Human body models as design requirements to prevent injury to onboard personnel

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LIGHTNESS BY DESIGN

SWEDISH DEFENCE MATERIEL ADMINISTRATION

FMV

Background

- Design requirements are defined for damage to equipment, but not to the same extent for human injury (limited to traditional ergonomics).
- Injurious impact loading may occur during high-speed boat operations, for example due to slamming.
- Finite element human body models (HBMs) have been & are used in traffic safety research, product development and consumer testing to prevent impact injury.

AIM: To assess whether HBMs can be used as design requirements to prevent impact injuries to onboard personnel.

Human Body Models – a brief history for automotive applications

1960's 2D-models

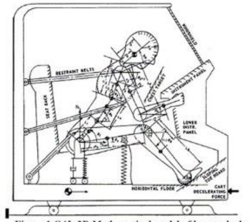
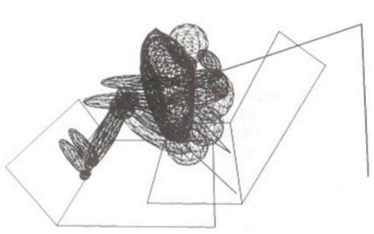
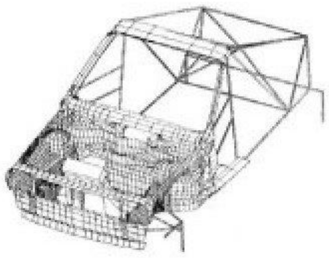


Figure 1 CAL-2D Mathematical model of human body and restraint system on test cart (11 degrees of freedom)

1970's
2D & 3D multibody models

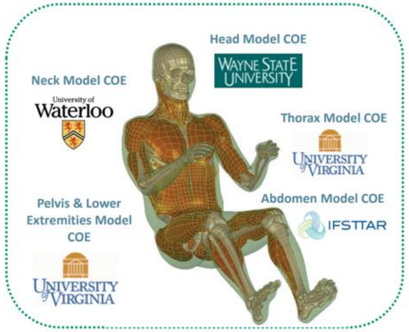


1985 First FE-simulation of full vehicle crash

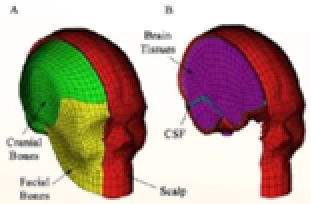


HUMOS Model

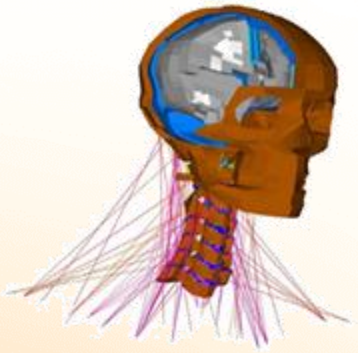
THUMS Version One launched in 2000



1990's
Detailed body segment FE models



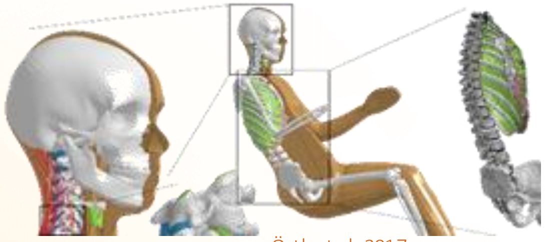
Ruan et al 1993, Zhou et al 1995



Halldin 2001, Kleiven 2002, Brolin 2002.

2000's Start of development of full body models (M50)
Europe: HUMOS, Japan: THUMS, Global: GHBMC

2010's
First average female & HBM used in product development



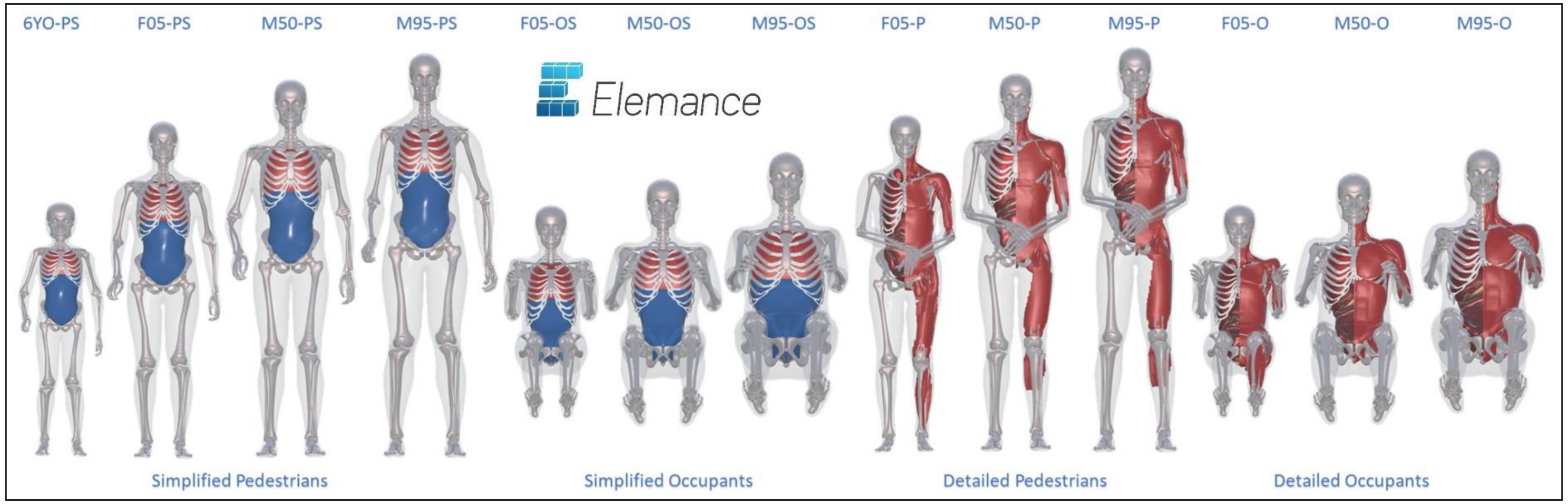
Östh et al. 2017.

© Toyota, Japan

2020's
HBM introduced in Euro NCAP

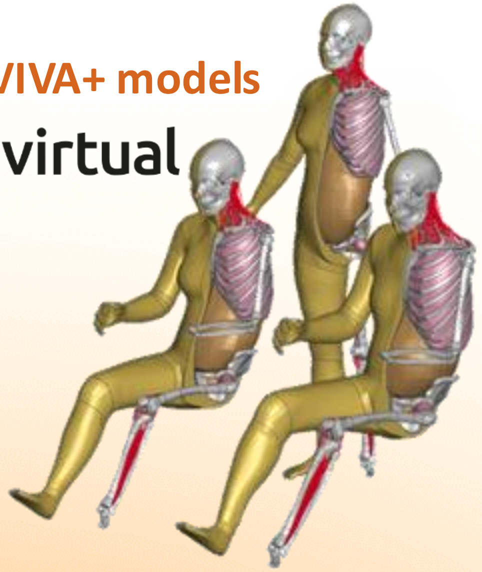
Human Body Models – accessible state-of-the-art models

Global Human Body Models Consortium (GHBMC)



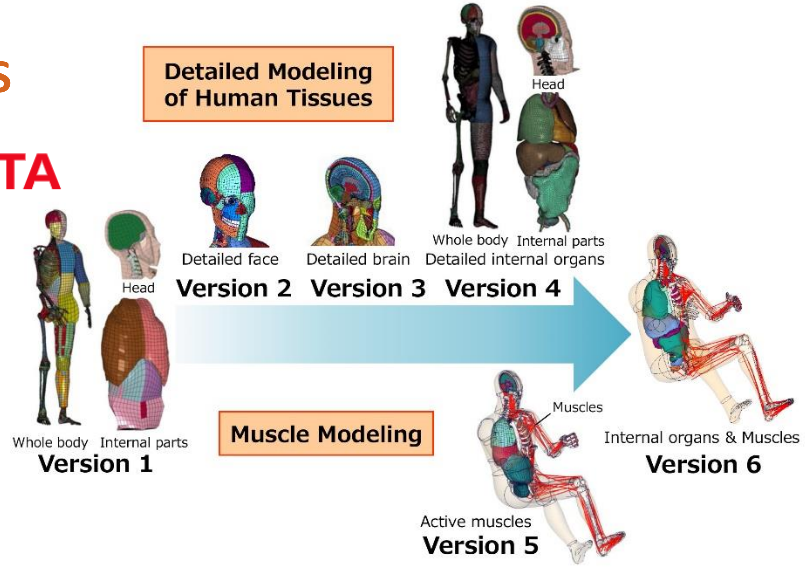
VIVA+ models

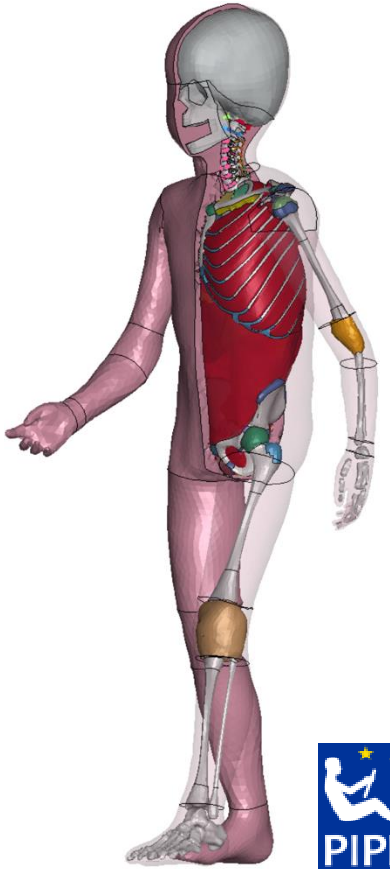
virtual



THUMS

TOYOTA



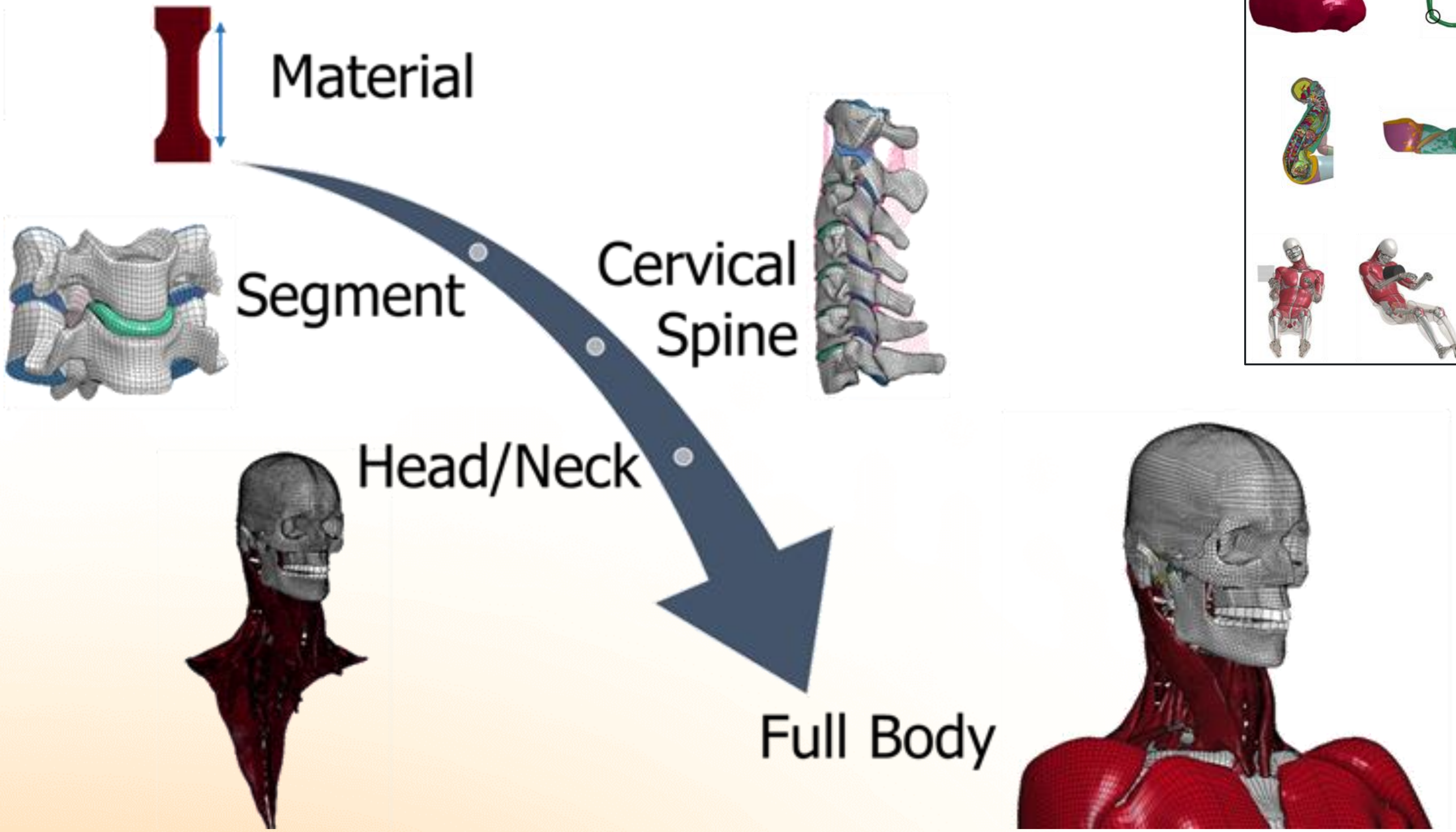


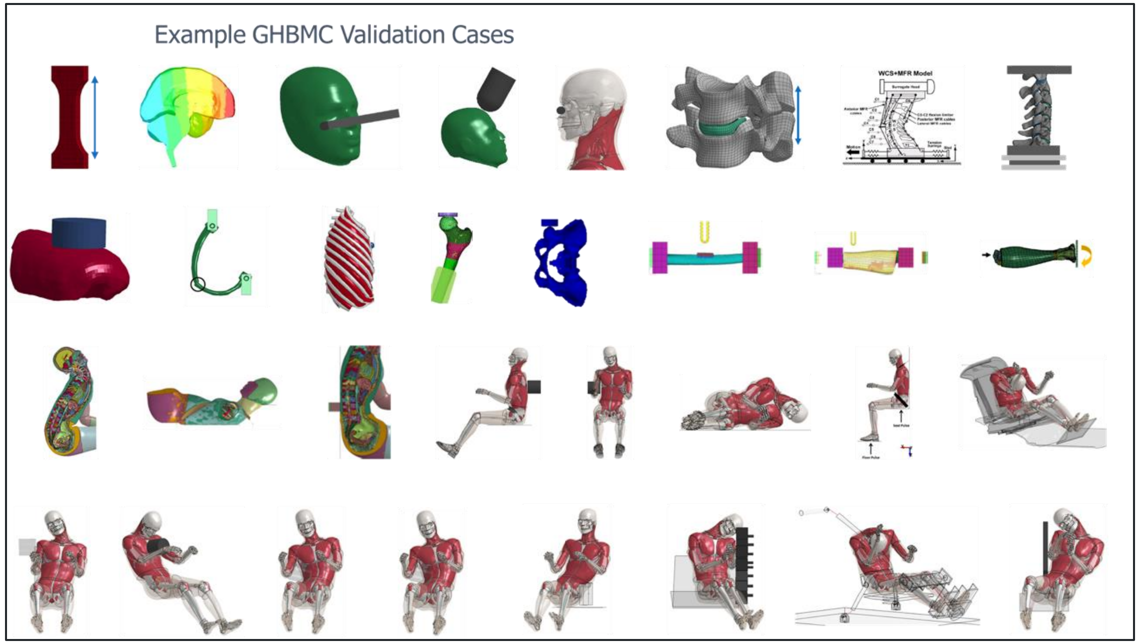
PIPER

PIPER, scalable child model

Human body models – Validation

Hierarchical Validation for GHBMC –
Comparing HBM response to tissue testing, ex-vitro testing, postmortem human subjects & volunteer experiments.

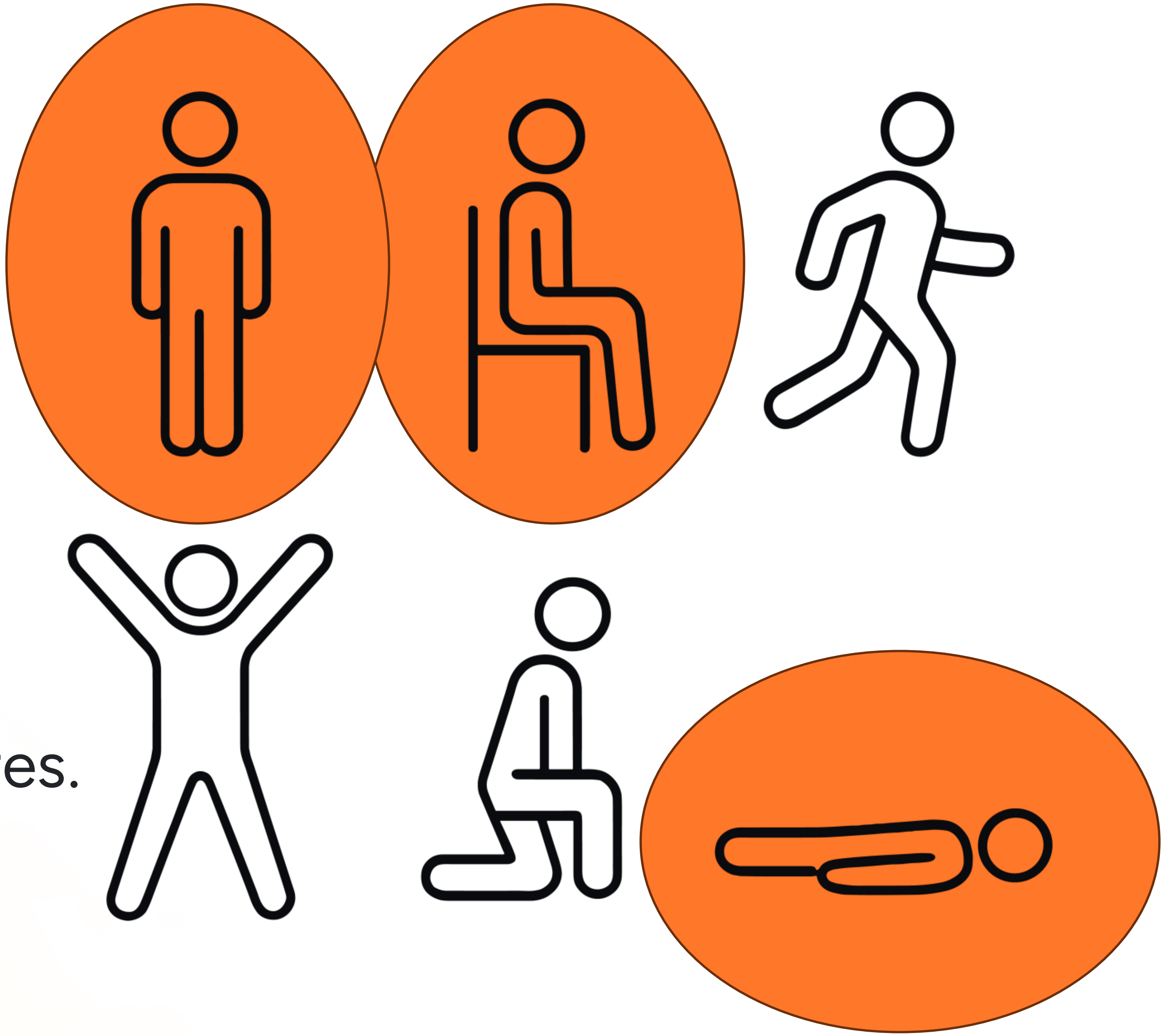




Onboard personnel

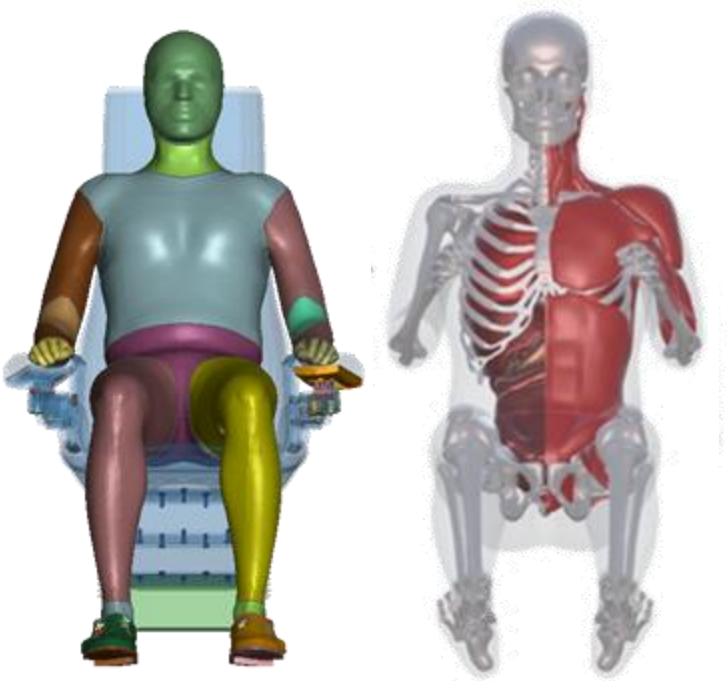
- Steering
- Navigating
- Performing other tasks
- Resting
- Transportation of injured personnel - casevac

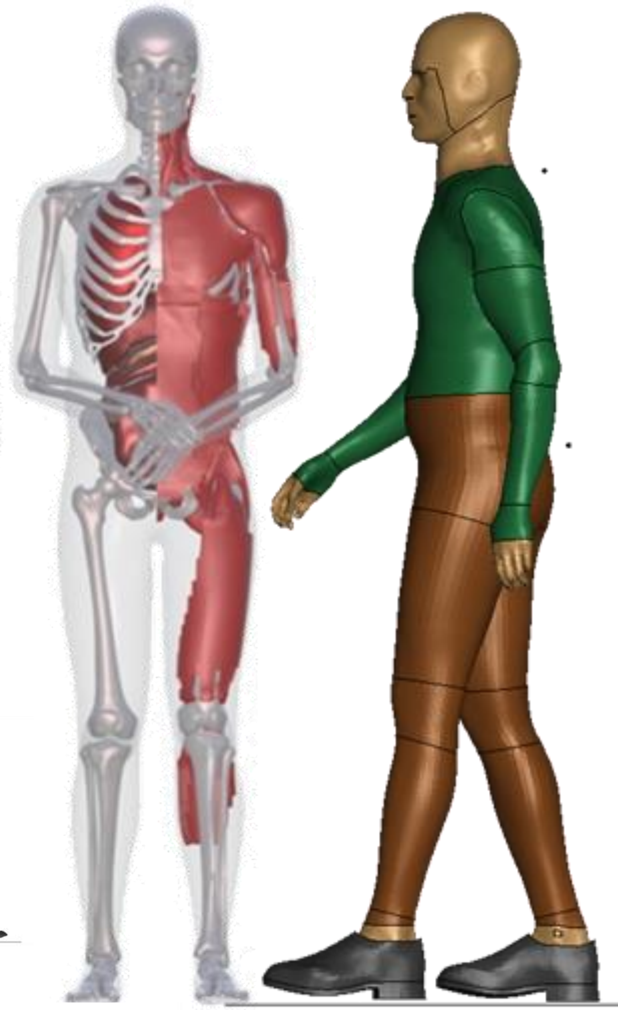
Sitting, standing & lying postures.

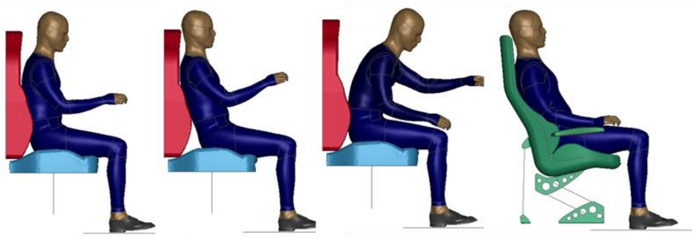


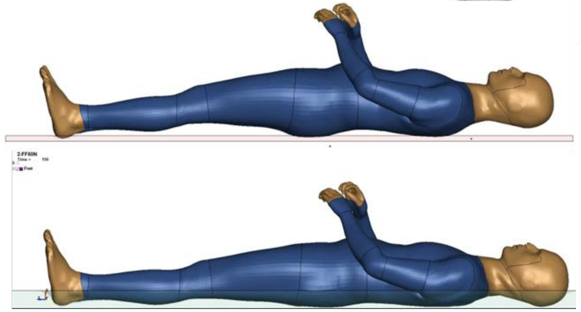
Methodology

- FE HBM:
  - GHBMC M50 Occupant
  - GHBMC M50 Pedestrian
  - Global Human Body Model Consortium-owned
  - Licensed by Elemance Ltd.
- Environment, FE models of:
  - Generic seat
  - Bucket seat
  - Bunk beds
  - Floor





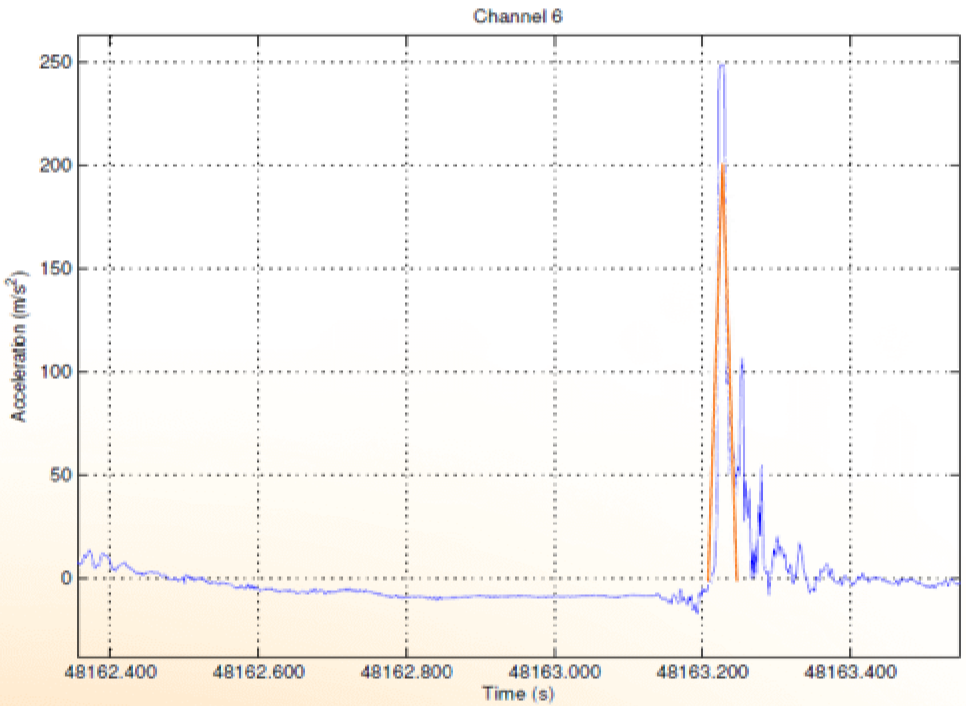




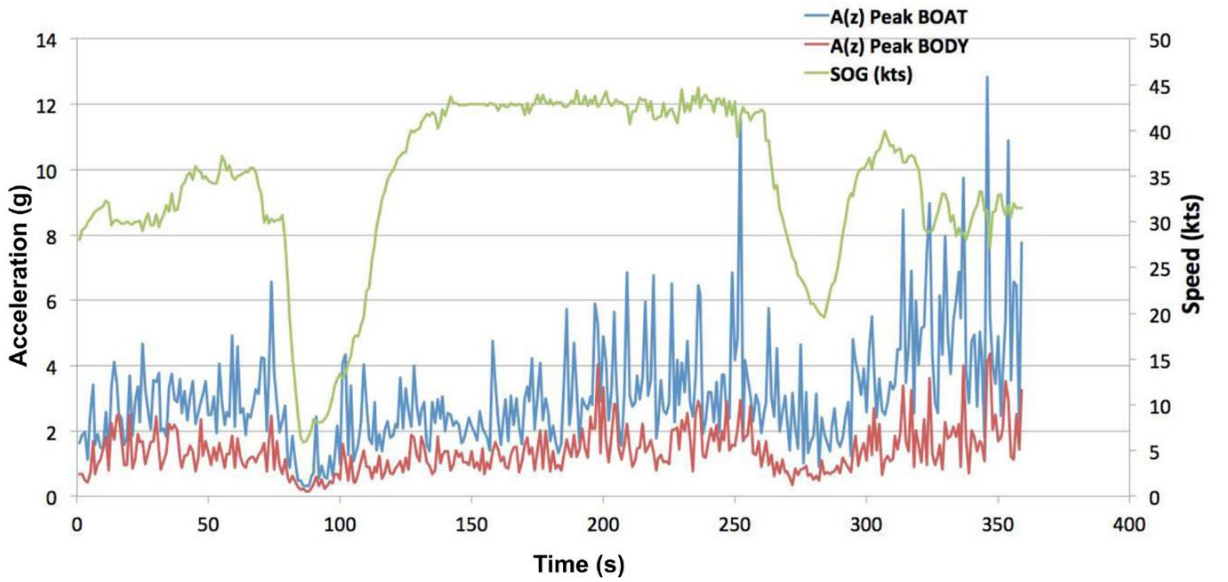
- Reposition HBM using Ansa (Beta CAE)
- FE solver: LS-Dyna

Slamming – simplified pulse

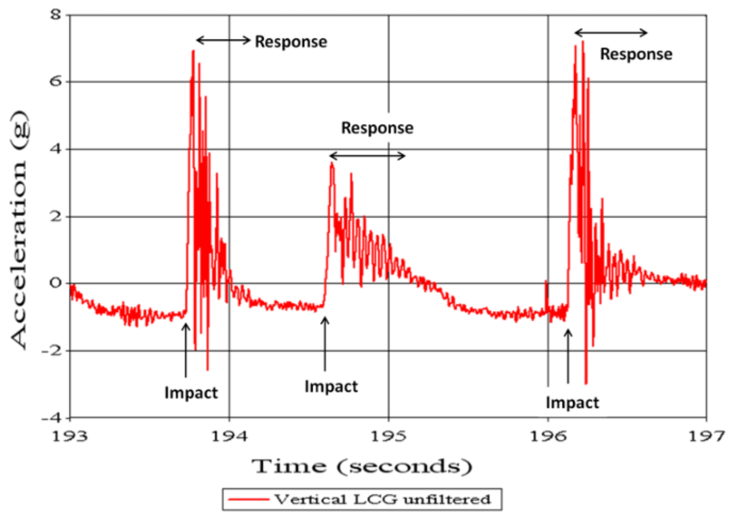
- Acceleration pulse
  - Peak = 20 g
  - Rise-time = 10 ms



Ullman et al. "Lab testing of suspension seats for high-speed boats", High Speed Vessels, 1-2 June, London, UK, 2020.



Ullman et al., "MultiAgency, prospective, exploratory, non-intervention, cohort Study on Human Impact Exposure oNboard high-speed boats (MASHIEN): protocol". *BMJ open*, *15*(5), e090993. 2025, https://doi.org/10.1136/bmjopen-2024-090993

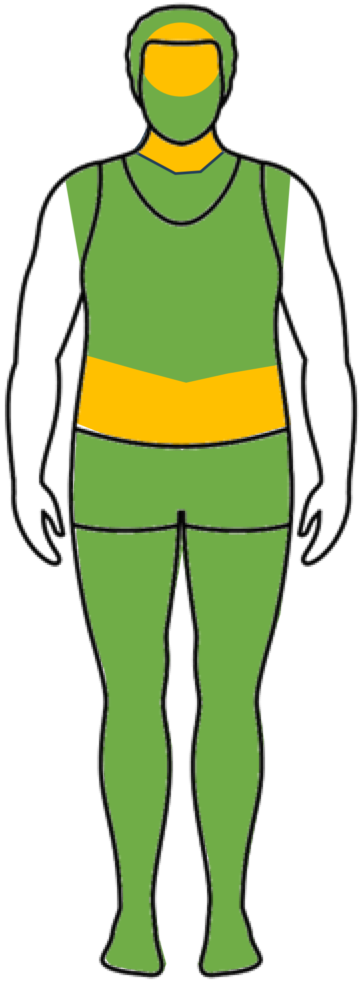


Riley et al., "A deterministic approach for characterizing wave impact response motions of a high-speed planing hull," tech. rep., NAVAL SURFACE WARFARE CENTER CARDEROCK DIV NORFOLK VA COMBATANT CRAFT DEPT, 2012.

GHBMC – injury prediction based on tissue responses

Table 21. CII assessment capability scale for GHBMC models.

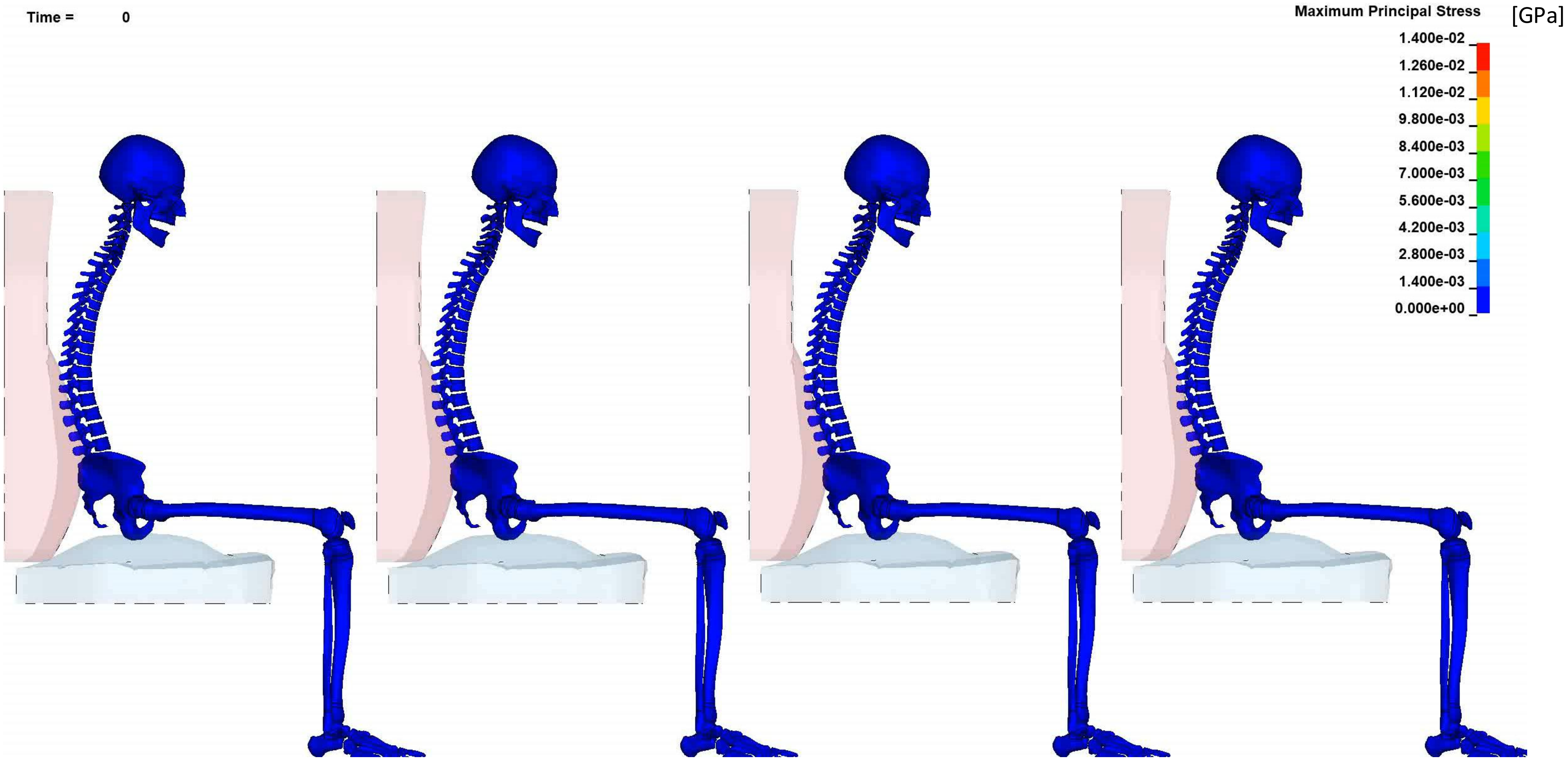
Category	Description	Color Code
0.	Model detail sufficient, test data available, injury mechanism understood, correlation carried out	
1.	Model detail sufficient, test data available, injury mechanism understood, but validation work is incomplete or inconclusive	
2.	Model detail sufficient, but test data unavailable or insufficient	
3.	Model detail insufficient, test data available, additional modeling should help predict this CII	
4.	Model detail insufficient, test data unavailable; additional modeling effort and test data should help predict this CII	
5.	Injury mechanism needs some more investigation	
6.	Injury mechanism needs extensive additional investigation	



”Average” quality of injury prediction with GHBMC-implemented criteria.

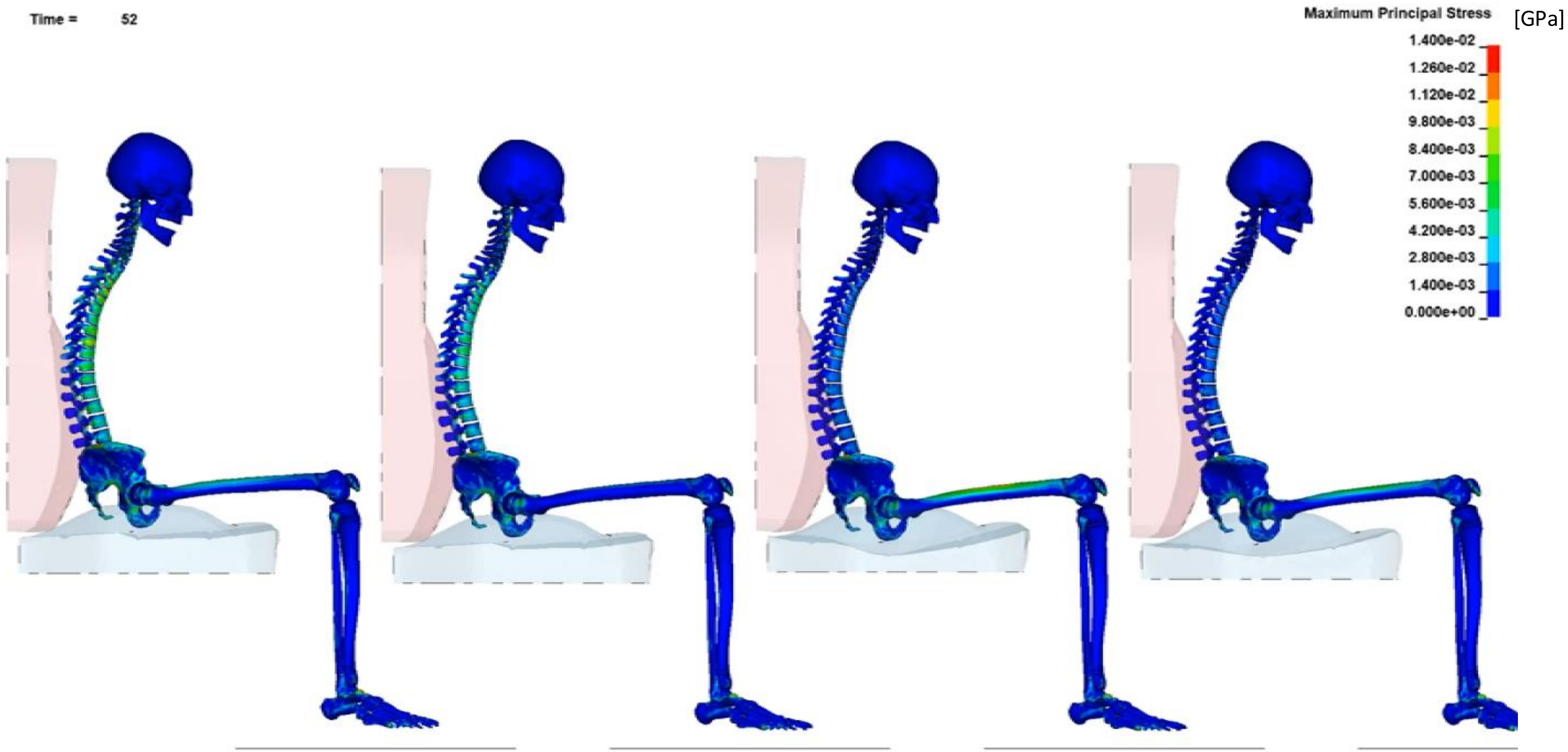
Results

Skeletal loading – compact bone



Suspension	Foam	Pos 1	Pos 1	Pos 1	Pos 1
Stiff	Soft			X	
	Stiff	X			
Olausson-Garme (2015)	Soft				X
	Stiff		X		

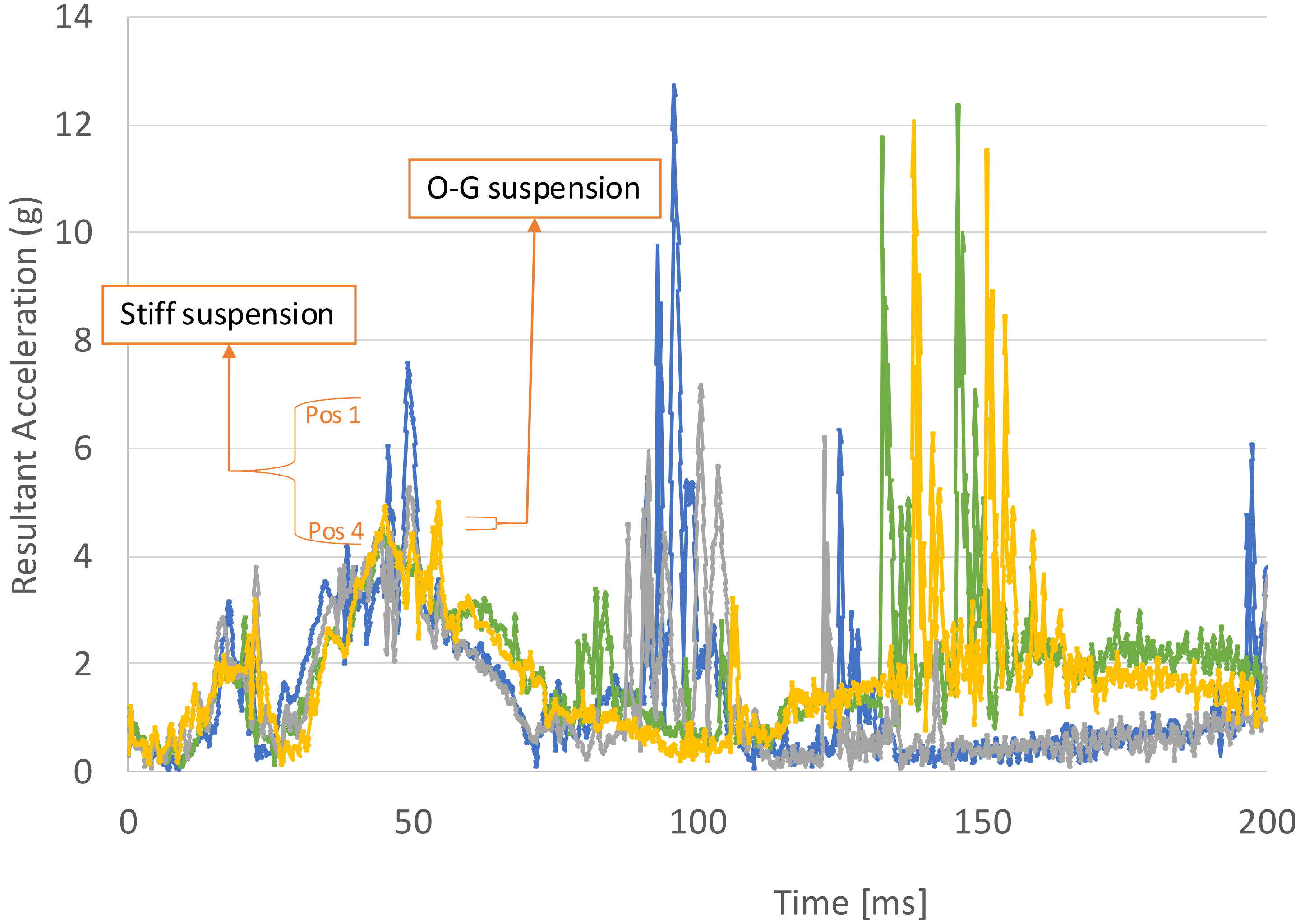
Skeletal loading – compact bone

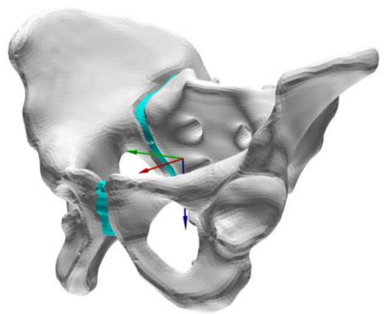


Suspension	Foam	Pos 1	Pos 1	Pos 1	Pos 1
Stiff	Soft			X	
	Stiff	X			
Olausson-Garme (2015)	Soft				X
	Stiff		X		

Pelvic accelerations – Pos 1 vs. 4

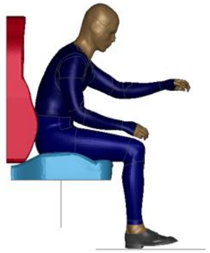
Suspension	Foam	Pos 1	Pos 2	Pos 4
Stiff	Soft	x	x	x
	Stiff	x		
Olausson-Garme (2015)	Soft	x	x	x
	Stiff	x		
Daytona seat	Soft			



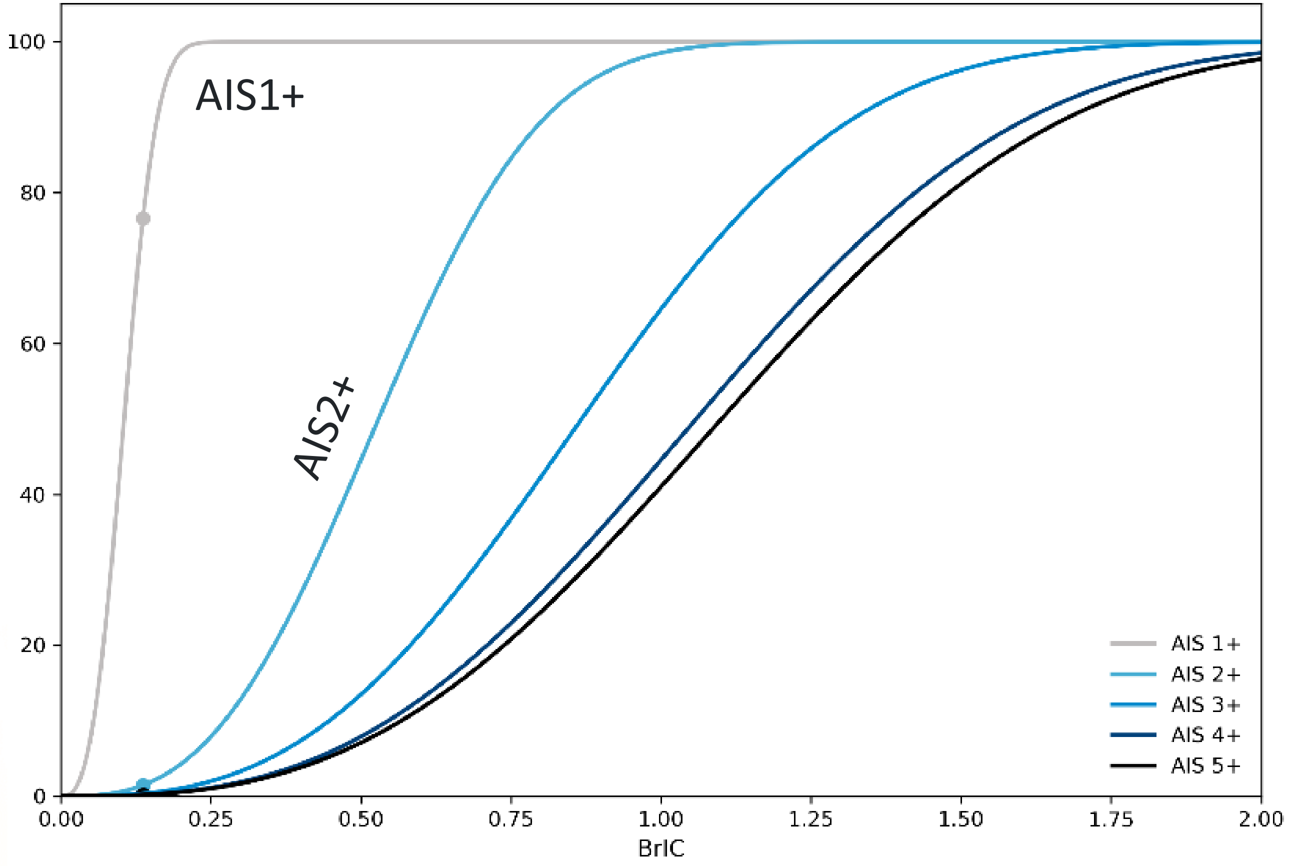


Head and brain injury prediction

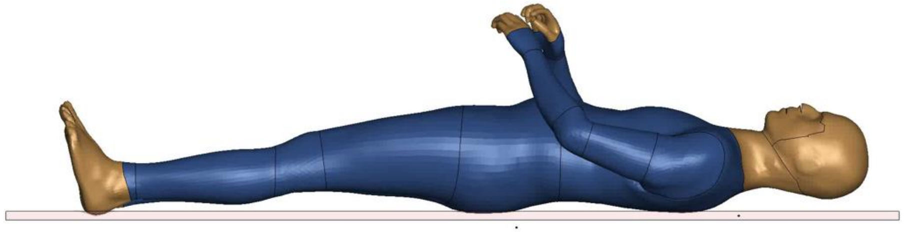
- Multiple injury criteria
  - HIC – linear acceleration
  - **BRIC – rotational velocity**
  - Strain based

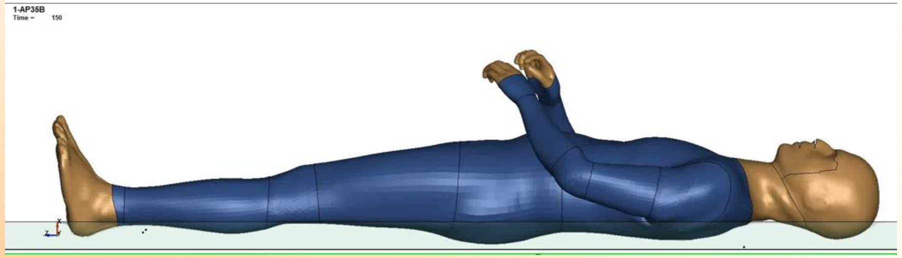



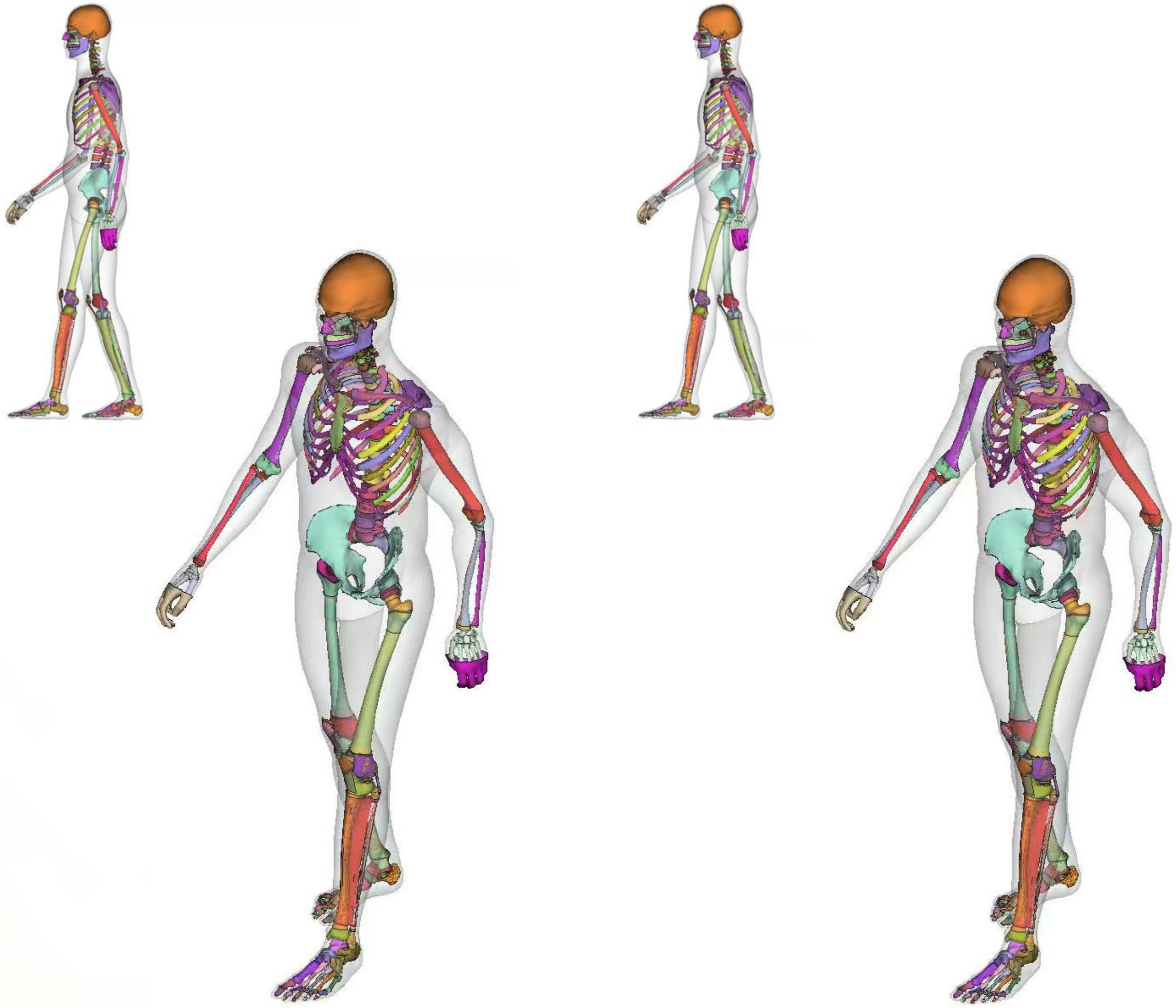

AIS1+	58 - 80%	100%	16%
AIS2+	1-2%	8%	0%



Standing & supine – different surface/floor configurations







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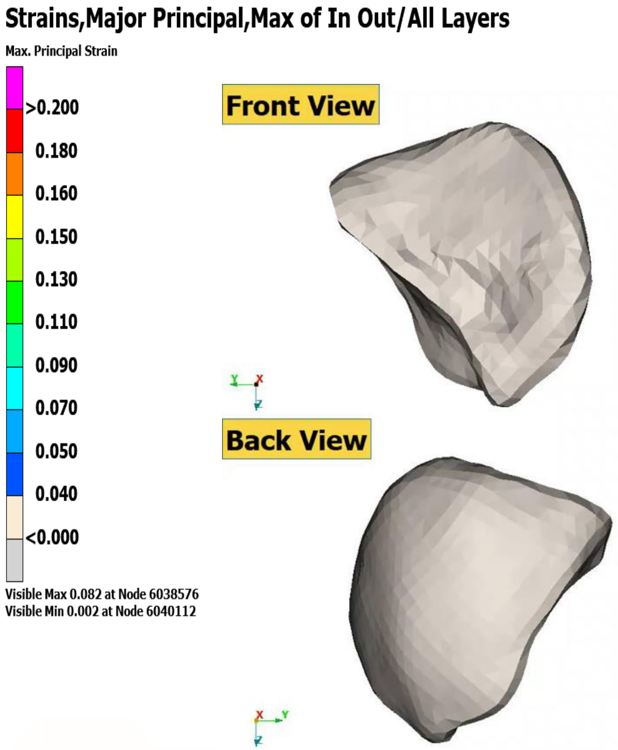
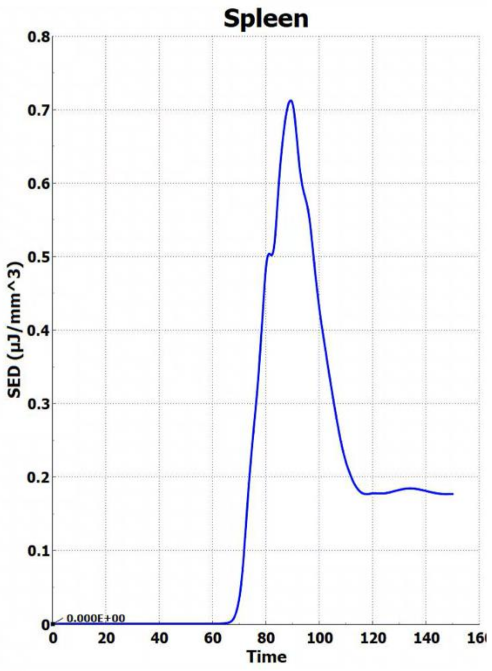
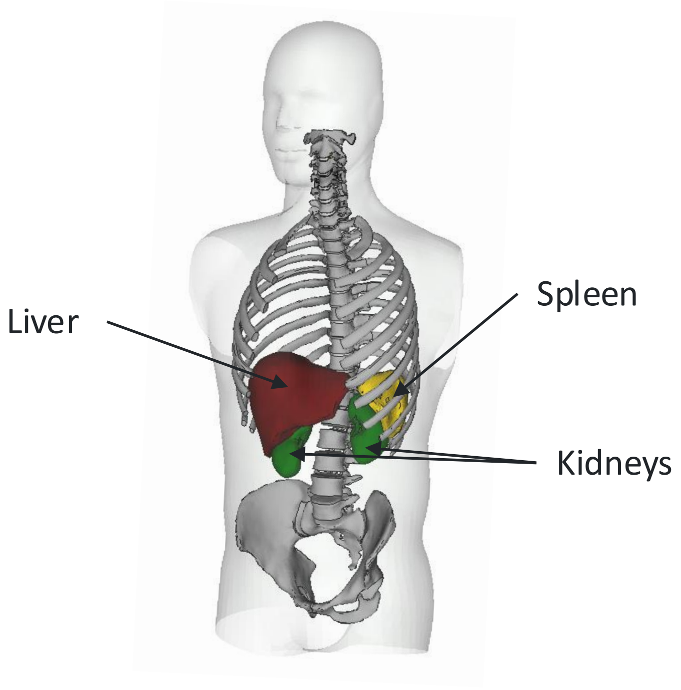
Internal organs

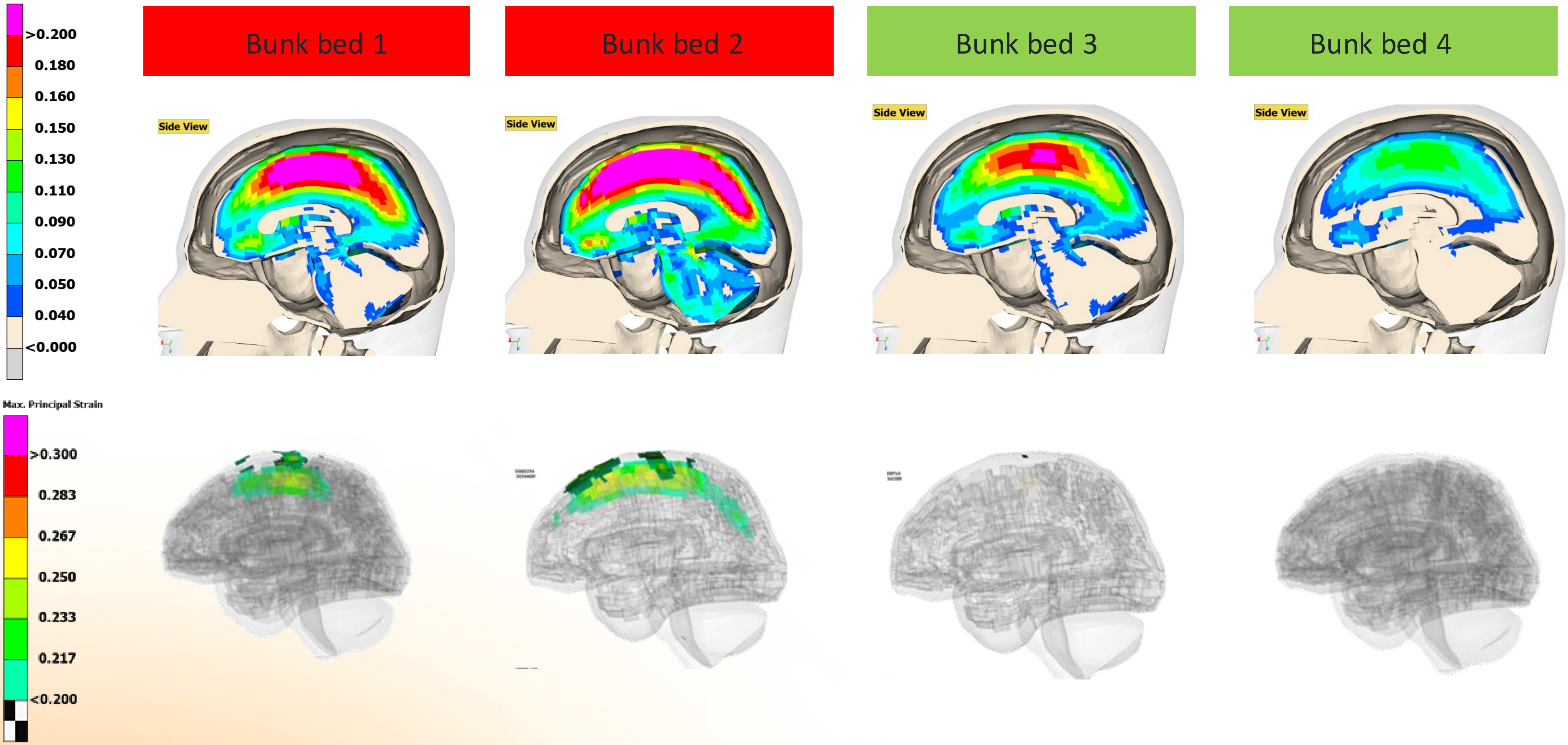




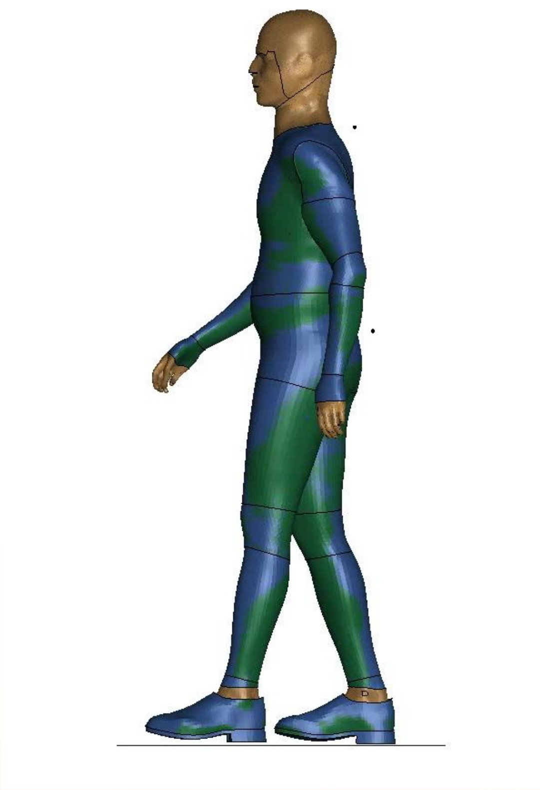


Organ	Minimum strain energy density below which injury is not seen.	Bunk bed 1	Bunk bed 2	Bunk bed 3	Bunk bed 4
Kidneys	2.2 µJ/mm^3	0.44 µJ/mm^3	0.47 µJ/mm^3	0.36 µJ/mm^3	0.26 µJ/mm^3
Spleene	0.6 µJ/mm^3	0.64 µJ/mm^3	0.71 µJ/mm^3	0.53 µJ/mm^3	0.41 µJ/mm^3
Liver	0.6 µJ/mm^3	0.37 µJ/mm^3	0.44 µJ/mm^3	0.31 µJ/mm^3	0.24 µJ/mm^3

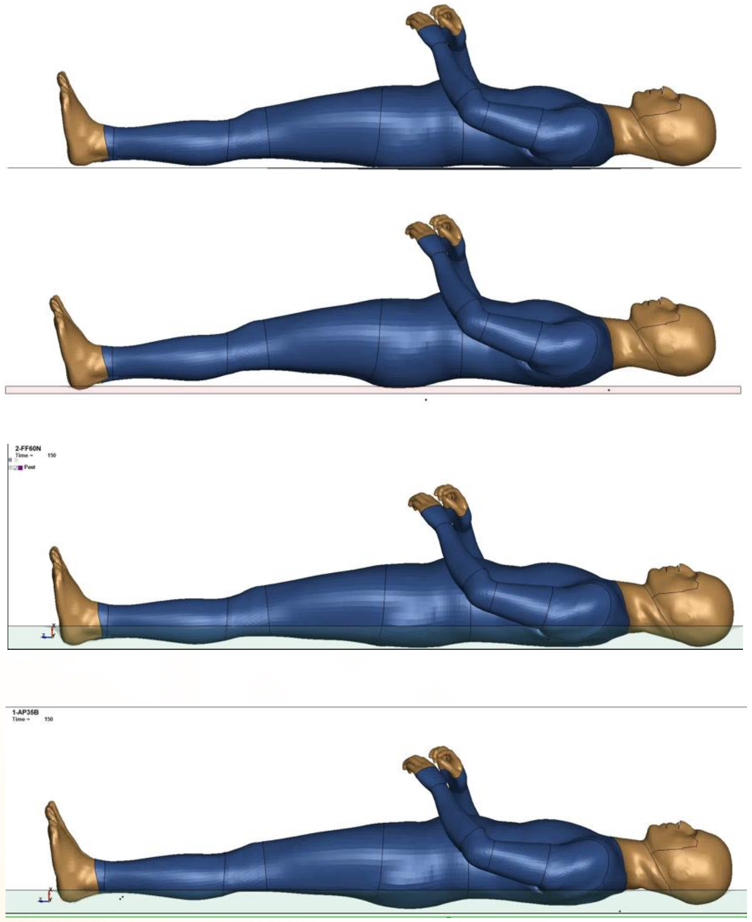
Brain strain



Summary – standing & supine

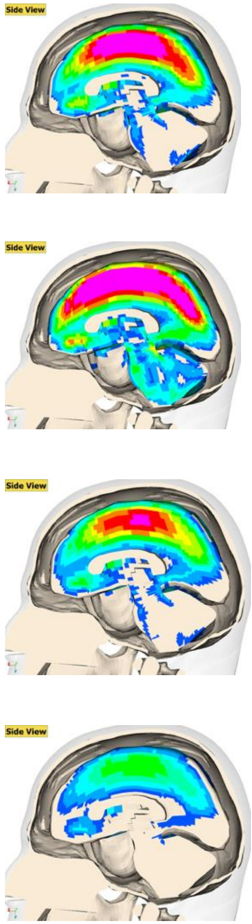


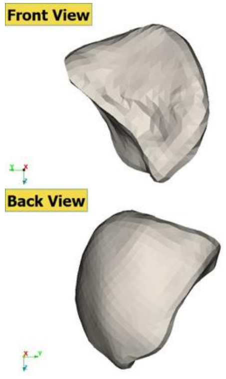
Knee fractures & ligament injuries

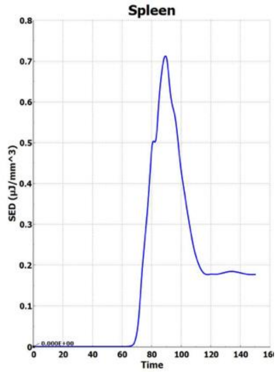


Fractures & ligament injuries in foot and knee

No injuries







- Limitations of the performed study
  - Loading:
    - Only one (simplified) shock pulse shape and amplitude.
    - Only vertical direction.
  - Seat FE models
    - Foam material properties taken from literature, rather than testing of actual seat.
    - Generic seats, bunk beds & floor – not validated.
  - Lack of active musculature in HBM.

- Conclusion
  - Promising method using HBM for injury prediction & seat assessment.
  - Straight forward method
    - Requires simulation resources and time
  - Predicted the expected differences in severity between different positions and seats.
  - Could study how the energy was absorbed by the human-seat system, down to organ level.

Future Work

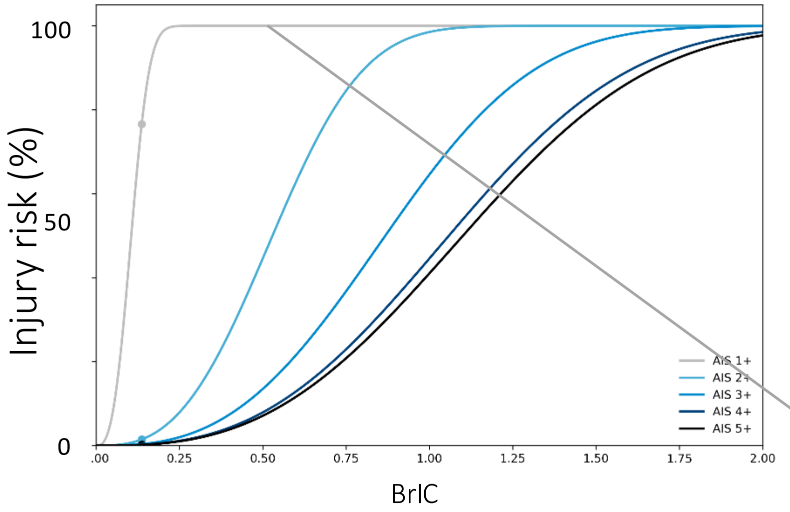
- Assess seat design with regards to impact injury prediction.
- Study variations in onboard personnel body mass & anthropometry.
- Vary load direction and multiple impacts.
- Study human kinematics to determine a safe space.

- **Casevac: How should injured personnel be safely transported in supine position for different sea states?**

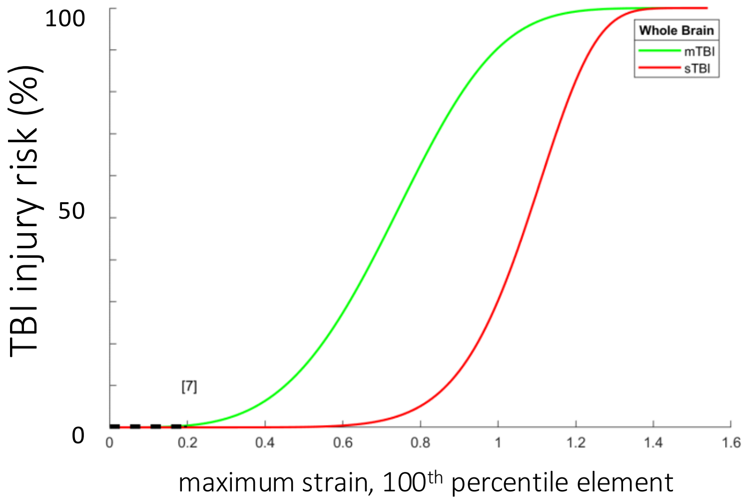
Conclusion:

HBMs can be used as **design requirements** to prevent impact injuries to onboard personnel.

Head and brain injury criteria



Suspension	Foam	Pos 1	Pos 1	Pos 1	Pos 1	Pos 4	Pos 4	Pos1_1
Stiff	Soft			X		X		
	Stiff	X						
Olausson-Garme	Soft				X		X	
	Stiff		X					
Daytona	Soft							X
HIC 15		5.8	2.3	0.4	0.4	1.4	1.2	1.8
BrIC		0.1274	0.1139	0.1369	0.1319	0.251	0.2449	0.007
AIS1+ injury risk		70%	58%	80%	73%	100%	100%	16%
AIS2+ injury risk		1%	1%	2%	1%	8%	8%	0%
Brain Strain		0.2	0.15	0.11	0.11	0.15	0.14	0.11
mild TBI risk		0%	0%	0%	0%	0%	0%	0%



HIC = Head Injury Criteria, threshold 700 for HIC 15
BrIC = Brain Injury Criteria, risk curves for different injury severity (AIS)
mTBI = mild Traumatic Brain Injury, i.e. concussion
sTBI = severe Traumatic Brain Injury, i.e. diffuse axonal injury