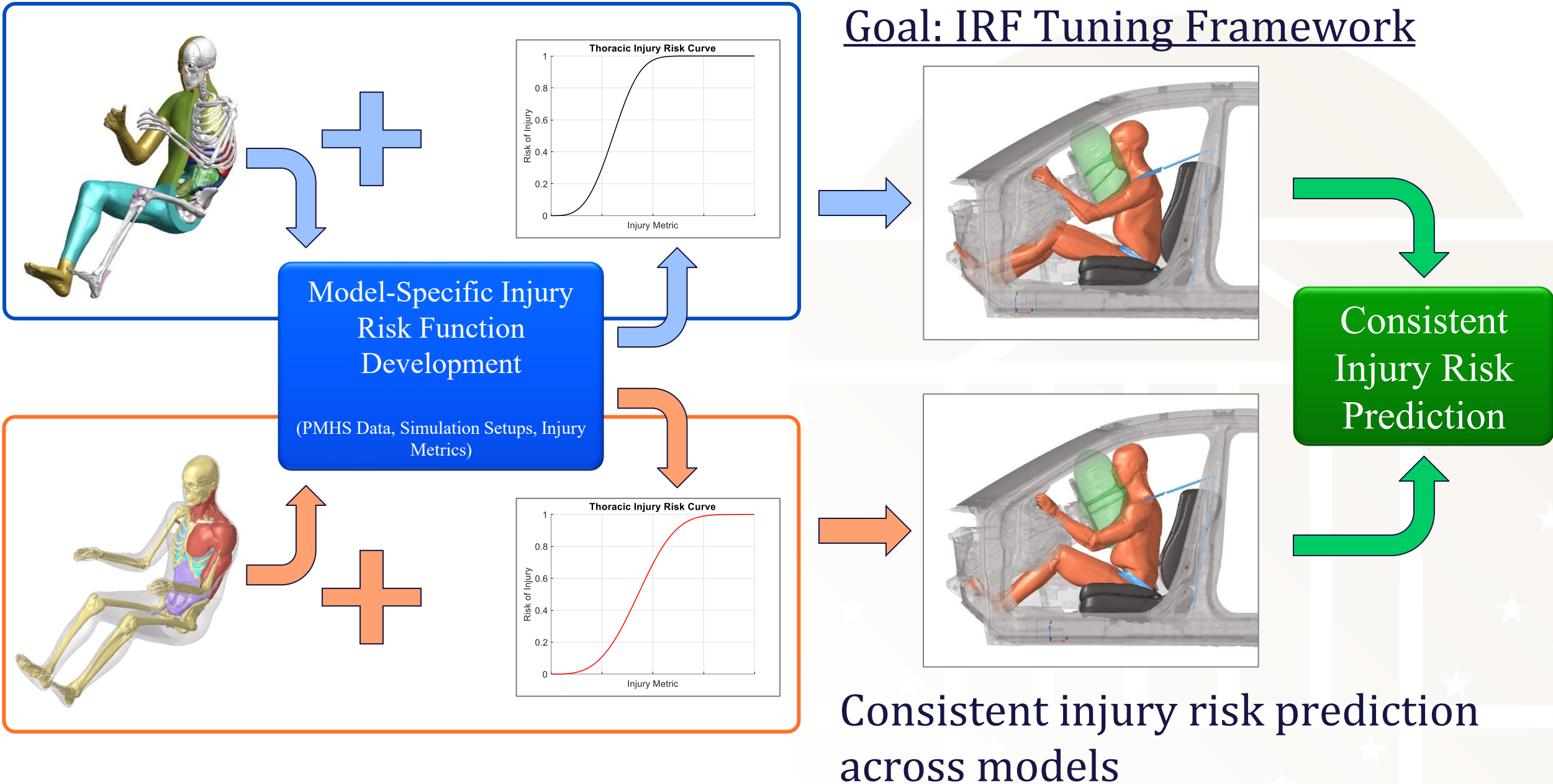


Single
Injury Risk
Function

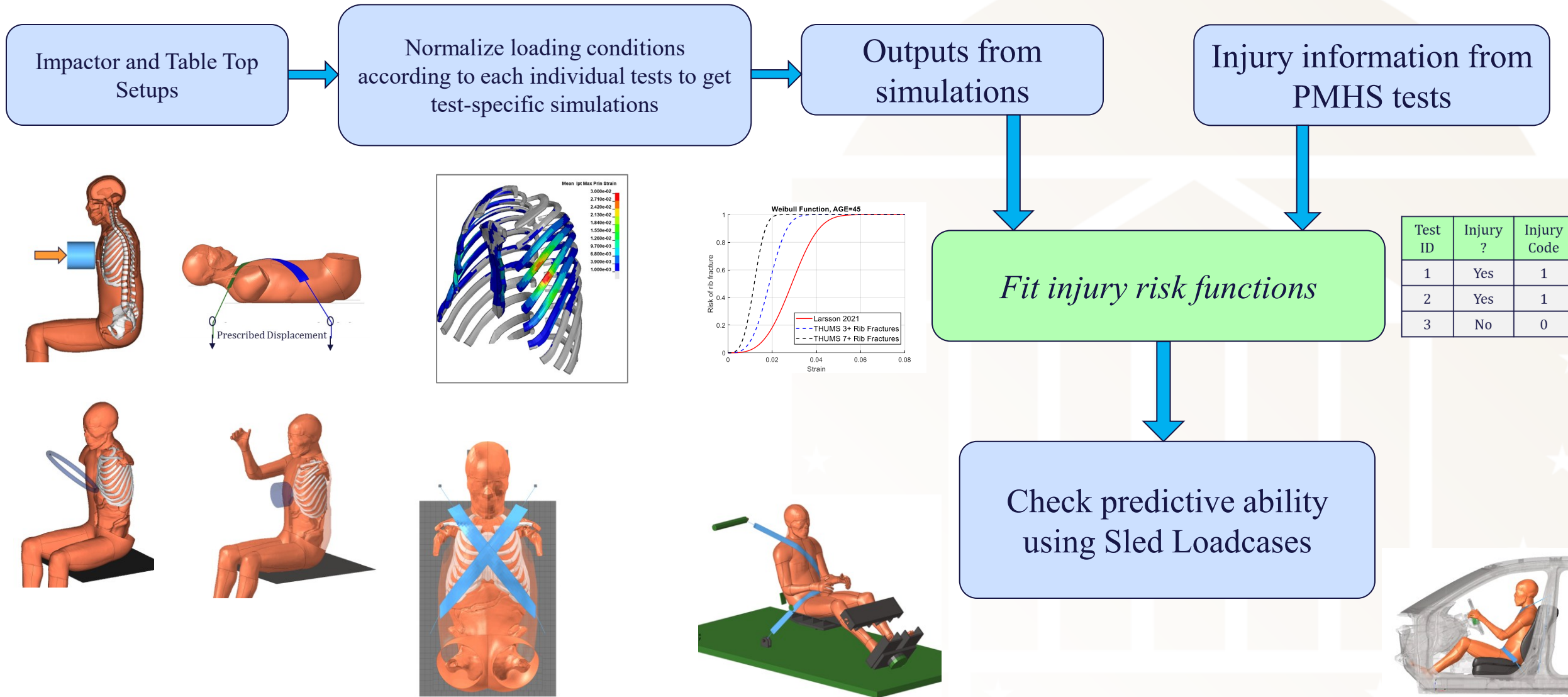
Different
Injury Risk
Prediction



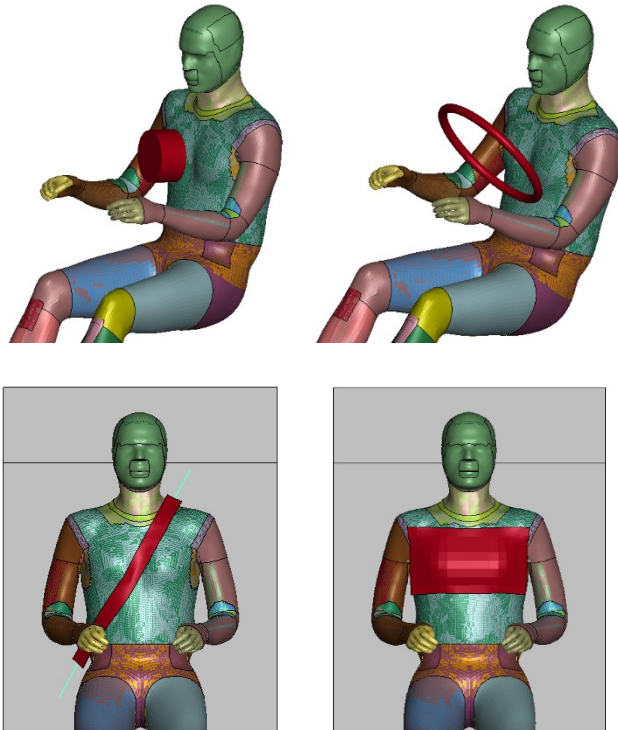
Goal: IRF Tuning Framework



IRF Development Strategy

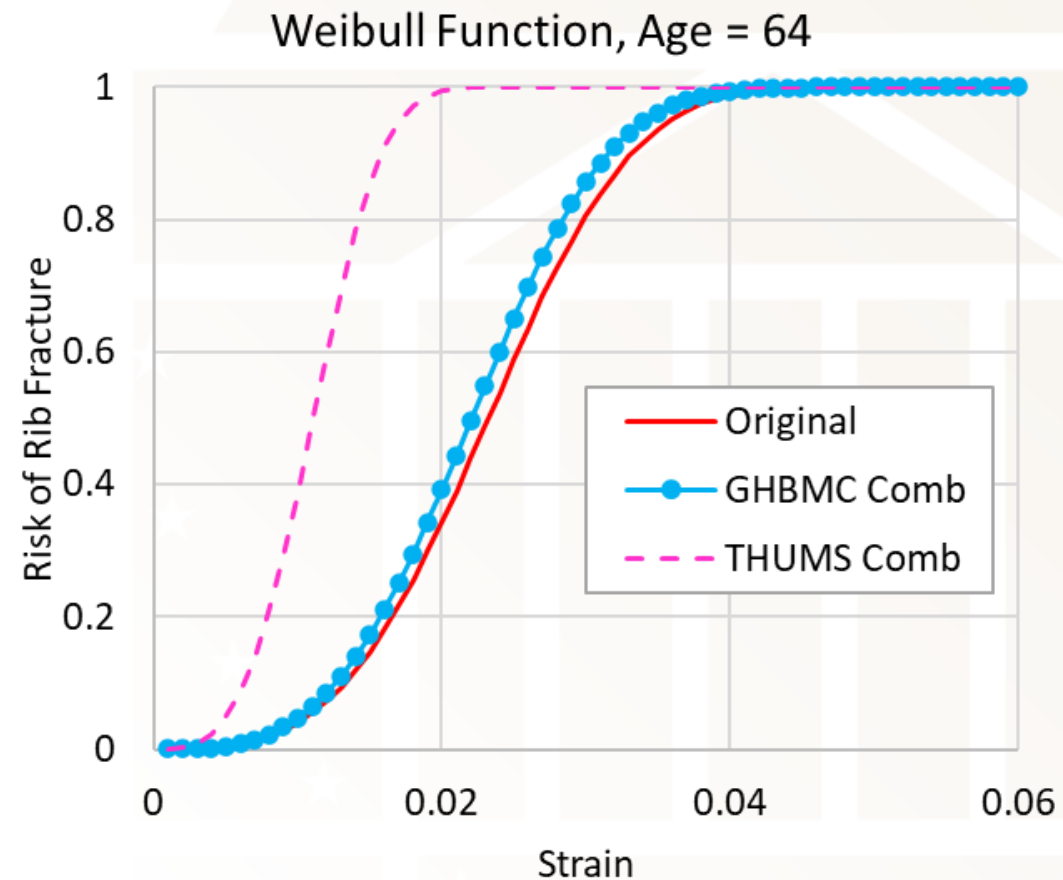


Results: Comparison of IRFs Fit for THUMS and GHBMCM50-0 v.6.0



170 PMHS tests in 13 frontal load cases
used to tune the local rib strain IRF
(Forman et al. 2022 IRCOBI)

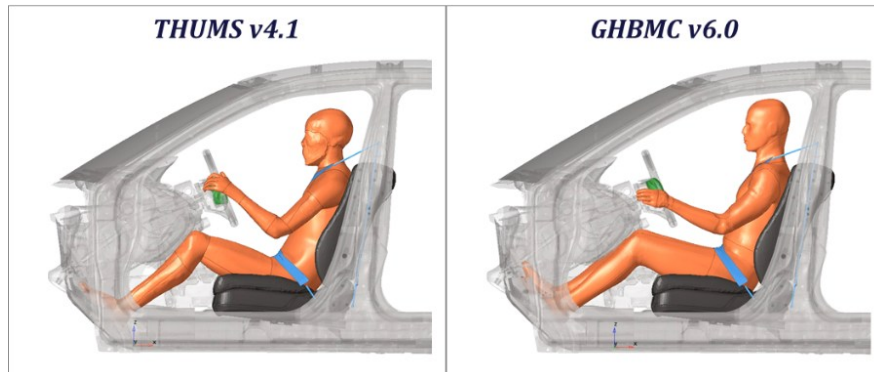
Comparison of THUMS v4.1 and GHBMCM50-0 v.6.0
rib fracture risk curves



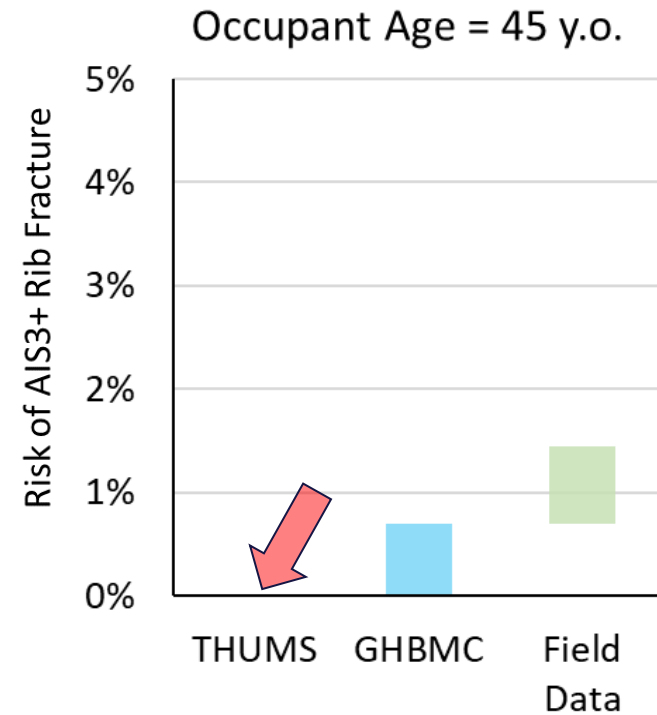
In-Vehicle Simulation

56 km/h Frontal Rigid Barrier Simulation

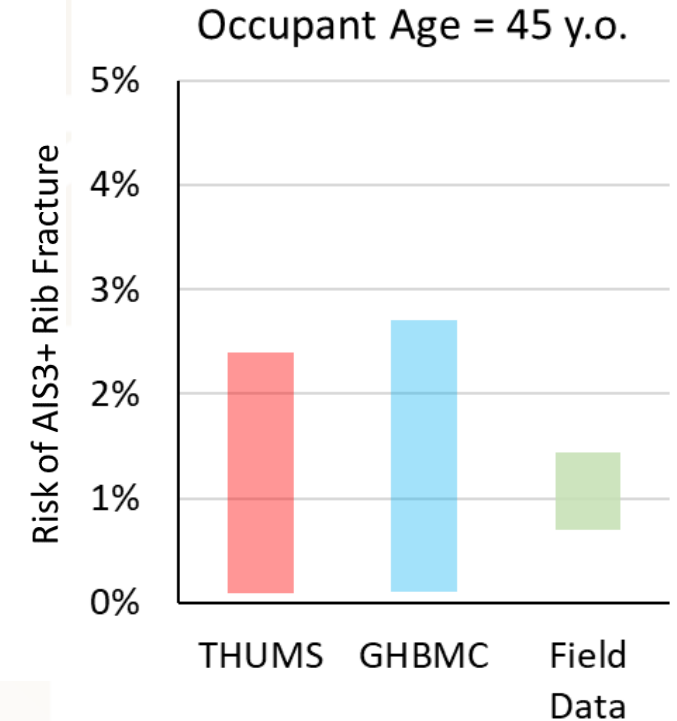
THUMS and GHBMC predicted similar risks when their tuned IRFs were used



With Untuned Larsson 2021 IRF



With Model-Specific IRFs



Note:

Field data estimates from regression models for AIS3+ thoracic injury for belted occupants in frontal collisions controlling for ΔV , vehicle model year, age, sex, stature from Forman et al. 2019 (NASS-CDS data) and follow-up study (CISS data). (Forman et al. 2022)

Conclusion

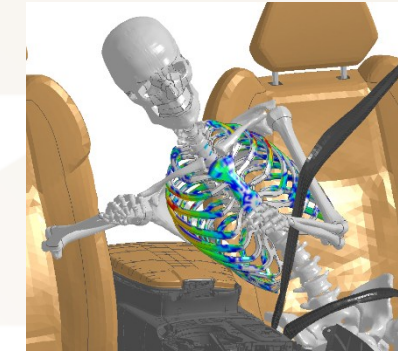
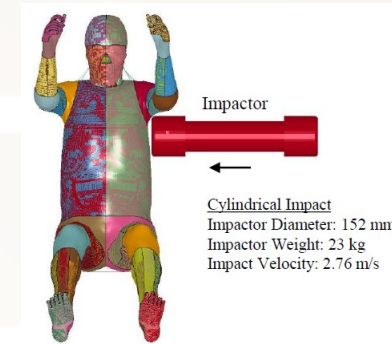
Consistent injury prediction is possible through tuning of model-specific injury risk functions

Thoracic IRF Development Framework for Human Body models

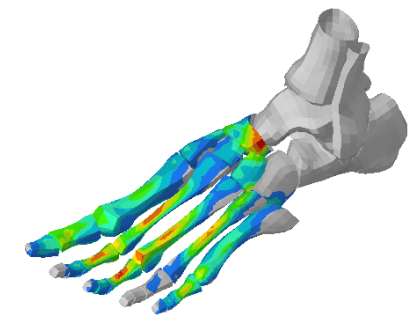
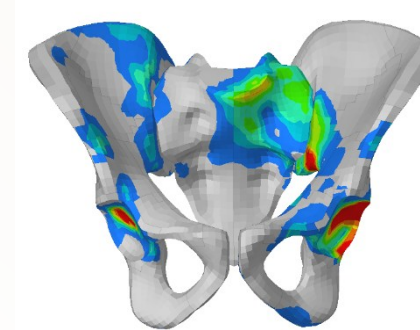
Method to tune strain risk curve in the probabilistic risk prediction framework for HBMs

Potential Areas for Expansion:

- Expand study for other impact directions like lateral impact (currently ongoing)



- Strain based IRFs for other body regions in HBMs



- Automated tools for IRF tuning (e.g. for model updates)

Strain-based Probabilistic Rib Fracture Prediction



Thank You!

Questions?

Email: jlf3m@virginia.edu

Jason Forman

University of Virginia Center for Applied Biomechanics

Extending the Application of Human Body Models: A Statistical Approach for Selecting Localized Strain-Based Metrics

F. Scott Gayzik, Ph.D.

Professor, Wake Forest University School of Medicine
Wake Forest University Center for Injury Biomechanics
CTO, Elemance

9 September, 2025



Center for Injury Biomechanics

Hostetler ZS, Gayzik FS. *Lower Extremity Injury Risk Curve Development for a Human Body Model in the Underbody Blast Environment.*

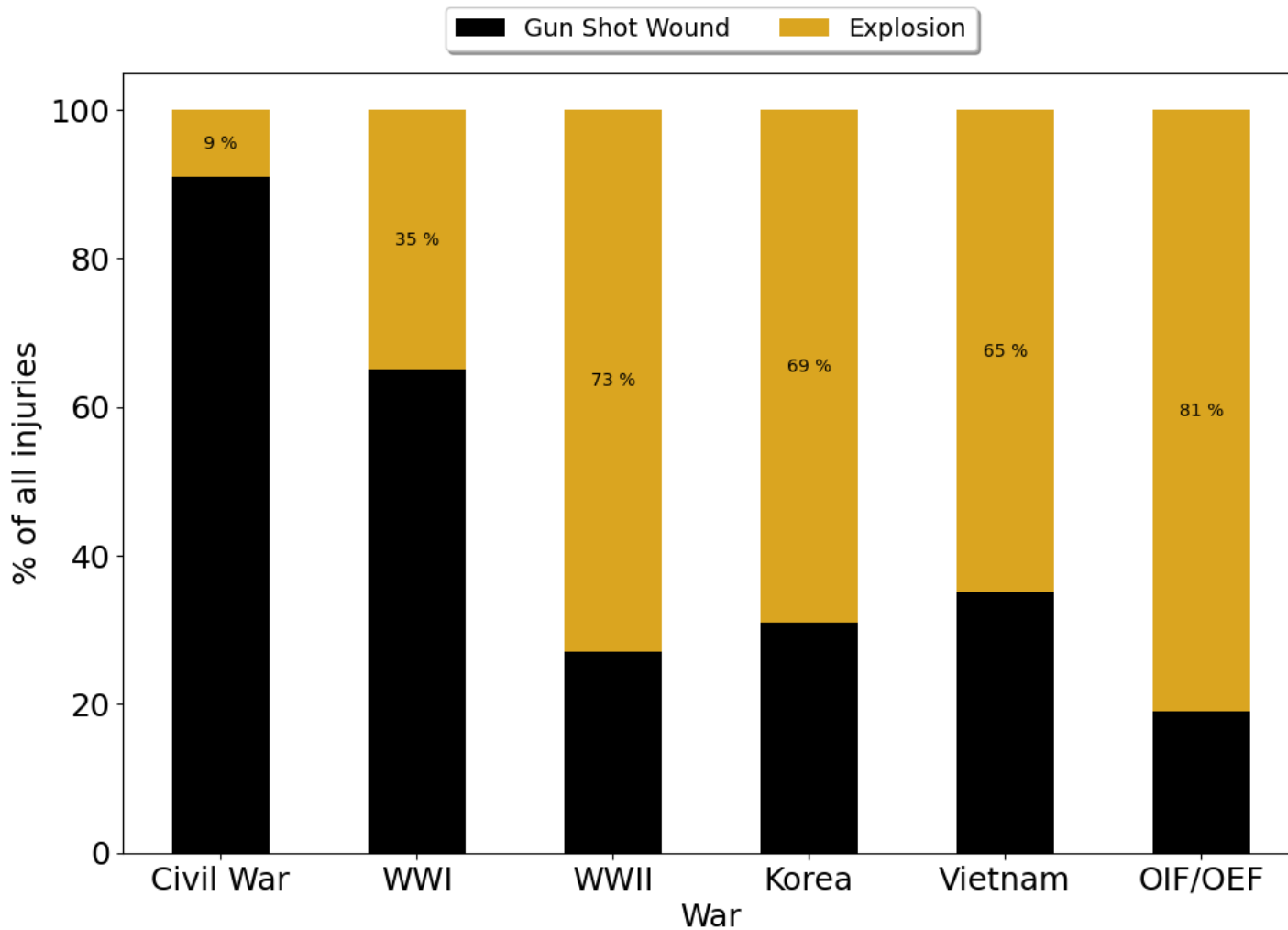
J Biomech Eng. 2024 Mar 1;146(3):031006.



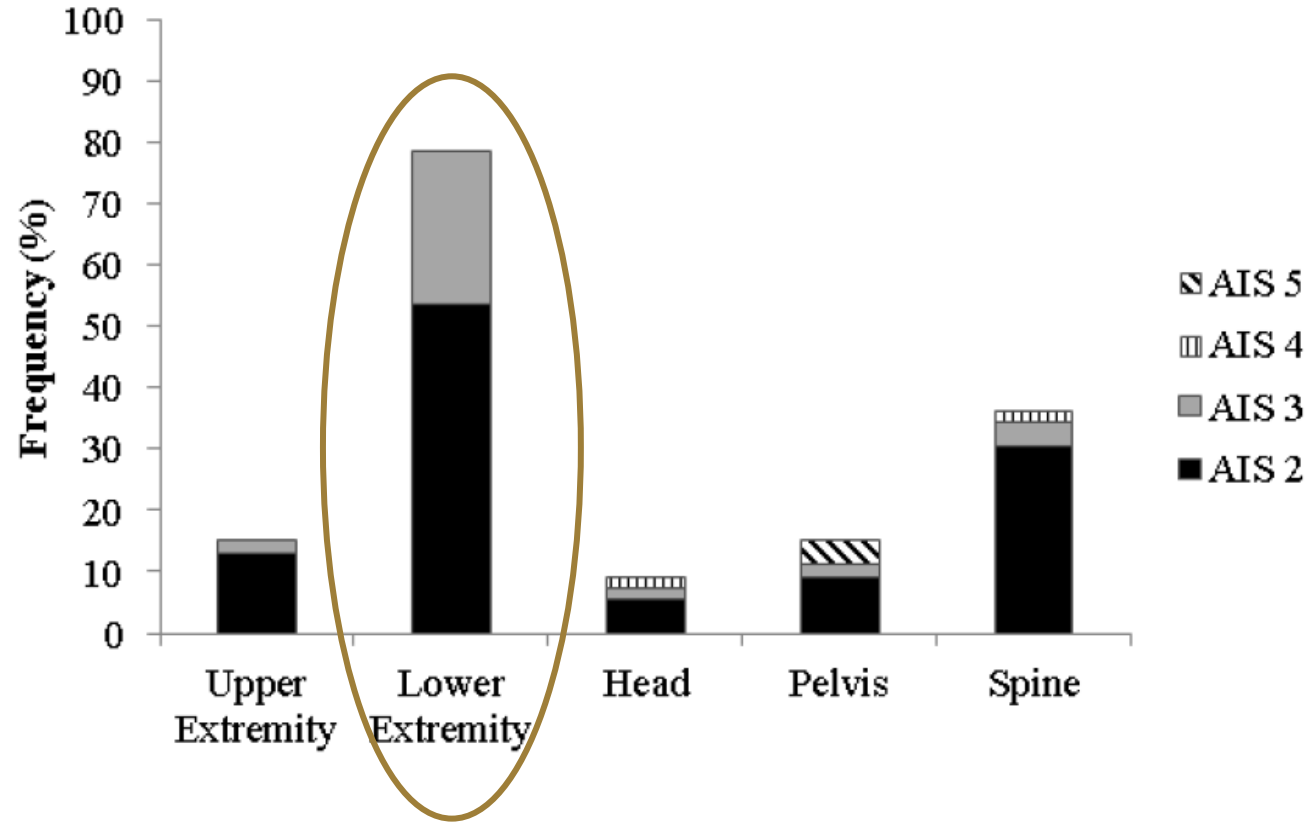
Zachary Hostetler

CANDIDATE INJURY METRICS FOR RISK CURVE DEVELOPMENT

Modern Warfare Threat: Improvised Explosive Devices (IED's)

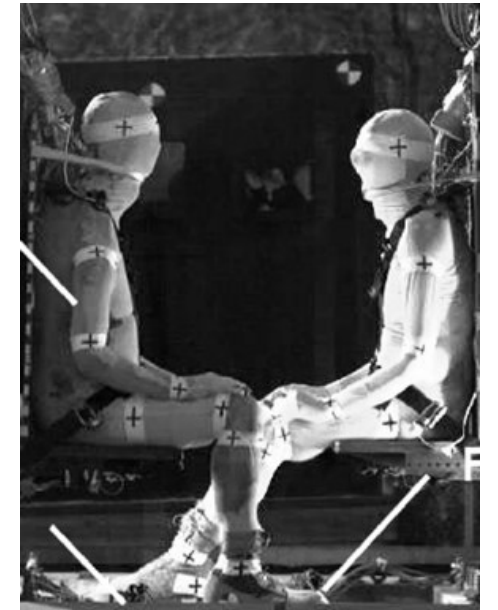
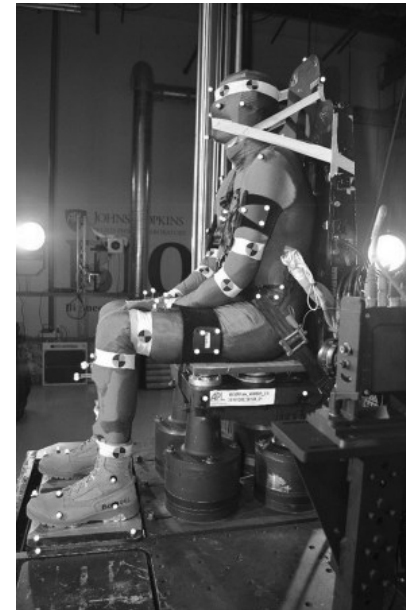
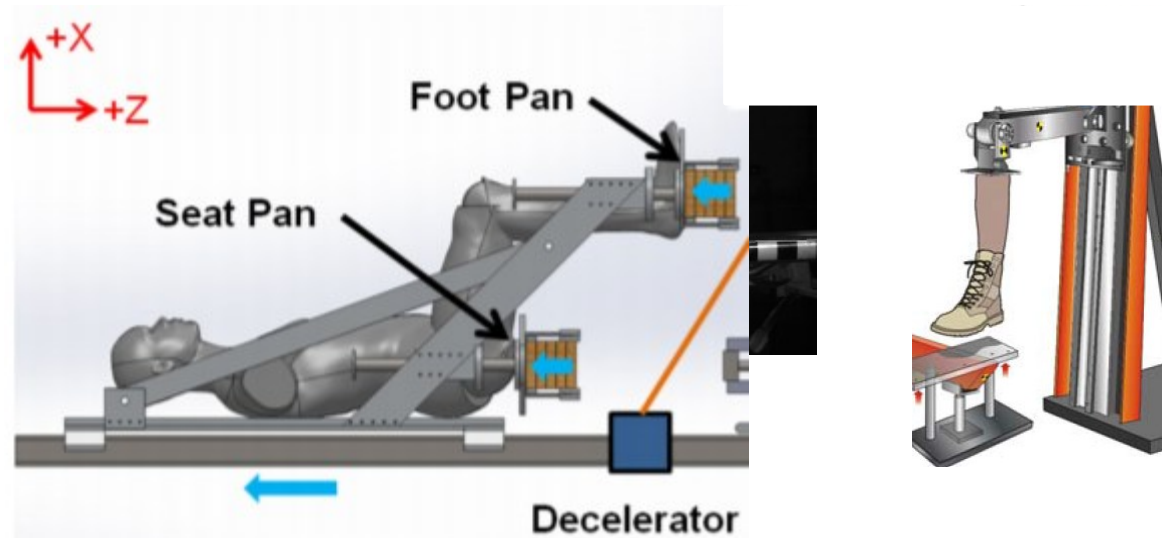


OIF and OEF Injury Statistics



Research Background: PMHS Studies

- Component level testing
 - Lower extremity ^[*]
- Whole body testing
 - Comparing PMHS to ATD response ^[**]
- Limited to smaller samples and older PMHS subjects



[*] Gallenberger, Kathryn. "Foot and ankle injuries in variable energy impacts." (2013).

[*] Pintar, Frank A., et al. *Biomechanical response of military Booted and Unbooted Foot-Ankle-Tibia from vertical loading*. SAE Technical Paper, 2016.

[**] Bailey, Ann M., et al. "Comparison of Hybrid-III and PMHS response to simulated underbody blast loading conditions." Proceedings of IRCOBI conference. 2013.

[**] Danelson, Kerry A., et al. Comparison of ATD to PMHS response in the under-body blast environment. SAE Technical Paper, 2015.

[**] Ott, Kyle A., et al. "Evaluation of the whole body spine response to sub-injurious vertical loading." *Annals of Biomedical Engineering* 49.11 (2021): 3099-3117.

Human Body Model: GHBMCM50-O

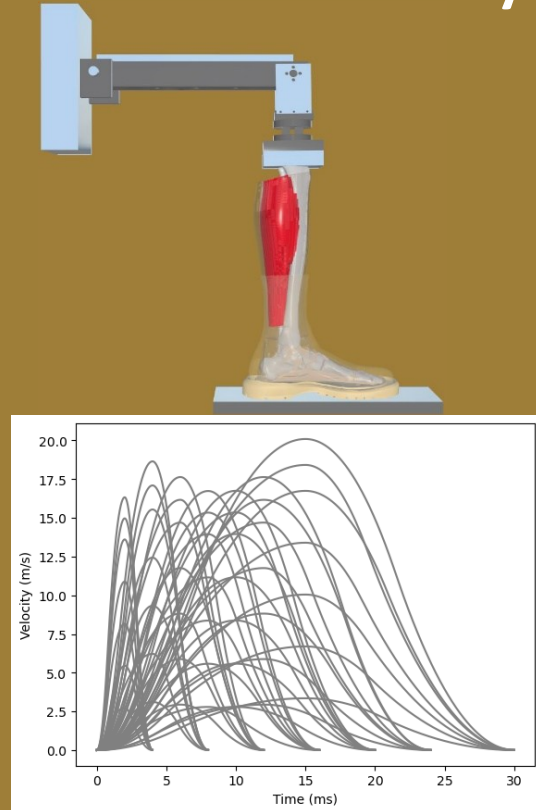
HBM Characteristics:

1. Biofidelity
2. Repeatability
3. Throughput
 - Large scale simulated testing (time saving)
 - Model response can be compared to PMHS on the local or global level
 - Injury prediction assessment using metrics that are difficult to instrument

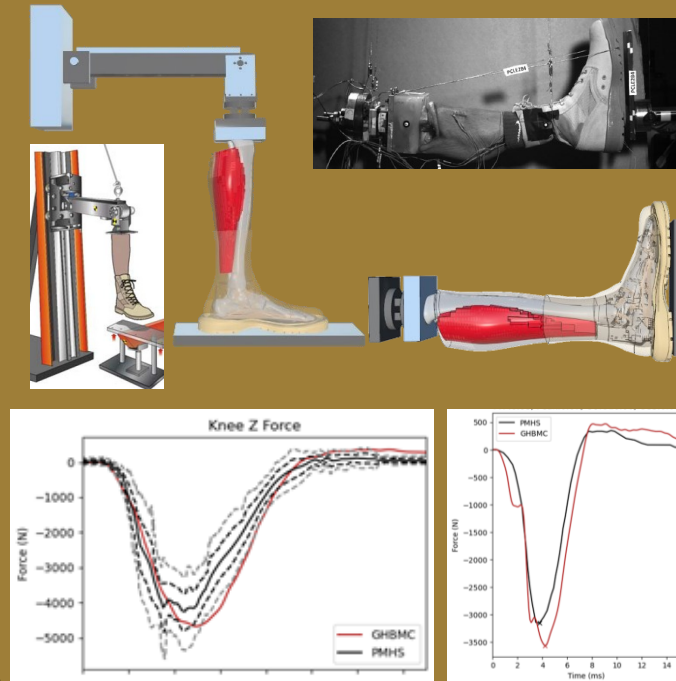


Study Overview

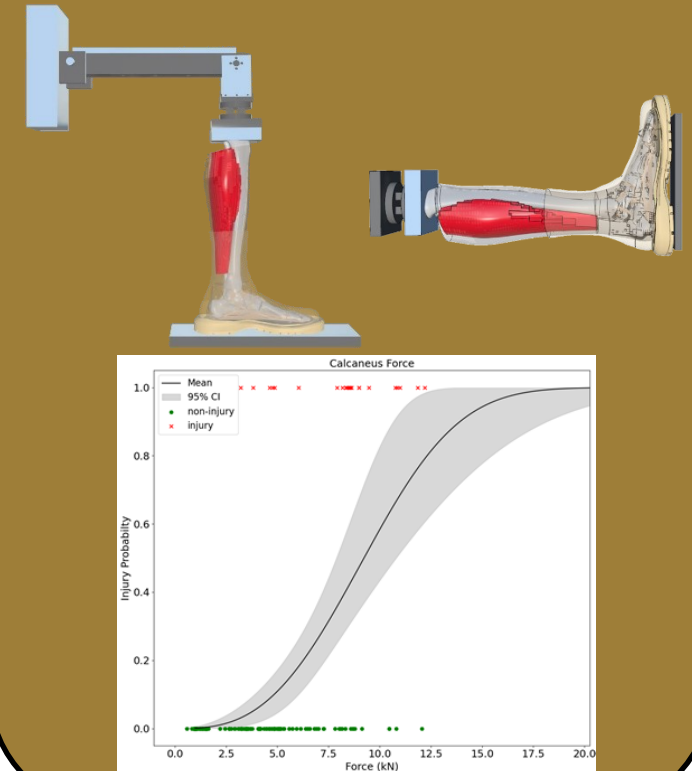
1. Model feasibility



2. Model validation

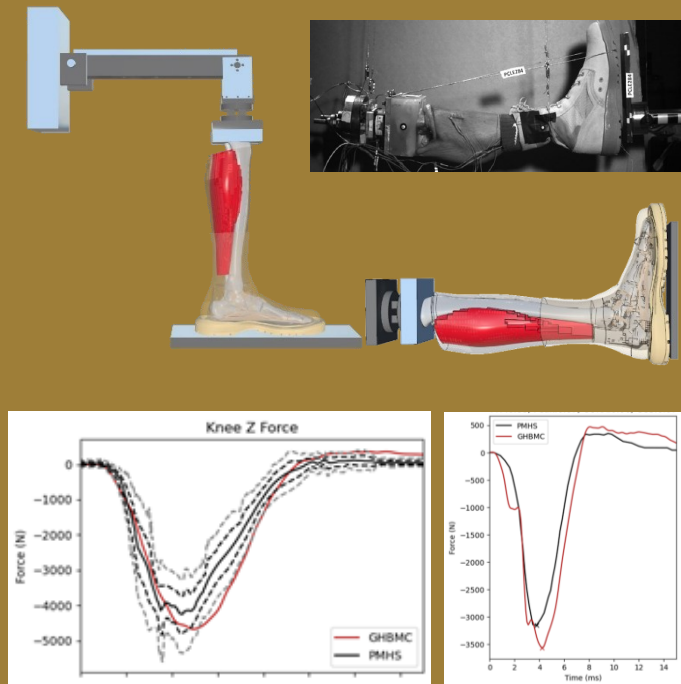


3. Injury risk curve development



Part 2: Model Validation

Model validation



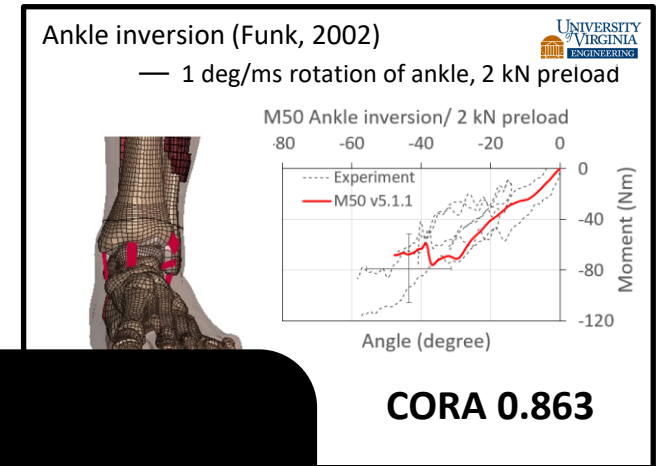
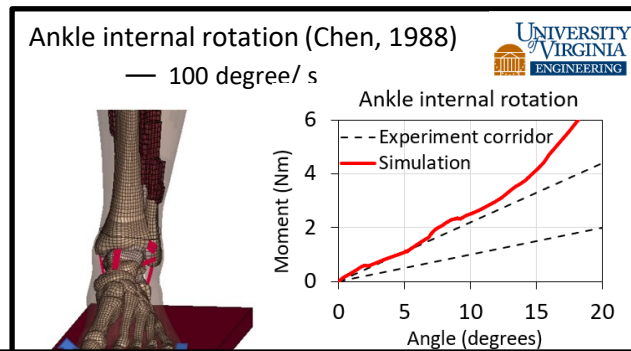
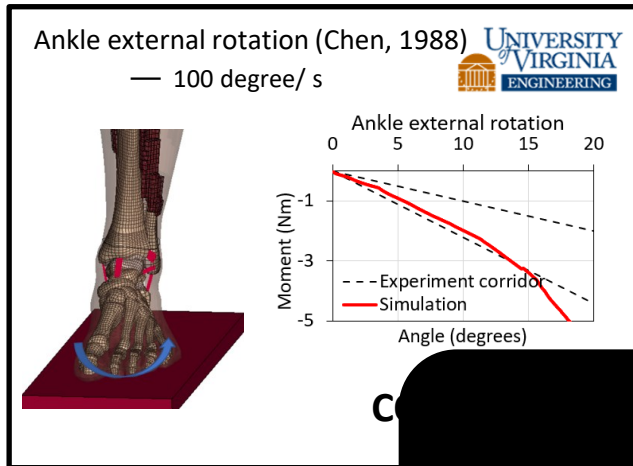
LOWER EXTREMITY VALIDATION OF A HUMAN BODY MODEL FOR HIGH-RATE AXIAL LOADING IN THE UNDERBODY BLAST ENVIRONMENT

The objective of this study was to validate the GHBMC lower extremity using a combined objective rating scheme in vertical and horizontal high-rate axial loading.

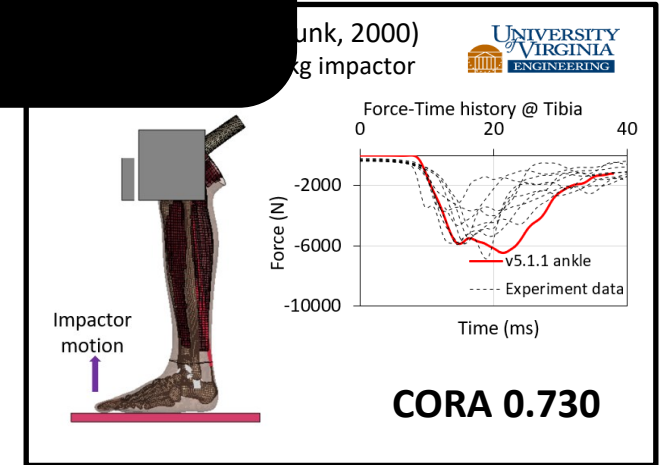
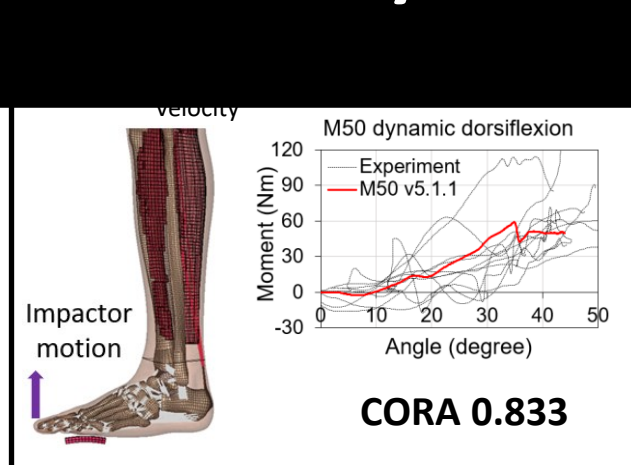
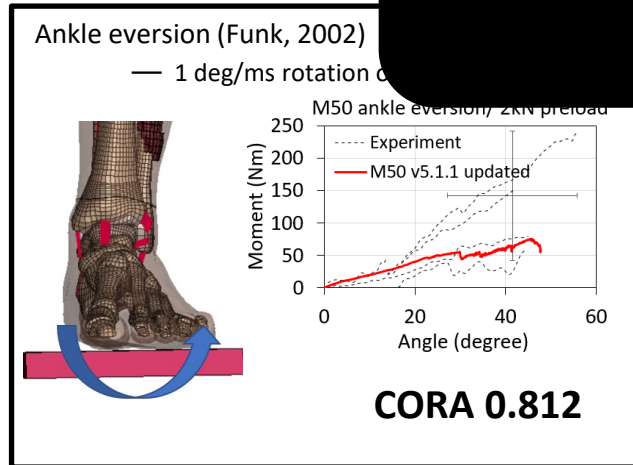
Hostetler ZS, Caffrey J, Aira J, Gayzik FS. Lower Extremity Validation of a Human Body Model for High Rate Axial Loading in the Underbody Blast Environment. Stapp Car Crash J. 2022 Nov;66:99-142.



GHBMC M50-O Lower Extremity Validation Cases



And many more!



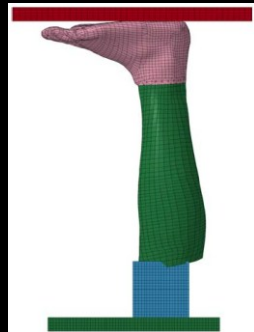
Validation Background, Prior Studies

- Lower extremity in the UBB environment
 - 2 PMHS studies PMHS Study
 - 3 modeling studies FE Modeling

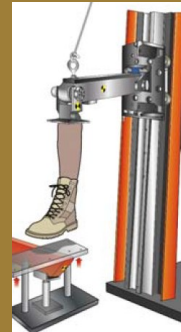
2013 Pendulum Data



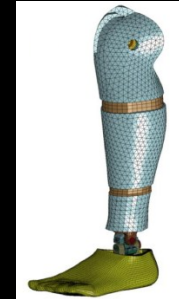
2014 Heel Properties



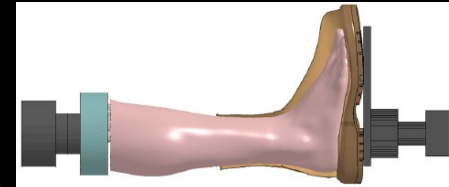
2016 VertAc Data



2018 WIAMan Validation



2019 Boot Study



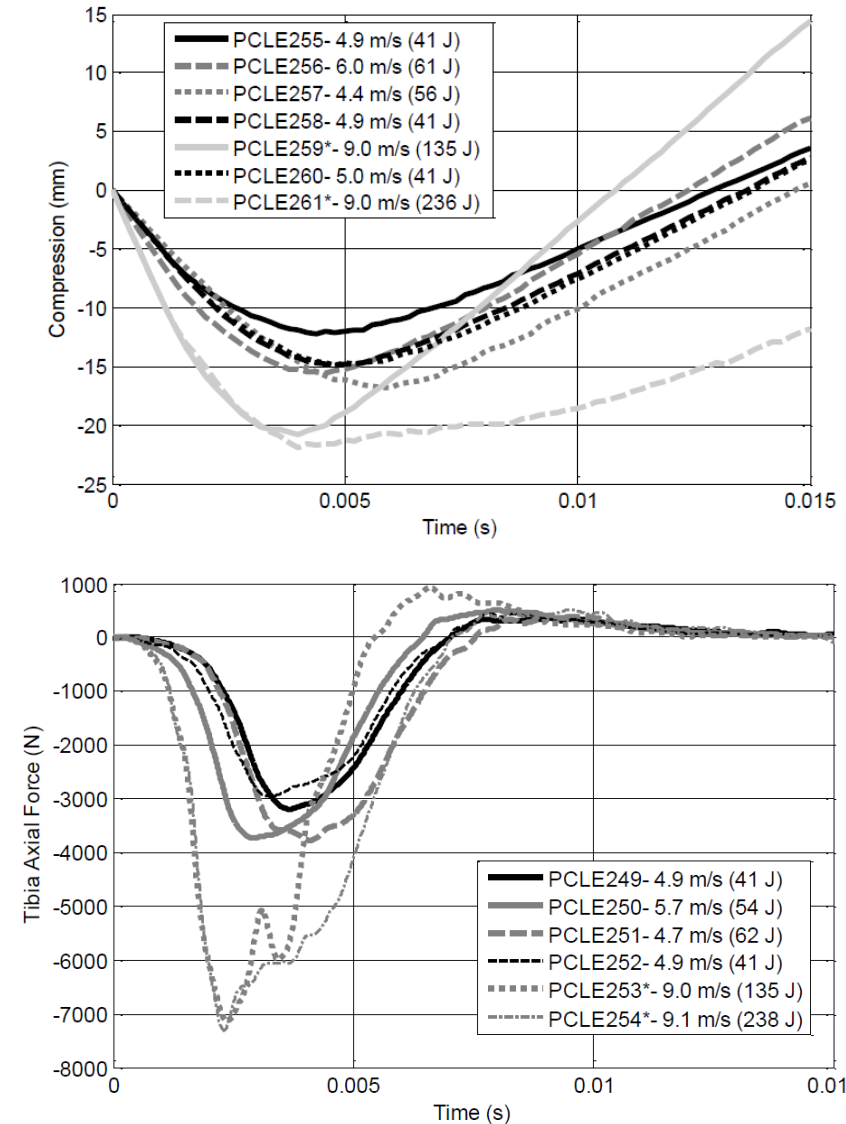
Pendulum Experimental Data

2013

Pendulum Data Gallenberger et al.



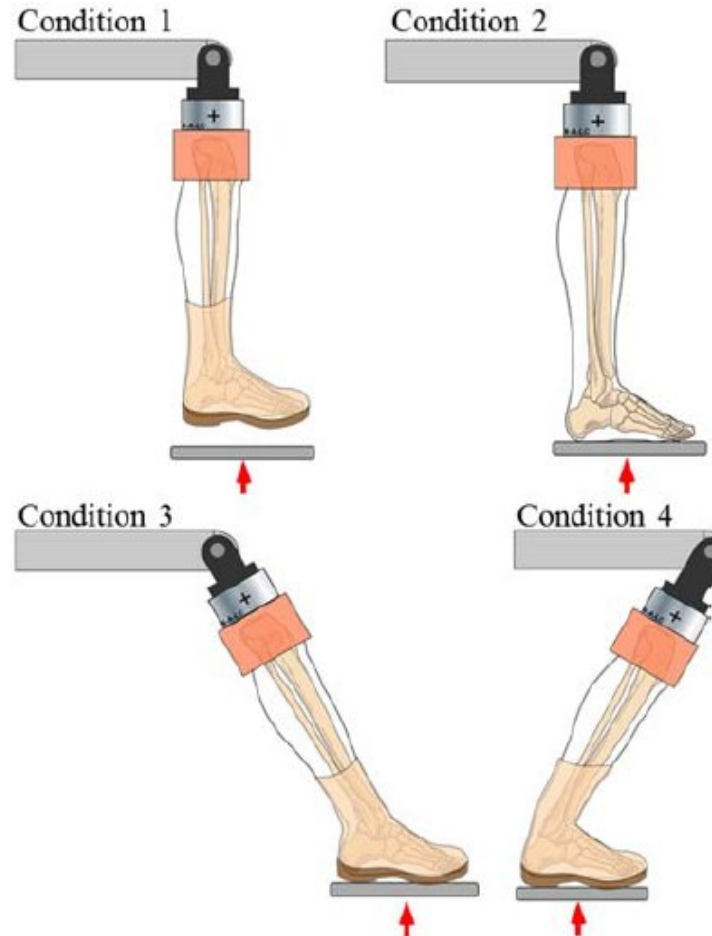
- Pendulum impacts
- 15 specimens- various impacts
- Recorded force and compression response
- Strain time histories from medial calcaneus wall



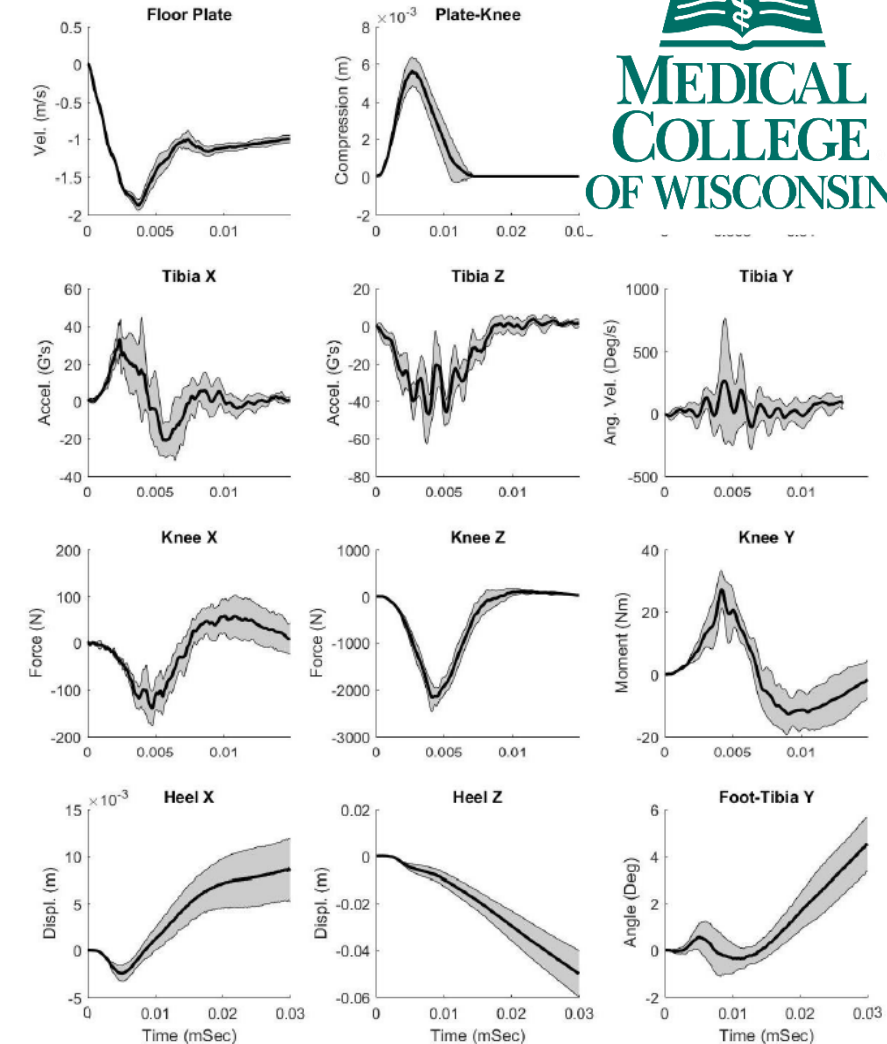
Vertac Experimental Data

2016

VertAc Data
Pintar et al.

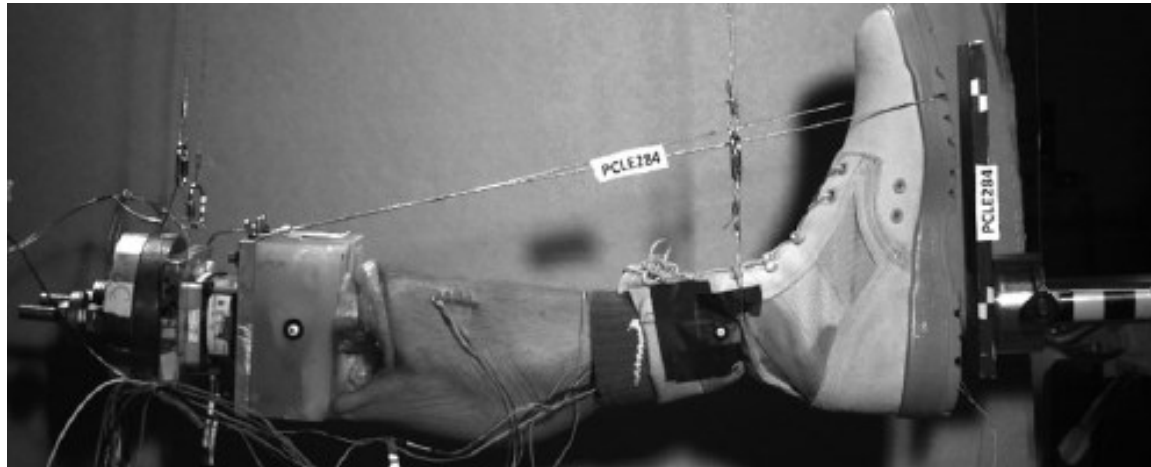
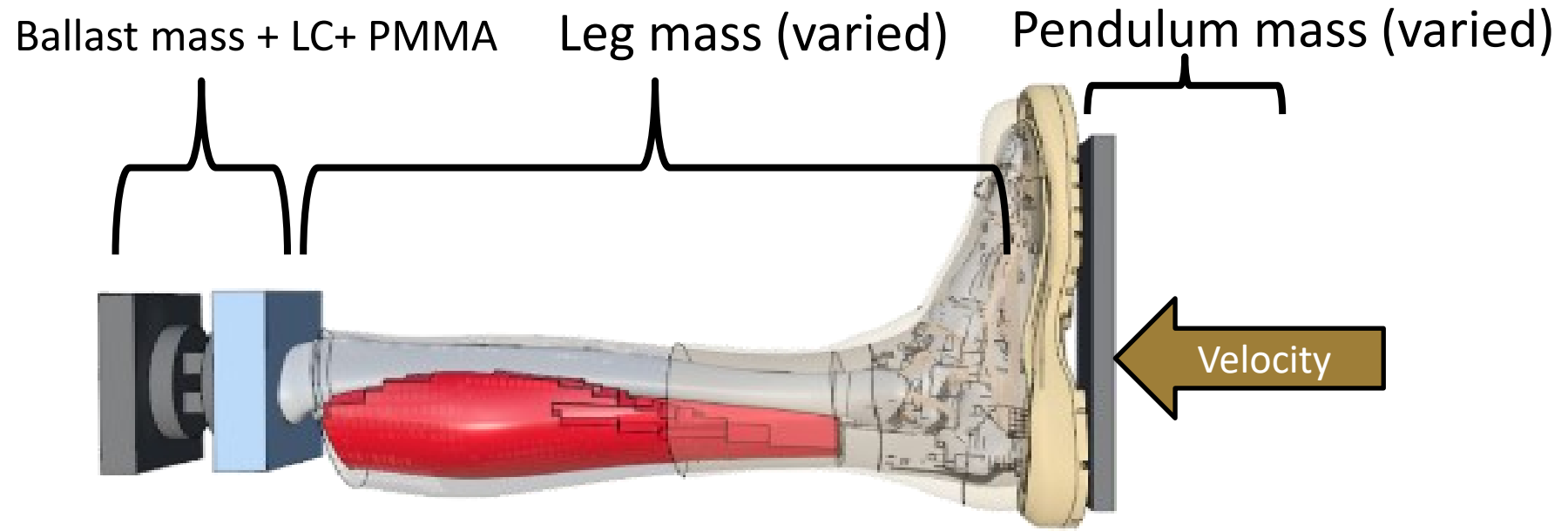


BRCs w/ RCs Unbooted, In-Contact, N

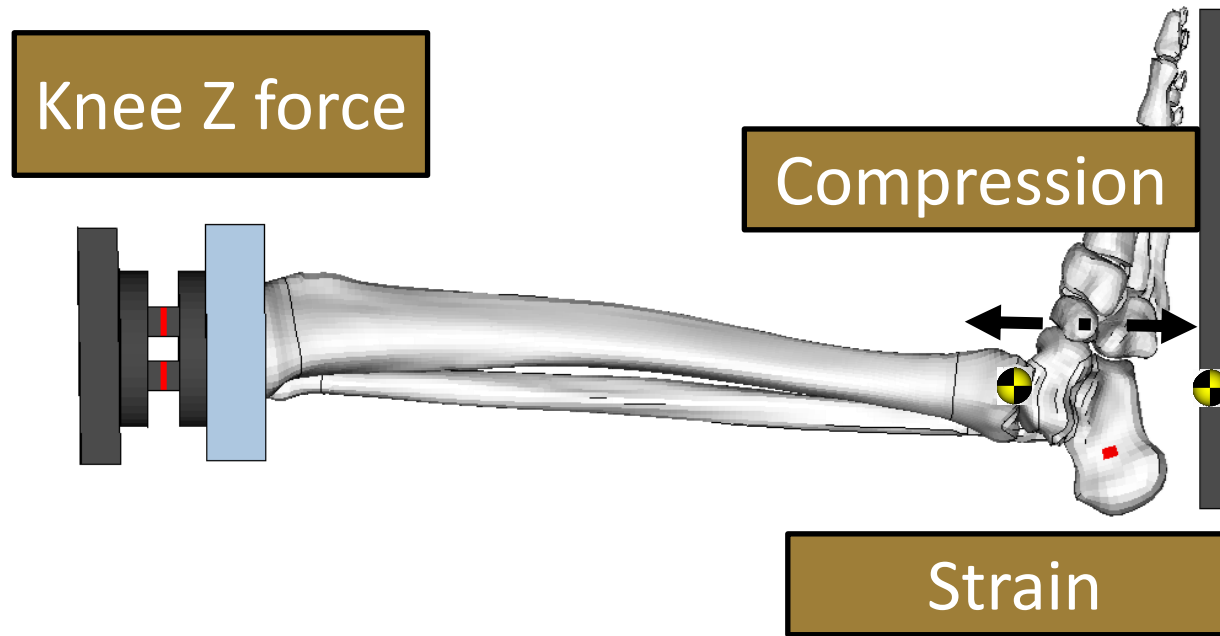


MODEL VALIDATION METHODS

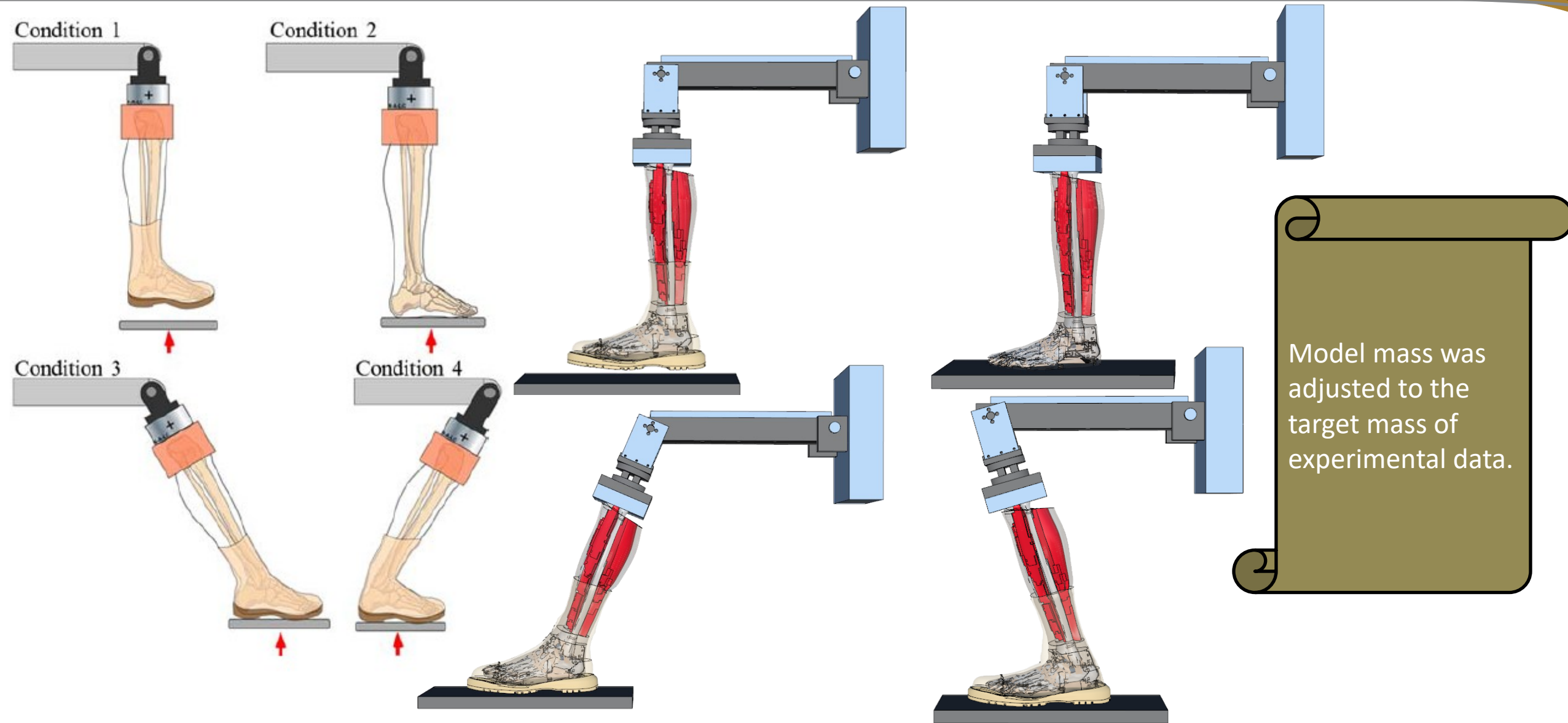
Pendulum Experimental Setup Methods



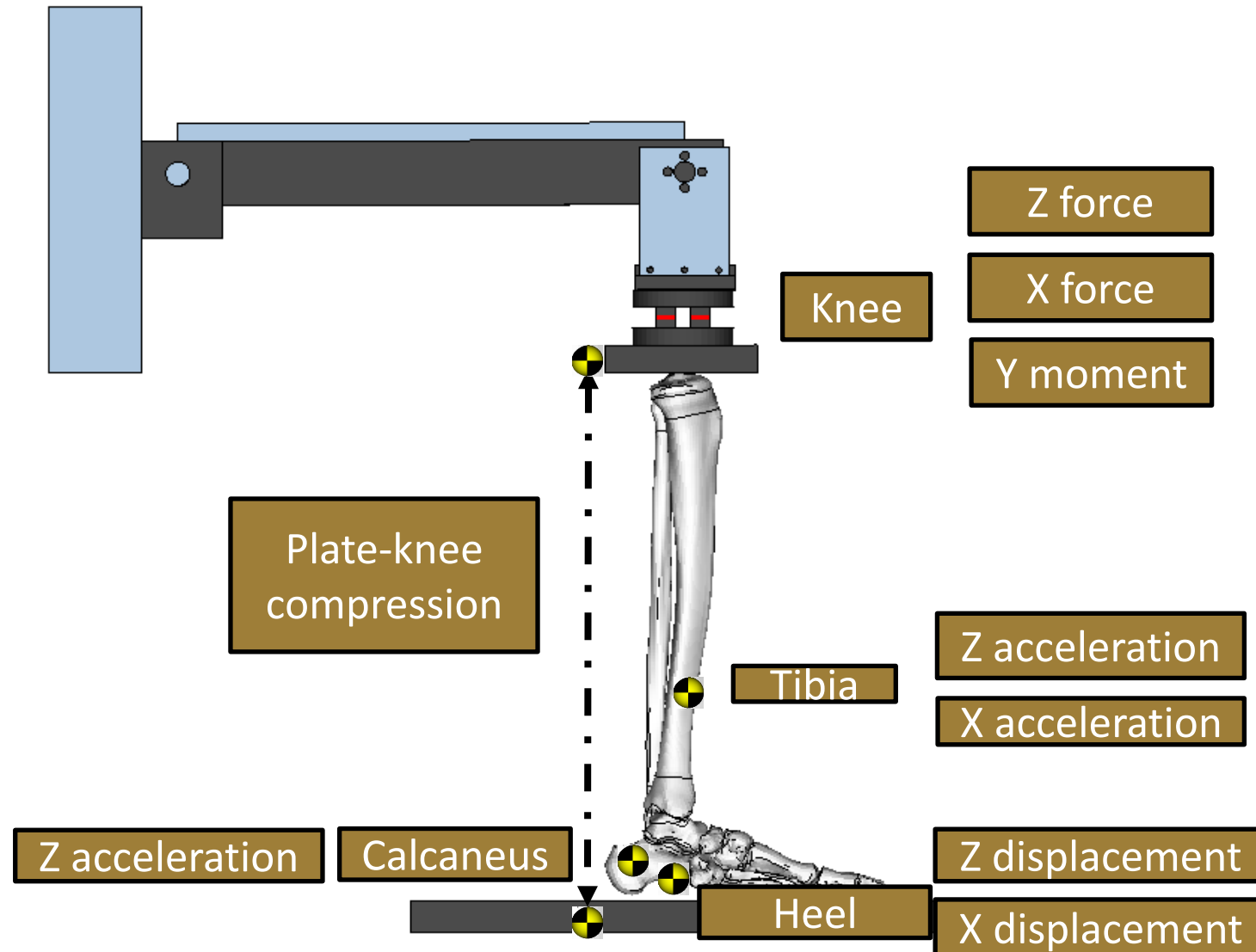
Pendulum Model Instrumentation Methods



Vertac Experimental Methods

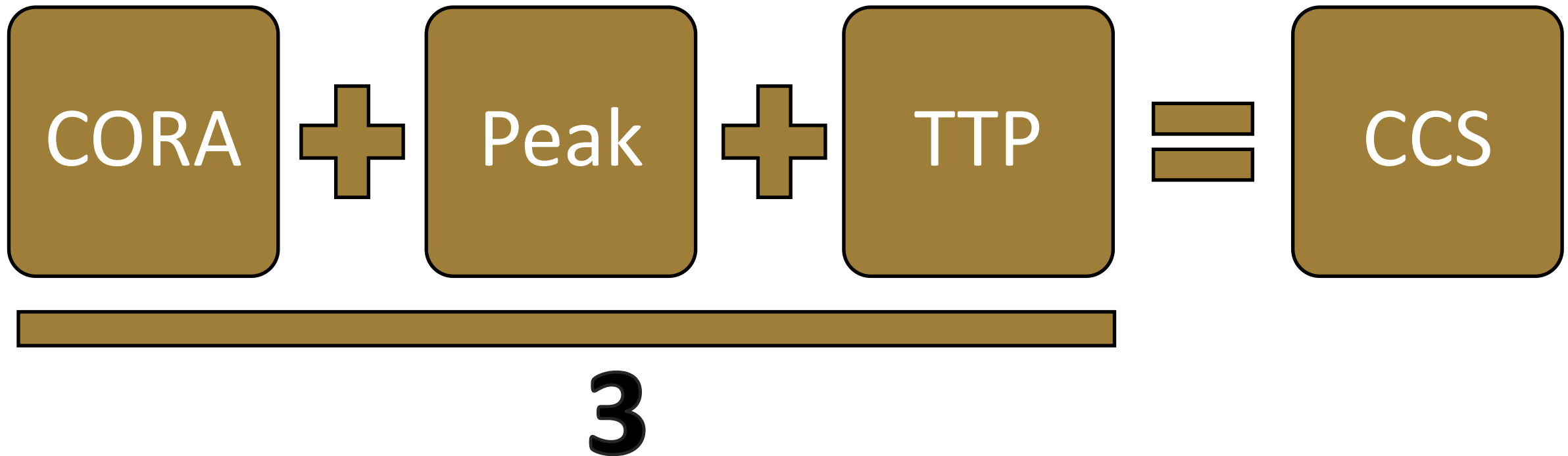


Vertac Model Instrumentation Methods



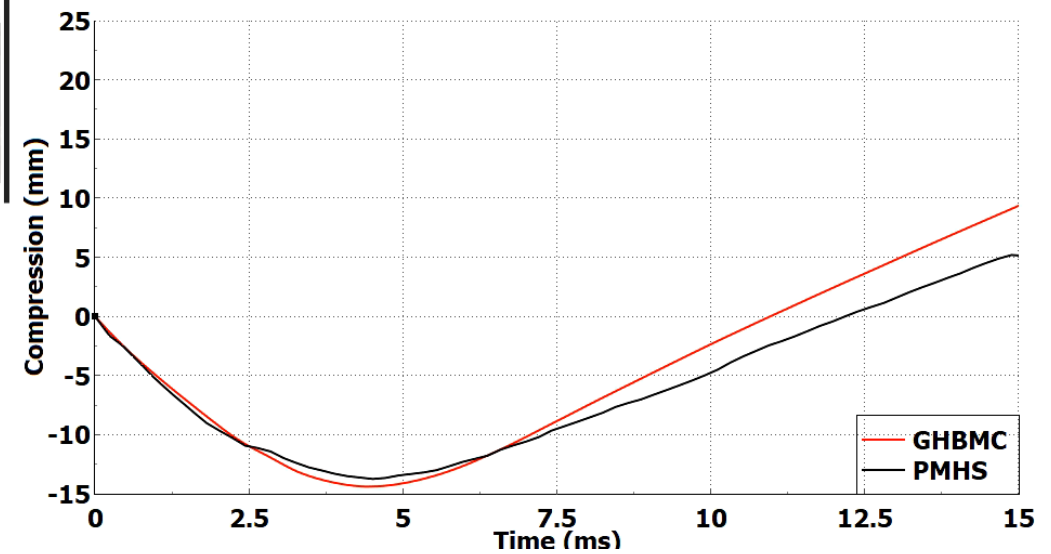
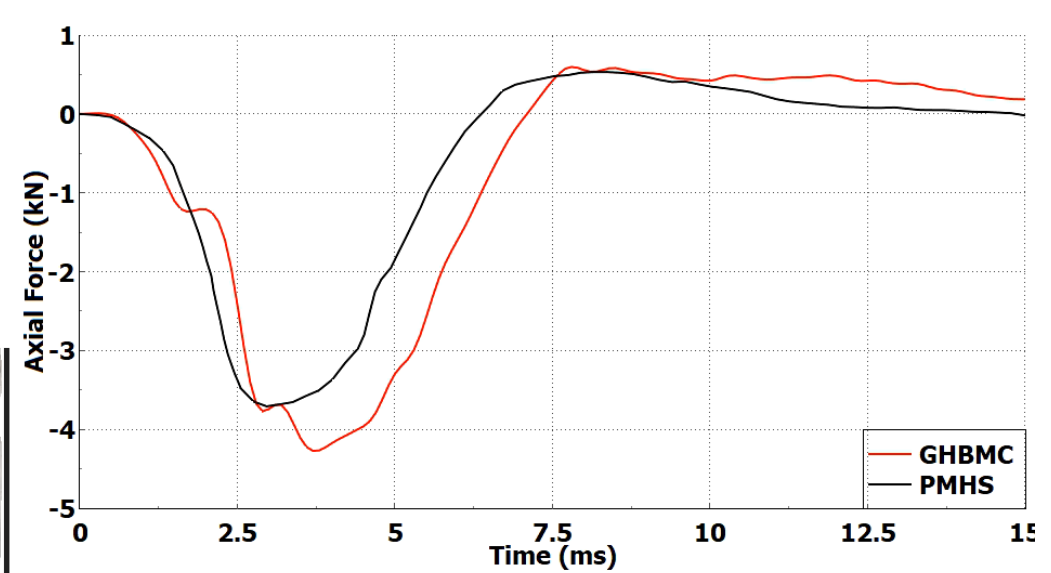
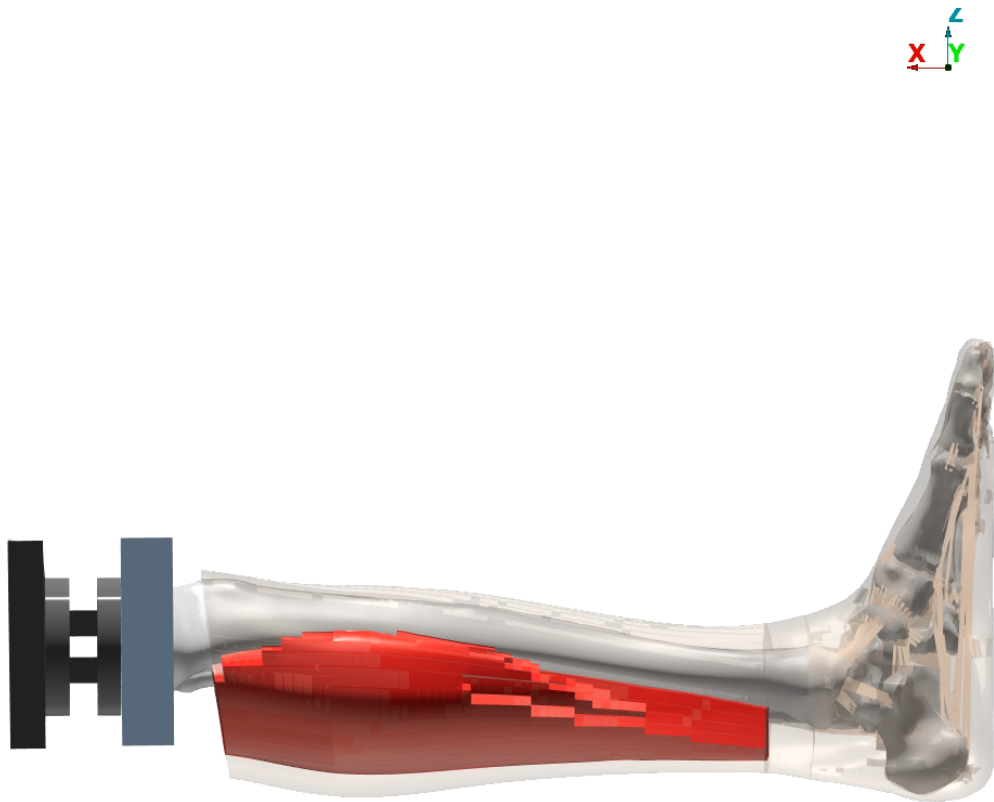
Model Evaluation Criteria: Combined CORA Score

Alexander Max, Baker, et al. "Hierarchical Validation Prevents Over-Fitting of the Neck Material Model for an Anthropomorphic Test Device Used in Underbody Blast Scenarios." *Journal of Biomechanical Engineering* 143.1 (2021).

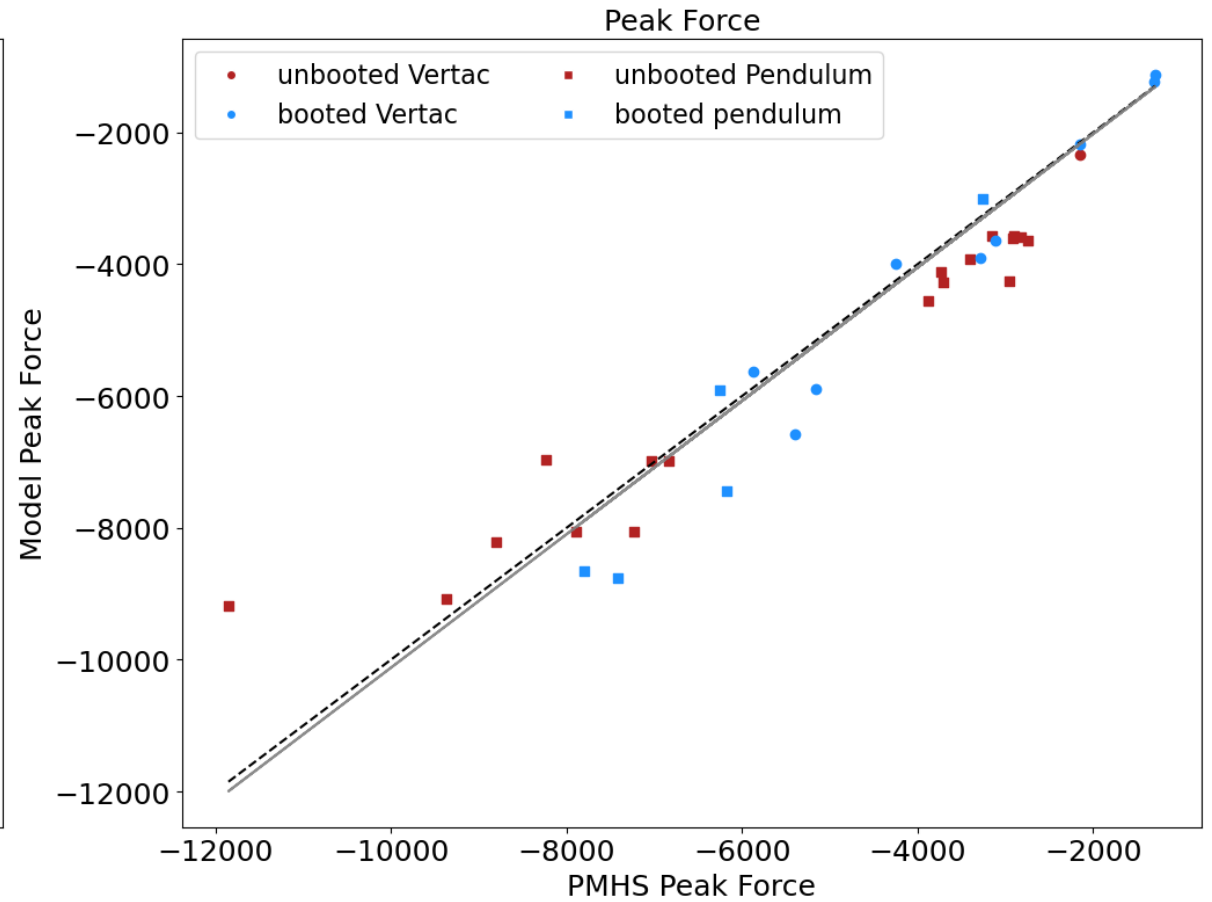
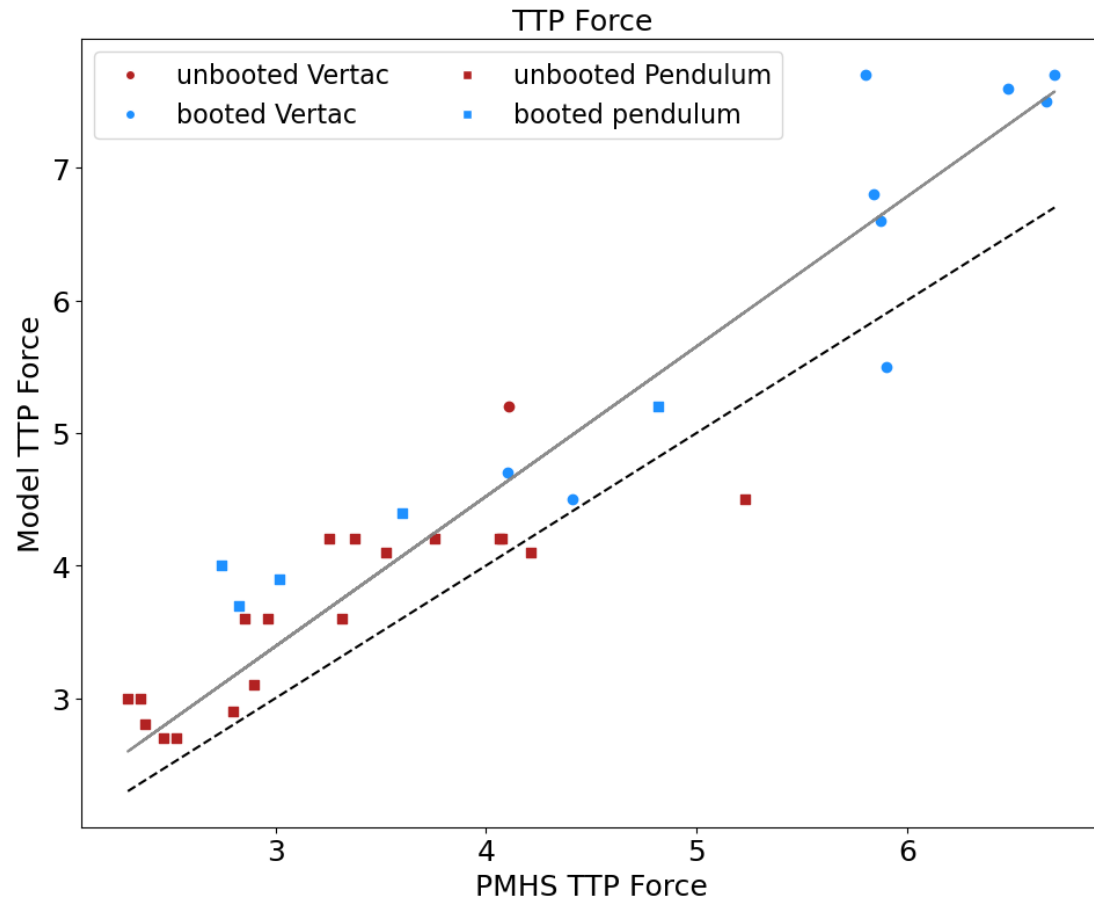


PENDULUM VALIDATION RESULTS

Pendulum Example Case



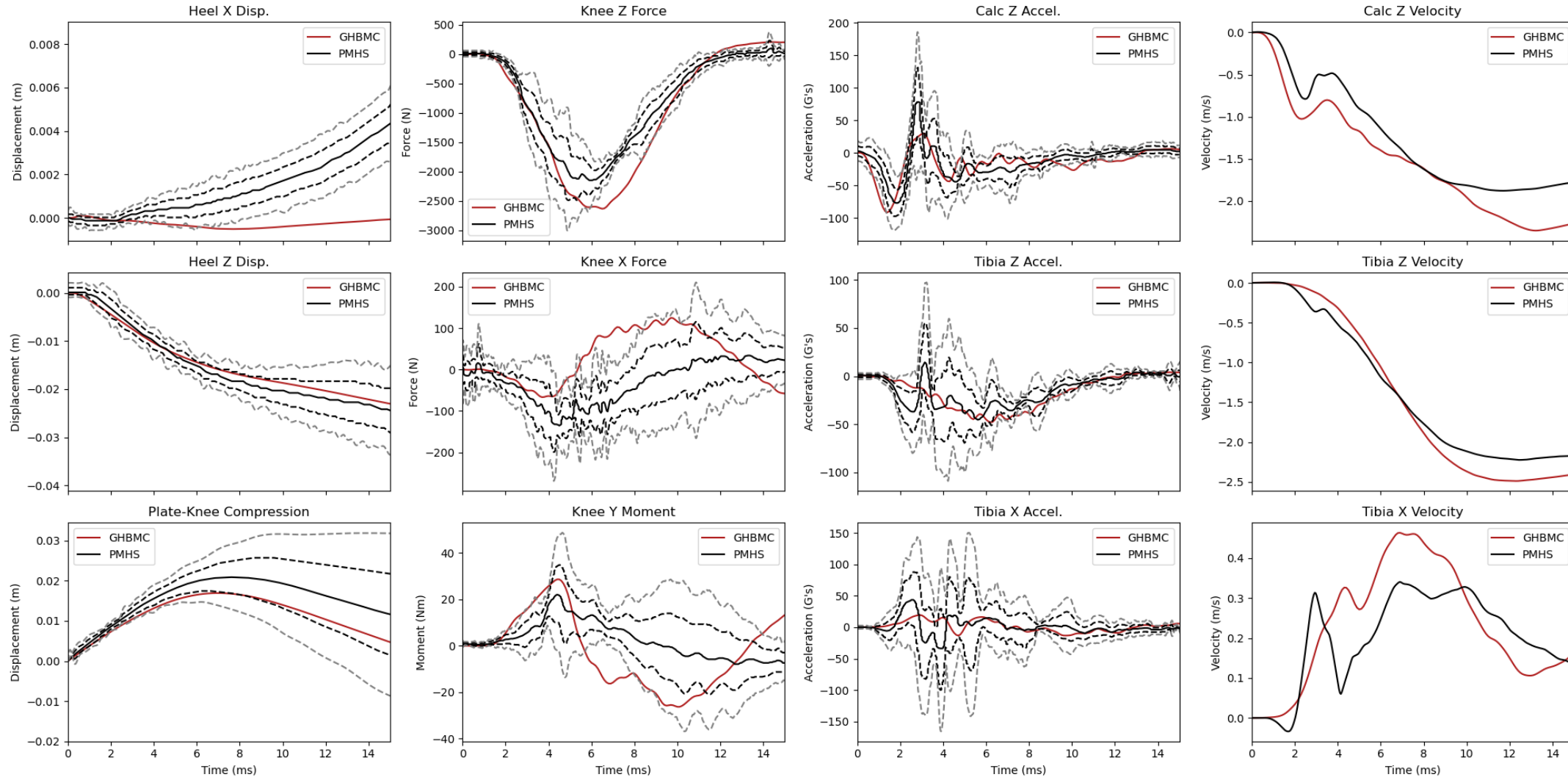
Linear Regression Peak Force Analysis



VERTAC VALIDATION RESULTS

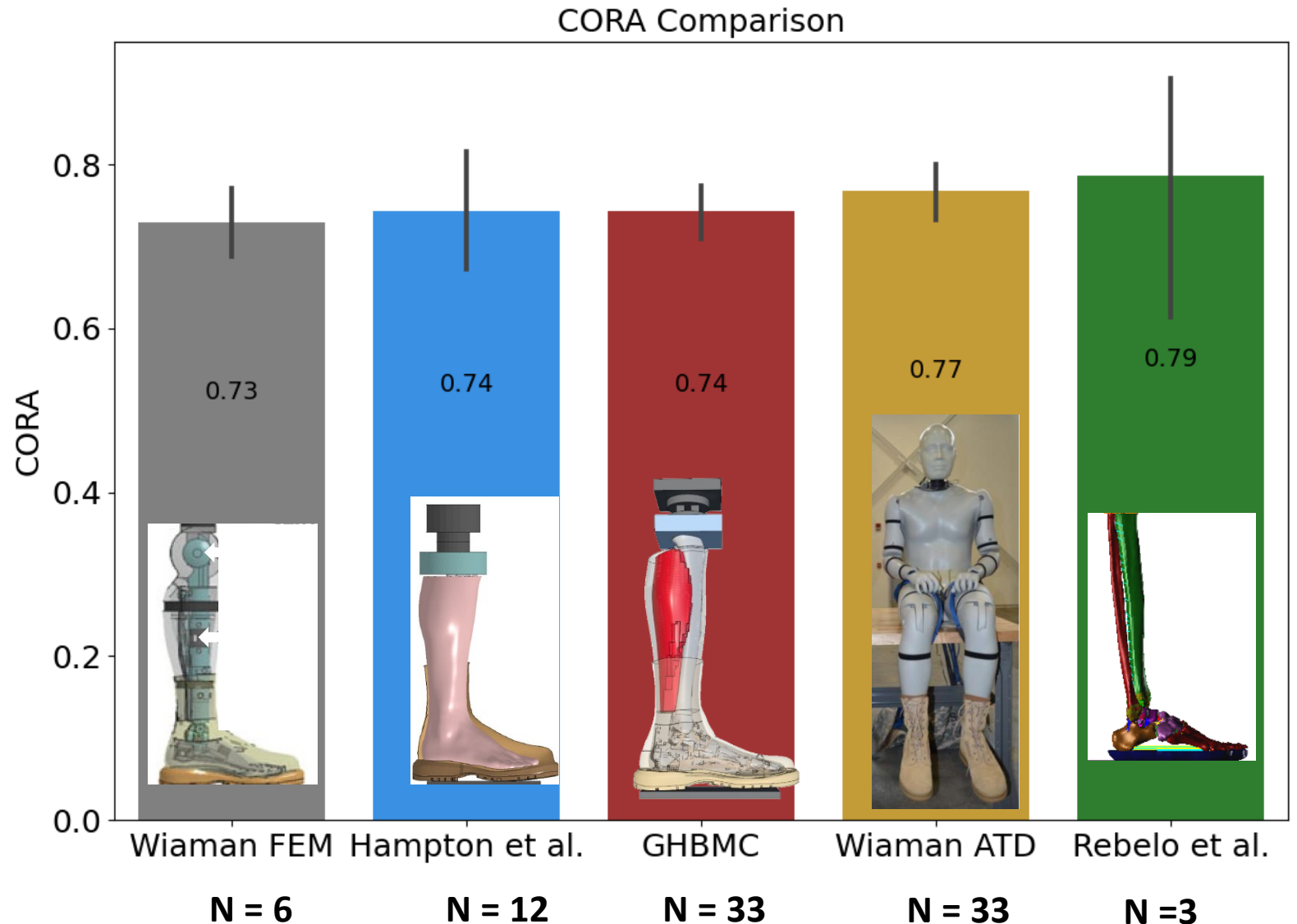
Vertac booted 4mps results

Vertac Booted neutral 4mps



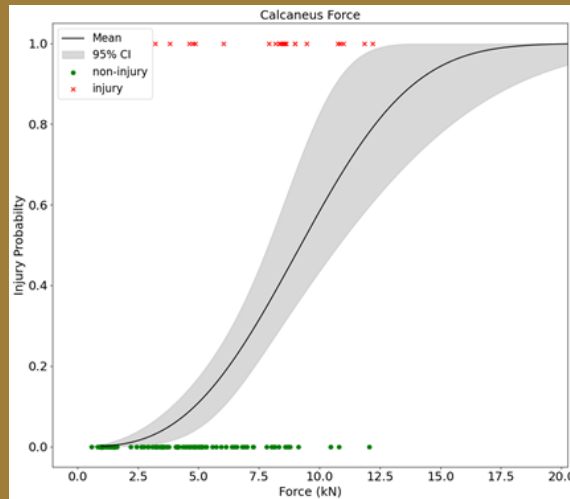
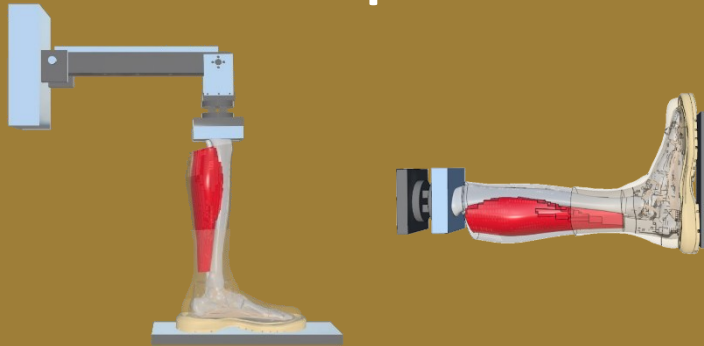
Validation Discussion

- Good agreement in vertical/horizontal loading directions
- **Next step: Develop injury risk curves based on this loading regime**



Injury Risk Curve Development Using Candidate Metrics

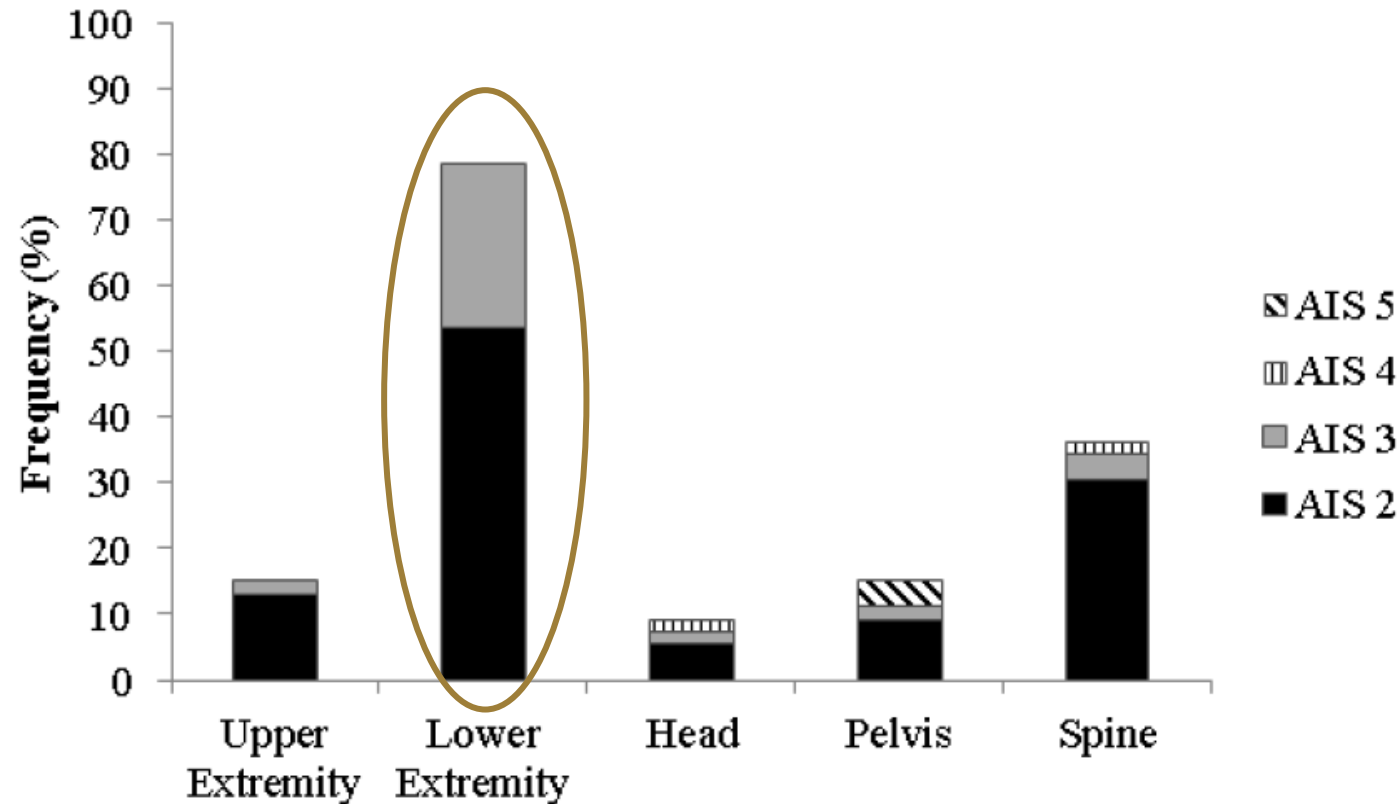
Injury risk curve development



Objective: Develop risk curves for three specific injuries based on FE model results.

Serve as a baseline for injury prediction, PPE evaluation, and informing future testing.

Background: Lower Extremity Injury Prevalence



Fracture Group	Percentage of Warfighters in Dataset
Calcaneus	40%
Forefoot	37%
Tibia, Distal	25%
Fibula, Diaphysis	21%
Midfoot	21%
Talus	19%
Tibia, Diaphysis	46%
Fibula, Distal	13%
Fibula, Proximal	8%

Danelson, Kerry, et al. *Analysis of the Frequency and Mechanism of Injury to Warfighters in the Under-body Blast Environment*. No. 2018-22-0014. SAE Technical Paper, 2018.

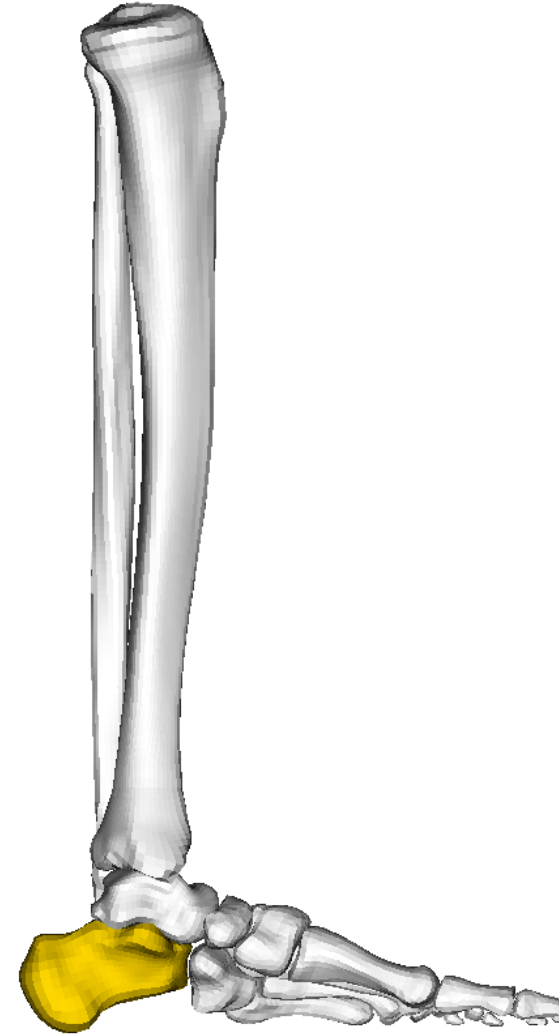
Aim 3 Objective

Given the prevalence of lower extremity injuries, the objective was to develop injury risk curves for 3 specific injuries

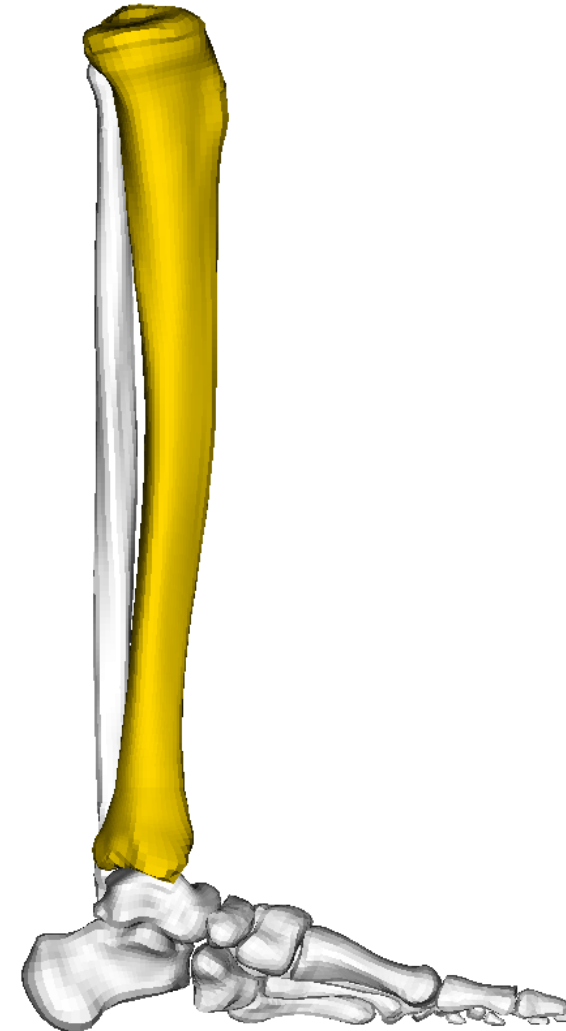
“Any Injury”



“Calcaneus Injury”



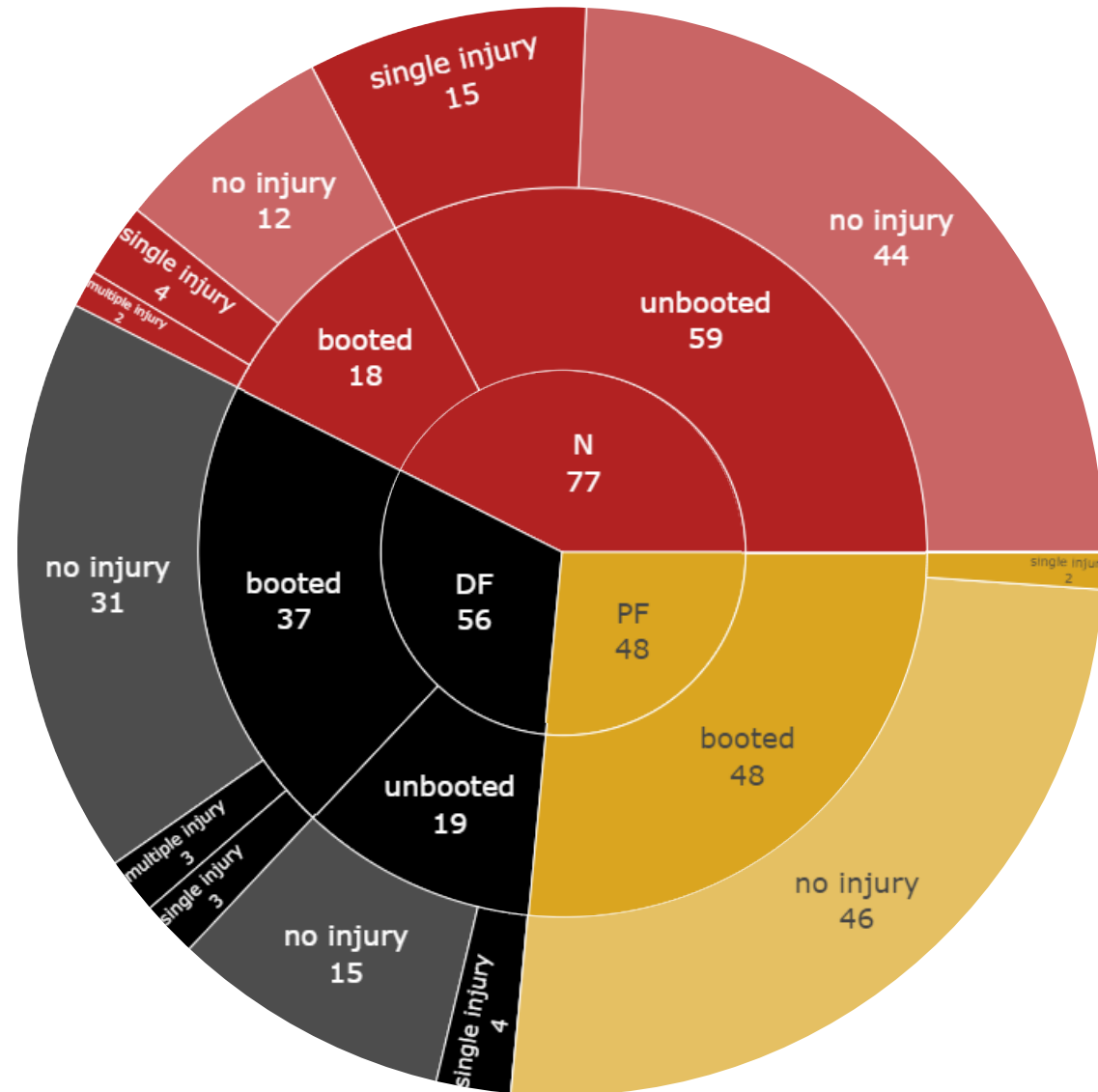
“Tibia Injury”



METHODS

Overview of Cases

- 181 total simulations
- Model mass and geometry **not** adjusted
- Right/left censoring for simulations



Model Instrumentation Advantages



Force, F

$$Impulse = \int_{t=0}^{t=20} F dt$$

Moment, M

$$Tibia Index = \frac{F}{F_c} + \frac{M}{M_c}$$

Energy, E

Strain, ϵ

Metric Count: 43

Model Instrumentation Advantages



Force, F

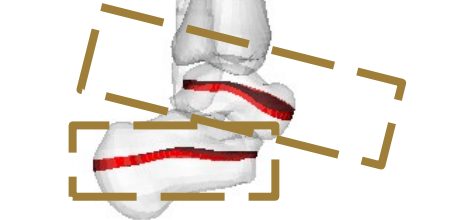
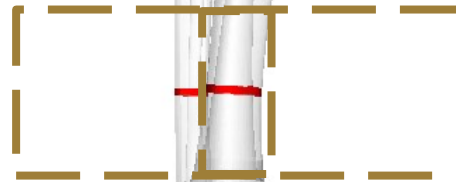
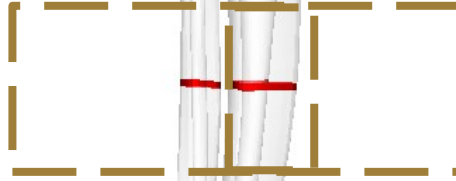
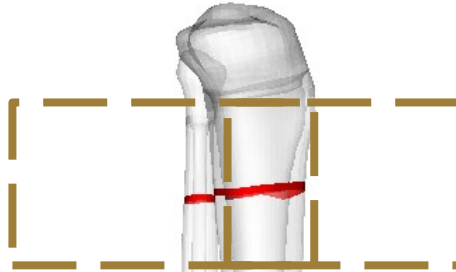
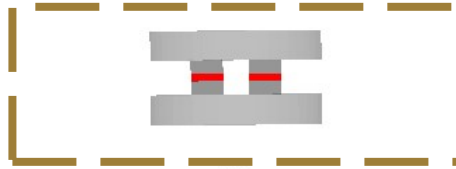
$$\text{Impulse} = \int_{t=0}^{t=20} F \, dt$$

Moment, M

$$\text{Tibia Index} = \frac{F}{F_c} + \frac{M}{M_c}$$

Energy, E

Strain, ϵ



Metric Count: 20

Model Instrumentation Advantages



Force, F

$$Impulse = \int_{t=0}^{t=20} F dt$$

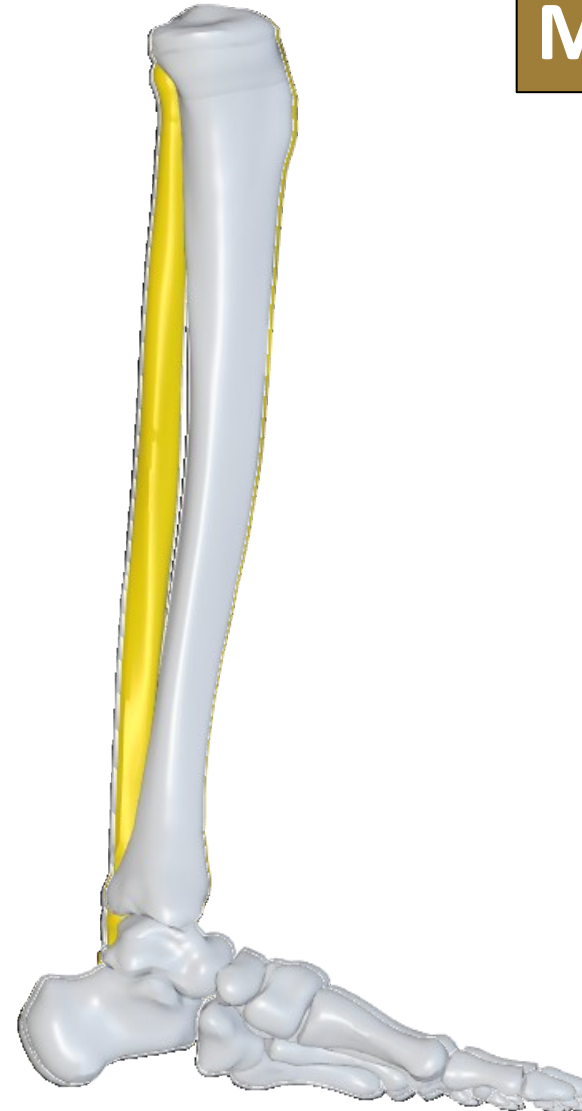
Moment, M

$$Tibia Index = \frac{F}{F_c} + \frac{M}{M_c}$$

Energy, E

Strain, ϵ

Metric Count: 30



Model Instrumentation Advantages



Force, F

$$Impulse = \int_{t=0}^{t=20} F dt$$

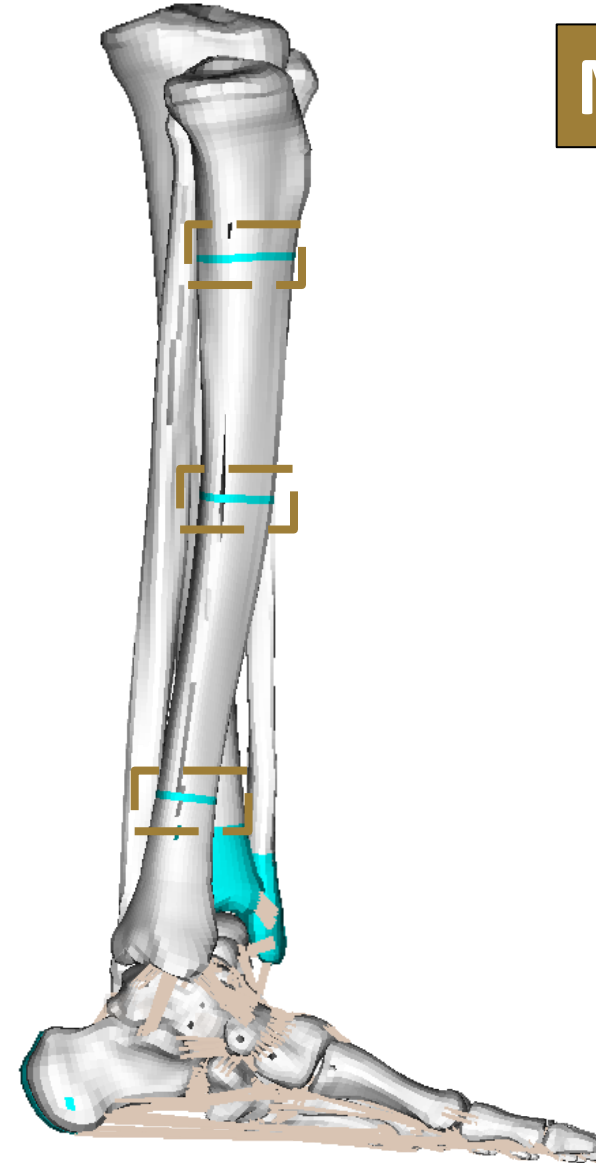
Moment, M

$$Tibia Index = \frac{F}{F_c} + \frac{M}{M_c}$$

Energy, E

Strain, ϵ

Metric Count: 34



Model Instrumentation Advantages



Force, F

$$\text{Impulse} = \int_{t=0}^{t=20} F \, dt$$

Moment, M

$$\text{Tibia Index} = \frac{F}{F_c} + \frac{M}{M_c}$$

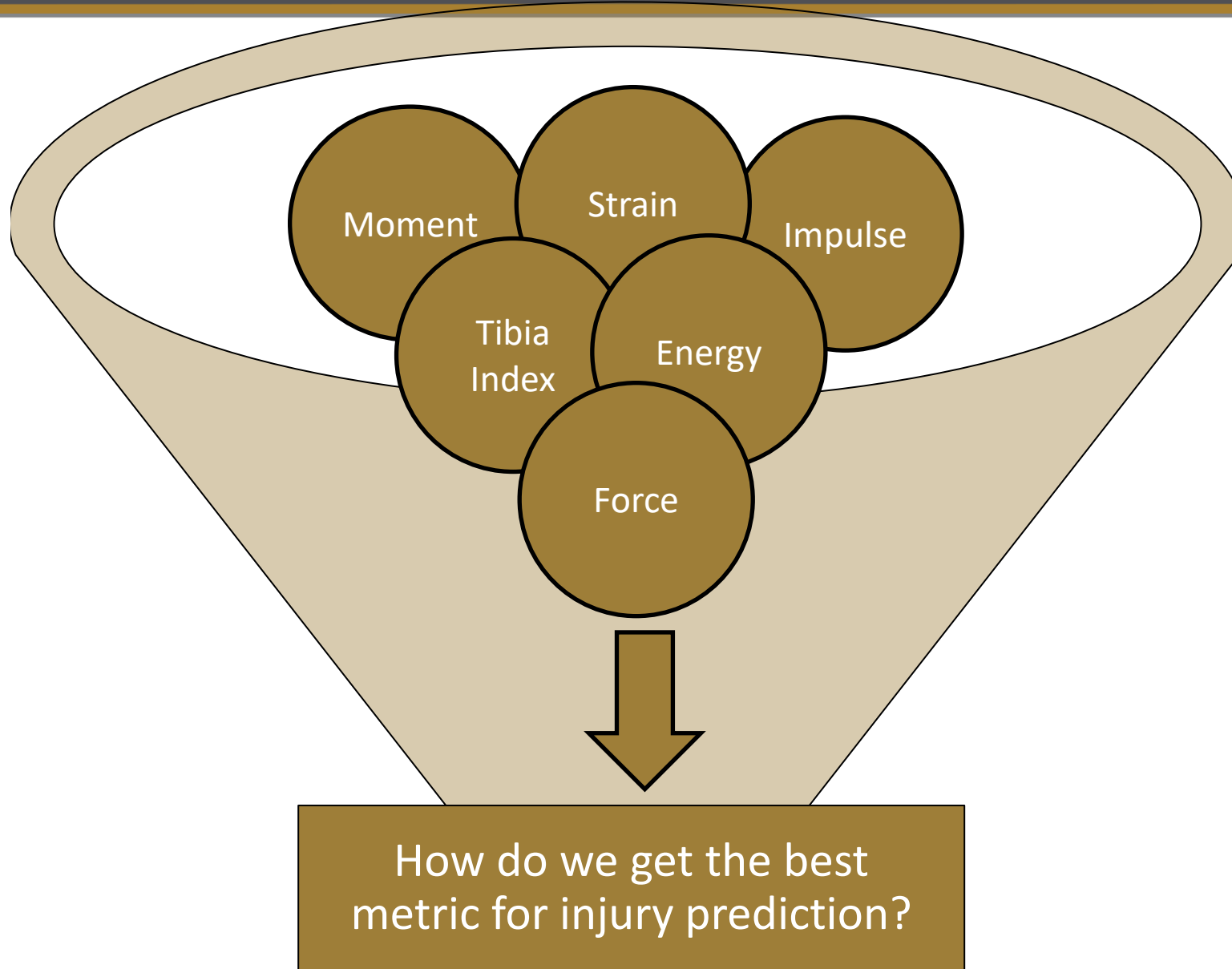
Energy, E

Strain, ϵ

Metric Count: 43



Model Instrumentation Advantages



$43 \times 181 = 7,783$
input time histories

Metric Selection for Injury Risk Curve Development

Annals of Biomedical Engineering (© 2020)
https://doi.org/10.1007/s10439-020-02686-8

WIAMan Biomechanics

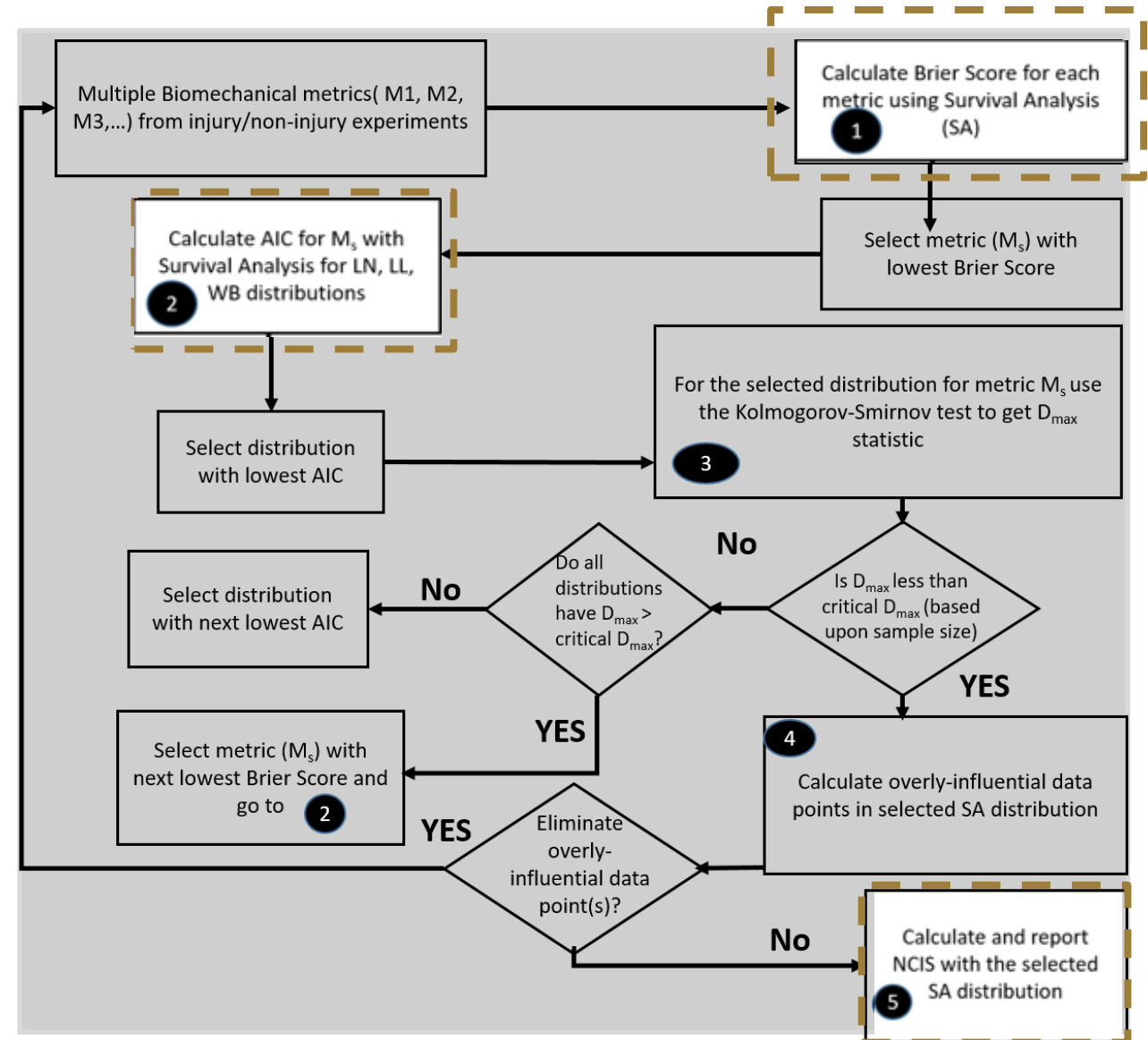
An Improved Method for Developing Injury Risk Curves Using the Brier Metric Score

ZACHARY S. HOSTETLER,¹ FANG-CHI HSU,² NARAYAN YOGANANDAN,³
FRANK A. PINTAR,³ ANJISHNU BANERJEE,⁴ LIMING VOO,⁵
and F. SCOTT GAYZIK¹

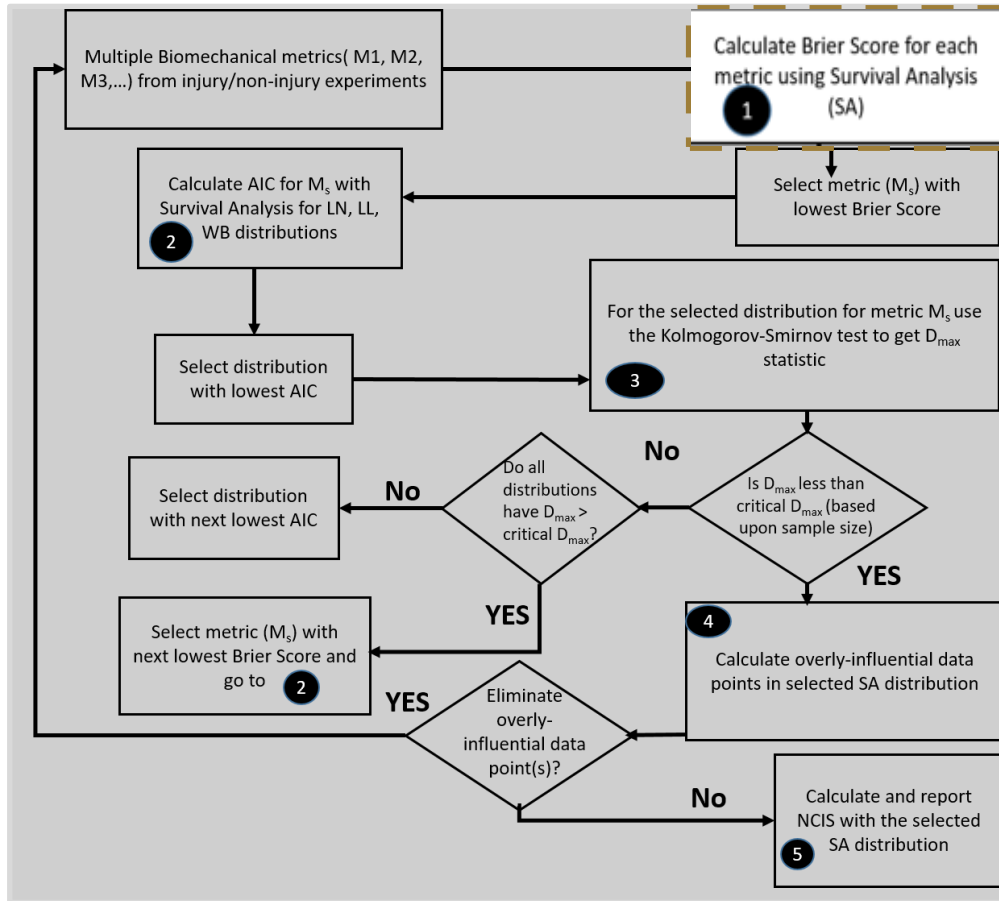
- calcaneus_energy.csv
- calcaneus_force.csv
- calcaneus_impulse.csv
- calcaneus_moment.csv
- calcaneus_strain.csv
- fibula_energy.csv
- fibula_strain.csv
- knee_force.csv
- knee_impulse.csv
- knee_moment.csv
- lower fibula_force.csv
- lower fibula_impulse.csv
- lower fibula_moment.csv
- lower tibia_force.csv



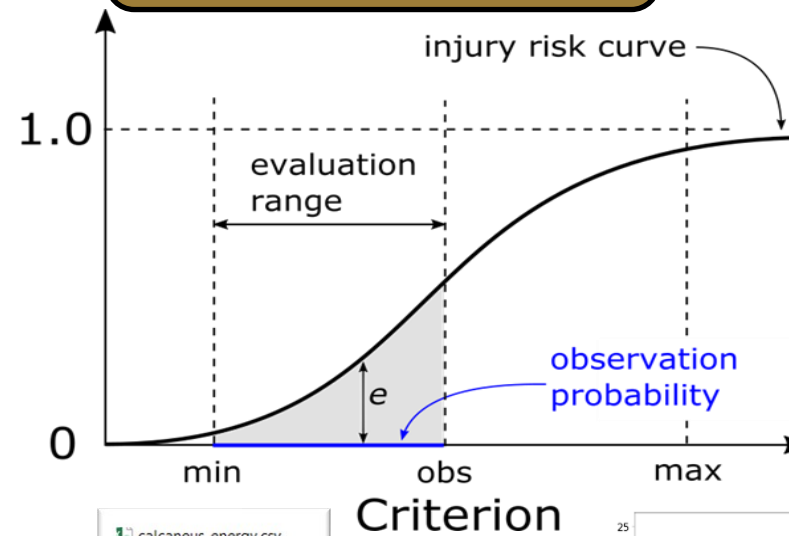
BMES BIOMEDICAL
ENGINEERING
SOCIETY



Metric Selection for Injury Risk Curve Development

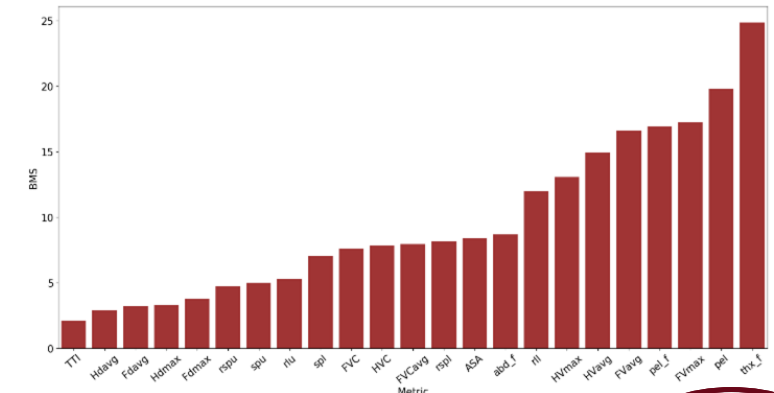


Brier Metric Score



- Objective ranking of injury risk curves
- $BMS = \frac{\sum_{obs} BS_{obs}}{N}$
- Lower BMS is better

calcaneus_energy.csv
 calcaneus_force.csv
 calcaneus_impulse.csv
 calcaneus_moment.csv
 calcaneus_strain.csv
 fibula_energy.csv
 fibula_strain.csv
 knee_force.csv
 knee_impulse.csv
 knee_moment.csv
 lower fibula_force.csv
 lower fibula_impulse.csv
 lower fibula_moment.csv
 lower tibia_force.csv



Methods: Metric Selection Overview

BMS RANK

1

2

3

•

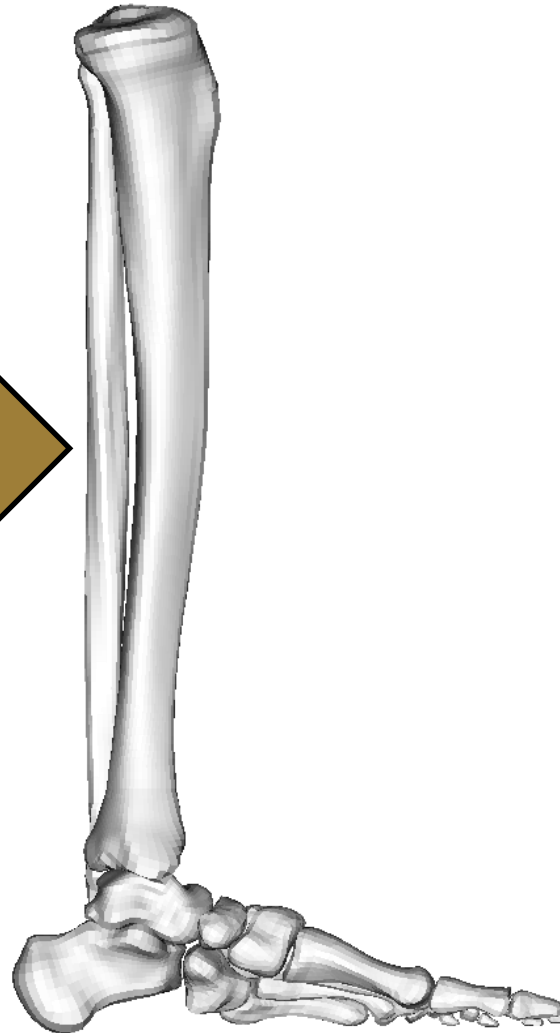
•

•

43

Injury Predictor

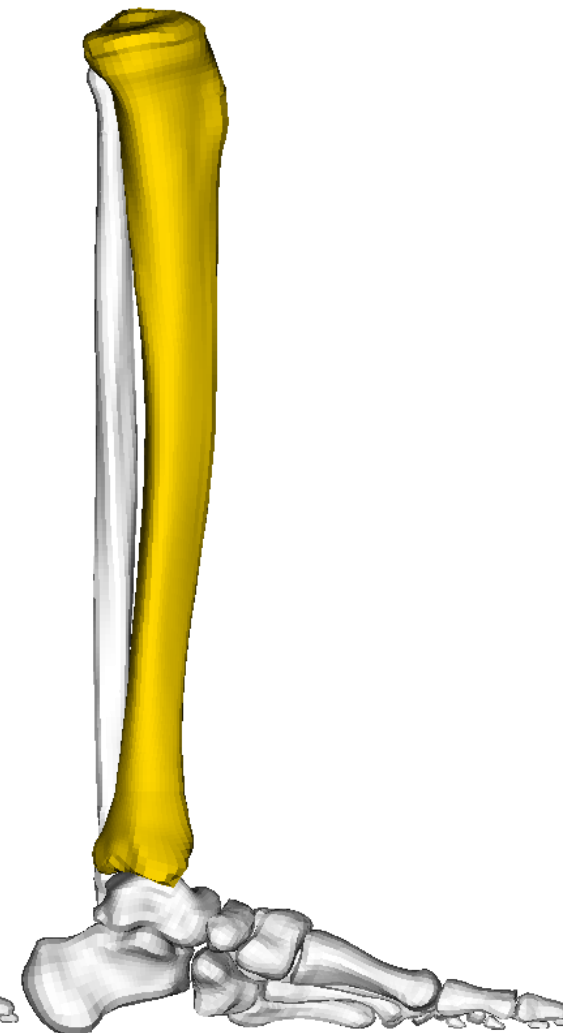
“Any Injury”



“Calcaneus Injury”



“Tibia Injury”



Methods: Covariate Exploration

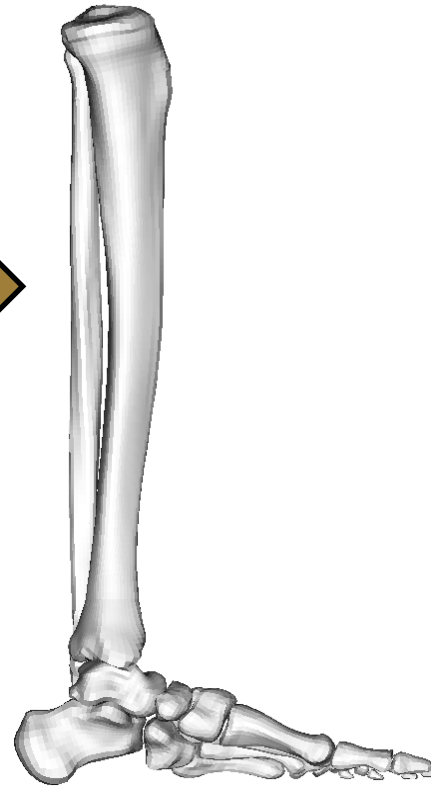
1

2

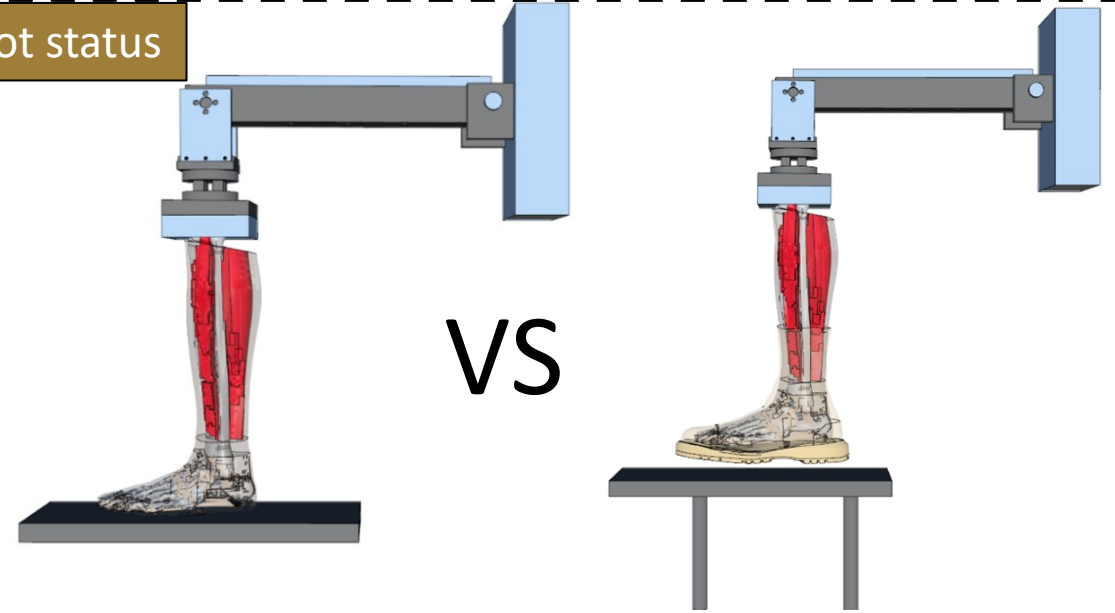
3



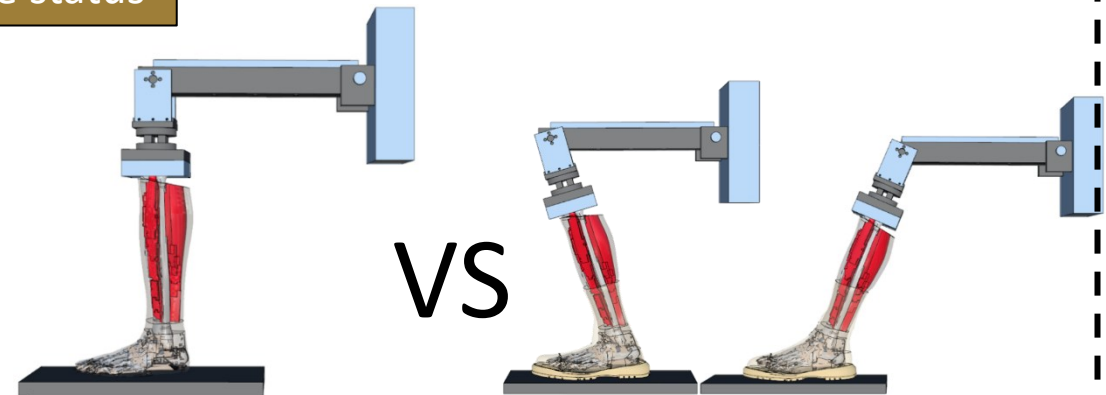
"Any injury"



Boot status



Posture status



RESULTS: INJURY RISK CURVE DEVELOPMENT

“Calcaneus Injury” Results

BMS RANK

1

2

3

•

•

•

43

Injury Predictor

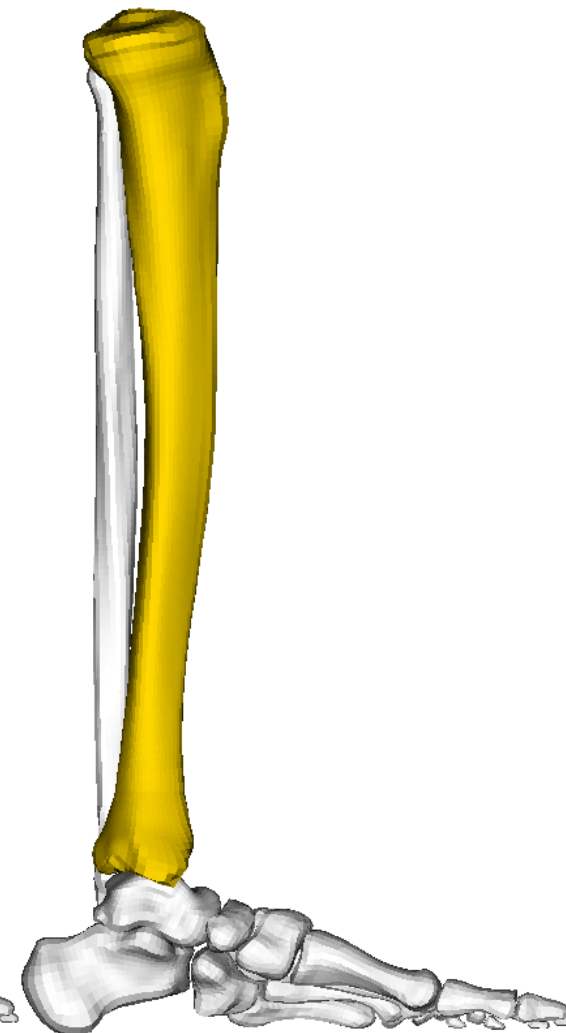
“Any Injury”



“Calcaneus Injury”

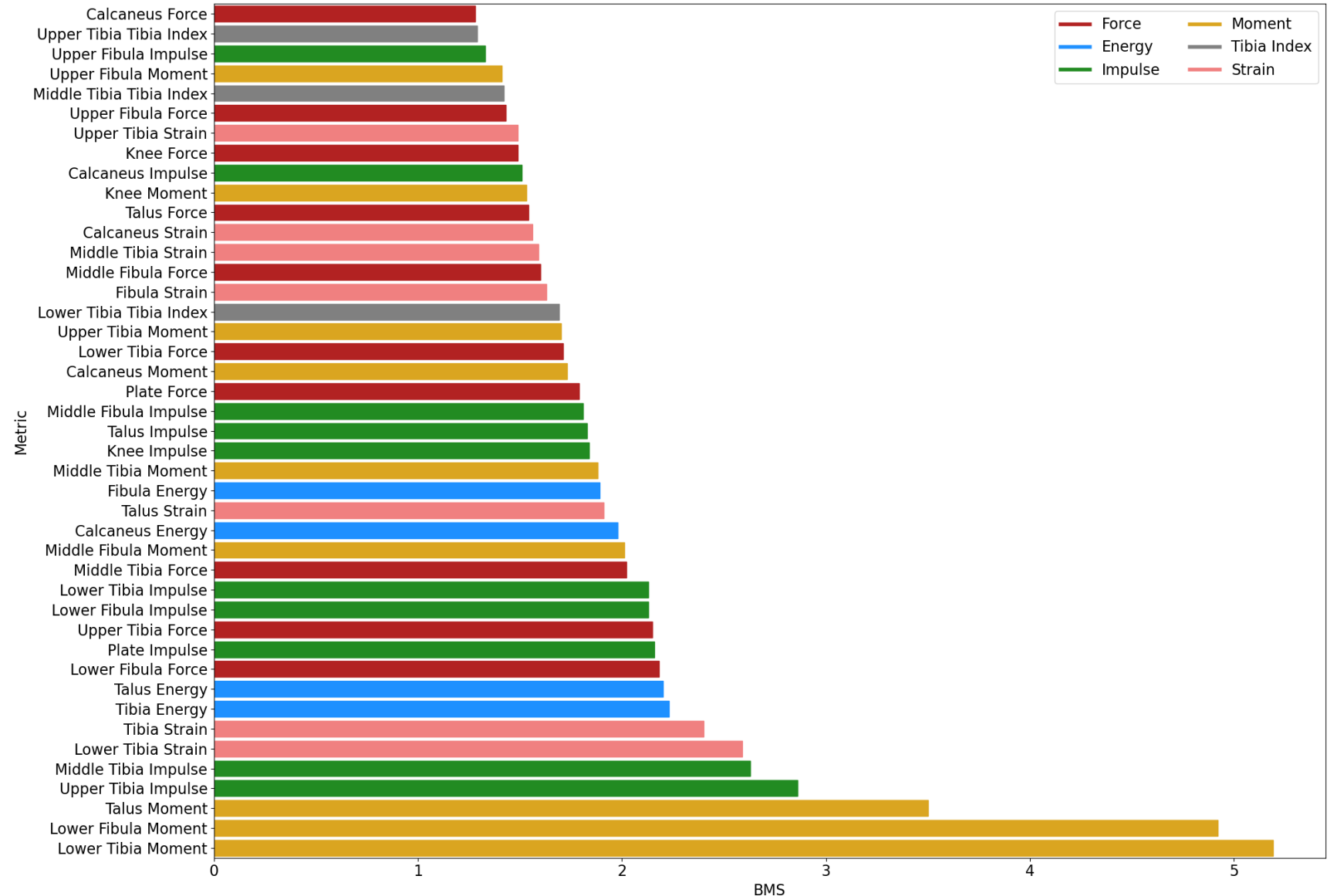


“Tibia Injury”

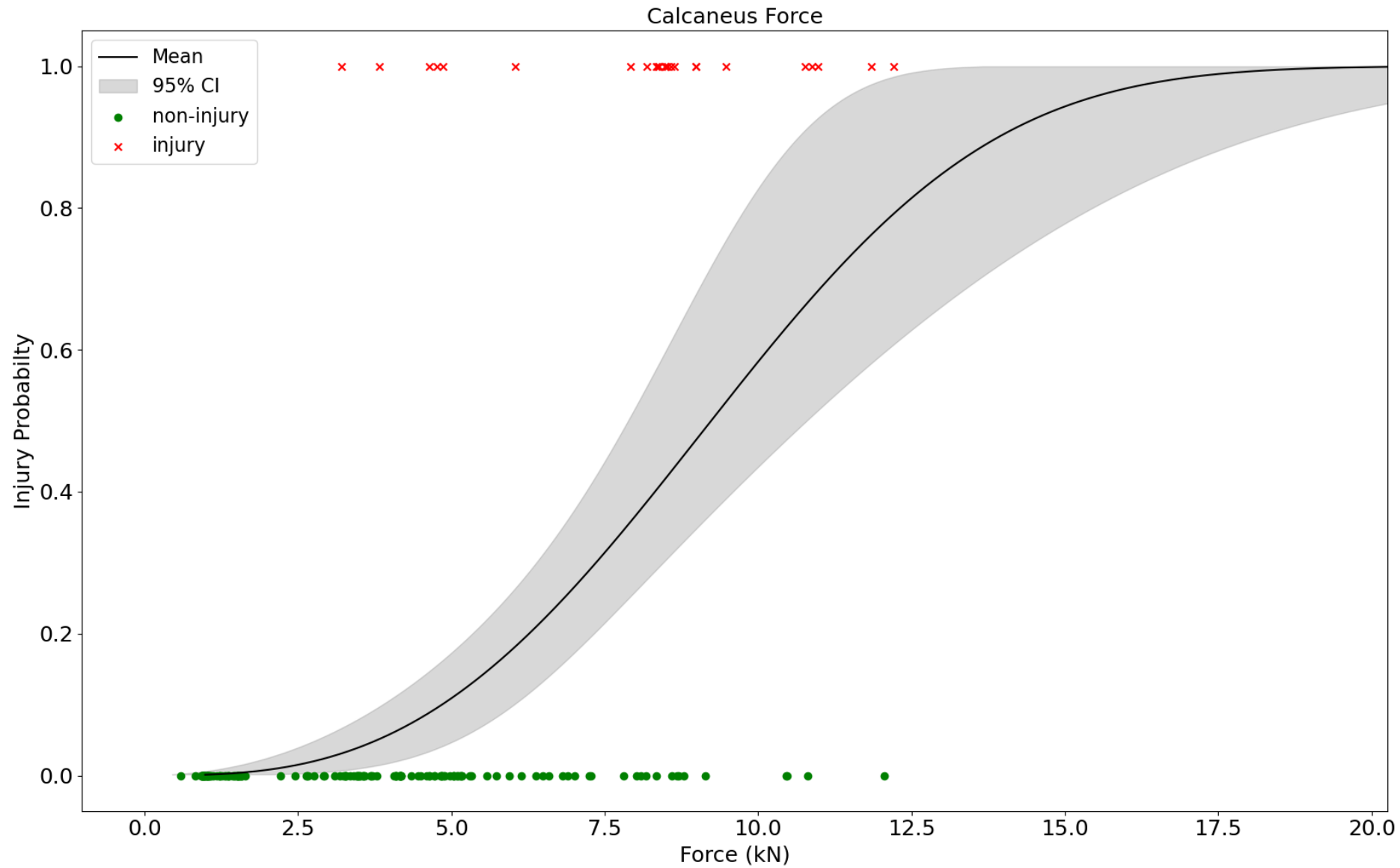


Ranking of BMS metrics: “Calcaneus Injury”

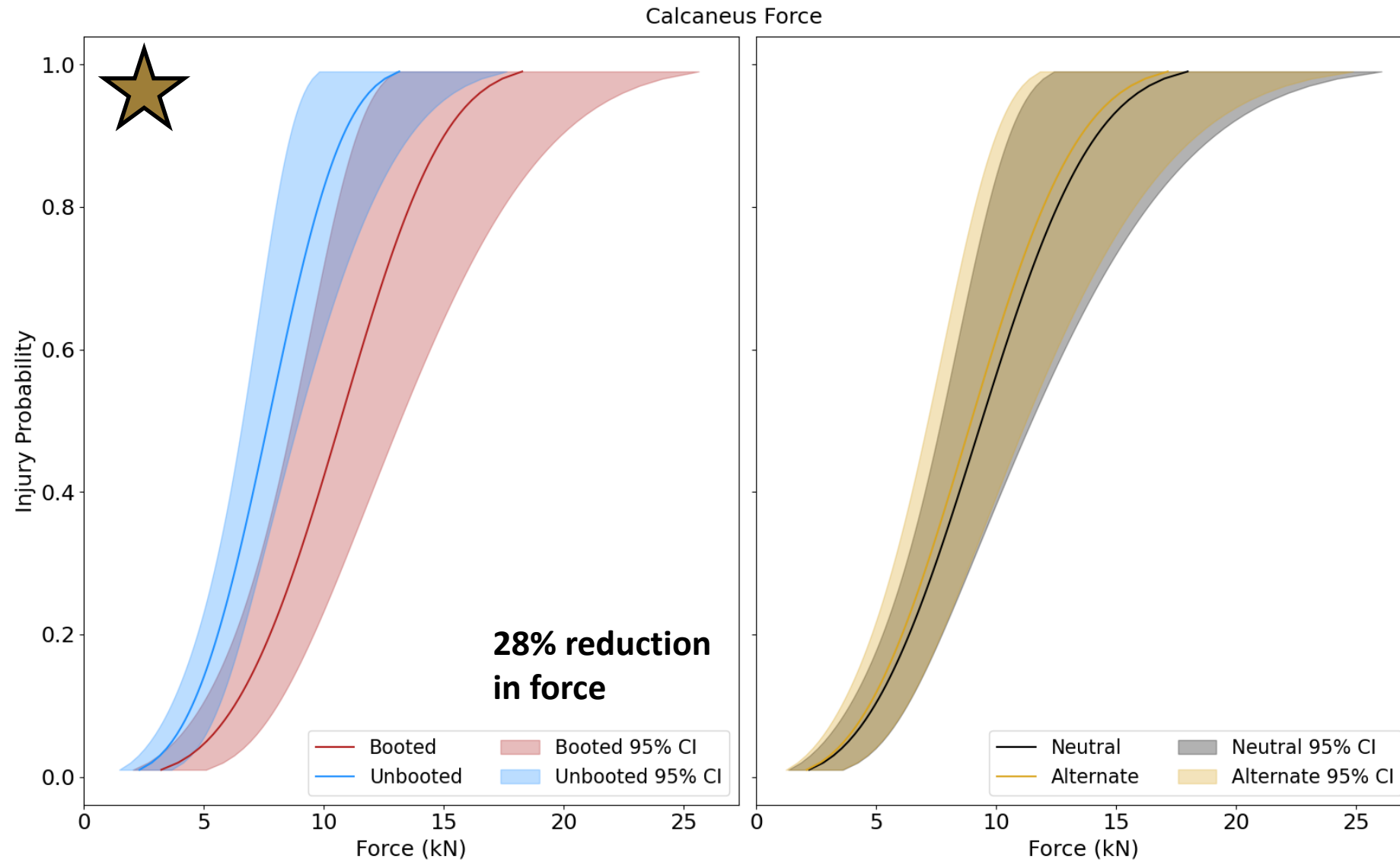
- BMS ranking of 43 biomechanical metrics
- Calcaneus force selected as best injury prediction metric



Calcaneus Force Injury Risk Curve



Calcaneus Force Injury Covariates



Discussion

- HBM advantage:
 - Lots of potential outputs, vastly surpasses what can be collected experimentally
- Needs:
 - Validation “+”
 - Well documented injury outcome data
- Stats framework can be used to determine the most predictive metrics
- Useful for...
 - Pre-test prediction tool
 - Experimental design
 - PPE evaluation (with validated PPE models)

What did we do?

- Applied a statistical method to select candidate injury metrics *among many HBM outputs*

Which outputs are useful?

- A rank order is provided, lots of options, not a lot of stratification
- In this case metrics related to cross sectional calcaneus force were best

How can we get more of them?

- HBMs are readily instrumented, no limit
- **Quality** > Quantity



Thanks to Drs. Michael Kleinberger and Caitlin Weaver, US ARL DEVCOM for their support

Dr. Gayzik is a member of Elemance, LLC, which provides academic and commercial licenses of GHBM C-owned models.

Data appearing in this document were prepared under the support of the named sponsor. Any opinions or recommendations expressed in this document are those of the authors and do not necessarily reflect the views of the Global Human Body Models Consortium or U.S. Army Research Laboratory.

Center for Injury Biomechanics



SCHOOL OF BIOMEDICAL ENGINEERING AND SCIENCES

Session 4: Effects of anthropometry and posture variations – what should be considered to foster robust occupant protection?

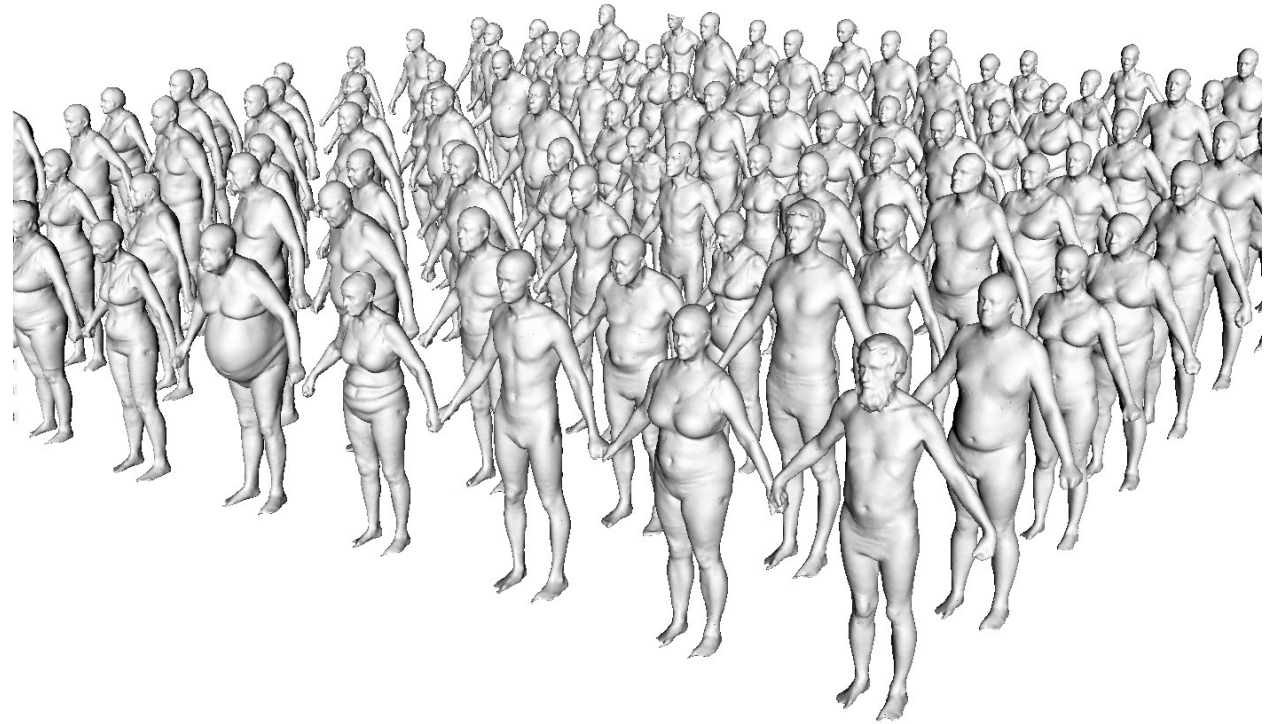
Effects of Occupant Size, Shape, and Posture on Injury Risk and Restraint Optimization

Matt Reed
Jingwen Hu
Wenbo Sun

September 2025

Human Variability Matters

The largest potential improvement in vehicle safety resulting from the use of HBMs is because they provide **better representation of human variability** than ATDs



Better biofidelity and injury prediction is a **bonus** with HBMs, but substantial improvements in safety optimization could be made even if they were “only as good as ATDs” because they have different sizes and shapes

**Occupant
Factors**

**Vehicle
Factors**

What Affects Crash Outcomes?

Occupant Characteristics

Sex, BMI, body shape, bone strength, ...

Restraint Parameters

Pre-tensioning, load limit, inflation pressure...

Posture

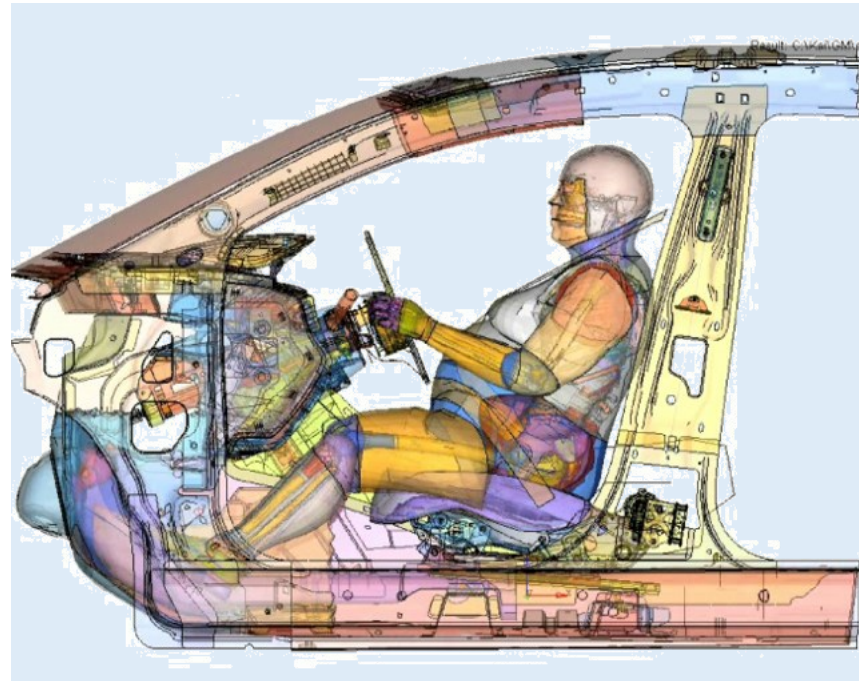
Torso recline & flexion, LX position, rotation, ...

Seat Position

Fore-aft/vertical/cushion angle

Belt Fit

Shoulder & lap



Restraint Geometry

Belt anchorage & knee bolster locations, airbag size & shape...

Vehicle Interior Geometry

Steering wheel & dash locations, pillars, header, ...

Crash Pulse

Direction, magnitude, phases

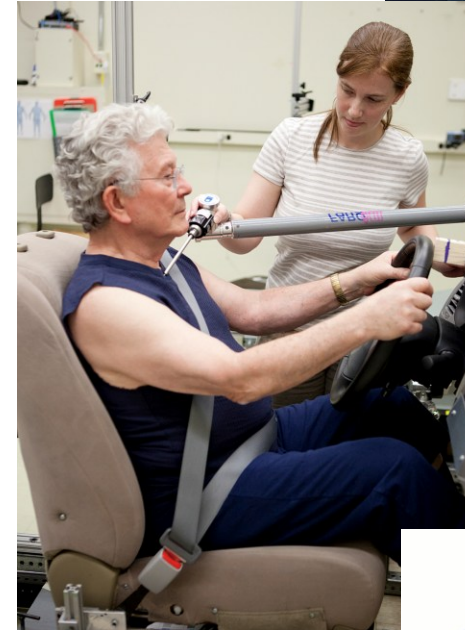
Pre-Crash Maneuver

AEB, FCW, lane change, ...

**Crash
Factors**

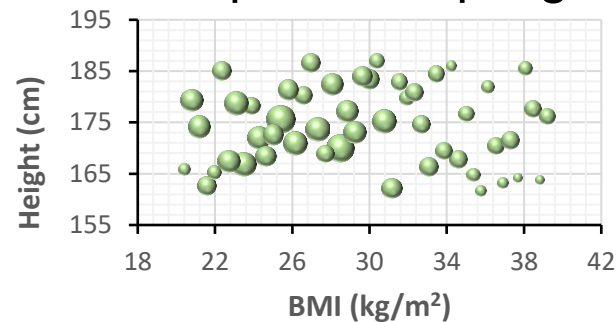
How Do We Know?

1. Field data analyses show differences in crash injury outcomes associated with body size
2. Volunteer studies show wide ranges of posture and belt fit
3. Both ATD and HBM simulations show outcome measures are affected by posture and belt fit
4. HBM studies show a large range of outcomes associated with body size and shape



Parametric Human Model

Occupant Sampling

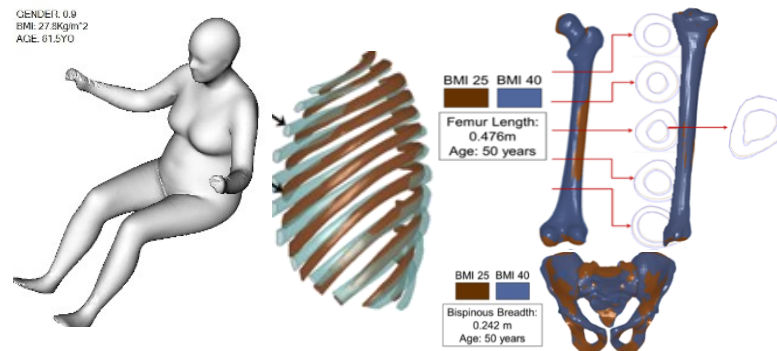


Mesh Morphing

Statistical geometry



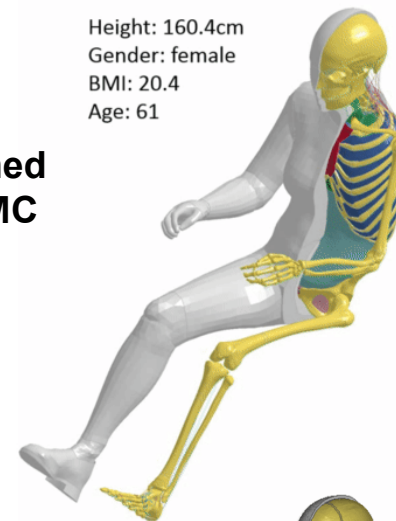
Baseline Model
GHBMCM50-OS



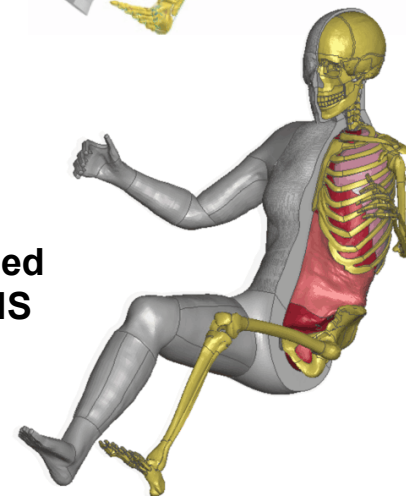
Female

Height: 160.4cm
Gender: female
BMI: 20.4
Age: 61

Morphed GHBMCM

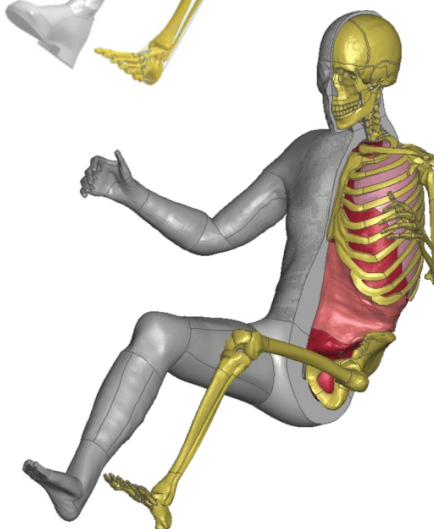
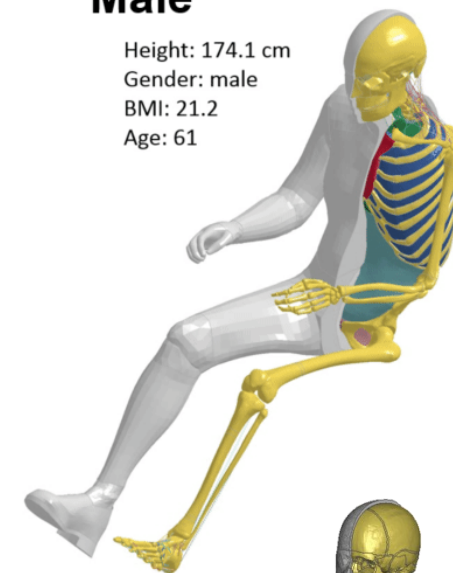


Morphed THUMS



Male

Height: 174.1 cm
Gender: male
BMI: 21.2
Age: 61

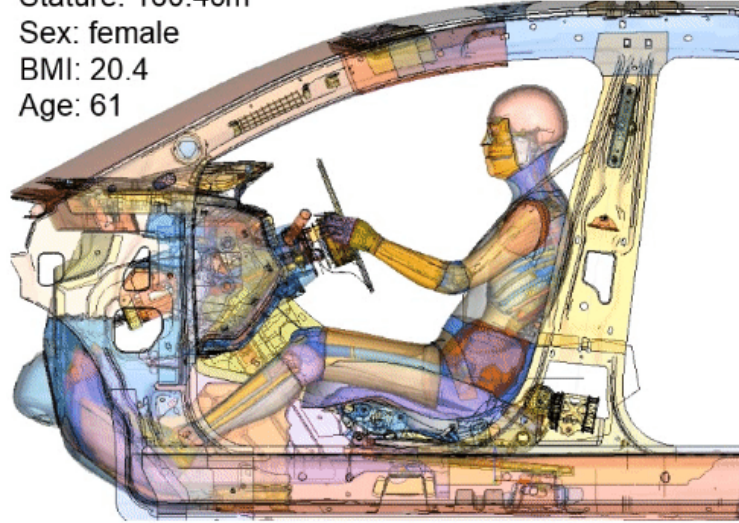


UMTRI has developed hundreds of morphed models based on GHBMCM, THUMS, SAFER, and UMTRI's HERMES human model.

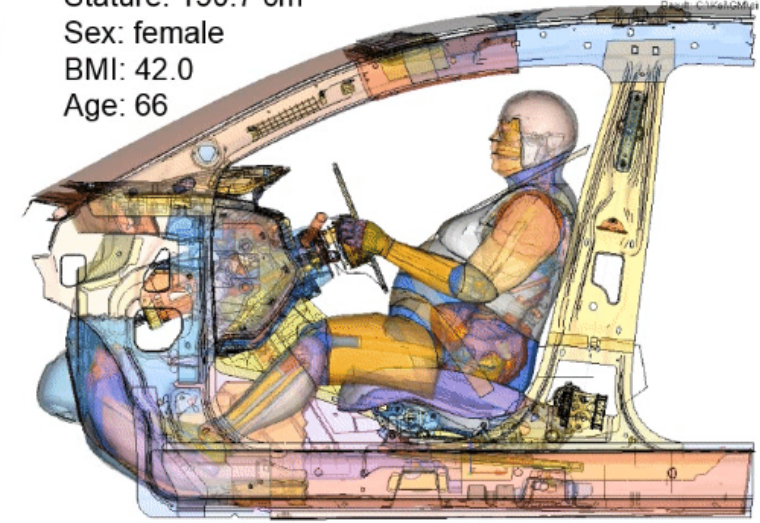
Restraint System Failure Modes Vary

- Occupants have different experiences with the restraint system that are non-linear with body size
- Occupants of different body size and shape drive the restraint system optimization in different ways

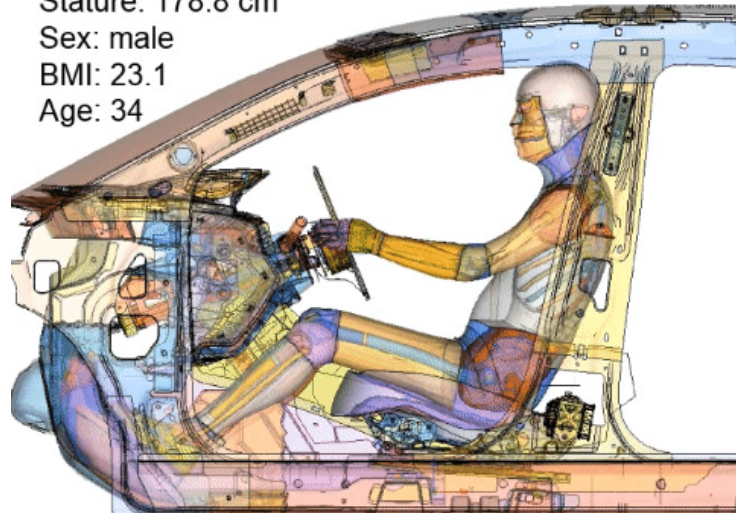
Stature: 160.4cm
Sex: female
BMI: 20.4
Age: 61



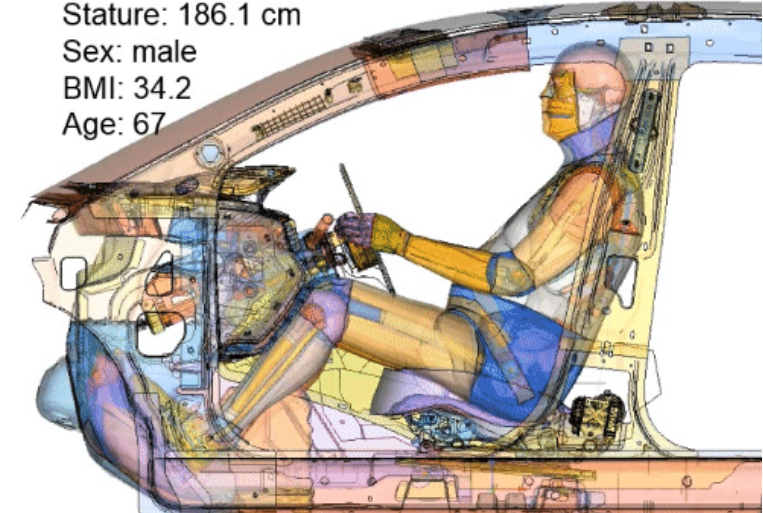
Stature: 150.7 cm
Sex: female
BMI: 42.0
Age: 66



Stature: 178.8 cm
Sex: male
BMI: 23.1
Age: 34

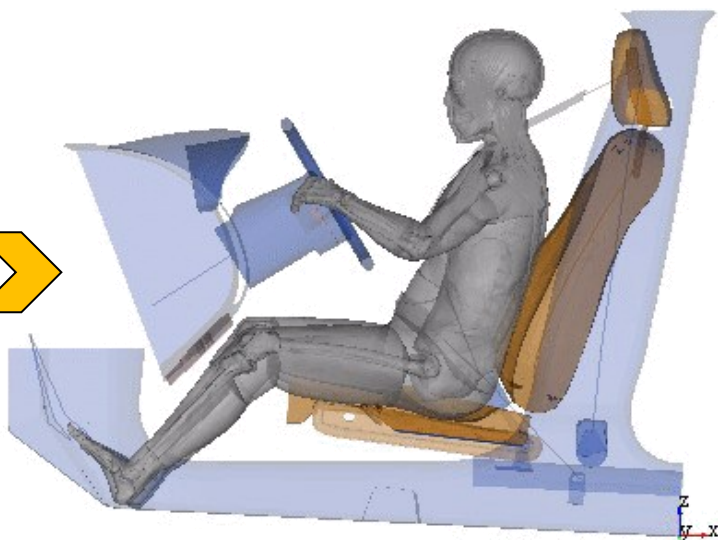


Stature: 186.1 cm
Sex: male
BMI: 34.2
Age: 67



US-NCAP Simulation Examples: THUMS

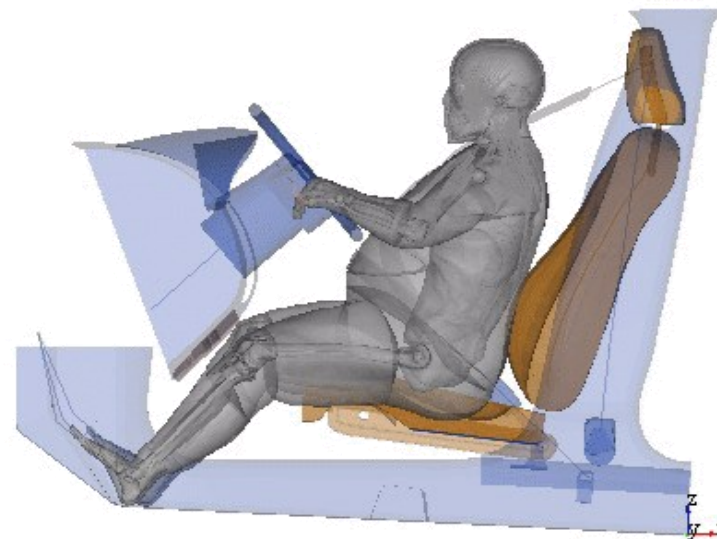
Mid-Stature
Lean Female



Time = 0.000000

Time = 0.000000

Short Obese
Female



Time = 0.000000

Time = 0.000000

Midsized
Male



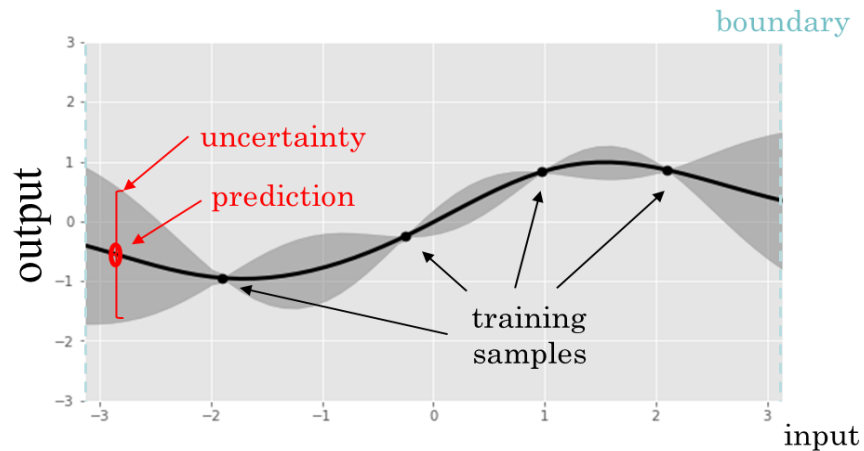
Tall Obese
Male



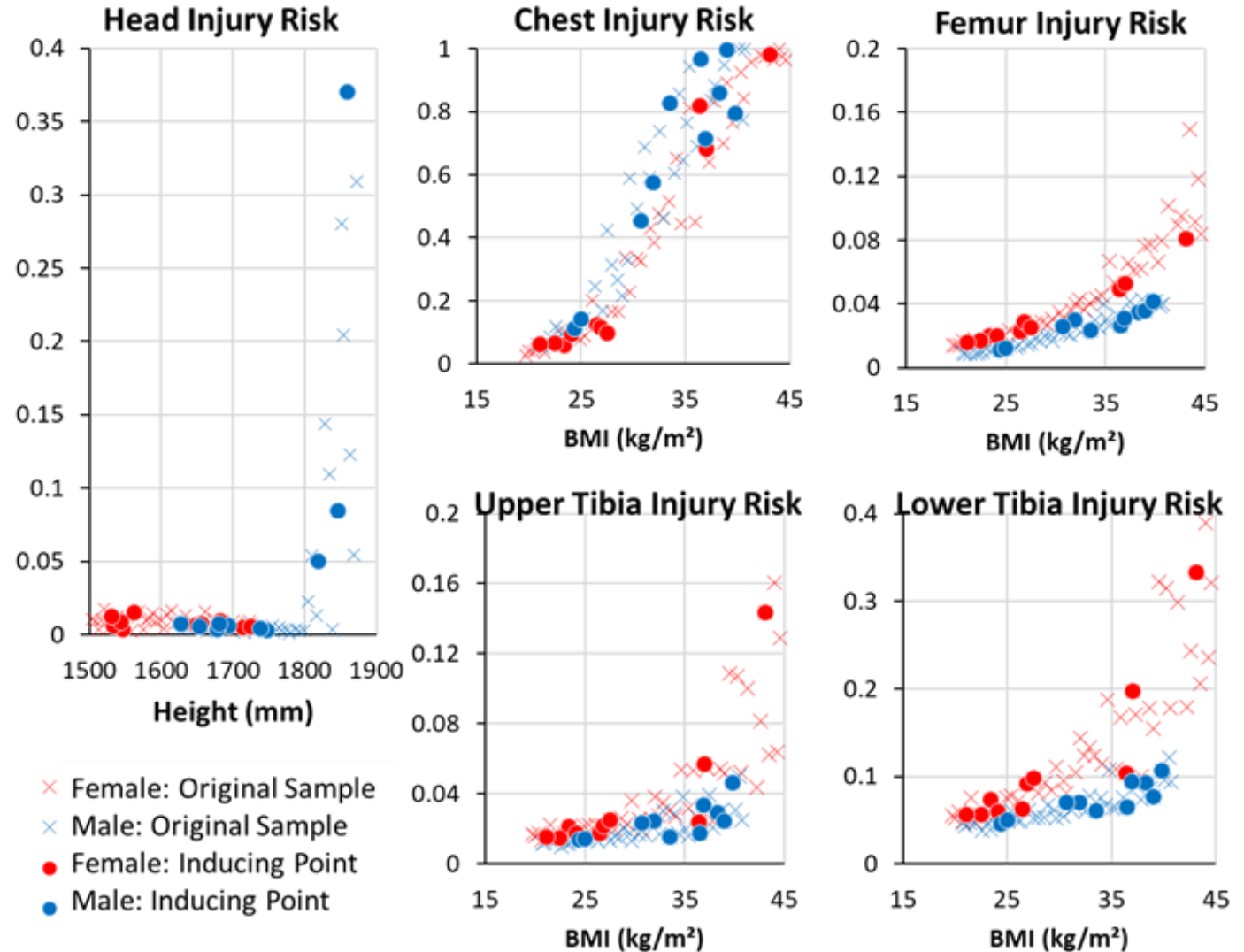
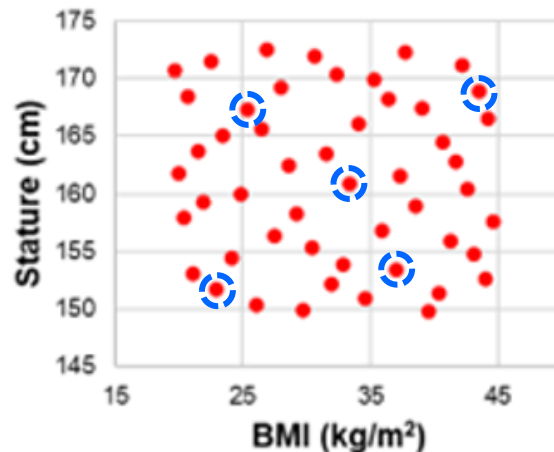
Gaussian Process (GP) Model & Inducing

Points

Inducing points: representative subjects that accounts for population variation



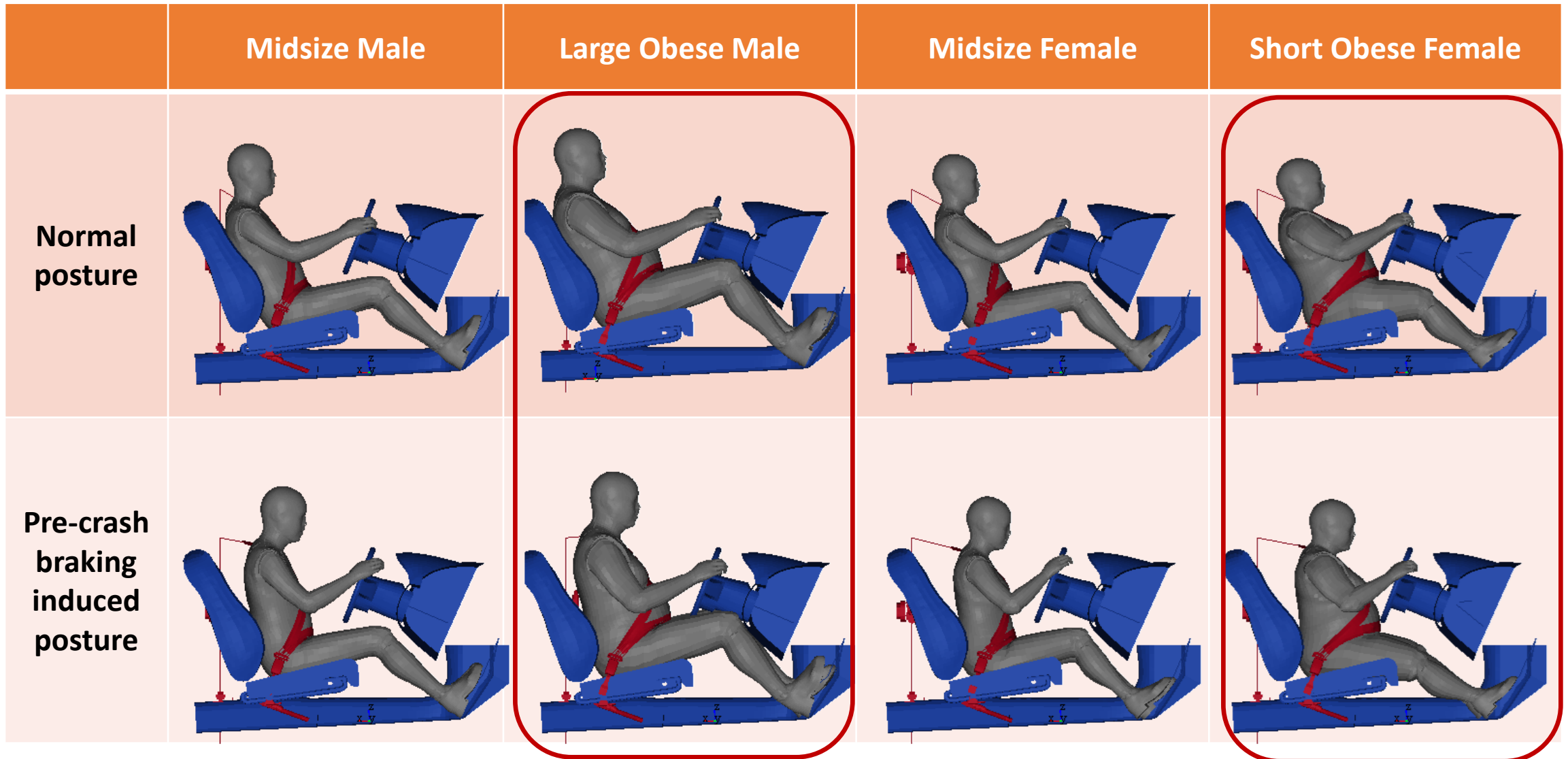
Gaussian Process Surrogate Model



Summary

- Human body models are the only feasible way to optimize occupant protection for a wide range of occupant size, shape, and posture
- The primary value of HBM simulations for restraint system optimization is the wide range of restraint system interactions due to body shape and posture, rather than the improved biofidelity and injury assessment
- The high dimension of the space (size x shape x belt fit x posture x crash...) necessitates identification of efficient approaches to selecting simulation conditions and estimating population-level outcomes from a “small” number of simulations

Pre-Crash Posture and Occupant Size Effects



Head to IP contact

LX concerns

Boyle et al. 2020 TIP

More Lives Saved



More Life Lived



Effect of anthropometry on rib fracture risk - How to predict the risk of the population?

IRCOBI pre-conference workshop 2025-09-09

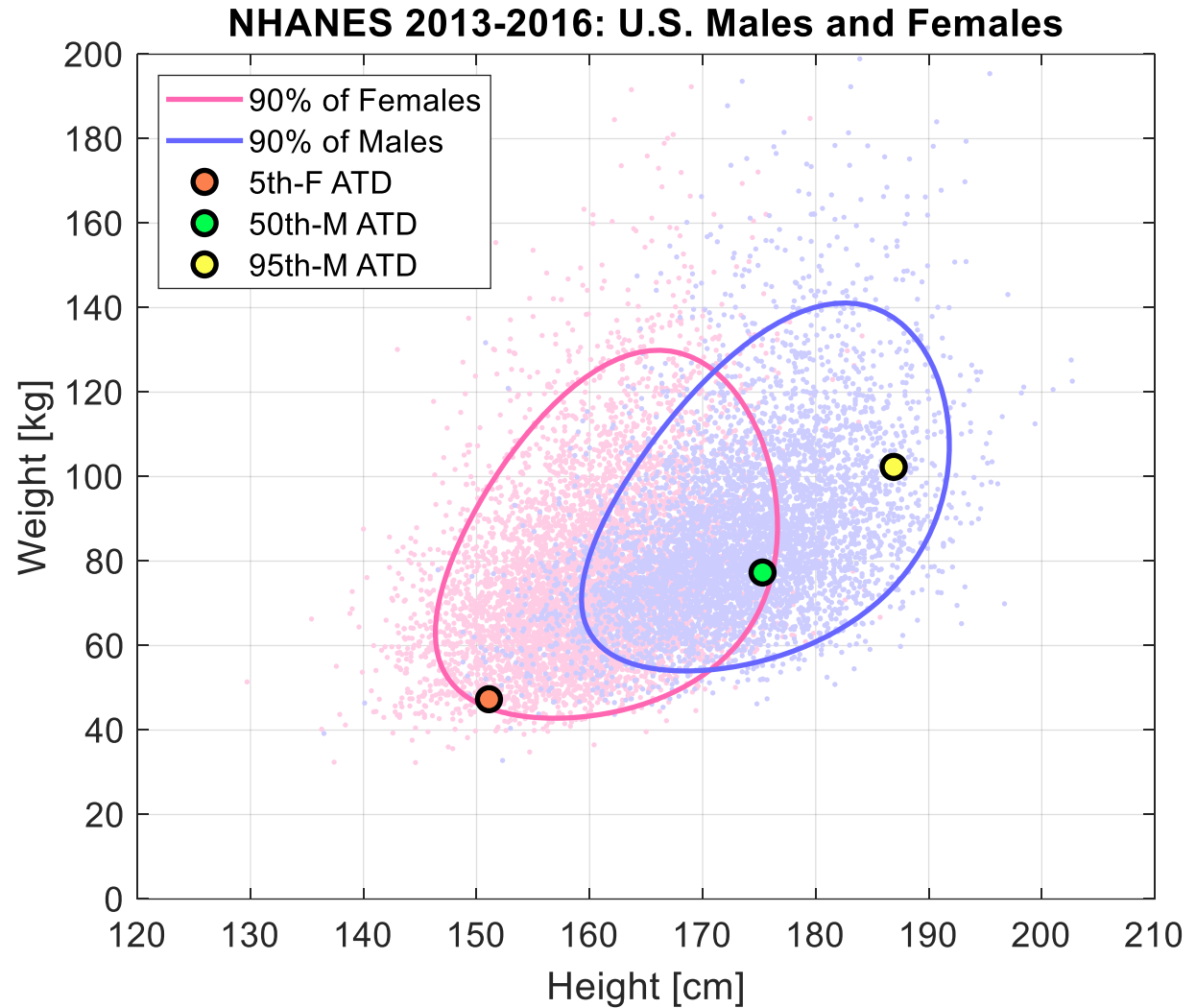
Karl-Johan Larsson, Senior Research Engineer

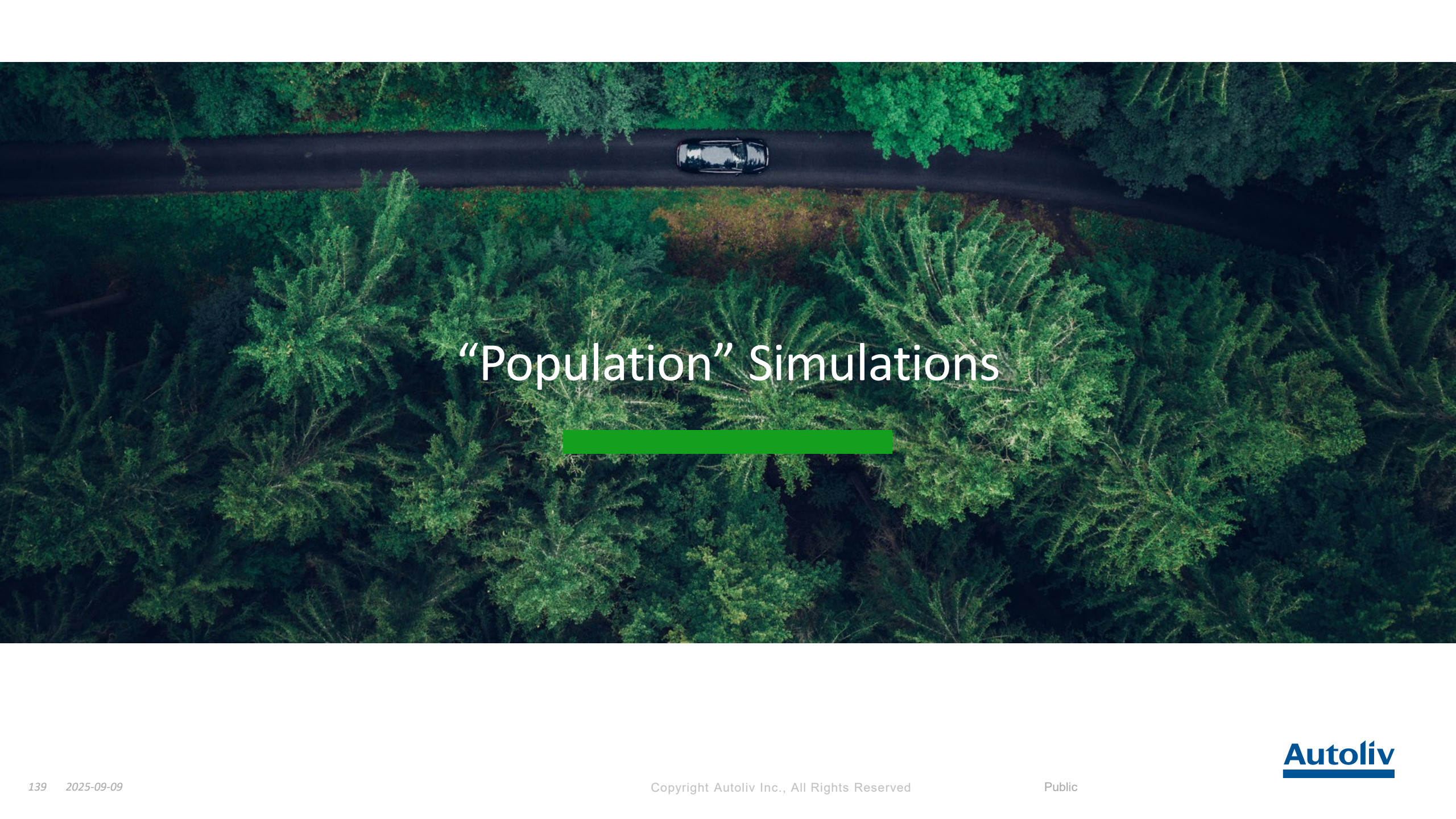
Background and Aim

- Height and Weight varies in the population
 - Obesity has become more prevalent since ATD sizes were determined
- Regions containing 90% of adult U.S. Female and Males body sizes can be defined
 - Height and weight distributions

Aim of presentation

- Present results from crash simulations with HBMs representing the 90% height and weight variability
- Focusing on rib fracture risk:
 - Demonstrate how many HBMs of different sizes are needed to get a good prediction of “population” rib fracture risk (Larsson et al. 2024)



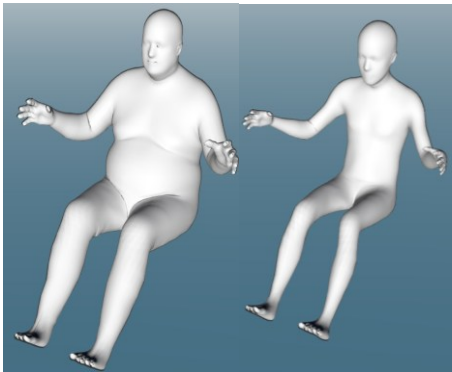
An aerial photograph showing a dark-colored car driving on a paved road that curves through a dense, green forest. The car is positioned in the upper center of the frame. The text "Population" Simulations is overlaid in white, with a green horizontal bar underneath the word "Population".

“Population” Simulations

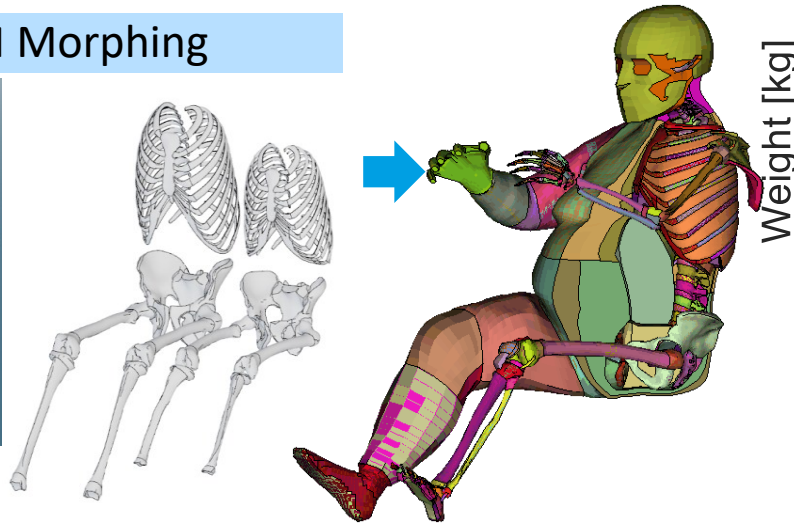
Methods

- Morphing of SAFER HBM to create 200 HBMs of each sex
 - SAFER HBM v.10
 - Sex, Height and Weight varied
 - Age = 45years

Parametric HBM Morphing

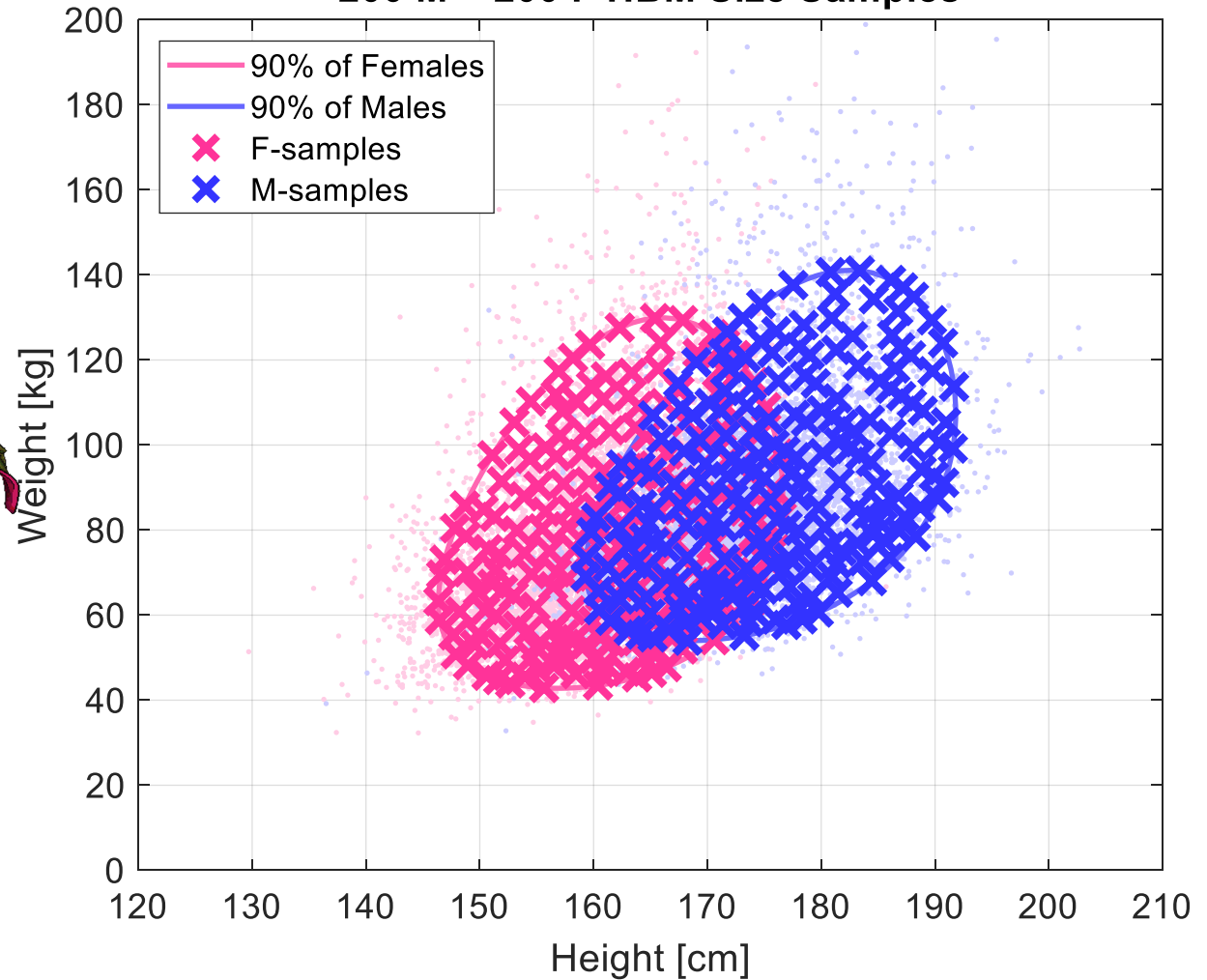


www.humanshape.org



- Validation of morphed SAFER HBMs:
 - Larsson et al. (2022), Larsson (2023)

200 M + 200 F HBM Size Samples



Sources:

Larsson et al. 2022

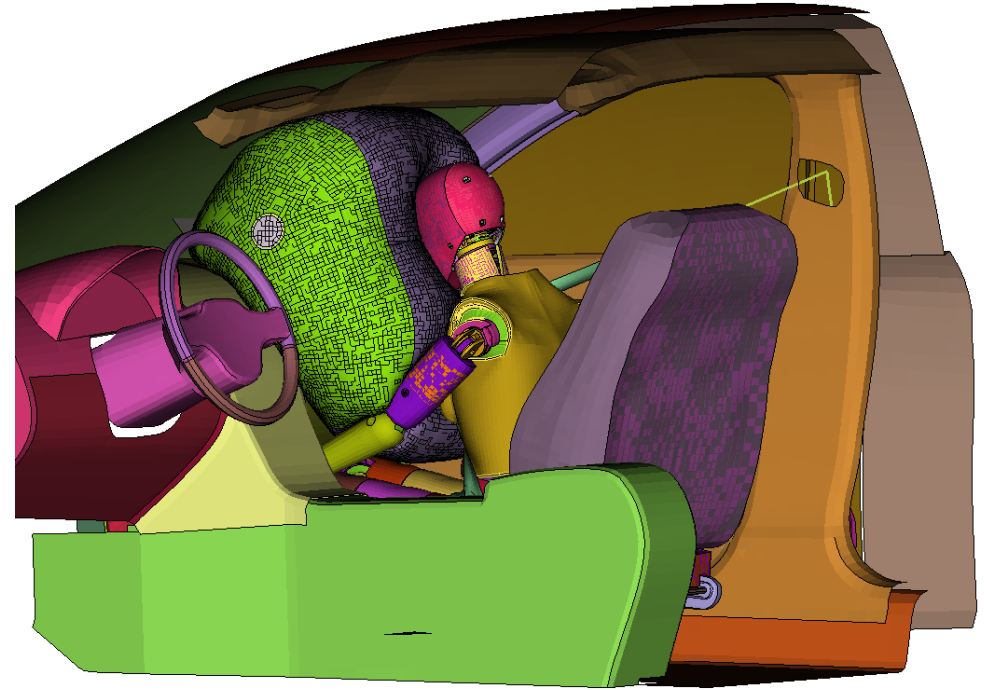
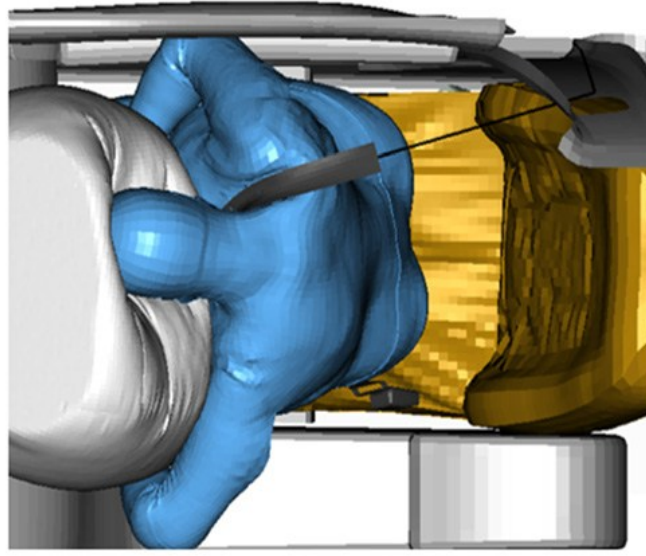
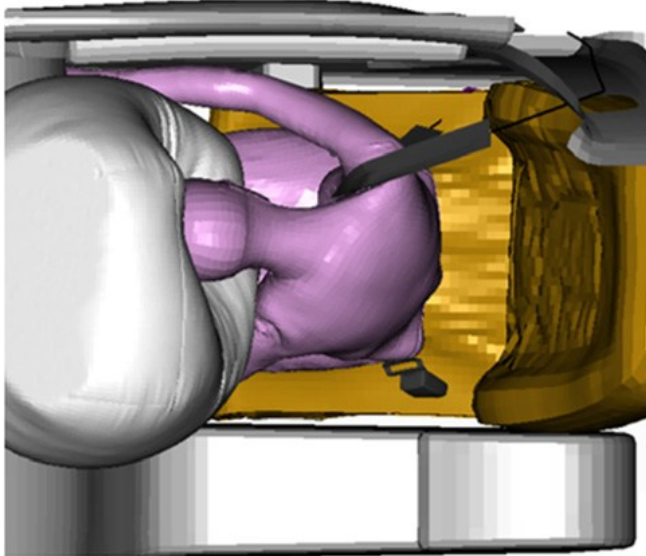
Larsson 2023

Evaluation of a diverse population of morphed human body models for prediction of vehicle occupant crash kinematics, Computer Methods in Biomechanics and Biomedical Engineering, Vol 25

Human Body Model Morphing for Assessment of Crash Rib Fracture Risk for the Population of Car Occupants, PhD Thesis, Chalmers University of Technology

Methods

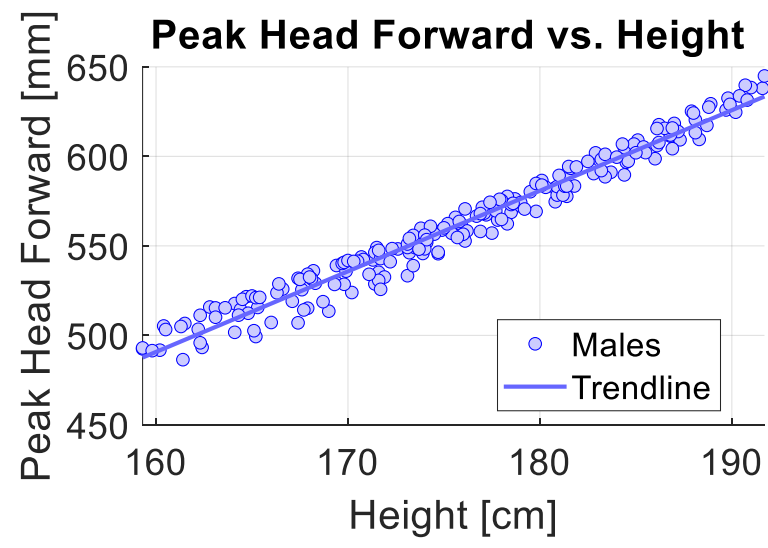
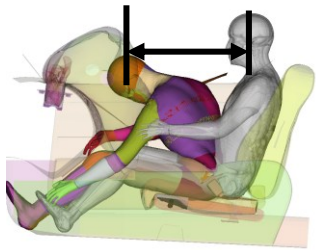
- Run **crash simulations** with each HBM as 1st row passenger
 - Iraeus generic sled, updated to passenger side
 - Load cases
 - Full frontal, $\Delta V = 48\text{km/h}$
 - Lateral impact, $\Delta V = 24\text{km/h}$ –with intrusion
 - Crash severity chosen such that M-50th HBM has 50% risk of 2+ rib fractures



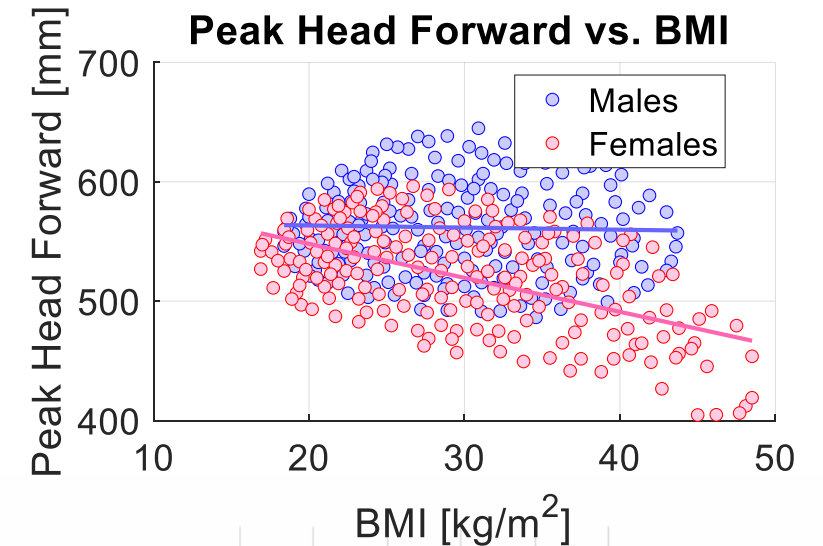
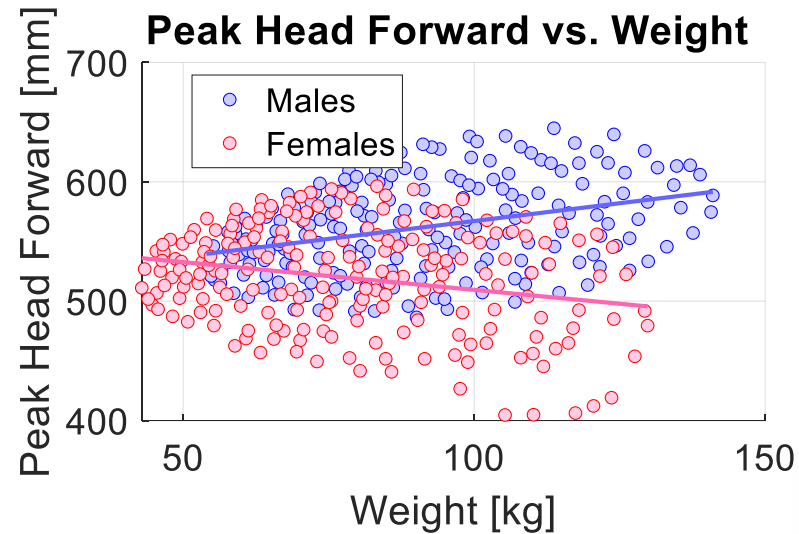
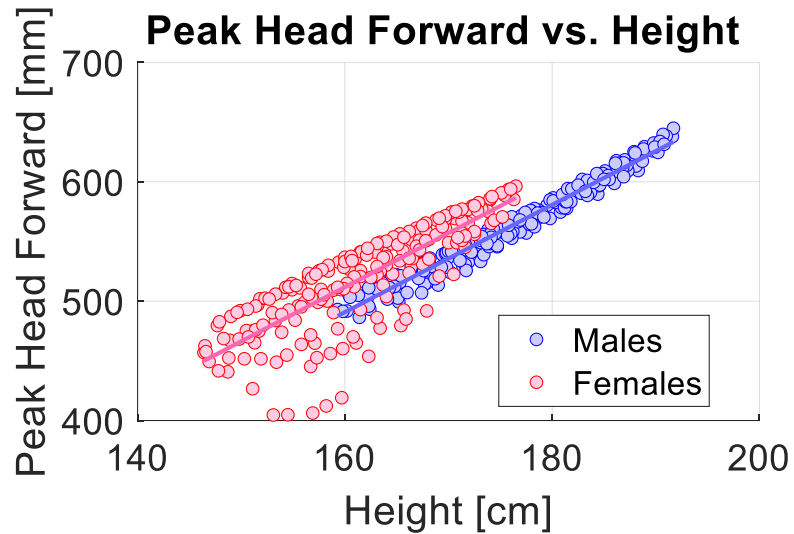
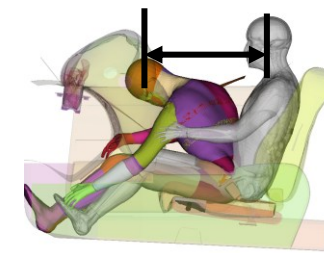


Population Results

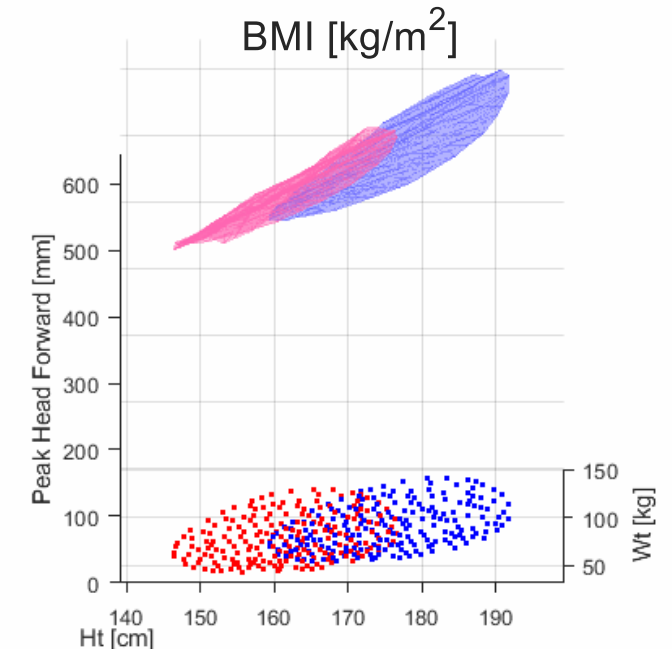
Frontal Impact: Peak Head Forward Excursion



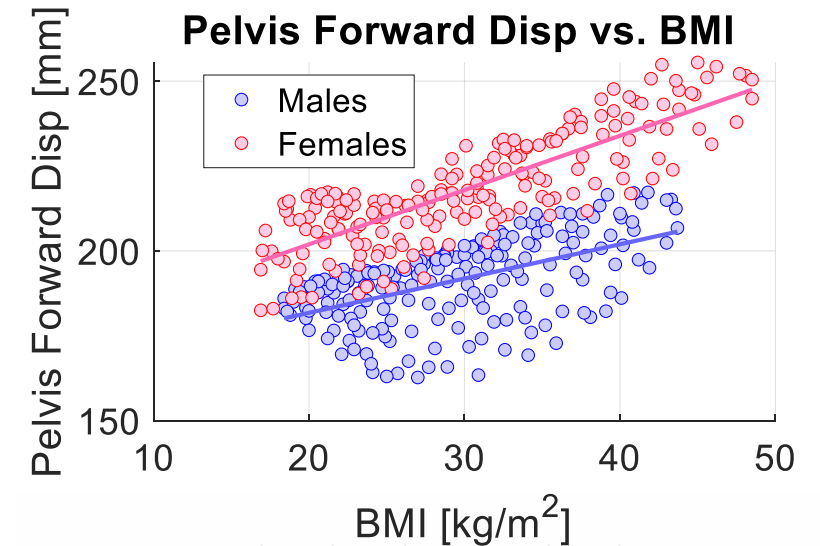
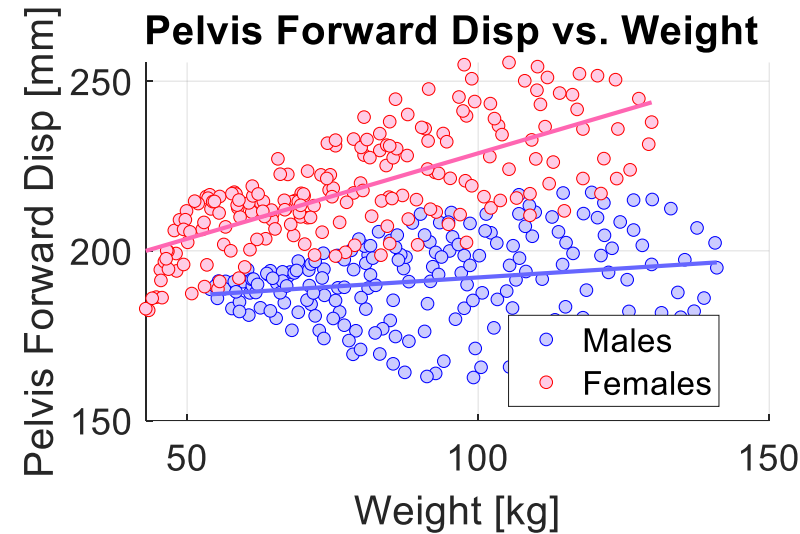
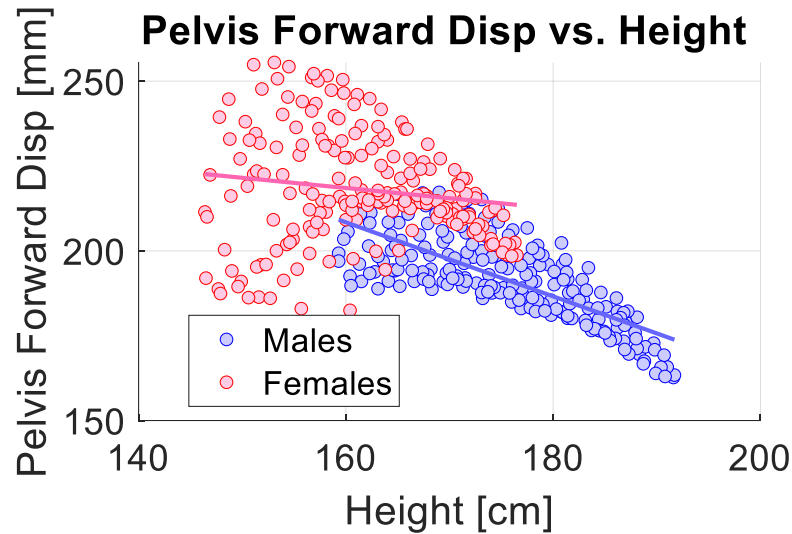
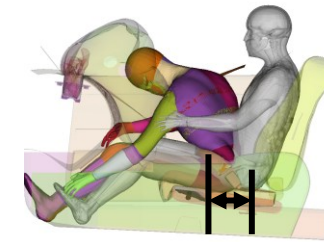
Frontal Impact: Peak Head Forward Excursion



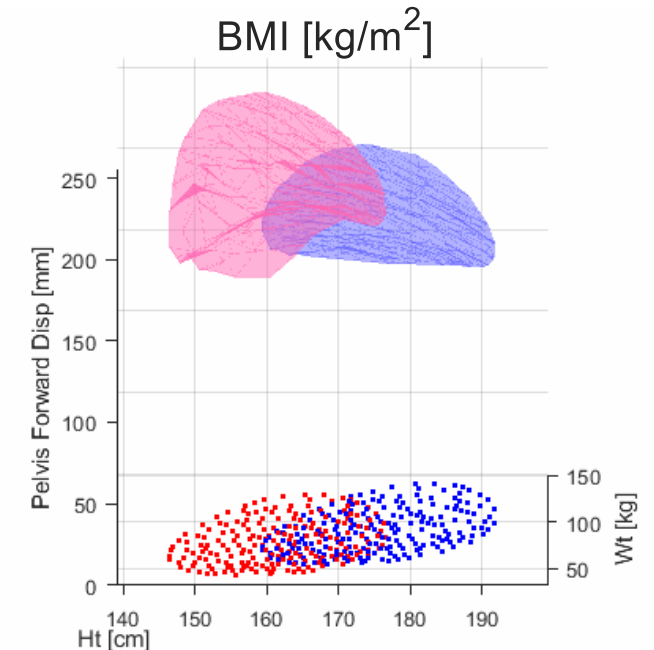
- Male / Female difference in Weight/BMI trends
- For similar heights and weights:
 - Female HBMs had ~20mm greater head excursion



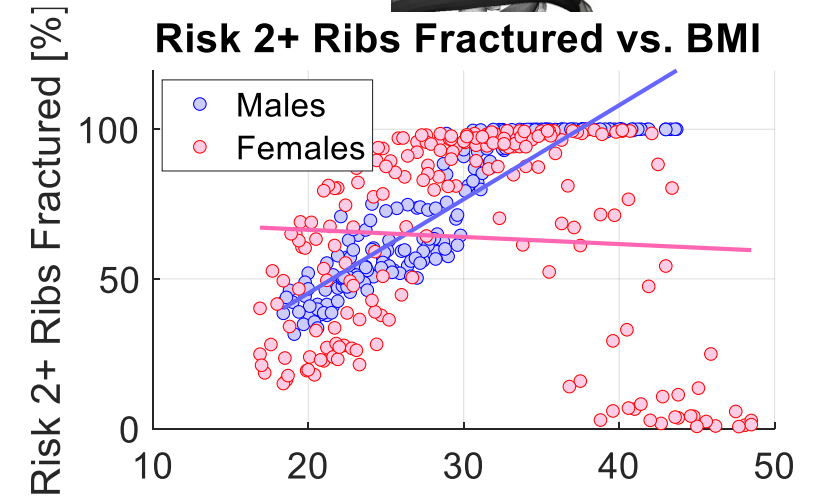
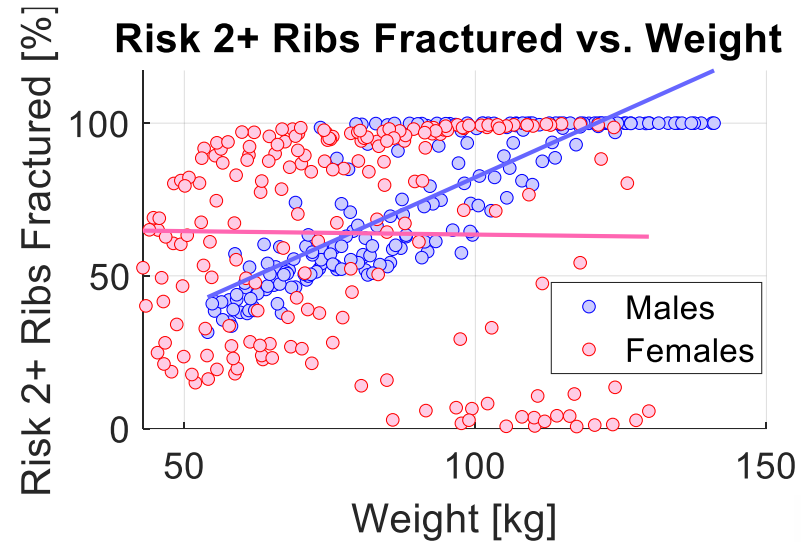
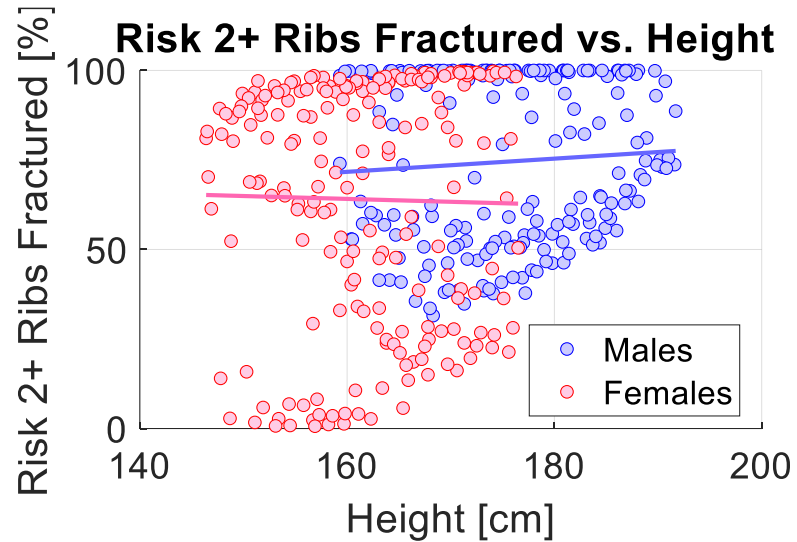
Frontal Impact: Peak Pelvis Forward Excursion



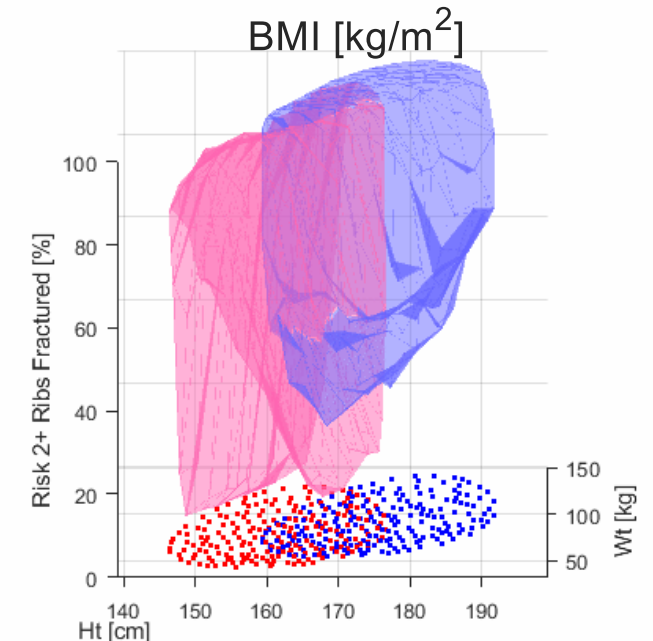
- Best explained by BMI
 - Higher BMI → More pelvis forwards excursion
- For similar heights and weights:
 - Female HBMs had ~25mm more pelvis excursion



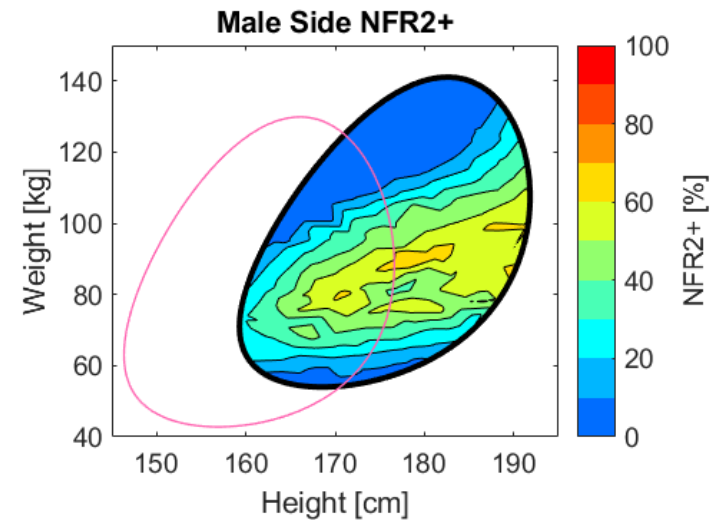
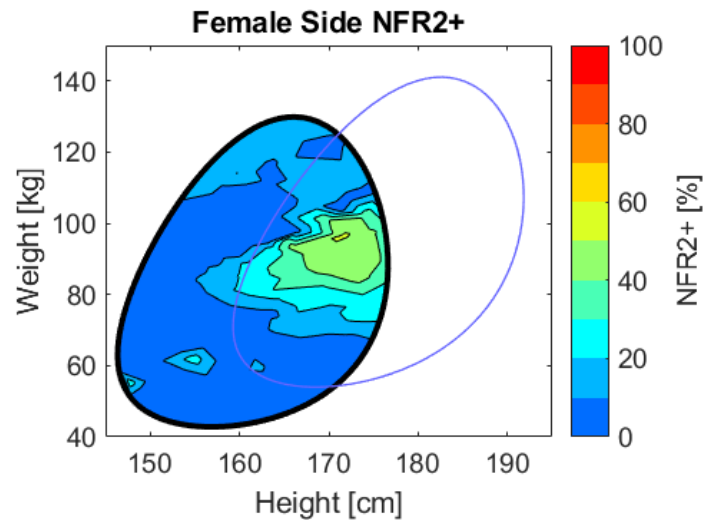
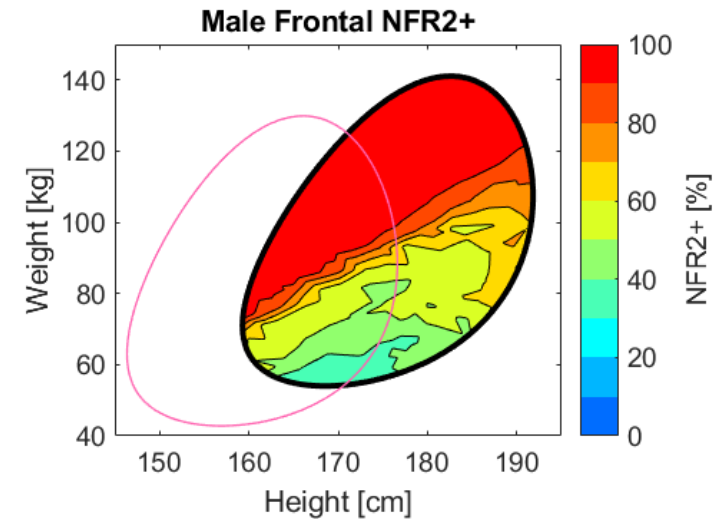
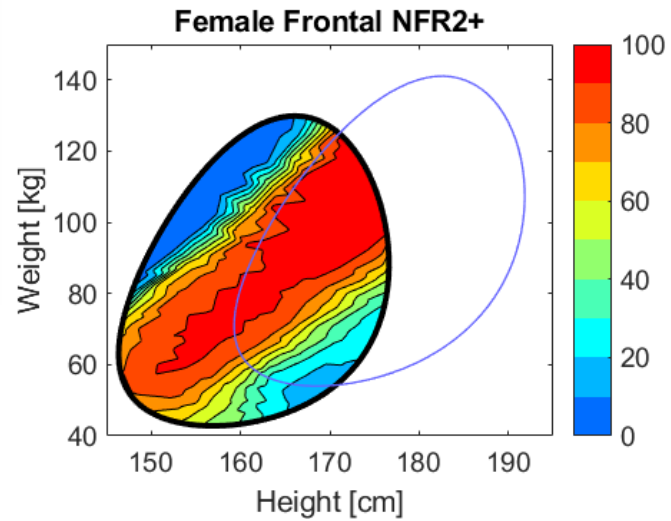
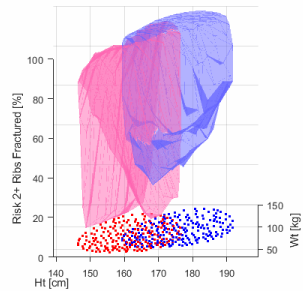
Frontal Impact: Rib fracture risk (NFR2+)

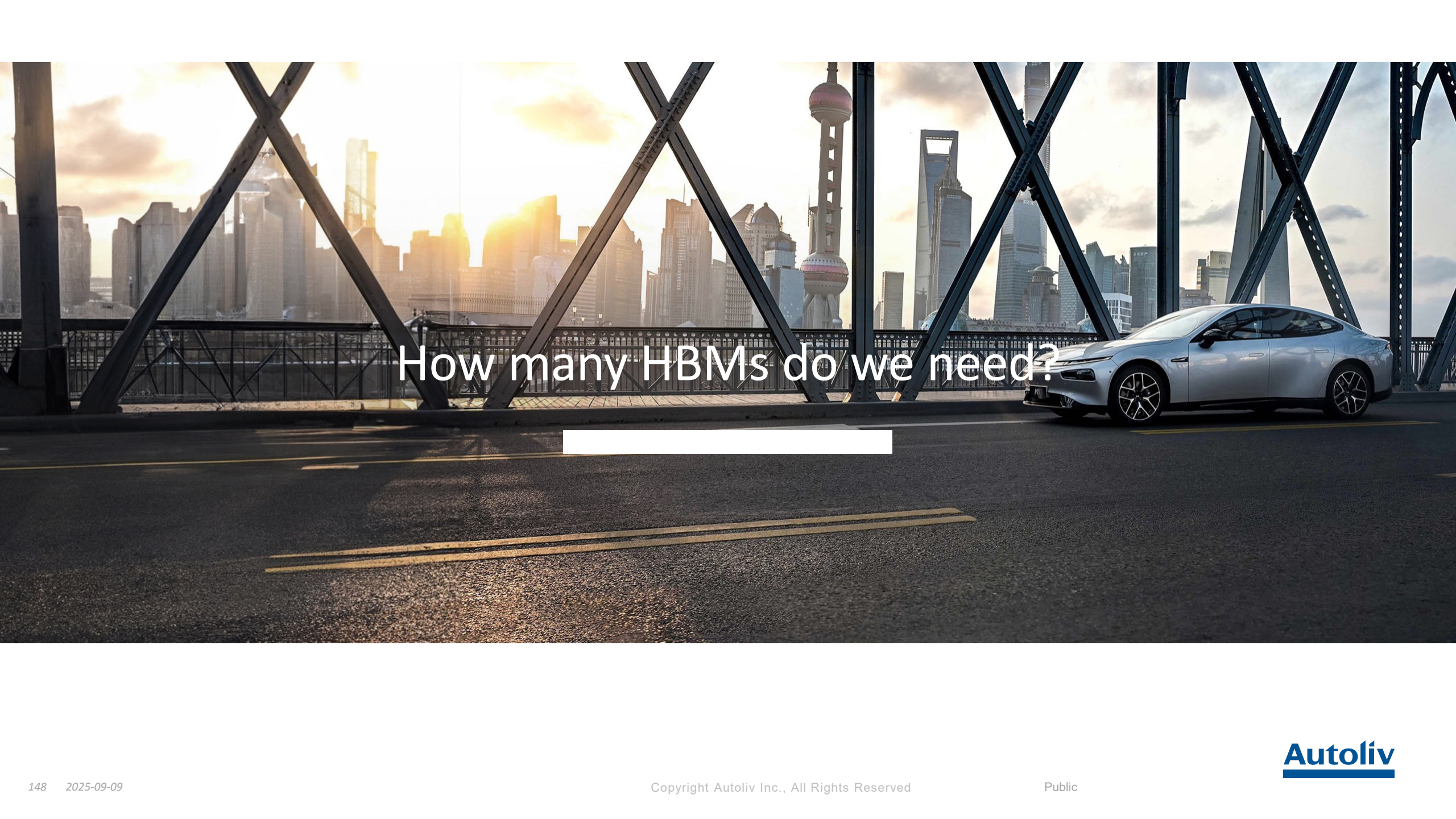


- No clear height trend
- An Inverted U-shape trend for females w.r.t BMI
- Risk drops down for high-BMI Females (more in discussion)



Rib fracture risk (NFR2+) in both frontal and lateral impacts

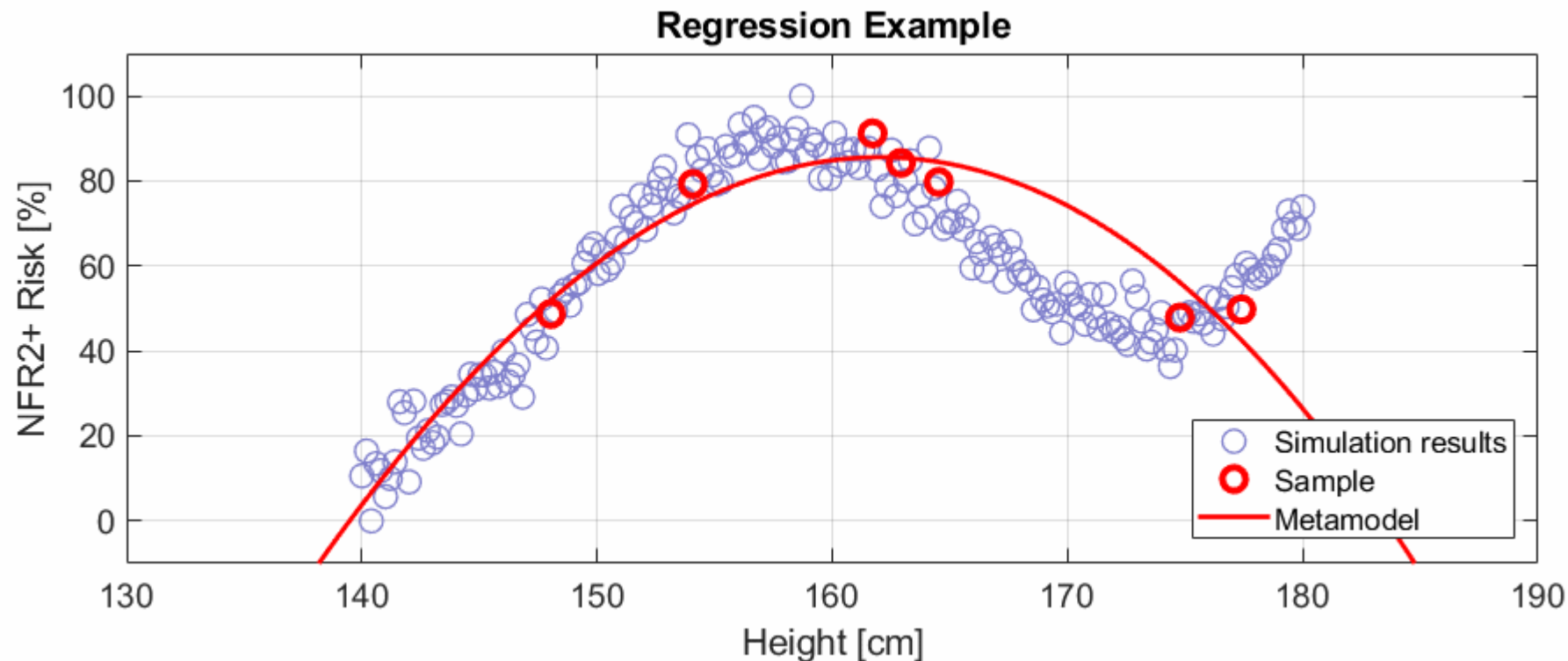


A silver sedan is parked on a bridge with a large steel truss structure. In the background, a city skyline is visible, featuring the Oriental Pearl Tower and other skyscrapers. The sun is low on the horizon, creating a warm, golden glow. The text "How many HBMs do we need?" is overlaid in white, with a white rectangular box below it.

How many HBMs do we need?

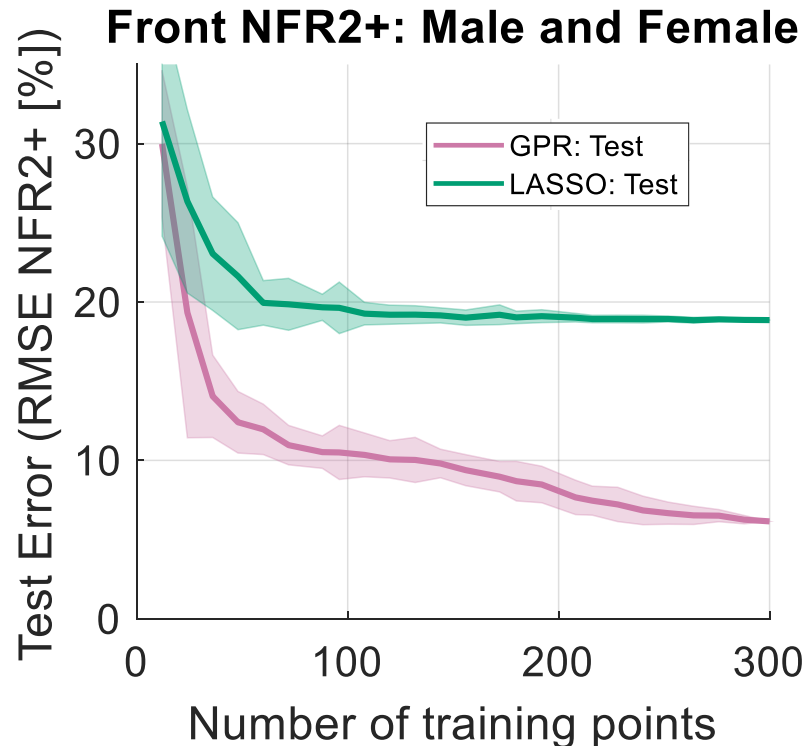
Metamodeling

- Some may say that 400 HBM simulations for a single load case evaluation is a bit much...
- Another way: choose a few points, connect the results with a regression model
 - A metamodel, i.e., a model of HBM model output
- But how many points to choose to get a good metamodel for population rib fracture risk?



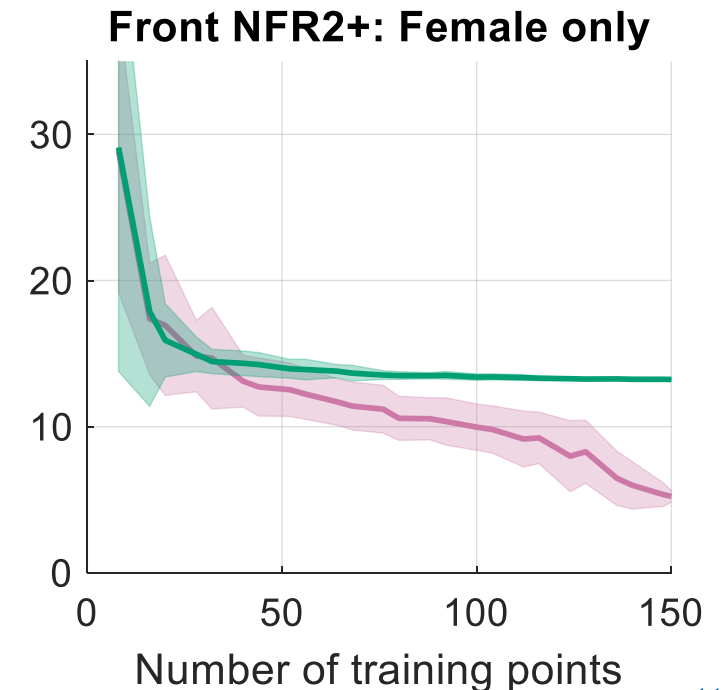
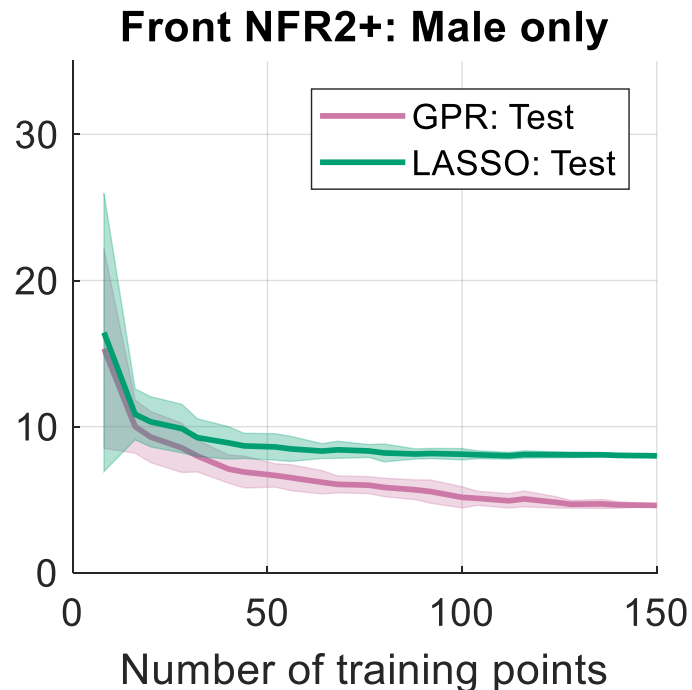
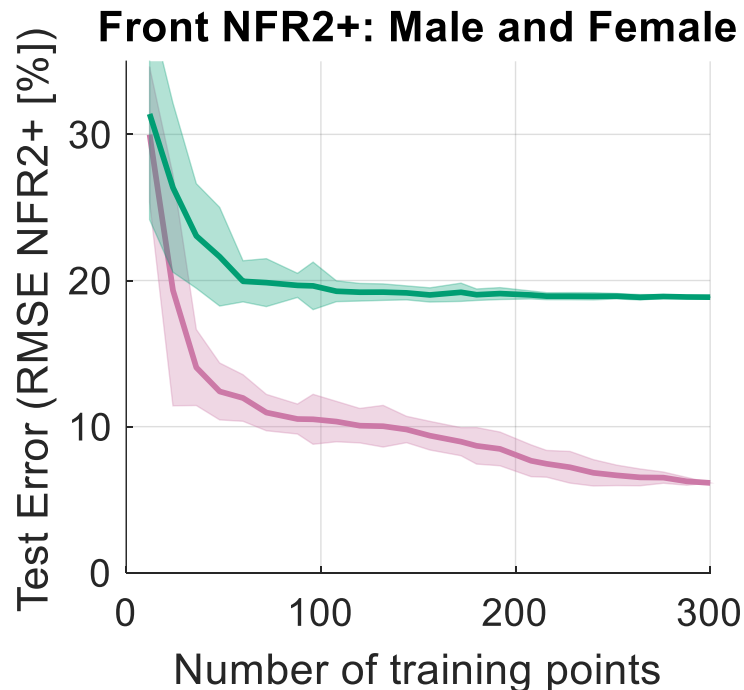
Metamodel error vs. Number of HBMs: Male and female rib fracture risk

- Evaluated different metamodeling methods
 - GPR: Gaussian Process Regression and LASSO: regularized second order linear regression
- Choose random HBM sizes, check metamodel test error, increase sample size
- Test error reduced rapidly up until ~50 HBMs (25 of each sex)
 - Beyond 25 males and females we get diminishing returns in metamodel improvement



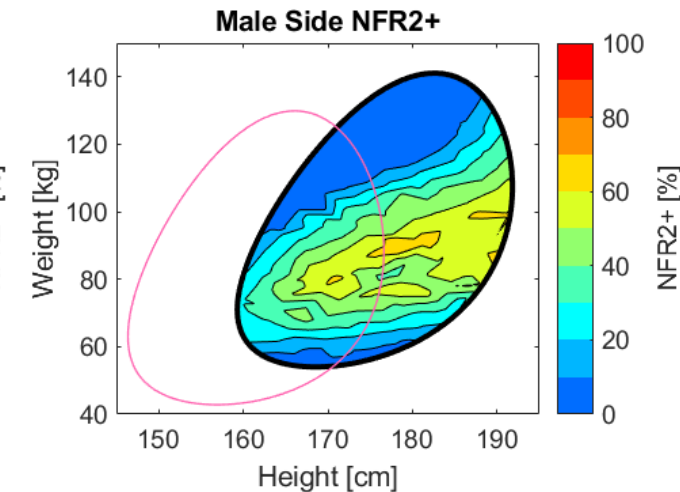
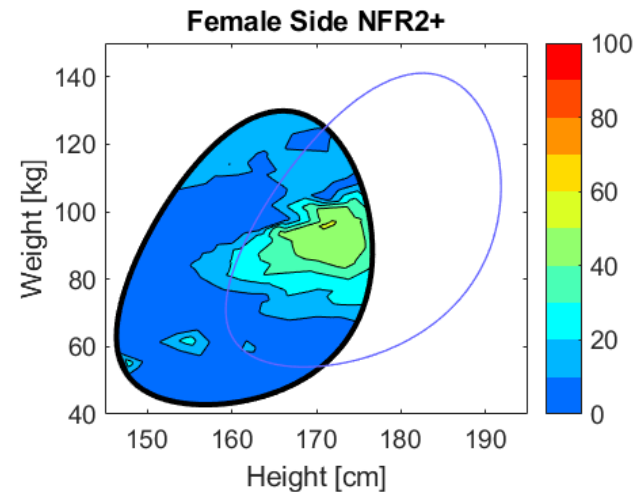
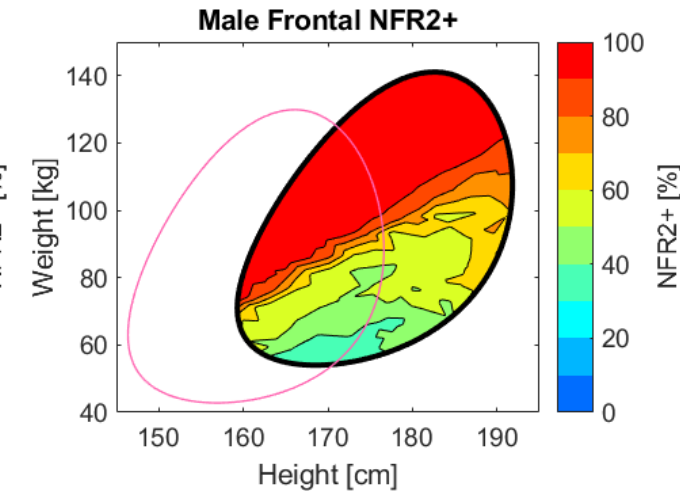
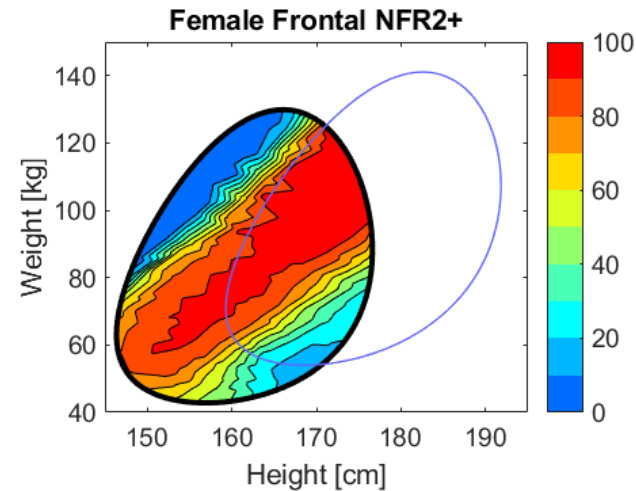
Metamodel error vs. Number of HBMs: Male and female rib fracture risk

- Metamodeling males and females separately – even lower errors
 - Still, diminishing returns around 25 of each sex.



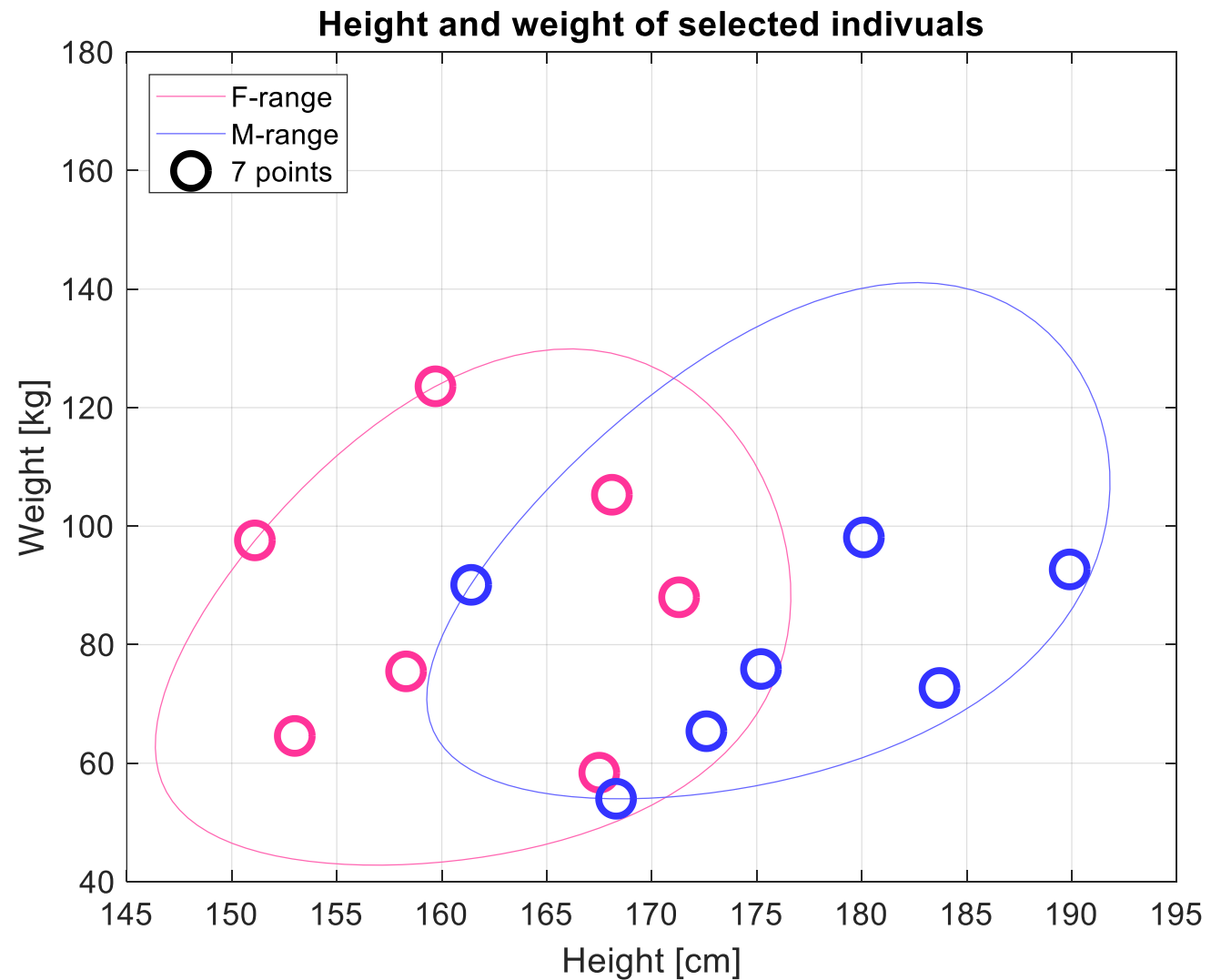
Optimization – Choose HBMs that predicts these two crashes

- 25 HBMs of each sex can still be considered a lot
 - Can we do better?
- Yes, if we tailor our choice to be predictive for these specific crashes
 - we can pick certain HBMs that are suitable for these results
- If we can only use **X** HBMs, which?
 - **X** = 3, 4, 5, ... :
 - Optimize which HBMs are in **X**
 - Criteria: minimize metamodel error for all points in population averaged across both crashes



Optimization – Choose HBM that predicts these two crashes

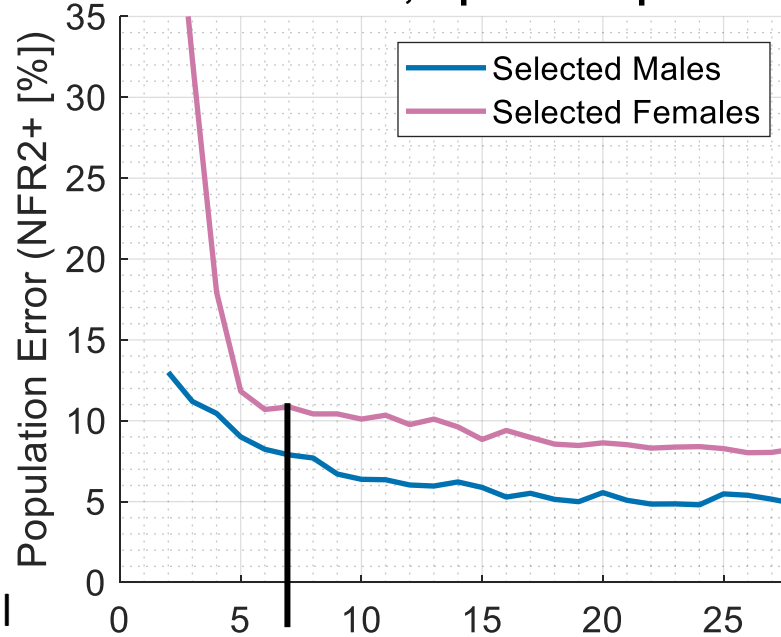
- Optimization result example:
 - For seven HBMs of each sex:
 - Pick these sizes:



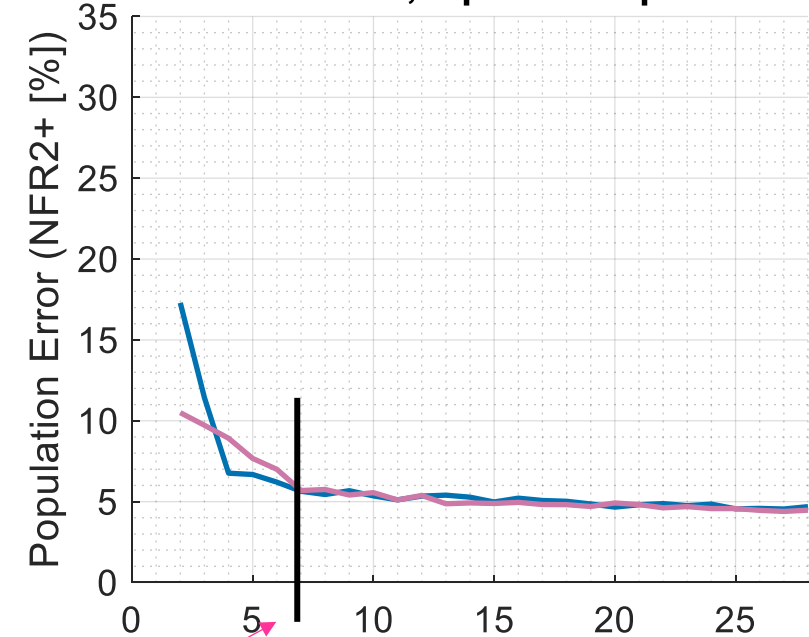
Optimization – Choose HBM that predicts these two crashes

- Optimization results:
 - Example
 - For seven HBMs:
 - Pick these sizes
- Get these model errors →
- ~5-10 HBMs of each sex can represent the population outcome well

Front NFR2+, Optimized points

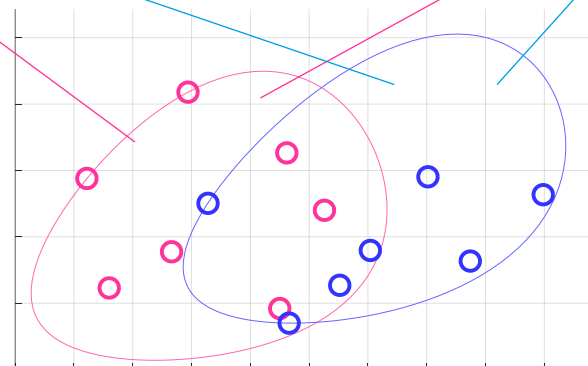


Side NFR2+, Optimized points



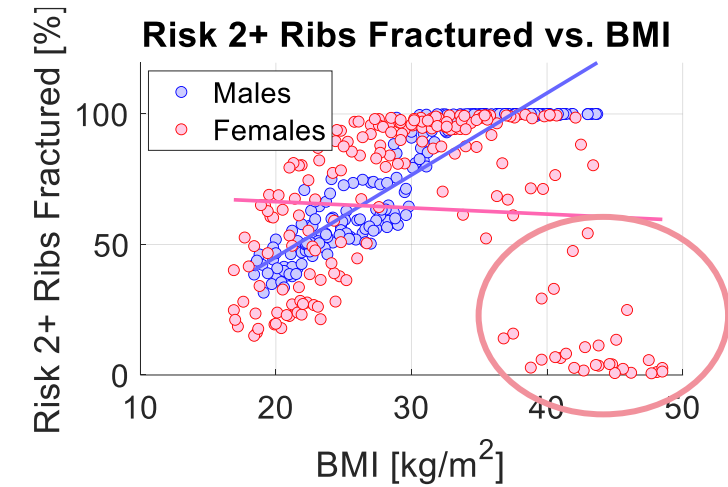
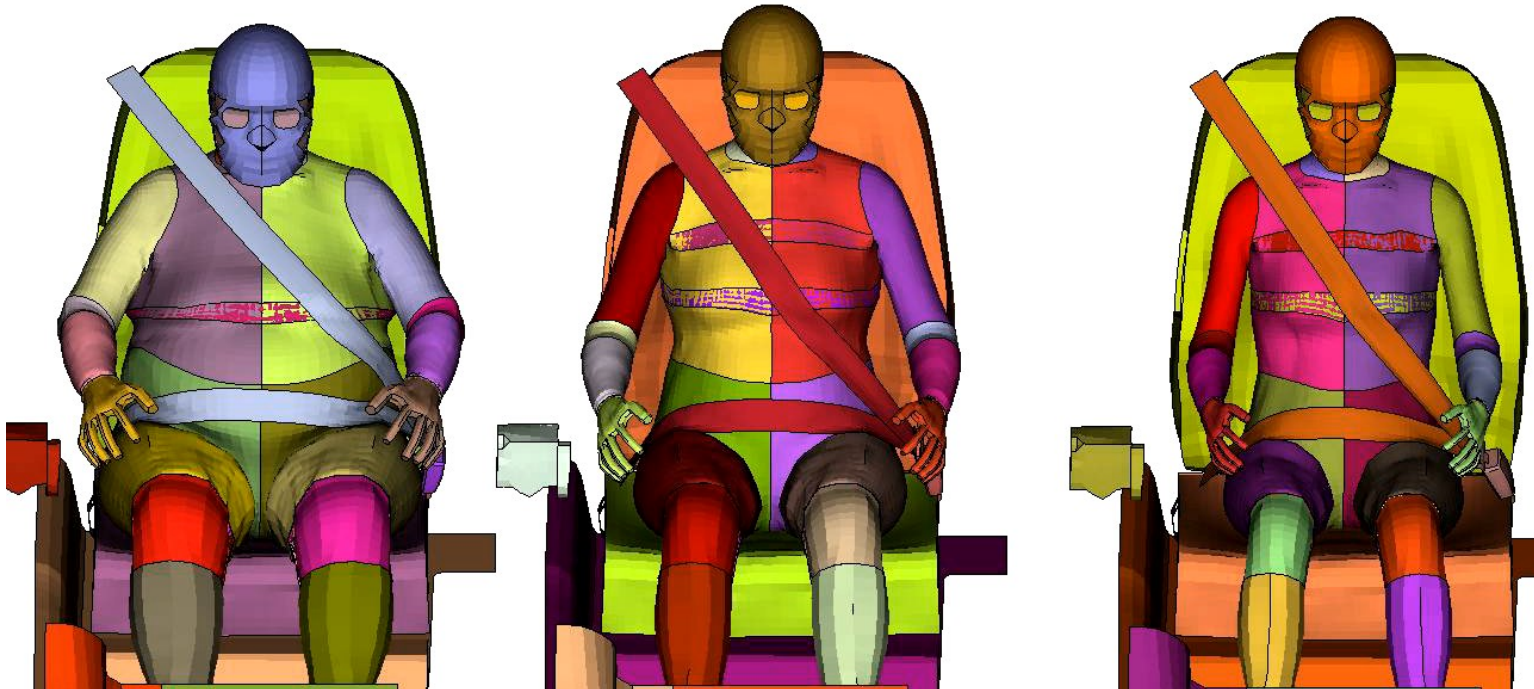
X selected HBMs

X selected HBMs



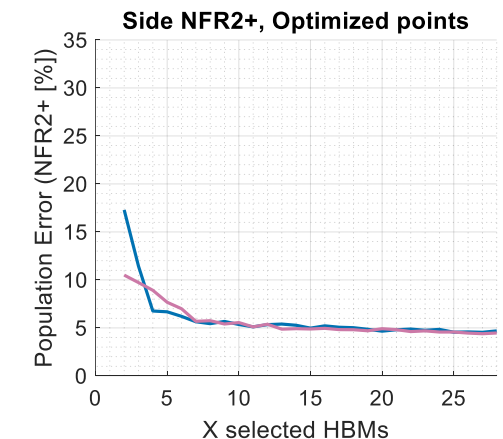
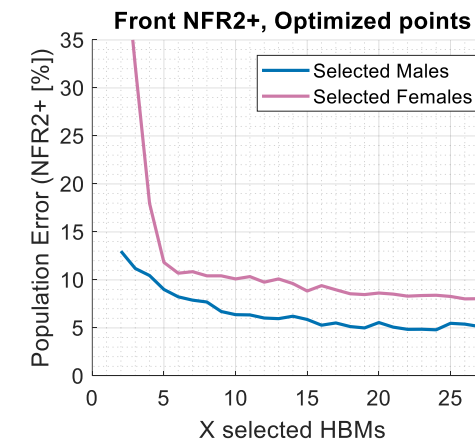
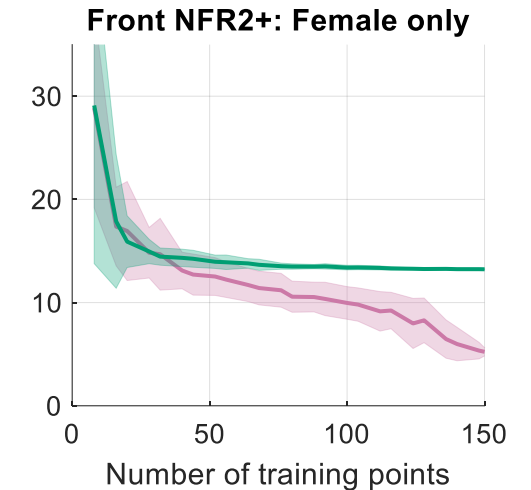
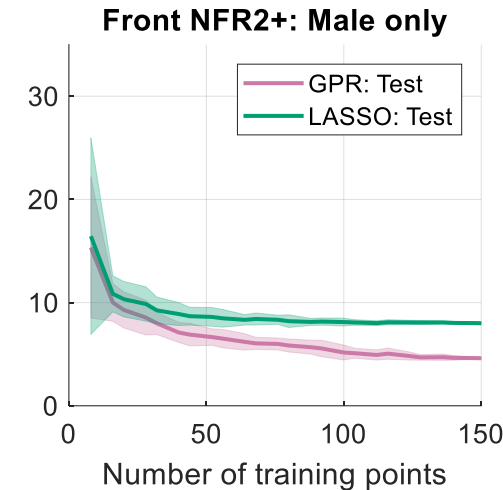
Discussion and Conclusion

- HBM rib fracture risk sensitive to sex, height and weight changes
 - Female and male HBMs – even of similar sizes, predict different kinematics and injury risks
 - Sex differences in body shape reflected in statistical shape models used for morphing
- High BMI females with low rib fracture risk
 - Seatbelt slipped towards neck



Discussion and Conclusion

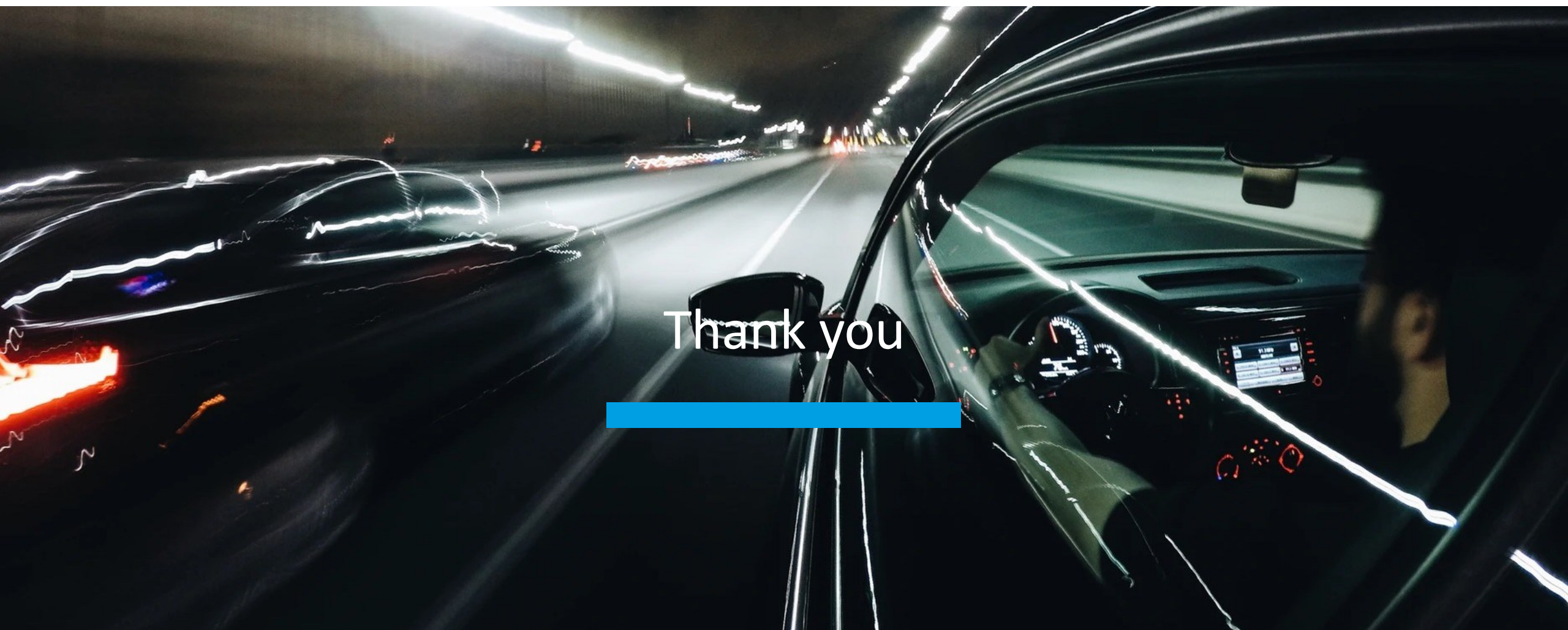
- **25 Male + 25 Female HBMs** of different sizes will give a metamodel that in *general* predicts population response well
- Optimizing the selection of sizes to be predictive for 2 crash scenarios: **5-10 of each sex** is sufficient
 - Will they be equally good choices if we change the crashes? The restraint? To predict other risks?
 - Sun et al. (2024) found that **10 HBMs of each sex** predictive of a joint injury risk (head*chest*legs) for a similar population in a single crash
- Many other factors influences risk
 - Age, Individual variability in bone size and strength, seating postures...



Sources:

Sun et al. 2024

Efficient injury risk predictions for a diverse population using parametric human modeling and inducing points in Gaussian processes, Traffic Injury Prevention



Thank you

IRCOBI pre-conference workshop 2025.09.09

Human Body Models used in standardized virtual testing



Effect of Pelvis Region on Submarining Outcomes

- How to find the most vulnerable population?

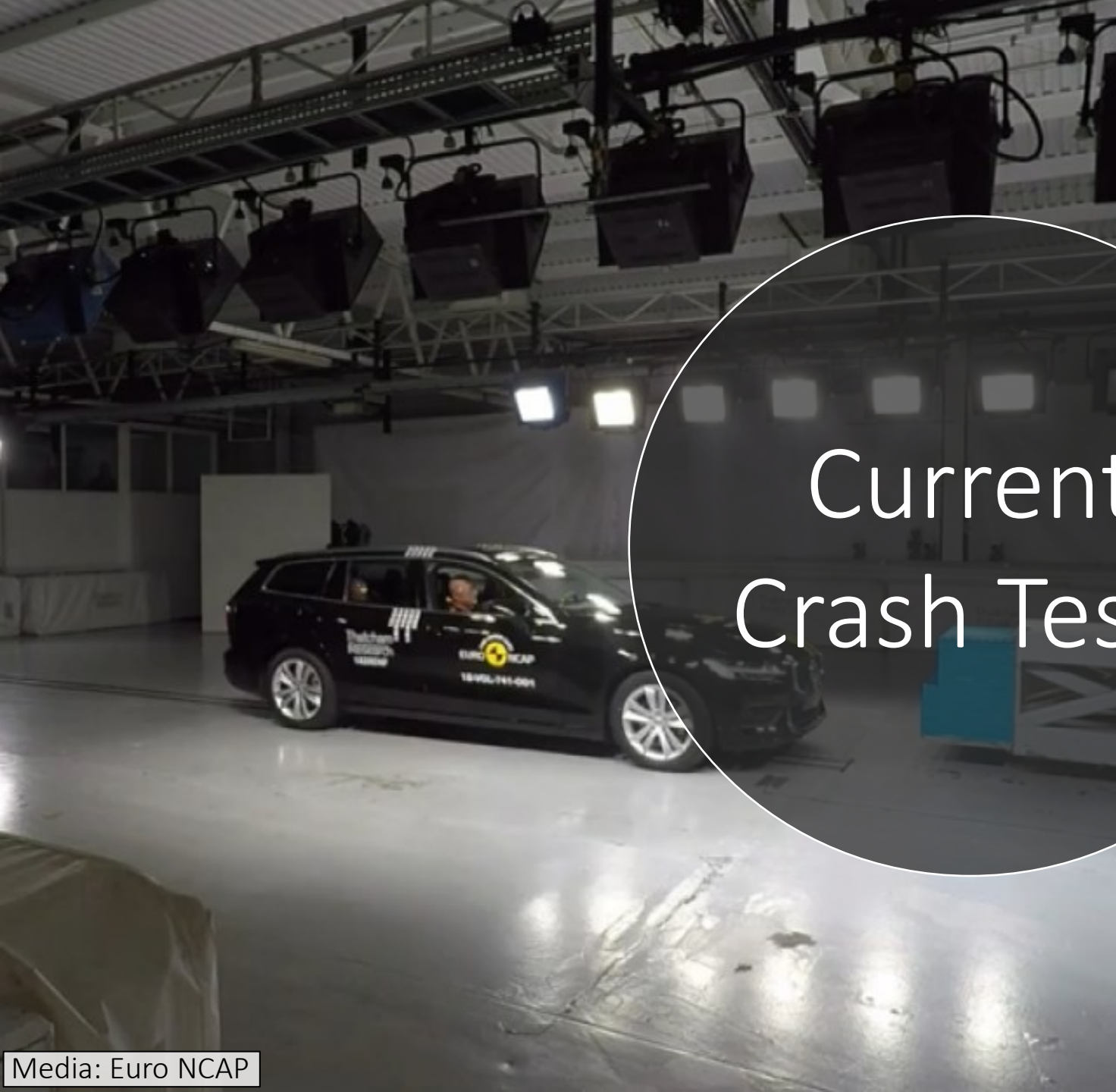
Erik Brynskog, PhD

Who am I?

- PhD in Traffic Safety from Chalmers University of Technology, Sweden
- Specialized in HBM development targeting pelvis injuries
- Part of developing the SAFER HBM since 2013
- Currently work as Child Restraint System Performance Lead for AXKID

Erik Brynskog





Current Crash Tests



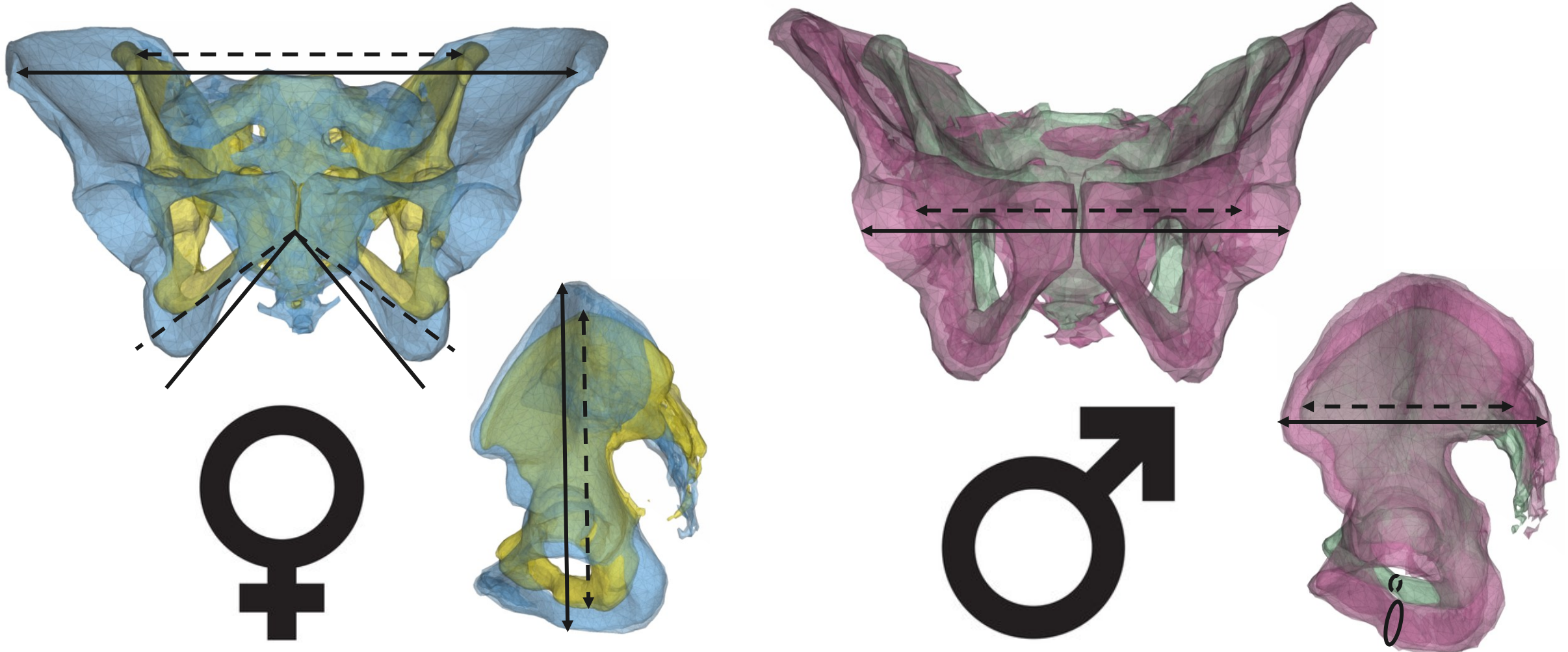


Real-World Variability

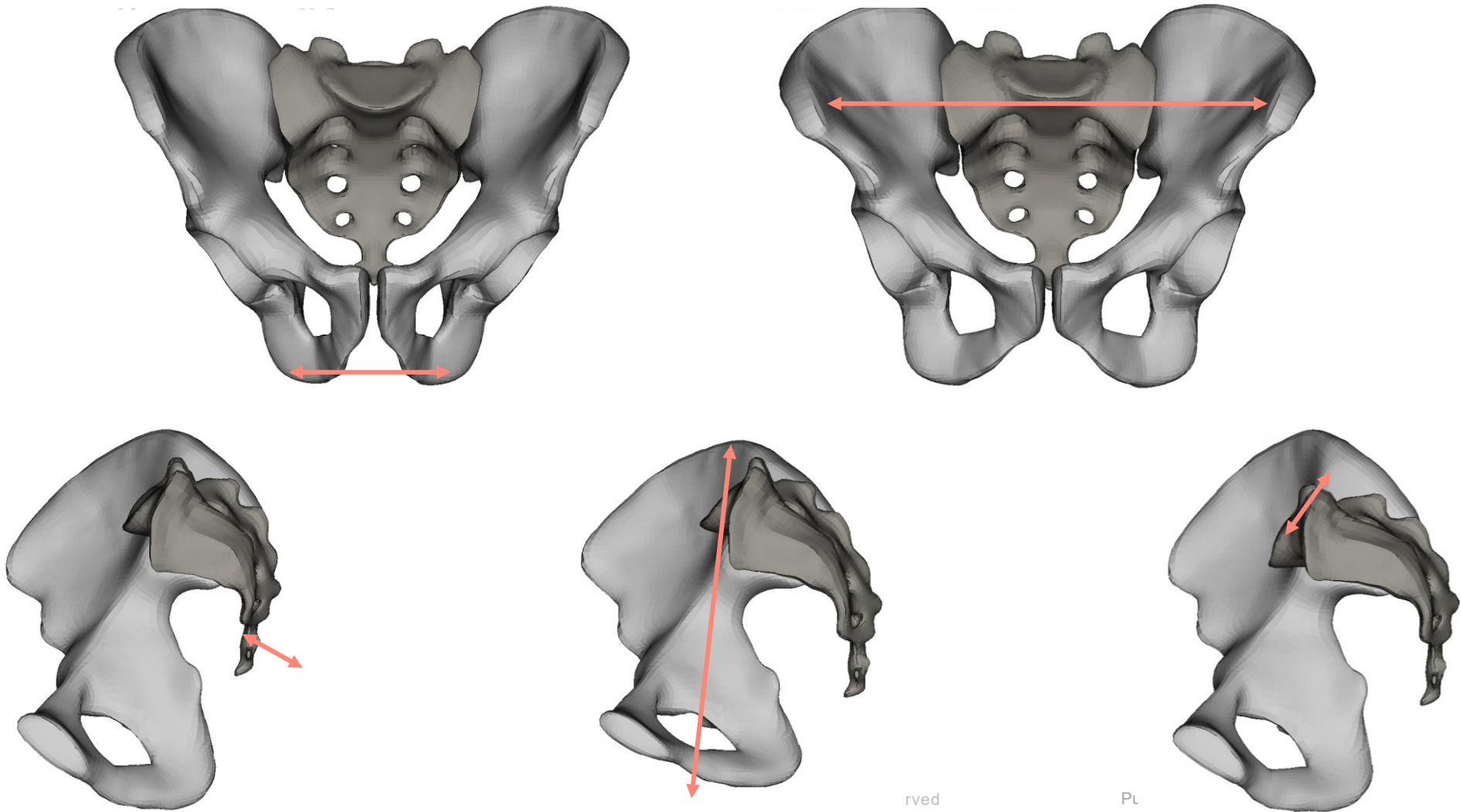
Media: China Out/AFP/TT

Media: Pixabay, B_Me

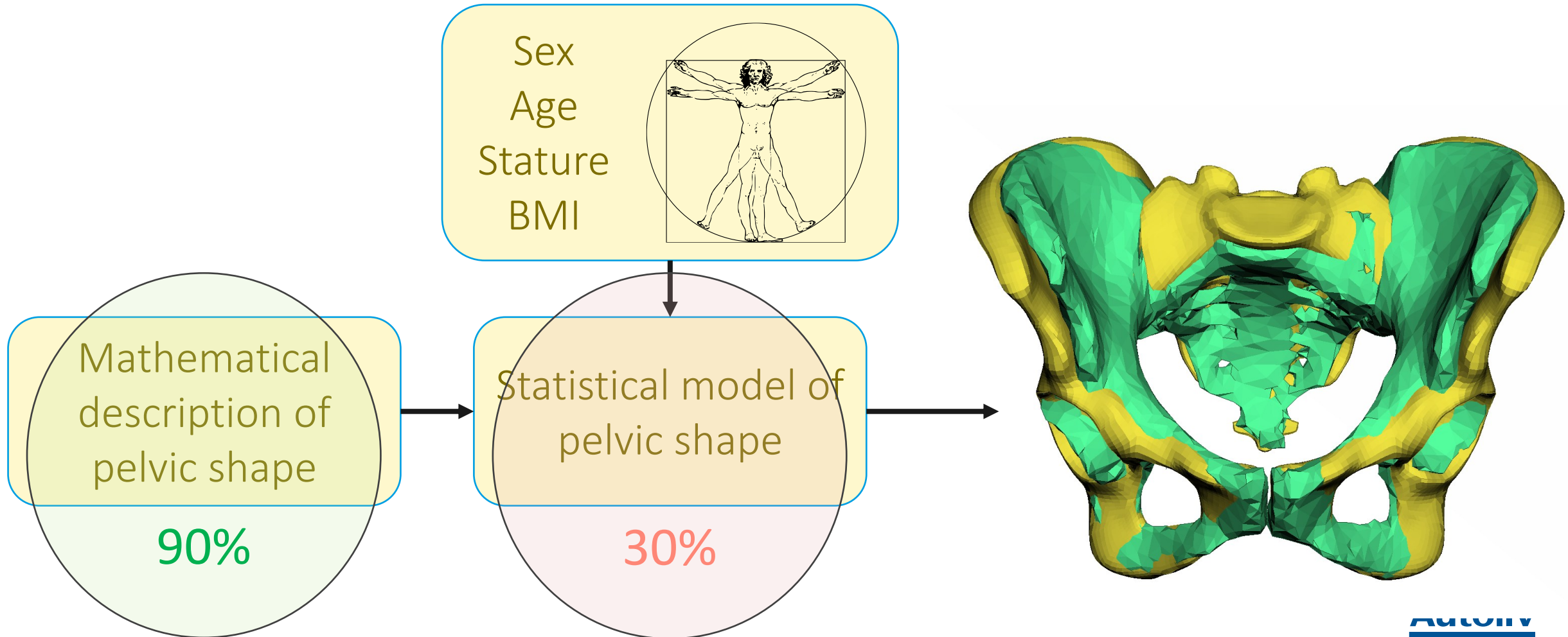
Pelvic Structural Shape Variability



Mathematical Description of Shape

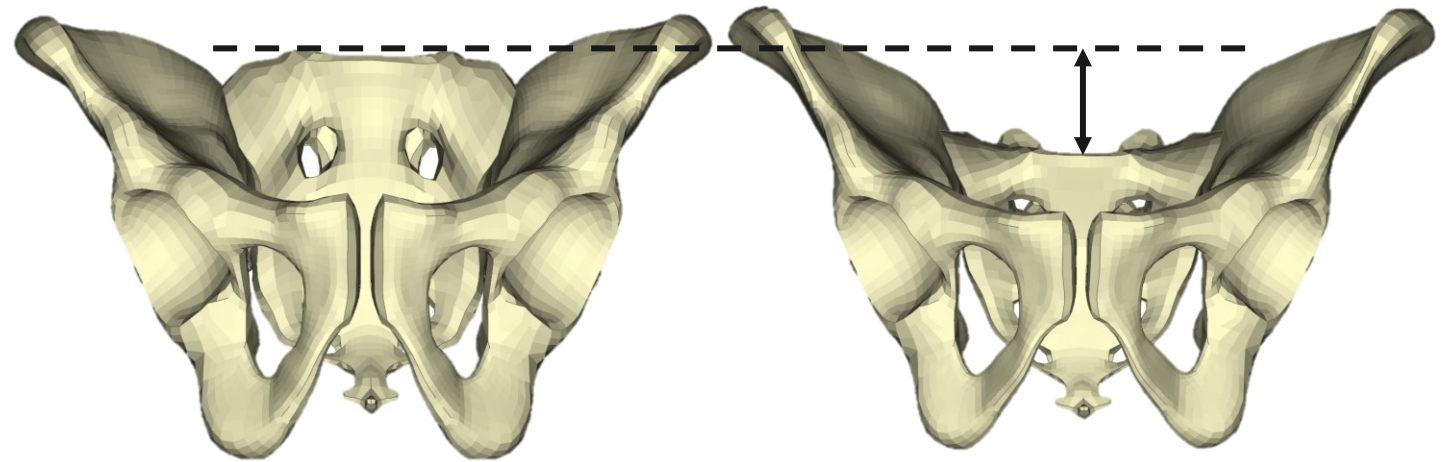
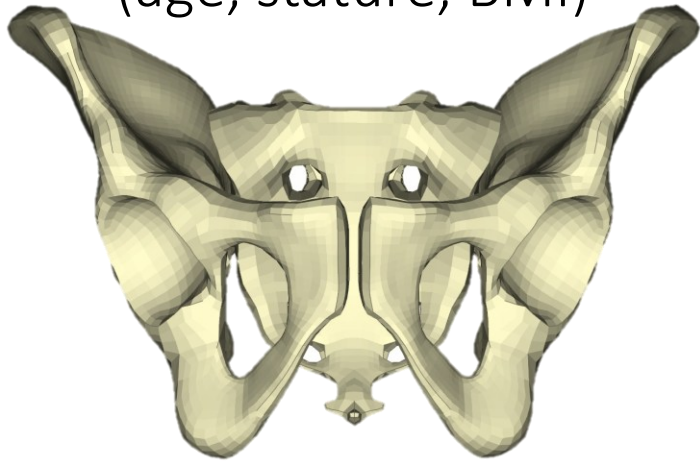


Statistical Shape Model



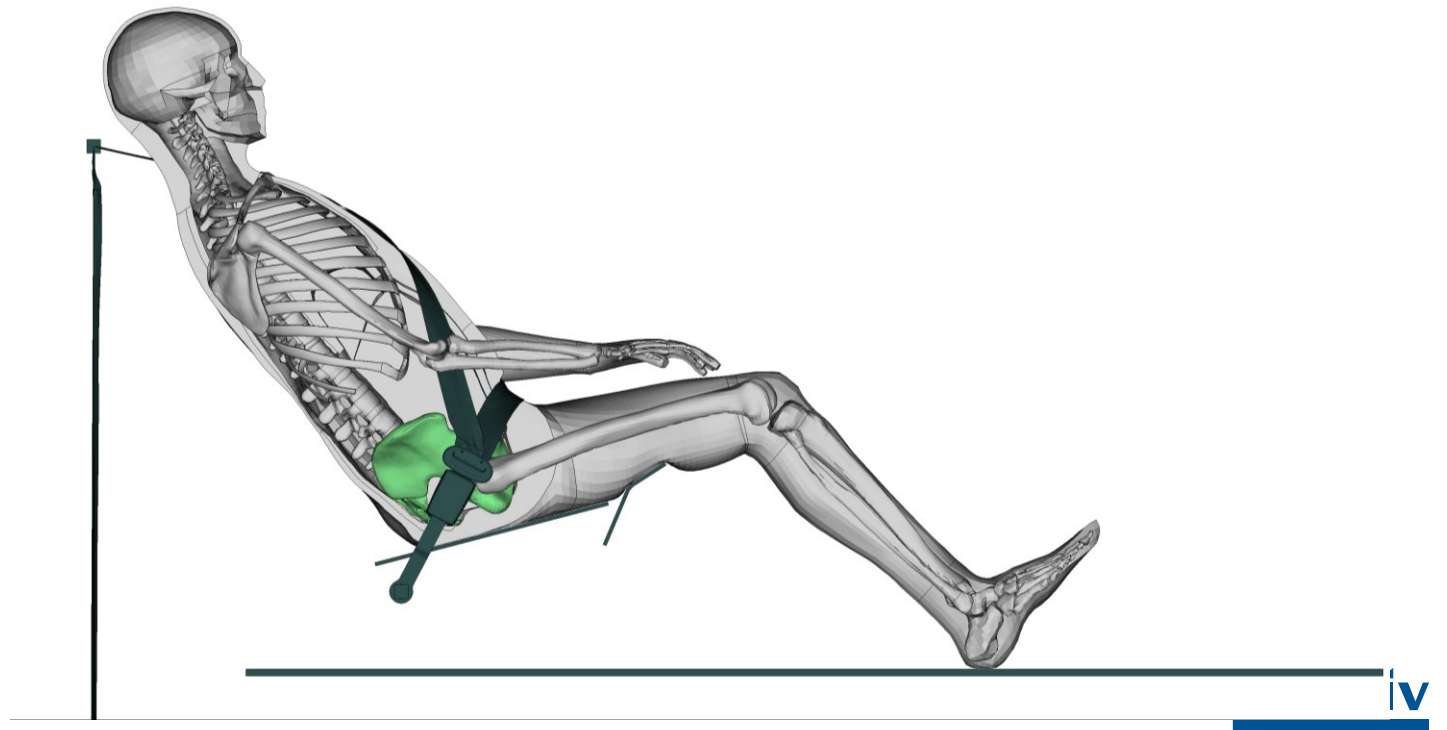
Accounting for Population Variance

Average male
(age, stature, BMI)



Also average males in terms of age, stature, and BMI!

Research question: Can population variance, associated with an average male, compare with vehicle restraint variation on submarining outcome in reclined seating scenarios?



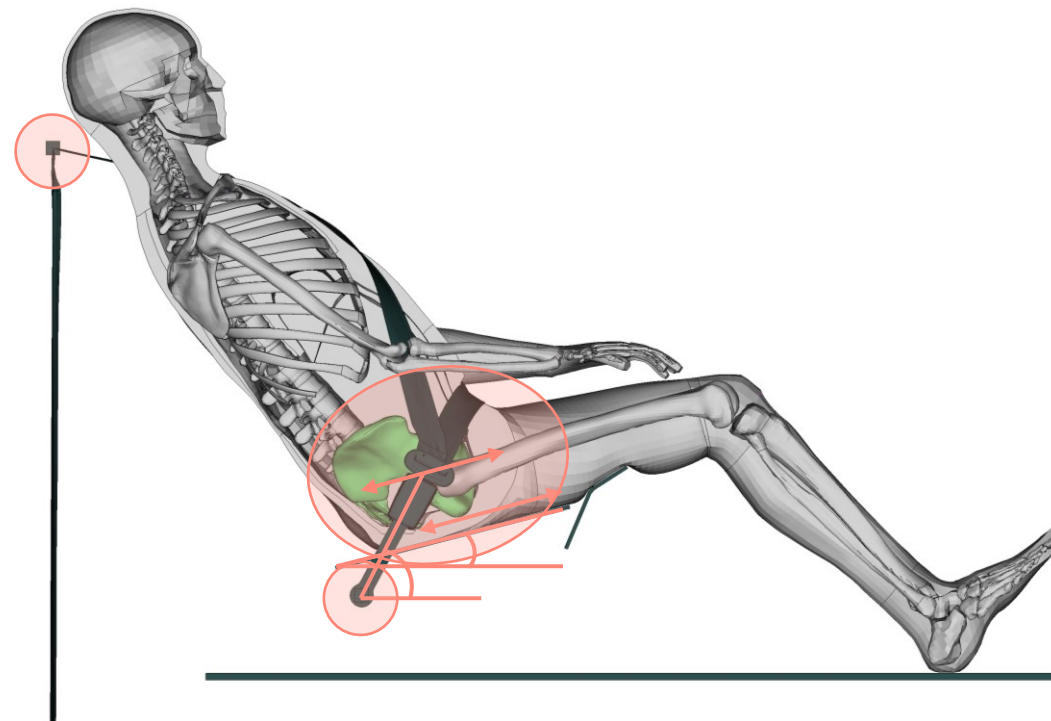
Research question: Can population variance, associated with an average male, compare with vehicle restraint variation on submarining outcome in reclined seating scenarios?

Occupant variables

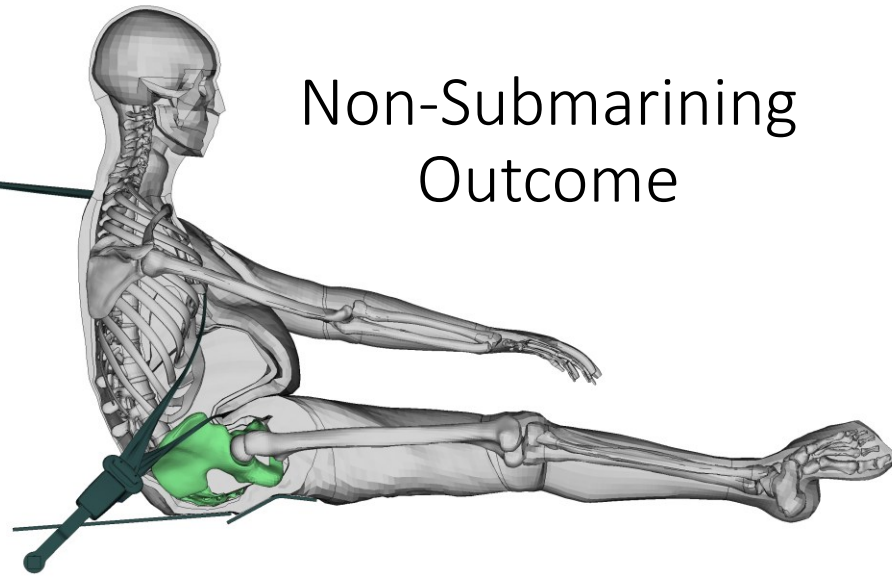
- Pelvic shape
- Fat material stiffness
- Fat thickness
- Pelvis forward position

Restraint variables

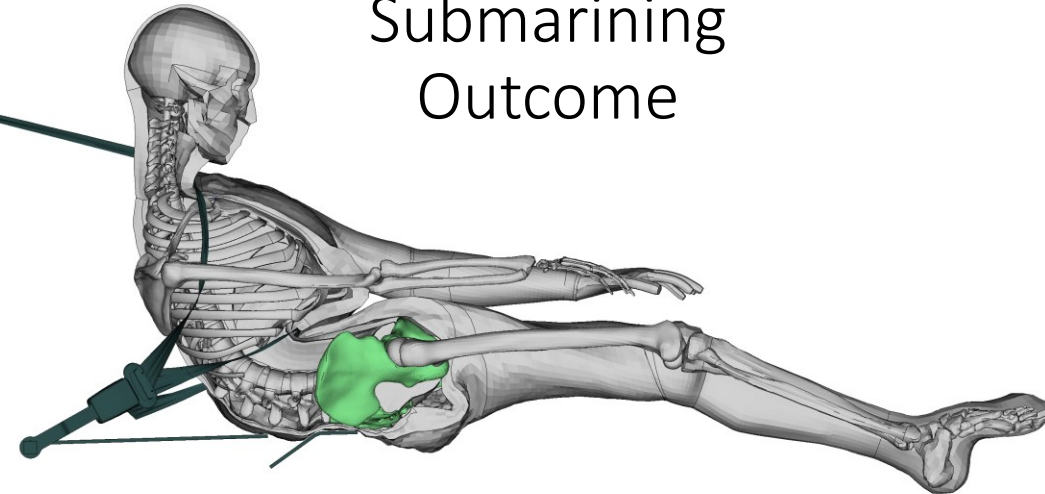
- Buckle angle
- Belt force limit (shoulder)
- Seat friction
- Seat angle
- Lap belt pre-tension (ON / OFF)



Automotive Safety – Population of Occupants

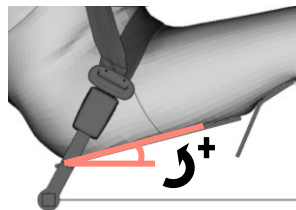
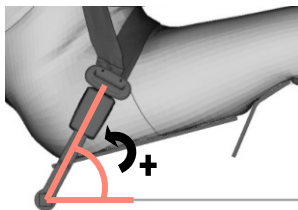
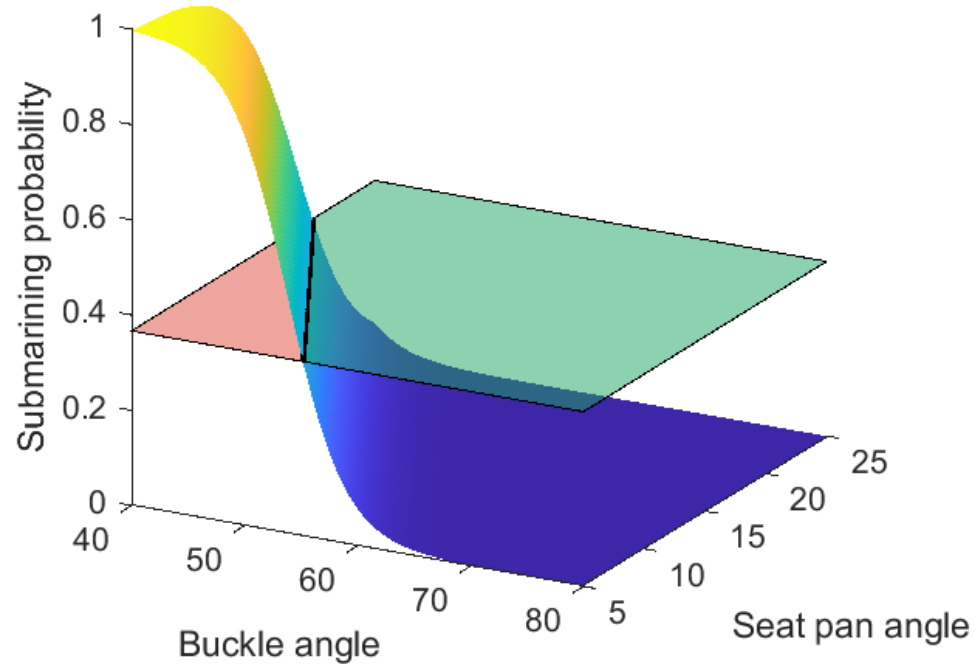


Non-Submarining
Outcome



Submarining
Outcome

Automotive Safety – Population of Occupants



Occupant variability

Pelvic shape

Fat material stiffness

Fat thickness

Pelvis forward position

Restraint variability

Buckle angle

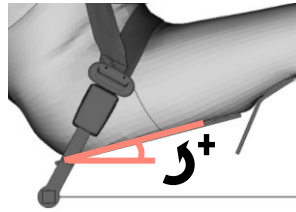
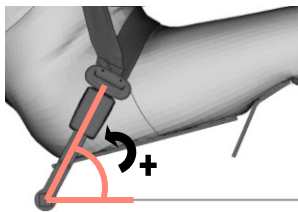
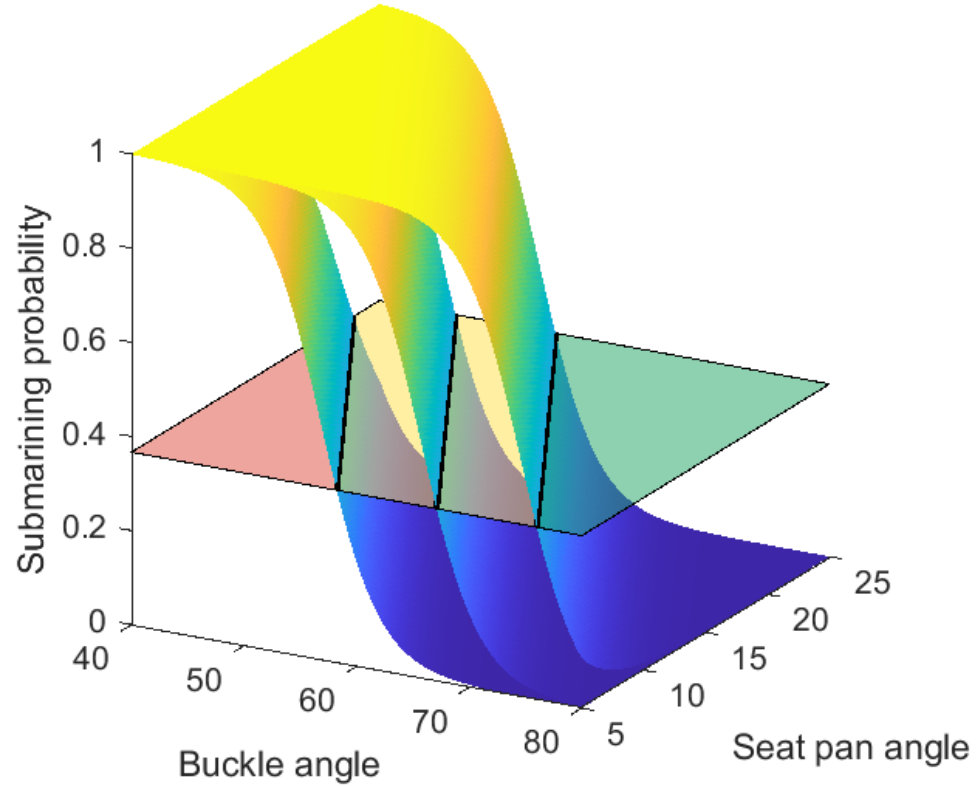
Belt force limit (shoulder)

Seat friction

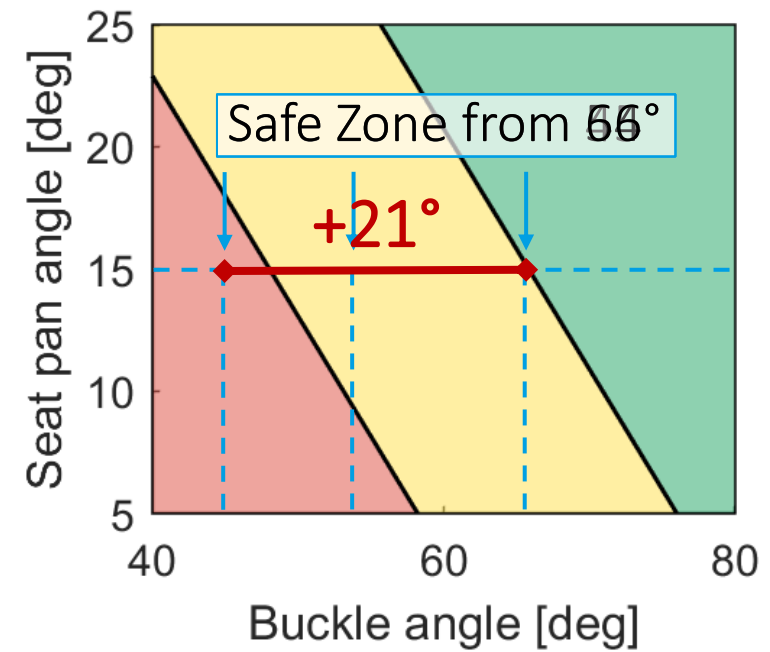
Seat angle

Lap belt pre-tension (ON / OFF)

Automotive Safety – Population of Occupants

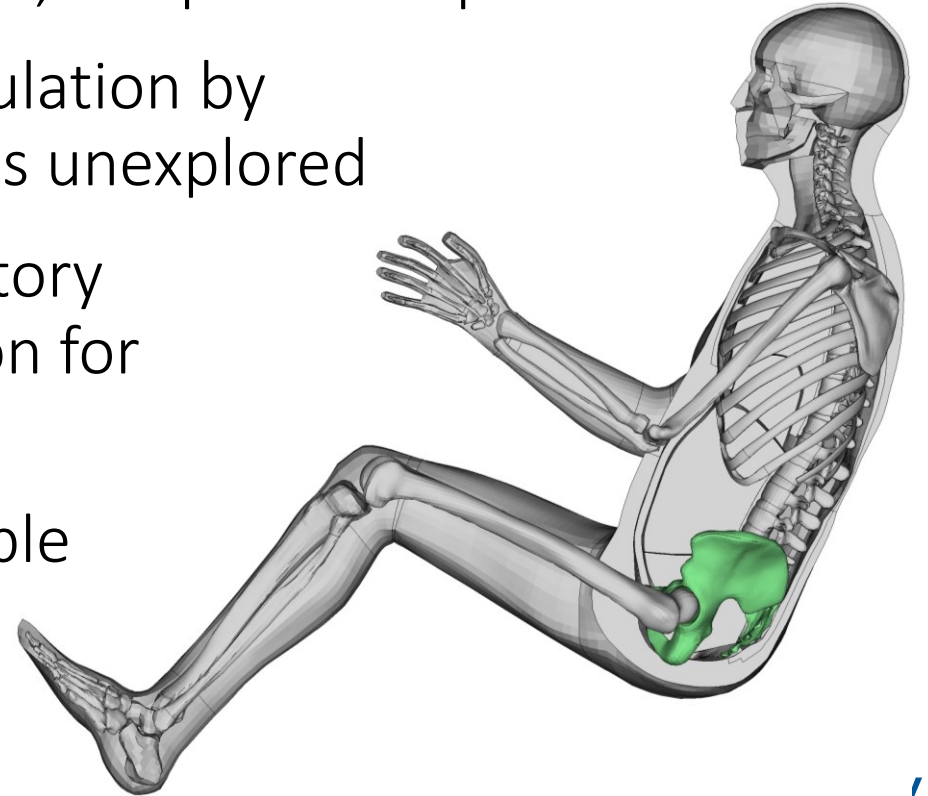


Baseline simulation setup
+ Seat friction and hip placement
+ Critical pelvic shape



Summary

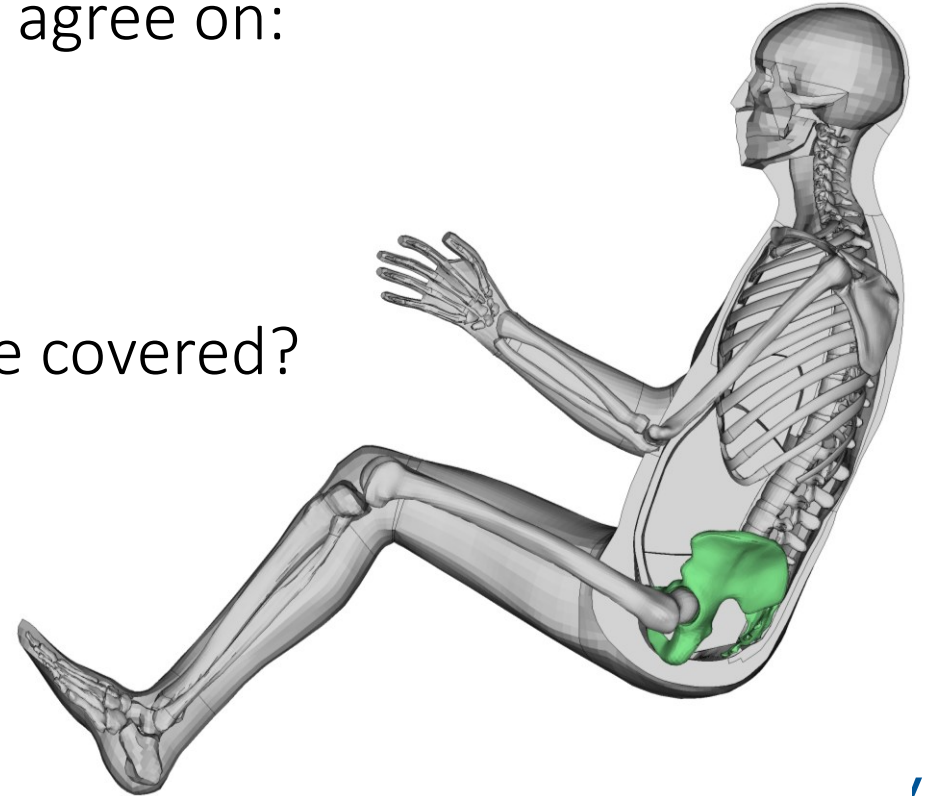
- Anthropometric variables like sex, age, stature, and BMI are poor predictors of some anatomical variations, like pelvis shape
- This means that when aiming to cover a population by these variables, substantial variability remains unexplored
- HBMs can be used to run large-scale exploratory studies to find the most vulnerable population for a given injury outcome
- HBMs generated from the identified vulnerable population could be used as design targets for development of robust safety systems



What is needed?

In order to define the vulnerable occupant / population, researchers, industry, and policy makers need to agree on:

- What is an acceptable risk level?
- What percentage of the population should be covered?





Real-World Variability

Media: China Out/AFP/TT

Media: Pixabay, B_Me

Thesis and Appended Papers

- Thesis** **Brynskog E.** (2025).
"Advancing Pelvis Computational Models for Automotive Safety Assessment".
Chalmers University of Technology, Gothenburg, Sweden.
- Paper I** **Brynskog E.**, Iraeus J., Reed M., Davidsson J. (2021).
"Predicting Pelvis Geometry Using a Morphometric Model with Overall Anthropometric Variables".
In: Journal of Biomechanics, Volume 126.
- Paper II** **Brynskog E.**, Iraeus J., Pipkorn B., Davidsson J. (2022).
"Population Variance in Pelvis Response to Lateral Impacts – A Global Sensitivity Analysis".
In: Proceedings of the IRCOBI Conference, Porto, Portugal.
- Paper III** **Brynskog E.**, Iraeus J., Pipkorn B., Davidsson J. (2025).
"Simulating Pelvis Kinematics from Belt and Seat Loading in Frontal Car Crash Scenarios:
Important Boundary Conditions that Influence the Outcome".
In: Annals of Biomedical Engineering, Volume 53.
- Paper IV** **Brynskog E.**, Östh J., Larsson K.-J., Iraeus J. (2025).
"Effect of Occupant and Restraint Variability in Reclined Positions on Submarining Probability
in Front Car Crash Scenarios".
In: Frontiers in Bioengineering and Biotechnology, Volume 13.





CHALMERS

Conclusions

Notes from the „Wrap Up“ based on the input from the audience and the discussion between the moderators and representatives of the rating agencies

Workshop Conclusions

- Common agreement to focus on targeting real-world crash outcomes
- Progress in injury biomechanics is reliant on strong collaboration between researchers, industry, and tool developers. We are all on the same path to keeping people safe in their everyday lives and we need to work together through data-driven solutions to limit injury risks. To continue engagement with expert contributions is highly valued and seen as driving process in the field.
- Expanding beyond traditional ATD demographics is incredibly useful. Morphing capabilities and population-based modeling can capture a wider range of body habitus, though mesh quality, validation, and handling population extremes remain as open challenges. Human variability extends beyond sex, size, and age; multiple factors should be considered in crash research and safety approaches
- Methods exist for identifying and combining useful output metrics for „simplified“ risk analyses (e.g. risk of more than 3 rib fractures). A method how to select the most appropriate output is also available.
- First qualification procedures are in place, but some challenges (e.g. sample sizes, inter-subject variability and difference between HBMs) remain
- While for some parts of the audience and some presenters, current developments in implementation are slow and too less ambitious, others see it the other way around. Especially industry cautioned against moving too quickly, highlighting the necessity of reasonable lead-times.
- In general the 3 year time-frame for updating requirements on the HBMs and introducing new HBM protocols was seen as reasonable
- Frameworks and tools are available from research to support the usage of HBMs in VT and continuously improved → during IRCOBi several relevant studies will be presented
- Anticipation for a follow-up workshop to review achievements in three years. Optimism regarding achieving further progress by the next workshop, considering the progress since the last workshop held in 2022

Appendix – Questions and Takeaways collected directly from the Audience

Questions from the Audience

- How is the process of developing the virtual testing protocol at Euro NCAP? Who is involved?
- Are there any plans for rear impact protection or protection in alternate seating configurations in vehicles exposed to omnidirectional impacts?
- What injury metrics are being considered for Euro NCAP frontal impact virtual testing? How to account for different HBMs in that process?
- Are there any plans to include more anthropometries in frontal impacts in Euro NCAP?
- "With regard to computing time, you often hear that argument. How long does it take to prepare and carry out a real test with dummies vs. setting up a virtual environment and simulation?"
- For IIHS / E NCAP: Are you soliciting feedback or maintaining list of gaps /needs that this community can fill? How would we best help you?
- Regarding safety of VRUs, are there any plans for EuroNCAP to assess VRU injuries sustained in ground contact?
- How important are cost benefits when talking about new load cases in VT? How do you assess that?
- How VT will be validated, especially for OOP?
- Who will perform the simulations? Automotive manufacturers, certification agencies (EuroNCAP, IIHS), external simulation experts, ...
- Does IIHS plan for virtual testing of VRU safety?
- How important and useful do you think understanding real-world data is to be able to gain insights on what injuries to predict in VT?
- The IIHS approach seems a lot more elaborate compared to EuroNCAP. Is EuroNCAP also considering meaningful differences that the VT load cases will make?
- What is that which IIHS can take as a base to learn from ENCAP for VT framework?
- Do you plan to incorporate morphed HBMs representing non-standard anthropometries in the virtual testing framework?
- Looking at the minimizing the burden on society caused by the road traffic crashes, is any of you (IIHS, Euro NCAP, ...) considering including looking at injuries related to long-term consequences / impairment?

Questions from the Audience (1/4)

- Information sharing: will you provide access to the models, simulation results, etc. to researchers and/or the public? If so, what level of access do you foresee and what issues might limit this access?
- First of all current ATD like 50th, 05th, 95th we are using from decades, but HBMs is new topic. Even though we are not fully developed evaluation criteria and not filled gaps between them, why looking towards age, sex, diversity without filling gaps between existing ATDs and respective HBMs?
- Is IIHS virtual testing HMBS need to be qualified? if qualification needed then don't have plan to develop qualification procedure ?
- Scaling of HBMs sounds easy however it is still a really challenging task and how do we make sure that we create meaningful/realistic new anthropometries not just with respect to the outer shape?
- Regarding model traceability, will changing numeration affect the HBM hashing?
- What are the important steps in the stepwise approach for industry adoption of HBMs?
- What is the need to run more than 120 ms simulation
- Thank you for the interesting talks, my question is to Michiel and Marcy, can you please comment on how Euro NCAP and IIHS may rate in future as there are variations in body with height, weight, obese, etc., and simulating all variations will also be a challenge.
- Generally, do you think we should agree on ONE HBM family to use for virtual testing within the industry? And if so, how can we achieve that?
- Knowing the output of VT also depends on computer infrastructure (different results depending on the processors, etc...), will we have corridors of results, as for experimental tests?
- In Euroncap2026+ farside test, test mode is expanded to 8 modes and required sled test validation. that means automaker can't reduce test runs. is it gonna be changing? increasing test mode is making hard development environment
- How to include real accident data
- IIHS/ENCAP what is main priority? Injury evaluation development or diversity introduction in next year 10 years ?
- When morphing the 50%ile HBM model to different sizes and weights (BMI), how are the models qualified if the specific data is missing? How can you trust those models?

Questions from the Audience (2/4)

- Is there a conflict in creating biomechanical tests for HBM validation and tests that are optimized for other purposes such as determining human tolerance levels or are these aims complimenting each other?
- How does one use the positioning information from PMHS testing from different research groups across the world to position the HBMs as far as harmonization is concerned?
- For the comparability cases, would users get specific information (like the nodes or part set definitions) from the HBM developer?
- What about the HBM mesh quality after the positioning? Will different quality criteria be defined for the VT?
- In CP550, should your model follow the line of a single PMHS test, which would theoretically be a “perfect” model, the score could be poor. Have the DALW scores from the individual PMHS tests been compared to the minimum requirements?
- For the HBM thresholds in HBM4VT: for the future, does it makes sense to include any of the “participating” HBMs of the developers? If I don’t get that wrong this means any HBM (as bad as it might perform) will be included within the thresholds and is qualified?
- Which method do you plan to use for biofidelity scoring? CORA or NHTSA BRS or both?
- Are you planning to develop comparability load cases which are closer to the assessment load cases?
- How is model validation post injury handled? For example, kinematics can change substantially post fracture. Some models aim to simulate the failure, while others only aim to predict the risk of injury. Will this be considered when stating what is a valid kinematic respons?
- Future question. Is the group looking at the use of HBMs for applications including muscle data, lacerations, burn injuries etc
- By Not matching the PMHS position in the test, this is not a biofidelity assessment but rather a qualification Procedure: call it correlation score and Not biofidelity score
- How about active muscles in HBM, any progress in this field?
- Which number for the rib fracture risk would you use as the output in a Rating Programme (3+?)
- So, the probabilities fx risk in ribs rely the strain calculation. Without fracture behavior in the model, the load path/strain fields change after the first fracture. The divergence from predictable behavior increases post fracture. How would one use this technique without post fracture behavior?
- Is this probability of calculated of rib fracture severity depending the impact speed is the same for powered two-wheelers ?

Questions from the Audience (3/4)

- Are the notebooks able to accommodate different unit systems?
- Is the positioning method influencing the HBM outputs? Should the HBM be always prepositioned within the same environment in each simulation to make it valid?
- Is it necessary to have protocols to conduct experiments focusing Hbm for VT?
- Could the Brier score method be applied to the HBM4VT setups to decide on the metrics to be used for VT?
- Any idea how sensitivity for HBM thorax or lower leg injury risk criteria compares to ATDs? Can the engineers use the criteria for optimisation of safety systems in a similar way?
- Should there be a focus on model strain validation for different load cases using strain gauge data collected in PMHS testing before developing model specific strain based injury risk functions? Maybe strain validation at some key landmarks that are frequently fractured?
- What is your view on the prevalence of fractures to rib 1? Seems like HBMs sometimes overpredict the risk for fracture there.
- Injury risk probabilistic process : peak strains calculated from shell element or solid element ? Which integrations did you consider whether it is middle point or near edges points ?
- Rib injury prediction Peak strains 95% would better or 100% ? Which is appropriate do you consider ?
- For Scott, do you think that applying the same method to select the best injury criterion but using a different HBM would have produced the same outcome? Do you know if something has tried to do it?
- how to make sure that even after calibrating risk curve for rib injury prediction that all available hbm will yield similar outcome for industry perspective
- What hypothesis did you make to be able to directly apply the ATD injury risk curve to the GHBM model and were the force cross sections defined on the bones at locations that were similar to the ATD or the PMHS ?
- is the risk curve calibration methodology having cases more aligned to real world cases
- if different model shows different location and different number, how is safety engineer going to use such outcome
- Have you developed a full skeleton statistical shape model to create the different body shapes and how did you handle the morphing of the soft tissues ?
- Given the different restraint system failure modes, how should future assessments select seat positions for different anthropometries to ensure robust real-world performance?

Questions from the Audience (4/4)

- Have you performed the study on VRU?
- Should we consider also exposure when selecting the HBM sizes/shapes?
- Question w.r.t to modeling high-BMI occupants: Can you comment on the lap belt fit in HBMs vs. real humans (with the belt sitting on the outside for the HBM)?
- What does model certification look like for different sizes? It could become a lot to do even with 5-10. We currently have 60 plus cases. 600 cert cases?
- How big is the difference of pelvic angle vs. pelvic shape?
- Based on your research, how should pelvic shape be defined for HBMs used in NCAP assessments?
- @Karl, the way you selected the Body sizes of the representative HBM Family considered age and age related changes (e.g.posture)? Are 25 male and 25 female sizes really enough?
- Children have different anthropometry and posture, and are arguably the most vulnerable population, but they haven't been mentioned so far today. Is there a risk our child safety tools and knowledge won't keep pace with those of adults?
- Should HBMs come with a morphing algorithm or software to ensure mesh and model quality? Similar to model specific injury risk curves.
- How did you decide the influencing factors or the covariates to be considered in regression?
- Erik: Did you look further into Pelvis Angles and could you define a range of pelvic angles with your shape model as well?
- How did you select the pelvic shapes?
- Can we use field data to validate the responses from morphed HBM simulations ?
- What timeline do you envision when talking about using the population based approach? Do you think that a stepwise approach makes sense and if what are these steps?

Key Takeaways from the Audience

- Even setting biofidelity improvements compared to ATDs aside, HBMs add great value as they are able capture anthropometry differences seen in the population.
- Collaboration within the HBM community, the rating agencies and the final users (OEMs) is important
- HBMs should be sensitive to the changes which matter in PMHS tests and the field
- There are methods available to select the HBMs most appropriate to predict responses for the whole population and methods to select the most vulnerable population
- Realistic variation of occupant size, shape and posture is needed to get closer to what is happening in the field
- HBM outputs are different to dummy outputs - with probabilistic approaches we can combine the output of a strain field into a single probability
- Work on the fundamentals is needed. Some ideas seem to go too far into the future
- Sure, but needs to be consensus and data driven. Involve all OEMs and ensure that there is enough time provided for updates
- Human Body Model Qualification is now in place but needs to be stricter and thresholds raised in the future
- HBMs are expected to be updated continuously in contrast to ATDs