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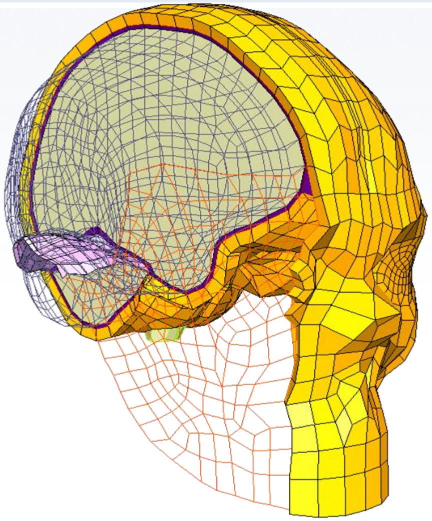

Menschmodelle- Dynamore
Stuttgart June 2016

Model based
Head & Neck injury criteria

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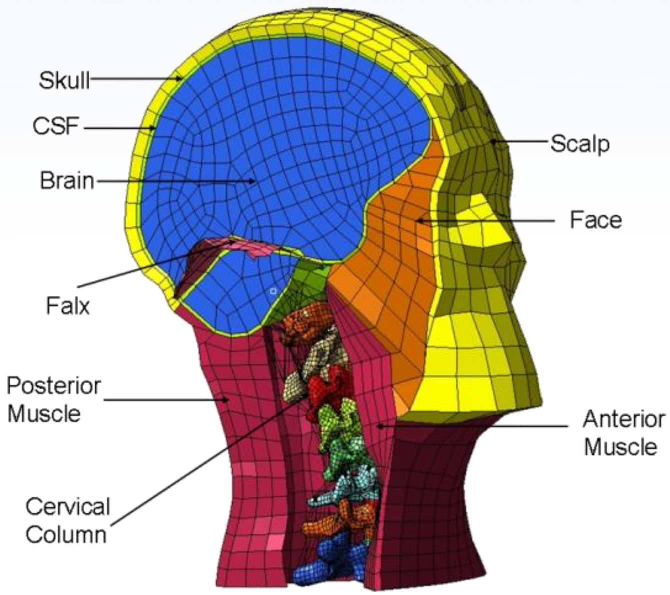
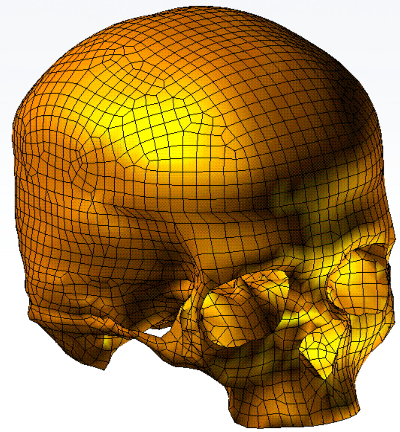
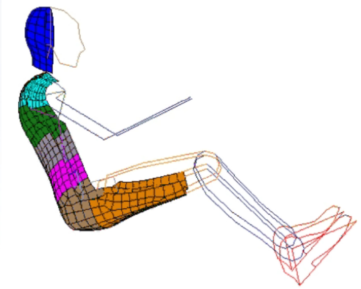
INTRODUCTION

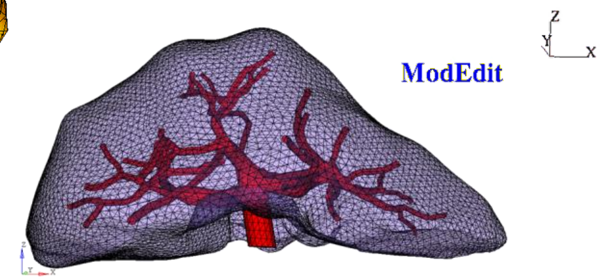
- Critical issue with current head injury criteria
- State of the Art head FE modelling and validation
- Focus on head trauma database and accident reconstruction
- Tissue level head injury criteria and risk assessment tool
- Neck FE modelling and validation
- Whiplash injury criteria based on modelling

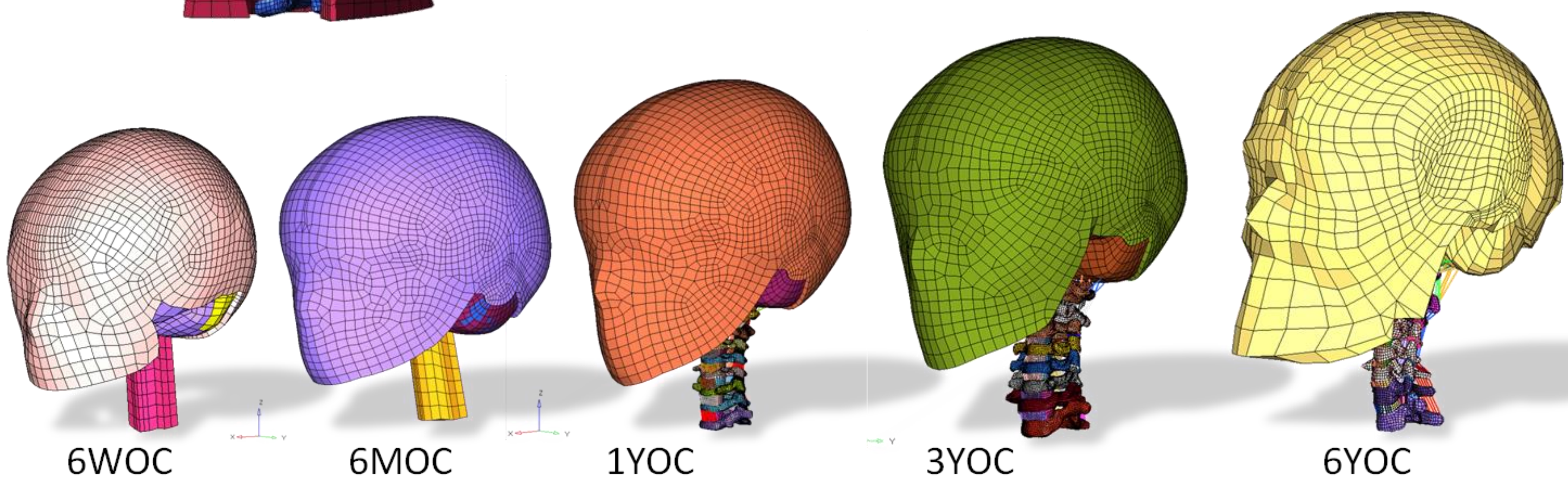
HUMAN SEGMENTS



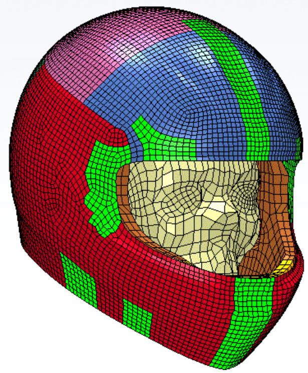


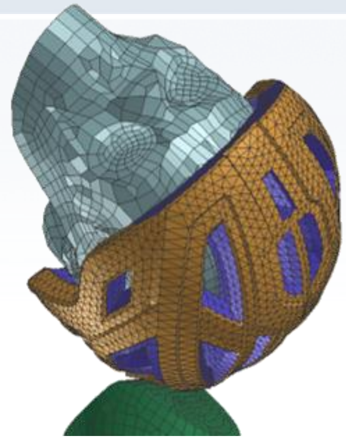


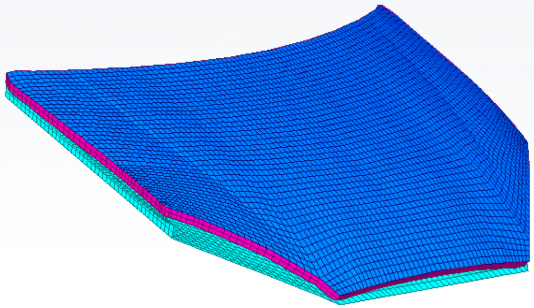


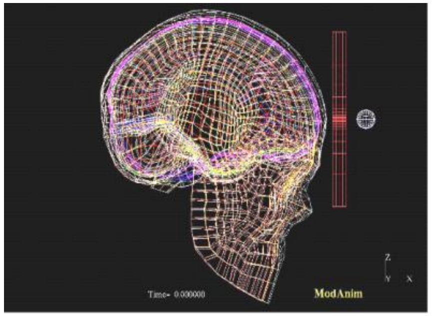


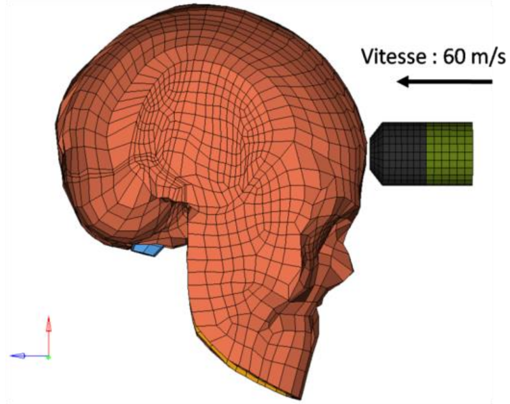
PROTECTIVE SYSTEMS

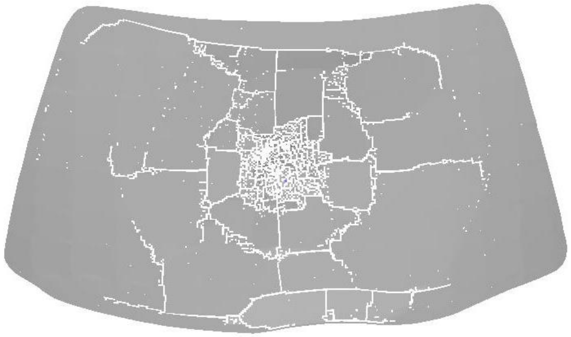


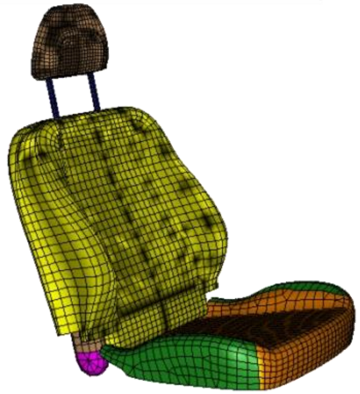


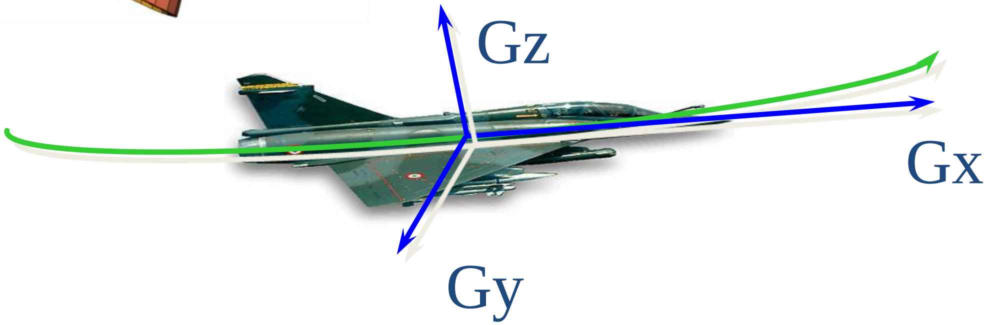










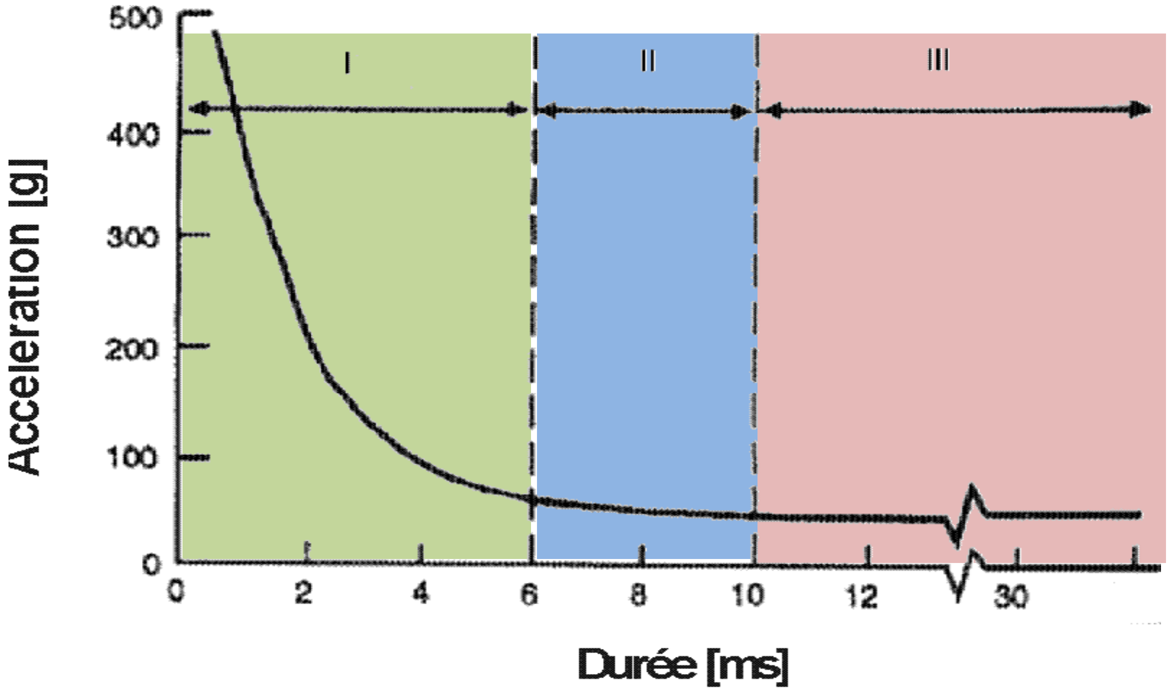


Head tolerance limits and head injury criteria

Head tolerance curve proposed by Wayne State University given linear head accelerations versus time : WSUTC (1966).
Head injuries occur in the part upper the curve.

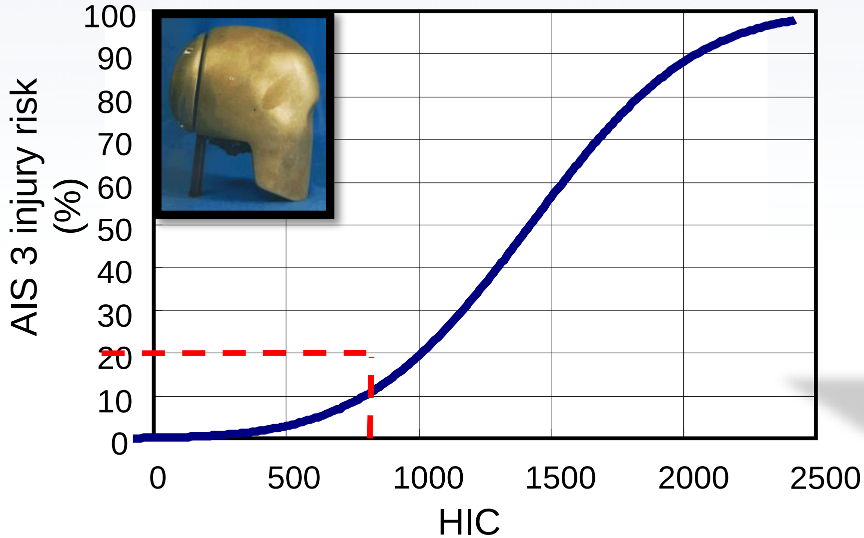
Part I : tests on cadavers, skull failure considered as head injury.

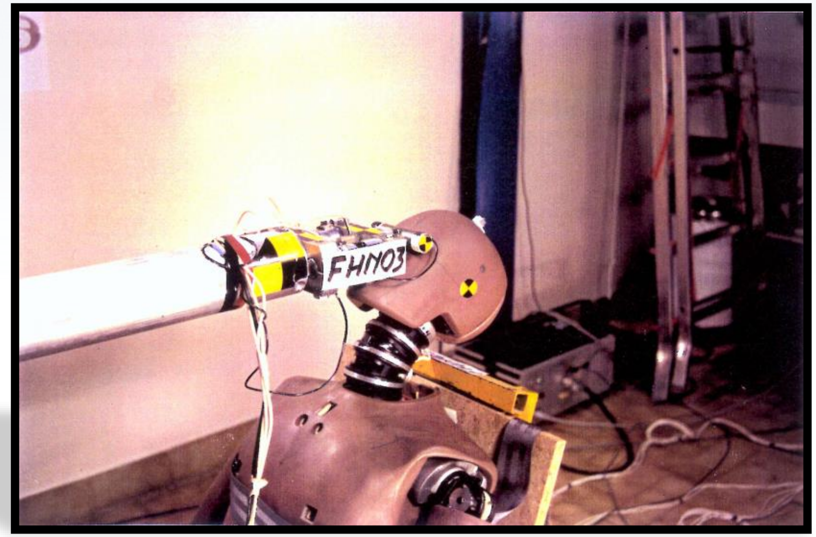
Part II : intracranial pressure recorded on anatomical subjects and animals, head injury : commotion.



Part III : tests on human volunteers, no head impact, head kinematics recorded during sled tests.

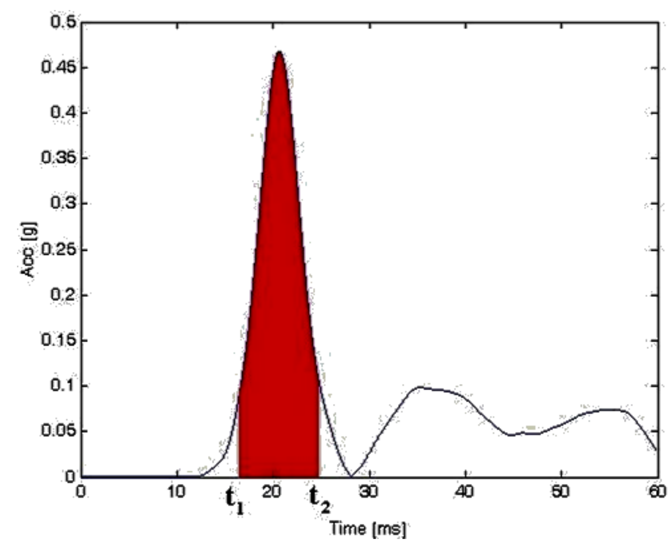
HEAD INJURY CRITERION (1972) : HIC DEFINITION





Head mass = 4.58 kg; HIC = 1000

$$HIC = \max_{(t_1,t_2)} \left\{ (t_2 - t_1) \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)dt \right]^{2.5} \right\}$$



Context of Head Protection Standards

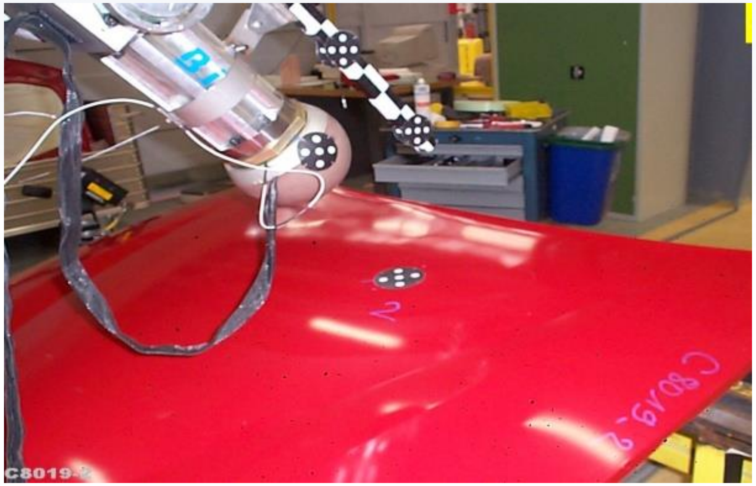
- Inside a car (1970)
  - Dummy head; **HIC 1000**

- Outside – pedestrian (2005)
  - Headform; V=11 m/s ;
    e = 7 cm ; **HIC 1000 à 1700**

- Motorcyclist (2002)
  - Headform; V = 7.5 m/s ;
    e = 5 cm ; **HIC 2400** ; **Γ= 275G**

- Cyclist
  - Headform; V = 5.42 m/s ;
    e = 2.5 cm ; **Γ= 250G**

… for a same human head !



Limitations of Existing Standards

- Poor correlation with real world observation
- HIC was defined for a frontal impact…and is not direction dependent
- Not injury mechanism related
- No consideration of rotational acceleration
- No criteria for children (6 YOC, 3 YOC…)

CRITICAL ASPECT OF ROTATIONAL LOADING

It is **well known** that brain is sensitive to rotational acceleration

since Holbourn (1943)

This phenomenon has essentially been addressed qualitatively with animal or physical models.

Ommaya et al. (1967, 1968), Unterharnscheidt (1971), Ono et al. (1980), Gennarelli et al. (1982), Newman et al. (1999,2000)…..

By using **Finite Element Head Models** it was expressed quantitatively how dramatic the influence of the rotational acceleration is on intra-cerebral loading.

Deck et al. (2007), Kleiven et al. (2007), Zhang et al. (2001)...

A number of experimental in vivo investigations emphasized that **axonal strain** was the most realistic mechanism of DAI (Bain and Meaney, 2000, Meythaler *et al.*, 2001, Morrison *et al.*, 2003)

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Global parameters (rotation)

Authors		Global parameters
Gennarelli, Thibault, Ommaya (1972)	25 Monkeys alive	1800 rad/s² à 7500 rad/s² 60 rad/s à 70 rad/s
Pincemaille et al. (1989)	Boxers training	13600 rad/s² à 16000 rad/s² 28 rad/s à 48 rad/s
Gennarelli et al. (1982)	More than 100 primates alive	15000 rad/s² 150 rad/s
Margulies et al. (1989)	Based on Gennarelli et al. (1982)	16000 rad/s² 46.5 rad/s

No agreement

Global parameters-Combined

GAMBIT:

$$G(t)=\left[\left(\frac{a(t)}{a_c}\right)^m+\left(\frac{\alpha(t)}{\alpha_c}\right)^n\right]^{\frac{1}{s}}$$

Newman et al 1986

n = m = s = 2.5, a_c=250g, α_c = 25.000 rad/s²

HIP:

Newman et al 2000

$$HIP = m a_x \int a_x\,dt + m a_y \int a_y\,dt + m a_z \int a_z\,dt + I_{xx}\alpha_x \int \alpha_x\,dt + I_{yy}\alpha_y \int \alpha_y\,dt + I_{zz}\alpha_z \int \alpha_z\,dt$$

PRHIC:

Kimpara et al. (2011)

$$PRHIC=\left[\left\{\frac{1}{(t_2-t_1)}\int_{t_1}^{t_2} HIP\_ang(t)\,dt\right\}^{2.5}(t_2-t_1)\right]_{max}$$

Global parameters - Rotation

BrIC:

Takhounts et al. 2011

$$BrIC = \frac{\omega_{max}}{\omega_{cr}} + \frac{\alpha_{max}}{\alpha_{cr}}$$

Takhounts et al. 2013

$$BrIC = \sqrt{\left(\frac{\omega_x}{\omega_{xC}}\right)^2 + \left(\frac{\omega_y}{\omega_{yC}}\right)^2 + \left(\frac{\omega_z}{\omega_{zC}}\right)^2}$$

RIC:

Kimpara et al. (2011)

$$\text{RIC} = \left[(t_2 - t_1) \left\{ \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} \alpha(t)\,dt \right\}^{2.5} \right]_{\max}$$

BRAIN INJURY CRITERIA

- There is no relevant combined, time and direction dependent brain injury criteria in terms of global head acceleration
- A number of tentatives exist
- There is a need to set properly :
  - A tissue level brain injury criteria
  - A measure of the quality of an injury criteria

STATE OF THE ART
FE HEAD MODELS AND VALIDATION

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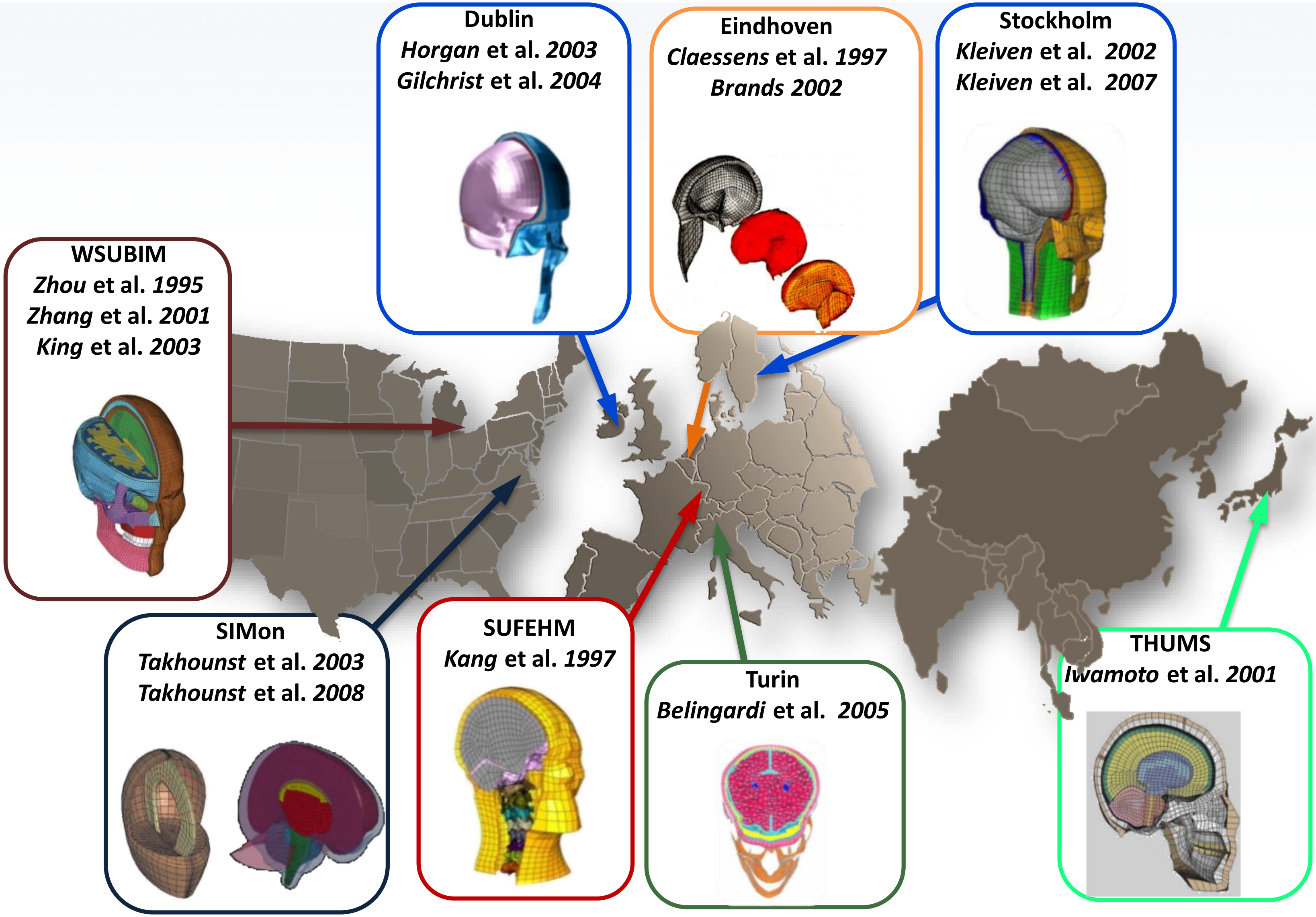
HEAD FE MODELS AROUND THE WORLD



VALIDATION DATA

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cnrs

Nahum & Trosseille
(1977) (1992)

Impact area : front
Impactor : Cylinder with padding
Impact velocity : 6.3 m/s
Duration : 6.2 ms

Intra-cranial behaviour validation

Hardy
(2001)

Impact area : occipital
Impactor : Cylinder
Impact velocity : 2 m/s
Duration : 20 ms

Yoganandan
(1994)

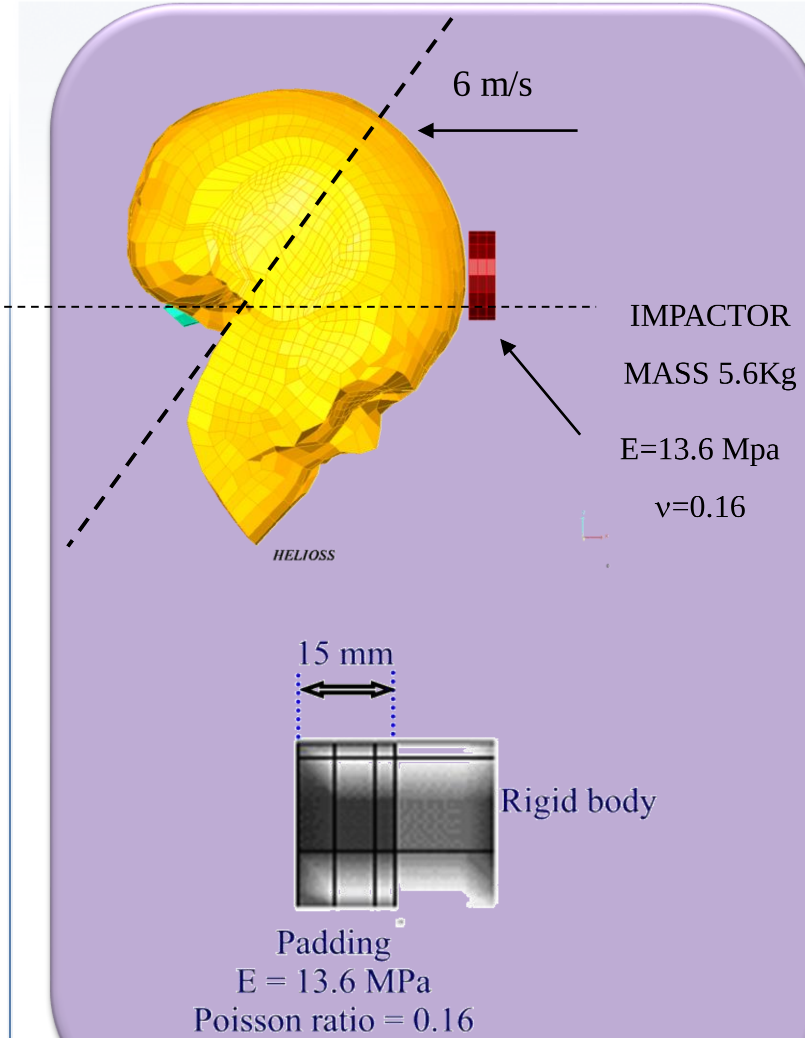
Impact area : vertex
Impactor : Rigid sphere
Impact velocity : 7.3 m/s
Duration : 2 ms

Skull validation

Sarron
(1999)
Back face effect

Under Balistic conditions

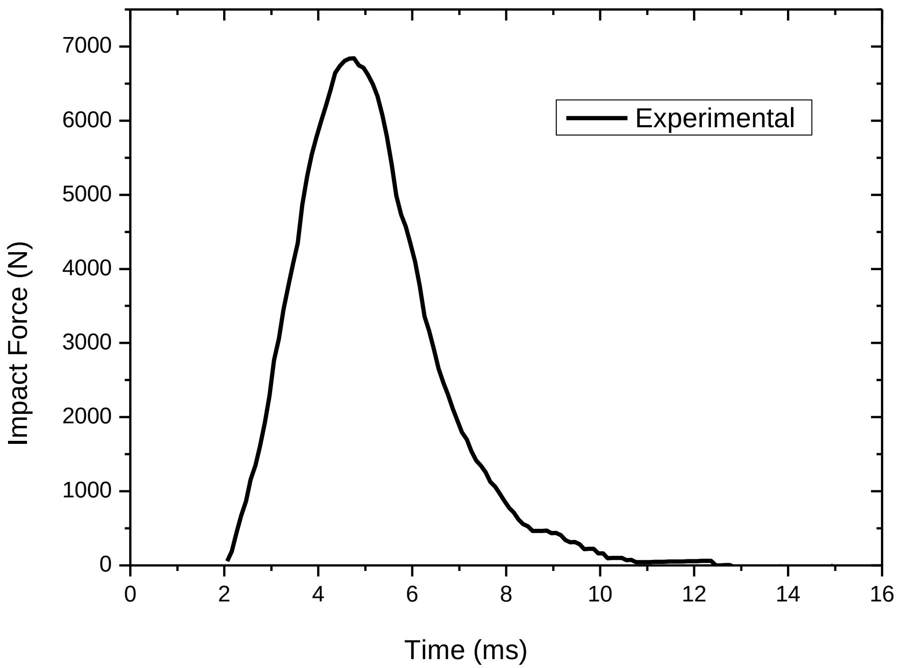
BENCHMARK PROCEDURE : NAHUM INPUT



[Nahum et al., 1977]

Input :

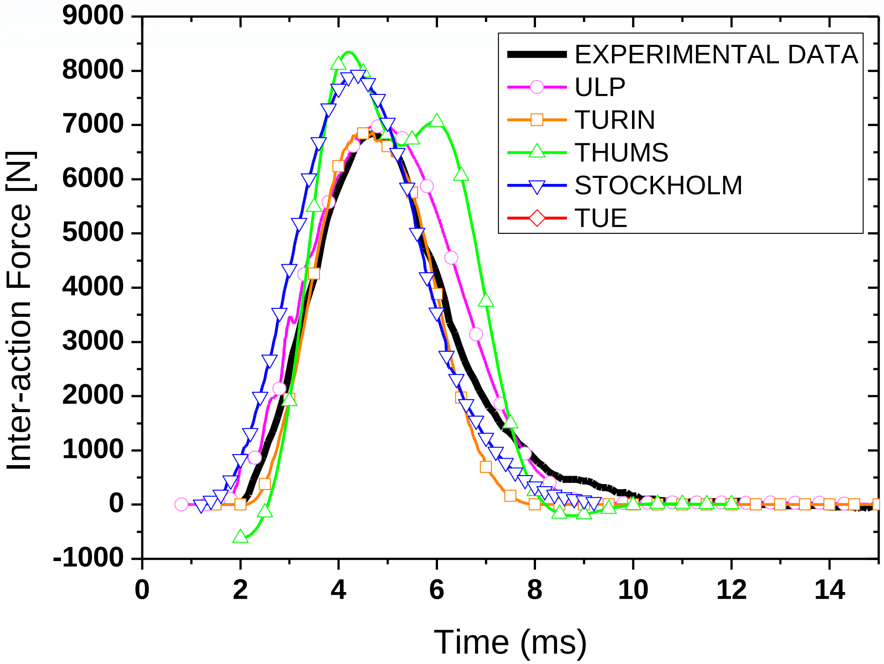
- A 5.6 kg cylindrical impactor (with padding).
- An initial velocity about 6.3 m/s
- Boundary conditions : Head free

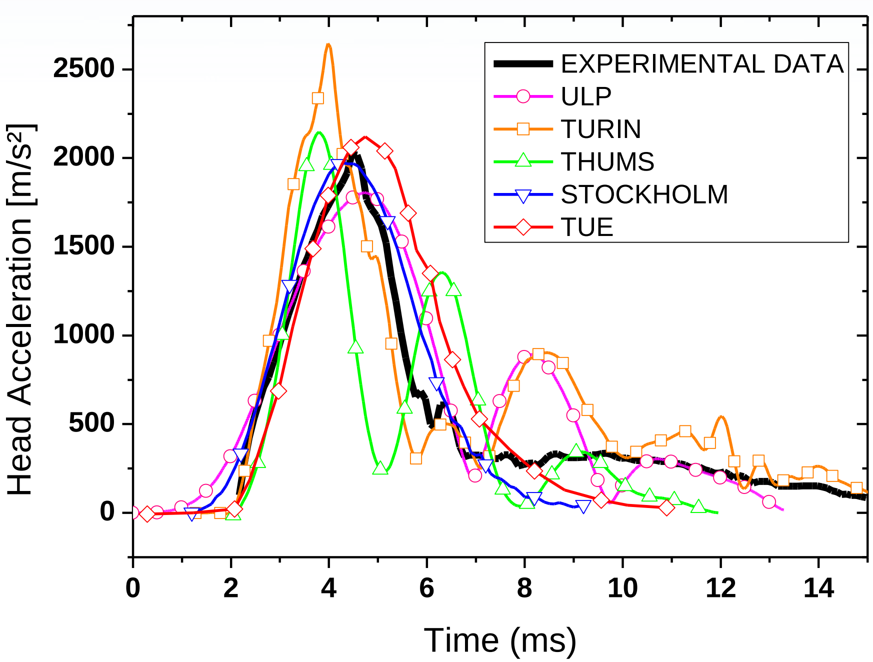


Interaction force between the head and the impactor

NAHUM IMPACT NUMERICAL RESULTS

- **Impact force, head acceleration**





Some oscillations can appear in head acceleration results

NAHUM IMPACT NUMERICAL RESULTS

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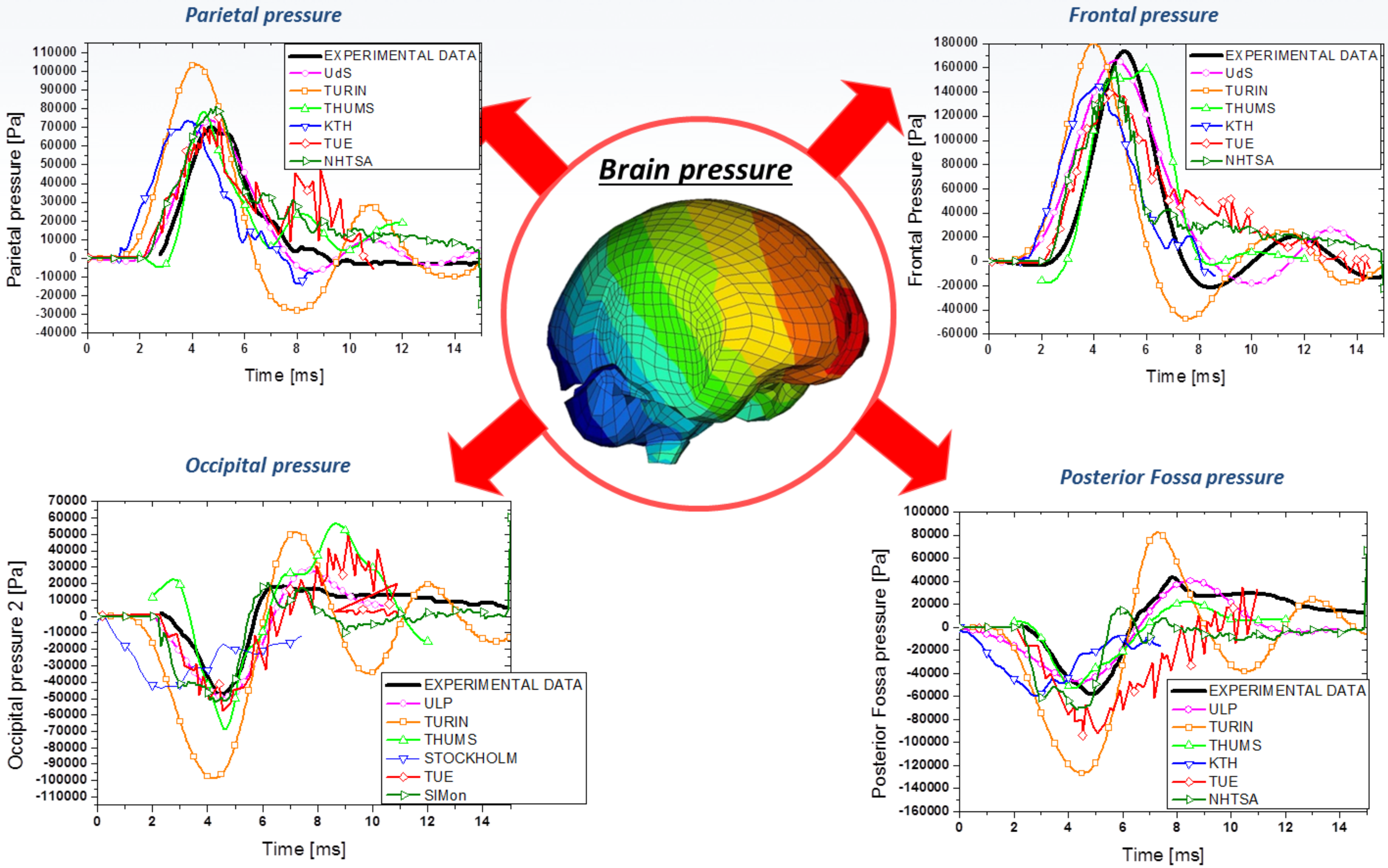

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Normalised Integral Square Error (NISE) measures

The NISE provides a means of comparing the differences between two time history responses

$$NISE_{total} = NISE_{phase} + NISE_{shape} + NISE_{amplitude}$$

$$NISE_{total} = 1 - \frac{2R_{xy}(0)}{R_{xx}(0) + R_{yy}(0)}$$

$$\begin{cases} R_{xy}(0) = \frac{1}{N}\sum_{i-1}^{N} X_i Y_i \\ R_{xx}(0) = \frac{1}{N}\sum_{i=1}^{N} X_i X_i \\ R_{yy}(0) = \frac{1}{N}\sum_{i=1}^{N} Y_i Y_i \end{cases}$$

Xi = a point *i* of a data set (*eg* measured time history)
Yi = a point *i* of another data set (*eg* predicted time history)
N = number of discretized points in each data set

The Russel's Error measures (RUS)

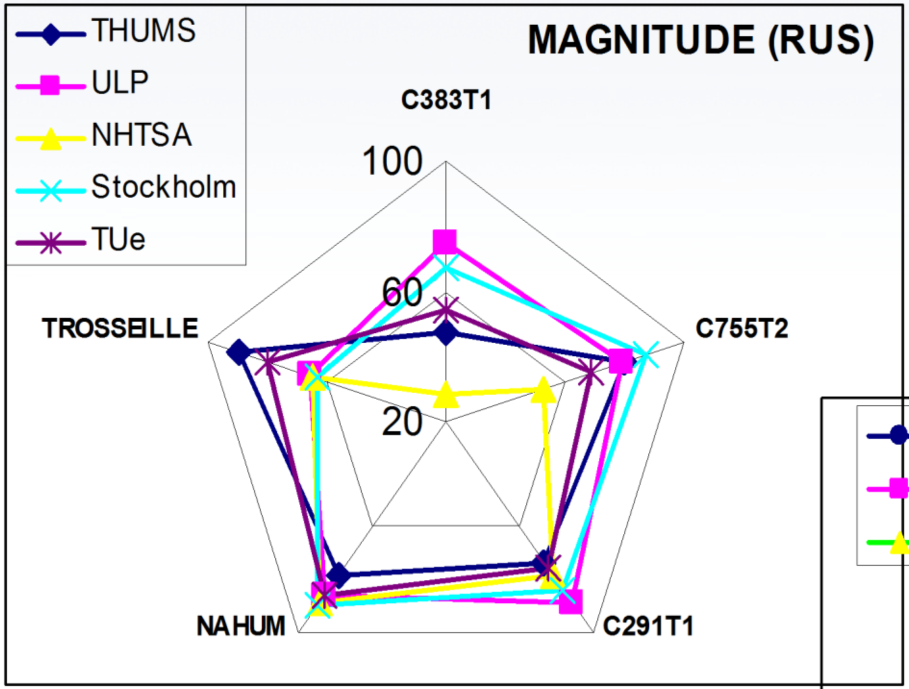
The Russel's error measures provide a robust and non-biased means of assessing the differences in the characteristics of two functions. The relative magnitude error is determined according to:

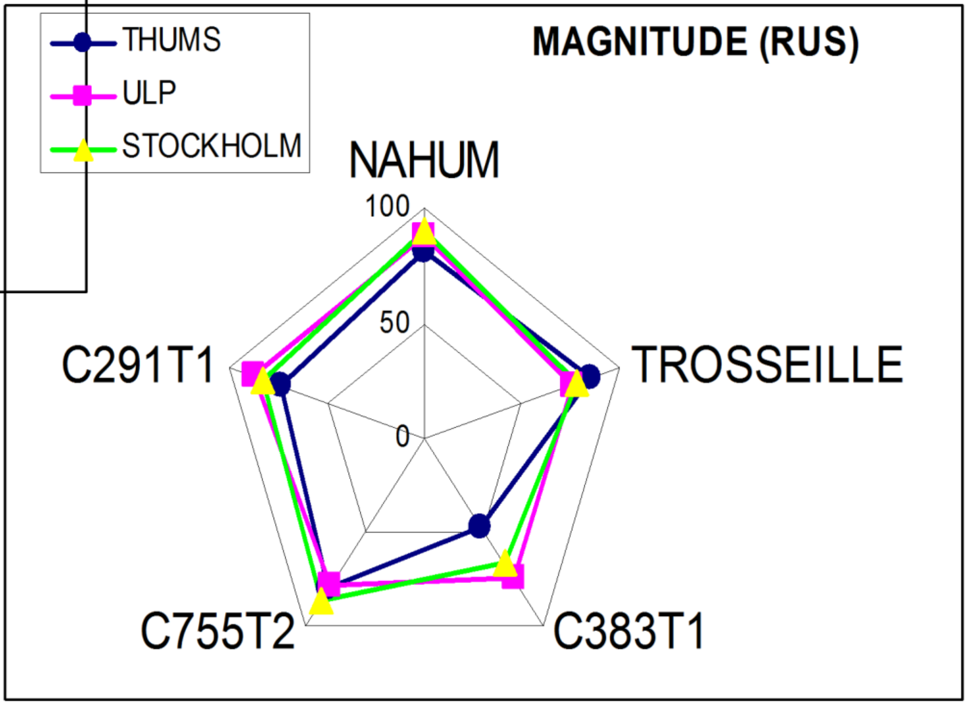
$$m = \frac{A - B}{\sqrt{AB}} \qquad A = \sum_{i=1}^{N} f_1(i)^2 \qquad B = \sum_{i=1}^{N} f_2(i)^2$$

The phase correlation between two functions is determined according to:

$$p = \frac{C}{\sqrt{AB}} \qquad C = \sum_{i=1}^{N} f_1(i) f_2(i)$$

Statistical analysis : Results





STATE OF THE ART NUMERICAL HEAD MODEL

- Brain acceleration and pressure

  - THUMS, SUFEHM and KTH models provided a comparable level of accuracy for brain acceleration

  - Pressure prediction was at similar level of accuracy for all models

- Brain displacement

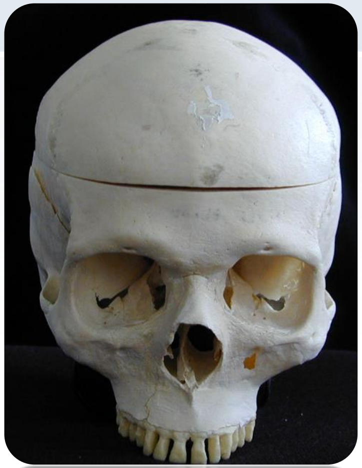
  - THUMS, SUFEHM and KTH presented best accuracy

  - NHTSA and TUE were less accurate

- Skull deflection

  - Only THUMS and SUFEHM models predicted an accurate skull deflection as well as skull rupture

STRASBOURG UNIVERSITY FE HEAD MODEL



50th percentile adult skull

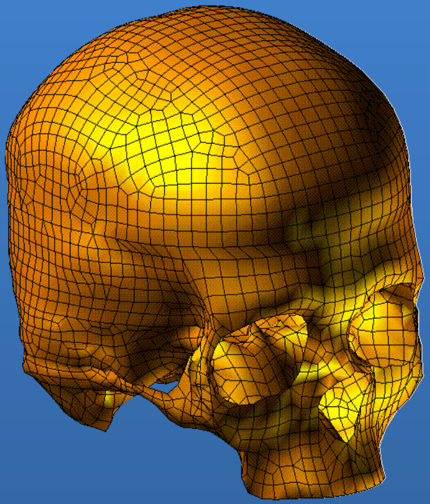
Digitalisation

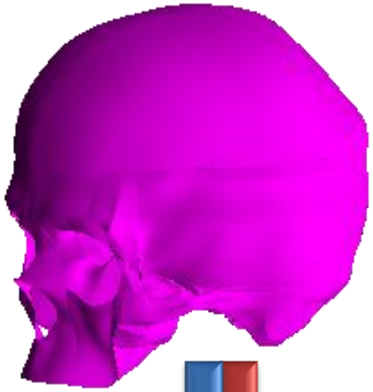
[Kang, 1997]

SUFEHM 98

Accident reconstructions

Tolerance limits





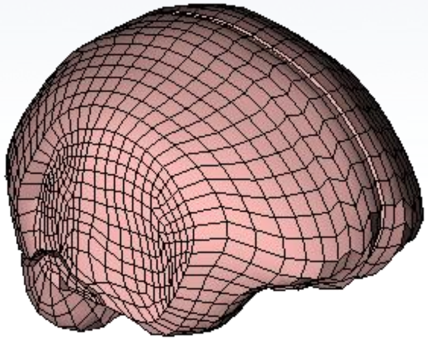
[Deck, 2004]

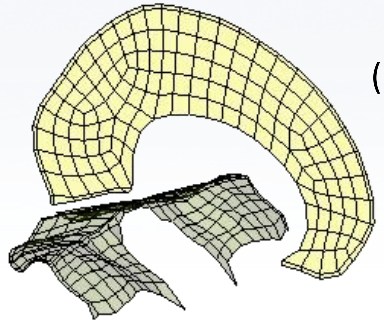
Skull Model Improvement

- Refined meshing
- Skull thickness variation
- Inclusion of reinforced beams
- Improvement of non-linear material characteristics

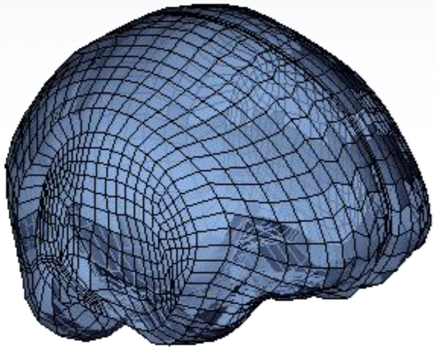
SUFEHM Presentation

Brain
(Viscoelastic G_0=49kPa, G_∞=16.7kPa, β=145s^{-1})



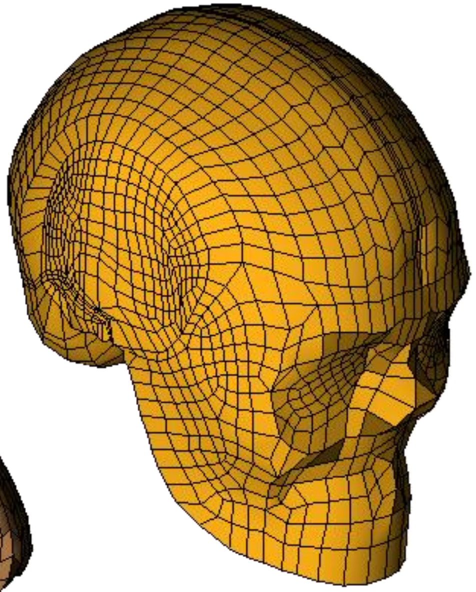


Membranes
(Elastic E=31.5MPa, γ=0.23)

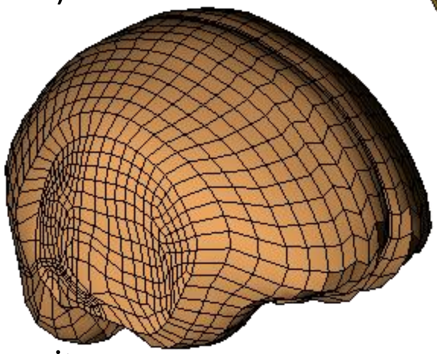


CSF
(Elastic E=12kPa, γ=0.49)

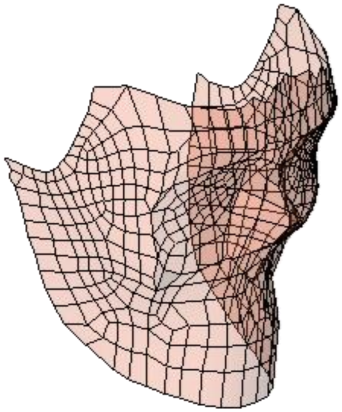
Brainstem
(Viscoelastic G_0=49kPa, G_∞=16.7kPa, β=145s^{-1})



Scalp
(Elastic E=16.7MPa, γ=0.42)



Skull
(Shell elements, composite law with failure criterion)



Face
(rigid)

Identification of Skull mechanical parameters

Failure mode

- **Determination and characterization of the mechanical behavior of biological tissues and damage**

➢For tensile fiber mode

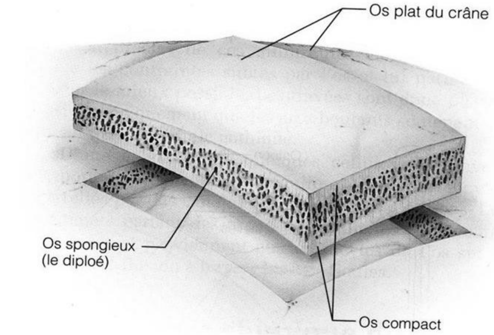
$$\sigma_{aa} > 0 \ then \ e_f^2 = \left(\frac{\sigma_{aa}}{X_t}\right)^2 + \beta\left(\frac{\sigma_{ab}}{S_c}\right) - 1 \begin{cases} \geq 0 \ failed, \\ < 0 \ elastic \end{cases}$$

➢For compressive fiber mode

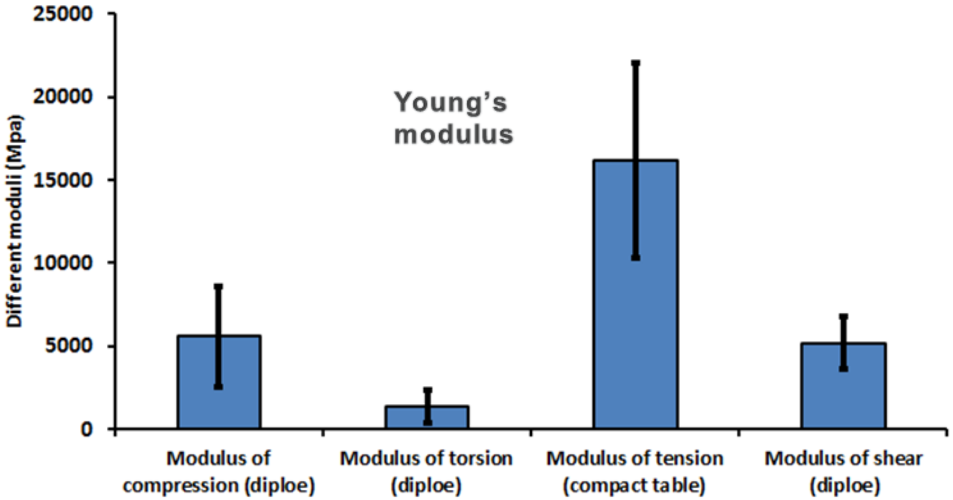
$$\sigma_{aa} < 0 \ then \ e_c^2 = \left(\frac{\sigma_{aa}}{X_c}\right)^2 - 1 \begin{cases} \geq 0 \ failed, \\ < 0 \ elastic \end{cases}$$

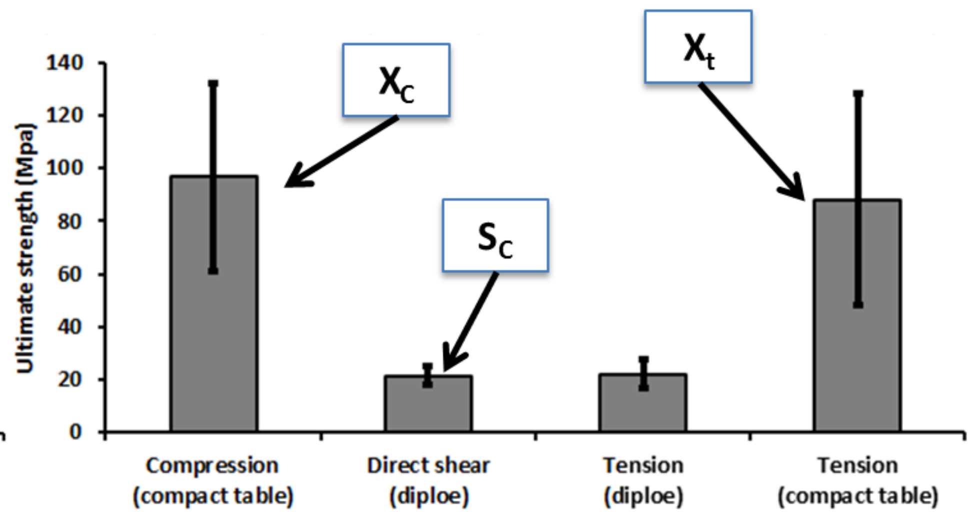
➢The failure criterion for the tensile and compressive matrix mode is given as :

$$e_{md}^2 = \frac{\sigma_{bb}^2}{Y_c Y_t} + \left(\frac{\sigma_{ab}}{S_c}\right)^2 + \frac{(Y_c - Y_t)\sigma_{bb}}{Y_c Y_t} - 1 \begin{cases} \geq 0 \ failed, \\ < 0 \ elastic \end{cases}$$



Skull was modelled by a three layered composite shell and damage mechanism based on Tsai and Wu criterion (Tsai and Wu ,1971).

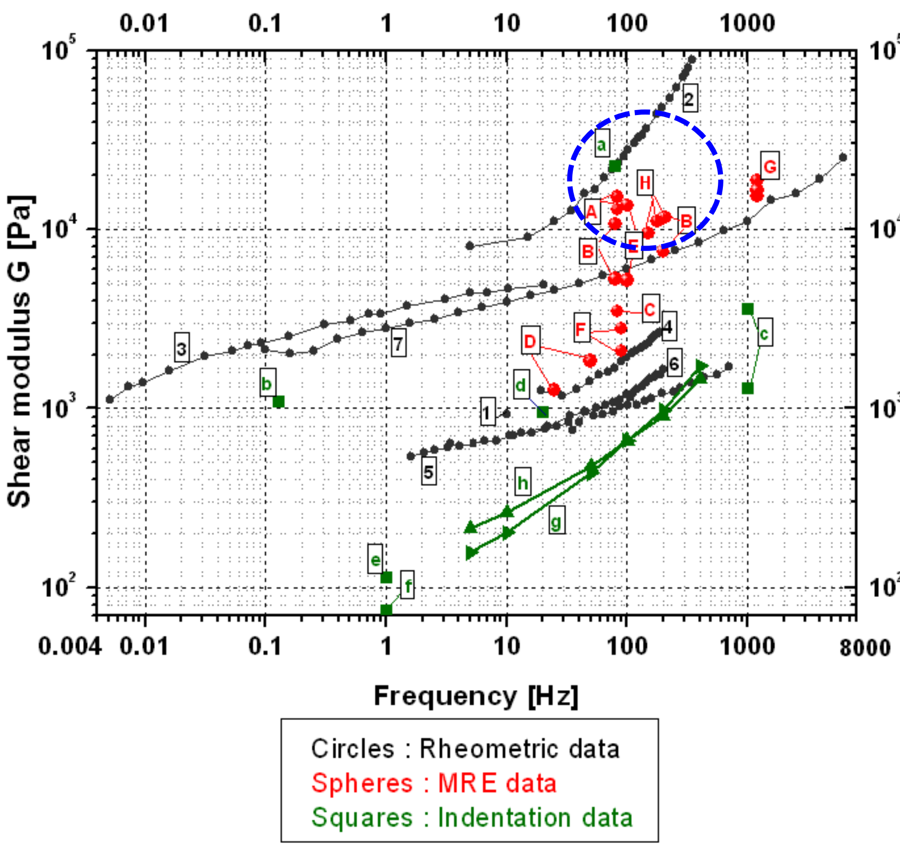




[Wood et al. 1969, McElhaney et al. 1970, Hubbard et al. 1971, Peterson and Dechow, 2002]

Brain mechanical properties

- **Determination and characterization of the mechanical behavior of biological tissues and damage**



[1] Fallenstein *et al.* 1969 - Monkey
[2] Shuck & Advani 1972 - Human
[3] Bilston *et al.* 1997 - Bovine
[4] Arbogast *et al.* 1997 - Porcine
[5] Brands 2002 - Porcine
[6] Thibault& Margulies 1998 - Porcine
[7] Nicolle *et al.* 2004 - Porcine

[A] Uffmann *et al.* 2004 - Human
[B] McCracken *et al.* 2005 - Human
[C] Hamhaber *et al.* 2007 - Human
[D] Sack *et al.* 2007 - Human
[E] Kruse *et al.* 2007 - Human
[F] Green *et al.* 2008 - Human
[G] Atay *et al.* 2008 - Mouse
[H] Vappou *et al.* 2008 - Rat

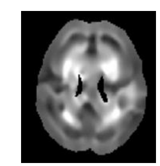
[a] Wang *et al.* 1972 - Monkey
[b] Miller *et al.* 2000 - Porcine
[c] Gefen *et al.* 2003 - Porcine
[d] van Dommelen *et al.* 2010 - Porcine
[e] Christ *et al.* 2010 - Rat (Gray matter)
[f] Christ *et al.* 2010 - Rat (White matter)
[g] Elkin *et al.* 2010 - Porcine, (AFM *in vitro* 1µm depth)
[h] Elkin *et al.* 2010 - Porcine, (AFM *in vitro* 2.5µm depth)

Rheometry

- 0.004 to 8000Hz

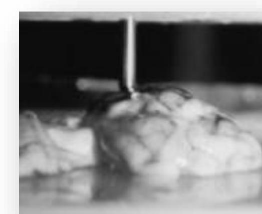
MRE

- Mean values for the whole brain
- 20 to 200Hz



Indentation

- 1 to 1000Hz



- ❑ High discrepancy of values for shear modulus
- ❑ Confirms the stiffest in vitro results (shear modulus ~10KPa at 100Hz)

Recent Devlopments

- Marjoux, D., Bourdet, N., and Willinger, R. 2009 . Computation of axonal elongations: towards a new brain injury criterion. International Journal of Vehicle Safety, Vol.4 No 4, 271
- Chatelin S., Deck C., Renard F., Kremer S., Heinrich C., Armspach JP, Willinger R : 2011 Computation of axonal elongation in head trauma finite element simulation. J of Mech. Behavior of Biomed Material, V4, 1905-1919.
- Cloots, R.J.H., van Dommelen, J.A., Nyberg, T., Kleiven, S., Geers, M.G., 2011. Micromechanics of diffuse axonal injury: influence of axonal orientation and anisotropy. Biomechanics and Modeling in Mechanobiology. 10, 3, 413-422.
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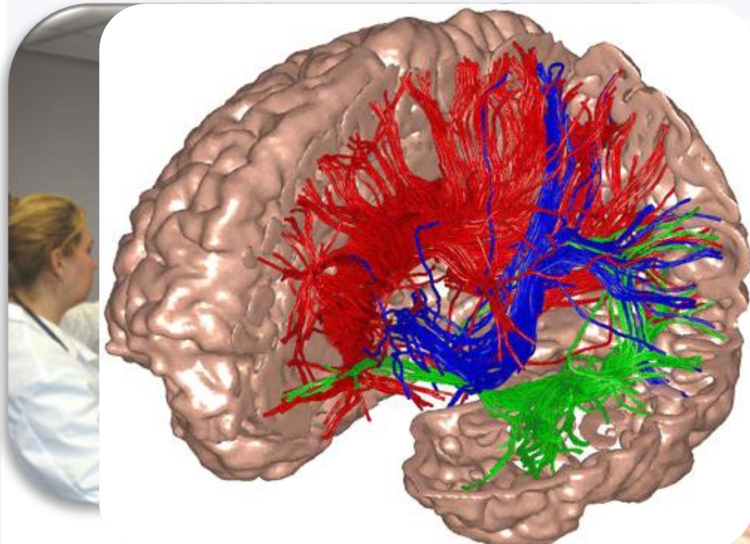
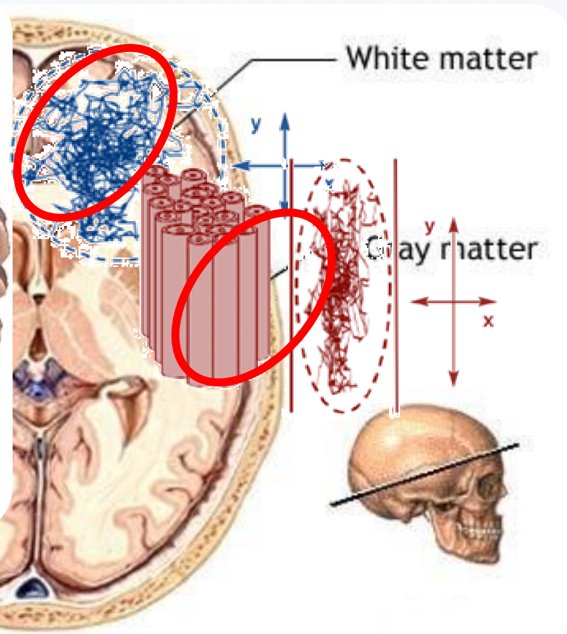
DTI OF THE BRAIN

ISOTROPIC DIFFUSION

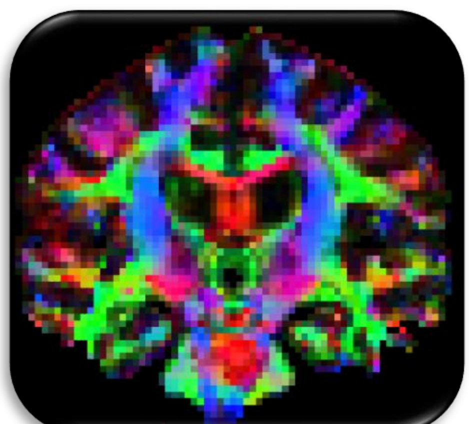


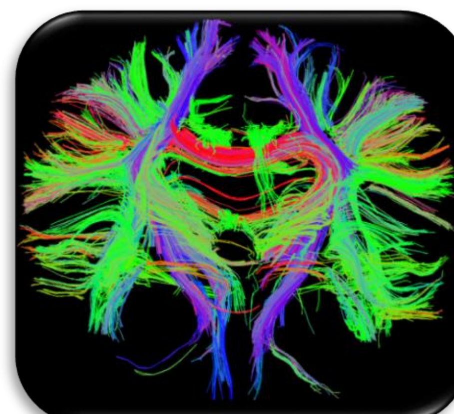
DIFFUSION TENSOR IMAGING



ANISOTROPIC DIFFUSION

HEALTHY PERSONS





FRACTIONAL ANISOTROPY

Coupling of DTI data

Diffusion Parameters

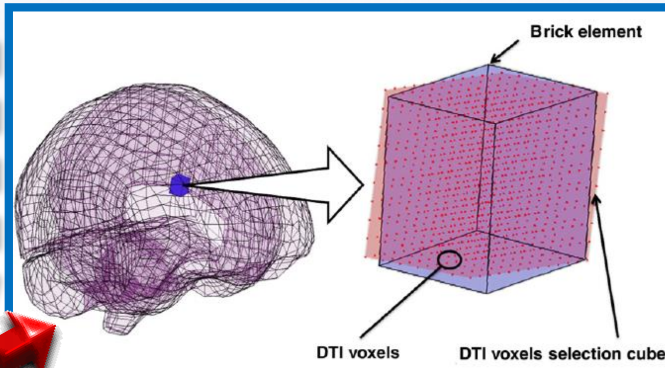
$$FA=\sqrt{\frac{3}{2}\frac{\sum_i(\lambda_i-\frac{1}{3}tr(D))^2}{\sum_i(\lambda_i)^2}}$$

Fractional Anisotropy

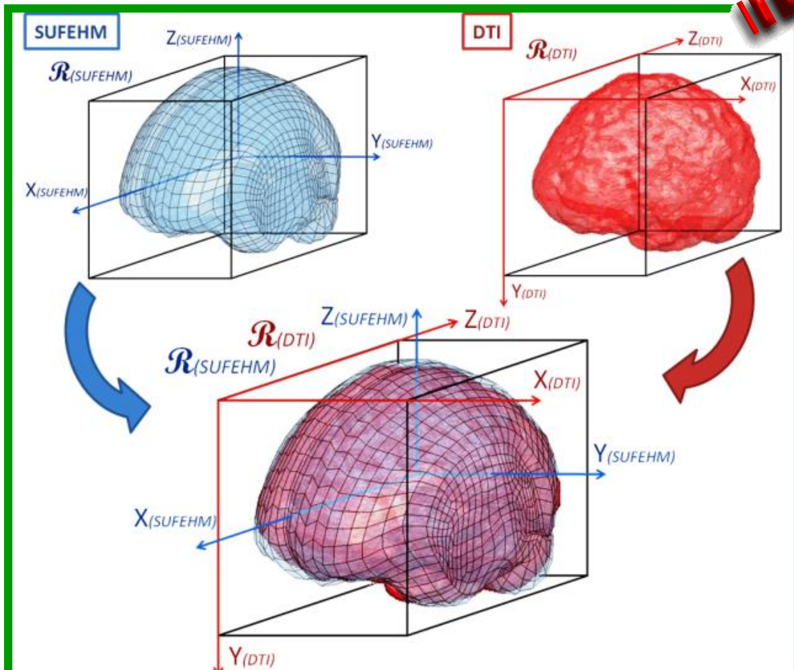
$$\vec{l}=FA\times\overrightarrow{e_{j|\lambda_j=\max(\lambda_i)}}$$

Fibers orientation

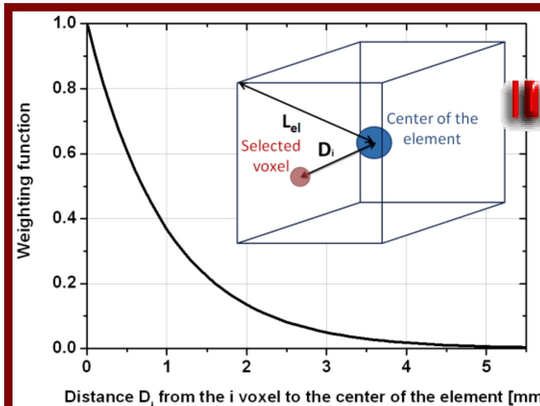
[Papadakis *et al.*, 1999; LeBihan *et al.* , 2001]



Voxel selection



Rigid transformation between mask of in vivo diffusion data (in red) and brain FEM (in blue)



Assign Weighting function

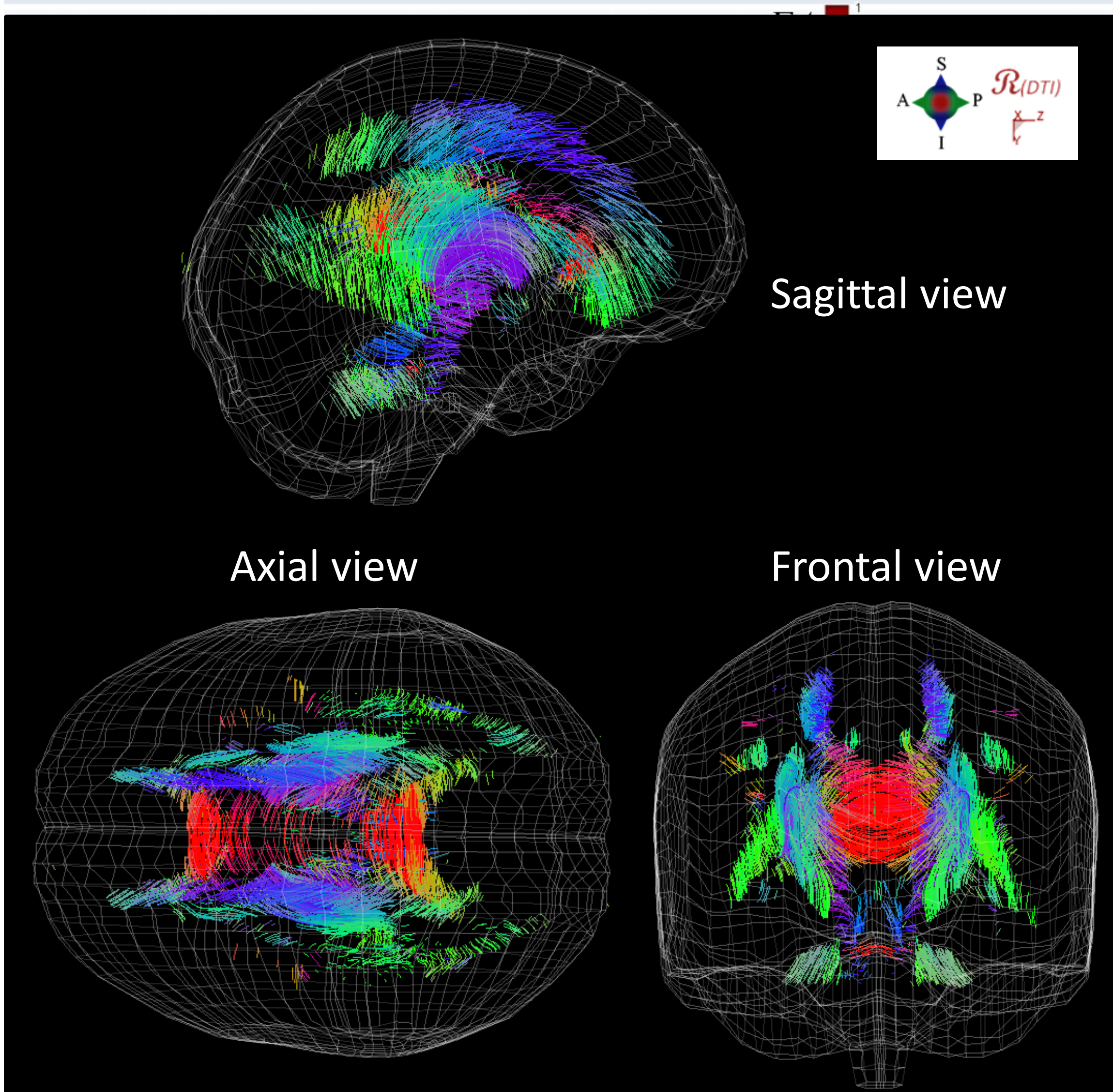
Fractional Anisotropy

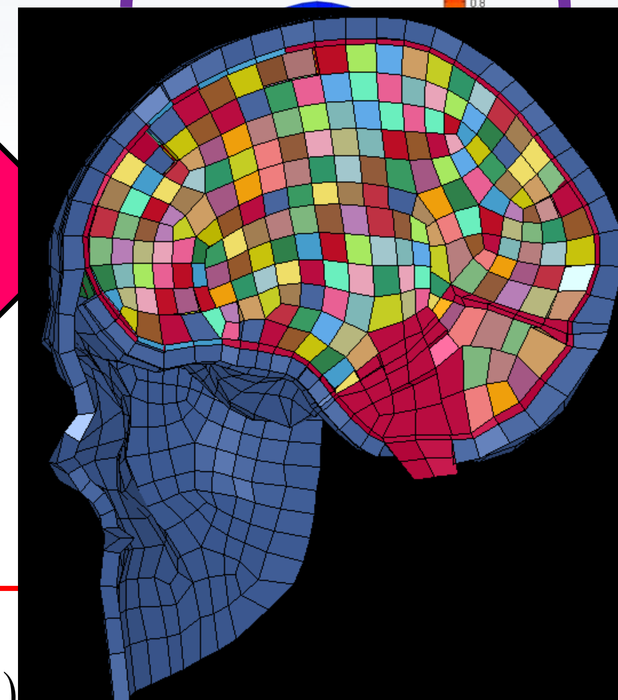
$$\langle FA\rangle_{el}=\frac{\sum_{i=1}^{N}FA_i e^{-D_i/L_e}}{\sum_{i=1}^{N}e^{-D_i/L_e}}$$

Anisotropy vector

$$\langle\vec{l}\rangle_{el}=\frac{\sum_{i=1}^{N}\vec{l}_i e^{-D_i/L_e}}{\sum_{i=1}^{N}e^{-D_i/L_e}}$$

NEW ENHANCED BRAIN MODEL





Heterogeneous and anisotropic brain model

$$+\begin{cases} 0 & 0<\bar{\lambda}<1 \\ C_3\left(e^{C_4(\bar{\lambda}-1)}-1\right) & \bar{\lambda}\geq 1 \end{cases}$$

Fibers stress

Anisotropic visco-hyperelastic brain model (Chatelin et al. 2012)

Model Based Head Injury Criteria

Real World Head Trauma Simulation

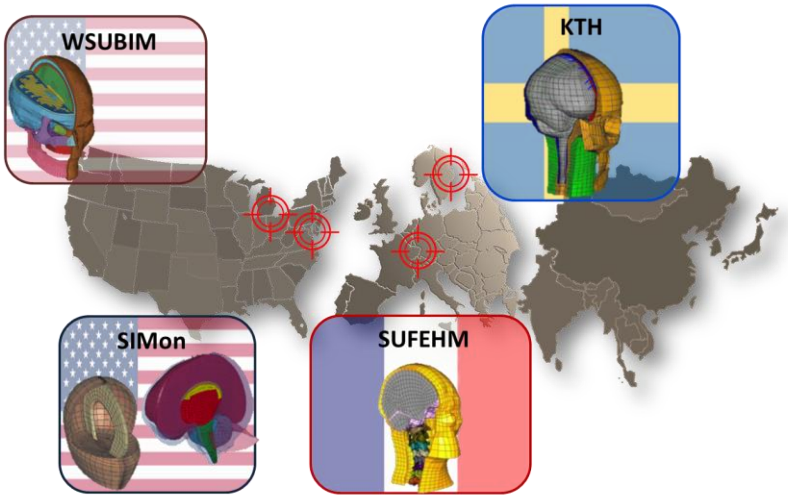
31

PUBLISHED TISSUE LEVEL INJURY CRITERIA

32

Local Parameters (FE)

Local tissue level brain injury criteria are based on SIMon, KTH, WSU, THUMS and SUFEHM finite element head models:



•	MPS	Max principal strain
•	SCC	Strain in Corpus Callosum
•	VM strain	Max VM strain
•	SSR	Strain*Strain rate
•	Pmax	Max pressure
•	VM stress	Max VM stress
•	CSDM	Cumulative Strain Damage Measure
•	MAS	Maximum axonal strain

INJURY CRITERIA FROM THE LITERATURE

UNIVERSITÉ DE STRASBOURG

cnrs

Tolerance limite to DAI

STRAIN

18%

In vivo pig optical nerve strain

Bain & Meaney

2000

21%

In vivo cell culture strain

Morrison et al

2003

25% (Moderate)
33% (Severe)

Brain First Principal Strain

Deck et al Strasbourg Univ

2006

21% (corpus callosum)
26% (gray matter)

Brain First Principal Strain

Kleiven KTH

2007

STRESS

Anderson et al. Adelaïde

27 kPA (moderate)
43 kPa (severe)

Baumgartner et al. Strasbourg

25 kPA (moderate)

Deck et al Strasbourg Univ

26 kPA (moderate)
33 kPa (severe)

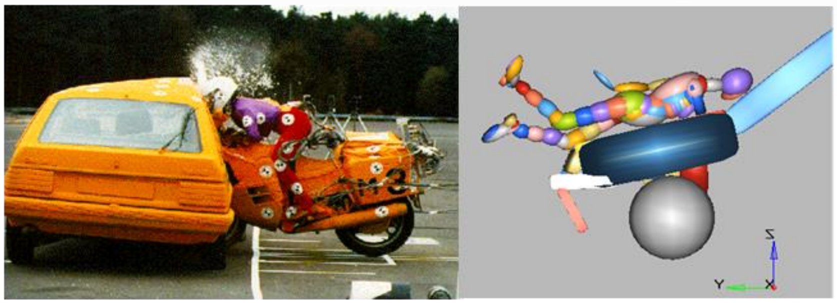
Criteria consolidation:

-Code dependance
-Age dependance

ACCIDENTS RECONSTRUCTIONS

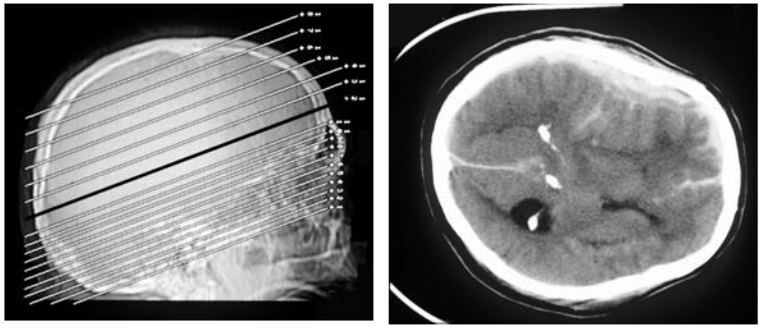
- **METHODOLOGY**

Experimental or analytical replication

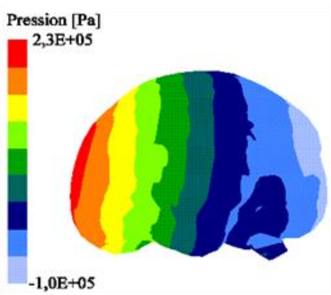


Real accidents

Detailed medical report

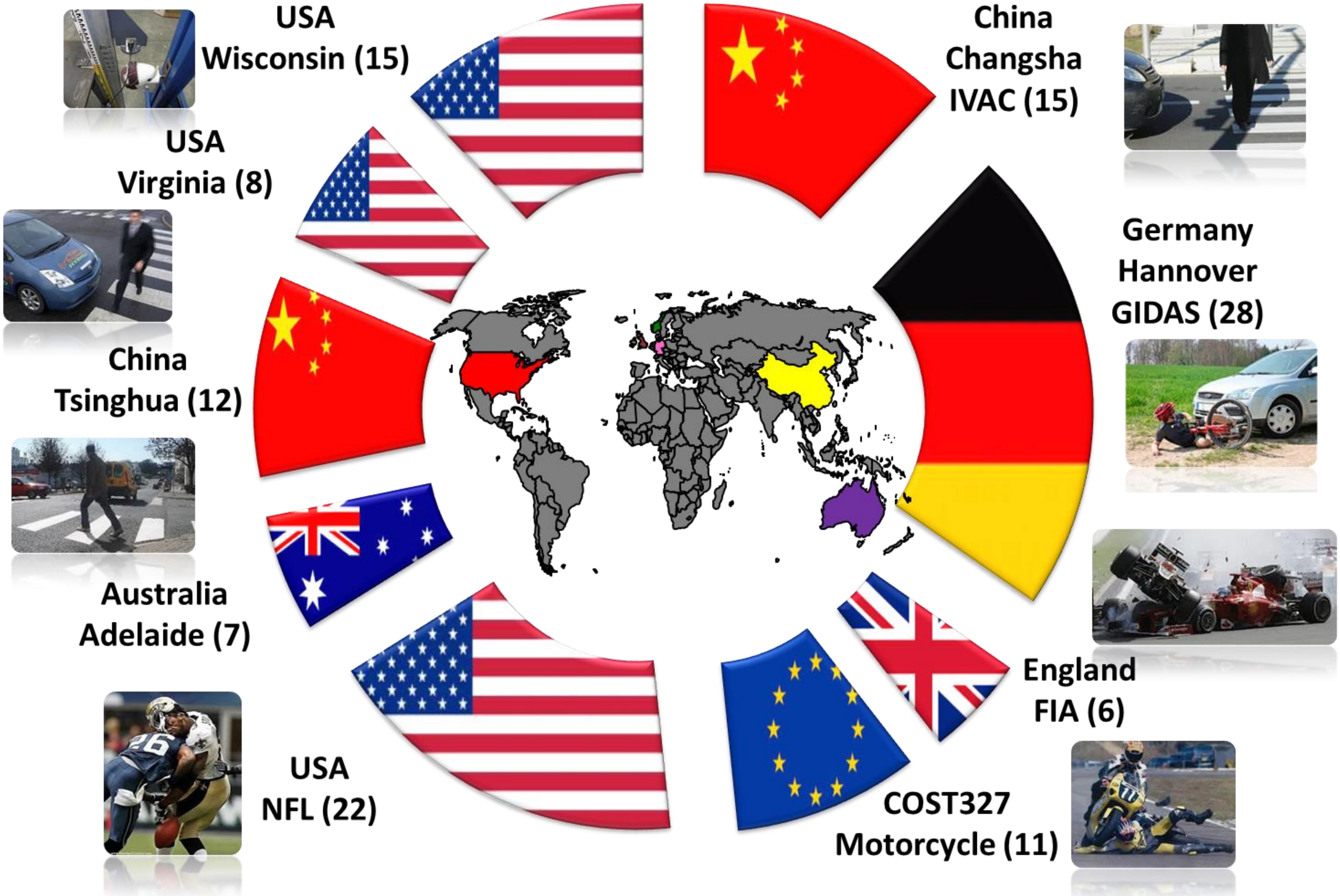


Numerical reconstruction



Injury mechanisms and tolerance limits

Database (125 cases)



HEAD TRAUMA DATABASE

UNIVERSITÉ DE STRASBOURG

CNRS

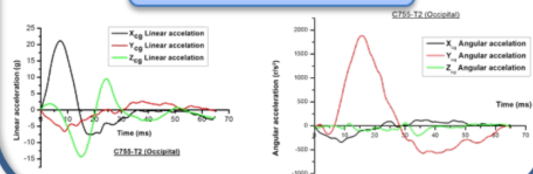
- FIA
- Motorcycles
- Footballers

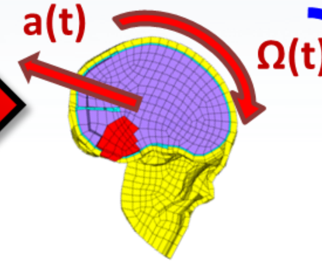
Total 125 accident cases

- Pedestrians
- Experiments

Experimental replications

6 accelerations

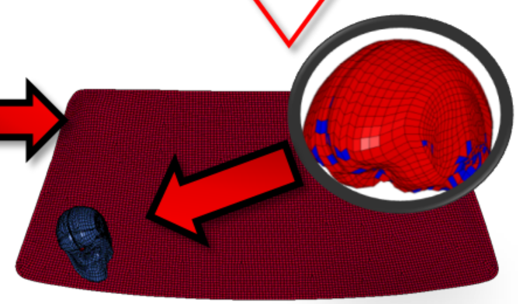




Numerical replications

Initial Head Velocity, Orientation Position

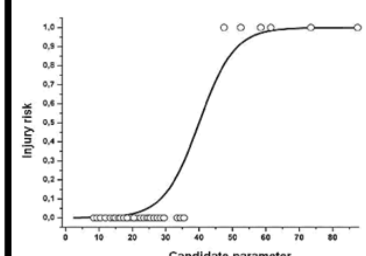
Numerical simulations



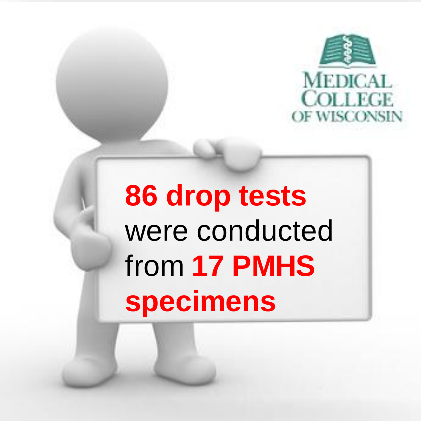
Injury Correlation

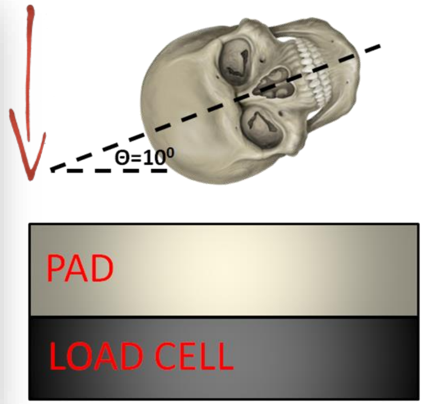
Statistical Analysis

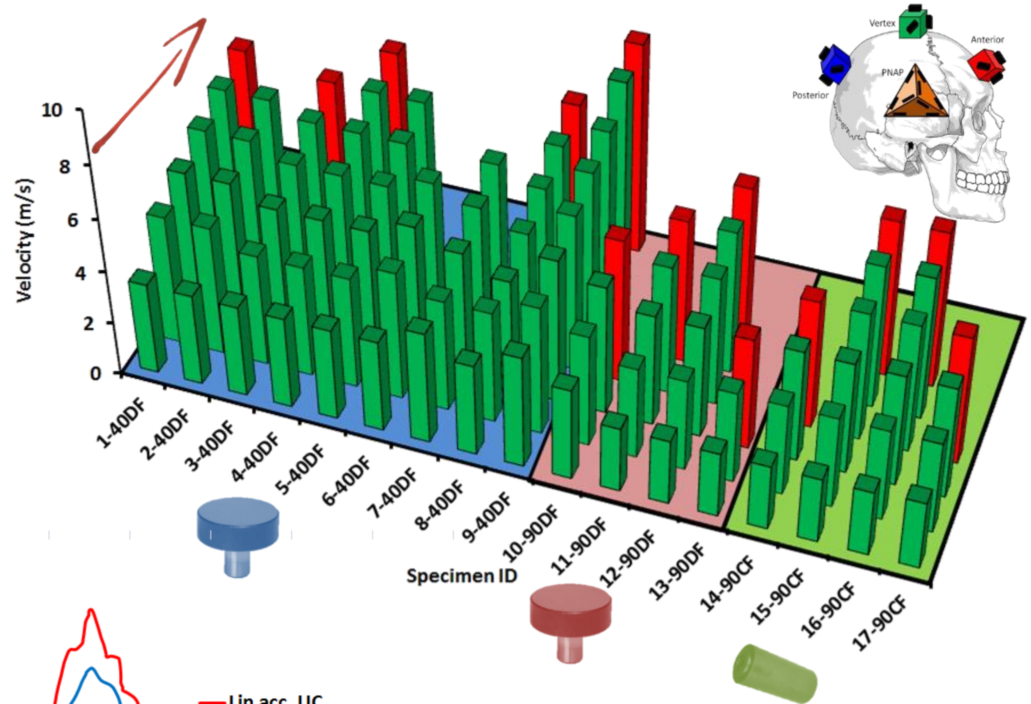
Model Based Criteria

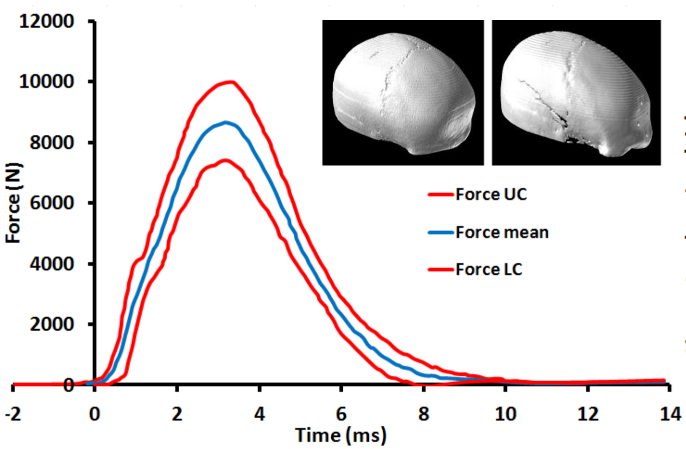


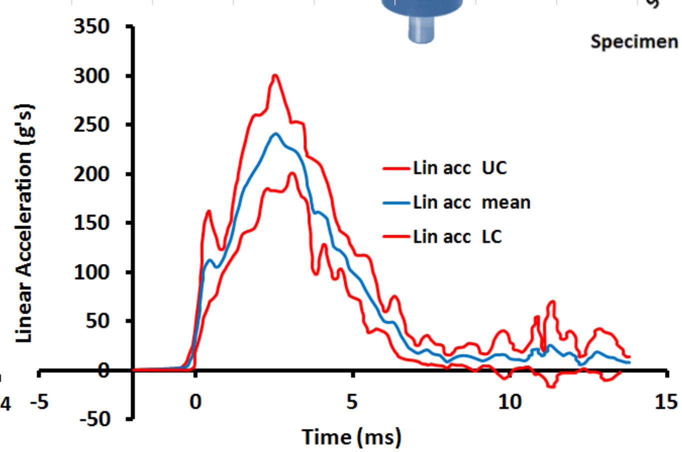
Experimental Skull fracture tests









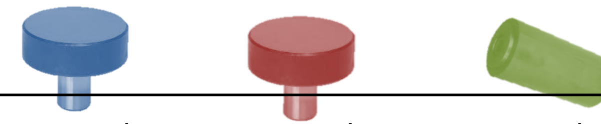


15 impact conditions

- 17 PMHS' heads are tested.
- Accelerometer packages are attached to the skull using screws.
- Drop techniques for impact with successively increasing input energies until fracture.

Identification of skull constitutive law

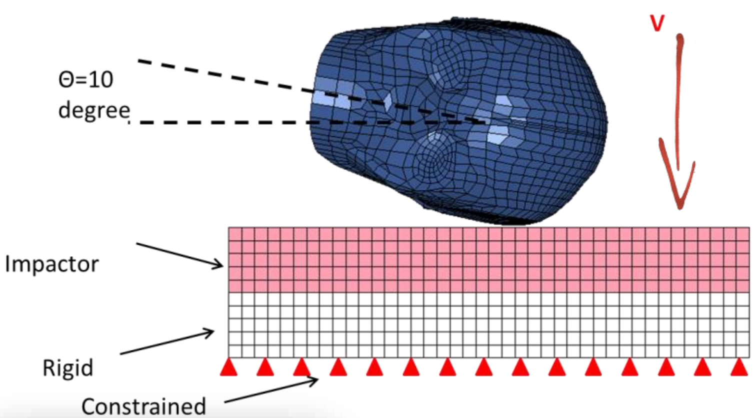
Impactor mechanical parameters definition

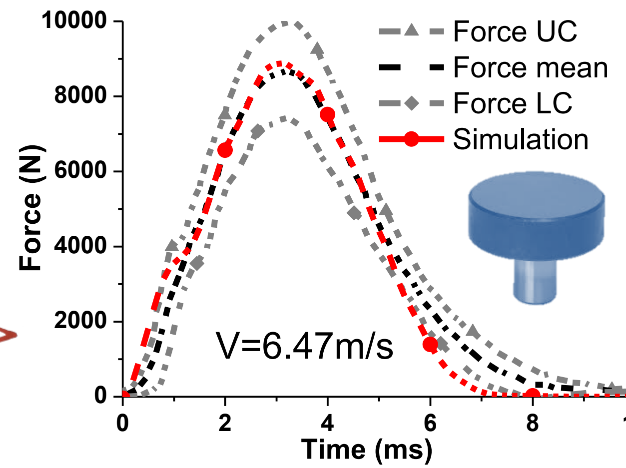


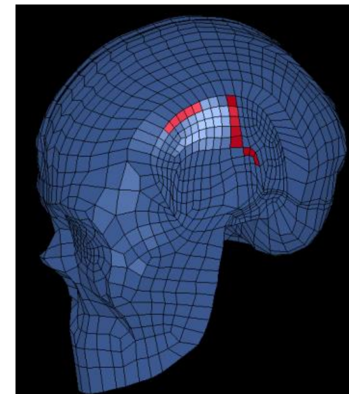
[Gent et al., 1958]
[Gray et al., 1991]
[Pampush et al., 2011]

Parameters	40D Flat	90D Flat	90D Cylindrical
Mass density (Kg/m^3)	4230	4930	4930
Young's Modulus (MPa)	9	12	12
Poisson's ratio	0.43	0.43	0.43

Numerical replication and skull mechanical parameters adjustment







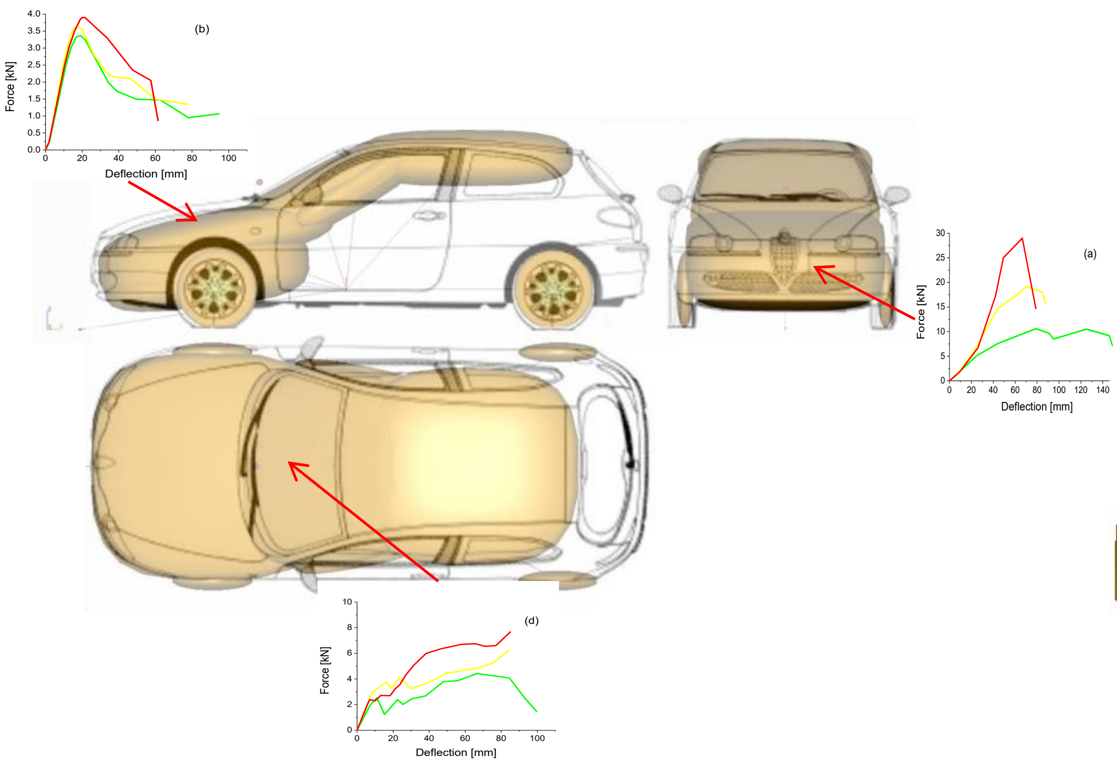
Parameters	Cortical bone	Diploe Bone
Mass density (Kg/m^3)	1900	1500
Young's Modulus (Mpa)	15000	4665
Poisson's ratio	0.21	0.05
Longitudinal and transverse compressive strength (Mpa)	132	24.8
Longitudinal and transverse Tensile strength (Mpa)	90	34.8

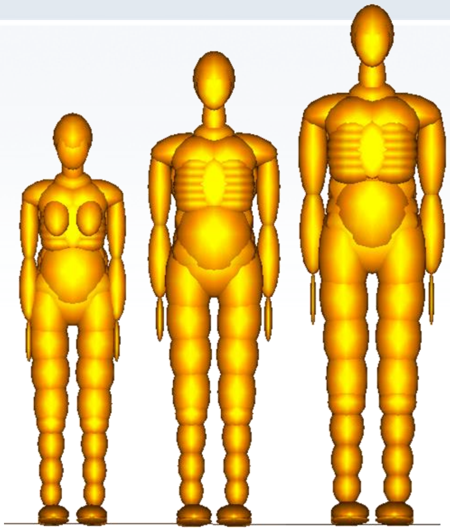
DETAILED ACCIDENT RECONSTRUCTION

Modeling of the accidents

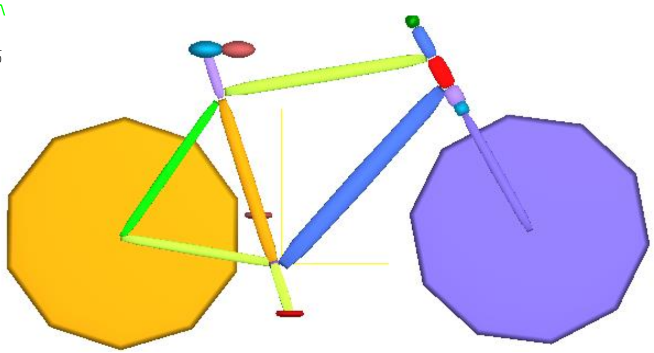
Unistra modeling

The contact force functions used on each part of the car are extracted from the study of Martinez *et al.*,2007





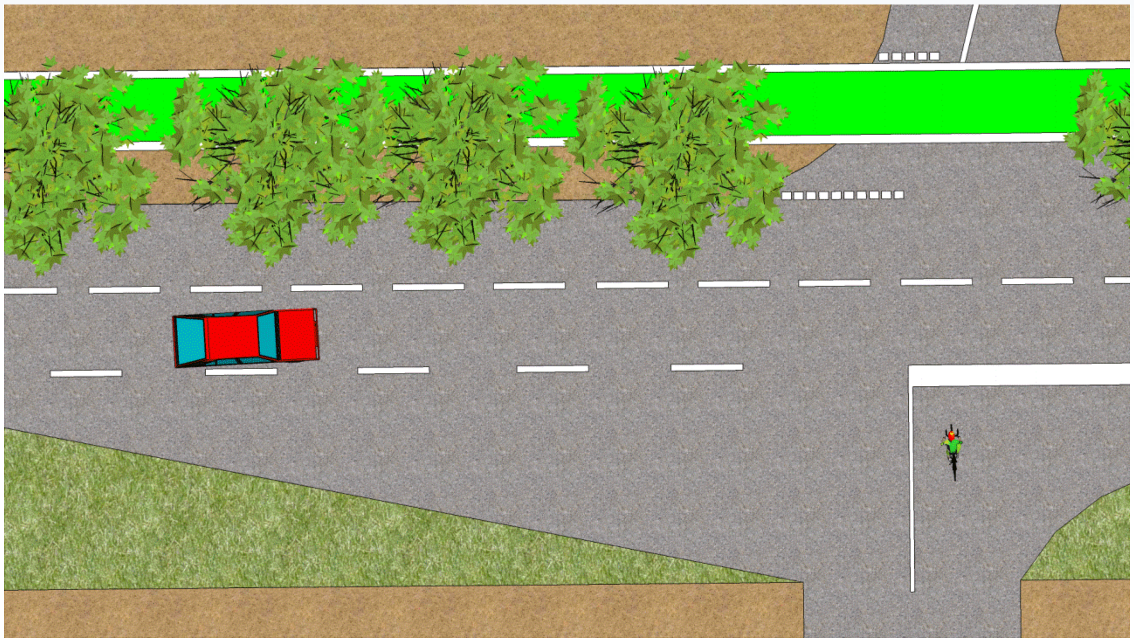
The scalable TNO Pedestrian model implemented in Madymo® package



The Unistra bicycle model

EXAMPLE : DESCRIPTION OF ACCIDENT CASE

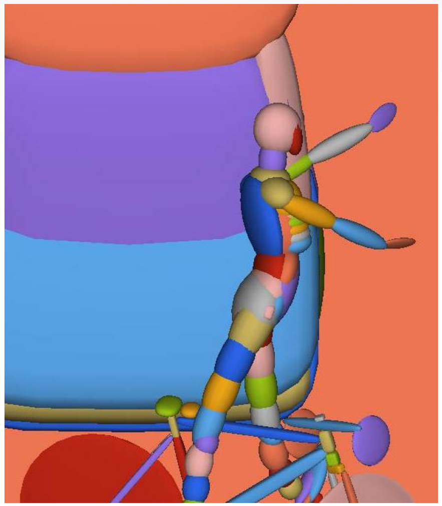
Unistra modeling

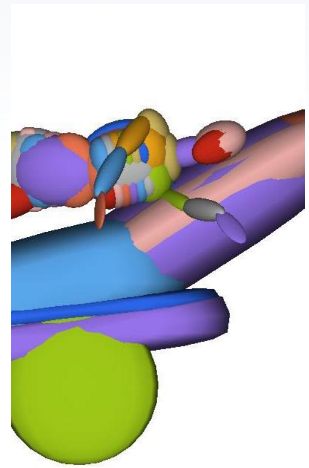


Impact Conditions
Car velocity ~ 45 km/h
Cycle Velocity ~ 5.5 km/h
Cycle/Car angle ~ 6°
Vehicle deceleration ~ 6,5 m/s²

Victim
Man, 91 years old,
Failure parieto-occipito-temporal
Coma with a Glasgow score of 5

Unistra modeling

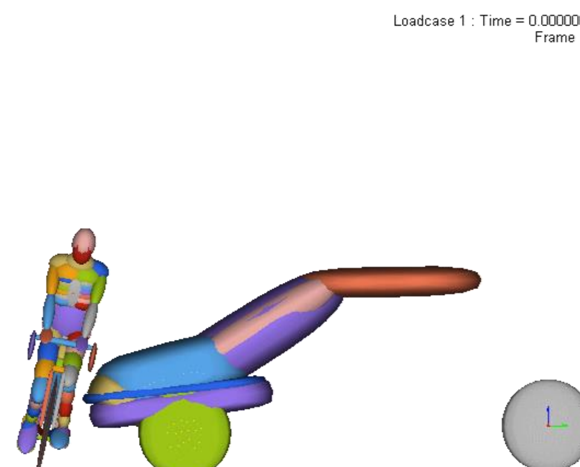




$V_{resultant} = 10.9$ m/s

$V_{normal} = 10.0$ m/s

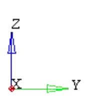
$V_{tangential} = 4.4$ m/s



Two impacts
- on windshield with the left shoulder,
- on pillar with head area occipito-parieto-temporal.

Projection distance of 16.3 m

WAD of 2.10 m



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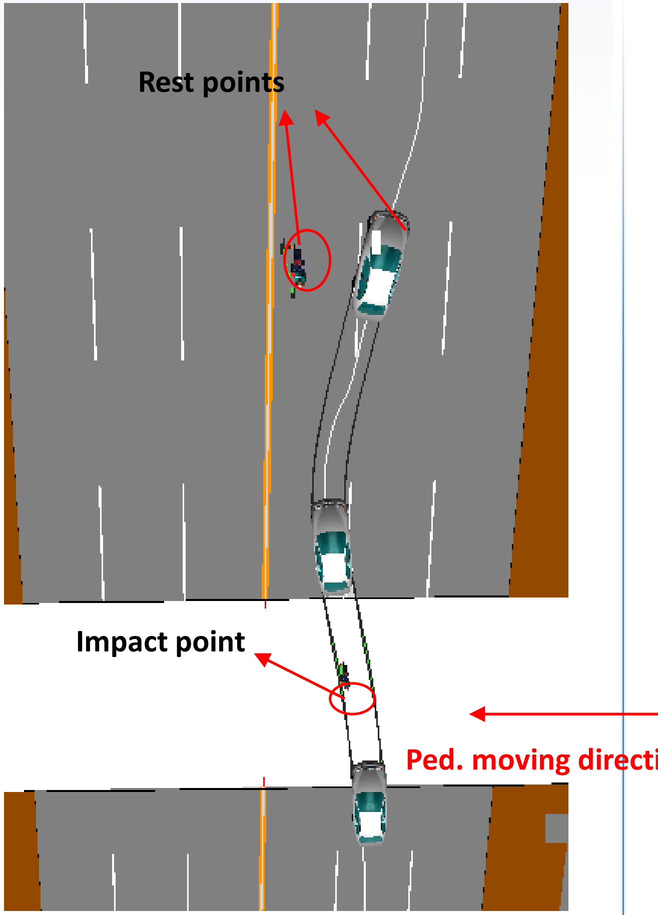
➢ *Exemple pedestrian case (2)*

From IVAC database

- Victim information: 49-year-old female, 158cm and 58kg
- Vehicle information: BMW 318
- Impact speed: about 62.9 km/h

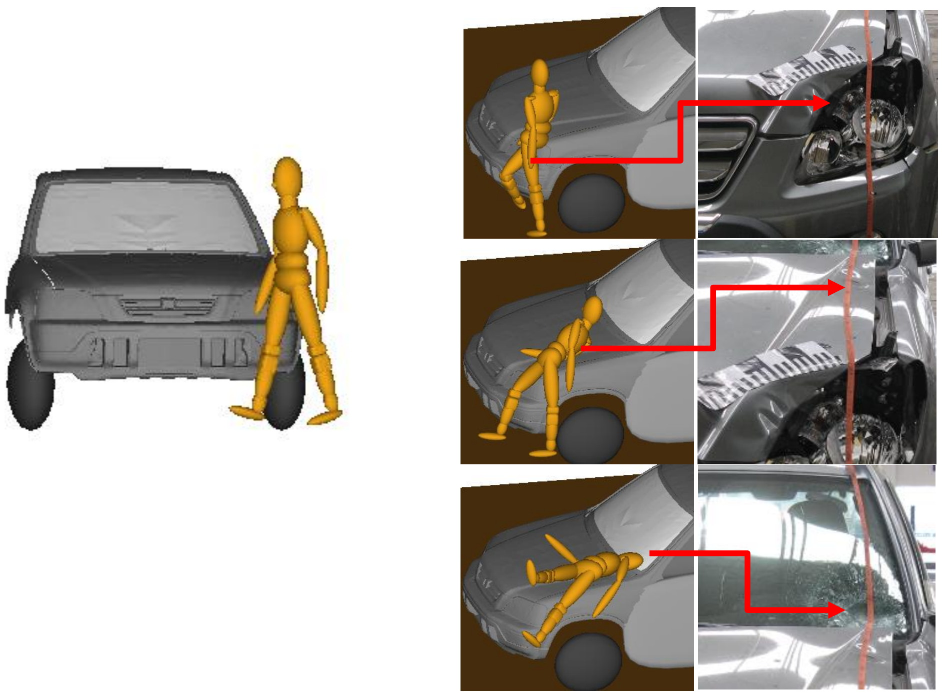
Injury details:

- Cerebral contusion (AIS3), Hematoma (AIS2), Fatal head injuries (AIS6)
- Right tibia (AIS3) and fibula (AIS3) fracture

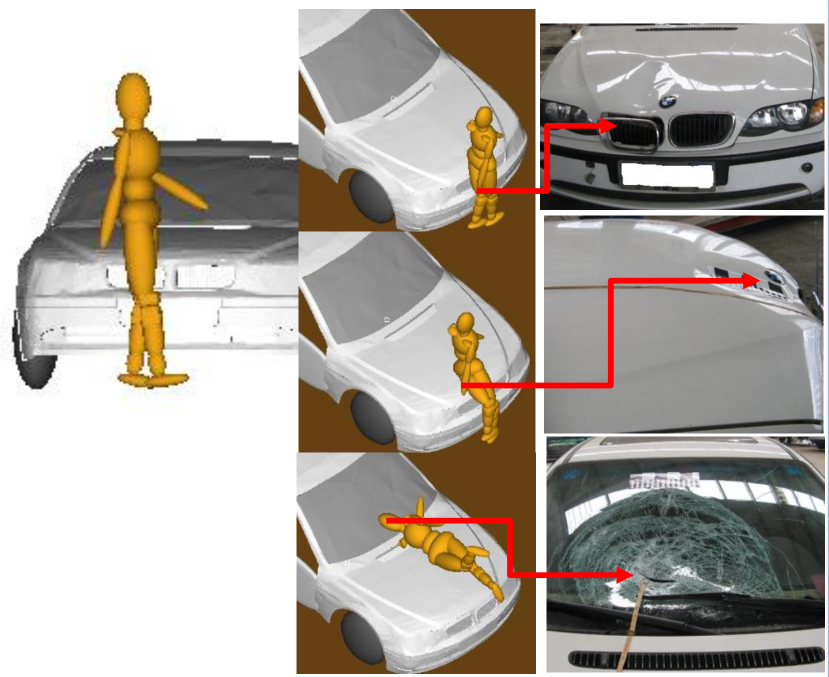


➢ *Reconstruction results*

	Example 1		Example 2	
	Accident	Simulation	Accident	Simulation
Throw distance (m)	12.4	11.3	18	17.5
WAD (mm)	2000	2030	1980	1940
Velocity (km/h)	60	54	60	62.9



Example 1



Example 2

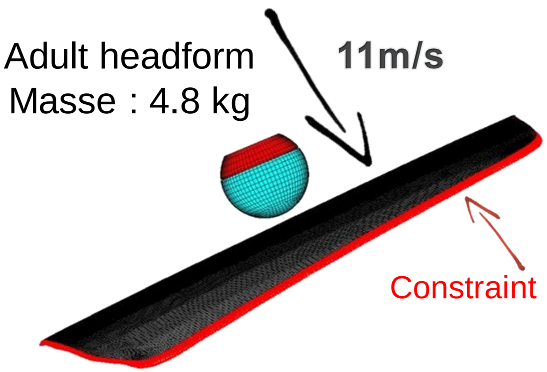
Windscreen FEM

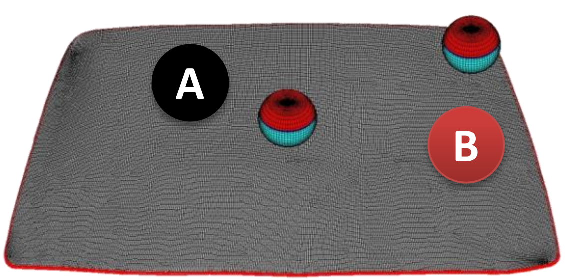
Perpendicular to the windshield at 40 km/h

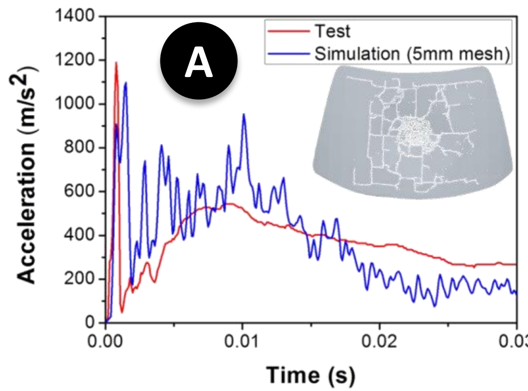
[Lex van Rooij et al, 2001]

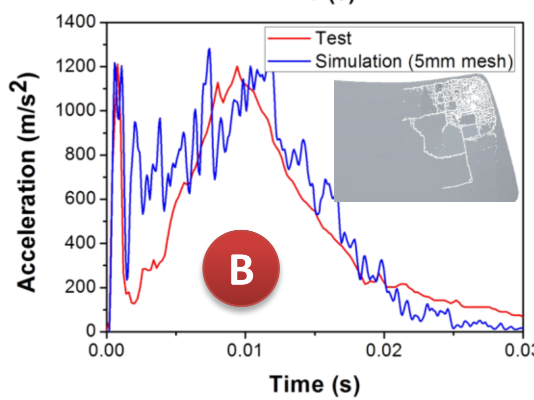
Windscreen Mechanical properties

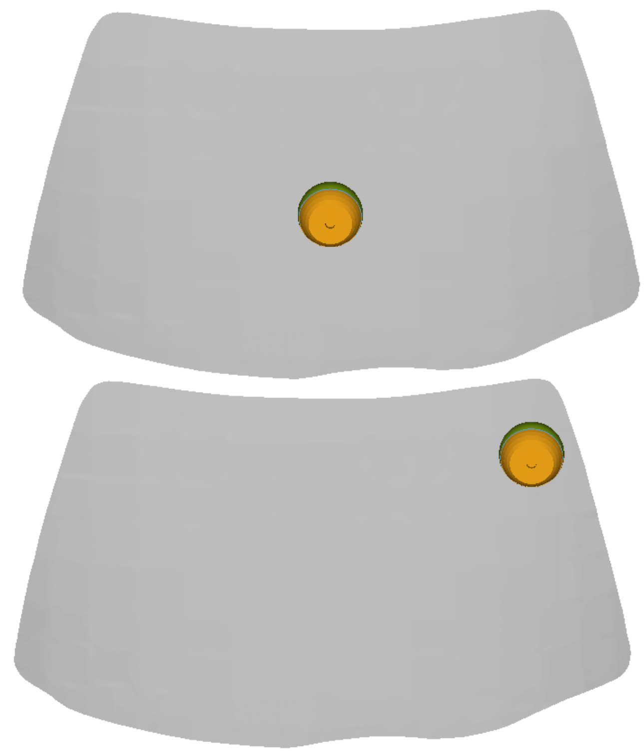
Material	Parameters
Glass	E=74GPa; ρ=2500kg/m3; μ=0.227; EFG=0.001
PVB	E=2.6GPa; ρ=1100kg/m3; μ=0.435









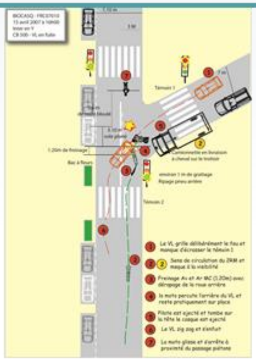


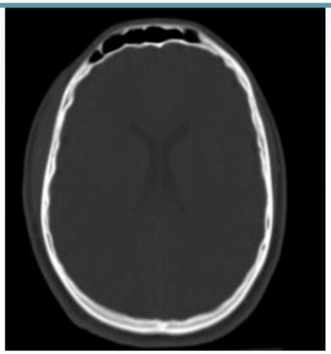
Accident case

Case 2

Accident description

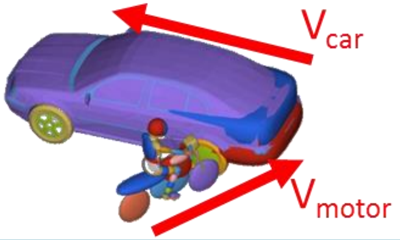
- Accident between a car and a motorcycle
- Doubt on helmet wearing
- Unconsciousness (Glasgow 7)
- AIS 3





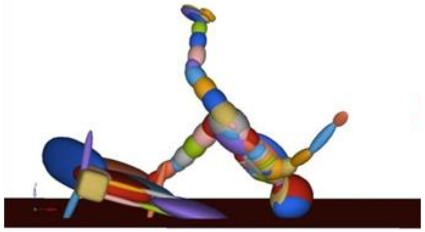
Accident reconstruction

Initial configuration



Impact kinematics

Extraction of head impact angle and velocity →



→ Inputs for the helmeted headform under RADIOSS

Model Based Head injury criteria

48

HEAD TRAUMA SIMULATIONS

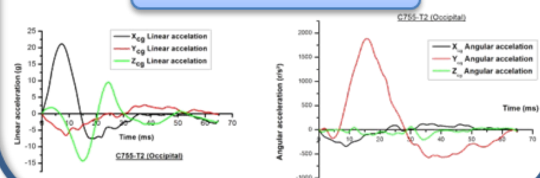
- FIA
- Motorcycles
- Footballers

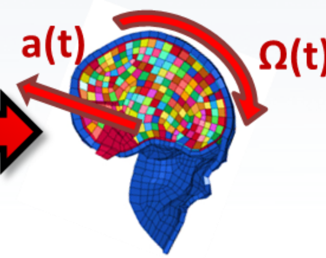
Total 125 accident cases

- Pedestrians
- Experiments

Experimental replications

6 accelerations

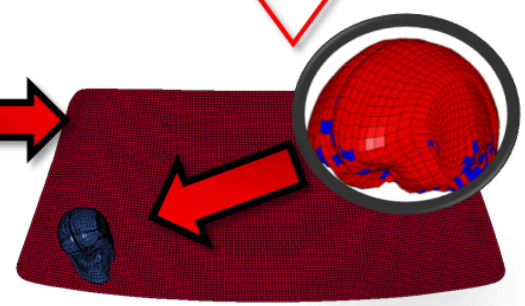




Numerical replications

Initial Head Velocity,
Orientation
Position

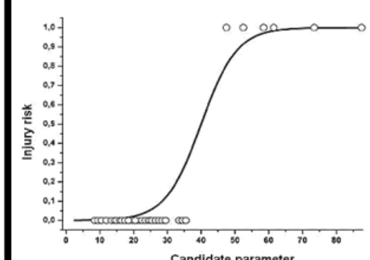
Numerical simulations



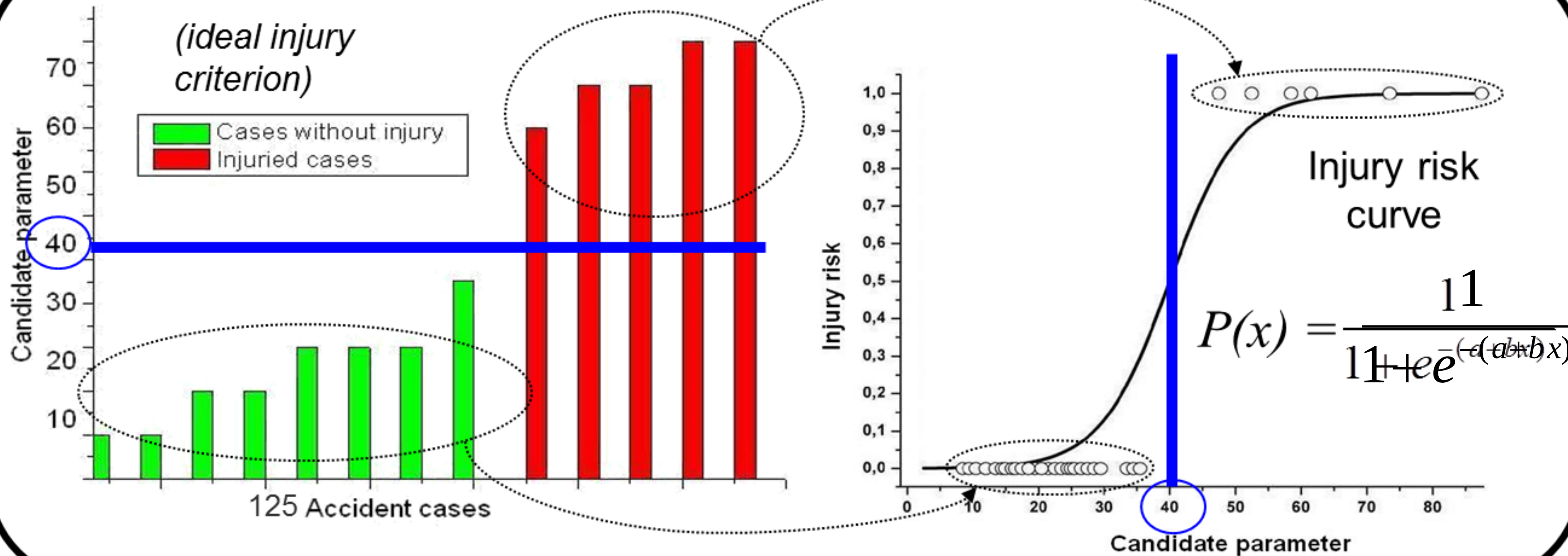
Injury Correlation

Statistical Analysis

Model Based Criteria



EXTRACTION OF CRITERIA

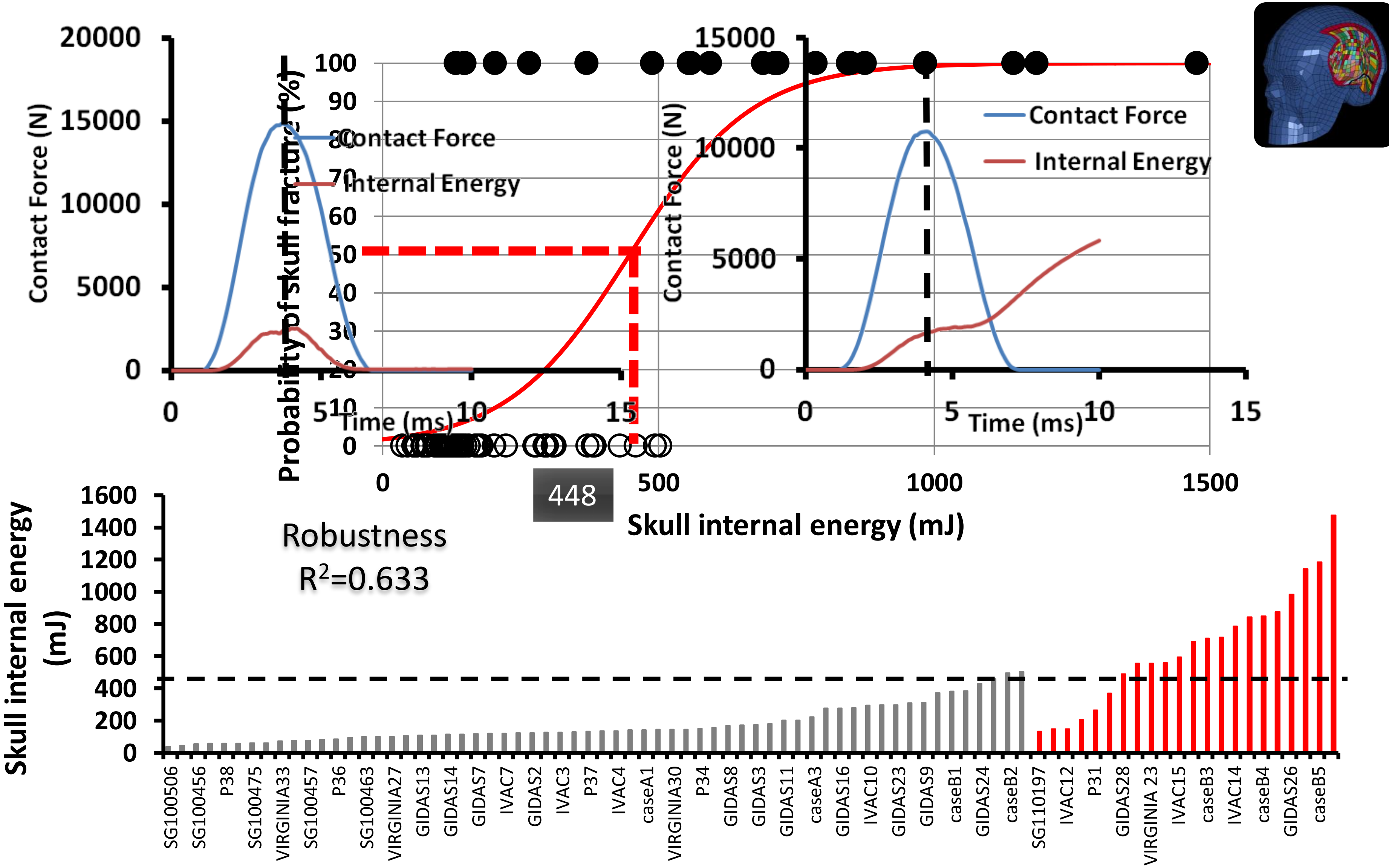


$$P(x) = \frac{1}{1+e^{-(a+bx)}}$$

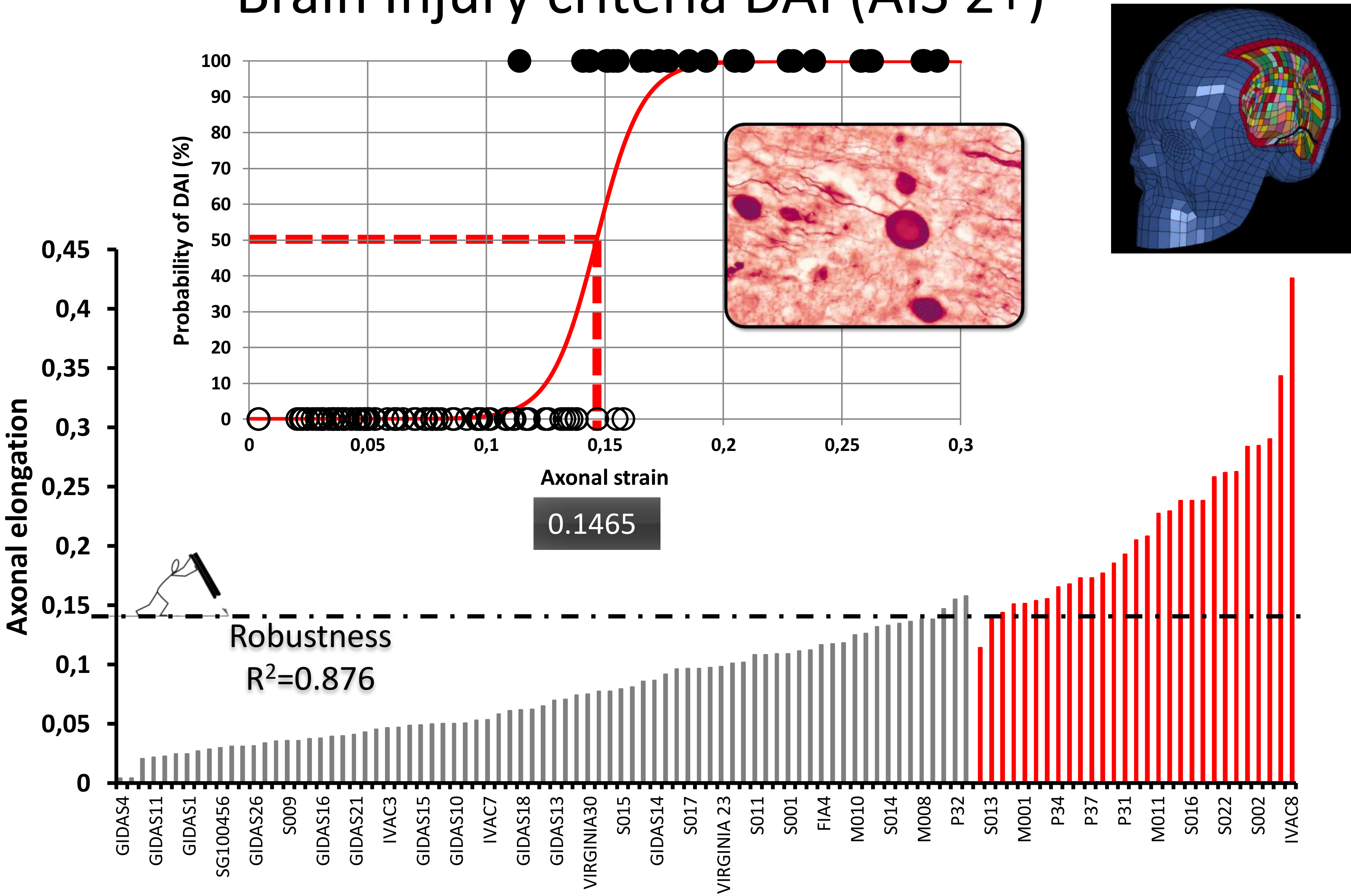
Binary logistic regression (*SPSS v14.0*)

we compared
the Nagelkerke R-sq statistics

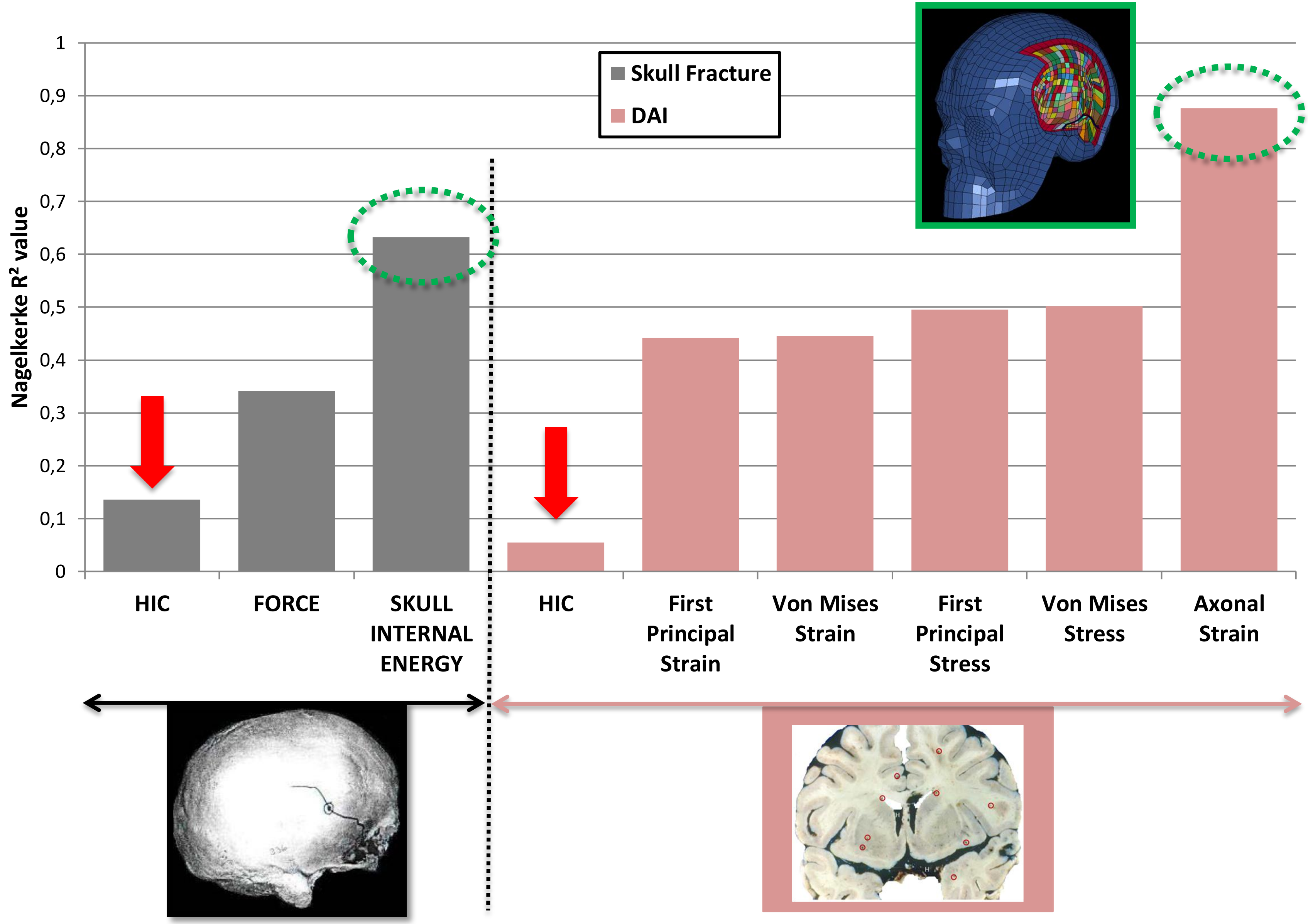
Skull fracture criteria



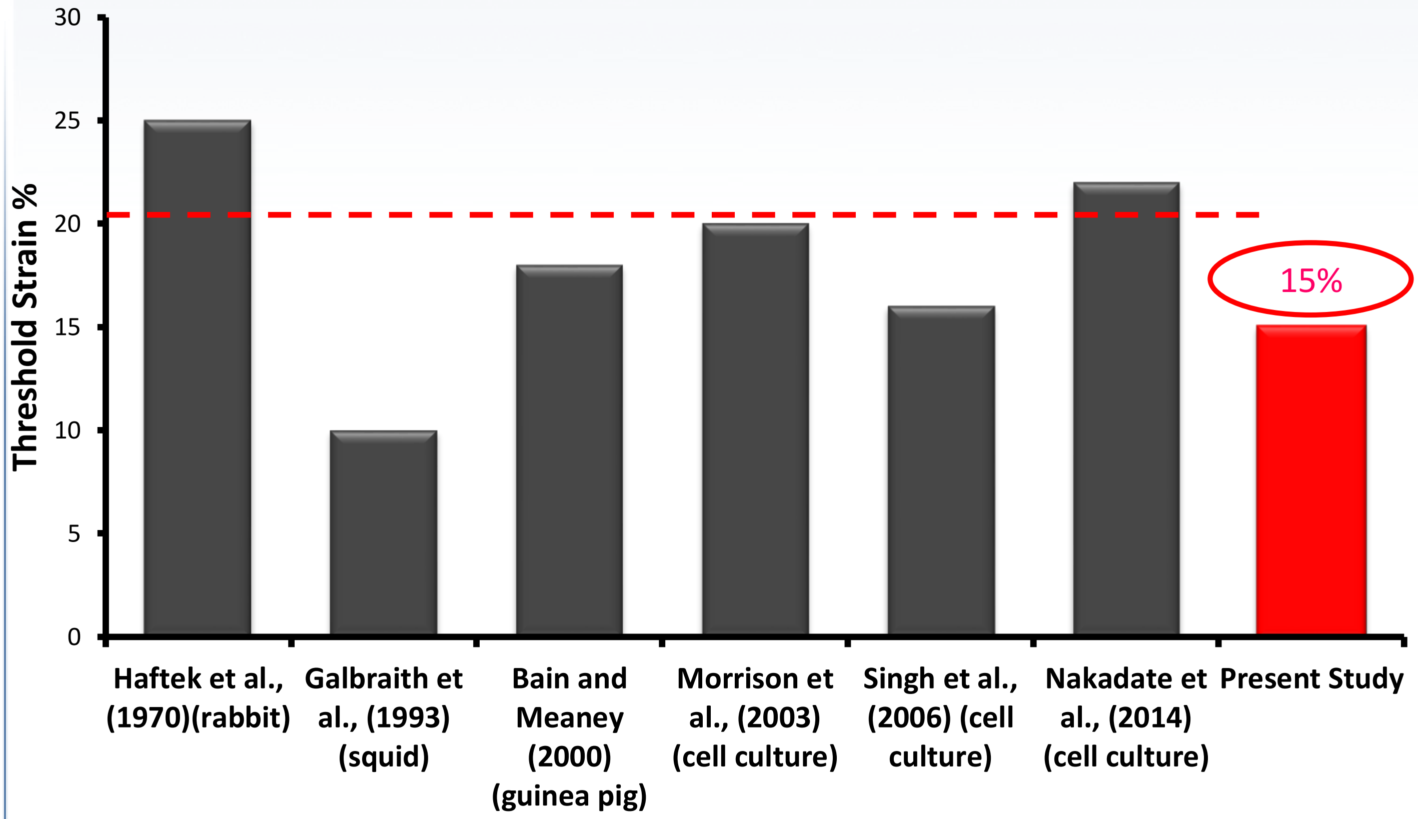
Brain Injury criteria DAI (AIS 2+)

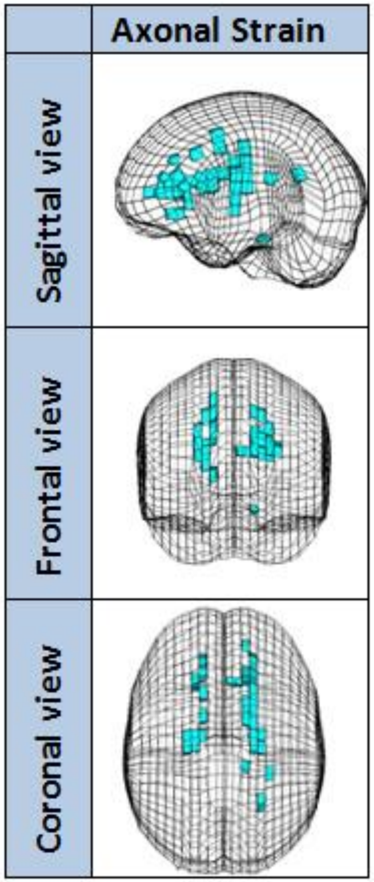


Evaluation of existing Head Injury Criteria



AXON STRAIN IN THE LITTERATURE





Proposed tolerance limit is in accordance with various studied reported in literature.

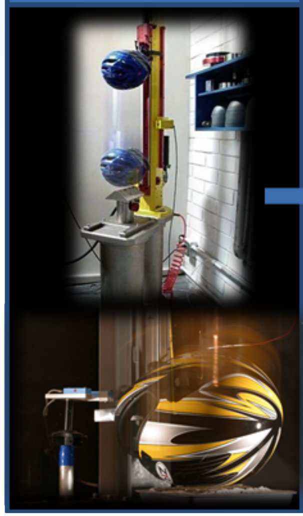
HEAD INJURY PREDICTION TOOL FOR END USERS

HEAD INJURY PREDICTION TOOL

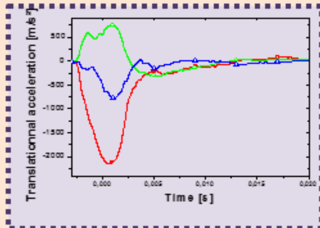
UNIVERSITÉ DE STRASBOURG

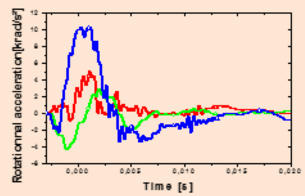
- **COUPLED EXPERIMENTAL VS NUMERICAL TEST METHODS**

TEST CONDITIONS



LINEAR AND ROTATIONAL ACCELERATIONS



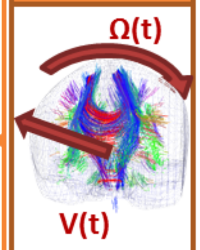


STANDARD PARAMETER

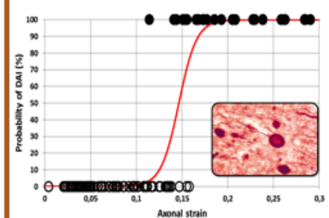
$$HIC = (t_2 - t_1)\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)\,dt\right]^{2.5}$$

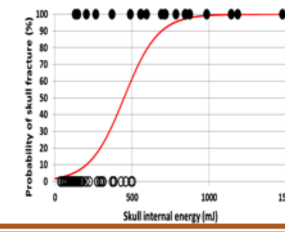
IMPROVED MODEL BASED HEAD INJURY CRITERIA

SUFEHM

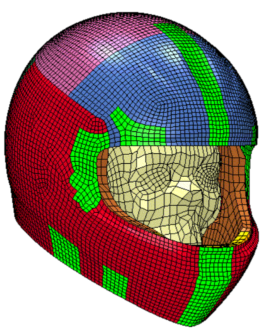


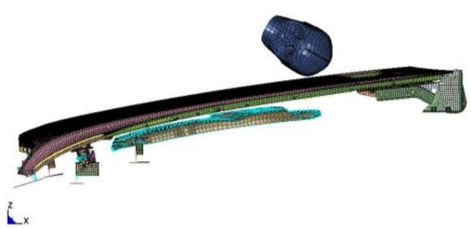
INJURY RISK ASSESSMENT

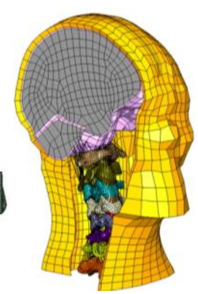


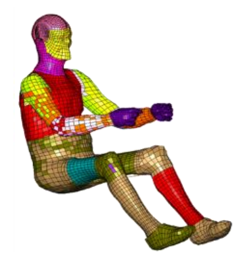


- **FULL FE APPROACH**



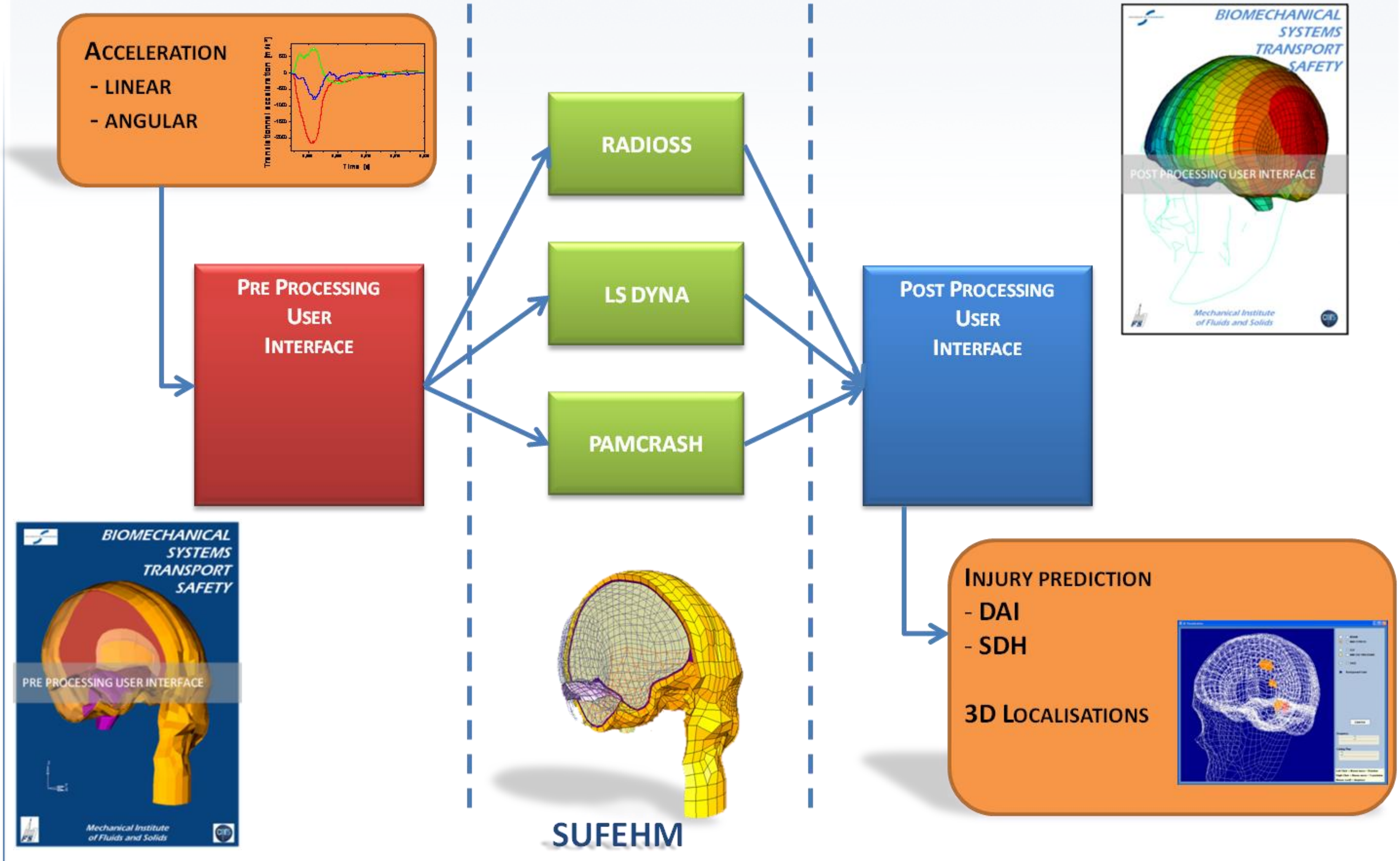






FROM RESEARCH TO END USERS

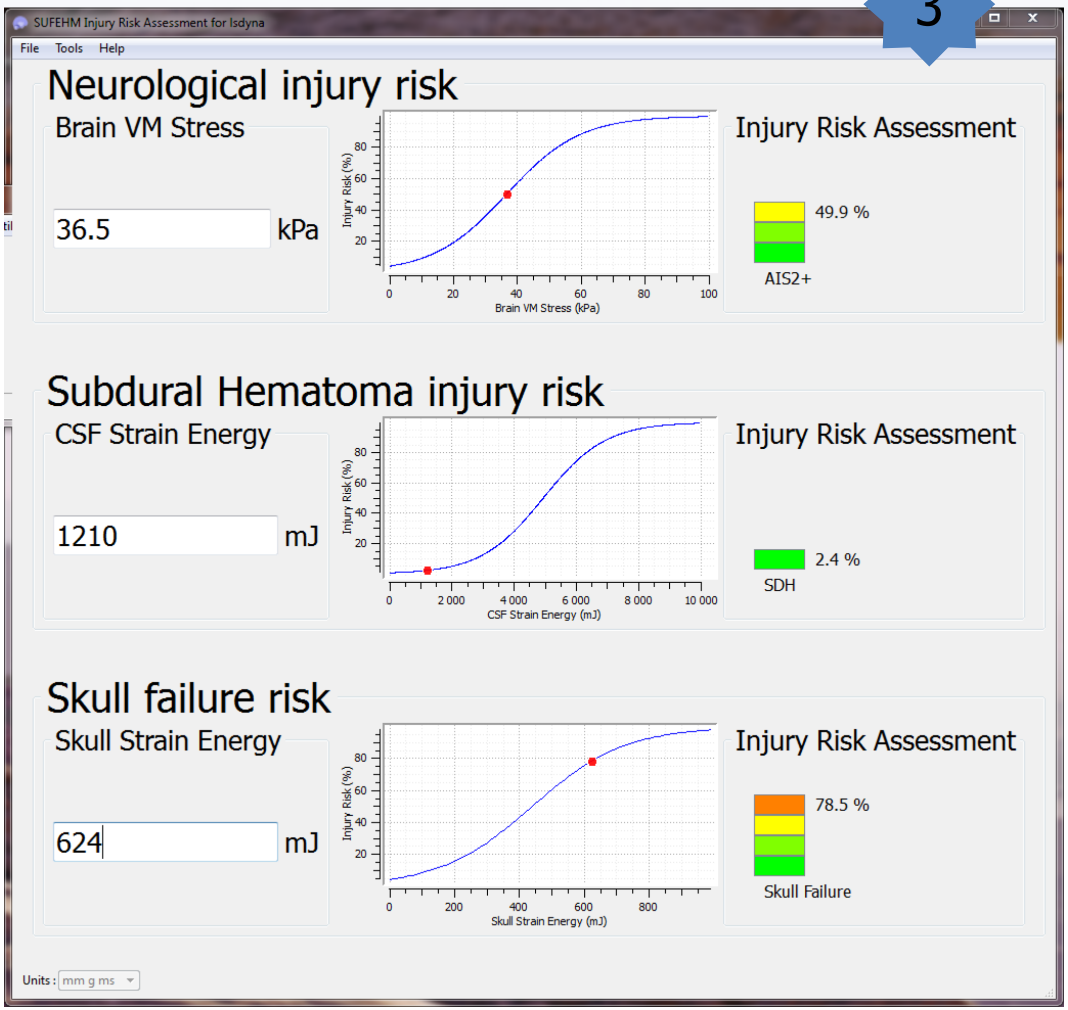
- PRE-POST-PROCESSING USER INTERFACES :



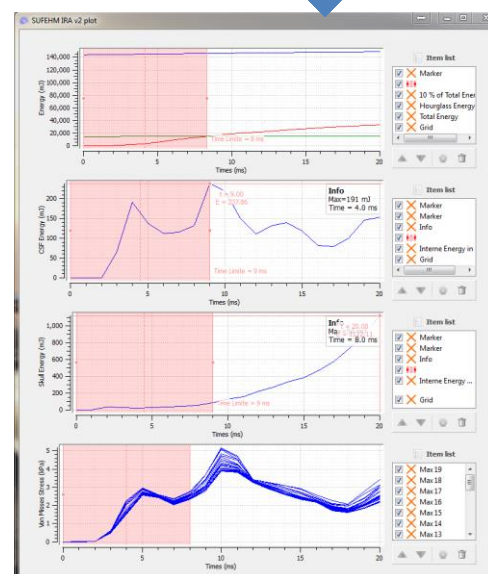
SUFEHM IRA TOOL

INJURY RISK ASSESSMENT

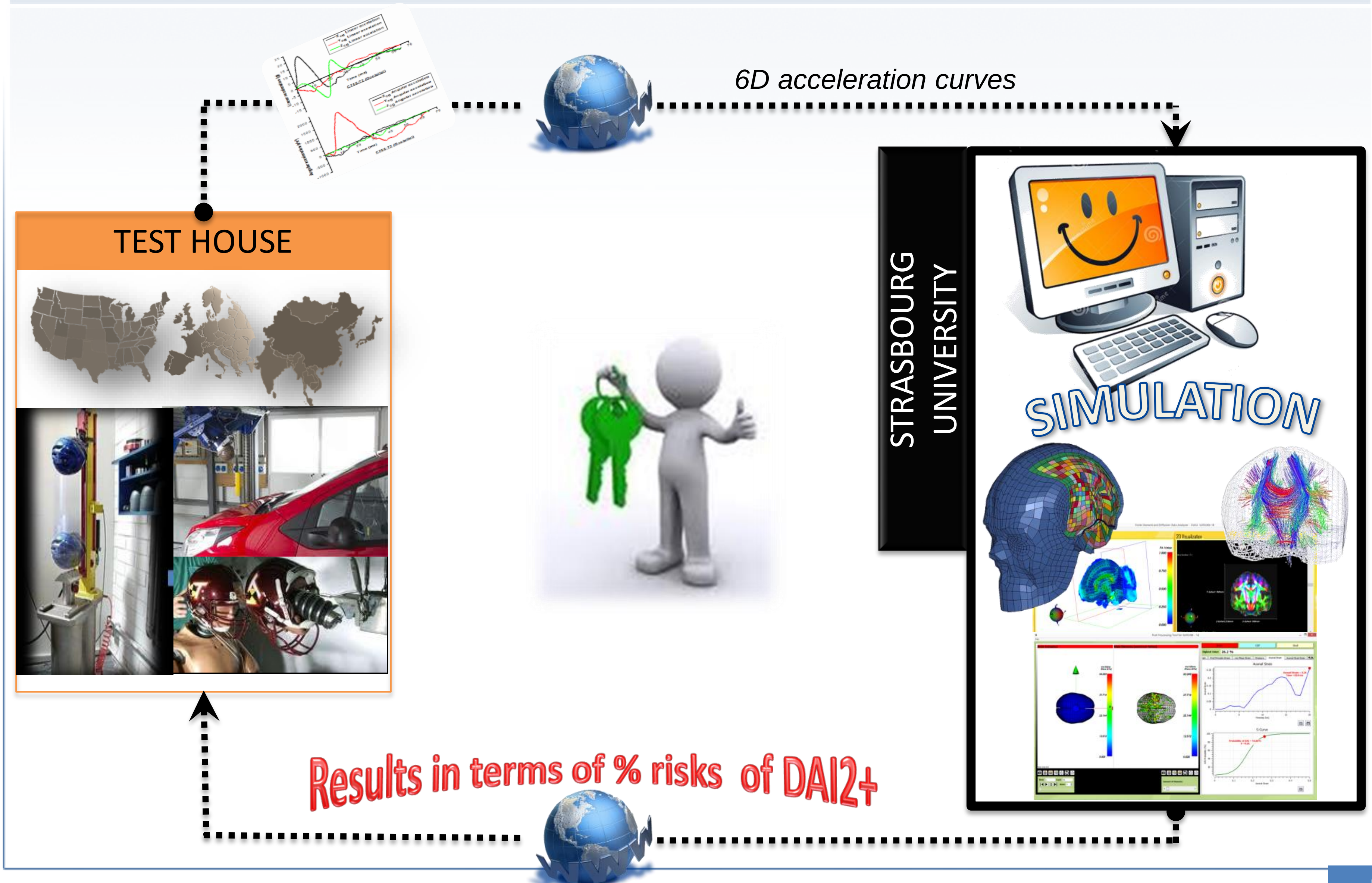
3



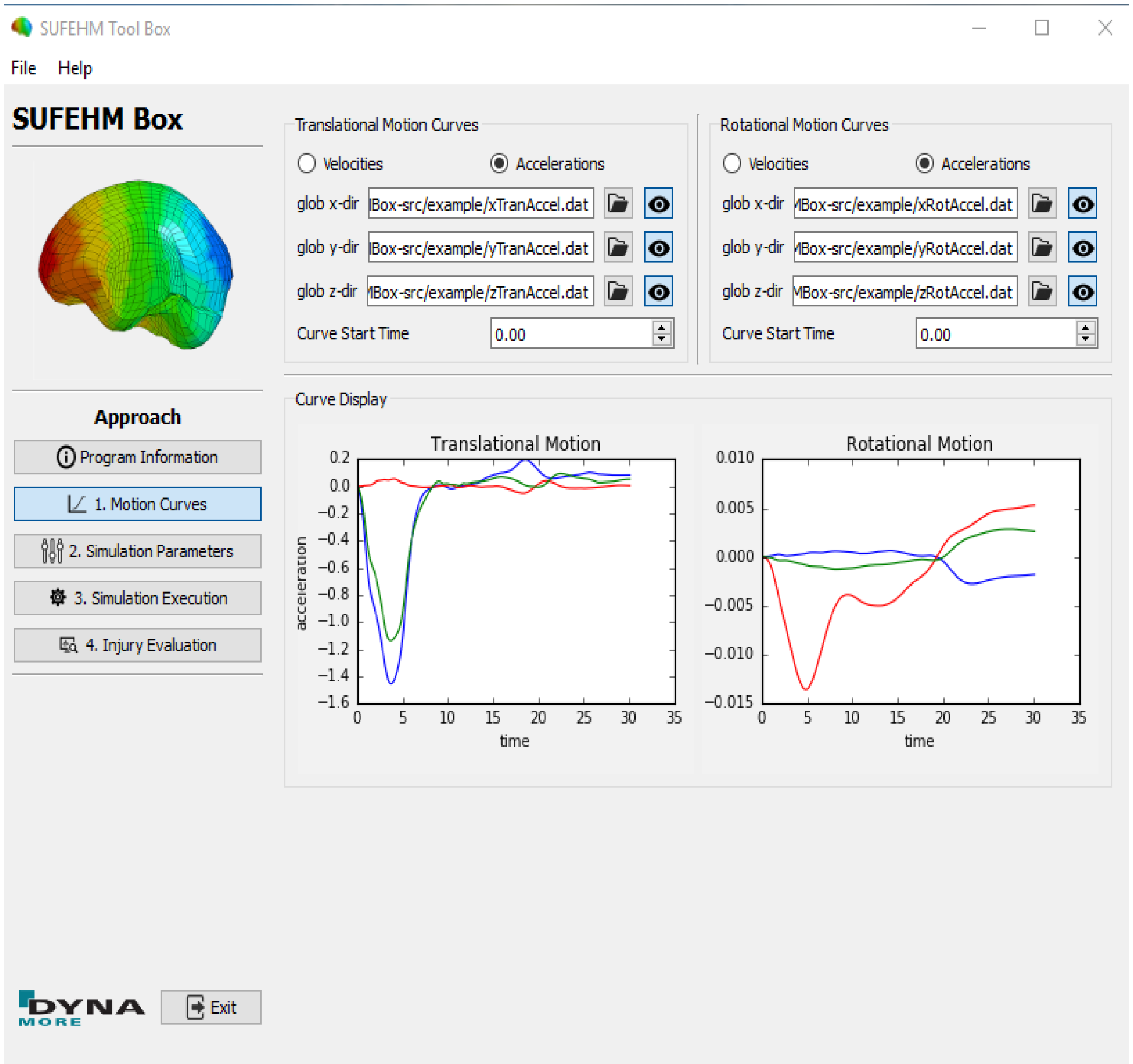
4



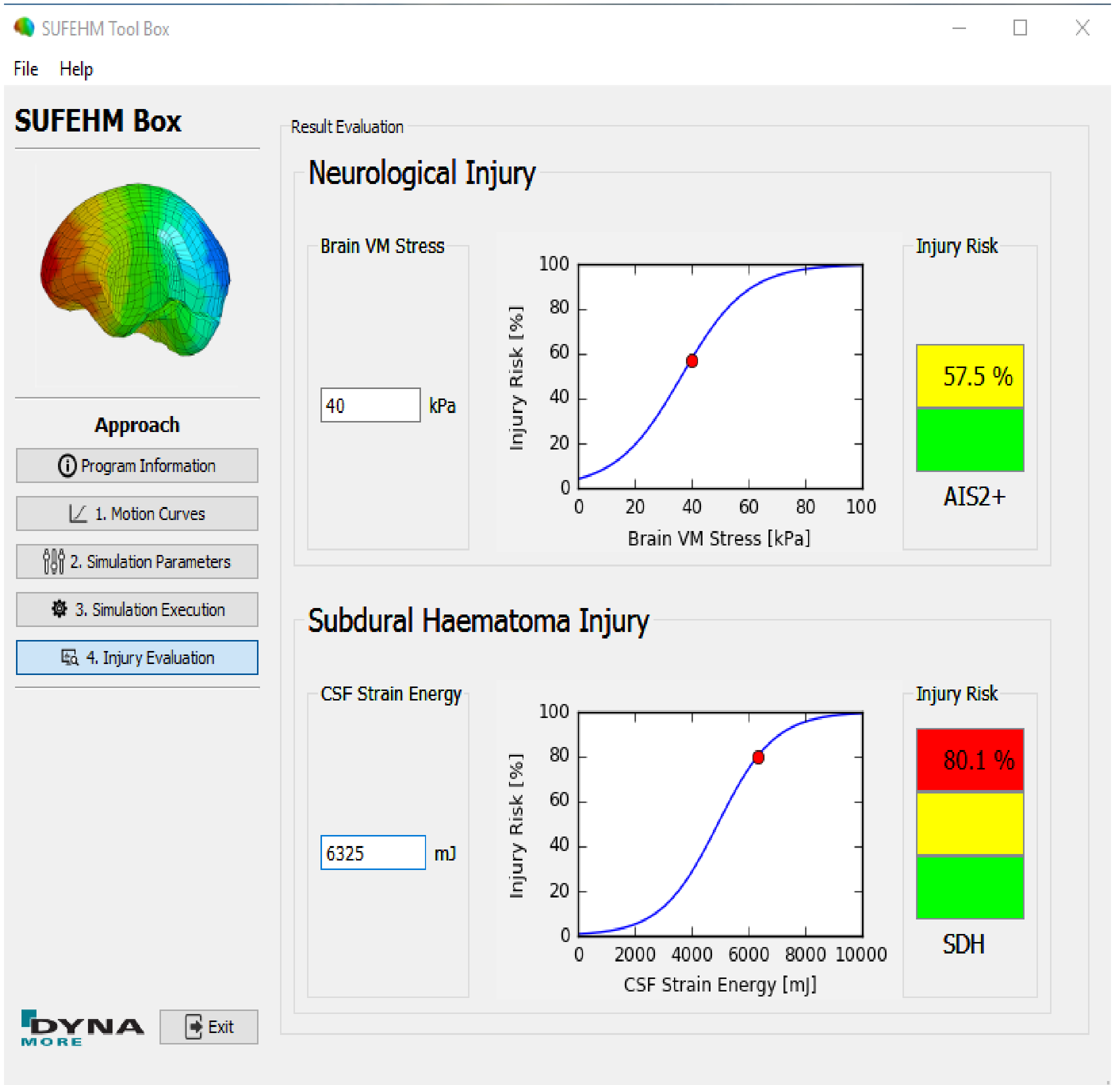
Computation of SUFEHM criteria via WEB simulation



STEP 1. IMPLEMENTATION OF LOADING CURVES



STEP 4. INJURY RISK ASSESSMENT

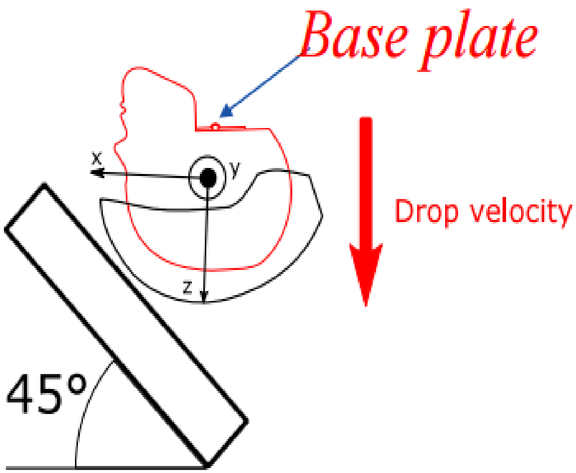


HEAD PROTECTIVE SYSTEMS EVALUATION & OPTIMISATION

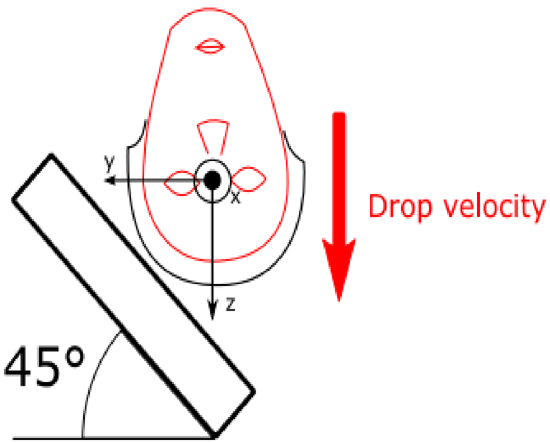
HELMET CONSUMER TESTS: TOWARDS NEW HELMET STANDARDS

Tangential Test Method (CEN TC158)

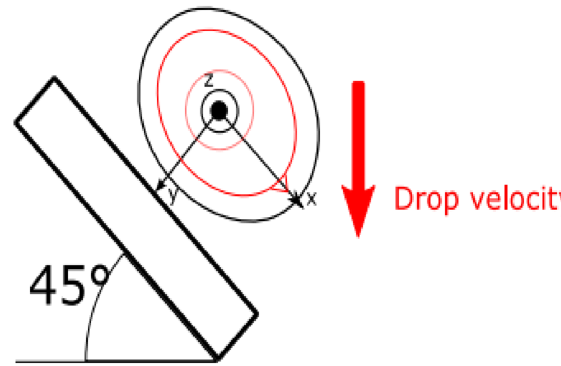
Three tangential impacts at 6.5 m/s



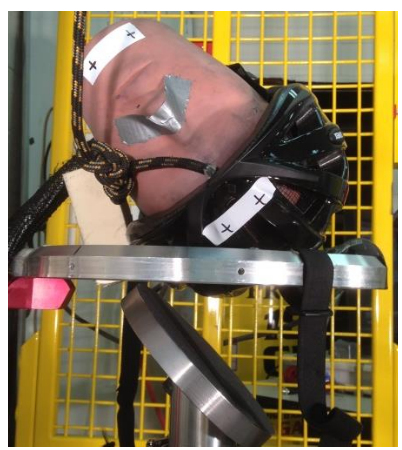
Front_y



Lat_x



Lat_z



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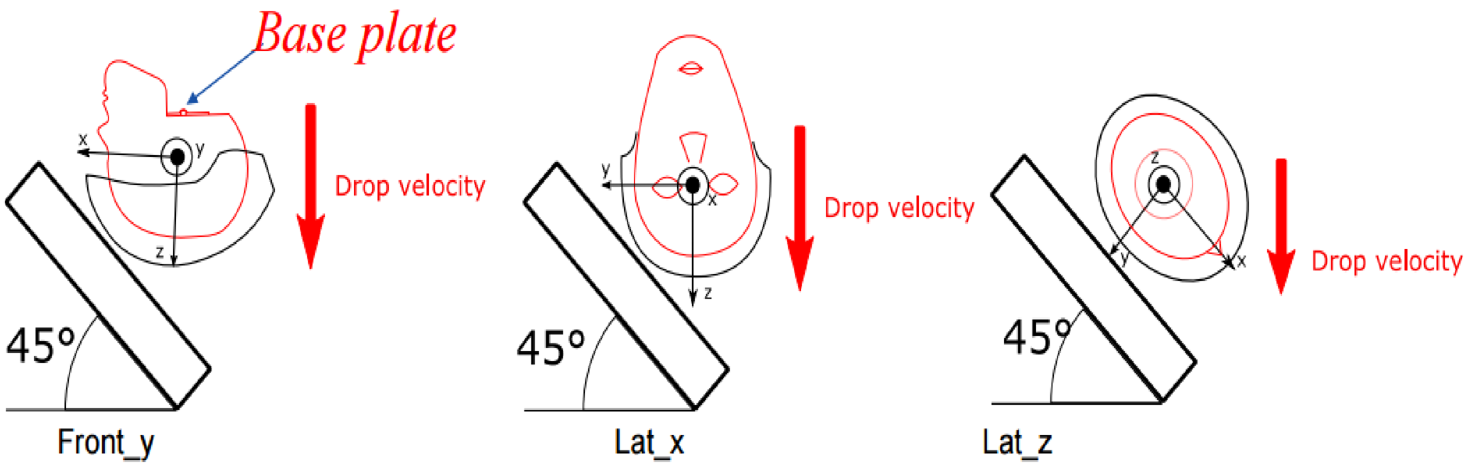
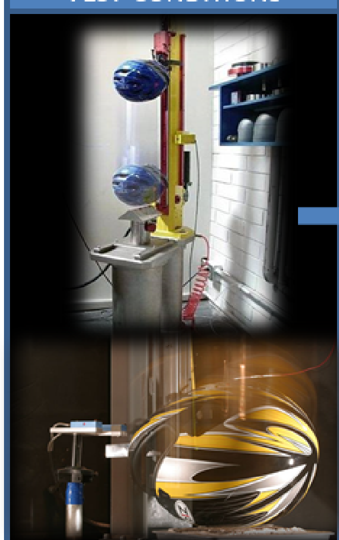
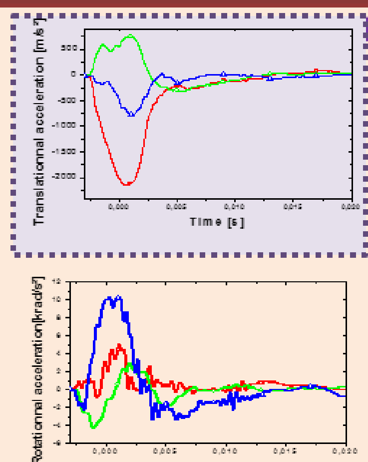
Tangential Test Method (CEN TC158)



Test conditions



Linear and Rotational Accelerations

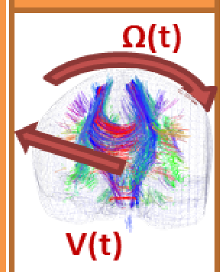


Standard parameter

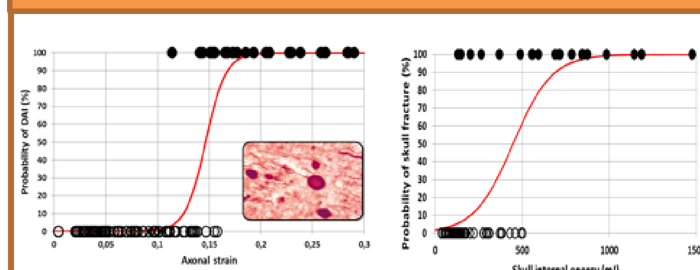
$$HIC = (t_2 - t_1)\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)\,dt\right]^{2.5}$$

Improved Model based Head Injury Criteria

SUFEHM



Injury risk assessment



HELMET CONSUMER TESTS IN FRANCE

Journal title:

60 Millions de consomateurs (F)
August 2015

12 moto helmets evaluated
based on SUFEHM criteria

ESSAI | ÉQUIPEMENT & LOISIRS

+++ Très bon 20 à 17
++ Bon 16,5 à 13
+ Acceptable 12,5 à 10
− Insuffisant 9,5 à 7
−− Très insuffisant 6,5 à 0

	SHOEI [illegible]	HJC FG-17	ARAI AXCES I	SCHUBERTH S2	CABERG EGO
Prix indicatif	465 €	190 €	380 à 430 €	400 à 450 €	180 à 200 €
Prix écran seul	59 €	43 €	60 €	72 €	31 €
Matériau de la coque	Fibre de verre	Fibre de verre	Fibres composites	Fibre de verre	Polycarbonate
Poids mesuré, taille M	1,45 kg	1,40 kg	1,55 kg	1,45 kg	1,55 kg
Poids mesuré, taille XL	1,50 kg	1,50 kg	1,65 kg	1,55 kg	1,60 kg
Nombre de calottes externes	3	2	1	2	1
Jugulaire	Crémaillère	Double anneaux	Double anneaux	Crémaillère	Crémaillère
Pare-soleil	Oui	Non	Non	Oui	Oui
Antibuée Pinlock	Oui	Oui	Non[1]	Oui	Oui
Absorption des chocs (40 %)	+++	+++	+++	++	++
Aptitudes routières (36 %)	+++	++	++	+++	++
Confort	+++	+++	+++	+++	++
Maintien	+++	+++	++	+++	+
Champ de vision	++	+++	+++	++	+++
Manipulation écran/pare-soleil	+++	+	−	+++	+++
Efficacité de la ventilation	++	+++	+++	+++	++
Étanchéité du casque	++	+	+	+	++
Isolation phonique (18 %)	++	+	−	++	+
Pressions acoustiques à 90/130 km/h	90/98 dB(A)	93/100 dB(A)	93/102 dB(A)	89/98 dB(A)	92/100 dB(A)
Entretien (6 %)	+++	+++	+	+++	++
Dépose écran	+++	+++	++	+++	+++
Dépose pare-soleil	+++		–	+++	++
Dépose garniture intérieure	+++	+++	+	++	+++
Documentation	+++	+++	−	+++	+
Note globale (100 %)[3]	**17/20**	**16,5/20**	**15,5/20**	**13/20**	**13/20**

(1) Pas de Pinlock fourni, alors que l'on note la présence de trous de fixation. (2) Traitement de l'écran antibuée. (3) La note globale [illegible]

Le critère de la sécurité avant tout

Nous avons sélectionné douze références de casques intégraux. Les prix annoncés correspondent à ces casques de couleur noire, la moins chère avec le blanc. Les habillages sont susceptibles de faire grimper l'addition.
Le matériau de la coque est mentionné, mais on ne peut pas en faire un critère de choix. Les fibres de verre ou composites sont plutôt dans le haut du tableau. Mais cette constatation ne vaut pas généralité en matière de résistance au choc. Celle-ci dépend de l'ensemble de la construction du casque, avec tous ses composants. Le matériau de la coque a sans doute son importance, mais il n'est pas suffisant aujourd'hui pour choisir un casque qui protégerait mieux.

Des poids et volumes très variables

Il faut rappeler que rien ne remplace un essayage pour faire son choix. Mieux vaut donc se rendre en magasin pour acheter son casque.

→ **Les poids annoncés** sont parfois éloignés du résultat de la pesée. On constate par ailleurs qu'il peut y avoir facilement 100 g d'écart entre deux casques de même taille. Mais en pratique, il n'est pas sûr que l'utilisateur perçoive la différence lorsqu'il les essaie.

→ **Le nombre de calottes externes** correspond au nombre de moules utilisés par le fabricant pour proposer des tailles différentes. S'il ne dispose que d'une calotte externe, il va jouer sur le remplissage pour faire varier la taille. Cela ne sera pas neutre en termes de volume et de poids. S'il en possède plusieurs, le casque de petite taille pourra être moins volumineux.

→ **Le traitement antibuée mérite une attention particulière.** De multiples traitements ou systèmes existent, parmi lesquels la lentille Pinlock qui se distingue aujourd'hui. Cette lentille en plastique souple s'applique à l'intérieur de l'écran et permet d'drainer les

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HELMET CONSUMER TESTS IN GERMANY

Journal title:

Stiftung Warentest
August 2015

18 bicy. helmets evaluated
based on SUFEHM criteria

Melon
70 Euro
GUT (2,4)

Testsieger. Gute Stoßdämpfung. Die Belüftung funktioniert akzeptabel. Guter Magnetverschluss. Nachts nicht gut sichtbar. Etliche Designvarianten.

KED
80 Euro
GUT (2,5)

Bester Sportlicher. Gute Stoßdämpfung. Gut belüftet. Vielseitig. Mäßige Abstreifsicherheit. Gut in der Handhabung. Riemen verstellen sich recht leicht beim Transport.

Nutcase
80 Euro
GUT (2,5)

Recht schwer. Gute Stoßdämpfung. Schränkt das Sichtfeld ein. Mäßige Belüftung. Guter Magnetverschluss. Nachts gut sichtbar. Etliche Designvarianten.

Alpina E-Helm
115 Euro
BEFRIEDIGEND (2,6)

Luftiger Helm. Kopfband kann am Hinterkopf drücken. Sehr guter Verschluss. Bestnoten beim Anpassen, Aufsetzen und Absetzen. Sehr gut im Dunkeln erkennbar.

Specialized
65 Euro
BEFRIEDIGEND (2,6)

Sportlich leicht. Kein Netz zum Schutz vor Insekten, dafür gute Belüftung. Bester im Test in Handhabung und Komfort. Nachts sehr gut sichtbar.

Uvex City v
120 Euro
BEFRIEDIGEND (2,6)

Neuheit. Schwerer Cityhelm mit Visier gegen Wind und Sonne. Reicht tief in die Stirn, was die Sicht beeinträchtigt. Nachts sehr gut sichtbar.

Bell
70 Euro
BEFRIEDIGEND (2,7)

Sportlich luftig. Helm mit großen Luftlöchern und Rundum-Insektenschutz. Gute Passform. Zu lange Kinnriemen. Nachts sehr gut sichtbar.

Uvex i-vo cc
70 Euro
BEFRIEDIGEND (2,7)

Sportlich leicht. Sehr gute Passform. Kopfband rutscht beim Festdrehen etwas nach oben. Riemenversteller schwergängig. Im Dunkeln nicht gut erkennbar.

Abus Hyban
49 Euro
BEFRIEDIGEND (2,8)

Gut sichtbar. Cityhelm mit guter Belüftung. Gute Passform, einfach zu handhaben. Bei Nacht gut erkennbar durch Licht auf der Rückseite und Reflektoren.

test Fahrradhelme

Gewichtung		Melon Urban Active	KED Crom	Nutcase Street Gen3	Alpina E-Helm Deluxe	Specialized Centro	Uvex City v	Bell Muni[1]
Mittlerer Preis ca. (Euro)		70	80	80	115	65	120	70
test-QUALITÄTSURTEIL	100 %	GUT (2,4)	GUT (2,5)	GUT (2,5)	BEFRIEDIGEND (2,6)	BEFRIEDIGEND (2,6)	BEFRIEDIGEND (2,6)	BEFRIEDIGEND (2,7)
UNFALLSCHUTZ	50 %	befried. (2,6)	befried. (2,8)*)	gut (2,5)	befried. (2,3)*)	befried. (2,3)*)	befried. (2,5)	befried. (2,9)
Stoßdämpfung / Erweiterte Stoßprüfung		+/○	+/○	+/○	○/○	○/○	○/⊖	○/⊖*)
Abstreifsicherheit / Belastbarkeit Riemen, Schloss		○/+	⊖/+	○/+	+/○	○/+	+/○	+/+
Erkennbarkeit im Dunkeln		⊖	○	+	++	++	++	++
HANDHABUNG, KOMFORT	30 %	befried. (2,8)	gut (1,5)	befried. (3,1)	gut (1,8)	sehr gut (1,3)	befried. (2,0)	gut (1,8)
Gebrauchsanleitung		⊖*)	++	+	++	+	++	+
Anpassen / Aufsetzen / Absetzen		○/+/++	+/+/++	○/+/++	++/++/++	++/++/++	+/+/++	++/++/++
Verstellen des Gurtsystems beim Transport		++	○	⊖	++	++	++	++
Tragekomfort: Passform / Kinnriemen und Verschluss		+/+	++/++	+/++	+/+	++/++	○/+	+/○
Sichtfeld / Belüftung		++/○	++/+	−/⊖*)	++/+	++/+	−/⊖*)	++/○
HITZEBESTÄNDIGKEIT	10 %	gut (1,5)	befried. (2,6)	gut (1,6)	gut (2,0)	gut (1,6)	gut (2,5)	sehr gut (1,4)
SCHADSTOFFE	10 %	sehr gut (1,0)	befried. (2,5)	sehr gut (1,0)	sehr gut (1,0)	sehr gut (1,0)	sehr gut (1,0)	sehr gut (1,5)
AUSSTATTUNG / TECHNISCHE MERKMALE								
Konstruktion / Verschlusstyp		Micro Shell / Magnet	Micro Shell / Raster	Hartschale / Magnet	Micro Shell / Raster	Micro Shell / Klick	Hartschale / Raster	Micro Shell / Raster
Angebotene Größen / Verstellbereich (cm)[1]		3 / 46–53	1 / 52–58	3 / 52–64	2 / 55–61	1 / 54–62	2 / 55–61	2 / 50–61
Gewicht (mittlere Helmgröße) (g)		291	313	473	327	289	490 (mit Visier)	[illegible]
Reflektoren / Licht / Schirm / Insektenschutz / Regenkappe		□/□/□/□/□	□/■/■/■/□	■/□/■/□/□	■/■/■/■/■	■/□/■/□/□	■/□/□/■/□	■/□/■/■/□

Bewertungsschlüssel der Prüfergebnisse:
++ = Sehr gut (0,5–1,5). + = Gut (1,6–2,5). ○ = Befriedigend (2,6–3,5). ⊖ = Ausreichend (3,6–4,5). − = Mangelhaft (4,6–5,5).

Bei gleichem Qualitätsurteil Reihenfolge nach Alphabet.
*) Führt zur Abwertung (siehe „So haben wir getestet" auf Seite 79).
■ = Ja. □ = Nein.

Micro Shell = Dünne feste Kunststoffschale über dem Helmkern aus Styropor.

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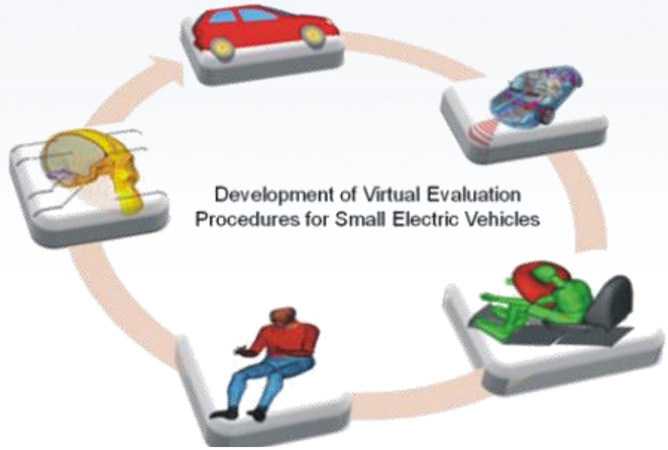
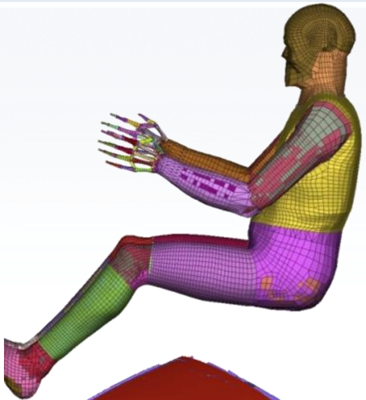
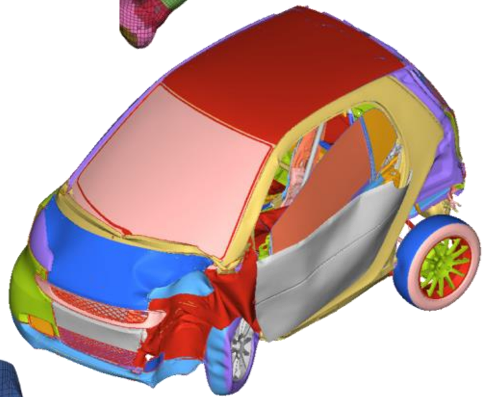
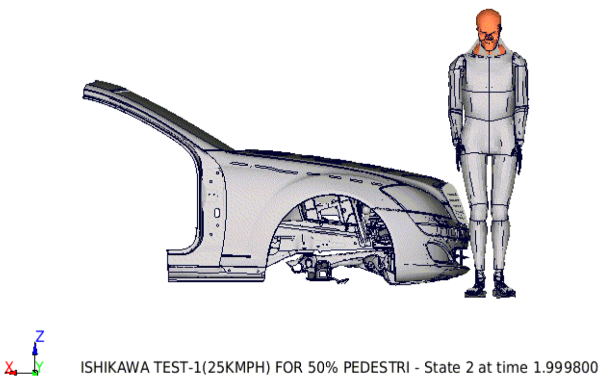
Pedestrian and passager Protection

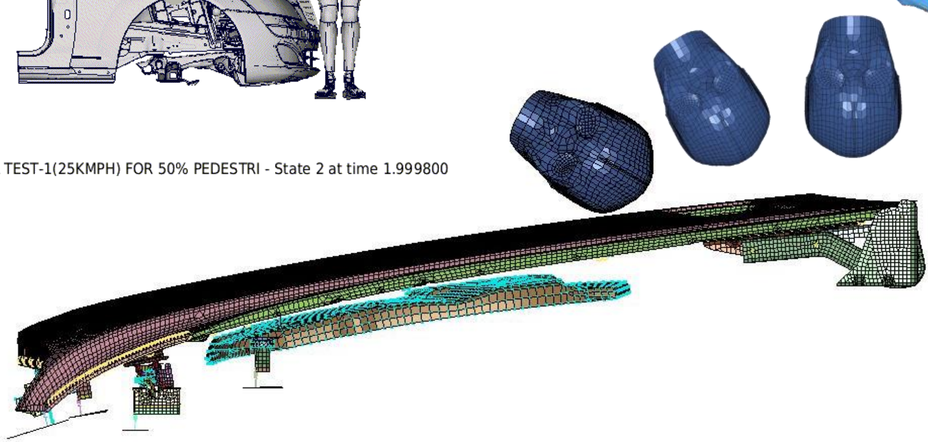
VIRTUAL TESTING IN AUTOMOTIVE ENVIRONMENT



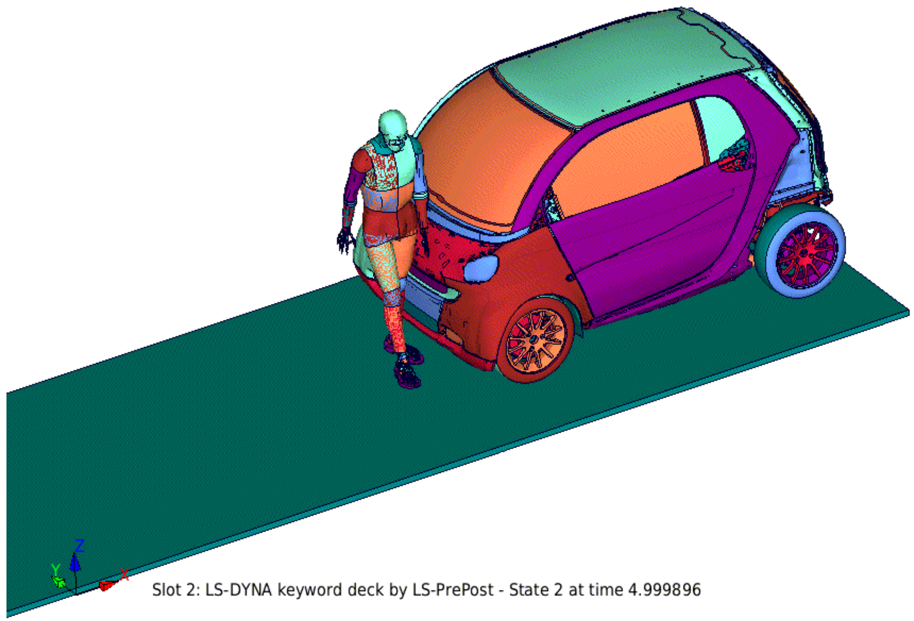


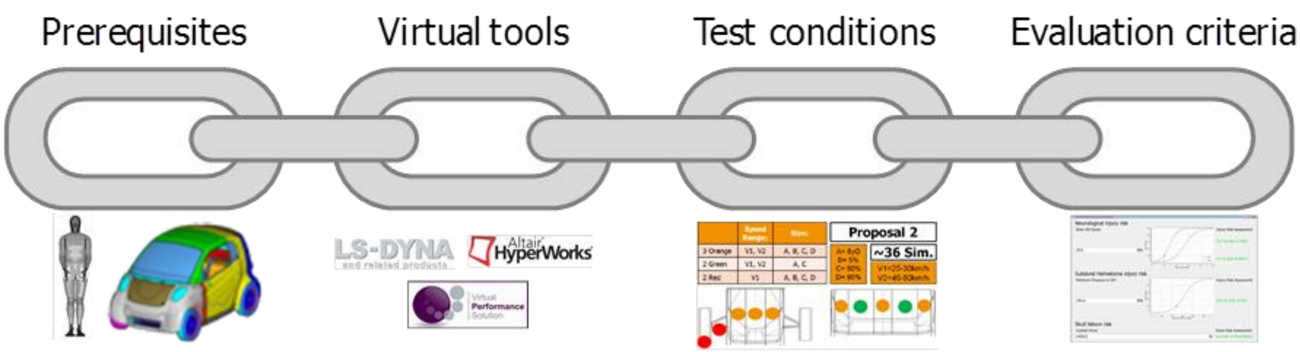






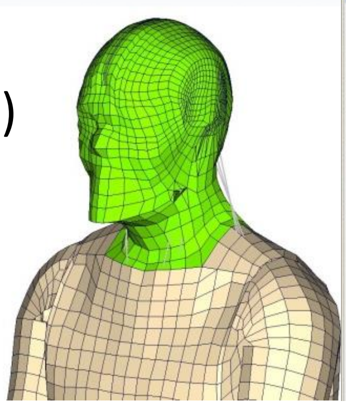
Safe-EV project
Pedestrian Passive Safety

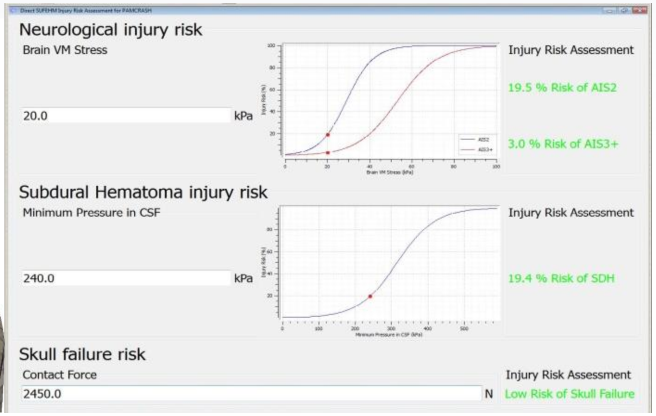




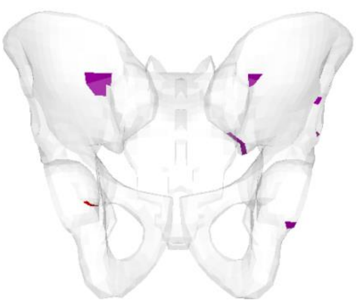
OVERVIEW OF ASSESSMENTS

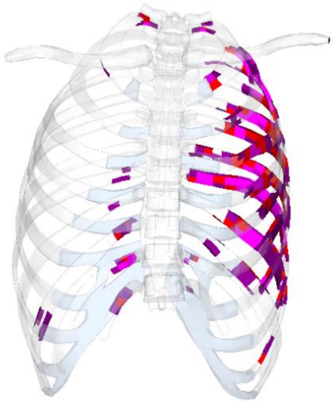
- Assessment of head injury risk
  (using SUFEHM –IRA tool under VPS)



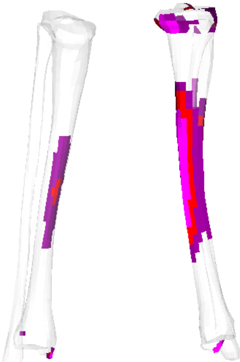


- Further possible injury risk indicators (based on max. pl. strain analysis)
  - ribs





- tibia/fibula and femur



Evaluation against biomechanical injuries

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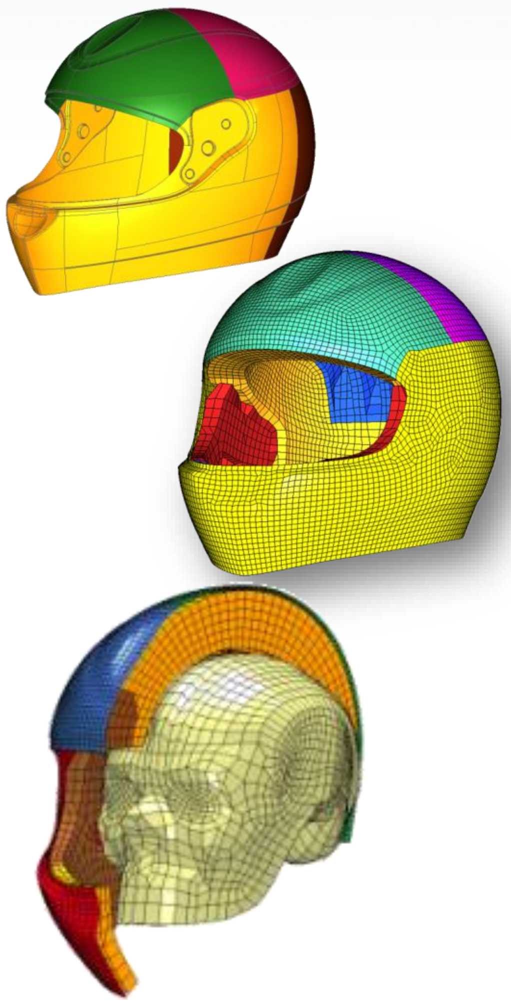
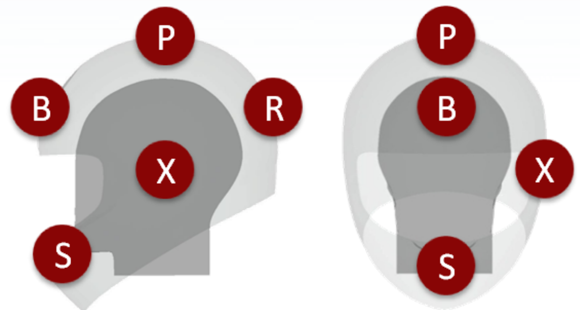
Development of helmet FEM and coupling with SUFEHM



ECE R022 standard

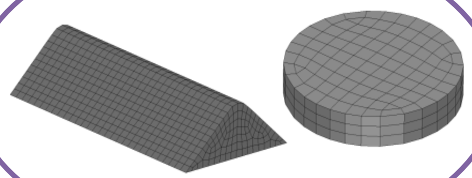
Localisation points impacts



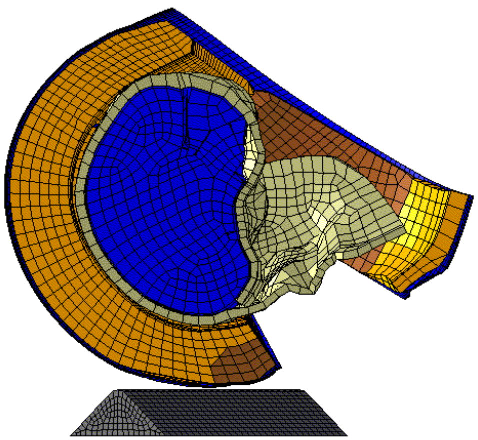
Vitesses d'impact

7.5 m/s pour les points B, P, R et X
5.5 m/s pour le point S

2 enclumes

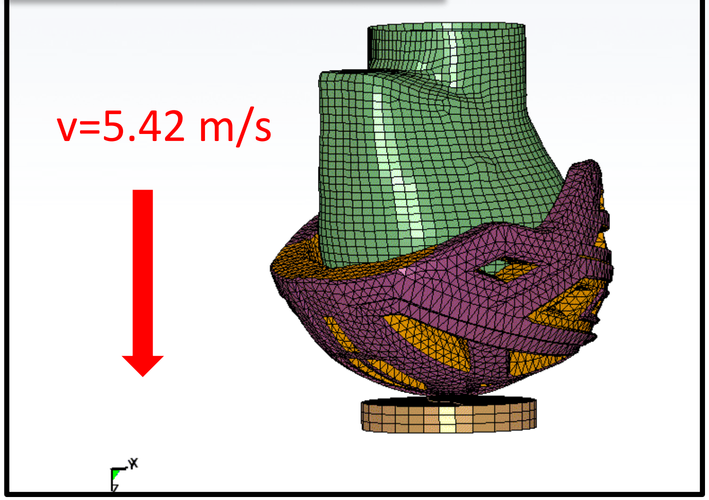


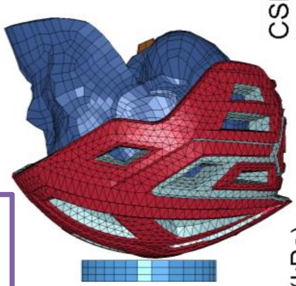
Injury riks evaluation with SUFEHM



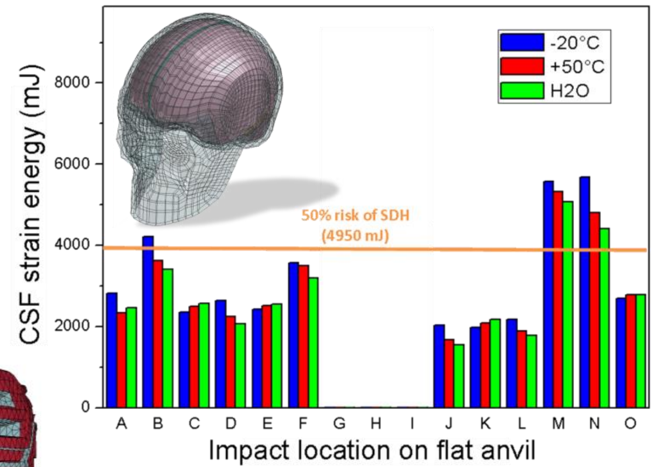
BICYCLE HELMET

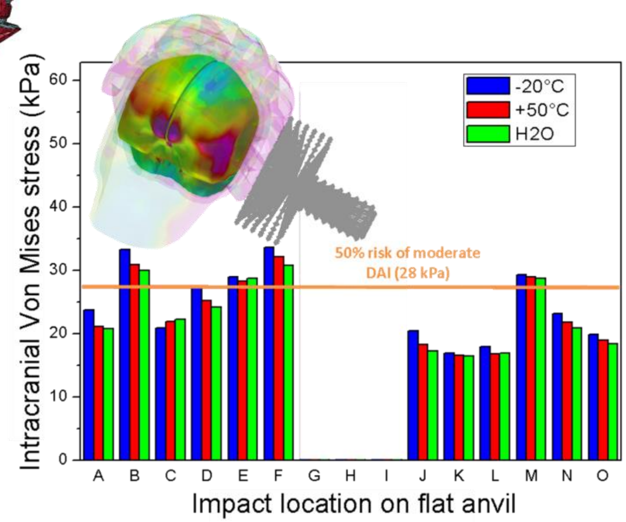
3 Validation



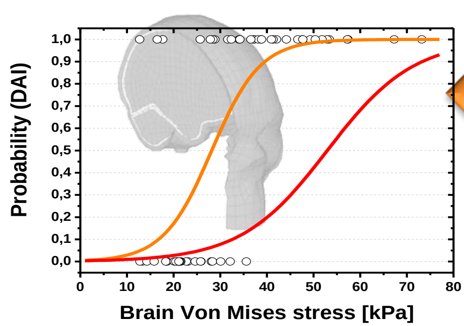


4 Head injury risks





5 Helmet optimisation against biomechanical criteria



LESS-THAN-LETHAL WEAPONS

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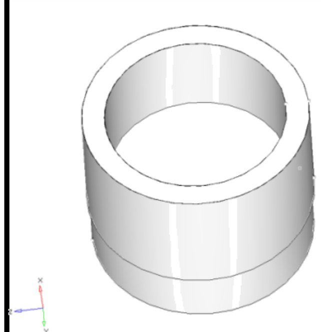
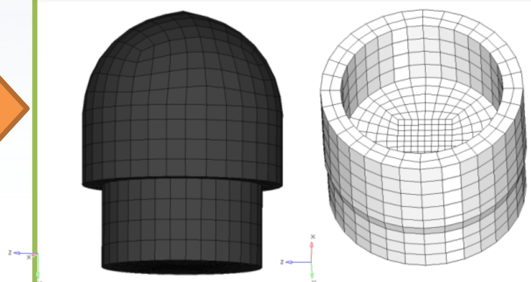
1 CAD

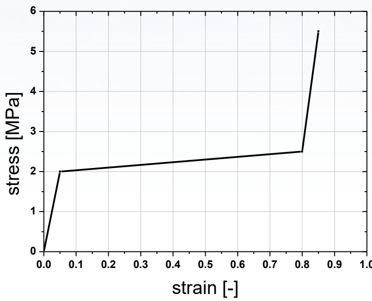


2 Meshing

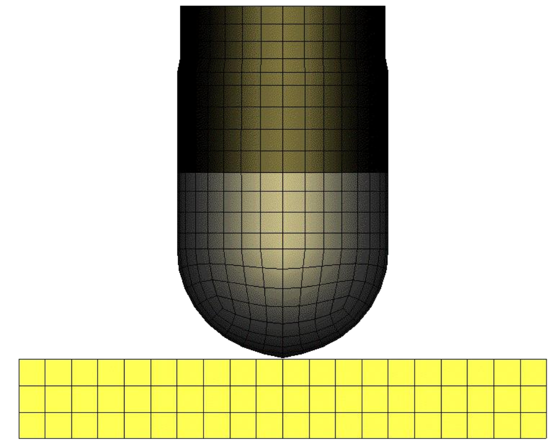


3 Mechanical properties definition

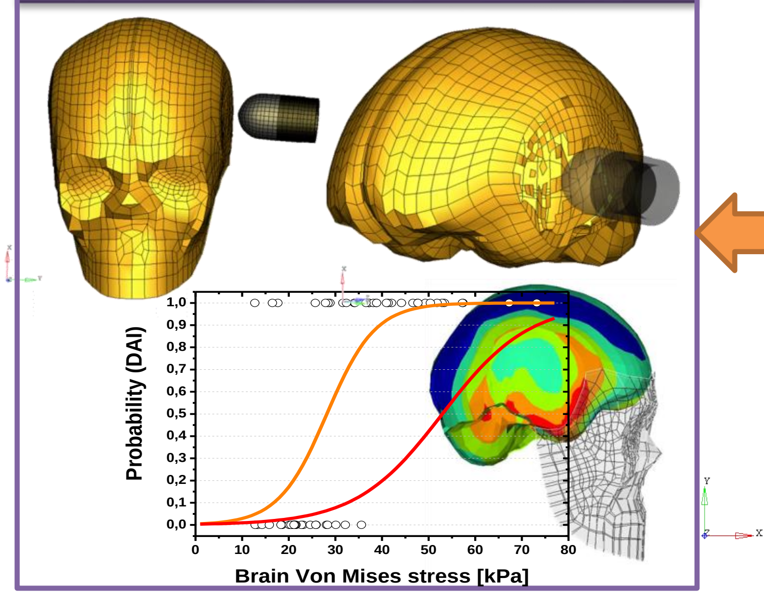
Foam description



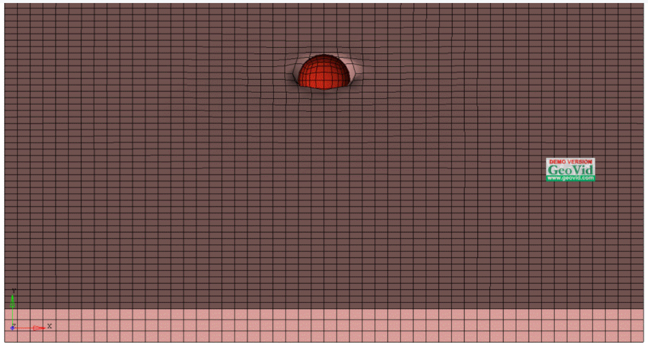
4 Validation against experimental data : Experiments on rigid wall



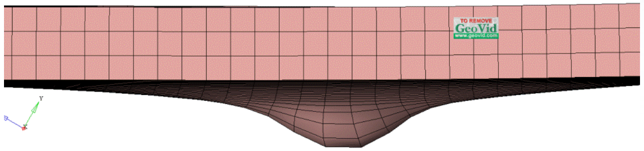
5 Evaluation of head injury risks

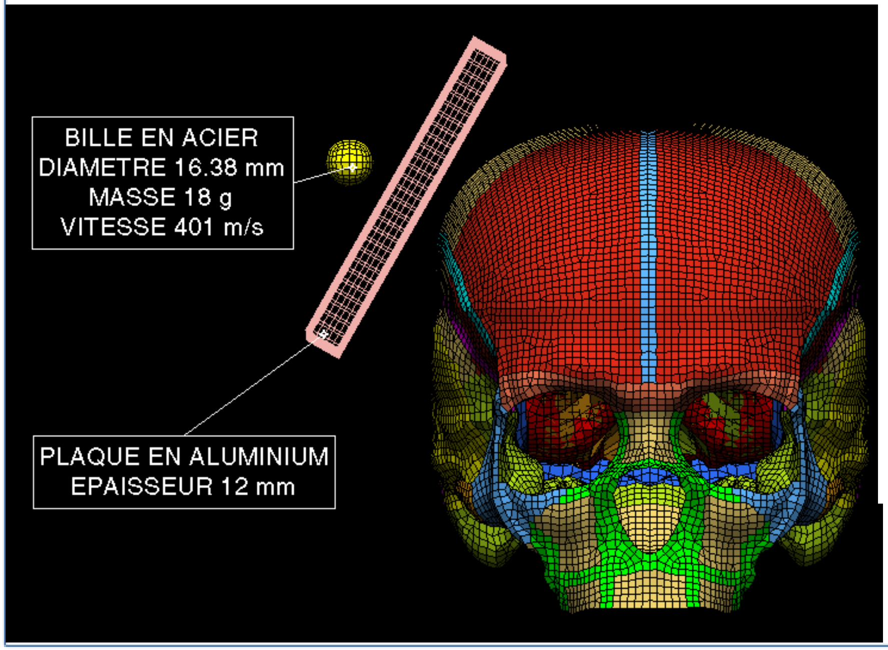


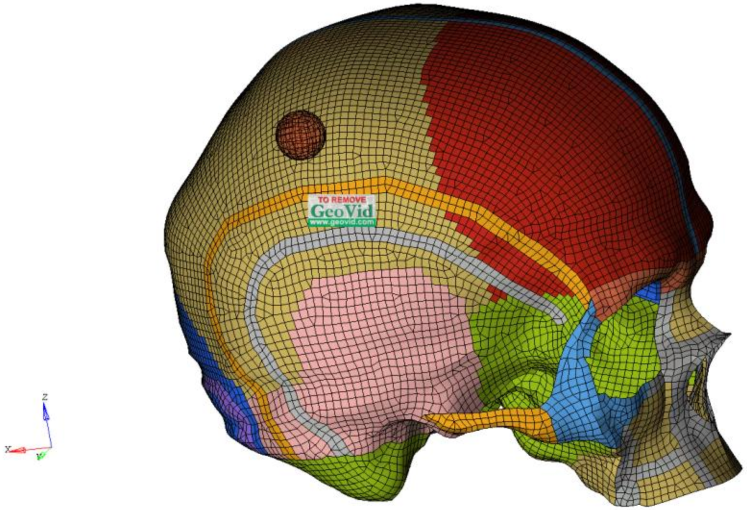
Back effect : Military helmet



VALIDATION



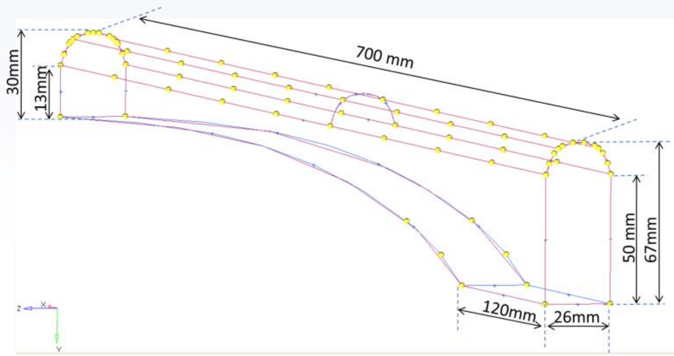


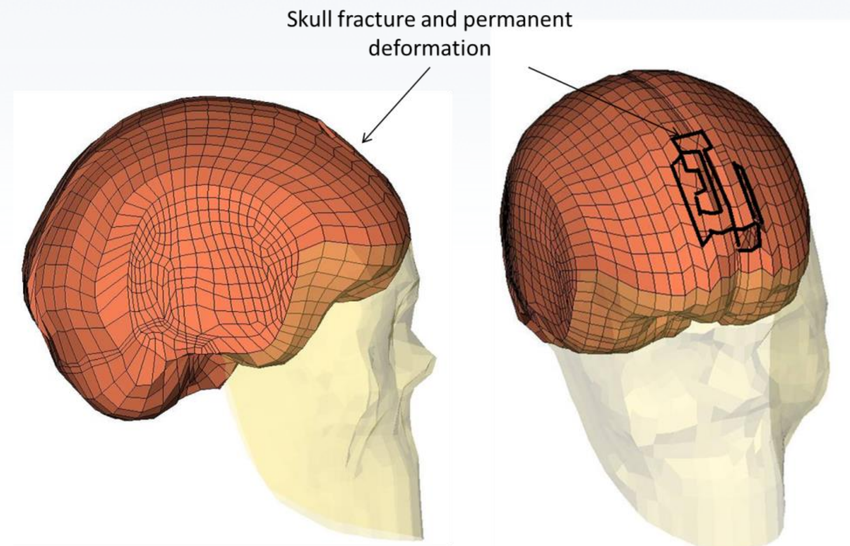


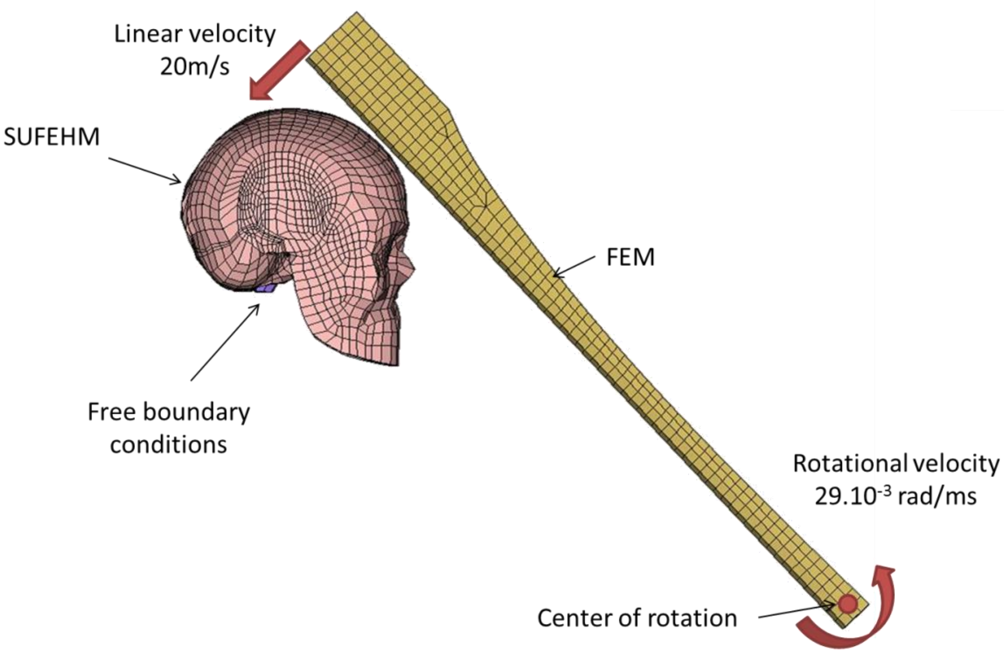
Linear and depressive skull failures prediction

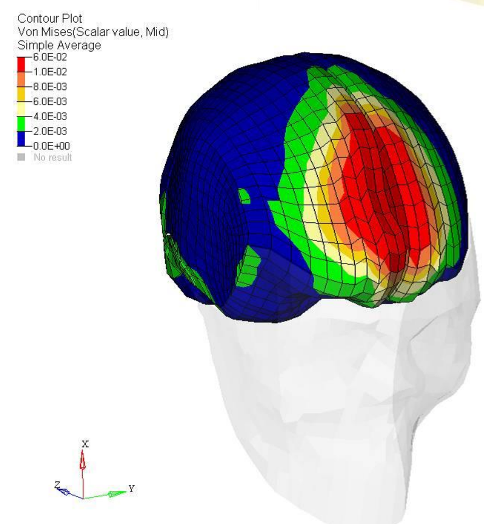
A LEGAL MEDICINE CASE

Head injury risks calculated with SUFEHM









Conclusion-Head

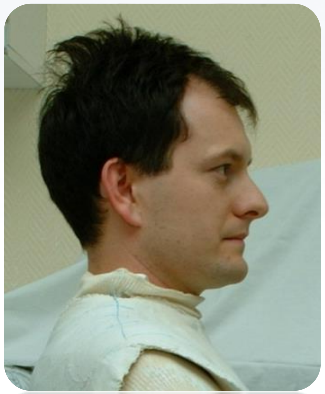
- Advanced brain FE models, Computation of axon strain
- Consolidated head trauma database with 125 cases.
- Very high Nagelkerke R^2 value (R^2=0.876) for brain injury
- Best candidate parameter for brain injury is axon strain
- The model based head injury criteria are:
- Axon strain for brain AIS2+ (ε_a= 15%)
- Skull strain energy for fracture (0.5 J)
- Head injury prediction tool for end users

77

Neck Modelling and Whiplash injury criteria

FE NECK MODEL : GEOMETRY

METHODS



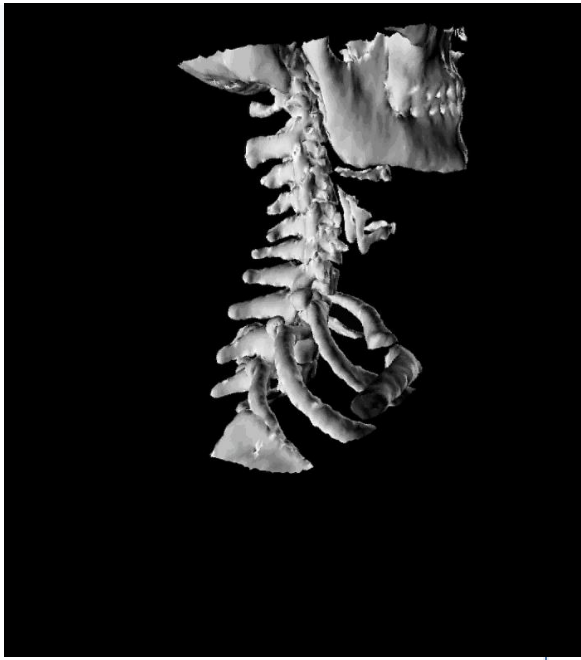
Height : 1m72 Weight : 72 Kg
Age : 33 Years (50th)

1

Millimetric scanner sections

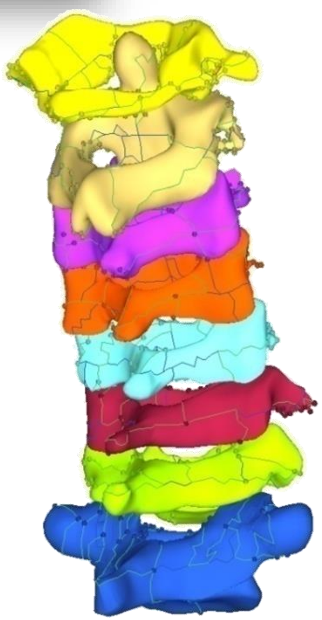
2

Stereolithographic format



3

Surface reconstruction

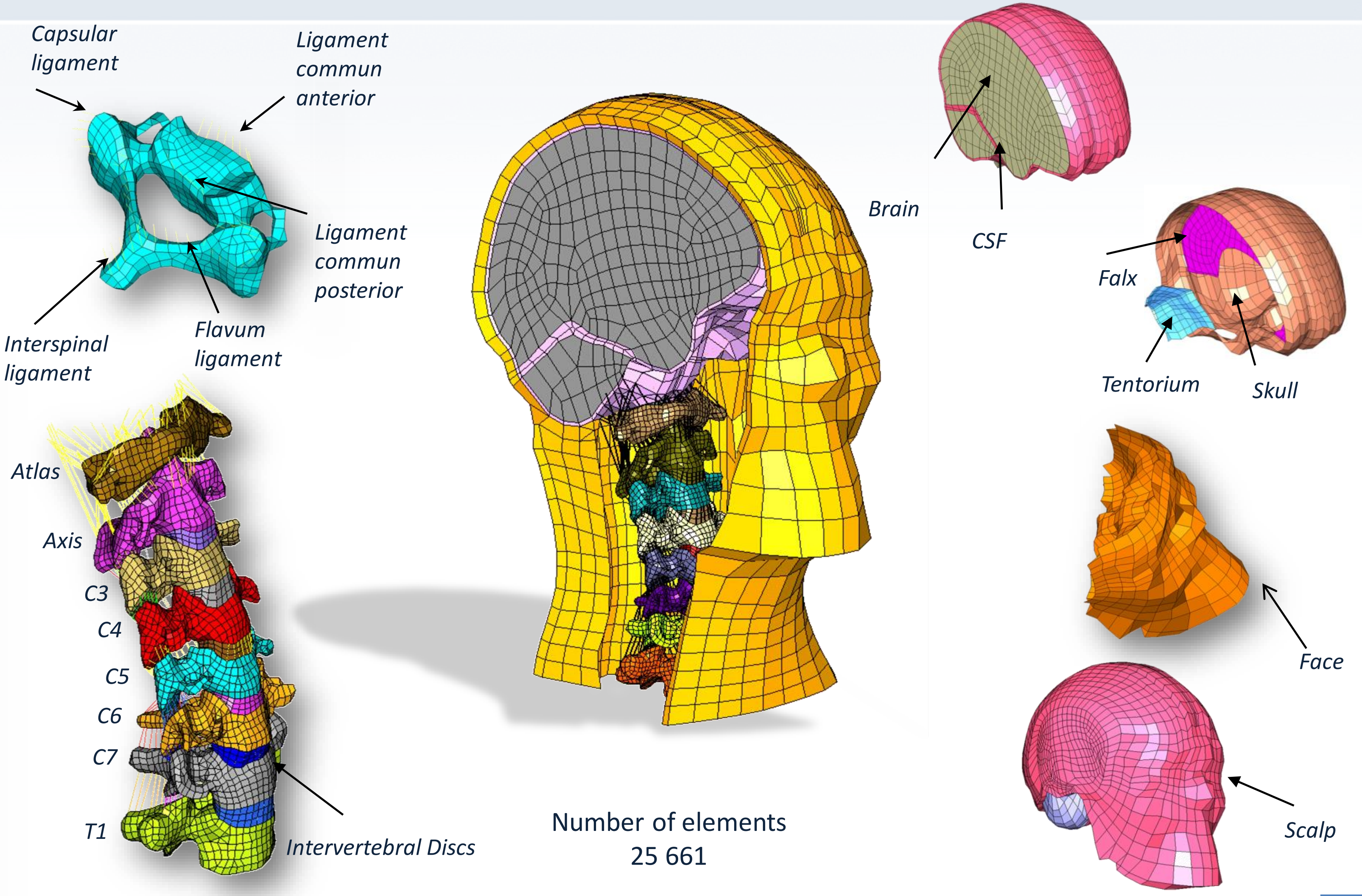


4

Meshing criteria

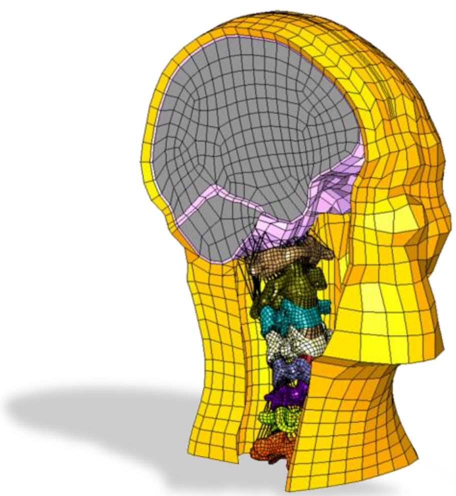
Criterion	Values
Length min	2.25 mm
Length max	3 mm
Aspect ratio	[1-2]
Warpage	[0-5]
Angle quad(°)	[70-110]
Angle Tria	[50-80]
Jacobien	[0.7-1]
% of tria	6

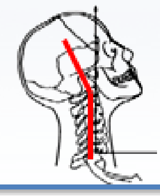
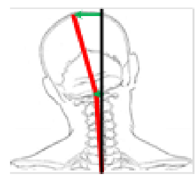
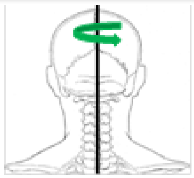
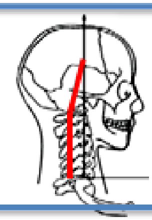
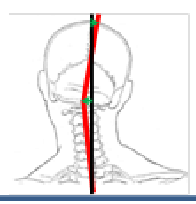
FEM OF THE HEAD-NECK SYSTEM



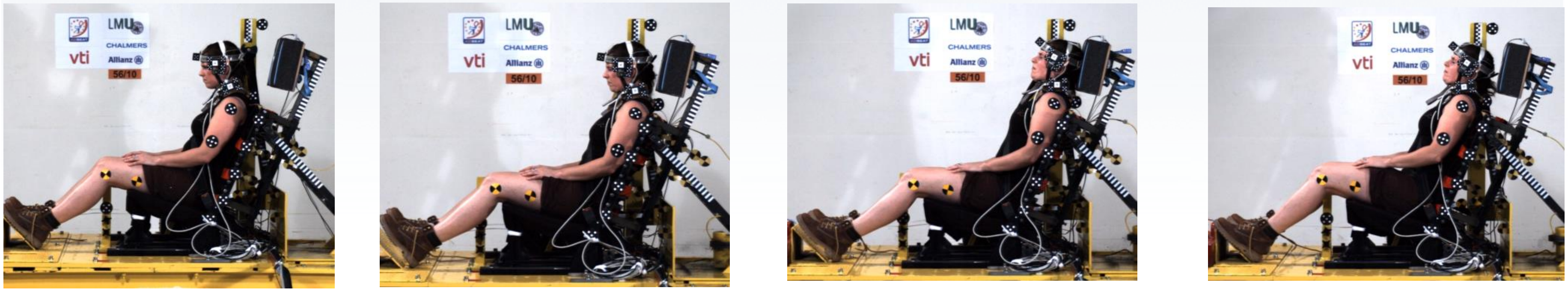
Number of elements
25 661

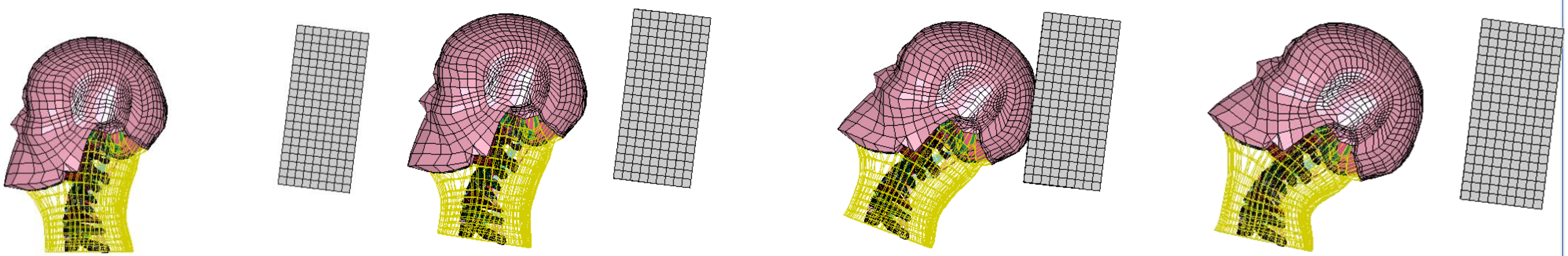
NECK FINITE ELEMENT MODEL (UNISTRA)

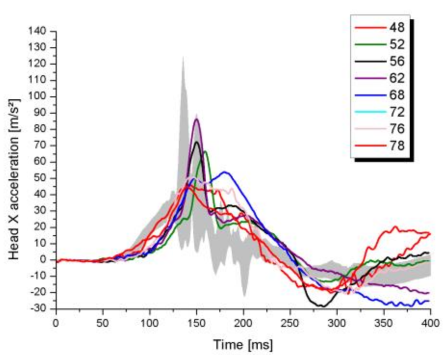


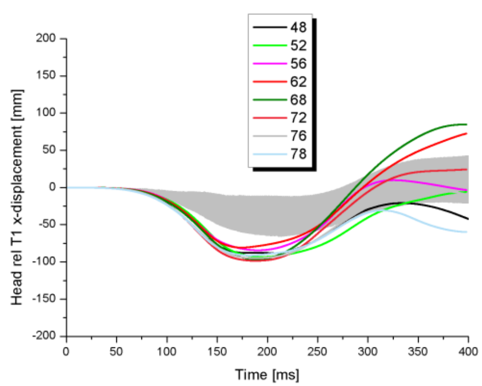
		Volunteers	UdS FEM
Flexion mode		1.6 Hz	2 Hz
Inclination mode		1.7 Hz	2.6 Hz
Coupled mode		3.7 Hz	3 Hz
S-Shape mode		8.8 Hz	11 Hz
lateral retraction mode		9.5 Hz	9.6 Hz

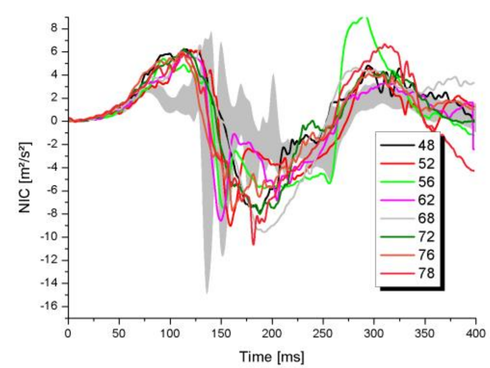
Neck Finite Element Model (UNISTRA)





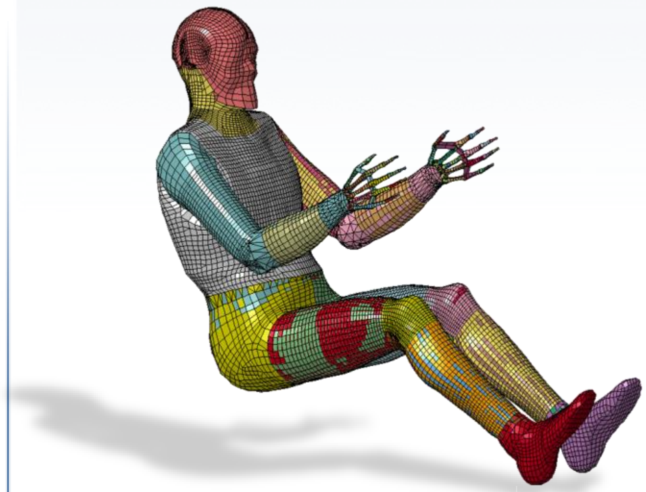


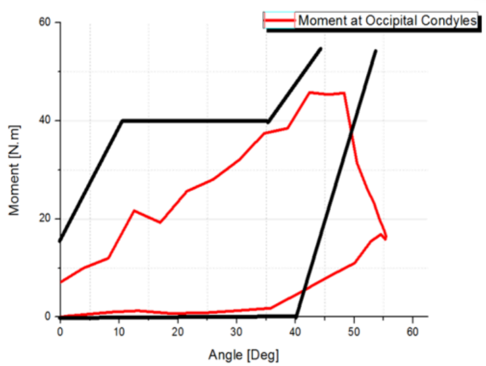




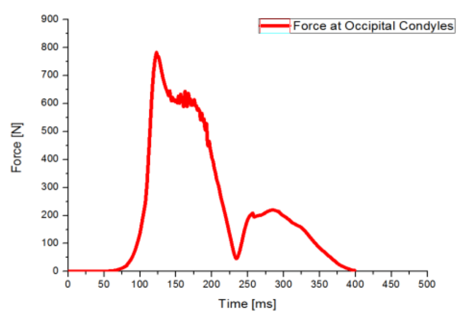
HEAD-NECK UNISTRA COUPLING

Coupling to THUMS Model (LS-Dyna)…..TUC !

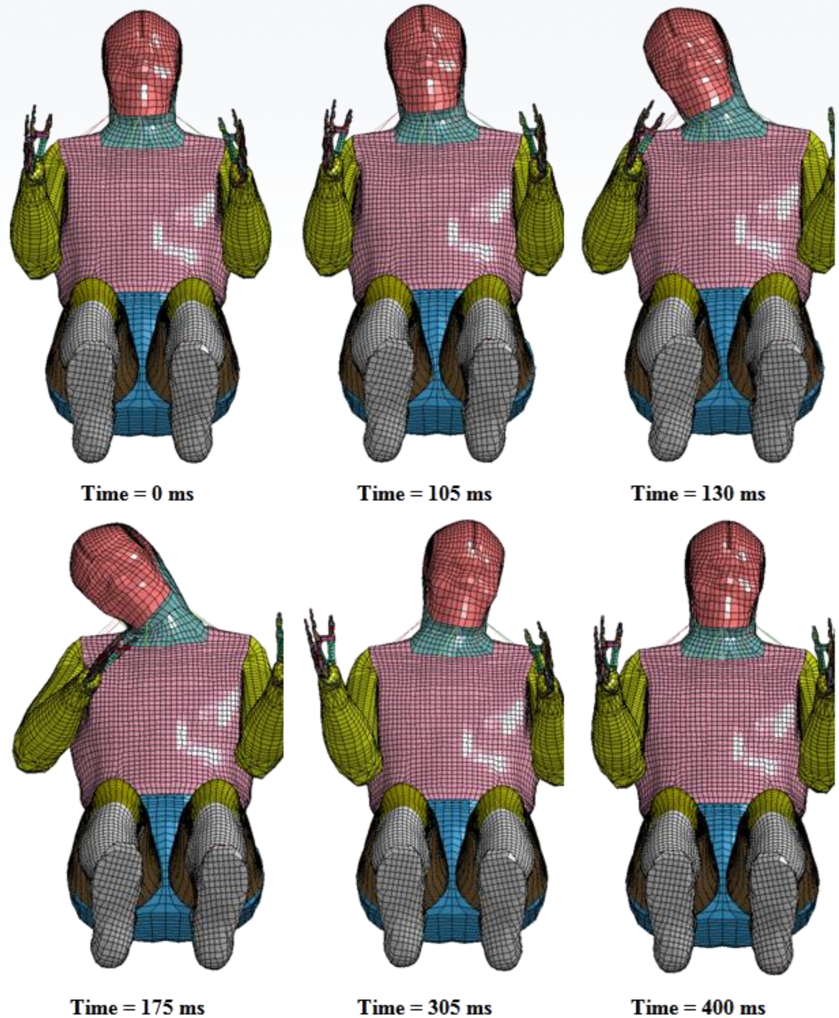




Moment at the Occipital Condyles calculated with the THUMS/Unistra-Head-Neck FEM superposed the corridor define by Patrick and Chou 1971

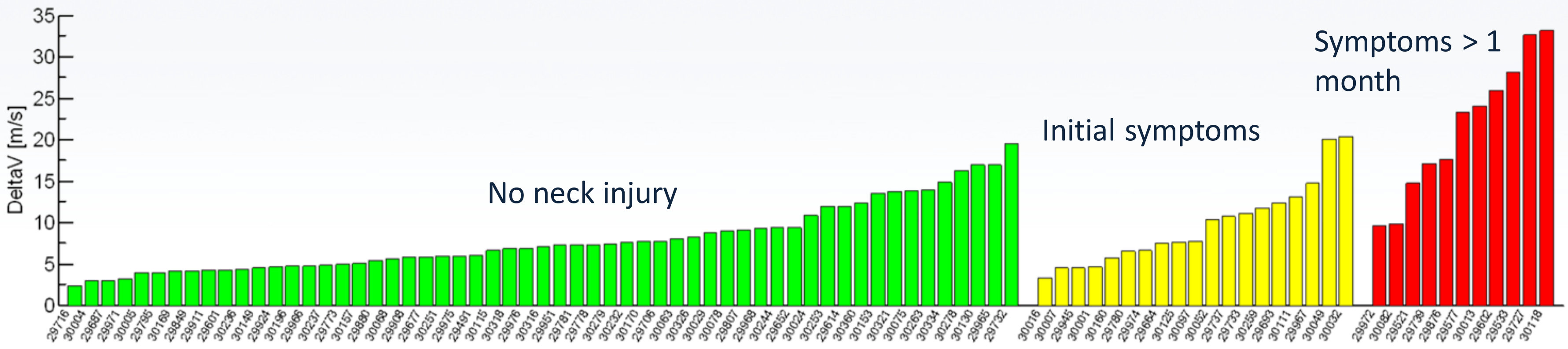


Force at the Occipital Condyles calculated with the THUMS/Unistra-Head-Neck FEM

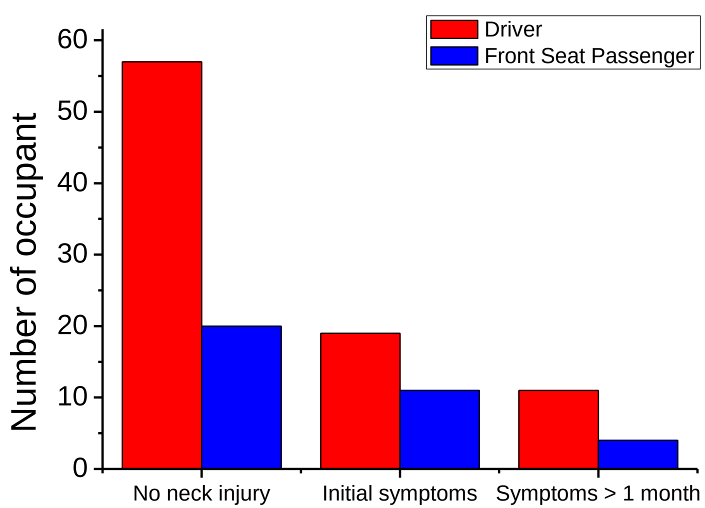


Lateral Impact (N.B.D.L) *Ewing et al. 1977*

FOLKSAM DATABASE : 87 REAR IMPACTS ACCIDENTS



Delta V of pulses versus injury severity.



=

122 accident cases :

- 77 no neck injury
- 30 initial symtoms
- 15 symptoms over than 1 month

Average age of 46 year old

METHODOLOGY

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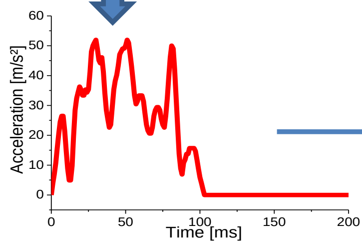
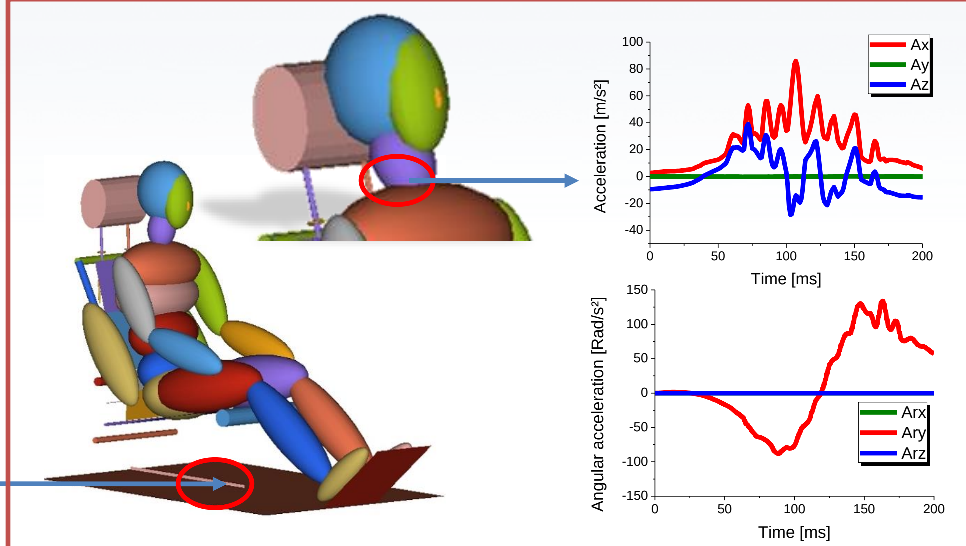
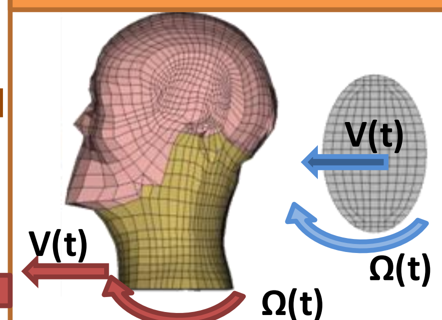
(FOLKSAM)



Linear and Angular Accelerations (T1 & headrest)

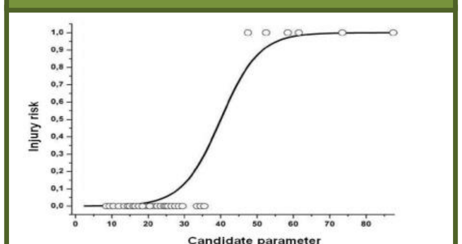


UdS MEF

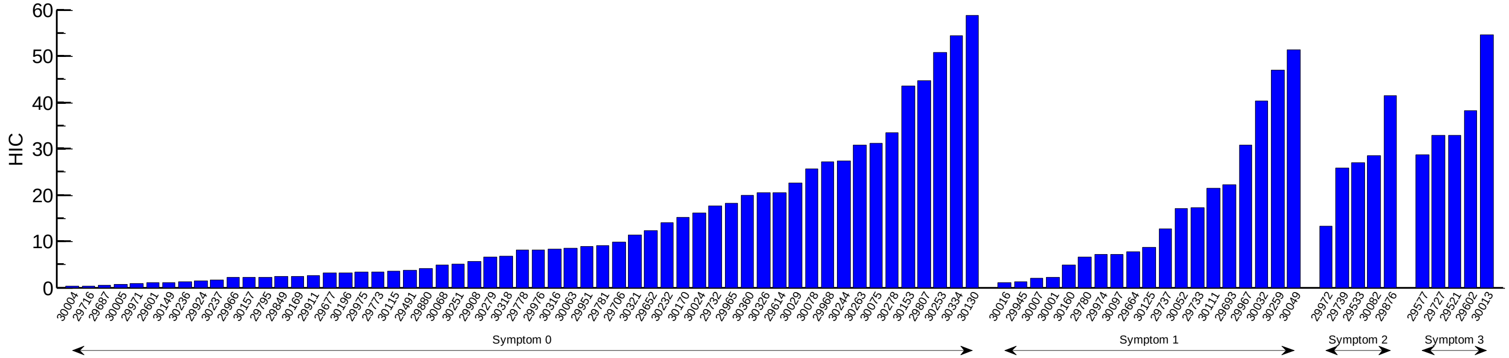


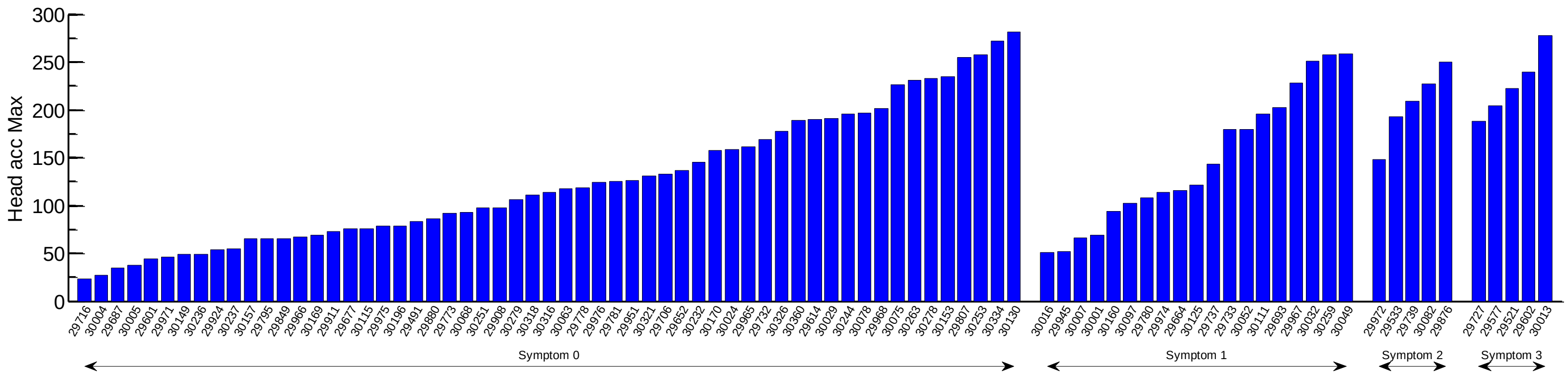
NIC, Nkm, MY, Fx,Fz

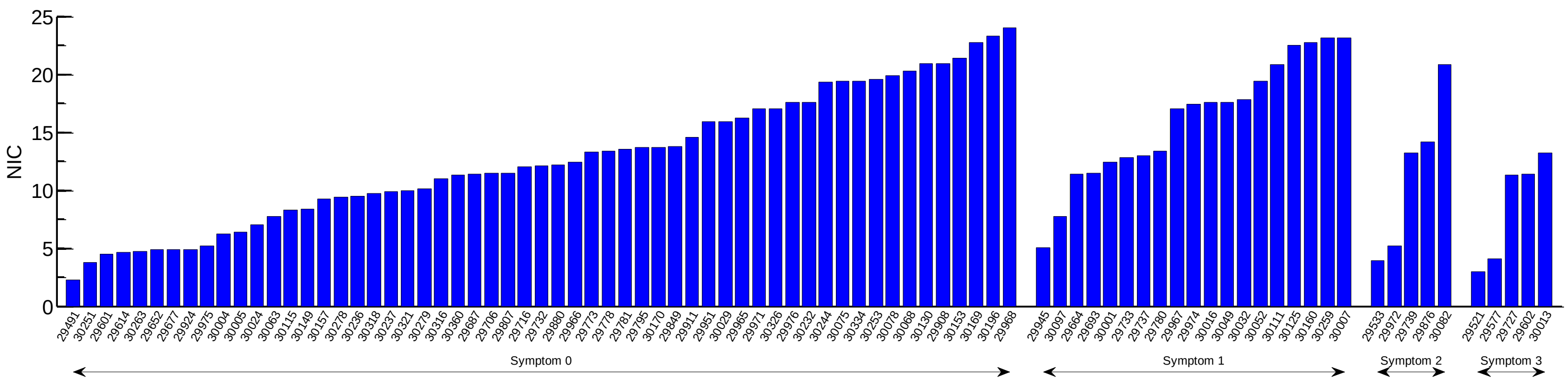
Injury risk curves/R^2 score



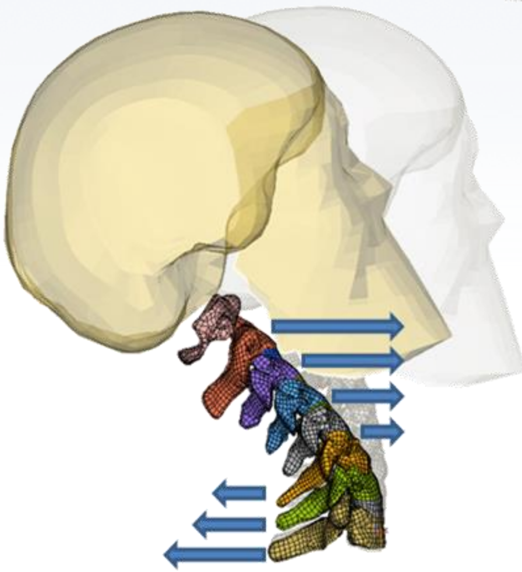
HIC, HEAD Max Acceleration, NIC

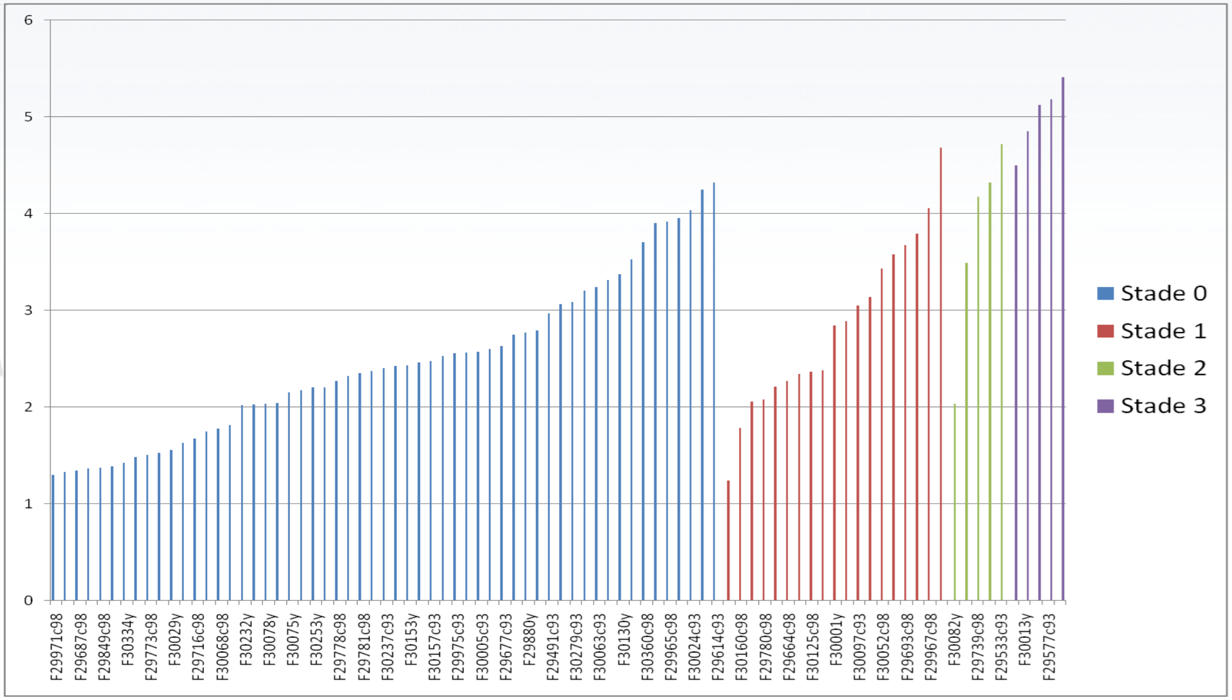






RESULTS

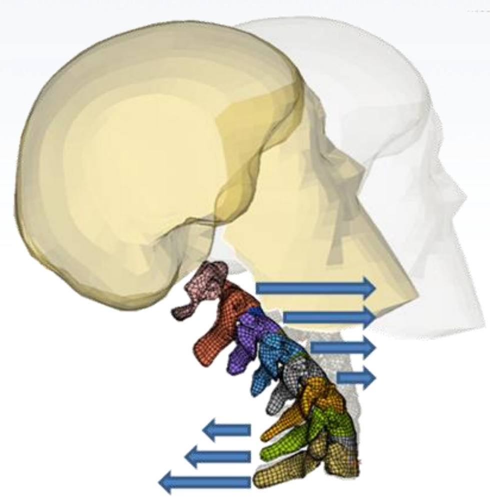




$$\sum_{i=1}^{6}|C_i - C_{i+1}|dx¶$$

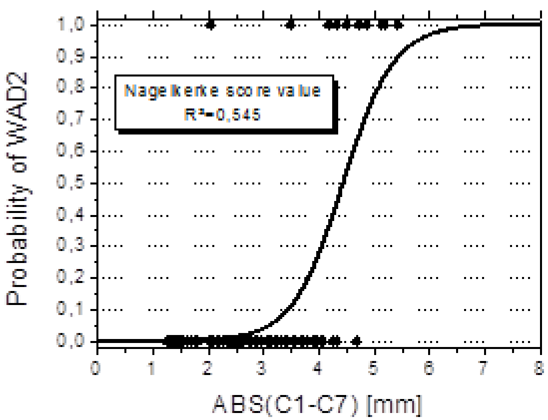
	R^2 Stade 1	R^2 Stade 2	R^2 Stade 3
NIC	**0.017**	**0.073**	**0.109**
Nkm	**0.086**	**0.324**	**0.266**
Fx upper	0.108	0.363	0.361
Fz upper	0.071	0.076	0.047
My upper	**0.127**	**0.433**	**0.495**
Abs (C1-C7)	**0.223**	**0.545**	**0.842**

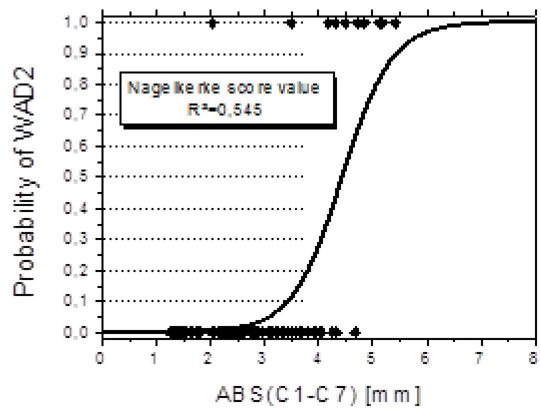
NECK INJURY CRITERIA BASED ON FE NECK MODEL AND REAL WHIPLASH ACCIDENT RECONSTRUCTION

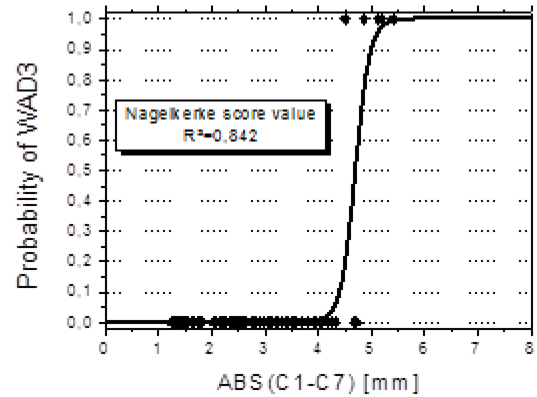


$$\sum_{i=1}^{6} |C_i - C_{i+1}| dx \P$$

	R^2 WAD1	R^2 WAD2	R^2 WAD3
Abs (C1-C7)	0.223	0.545	0.842





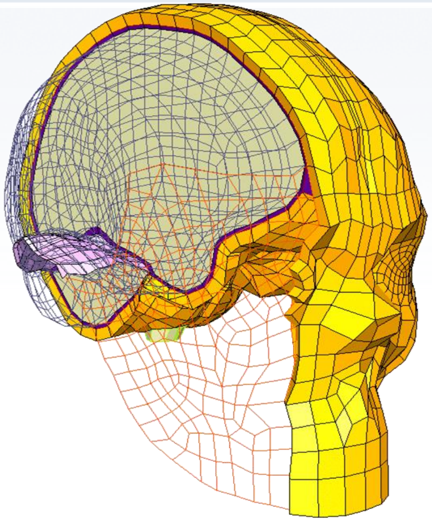


Meyer *et al.*2012 , 'Development and Validation of a Coupled Head-neck FEM – Application to Whiplash Injury Criteria Investigation', *International Journal of Crashworthiness*, 2012, 1–24

Conclusion-Neck

- Full validated neck model (time & frequency)
- Model based neck injury criteria (F,L,R,V)
- SUFEHM_onNeck coupled to THUMS-v3
- Transferred in automotive industry
- Injury Risk Assessment tool

Menschmodelle- Dynamore
Stuttgart June 2016



Model based Head & Neck injury criteria

Deck C, Meyer F, Bourdet N, Willinger R.

Rémy WILLINGER
remy.willinger@unistra.fr

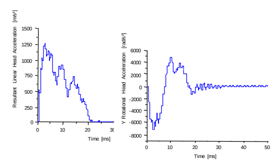
Strasbourg University
Laboratoire des sciences de l'ingénieur, de l'informatique et de l'imagerie (Icube)
Equipe Matériaux multi-échelles et Biomécanique (MMB)

HEAD INJURY RISK ON « BONNET POINT »

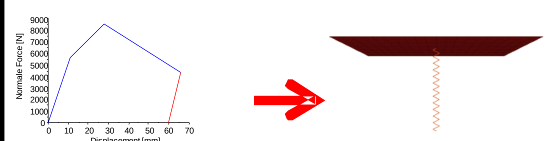
Step 1: Validation procedure

Real pedestrian test

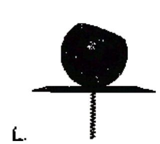
6 head accelerations



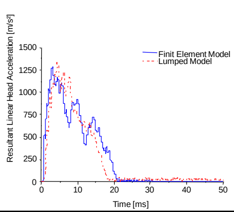
Force-displacement curves computed



Pedestrian test simulation

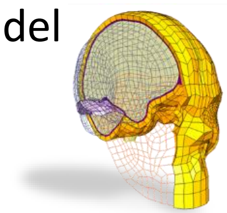


« Bonnet point » validation

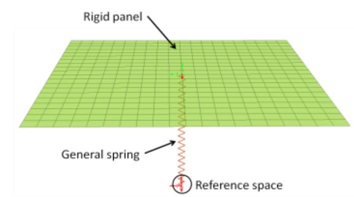


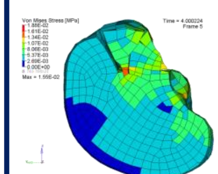
Step 2: FE test procedure

Predictif head FE model



« Bonnet point » validated model





Injury risk based on biomechanical criteria