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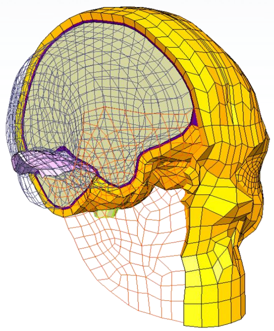

Pilzen, October 19th 2019

From head trauma biomechanics to Advanced Head Injury criteria for industry

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OVERVIEW

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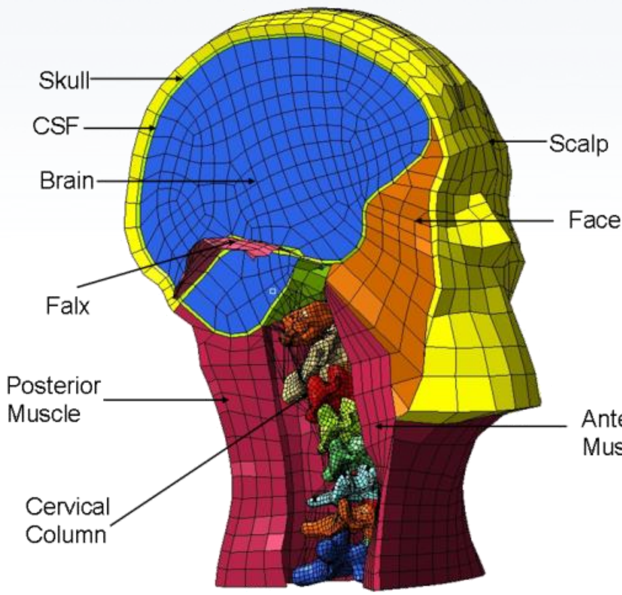
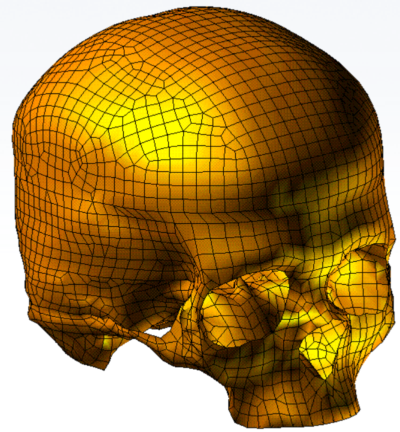
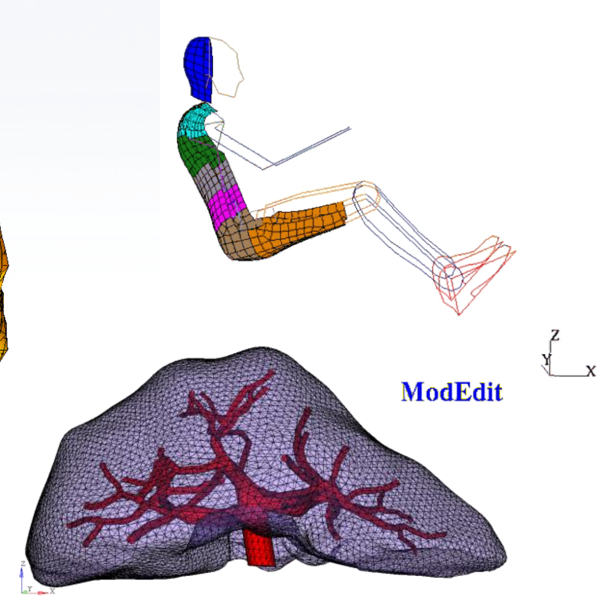
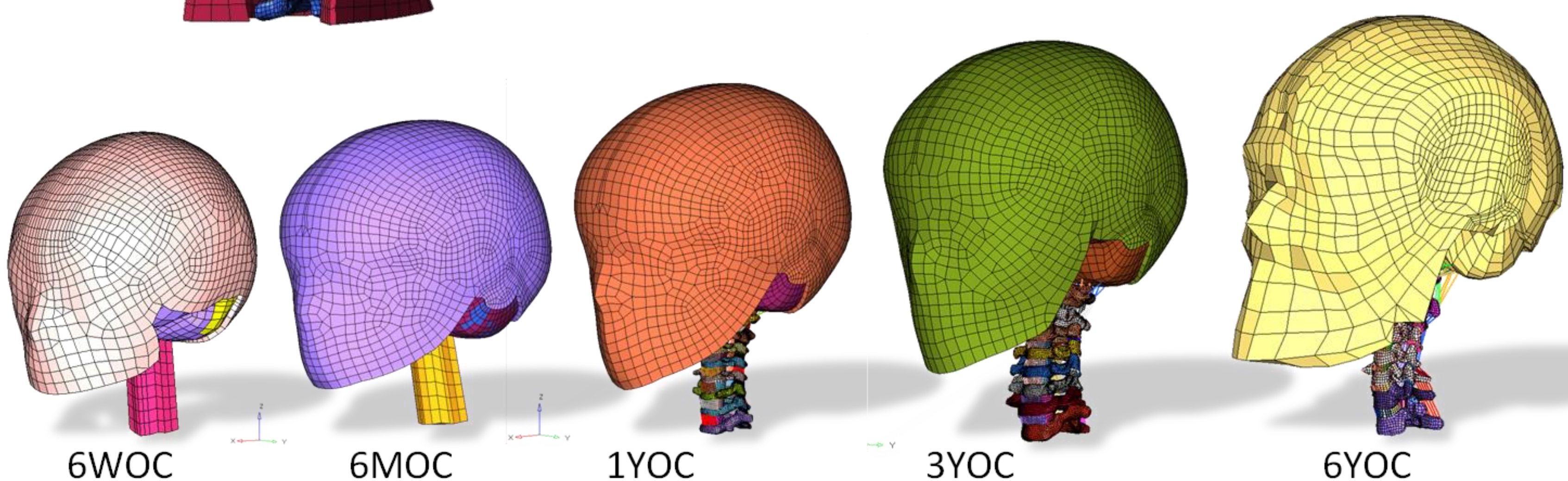
- Critical issue with current and existing head injury criteria
- State of the Art head FE modelling and validation
- Focus on head trauma database and accident reconstruction
- Model based head injury criteria
- Head injury prediction tool for end user
- Application in Product Design
- Application in Virtual testing
- Other applications
- Conclusions

Human Segments

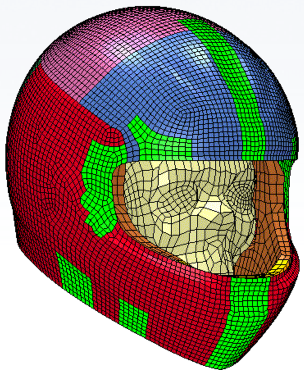


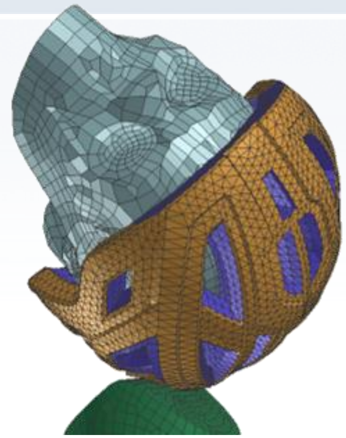


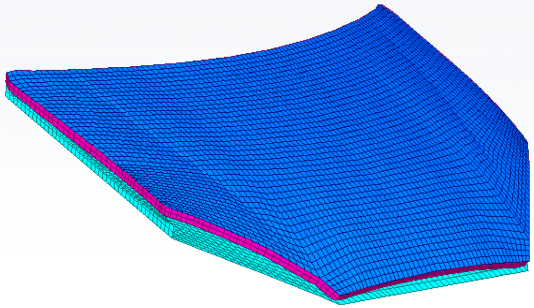


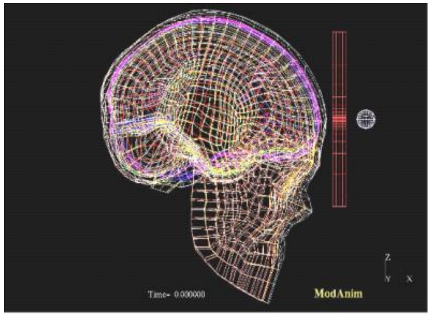


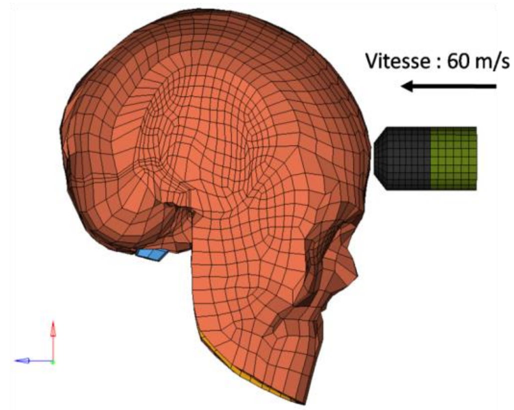
PROTECTIVE SYSTEMS

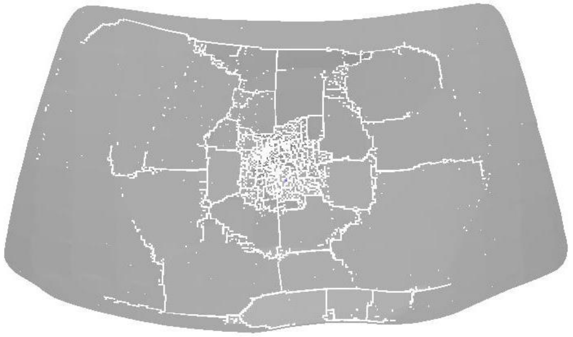


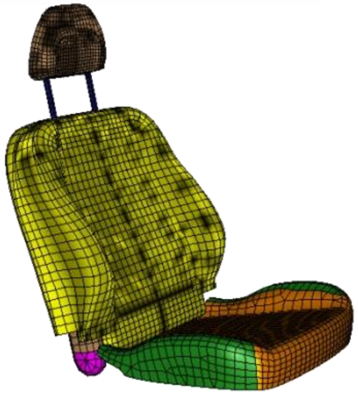


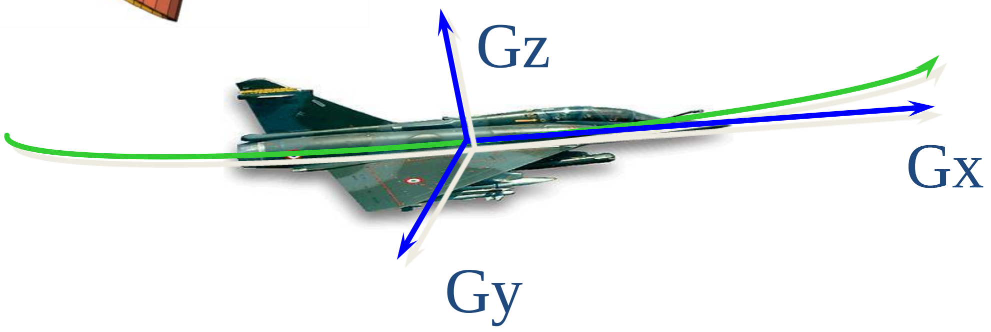










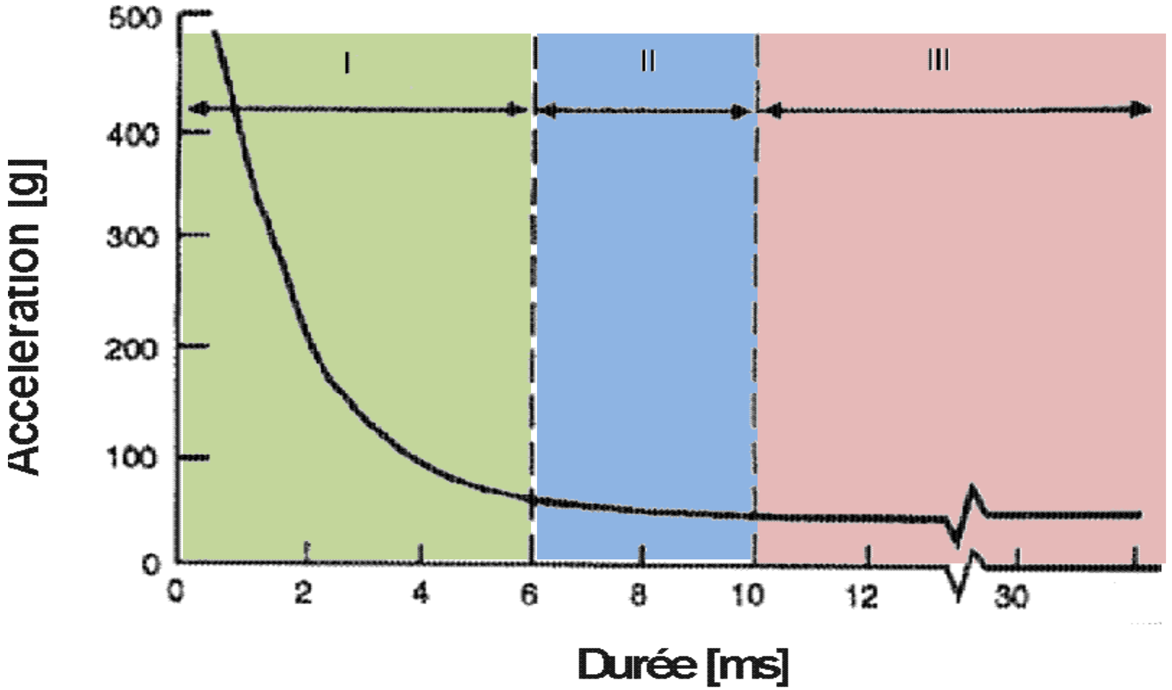


HEAD TOLERANCE LIMITS AND HEAD INJURY CRITERIA

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.

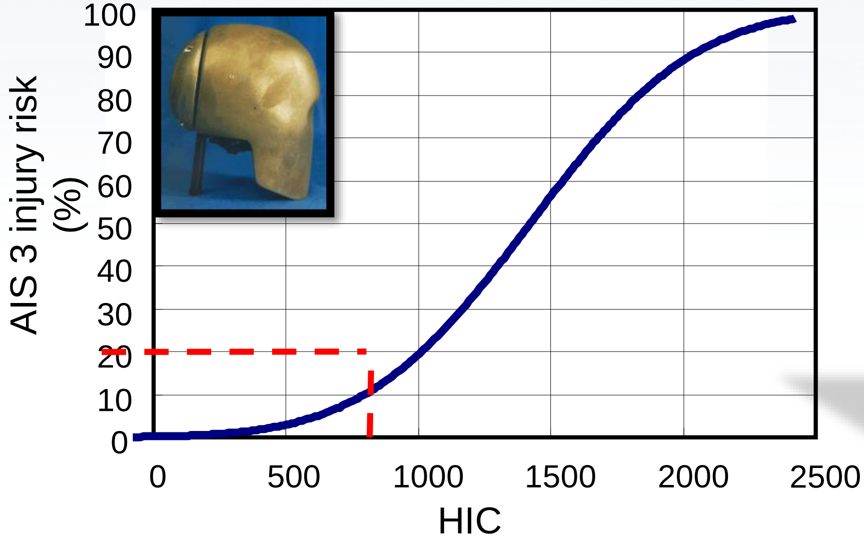
Part I : tests on cadavers, skull failure considered as head injury.

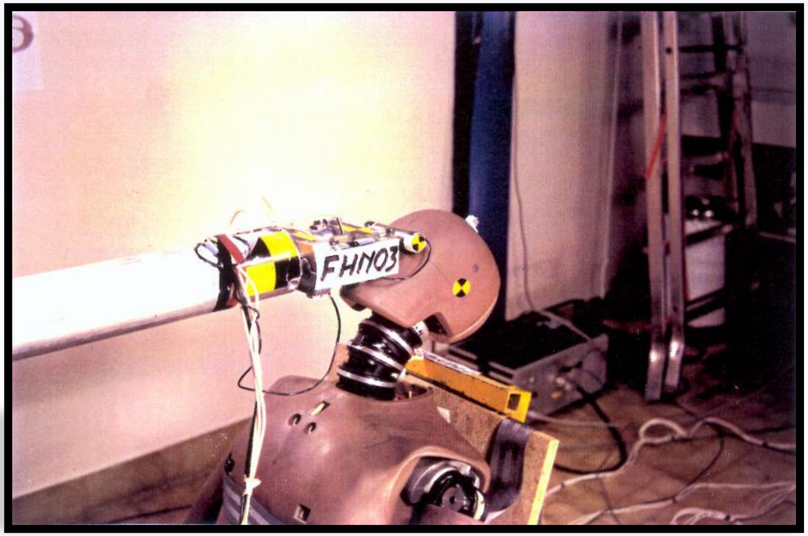
Part II : intracranial pressure recorded on anatomical subjects and animals, head injury : commotion.



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

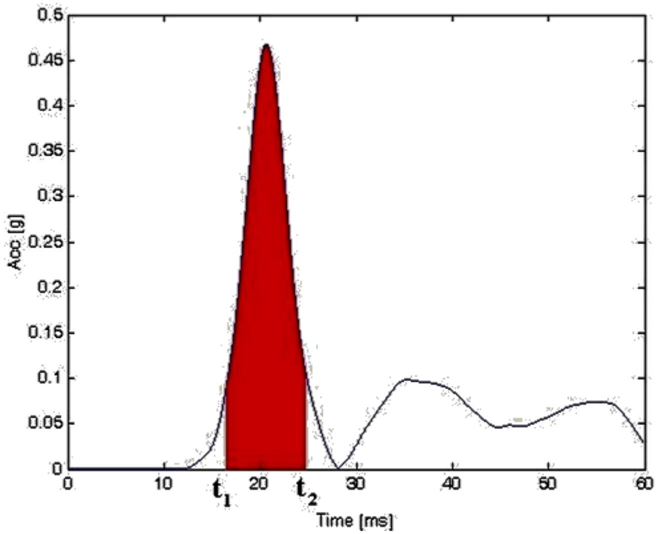
HEAD INJURY CRITERIA (1972) : DEFINITION OF HIC





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

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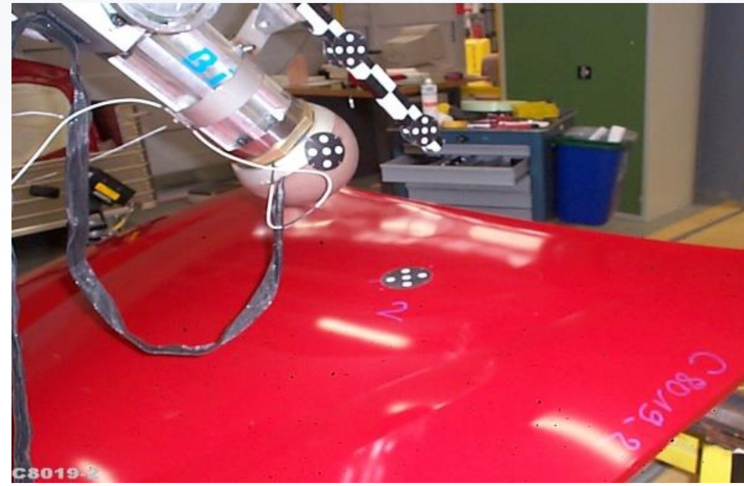
cnrs

- 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…)

ROTATION : A CRITICAL ISSUE

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** the dramatic influence of the rotational acceleration on intra-cerebral loading was quantified.

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

THE NEED OF OBLIQUE IMPACT TEST

A number of studies focussed on the victim kinematics in **real world accident** and demonstrated the effectiveness of oblique head impact conditions

Mills et al. (1996), Bourdet et al. (2011, 2012, 2015), Takount et al (2013)...

.

Despite this consolidated knowledge **no head protection standard are currently considering head rotational acceleration**.

The reason may be that there is no accepted brain injury criteria for 6D head kinematic

HEAD INJURY CRITERIA IN TERMS OF GLOBAL HEAD KINEMATIC

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 consensus

GLOBAL PARAMETERS - ROTATION

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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)

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

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)

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

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Global parameters-Combined

KLC Kleiven's Linear Combination *(Kleiven et al., 2007)*:

$$KLC = b_1 w_m + b_2 HIC_{36}$$

w_m is the maximum resultant rotational velocity, **β1** =0.004718, **β2** =0.000224

PCS Principal Component score: (*Greenwald et al. 2008*)

$$PCS = 10\left(\left(0.4718 + sGSI + 0.4742 sHIC + 04336 sLIN + 0.2164 sROT\right) + 2\right)$$

PCS is a weighted sum of translation and rotational accelerations, HIC, and SI with empirically determined weights

CP Combined Probability of Concussion *(Rowson et al., 2013)*:

$$CP = \frac{1}{1 + e^{-(b_0 + b_1 a + b_2 \alpha + b_3 a\alpha)}}$$

β0 =-10.2, **β1** =0.0433, **β2** =0.000873, **β4** =-0.00000092 , **a** is peak linear acceleration, **α** is peak rotational acceleration

Global parameters-Combined

BITS : The Brain Injury Threshold Surface (*(Antona et al., 2016)*:

Based on maximal linear and rotational acceleration and impact duration

CIBIC : Convolution of Impulse Response for Brain Injury Criteria : (*Takahashi et al. 2017*)

Based on rotational acceleration vs time

Immediate Dw *(Miyazaki et al., 2017)*:

Based on changes in rotational velocity

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CRITICAL ISSUES WITH GLOBAL KINEMATIC

- Considers only maximum values and no time evolution
- Most are not direction dependant for linear and or rotational parameter.
- Lack of human injury data
- Need for tissue level time-dependant and direction-dependent metric

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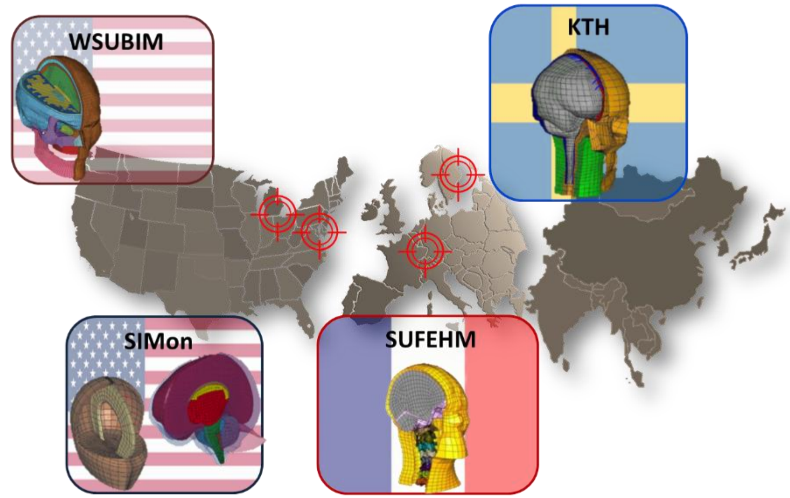
TISSUE LEVEL

BRAIN INJURY CRITERIA

LOCAL BRAIN INJURY CRITERIA

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

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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

STATE OF THE ART
HEAD FE MODELING AND VALIDATION

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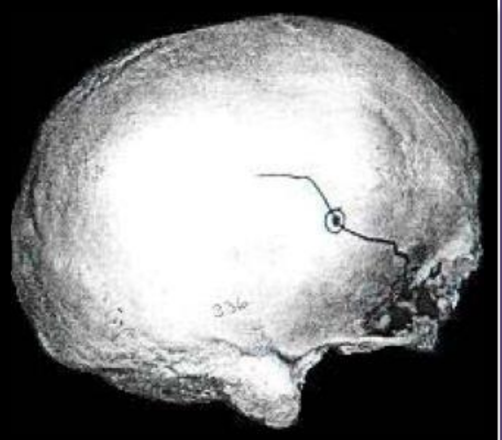
Injury mechanisms and mechanical parameters

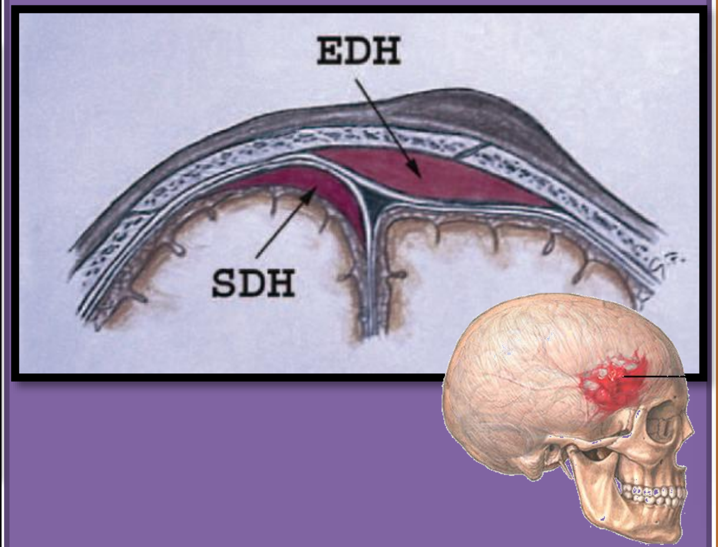


Skull Fracture

↕

Skull deformation

1

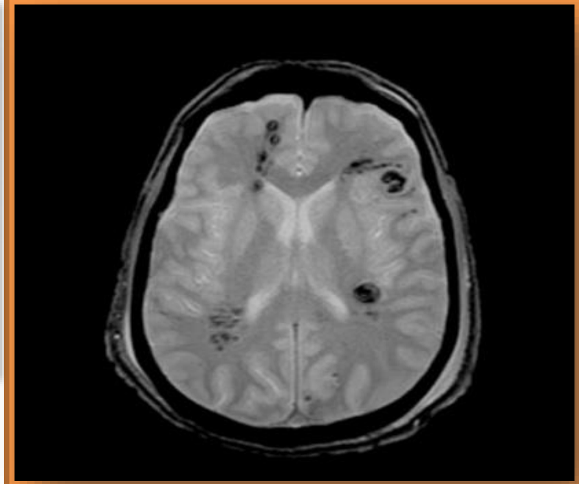


Subdural and subarachnoidal haematoma

↕

Relative motion between the brain and the skull

2

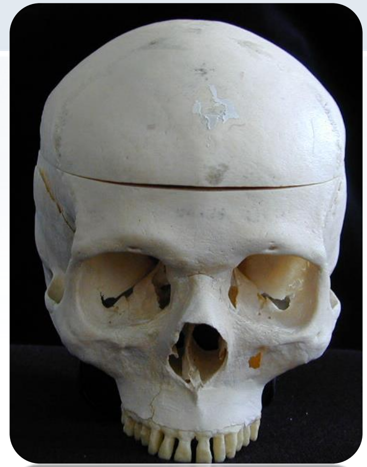


Diffuse Axonal Injuries (DAI)

↕

Intracerebral strains/stress

3



50th percentile adult skull

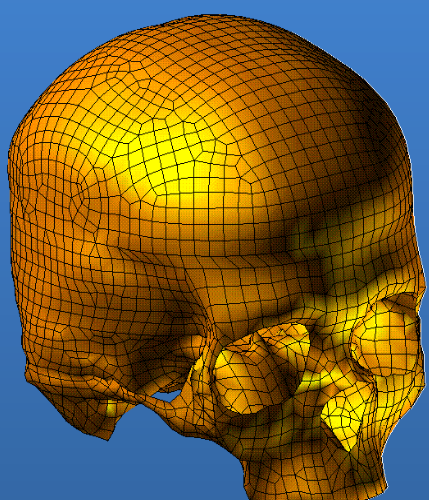
Digitalisation

[Kang, 1997]

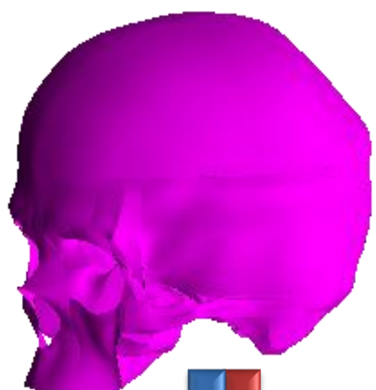
SUFEHM 98

Accident reconstructions

Tolerance limits



[Deck, 2004]



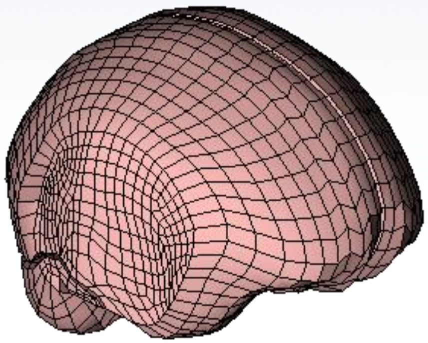
Skull Model Improvement

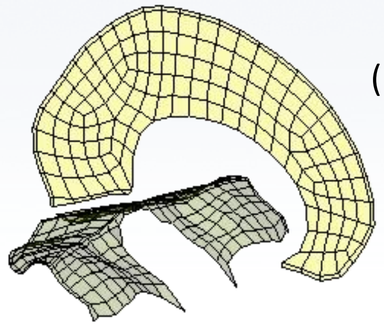
- Refined meshing
- Skull thickness variation
- Inclusion of reinforced beams
- Improvement of non-linear material characteristics

SUFEHM Presentation

Brain

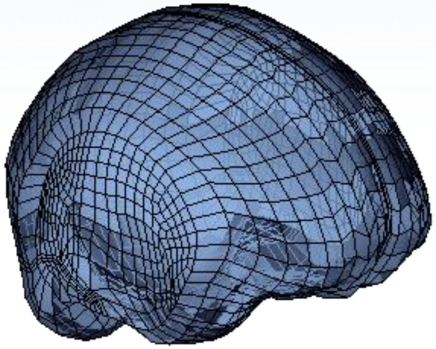
(Viscoelastic G_0=49kPa, G_∞=16.7kPa, β=145s^{-1})





Membranes

(Elastic E=31.5MPa, γ=0.23)

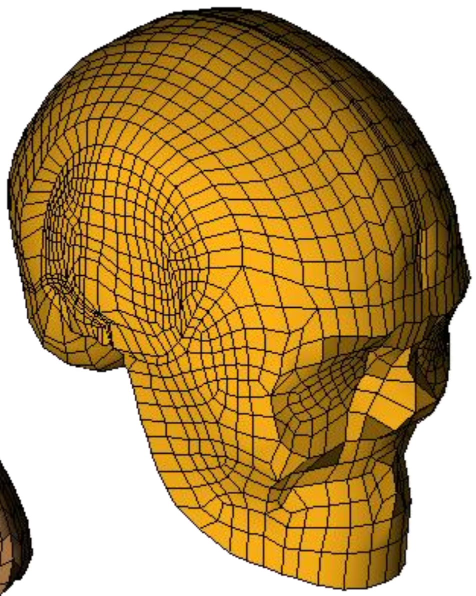


CSF

(Elastic E=12kPa, γ=0.49)

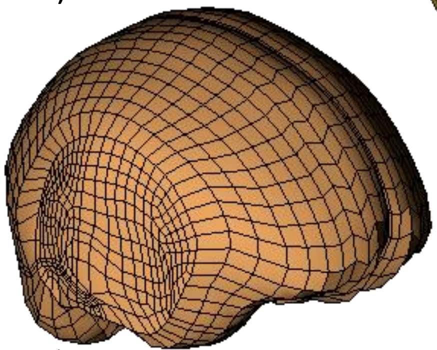
Brainstem

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



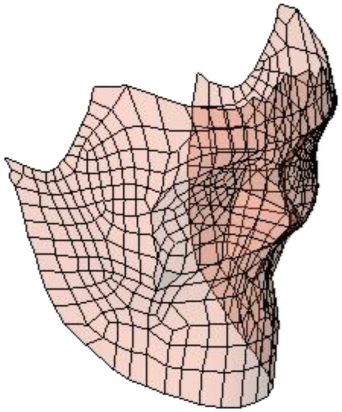
Scalp

(Elastic E=16.7MPa, γ=0.42)



Skull

(Shell elements, composite law with failure criterion)

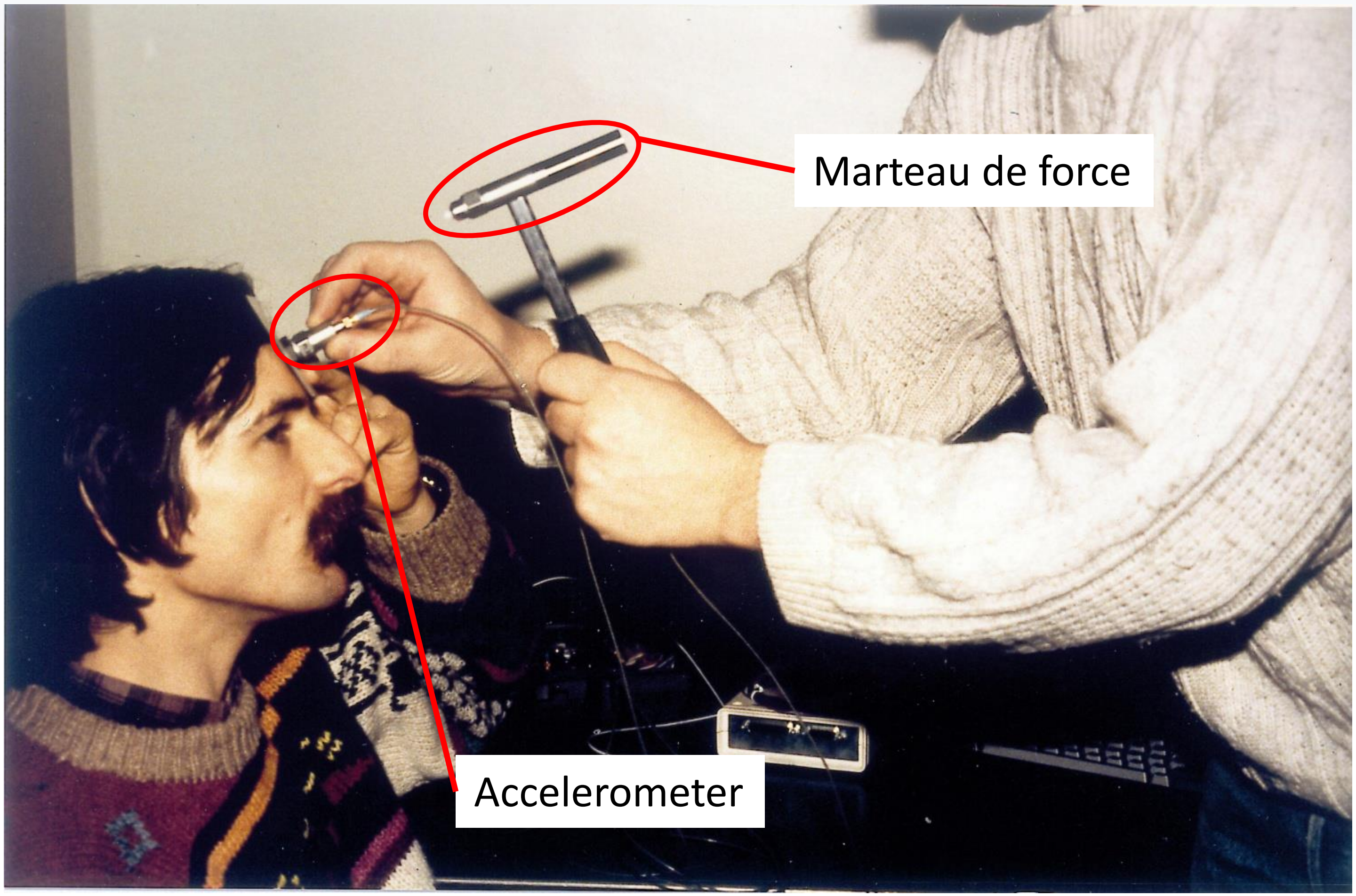


Face

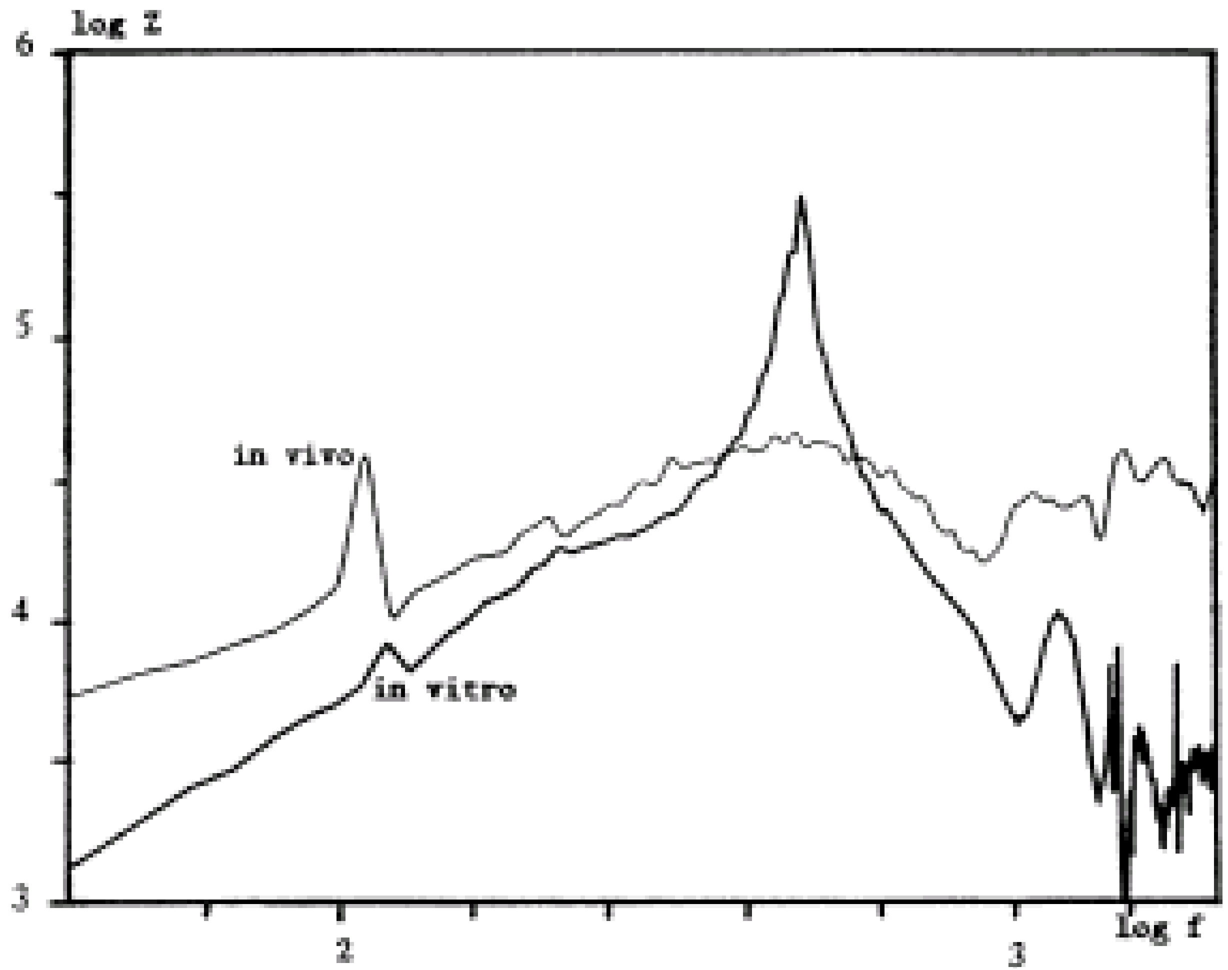
(rigid)

HUMAN HEAD CHARACTERIZATION & MODELLING

MECHANICAL IMPEDANCE IN VIVO



HUMAN HEAD MECHANICAL IMPEDANCE



Log(Z) vs Log(f) in vivo & in vitro

CHARACTERIZATION OF SKULL

Identification of Skull mechanical parameters

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

Failure mode

- For tensile fiber mode

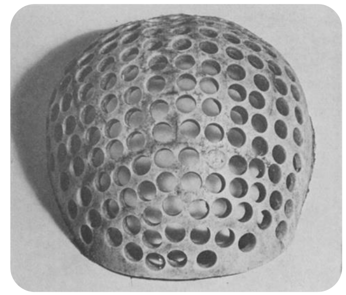
$$\sigma_{aa} > 0 \ then \ e_f^2 = \left(\frac{\sigma_{aa}}{X_t}\right)^2 + \beta\left(\frac{\sigma_{ab}}{S_c}\right) - 1 \begin{cases} \geq 0 \ failed, \\ < 0 \ elastic \end{cases}$$

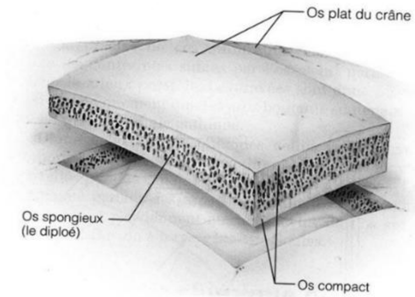
- For compressive fiber mode

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

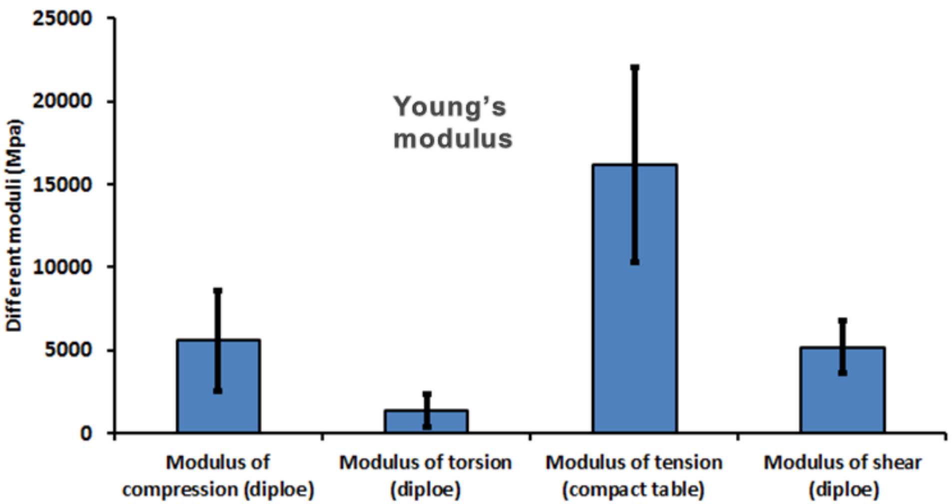
- The failure criterion for the tensile and compressive matrix mode is given as :

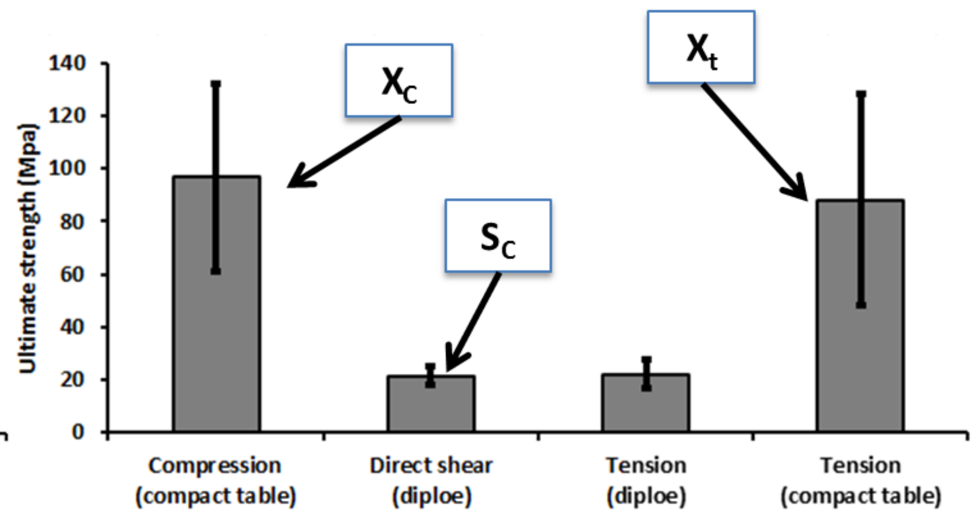
$$e_{md}^2 = \frac{\sigma_{bb}^2}{Y_c Y_t} + \left(\frac{\sigma_{ab}}{S_c}\right)^2 + \frac{(Y_c - Y_t)\sigma_{bb}}{Y_c Y_t} - 1 \begin{cases} \geq 0 \ failed, \\ < 0 \ elastic \end{cases}$$





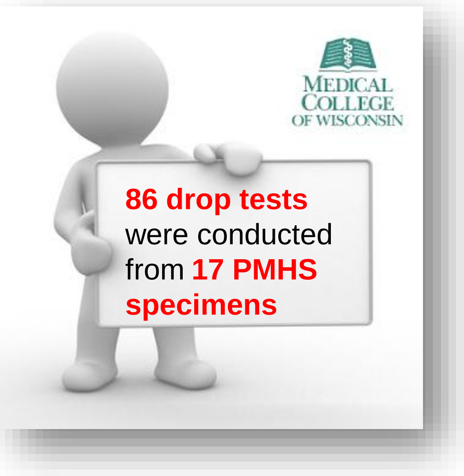
Skull was modelled by a three layered composite shell and damage mechanism based on Tsai and Wu criterion (Tsai and Wu ,1971).

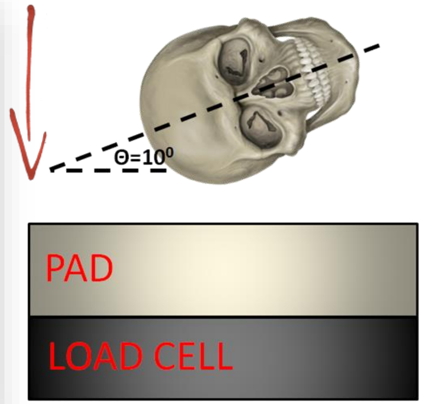


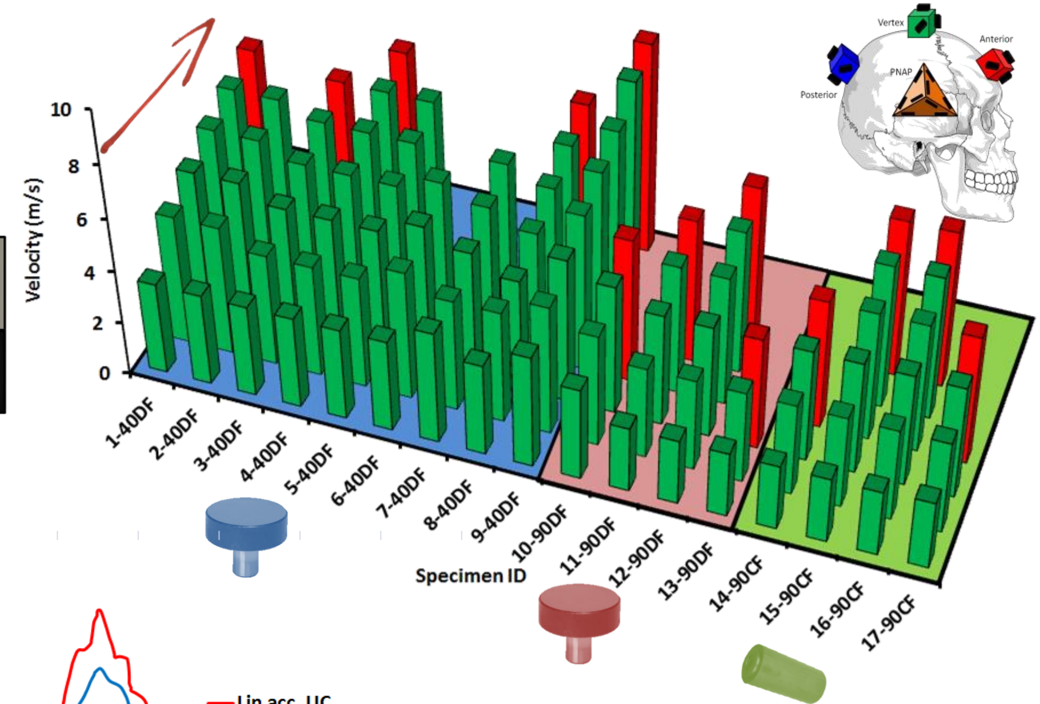


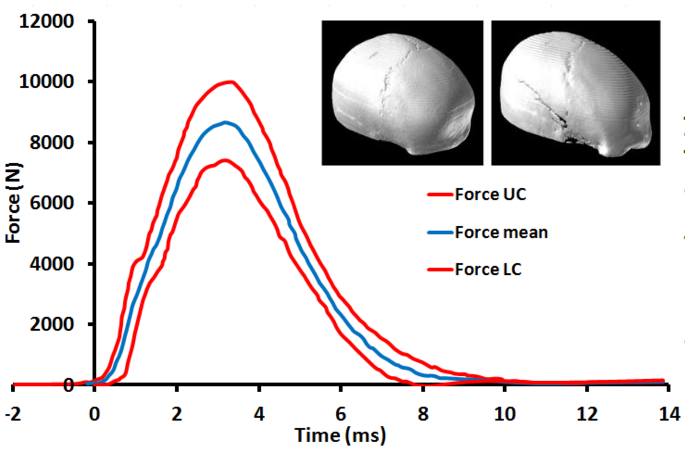
[Wood et al. 1969, McElhaney et al. 1970, Hubbard et al. 1971, Peterson and Dechow, 2002]

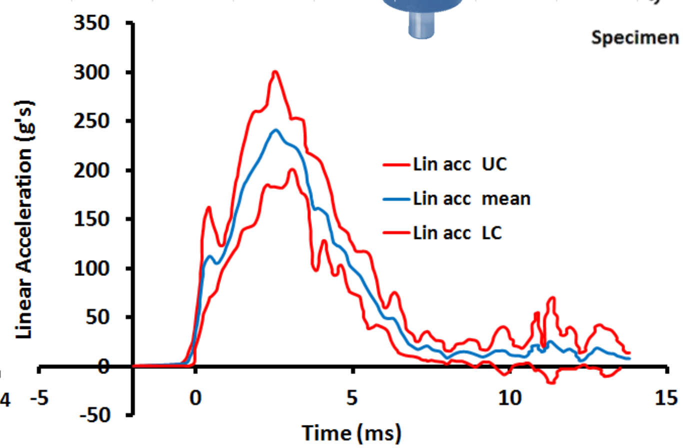
Experimental Skull fracture tests











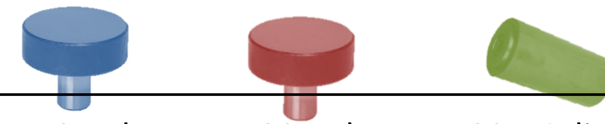
15 impact conditions

- 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

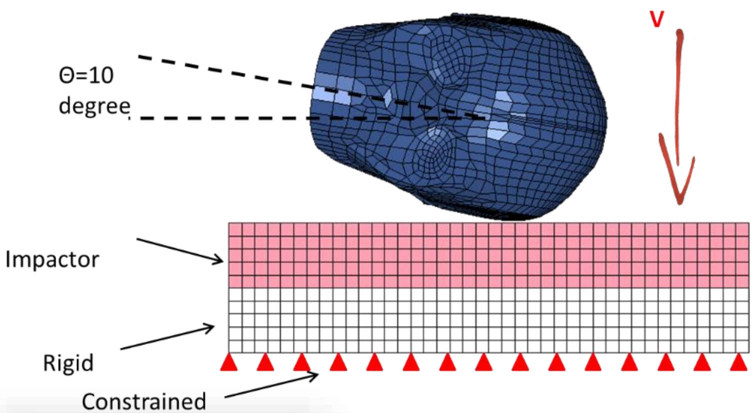
Impactor mechanical parameters definition

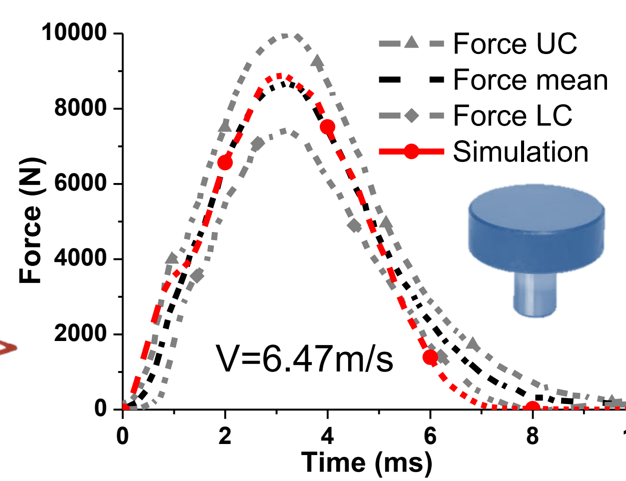
[Gent et al., 1958]
[Gray et al., 1991]
[Pampush et al., 2011]

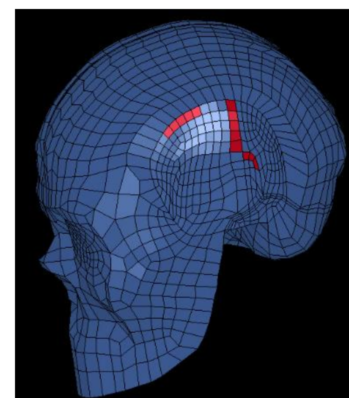


Parameters	40D Flat	90D Flat	90D Cylindrical
Mass density (Kg/m³)	4230	4930	4930
Young's Modulus (MPa)	9	12	12
Poisson's ratio	0.43	0.43	0.43

Numerical replication and skull mechanical parameters adjustment







Parameters	Cortical bone	Diploe Bone
Mass density (Kg/m³)	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

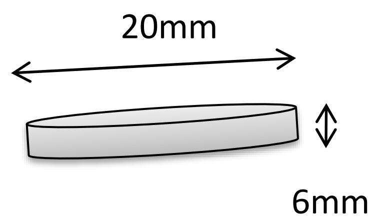
CHARACTERIZATION OF SOFT BIOLOGICAL TISSUE

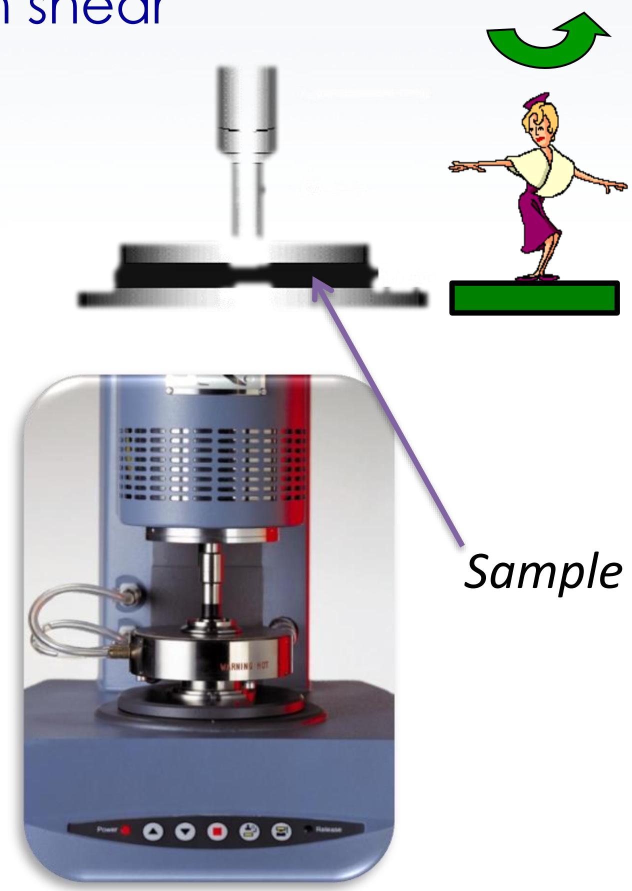
DYNAMIC MECHANICAL ANALYSIS (DMA)

- *In vitro* Dynamical Mechanical Analysis in shear
- G' & G'' (0.1Hz to 10Hz)
- Small deformations: 0.1% strain (linearity)

Organ

Cut samples





AR 2000 rheometer (TA-Instrument, New Castle, DE)

THE MAGNETIC RESONANCE ELASTOGRAPHY SYSTEM

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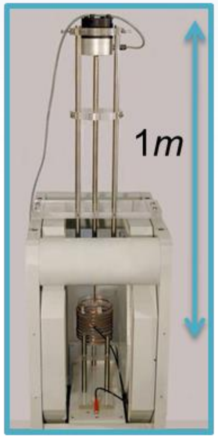
MRI System
(0.1T magnets)

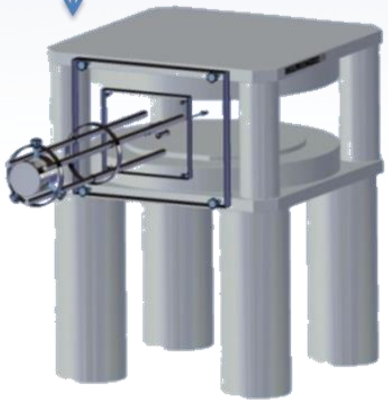
Mechanical excitation

Vertical excitation
(*in vitro* tests)

Horizontal excitation
(*in vivo* tests)

Experimental device with horizontal excitation





Experimental device with vertical excitation

Wave equation inversion 2D-algorithm

Assumption of a purely elastic medium

$$G = \rho.\left(\frac{\omega}{k}\right)^2$$

ρ : density

k : wavenumber

ω : frequency

λ : wavelength

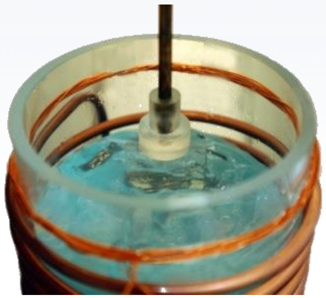
Assumption of a viscoelastic medium

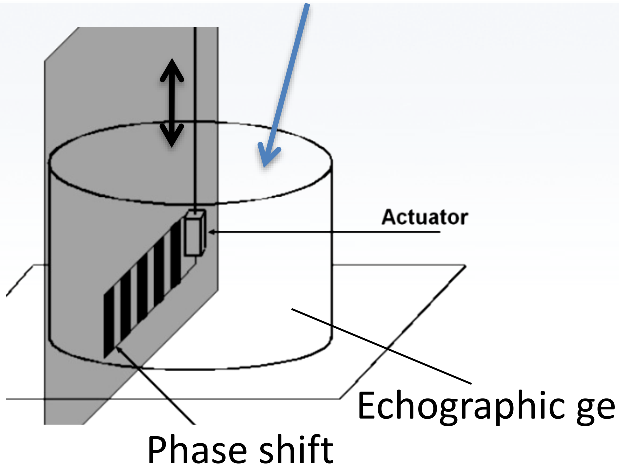
$$G' = \rho\omega^2 \frac{K'^2 - K''^2}{\left(K'^2 + K''^2\right)^2}$$

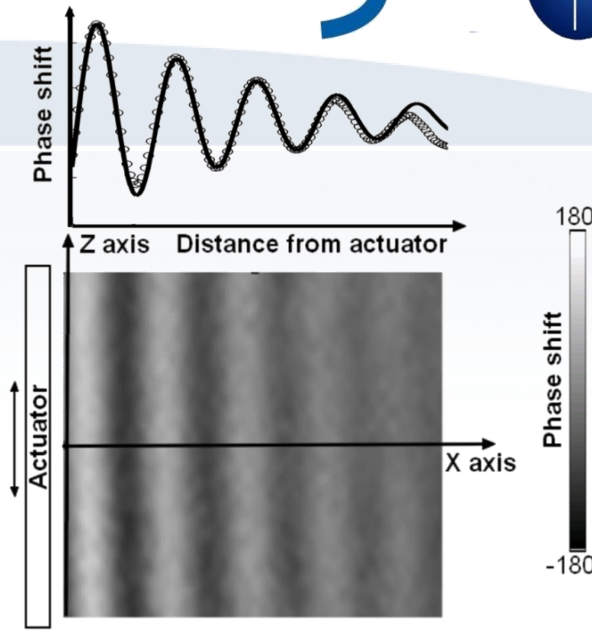
$$G'' = \rho\omega^2 \frac{K' K''}{\left(K'^2 + K''^2\right)^2}$$

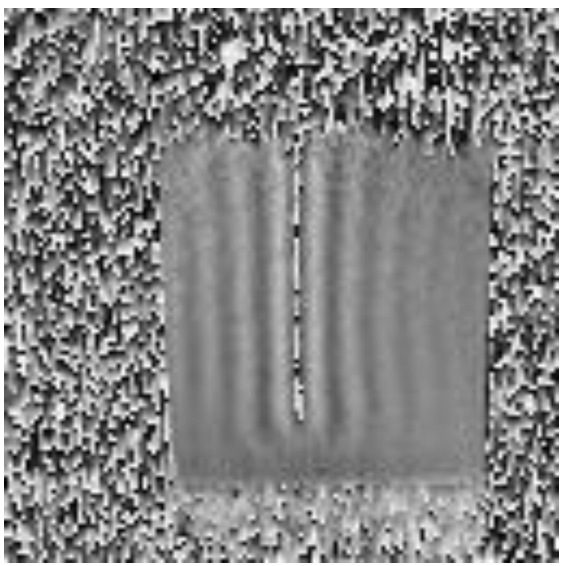
IN VITRO TESTS : VALIDATION ON SOFT HOMOGENEOUS GELS

Vertical MRE Experimental device for echographic gel

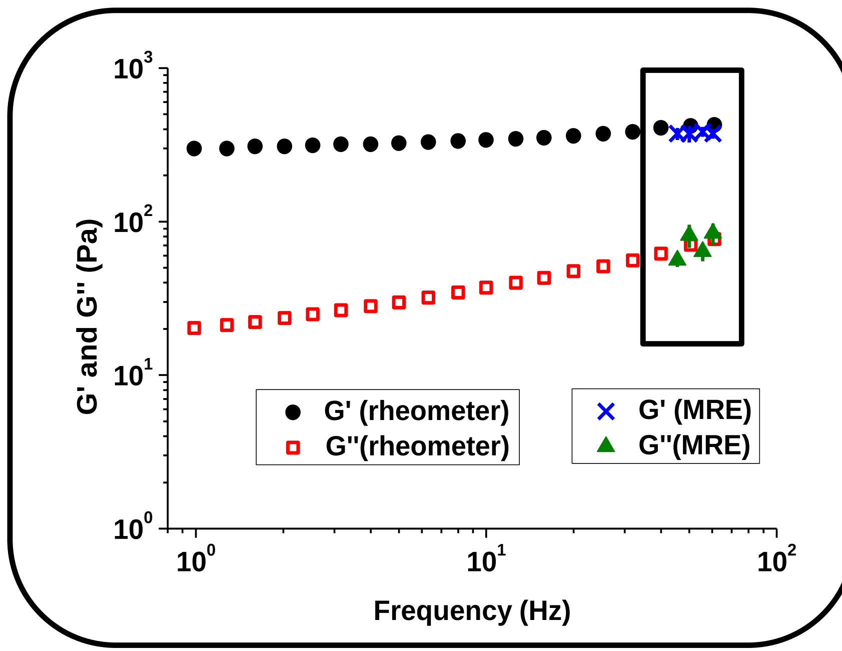




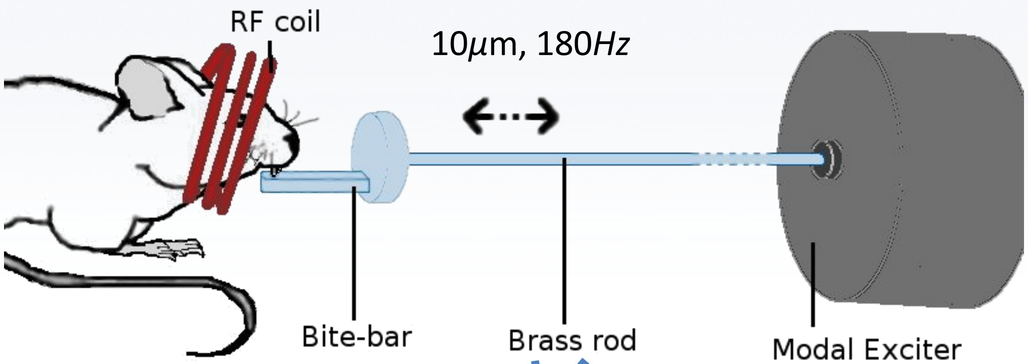


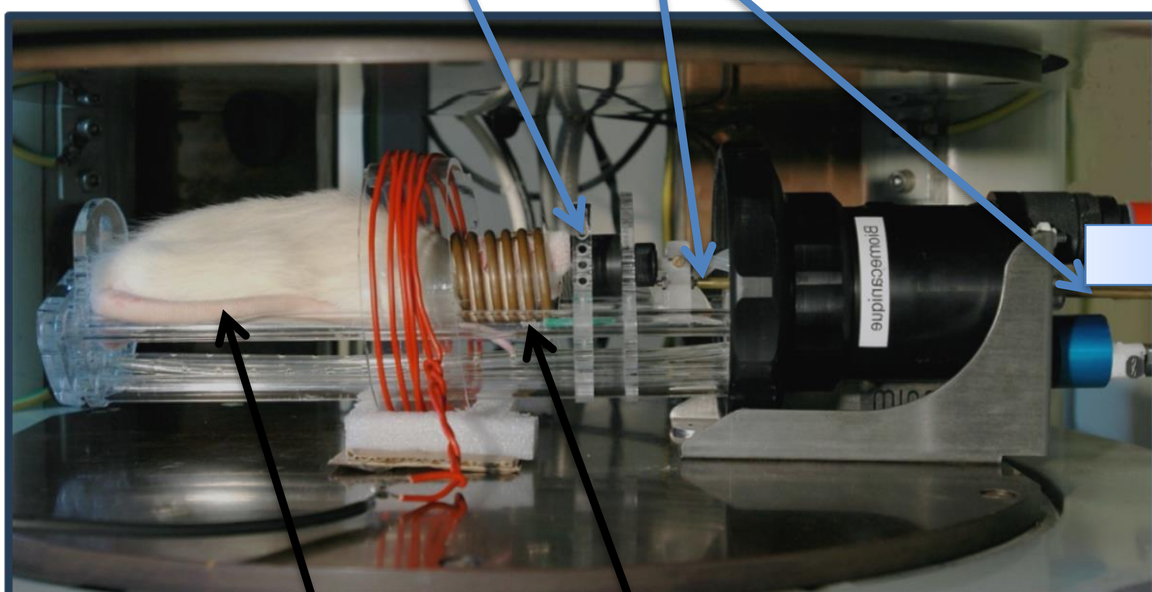


Shear wave propagation on echographic gel



IN VIVO TESTS : PRELIMINARY RESULTS ON 7 RATS

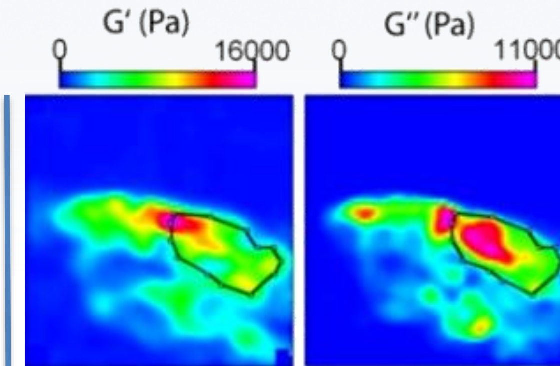




Sprague-Dawley anesthetized male rat

RF coil

Horizontal MRE Experimental device for* in vivo *rat brain



Rat brain distribution maps of G' and G'' with a manually selected region of interest

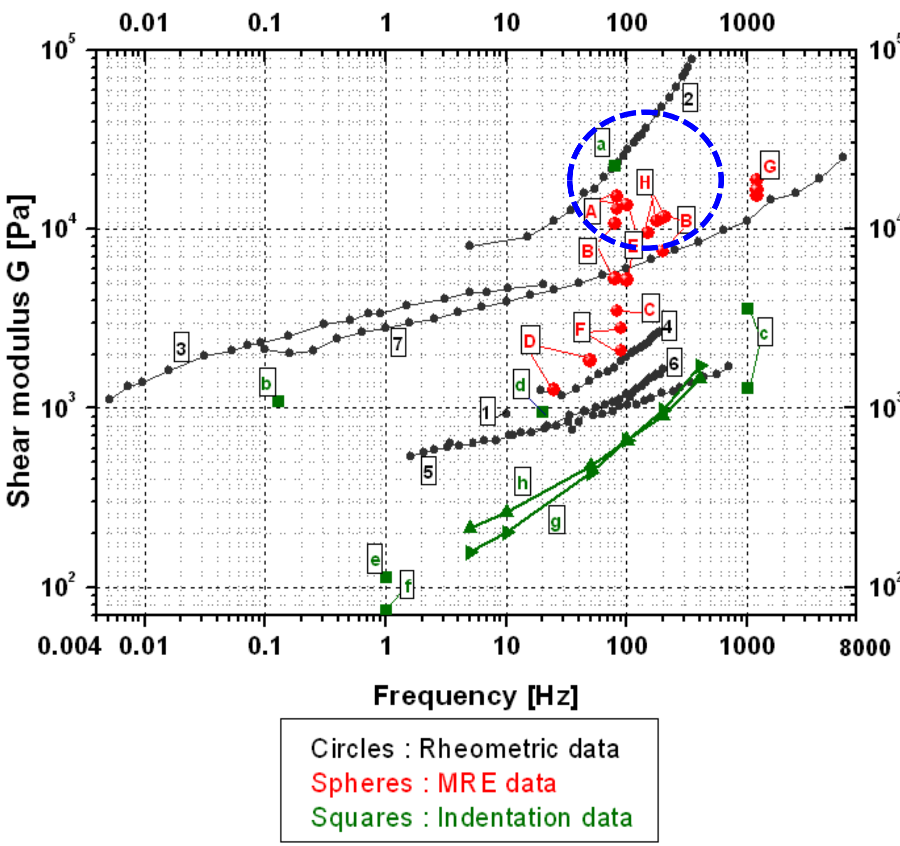
Mean shearing moduli at 180*Hz* for the 7 tested rats :

$$G' = 7600 \pm 650 Pa$$

$$G'' = 7500 \pm 1600 Pa$$

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

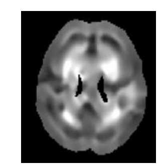
[a] Wang *et al.* 1972 - Monkey
[b] Miller *et al.* 2000 - Porcine
[c] Gefen *et al.* 2003 - Porcine
[d] van Dommelen *et al.* 2010 - Porcine
[e] Christ *et al.* 2010 - Rat (Gray matter)
[f] Christ *et al.* 2010 - Rat (White matter)
[g] Elkin *et al.* 2010 - Porcine, (AFM *in vitro* 1µm depth)
[h] Elkin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

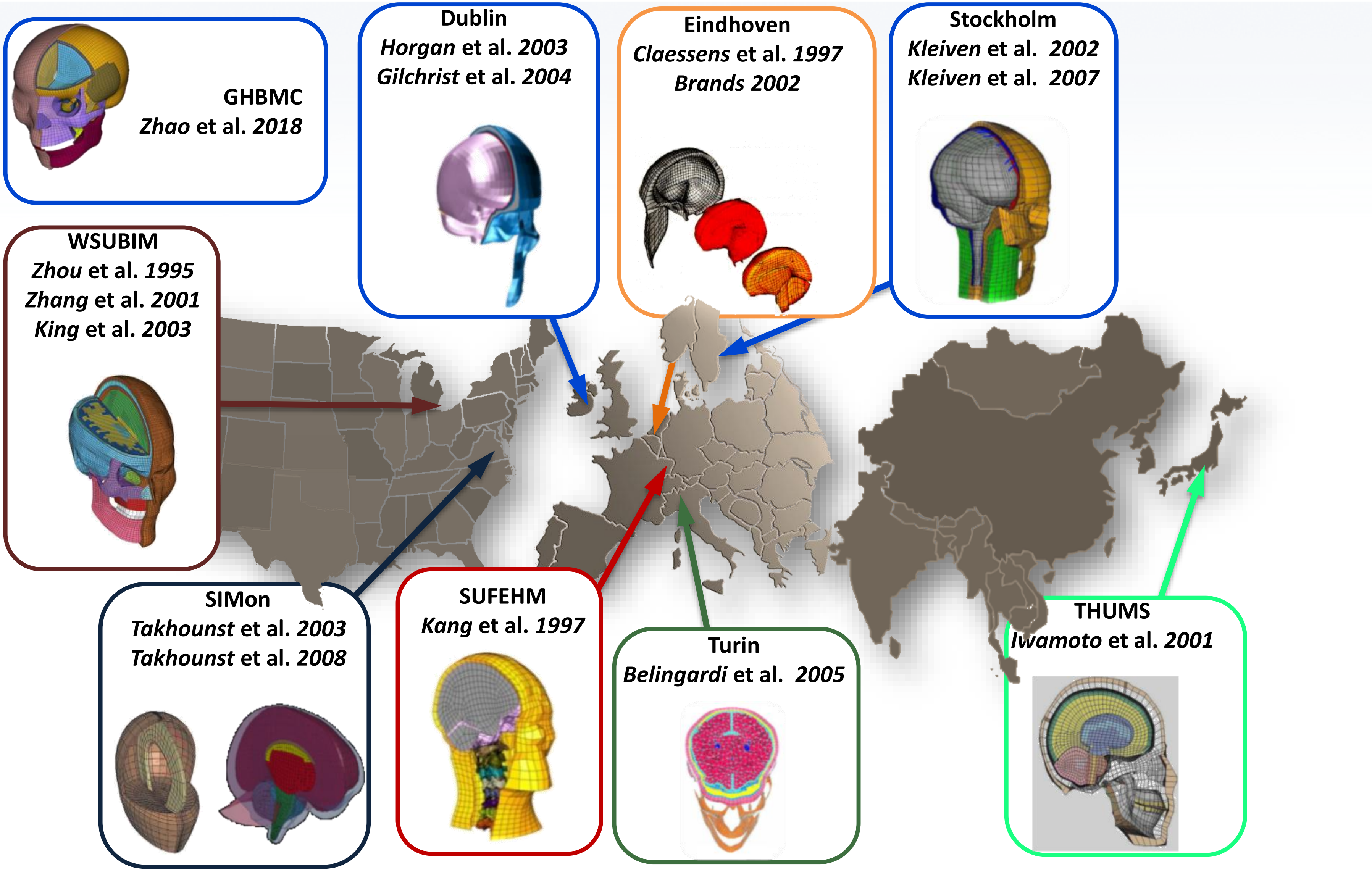


Indentation

- 1 to 1000Hz

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

HEAD FE MODELS AROUND THE WORLD



BENCHMARK PROCEDURE AND MODELS EVALUATION

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Intra-cranial behaviour validation

PRESSURE

1. Nahum (1977)
2. Trosseille (1992)

BRAIN MOTION

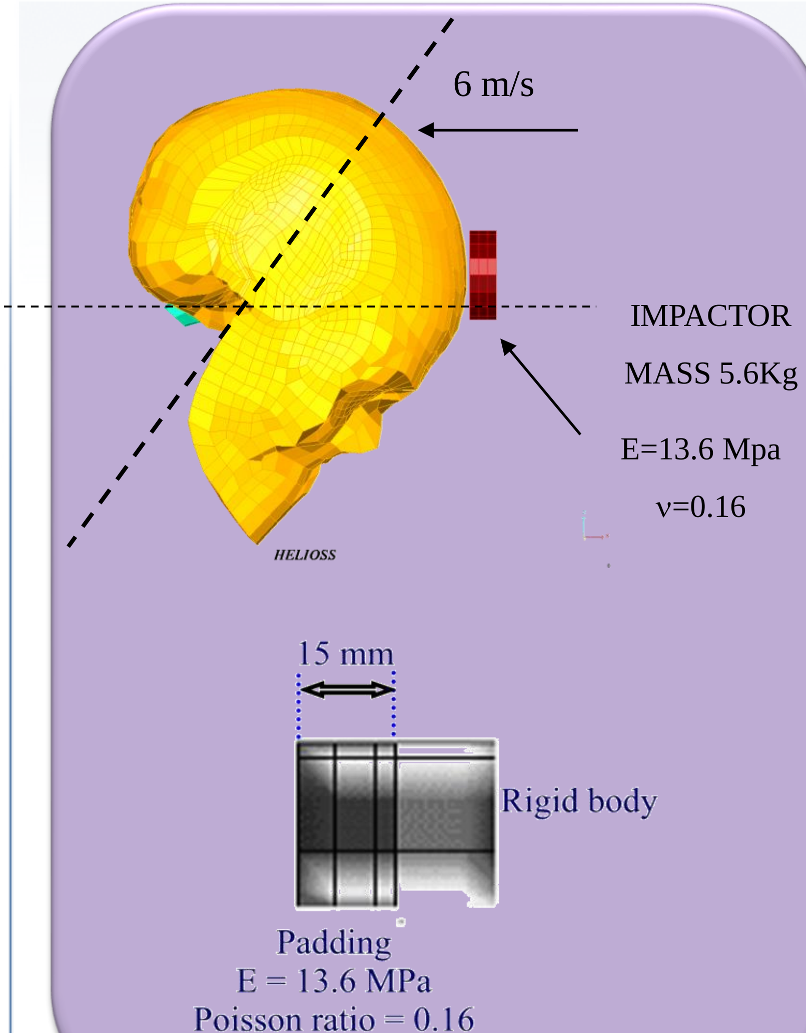
Hardy et al. (2001)

1. Frontal impact (Test C383-T1)
2. Occipital impact (Test C755-T2
3. Right lateral impact (Test C383-T1)

Skull validation

Yoganandan et al. (1994)

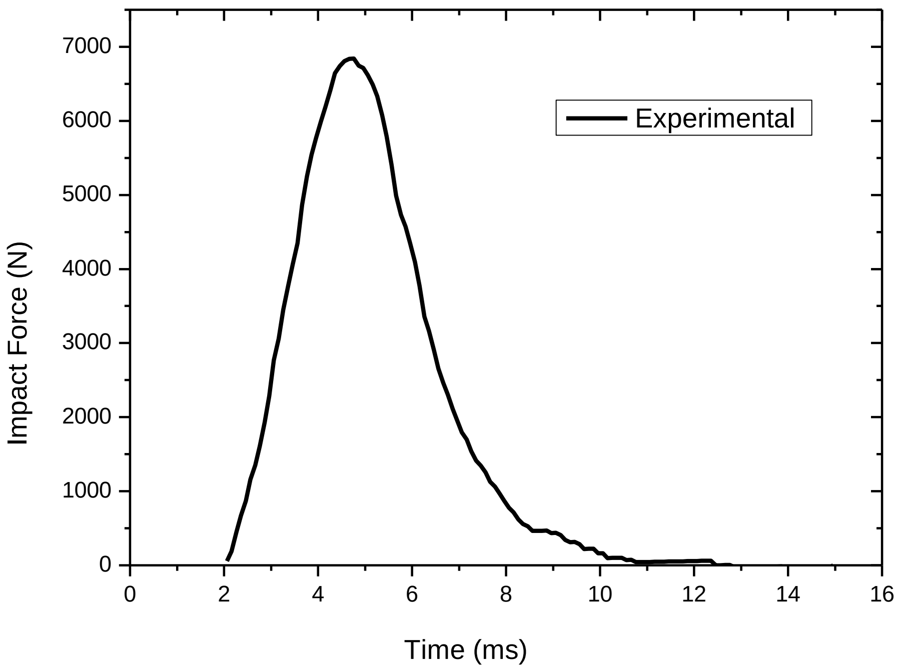
BENCHMARK PROCEDURE : NAHUM INPUT



[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

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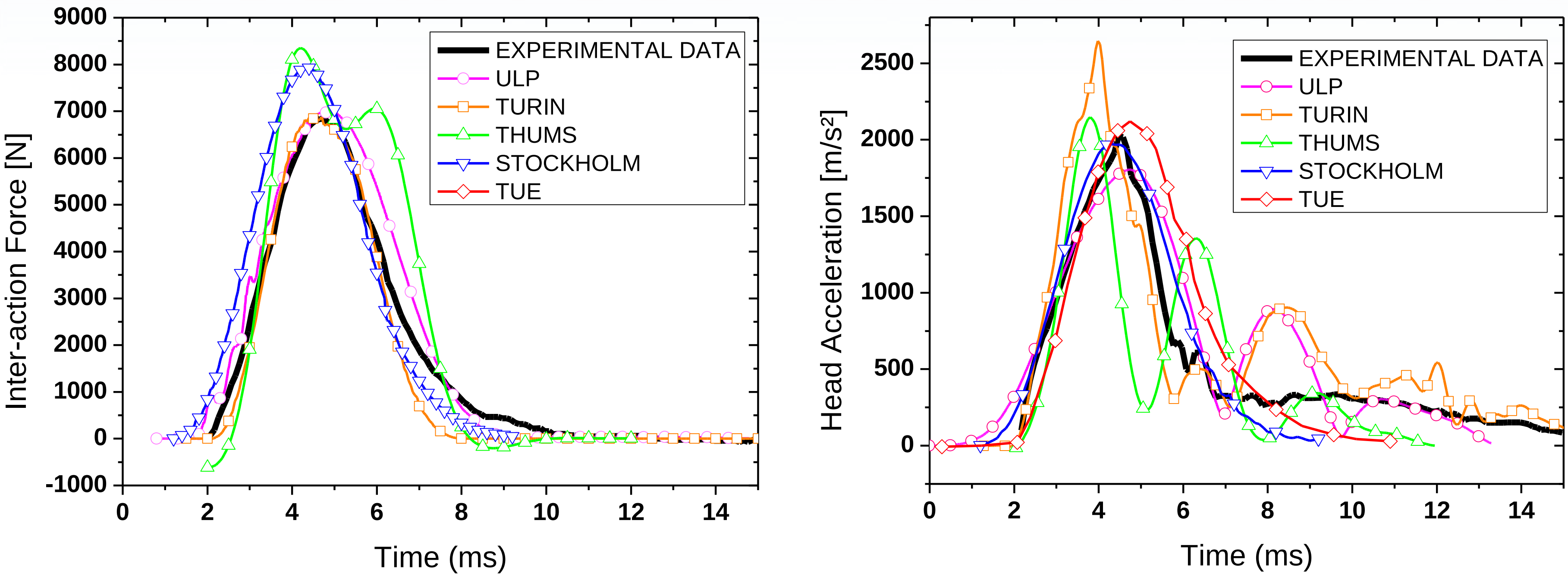
- Impact force, head acceleration



Some oscillations can appear in head acceleration results

NAHUM IMPACT NUMERICAL RESULTS

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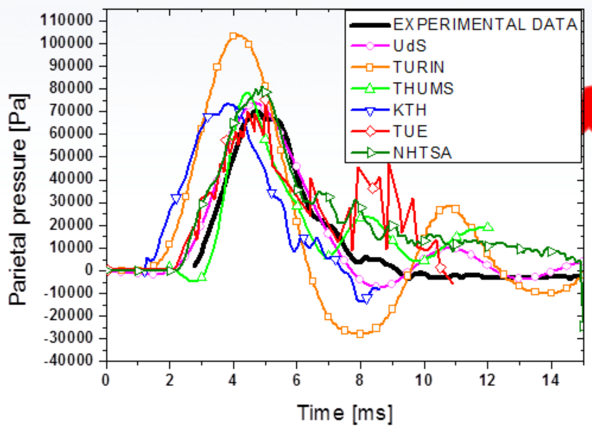
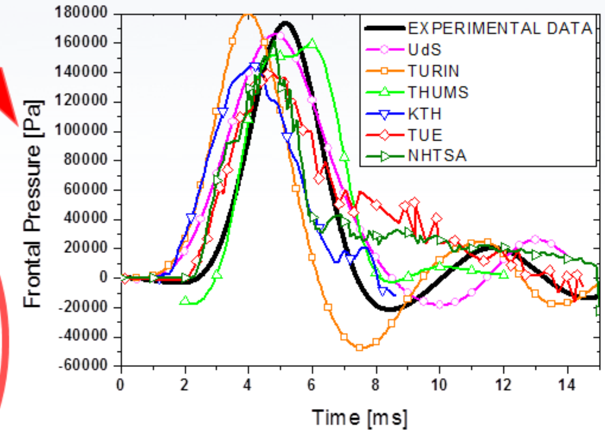
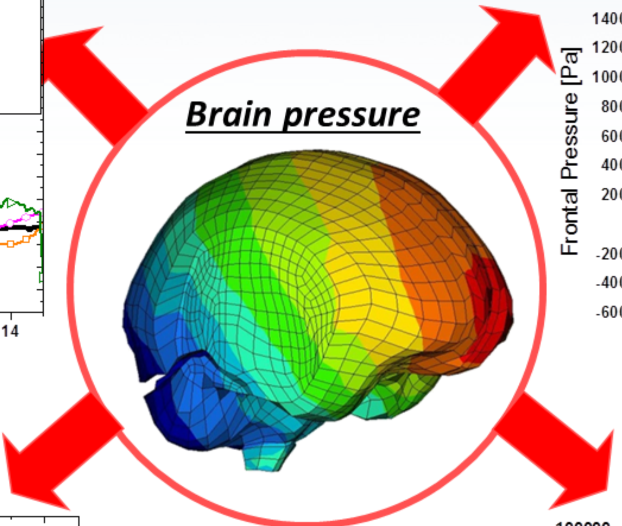
Parietal pressure

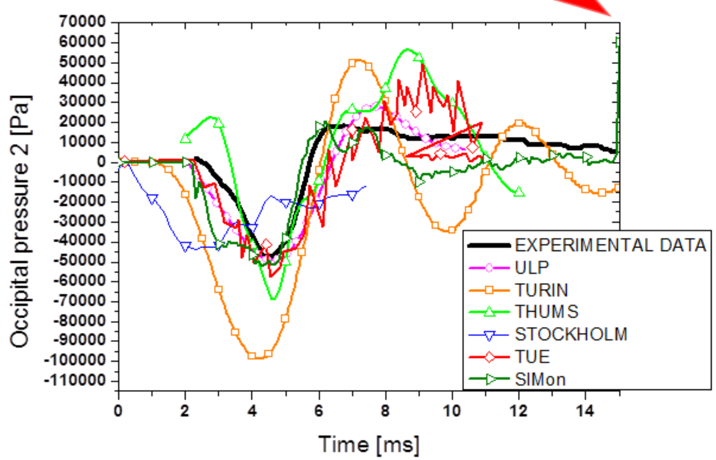


Frontal pressure

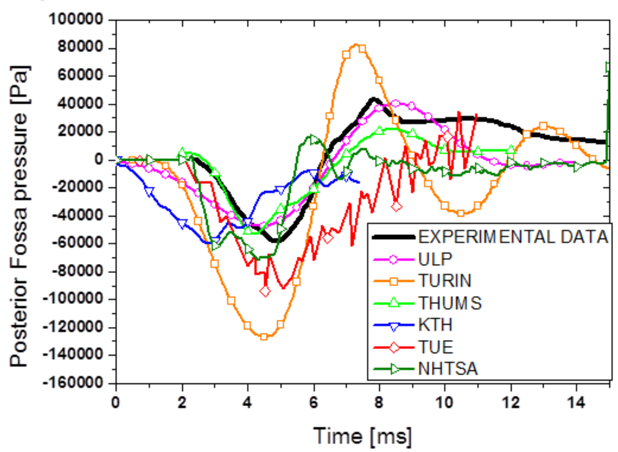




Occipital pressure



Posterior Fossa pressure



BENCHMARK PROCEDURE : TROSSEILLE INPUT

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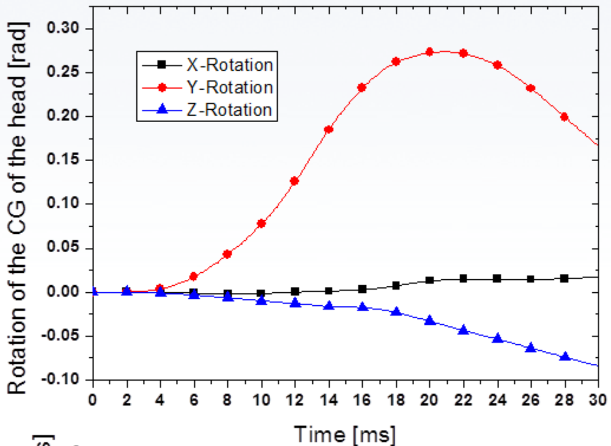
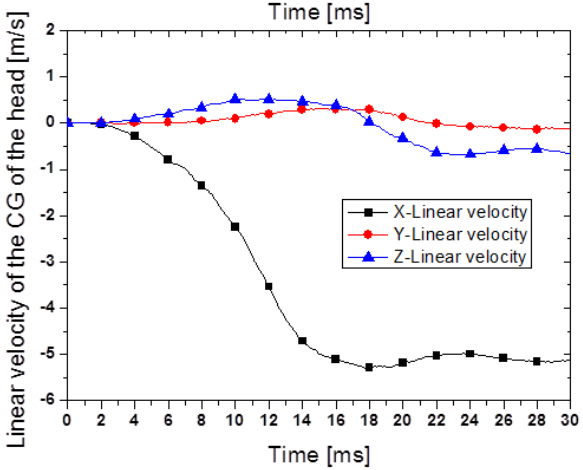


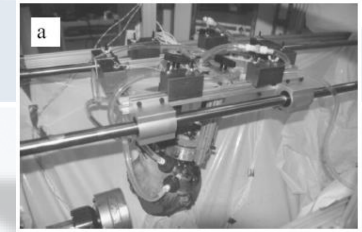


Input:

- Rigid Skull.
- Three rotations of the center of gravity of the head (in X, Y, and Z directions)
- Three linear velocities of the center of gravity of the head (in X, Y, and Z directions)

Test	Impact area	Impactor [kg]	Impactor velocity [m/s]	Force [N]	LA maxi [g]	RA maxi [rd/s^2]	Duration [ms]
Trosseille 1992 MS 428-2	face	steering wheel (23.4)	7	-	102	7602	15.8

BENCHMARK PROCEDURE : HARDY INPUT



•For this validation the skull is considered as a rigid body.

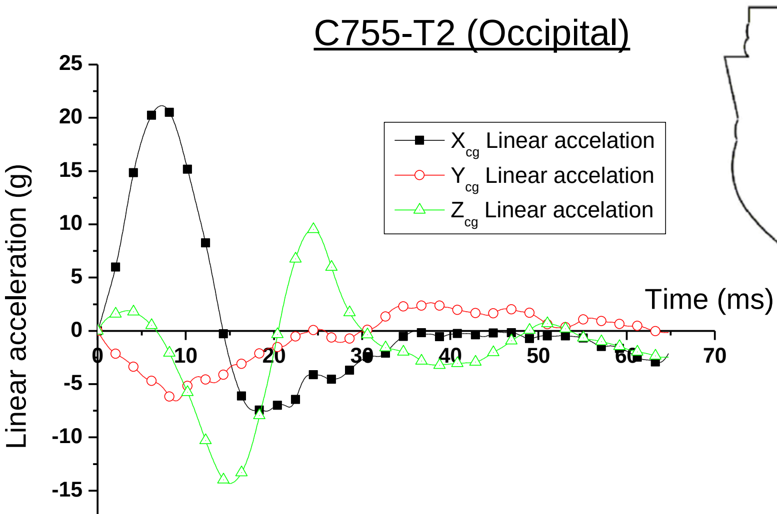
•The six components of the acceleration are applied to the center of gravity of the model.

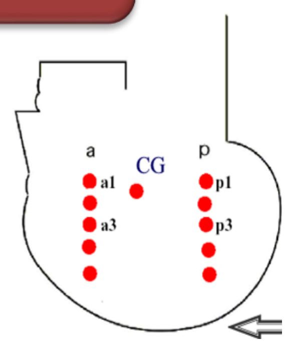
•Ten or twelve nodes in approximately the same position as Hardy's brain experimental targets are identified and their nodal displacement will be computed.

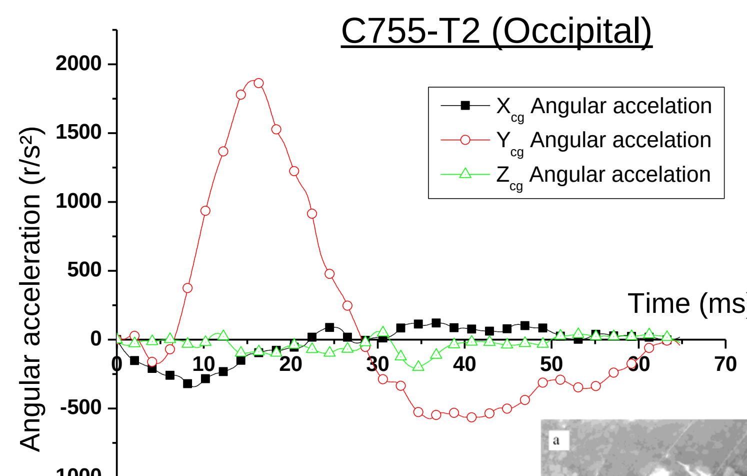
Input :

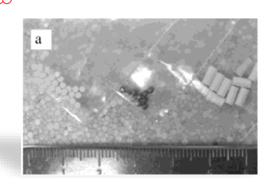
•6 Components of accelerations

•Rigid skull









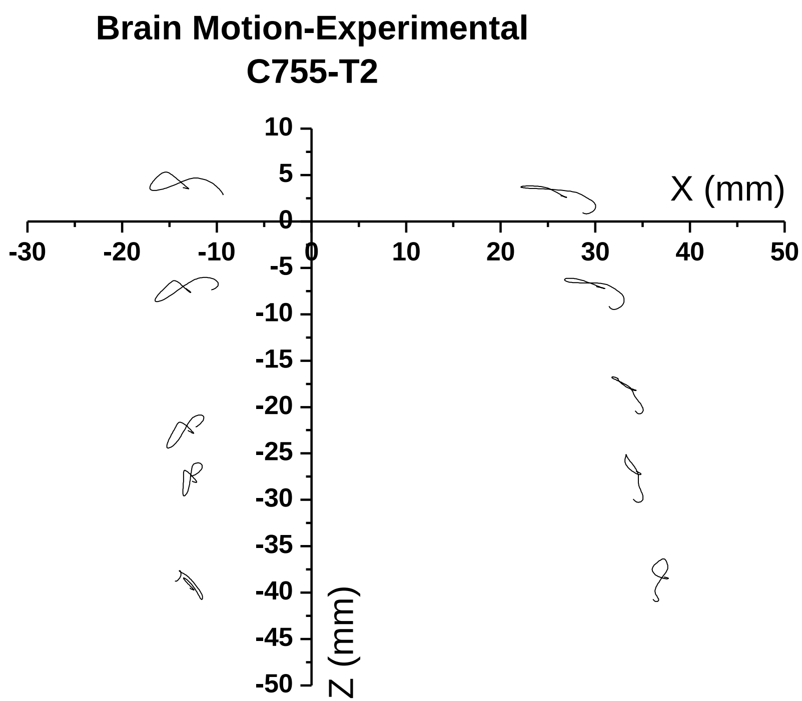
Input used for the C755-T2 test

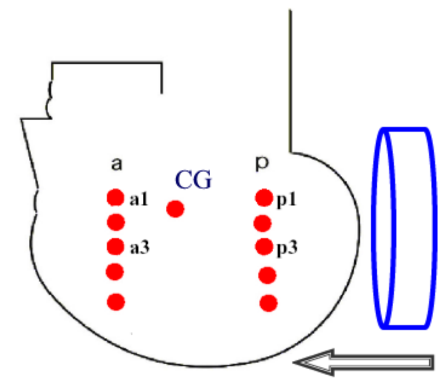
BENCHMARK PROCEDURE : HARDY OUTPUT

<u>*Output :*</u>

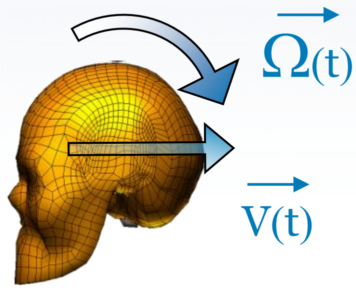
- Displacements time histories for all targets in each directions (x, y and z direction).

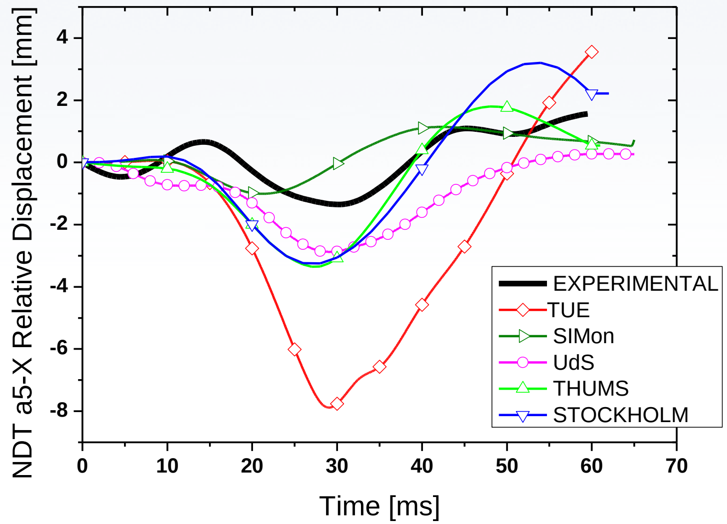
Targets displacement for test C755-T2



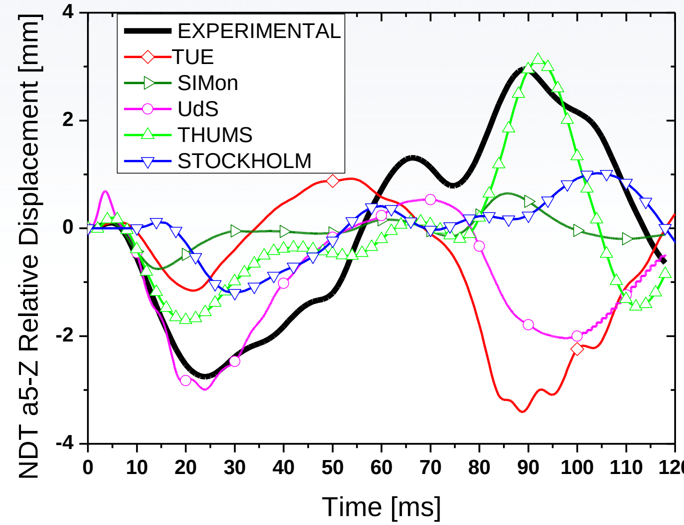


HARDY IMPACT NUMERICAL RESULTS





Test C755-T2

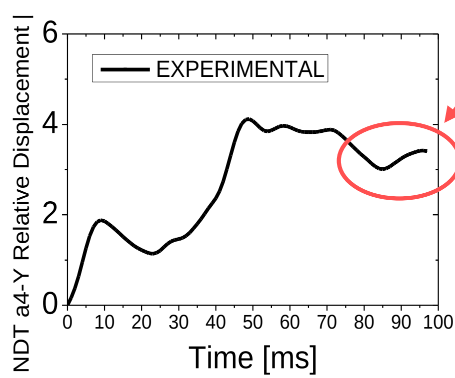


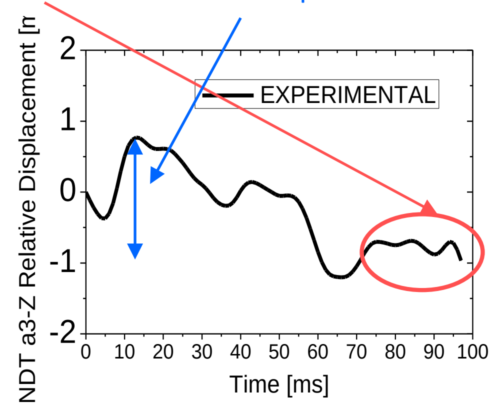
Test C383-T1

Comments about NDT's displacement

Residual displacement

Small displacement





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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

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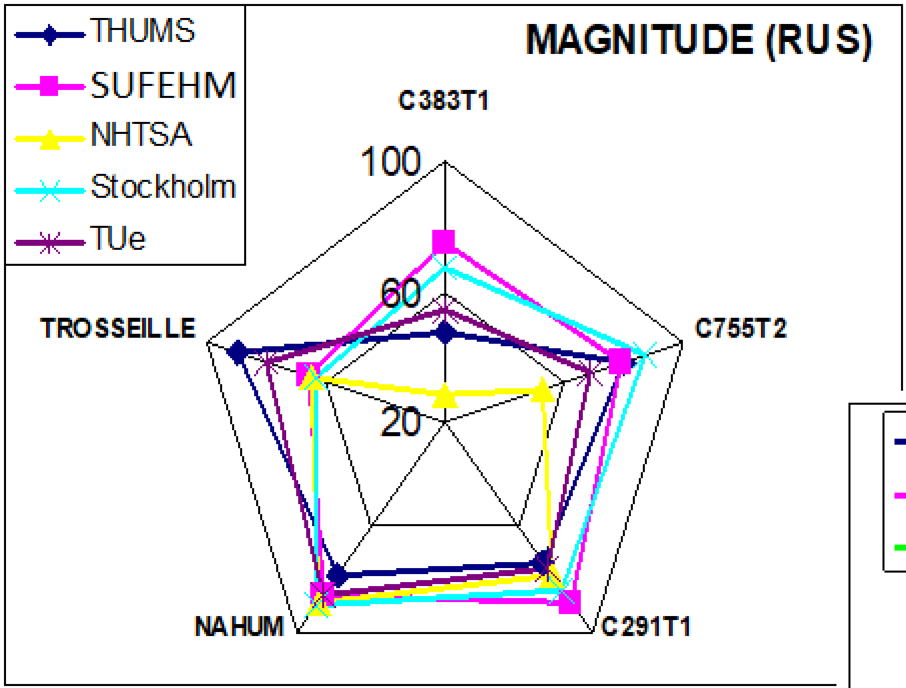

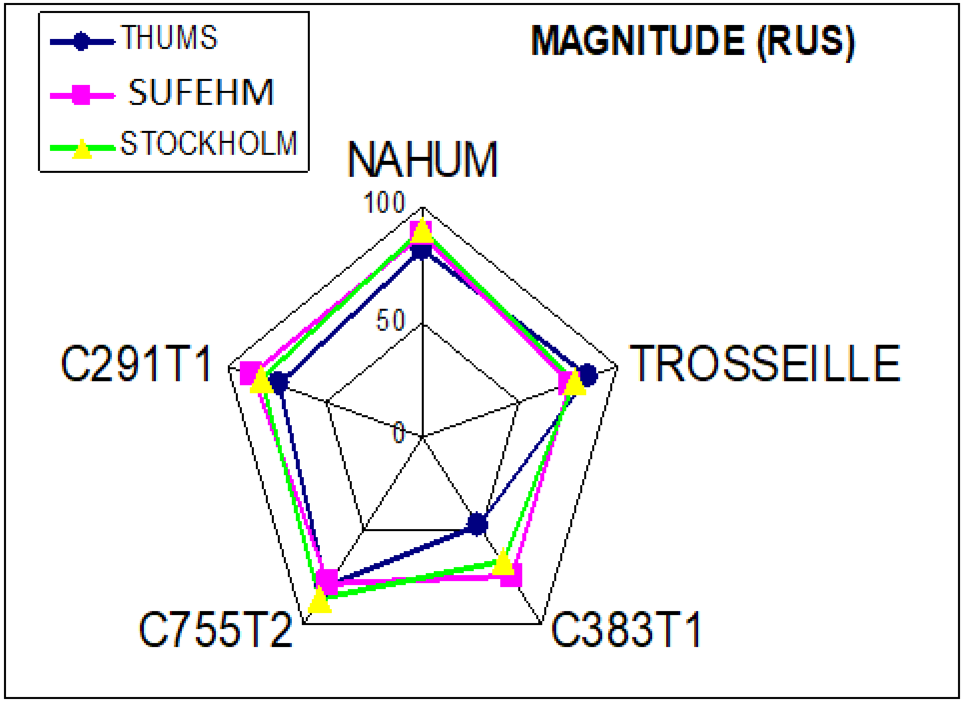

STATE OF THE ART NUMERICAL HEAD MODEL

- 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

REAL WORLD HEAD TRAUMA DATABASE

50

ACCIDENTS RECONSTRUCTIONS

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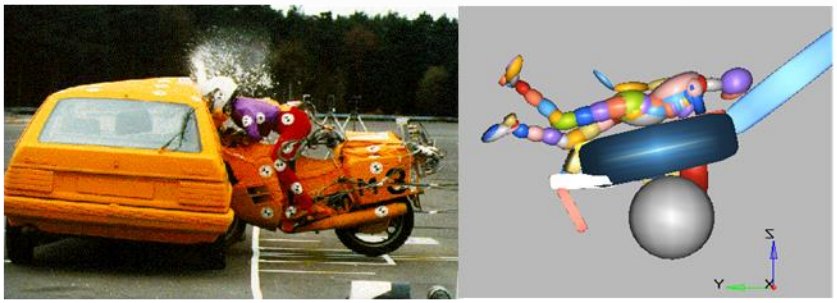
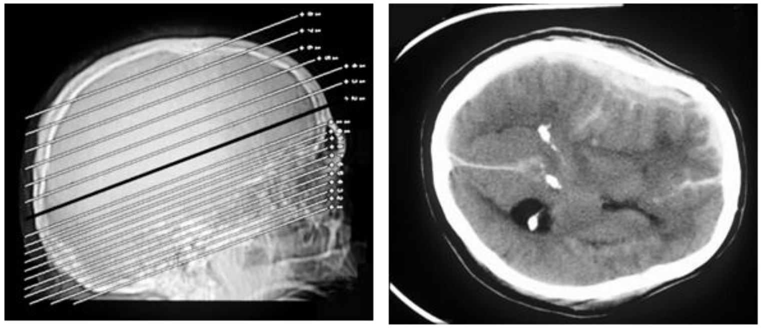
Experimental or analytical replication

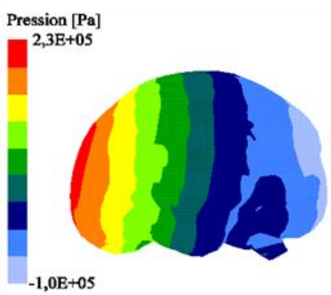


Real accidents

Detailed medical report

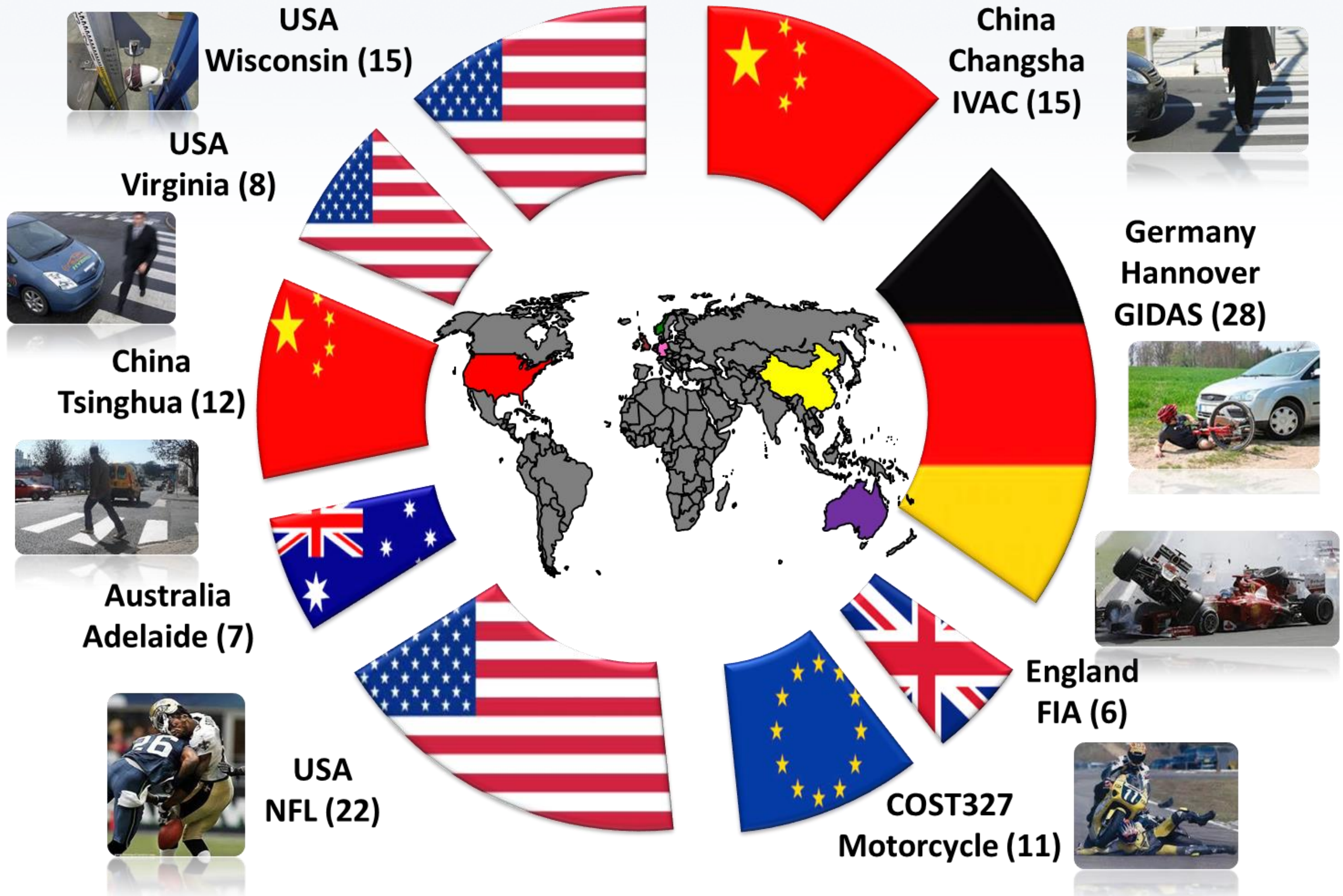


Numerical reconstruction



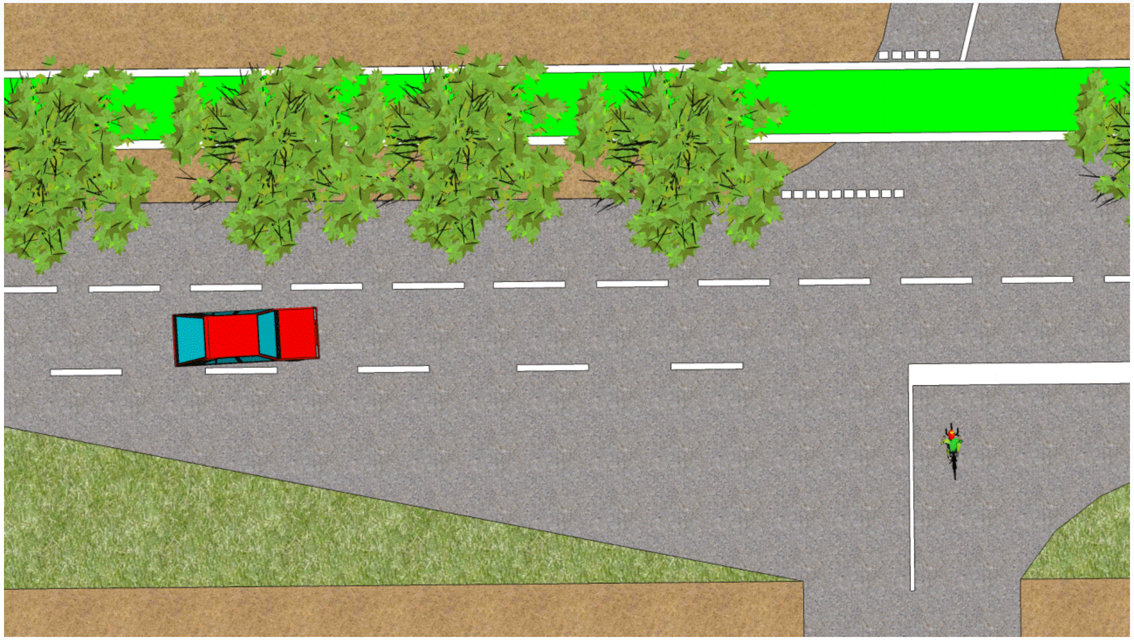
Injury mechanisms and tolerance limits

HEAD TRAUMA DATABASE (125 CASES)



DETAILED ACCIDENT RECONSTRUCTION

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

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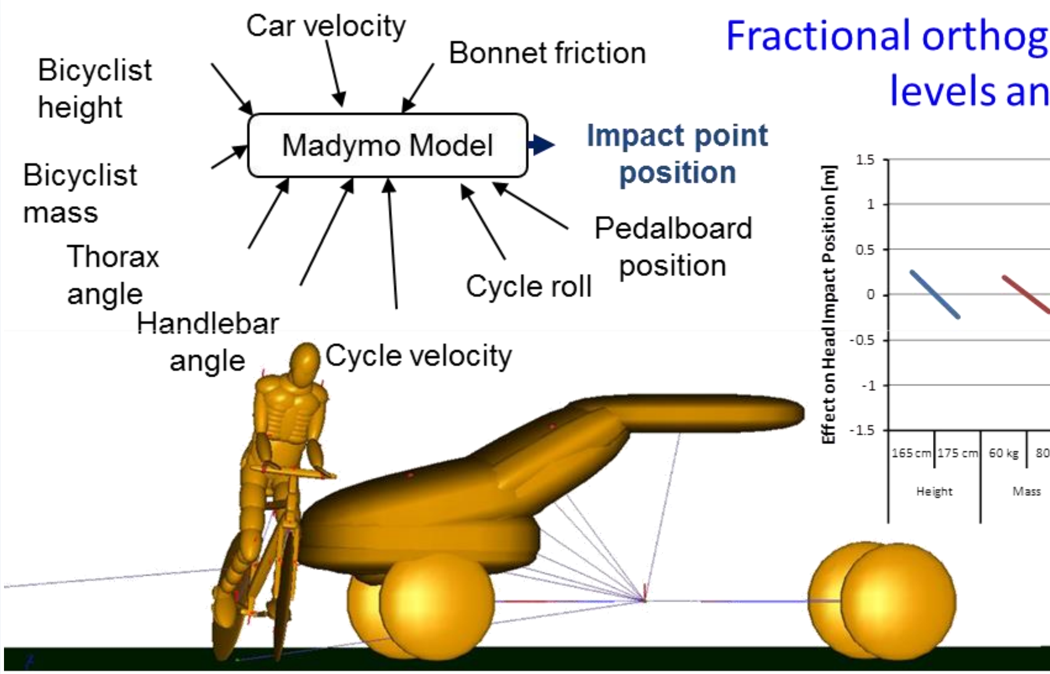
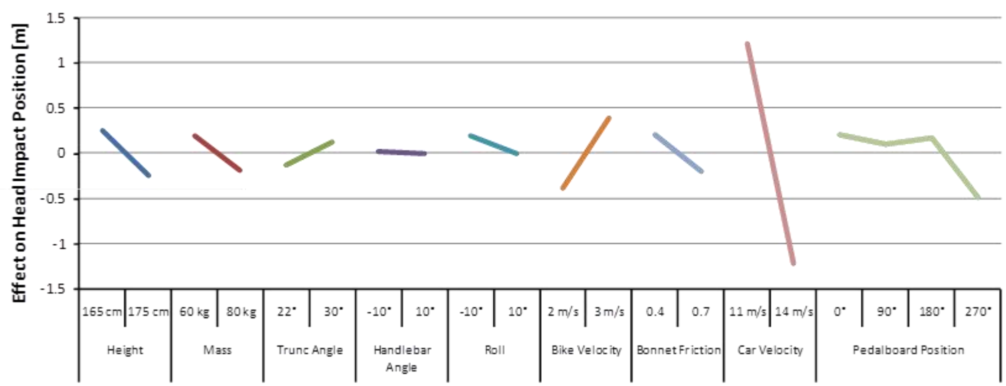
Unistra modeling

Parametric study
(~16 simulations)

	A	B	C	D	E	F	G	H	M
	Height [m]	Mass [kg]	Trunc Ang. [deg]	Handlebar Ang. [deg]	Roll [deg]	Bike Vel. [m/s]	Bonnet friction	Car vel.[m/s]	Pedalboard Ang. [deg]
Level 1	1.65	60	22	-10	-10	2	0.4	11	0
Level 2	1.75	80	30	10	10	3	0.7	14	90
Level 3									180
Level 4									270



Fractional orthogonal array L16 (12 factors at two levels and a factor with 4 levels)



Evaluation function F versus car velocity and bicyclist position

EXAMPLE : KINEMATICS RECONSTRUCTION

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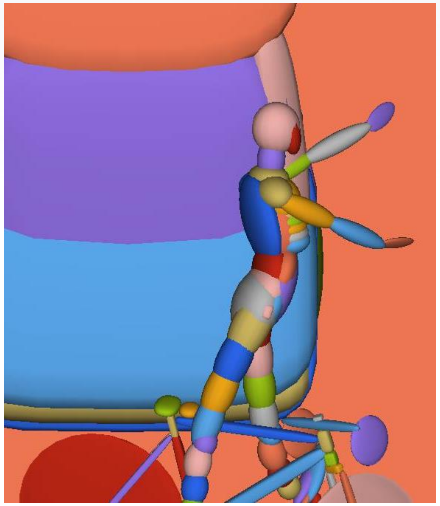
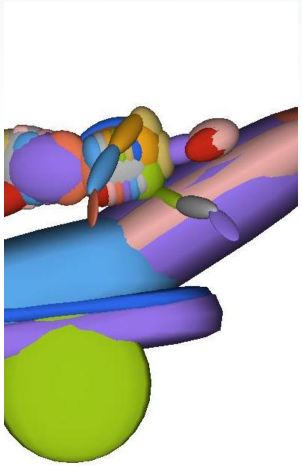
Unistra modeling





$V_{resultant}$ = 10.9 m/s

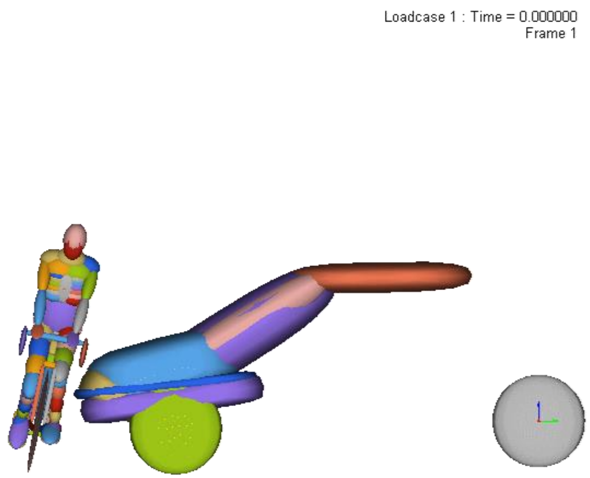
V_{normal} = 10.0 m/s

$V_{tangential}$ = 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



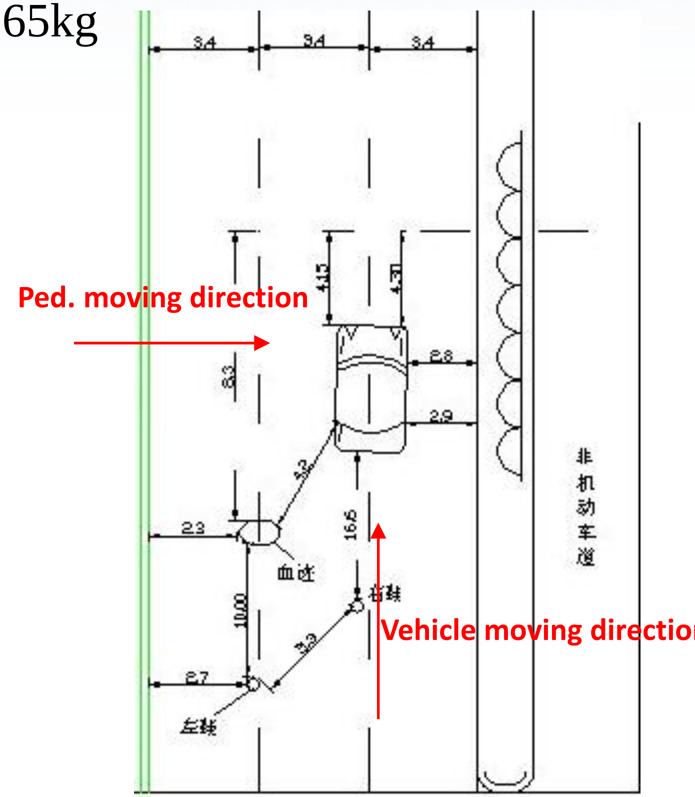
➢ *Exemple pedestrian case (1)*

From IVAC database

- Victim information: 32-year-old male, 170cm and 65kg
- Vehicle information: Honda
- Impact speed: about 54 km/h

Injury details:

- Scalp hematoma (AIS 1)
- Right knee laceration into joint (AIS 3) and right tibia fracture (AIS 3)



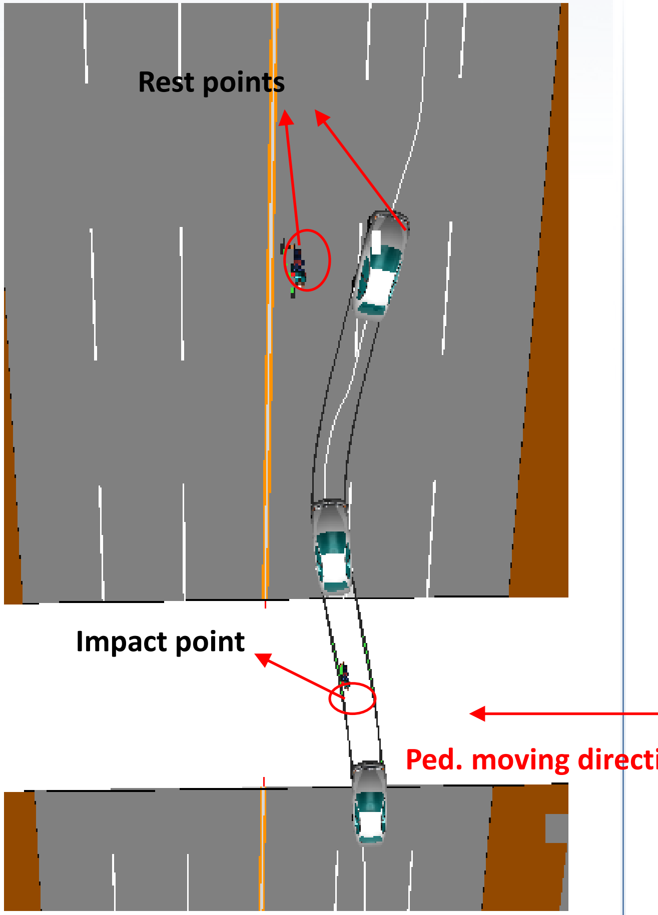
➢ *Exemple pedestrian case (2)*

From IVAC database

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

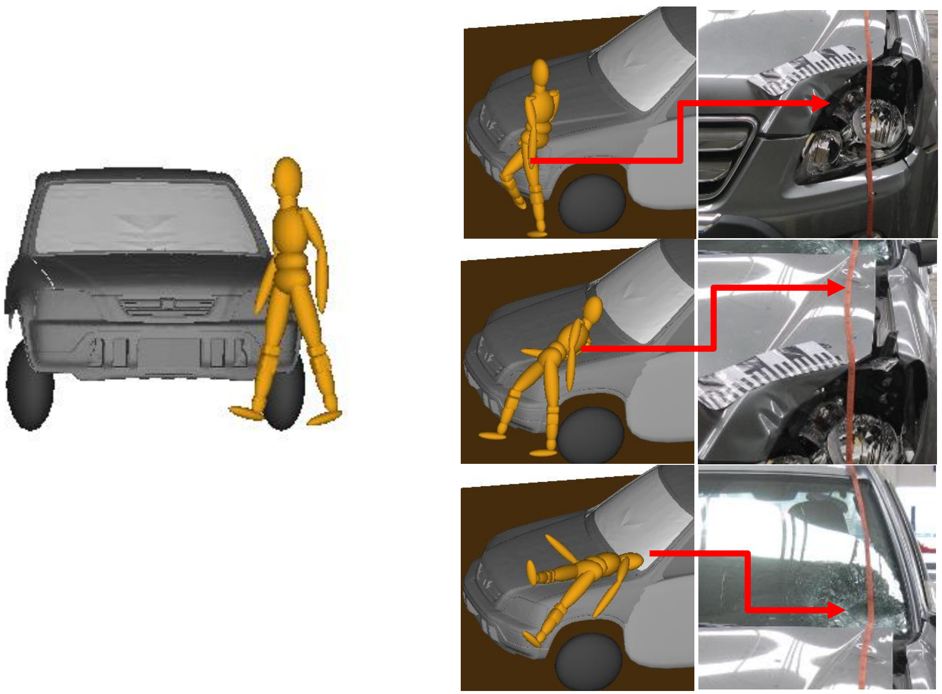
Injury details:

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

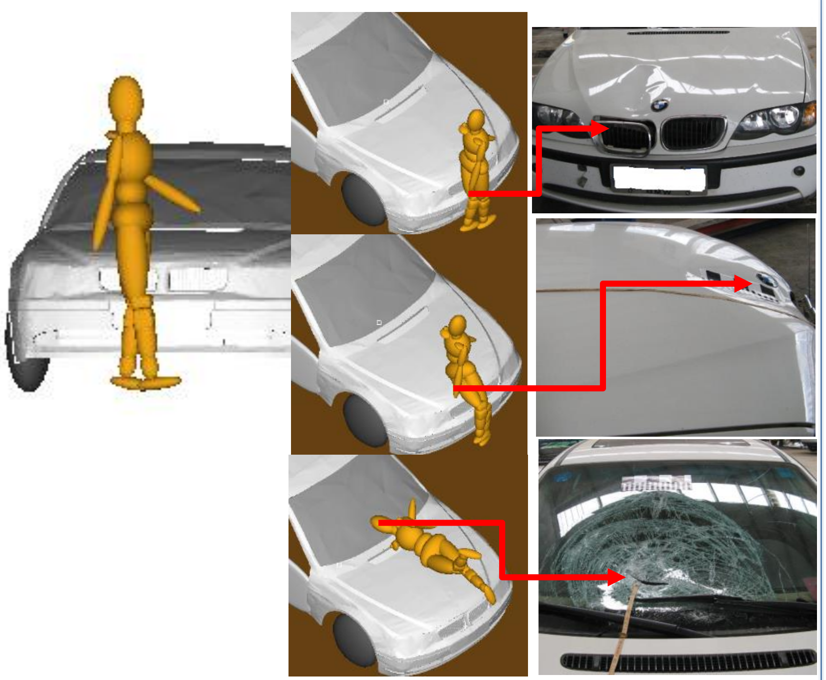


➢ *Reconstruction results*

	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

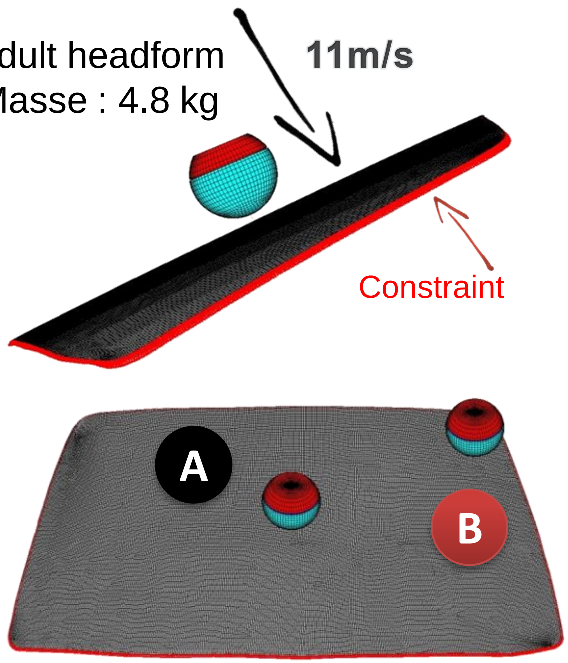
Perpendicular to the windshield at 40 km/h

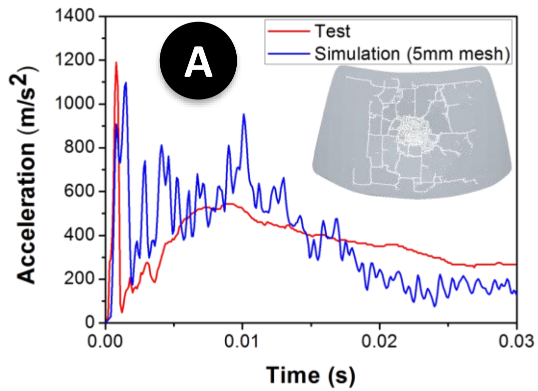
[Lex van Rooij et al, 2001]

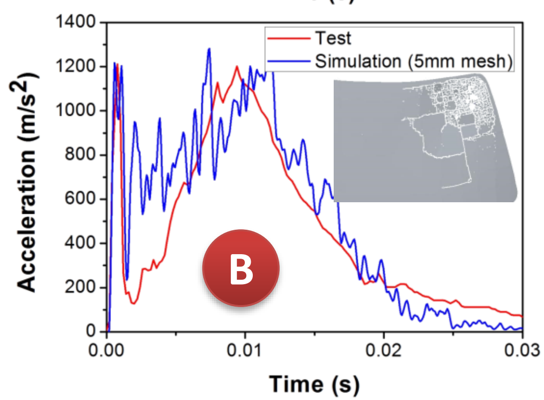
Windscreen Mechanical properties

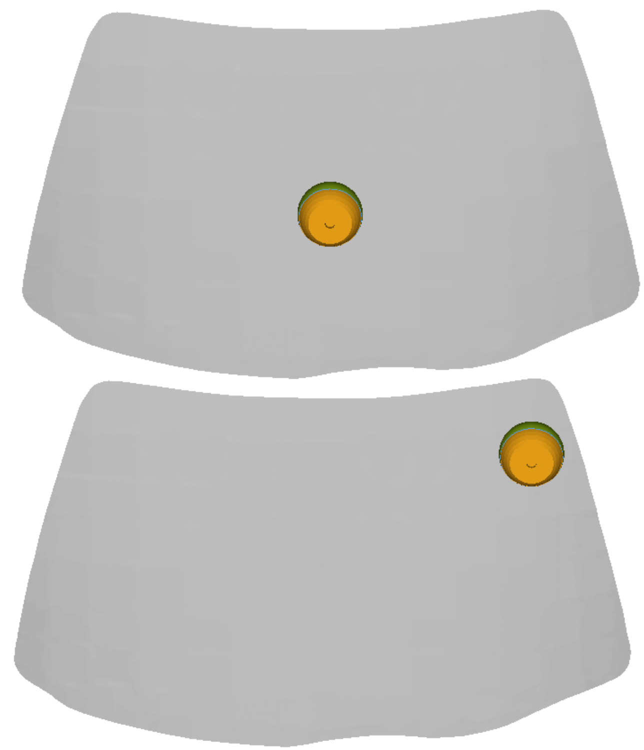
Material	Parameters
Glass	E=74GPa; ρ=2500kg/m3; μ=0.227; EFG=0.001
PVB	E=2.6GPa; ρ=1100kg/m3; μ=0.435

Adult headform
Masse : 4.8 kg









MODEL BASED HEAD INJURY CRITERIA

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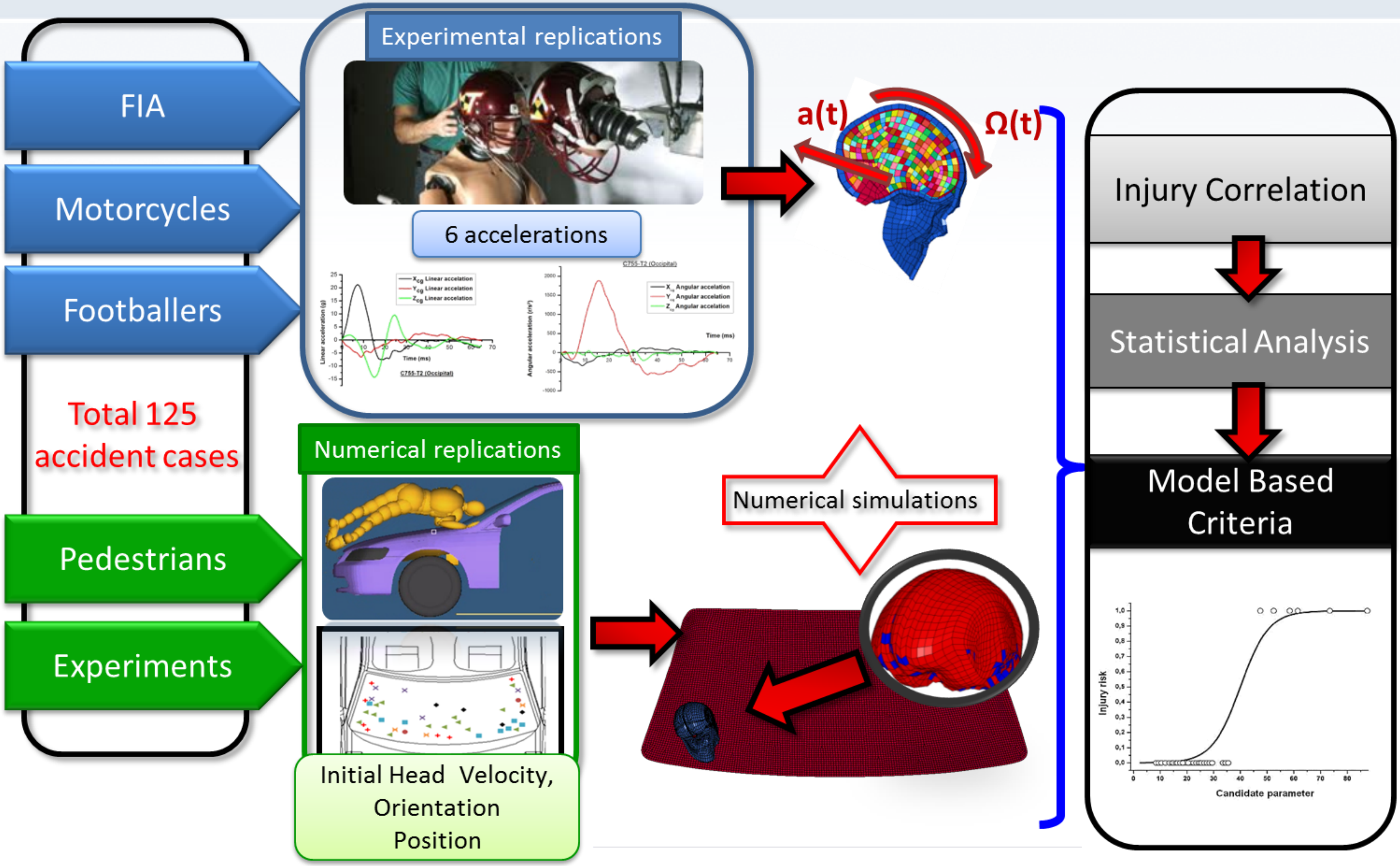
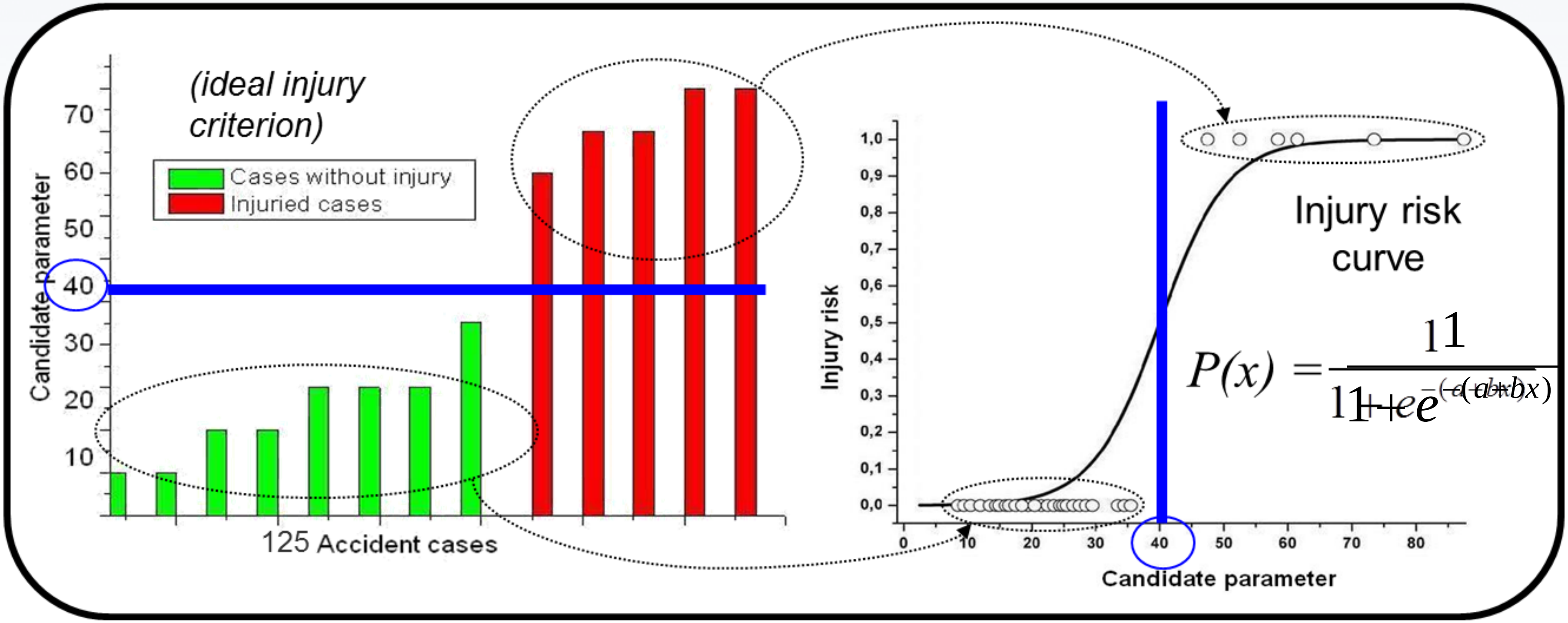
HEAD TRAUMA SIMULATIONS



EXTRACTION OF CRITERIA

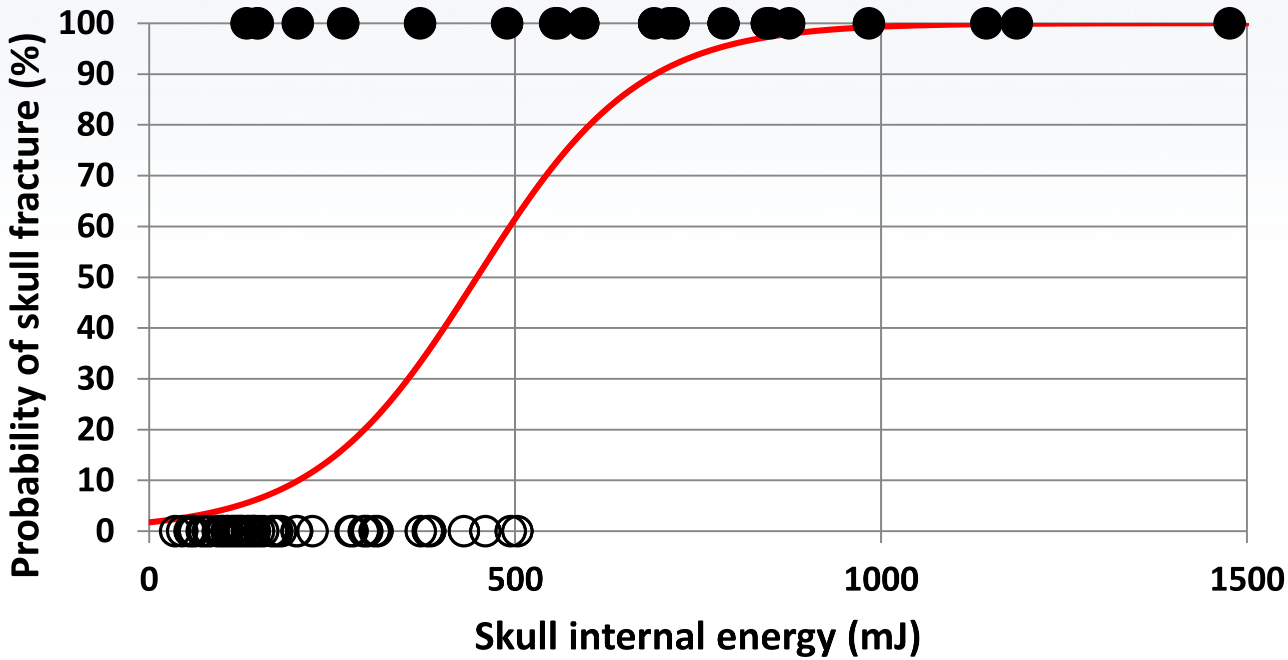


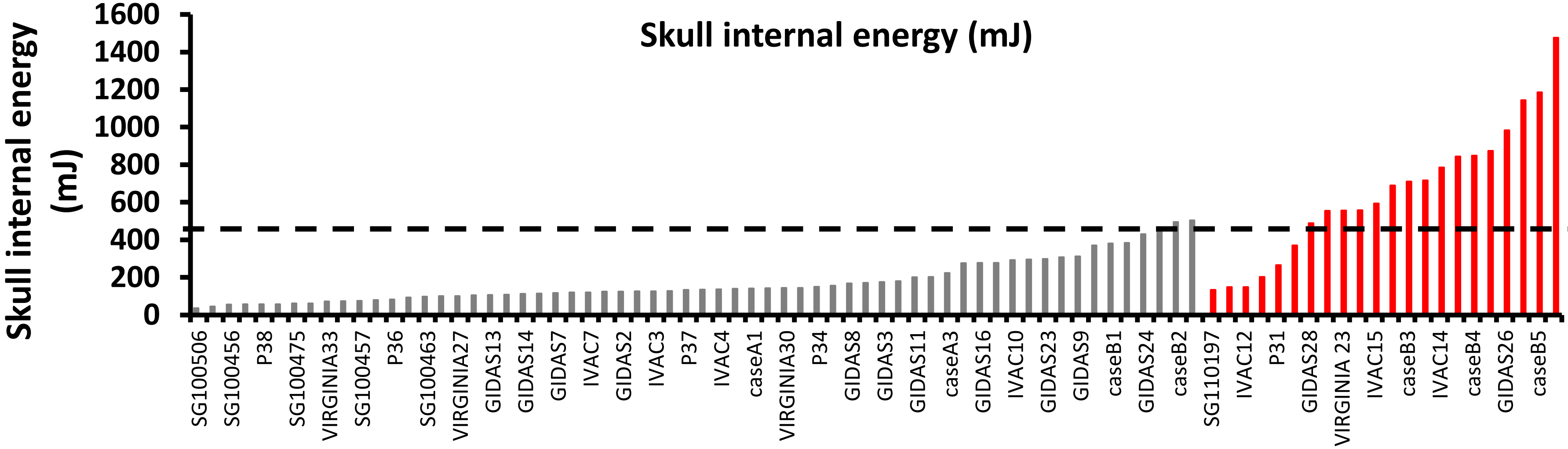
$$P(x) = \frac{1}{1 + e^{-(a + bx)}}$$

Binary logistic regression *(SPSS v14.0)*

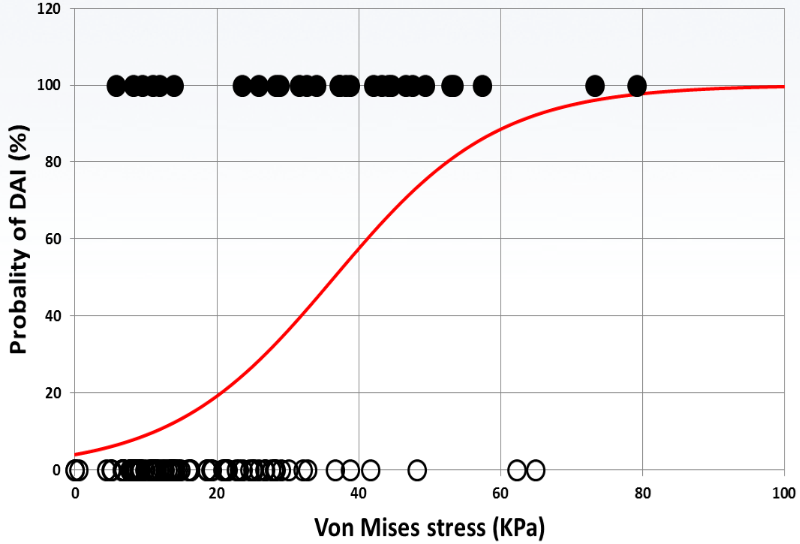
we compared
the Nagelkerke R-sq statistics

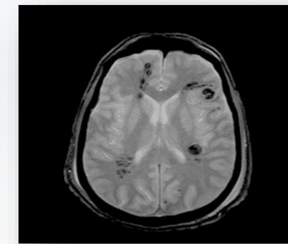
SKULL FRACTUR CRITERIA





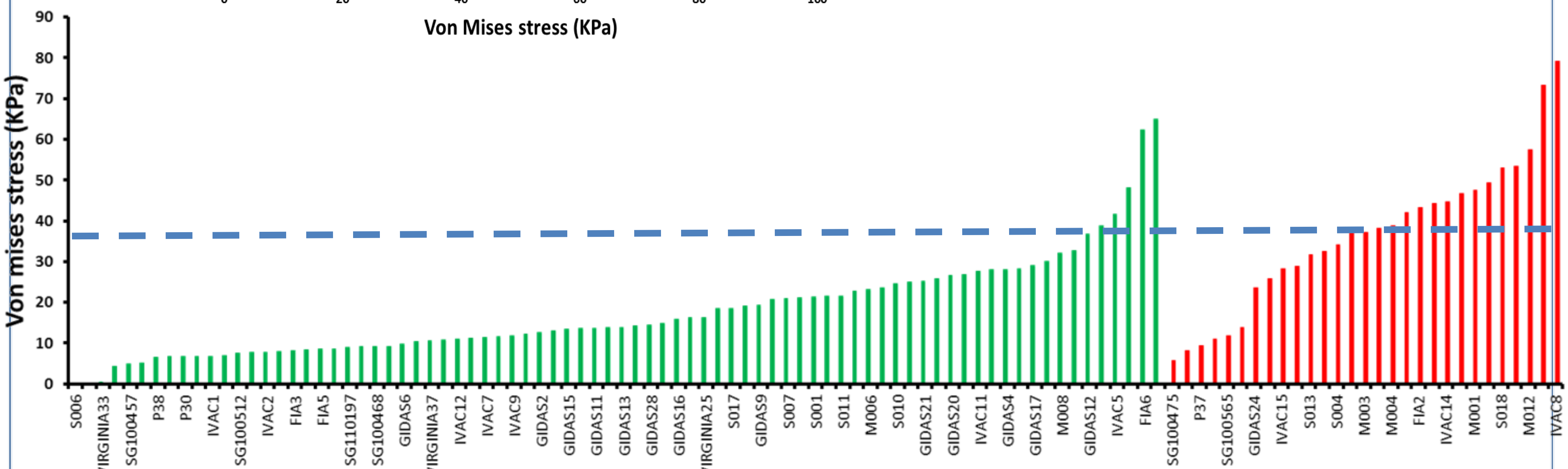
Brain Injury Criteria AIS2+



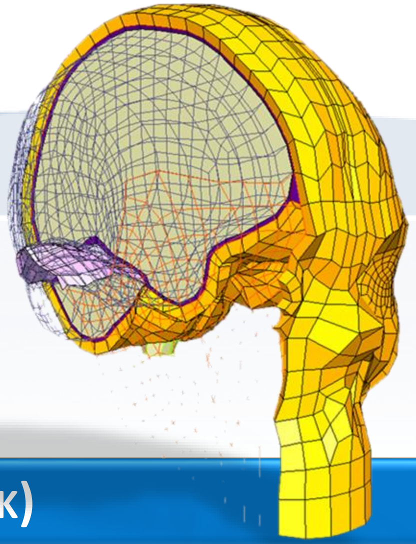


50% risk of DAI (AIS 2+):

VM Stress=37 kPa



SUFEHM INJURY CRITERIA



SUB-ARACHNOIDAL HAEMATOMA (50% RISK)

✓ CSF Internal Energy : -135 kPa

DAI (50% RISK) OF AIS 2+

✓ Intra-cerebral Von Mises stress : 37 kPa

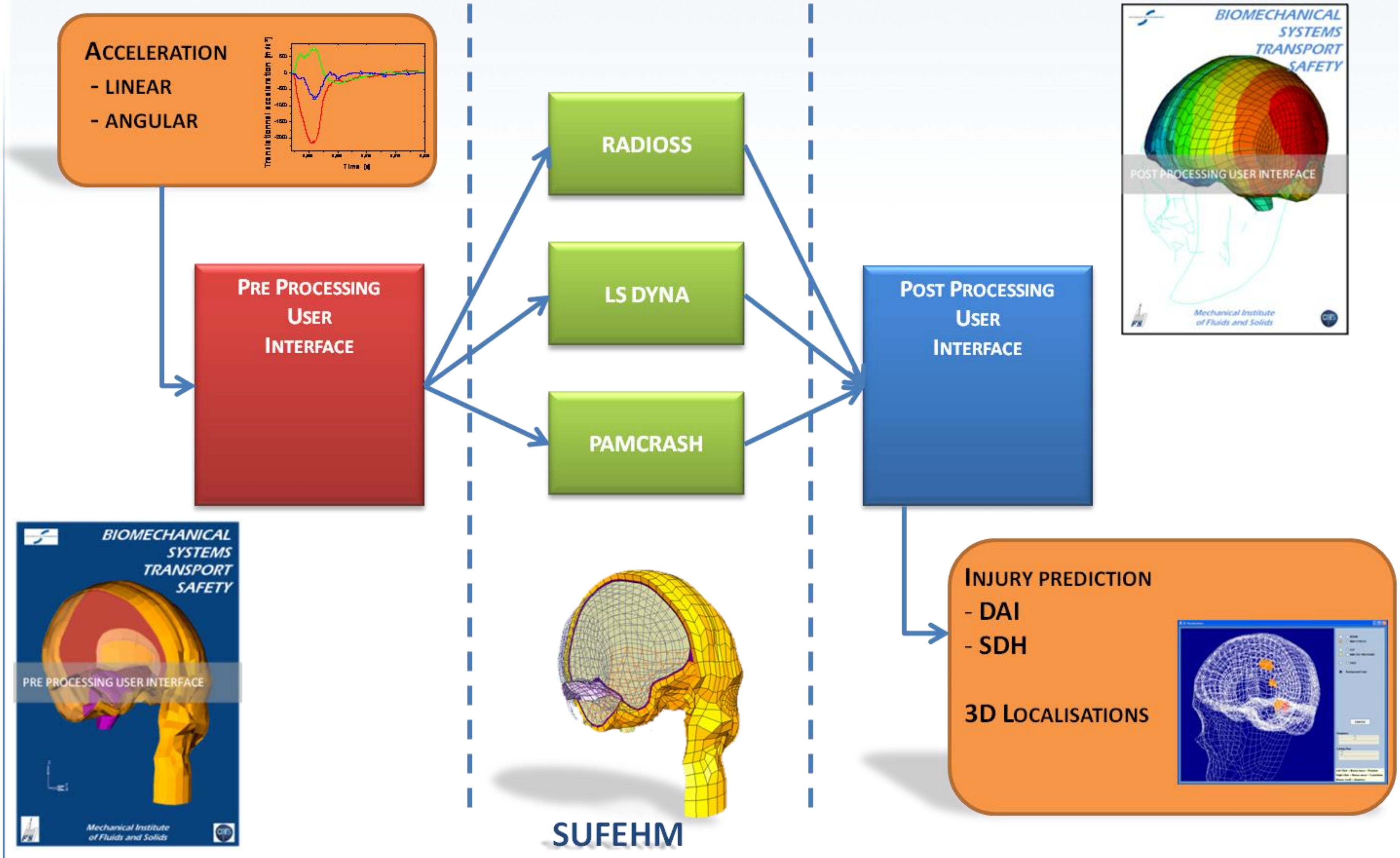
SKULL FRACTURE INJURIES (50% RISK) OF AIS 2+

✓ Skull strain Energy : 439 mJ

HEAD INJURY PREDICTION TOOL FOR END USERS

From Research to Automotive Industry

- **Pre-Post-processing user interfaces :**



SUFEHM IRA TOOL

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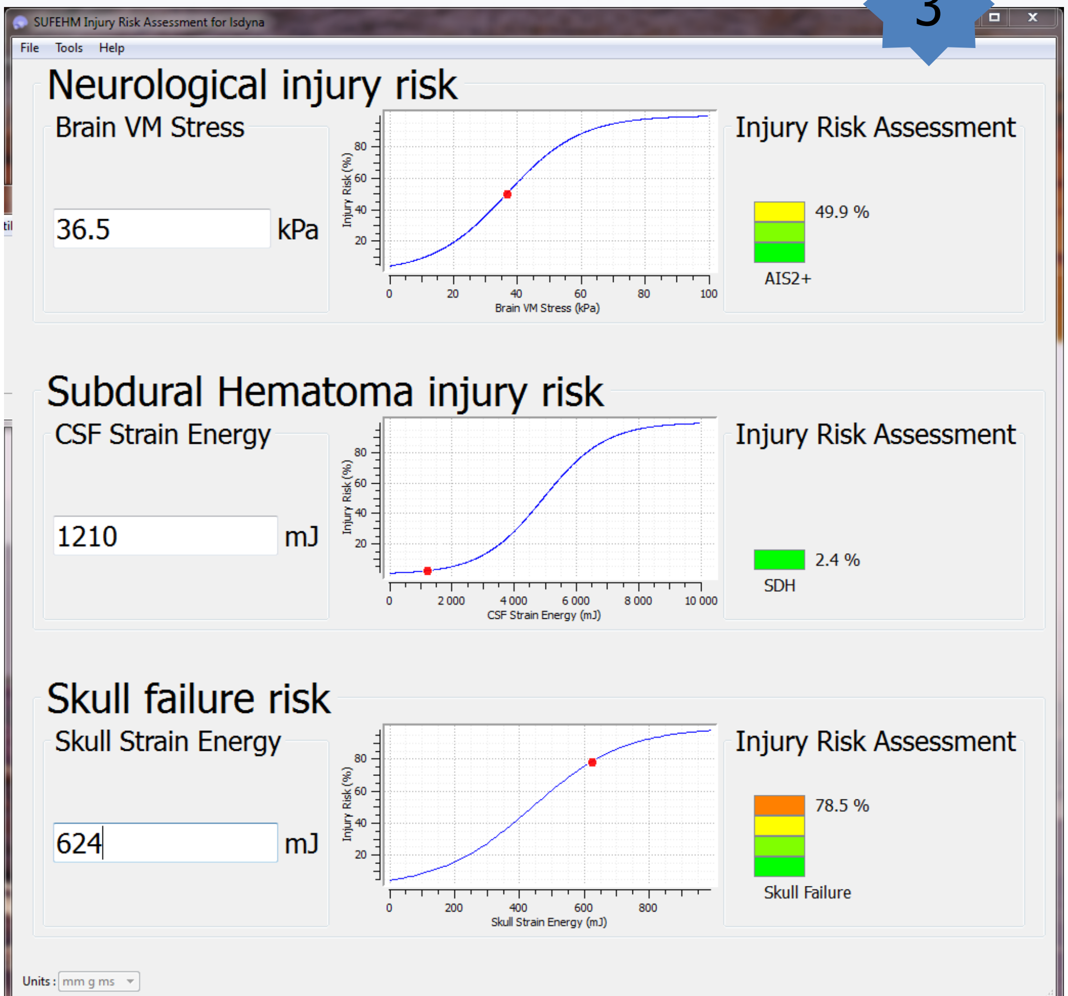
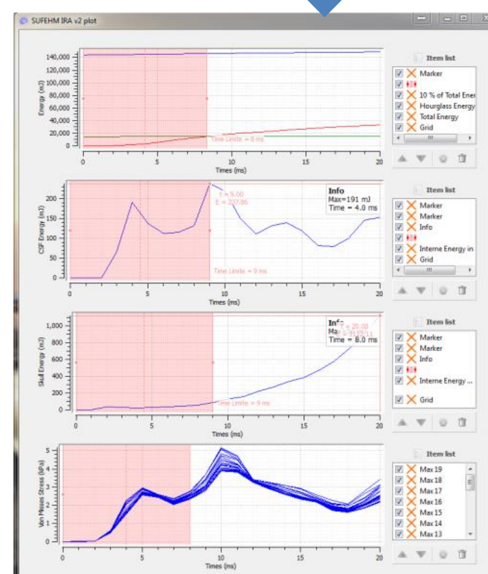
Injury Risk Assessment

3

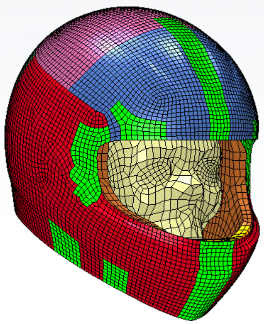
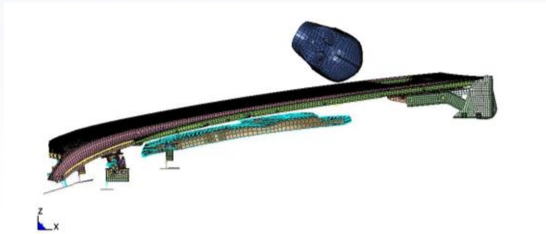
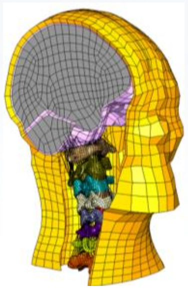
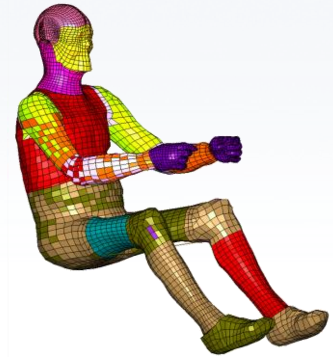


4

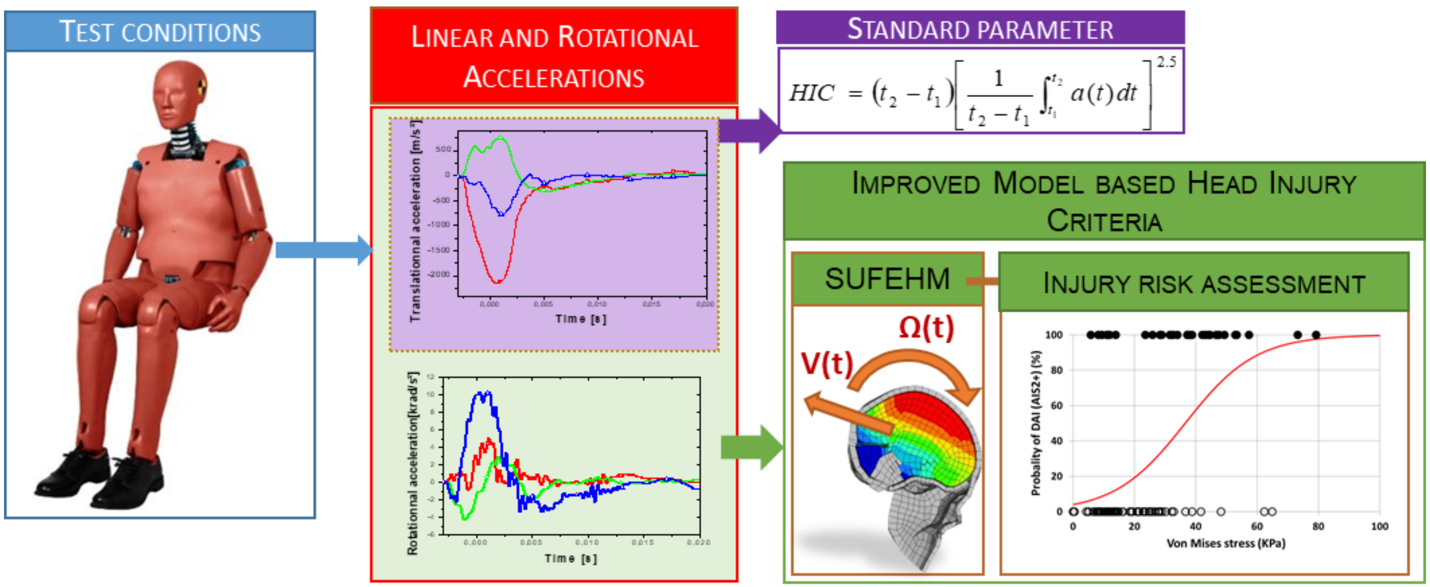


HEAD INJURY PREDICTION TOOL

- **FULL FE APPOACH**

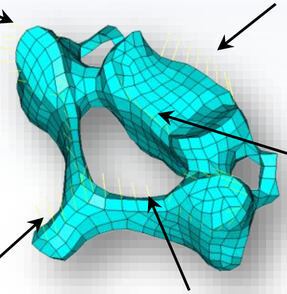
- **COUPLED EXPERIMENTAL VS NUMERICAL TEST METHODS**

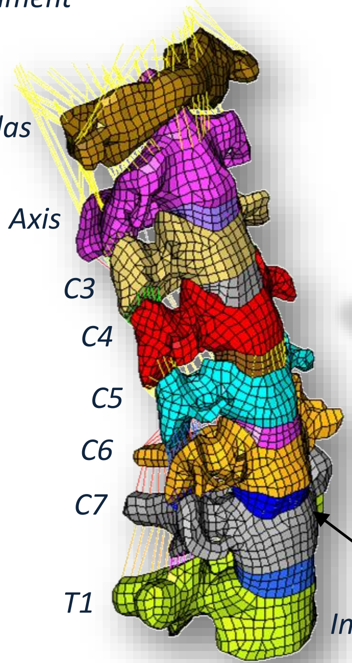


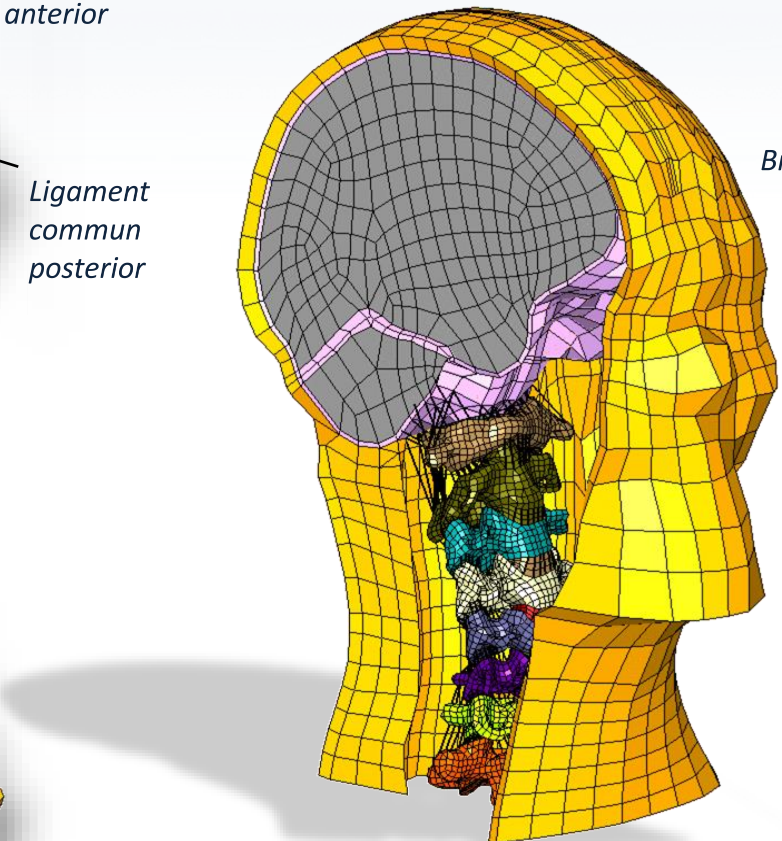
Virtual Testing

(SUFEHM_Full FE)

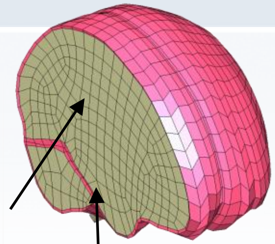
FEM OF THE HEAD-NECK SYSTEM

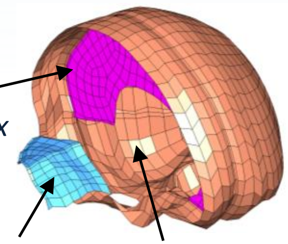


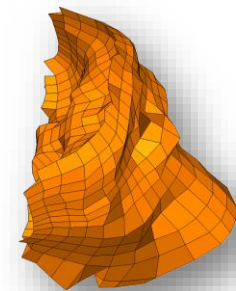


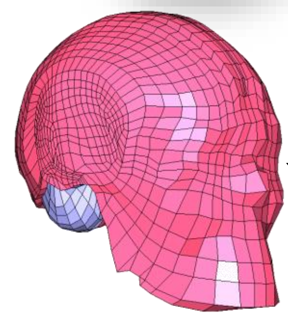


Number of elements
25 661



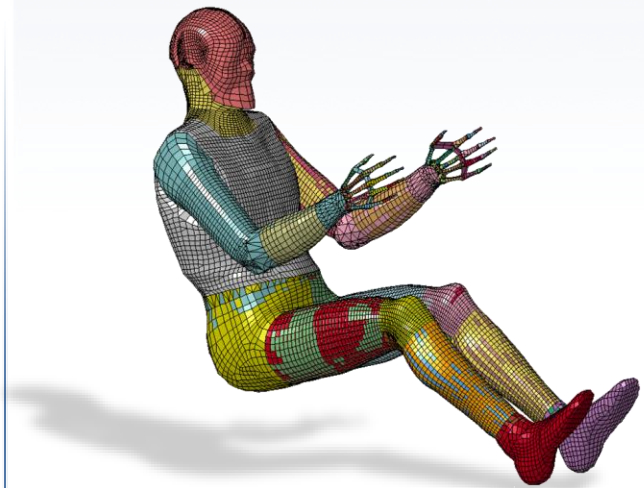


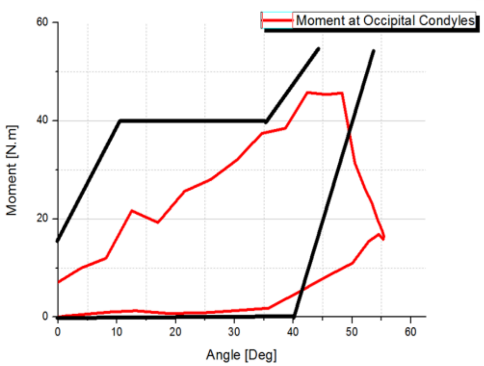




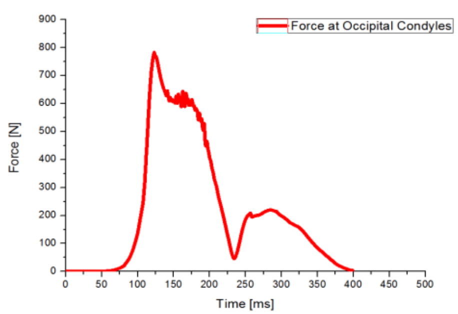
COUPLING SUFEHM TO THUMS

Coupling to THUMS Model under LsDyna

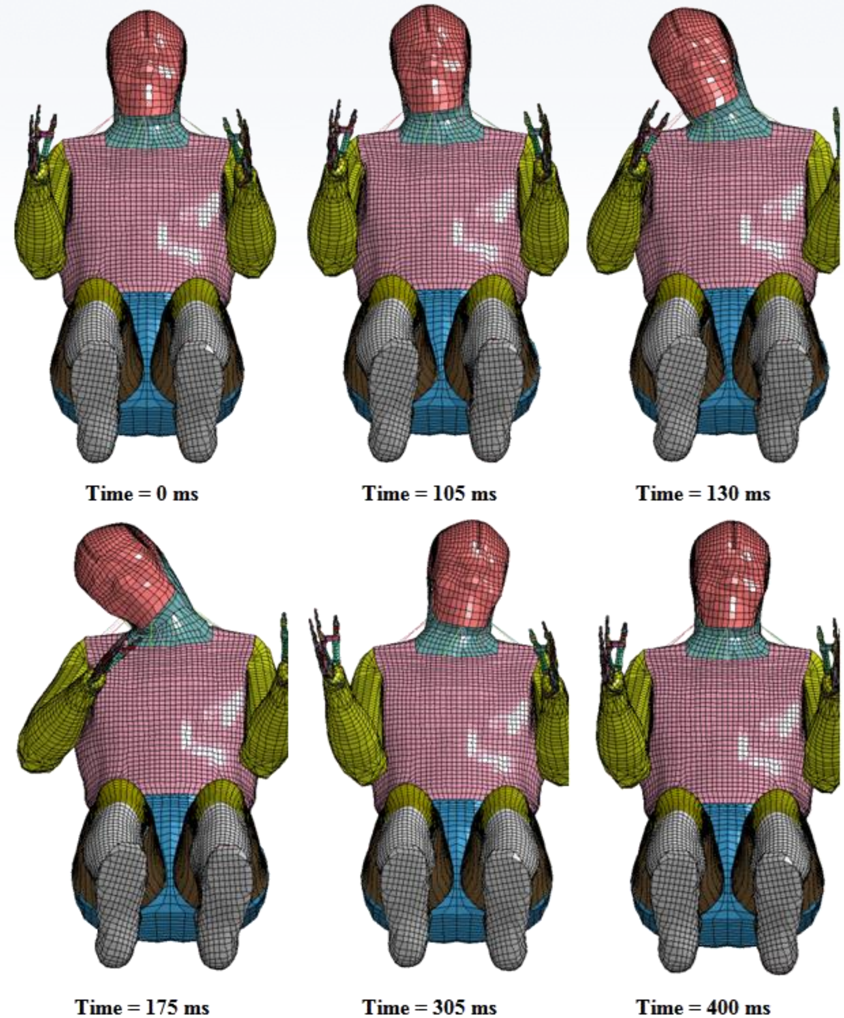




Moment at the Occipital Condyles calculated with the THUMS/Unistra-Head-Neck FEM superposed the corridor define by Patrick and Chou 1971



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



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

VIRTUAL TESTING IN AUTOMOTIVE ENVIRONMENT

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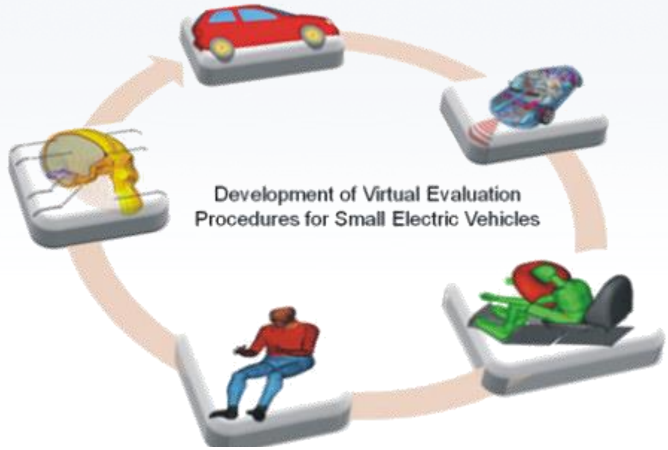
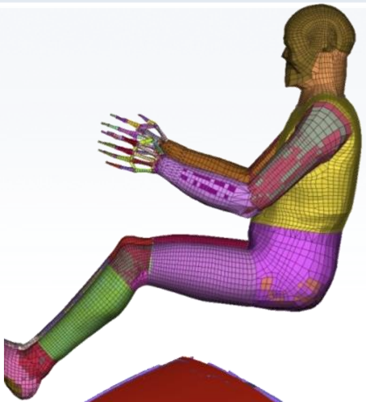
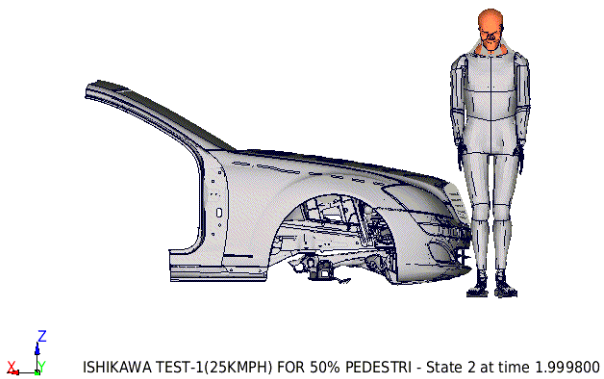
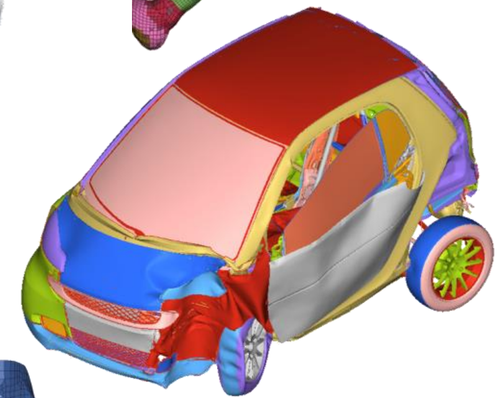
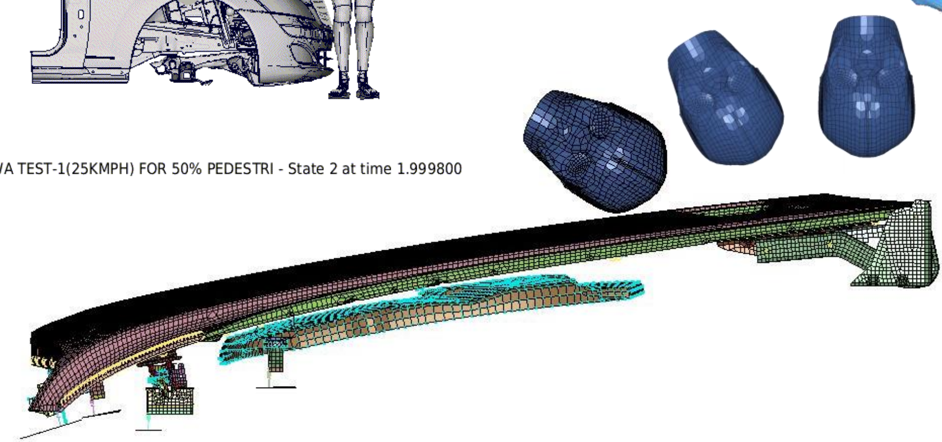








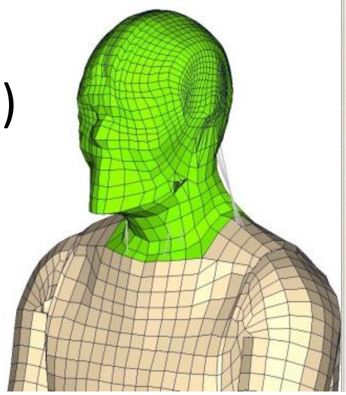


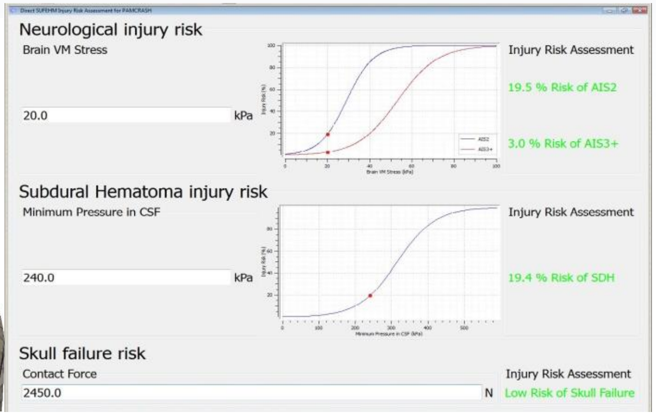
Results of pedestrian simulations

Overview of assessments

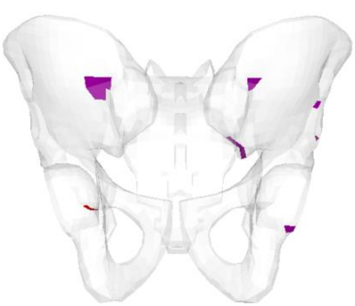
- Assessment of head injury risk

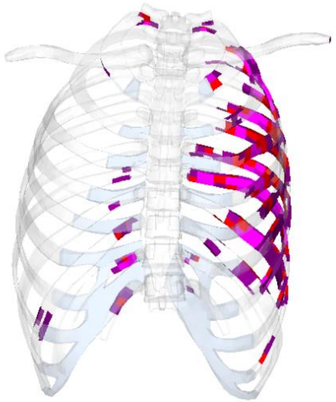
  (using SUFEHM –IRA tool under VPS)

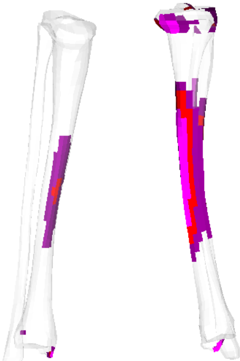




- Further possible injury risk indicators (based on max. pl. strain analysis)
  - ribs







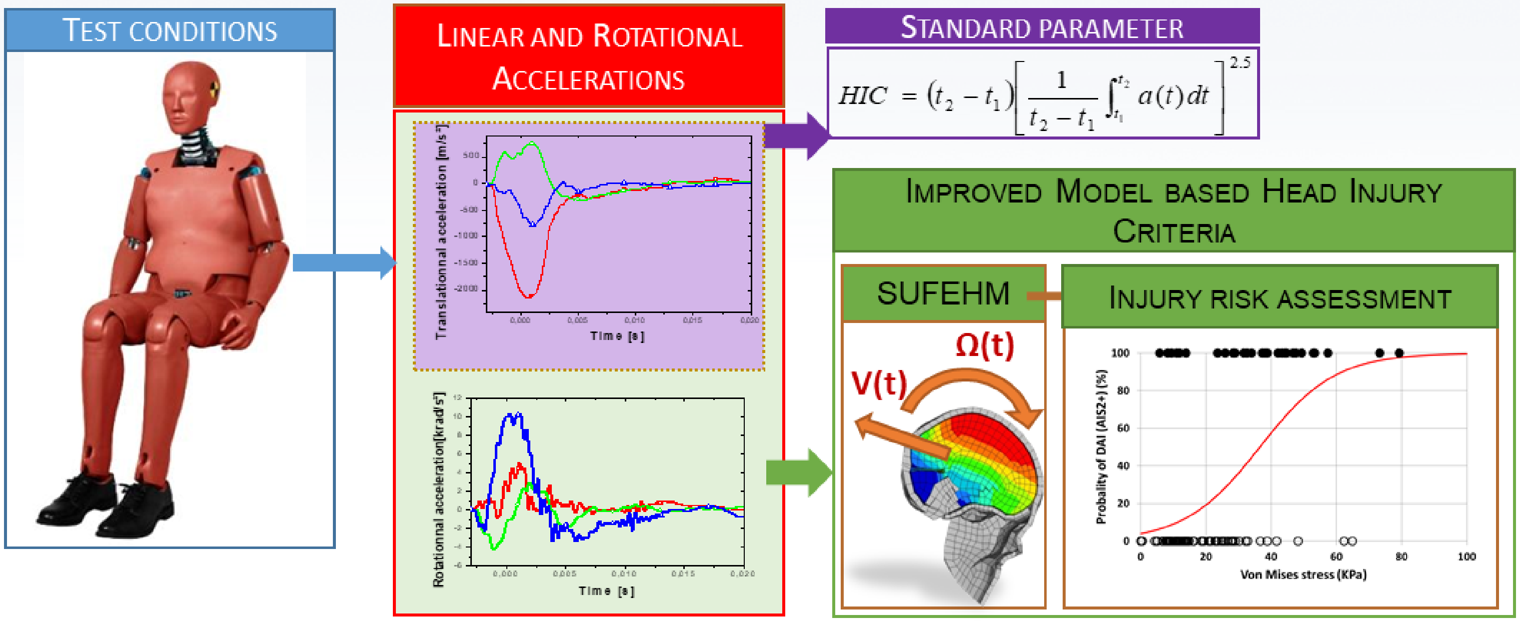
  - tibia/fibula and femur

Experimental vs Numerical Testing

(SUFEHM-Box)

Experimental versus Numerical Test Method

- **Model based brain injury in dummy testing**



Added value of tissue level injury criteria

- 6D acceleration field
- Direction dependents of head response
- Time evolution of acceleration
- Complexe head loading : Lin + Rot
- High correlation to AIS2+ brain injury

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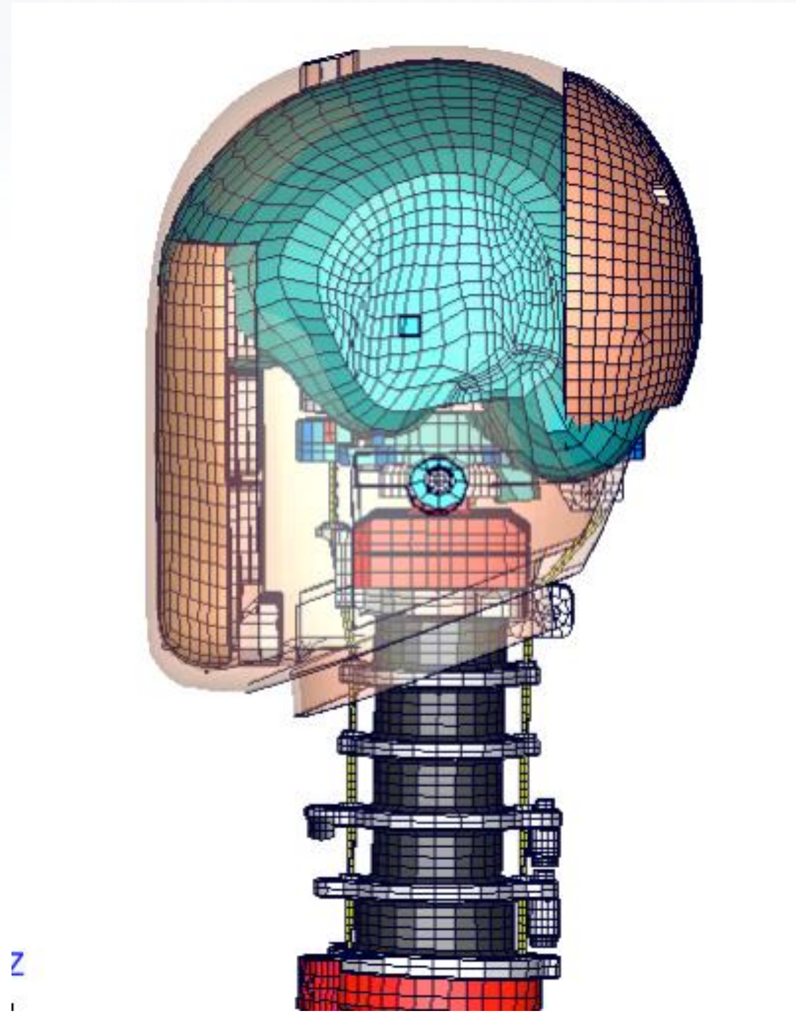
Simplification Hypothesis

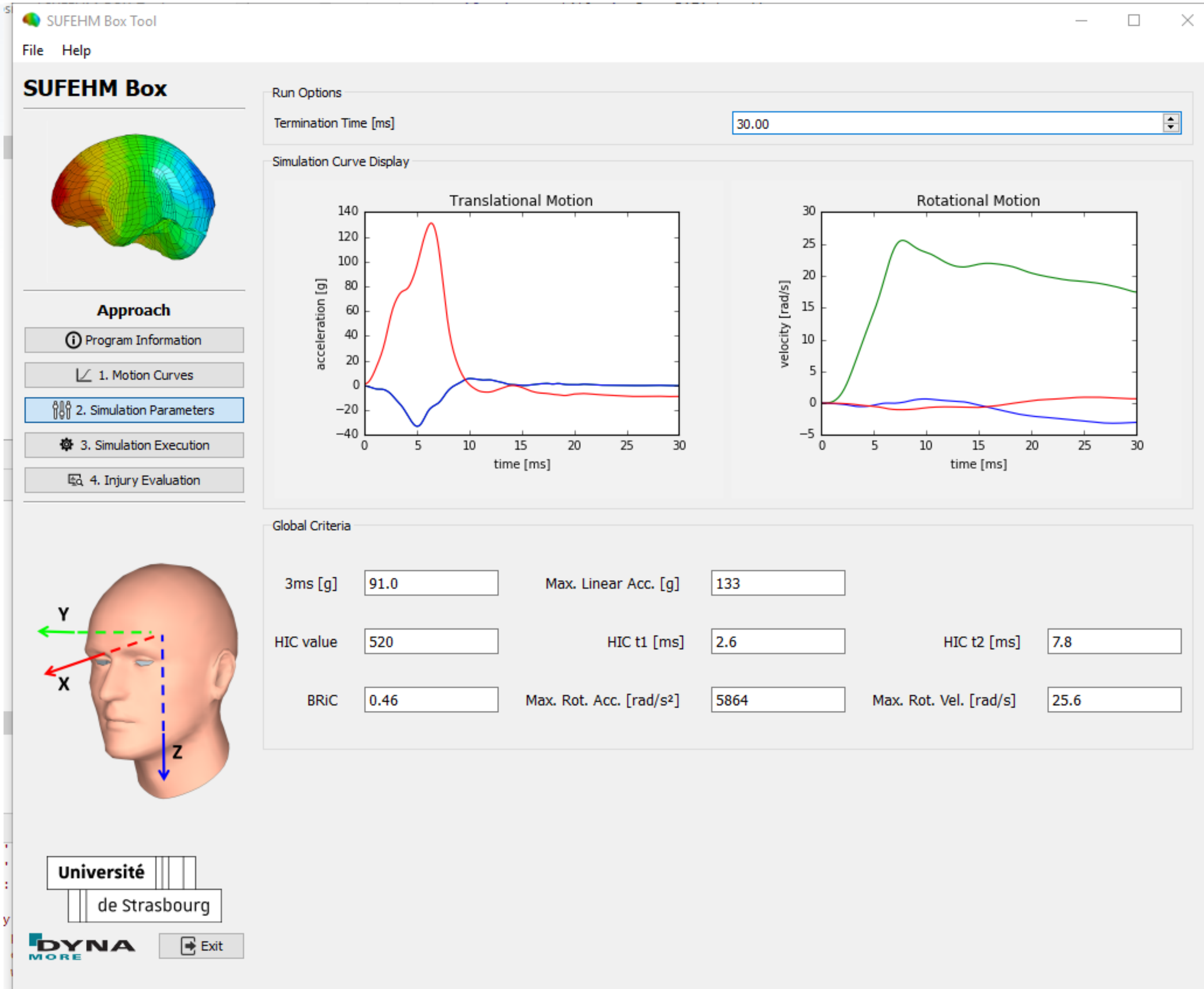
- Rigid Skull (Protected impact)
- Focus on Brain injury
- Moderate brain injury AIS2+



SUFEHM-Box

- Distributed by HUMANETICS

SUFEHM-Box Preprocessing



SUFEHM-Box Post Prcessing

EVALUATION OF SUFEHM

WITHIN EURONCAP

Head

If there is no hard contact a score of 4 points is awarded. If there is hard contact, the following limits are used:
Higher performance limit : HIC_{15} 500
Resultant Acc. 3 msec exceedence 72g

Lower performance and capping limit
HIC_{15} 700
Resultant Acc. 3 msec exceedence 80g

Advance head injury criteria
The SUFHEM criterion is calculated for monitoring purposes only.

AIS Injury definition

- AIS2+ : Moderate concussion (less 1h LOC)
- AIS3+ : Severe concussion (1h to 6 h of LoC)
- AIS4+ : Diffuse axonal injury (6h to 24h LoC)

Continuum between concussion and DAI

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GENERAL CONTEXT

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- Within EuroNcap-FIWG it was decided to evaluate SUFEHM criteria comparatively to current head injury criteria in use
- SUFEHM-Box has bee sent to a 45 Partners
- An agreement on use of SUFEHM-Box was signed by partners
- Evaluation is based on the comparative assessment of brain injury risk for existing pulses coming from Front impacts as well as Lateral impacts
- There is still a need to further discuss and agree on a methodology
- Draft methodology is proposed in this document
- First eedback and analysis is exposed
- Preliminary conclusions or proposed

Monitoring at EuroNcap /Conclusions

- SUFEHM was distributed to nearly 50 partners
- SUFEHM risk is not correlated with risks computed with other criteria:
- This demonstrates that -SUFEHM integrates new dimensions (combined loading, time evolution, direction dependent, tissue level)
- SUFEHM is not correlated with Maximum Input Parameter (when HIC and Bric are)
- Comparison between computed injury risk is difficult as considered AIS level are different. From now we will focus on AIS+2 only
- Risk computed with HIC is often zero as it does not consider rotation
- Brain injury risk computed with BRIC seams to be much higher as SUFEHM related risk.
- Risk (AIS2+) computed with SUFEHM ranges between 5 and 20 %

Next steps

- Monitoring of SUFEHM within Euroncap

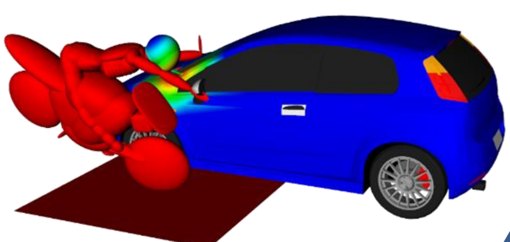
NEW HELMET TEST METHODS: (MOTORCYCLE AND CYCLE)

PRIX INNOVATION
2019 SÉCURITÉ ROUTIÈRE TOUS RESPONSABLES

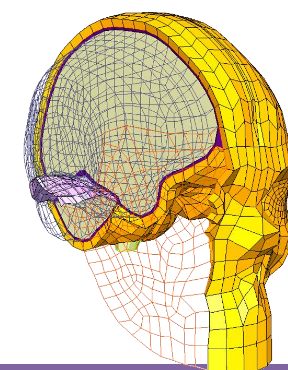
THRE KEY ASPECTS TO BE CONSIDERED

A more realistic 6D instrumented headform

New Test Method



More realistic impact conditions



More Biofidelic Injury criteria

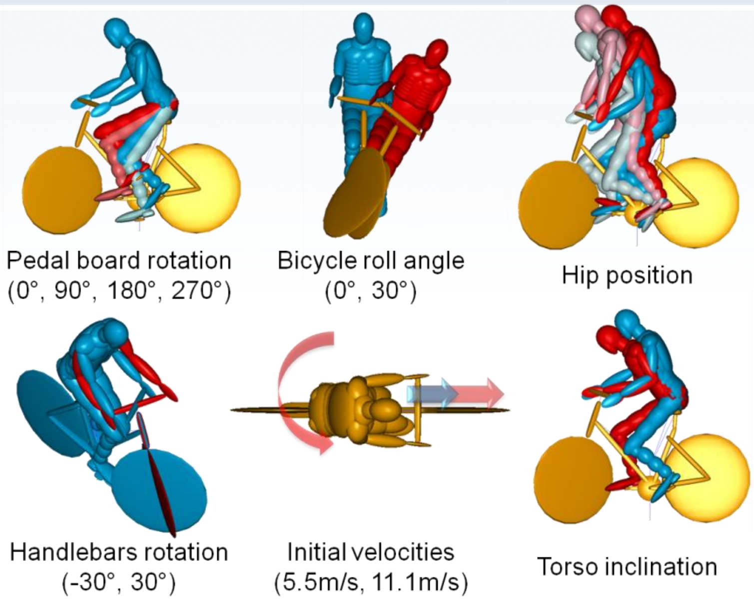
HEAD IMPACT CONDITIONS FOR BICYCLIST

➢in case of bicyclist falling

Study done by *Bourdet et al. (2012)*

- 8 selected factors have been studied
- 2 configurations of falling

A total of 1024 accident simulations was done

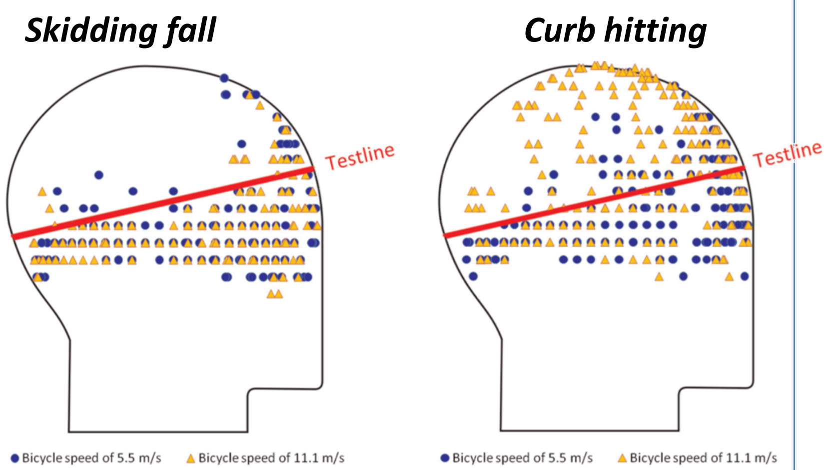


Head Impact conditions for a bicycle speed of ***5,5m/s*** *:*

	$V_{resultant}$ [m/s]	V_{normal} [m/s]	$V_{tangential}$ [m/s]	Impact angle [°]
Skidding fall	6.9±1.2	5.7±1.3	**3.7±0.9**	32.9±8.7
Curb hitting	6.4±0.9	5.2±1.0	**3.7±0.8**	35.4±7.7

Head Impact conditions for a bicycle speed of ***11,1m/s*** *:*

	$V_{resultant}$ [m/s]	V_{normal} [m/s]	$V_{tangential}$ [m/s]	Impact angle [°]
Skidding fall	11.3±1.1	6.2±1.0	**9.4±1.0**	56.6±5.1
Curb hitting	9.1±2.1	4.8±1.3	**7.7±1.9**	58.1±6.5



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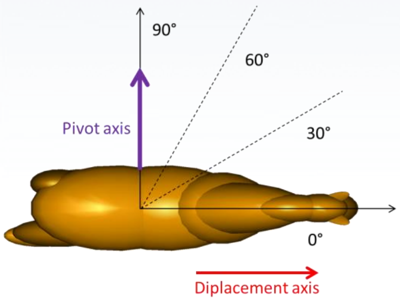
Parametric study definition



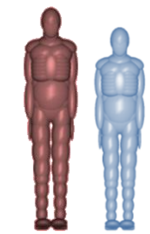
Horse orientation (4 orientations)

Initial horse velocity (6 velocities)

Horse kinematics (4 kinematics)

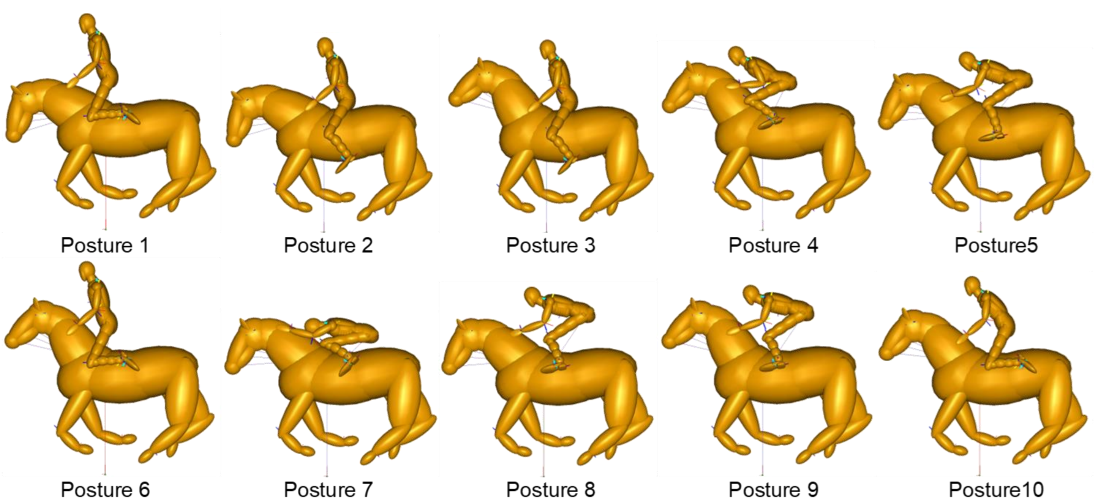
Rider posture (10 postures)

Size of the rider (2 sizes)



→ Multi body model

- **1920 simulations**
- **Head Impact Speed**
- **Head Impact Points**



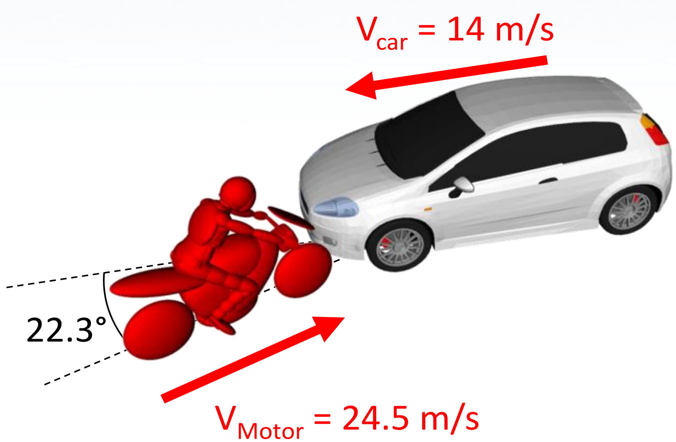
Gaits	Walk	Trot	Gallop			
Velocities [m/s]	2	4	6	9	12	15
Velocities [km/h]	7	14	22	32	43	54

HEAD IMPACT CONDITION

Example : Description of accident case

The initial conditions of the impact and extraction of the victim kinematics

Initial configuration

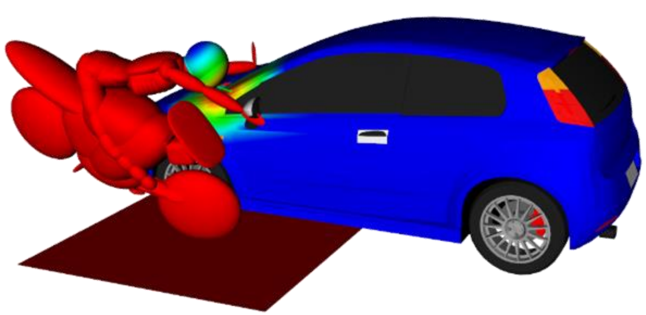


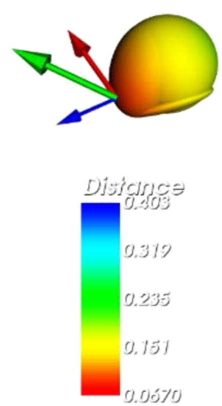
Impact kinematics

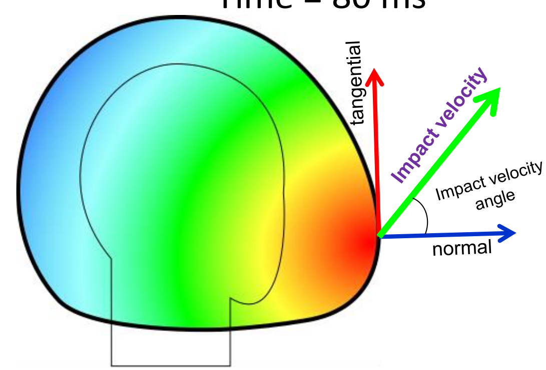
Time = 45 ms

Time = 80 ms

head impact conditions and extraction of the velocity vector



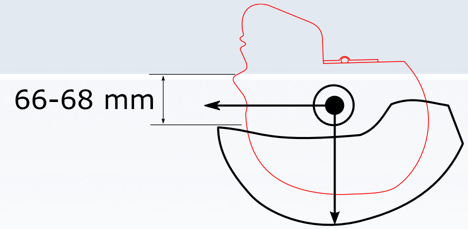




$V_{resultant}$ = 18 m/s
V_{normal} = 10.1 m/s
$V_{tangential}$ = 14.9 m/s
Impact $angle_{/normal}$ = 55.9°

Bicycle Helmet Test Method (CEN WG11)

- Hybrid III 50% head
- Number of repetitions: 3 tests



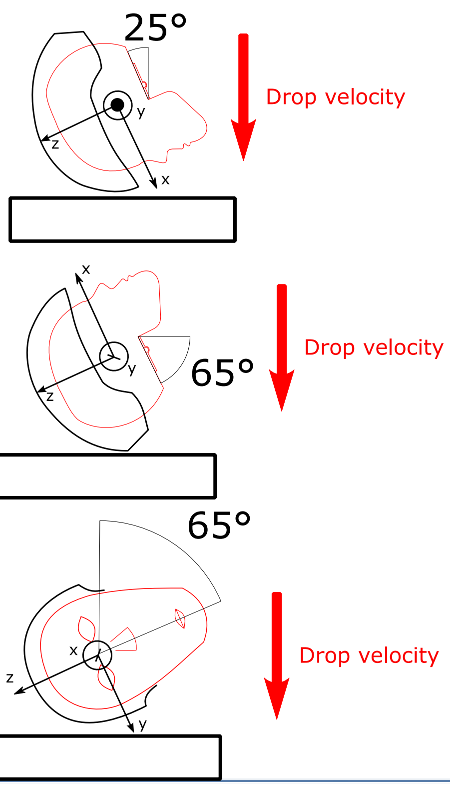
Linear Impacts

Drop velocity = 5.5 m/s

B

R

X



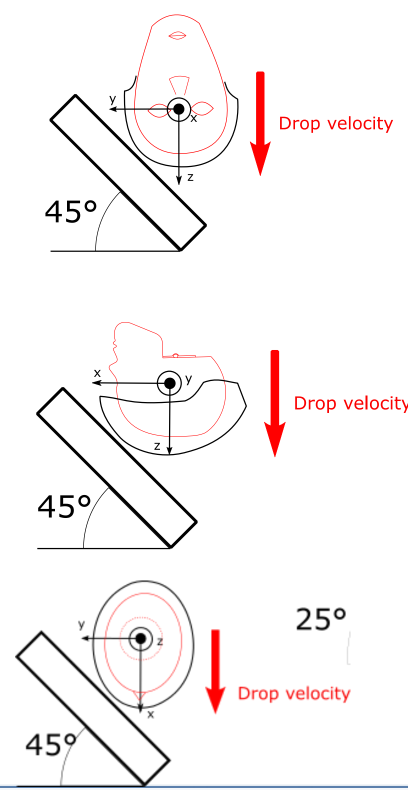
Oblique Impacts

Drop velocity = 6.0 m/s (V_N = 4.2 m/s)

LX

FY

LZ



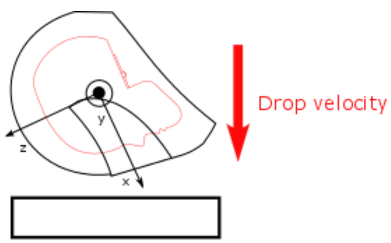
Motorcycle Helmet Test Method (UN-ECE R22-06)

- Hybrid III 50% head
- Number of repetitions: 3 tests

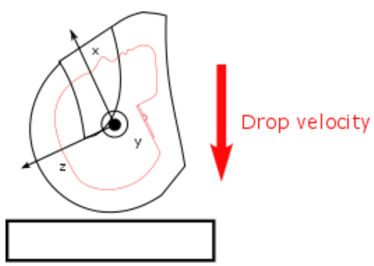
Linear Impacts

Drop velocity = 7.5 m/s

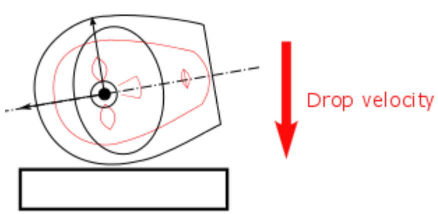
B



R



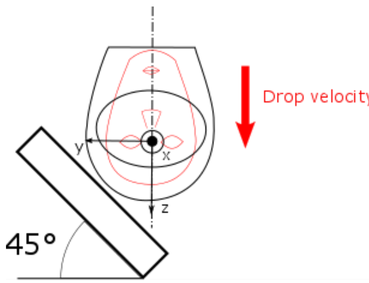
X



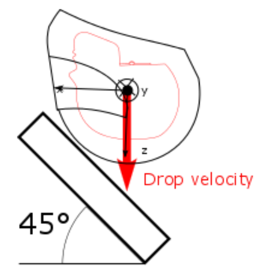
Oblique Impacts

Drop velocity = 8.5 m/s (V_N = 6 m/s)

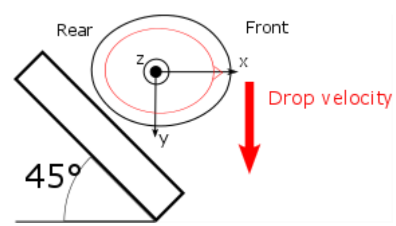
LX



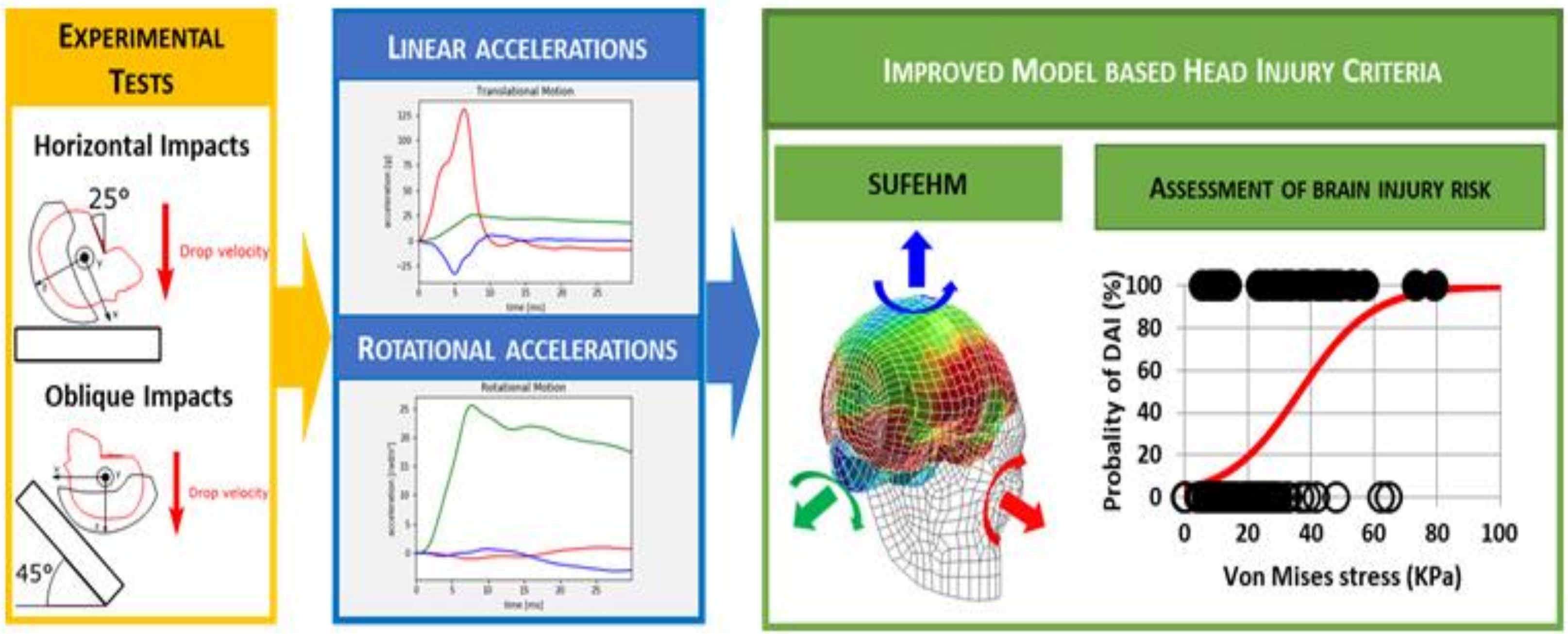
FY



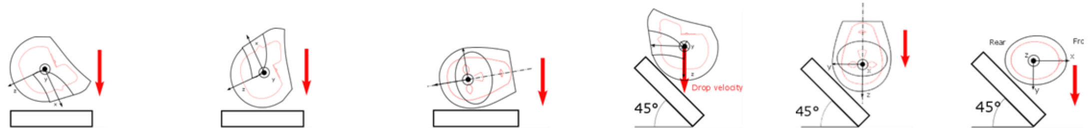
LZ



Experimental vs Numerical Test Method



New helmet rationg system

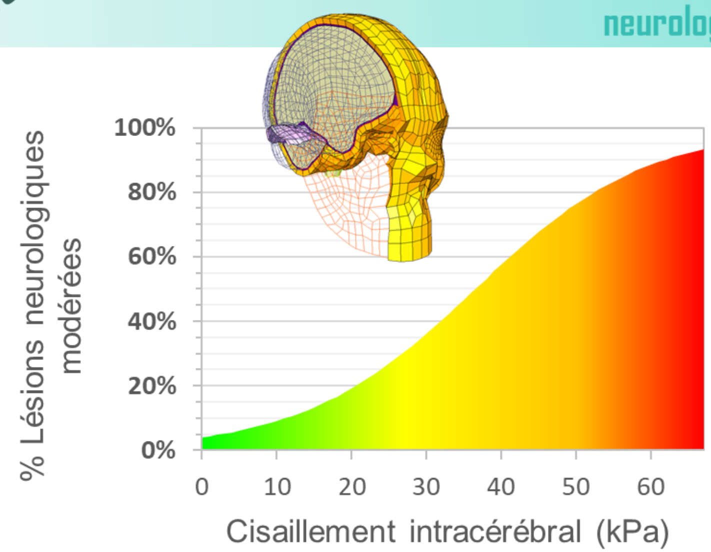


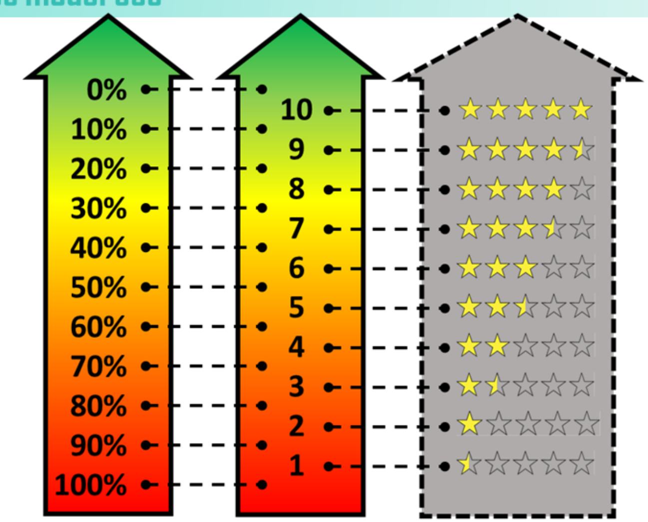
$$MMVMS = \frac{(MVMS_{FRONTAL} + MVMS_{OCCIPITAL} + MVMS_{LATERAL} + MVMS_{YRot} + MVMS_{XRot} + MVMS_{ZRot})}{6}$$

Avec *MMVMS* (*Mean Max. Von Mises Stress*), $MVMS_i$ est le maximum de contrainte de cisaillement pour la configuration *i* (*FRONTAL, OCCIPITAL, LATERAL, YRot, XRot, ZRot*).

évaluation

% Risques de lésions neurologiques modérées | Note /10 | Evaluation

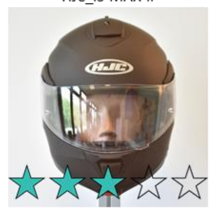




SHARK_SKAWL-2-BLANK-Mat

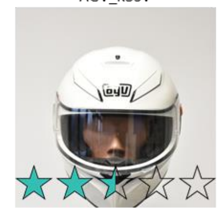

SCORPION_EXO-510-AIR-SOLID


SCORPION_EXO-920


HJC_IS-MAX-II


6DHELMET_ATS-1

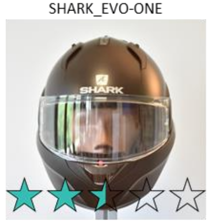

SHOEI_GT-AIR


AGV_K3SV


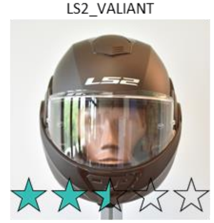
NOLAN_N44-EVO


HJC_IS-17


HJC_CS-15

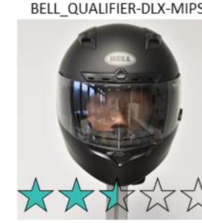

SHARK_EVO-ONE


ARAI_CHASER-X


LS2_VALIANT


SHOEI_NEOTEC


SHARK_SPARTAN-CARBON


BELL_QUALIFIER-DLX-MIPS


SHUBERTH_R2


SHARK_SKWAL


LS2_BREAKER


ASTON_MINIJET-RETRO

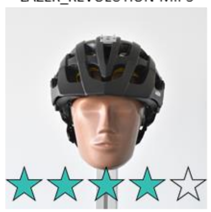

LEATT_GPX-6.5


NOLAN_N87

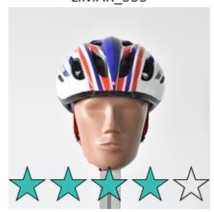

ALPINA_Mythos-3.0-LE

HARALD-NYBORG_BUSETTO

LAZER_REVOLUTION-MIPS

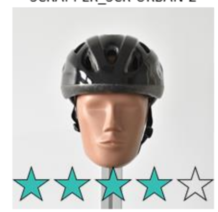


LIMAR_555

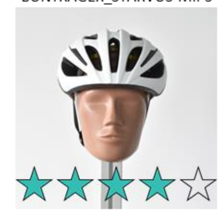


MET_ESPRESSO

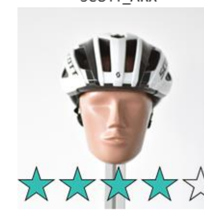
SCRAPPER_SCR-URBAN-2



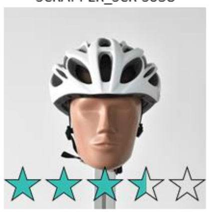
BONTRAGER_STARVOS-MIPS



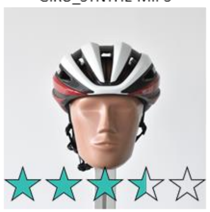
SCOTT_ARX



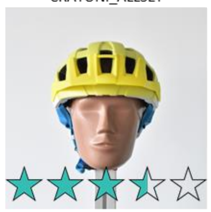
SCRAPPER_SCR-S038



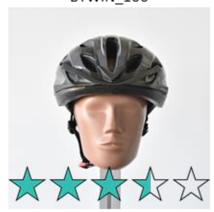
GIRO_SYNTHE-MIPS



CRATONI_ALLSET

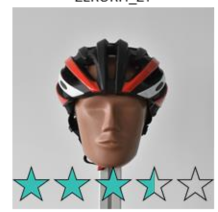


BTWIN_100

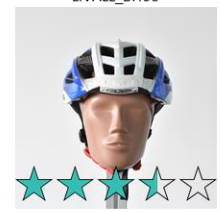


UVEX_city-i-vo

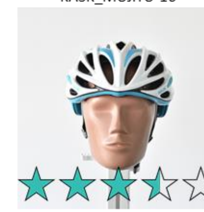
ZERORH_ZY



LIVALL_BH60



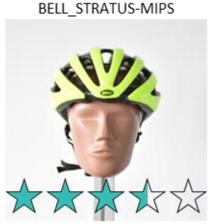
KASK_MOJITO-16



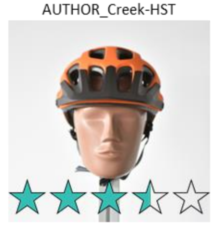
NUTCASE_Gen3-Cherry-Blossom

SPECIALIZED_PROPERO-3

BELL_STRATUS-MIPS

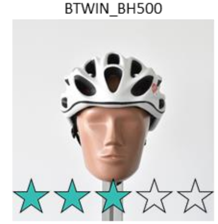


AUTHOR_Creek-HST



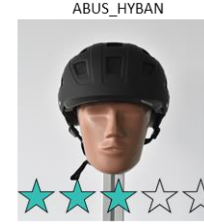
IKEA_SLADDA

BTWIN_BH500

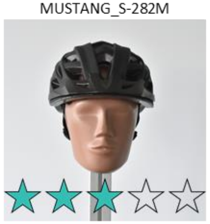


BBB_BHE35-CONDOR

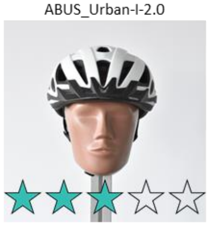
ABUS_HYBAN



MUSTANG_S-282M

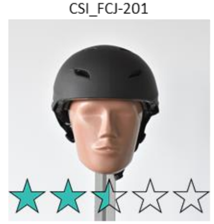


ABUS_Urban-I-2.0



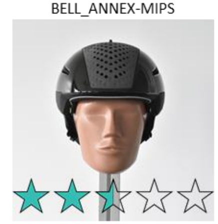
CANNONDALE_RADIUS

CSI_FCJ-201

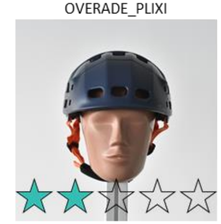


MANGO_X-Ride

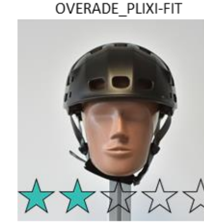
BELL_ANNEX-MIPS



OVERADE_PLIXI



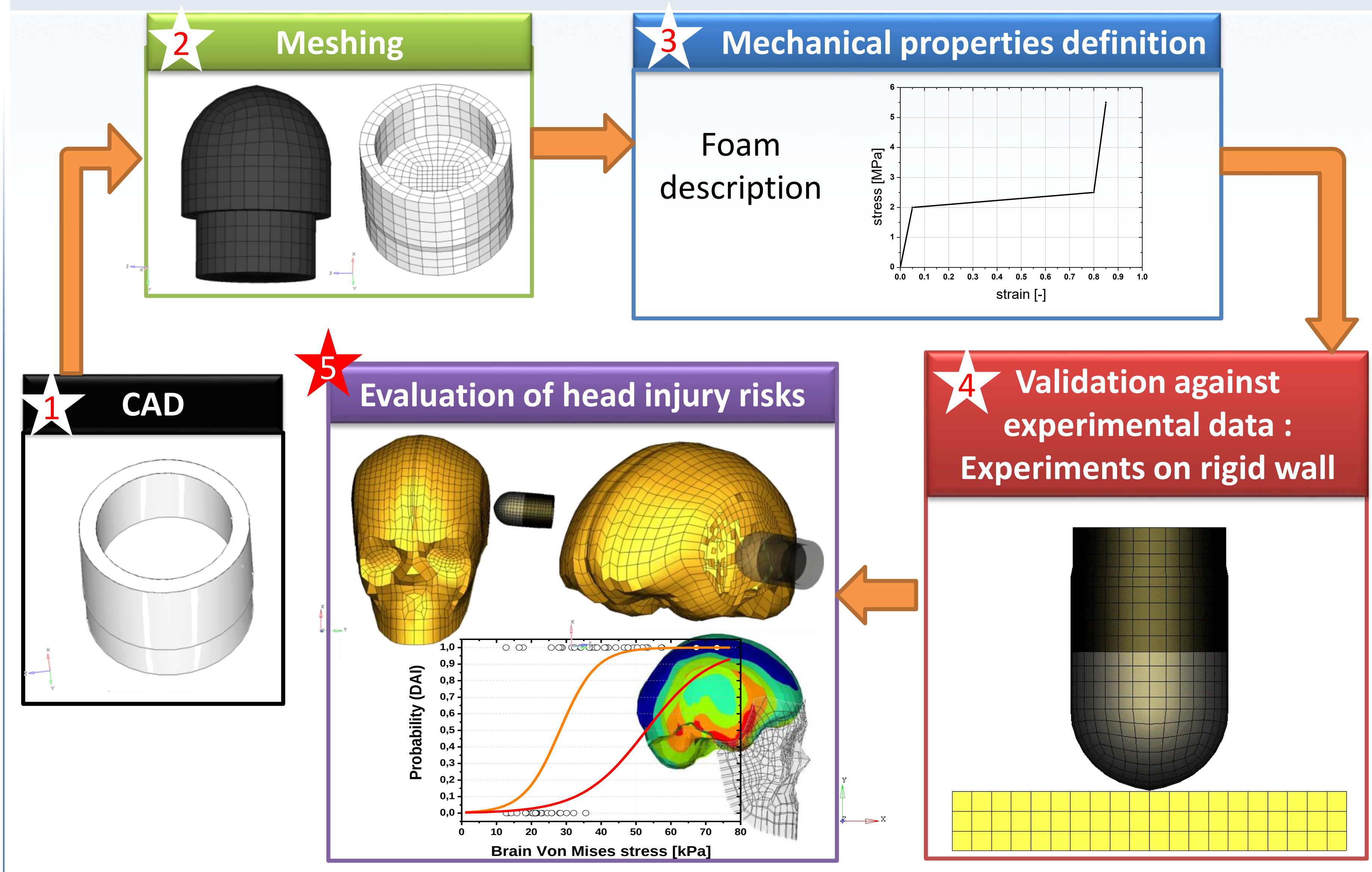
OVERADE_PLIXI-FIT



Balistic Protection

LESS-THAN-LETHAL WEAPONS

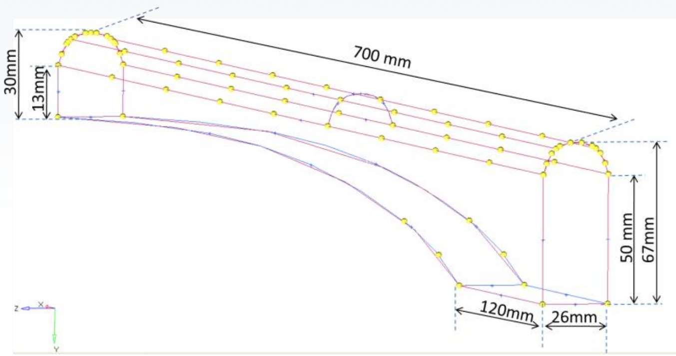
UNIVERSITÉ DE STRASBOURG
CNRS

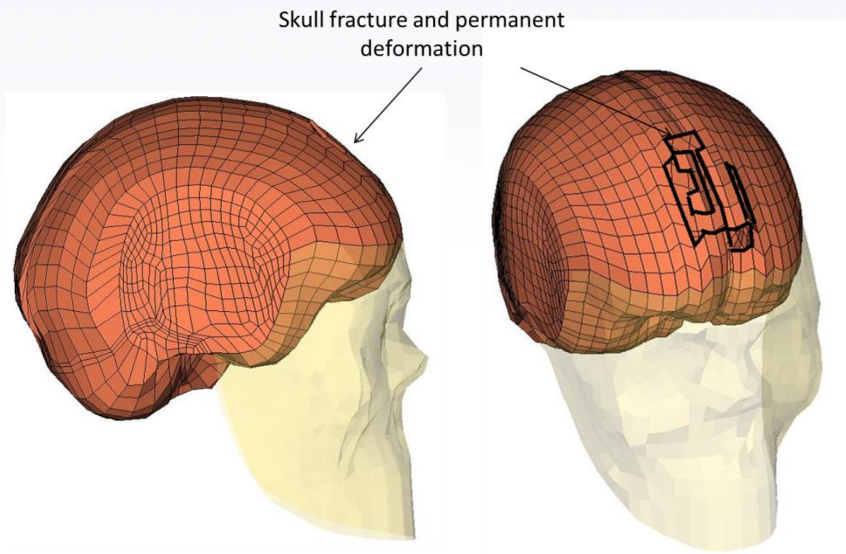


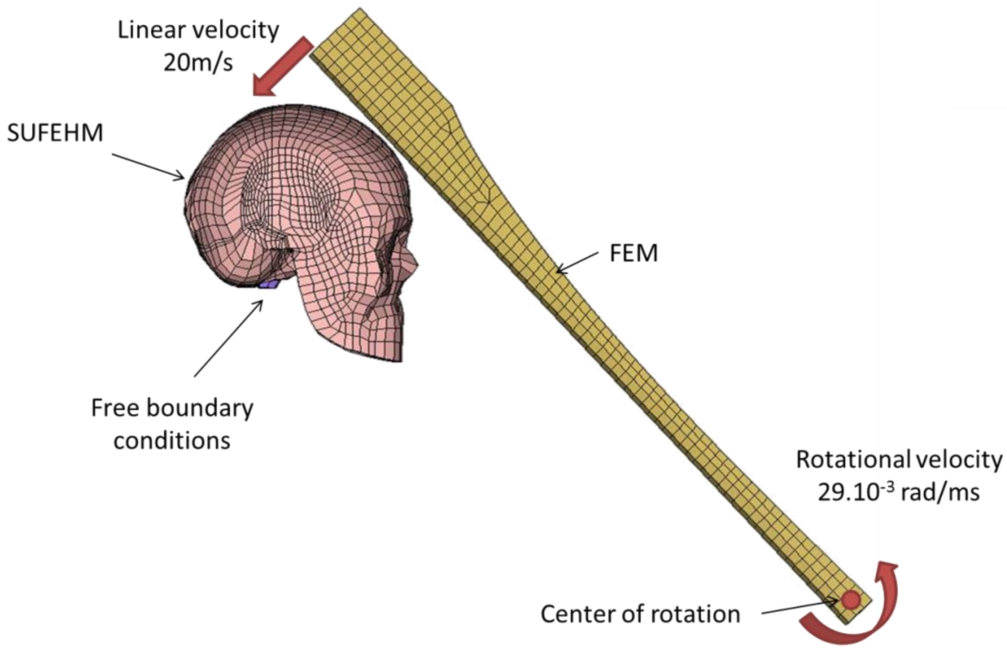
LEGAL MEDECINE

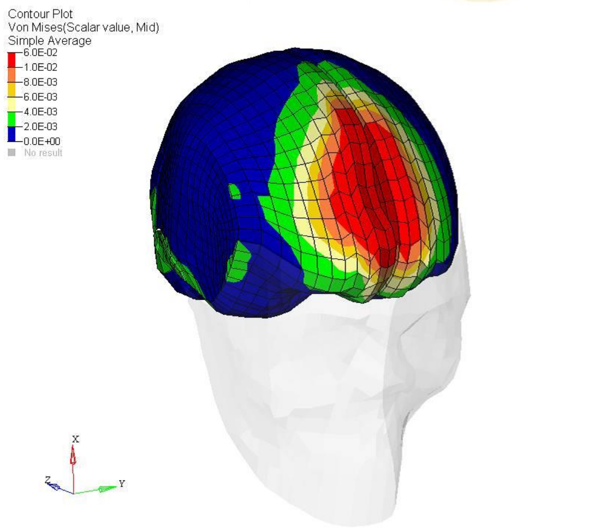
A LEGAL MEDICINE CASE

Head injury risks calculated with SUFEHM







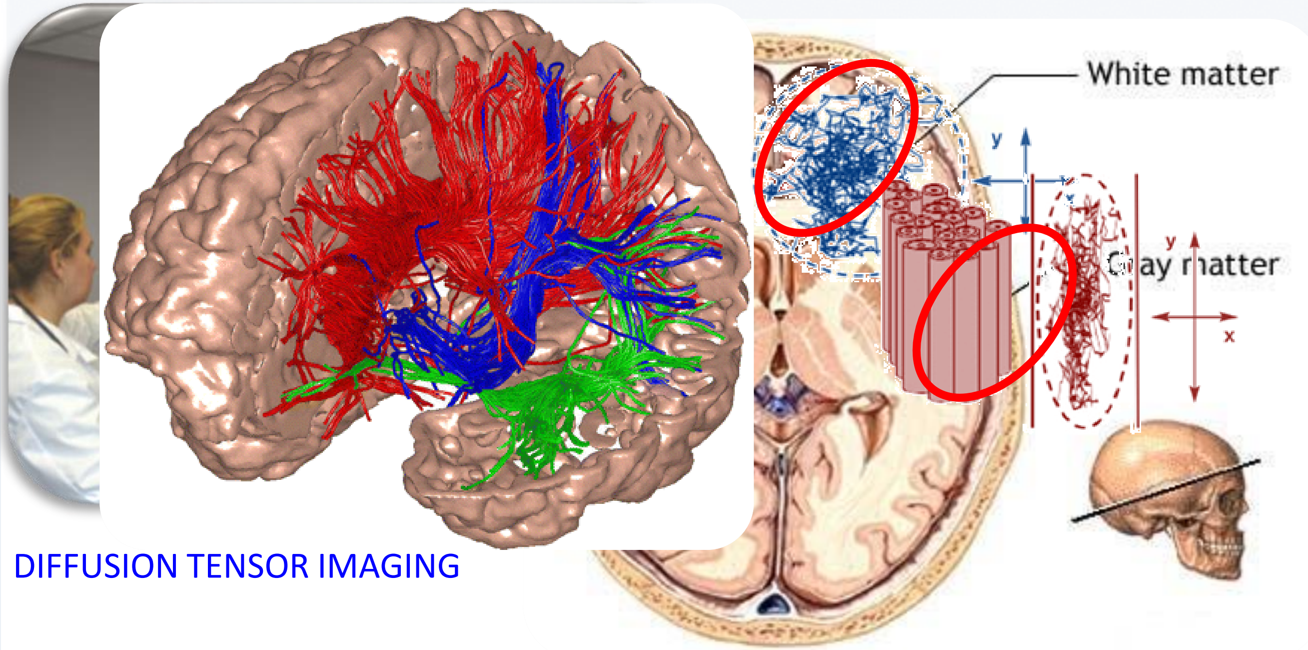


SUFEHM
CONSOLIDATION & RECENT DEVLOPENT

101

DTI OF THE BRAIN

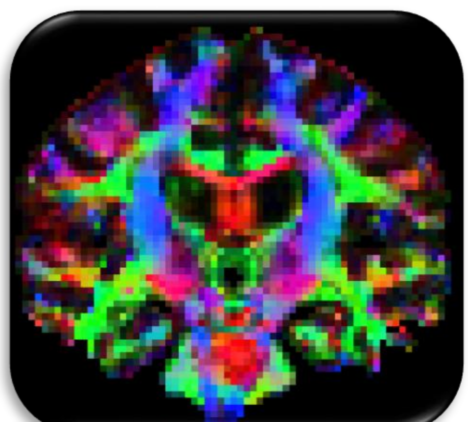
ISOTROPIC DIFFUSION

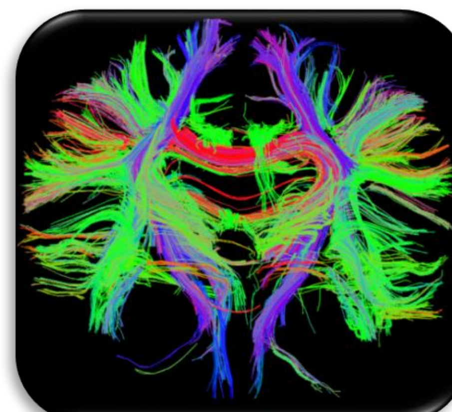


DIFFUSION TENSOR IMAGING

ANISOTROPIC DIFFUSION

HEALTHY PERSONS

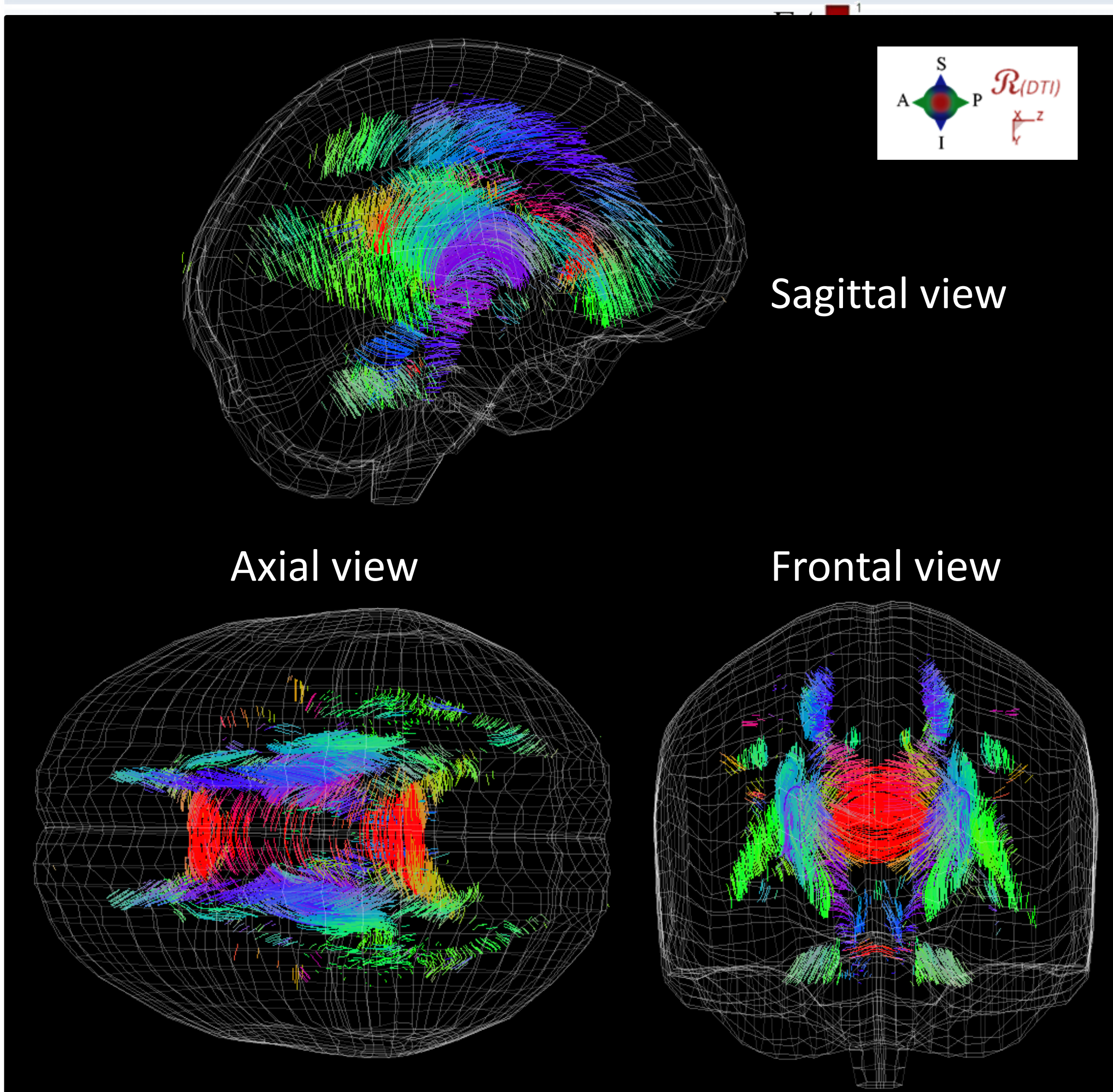


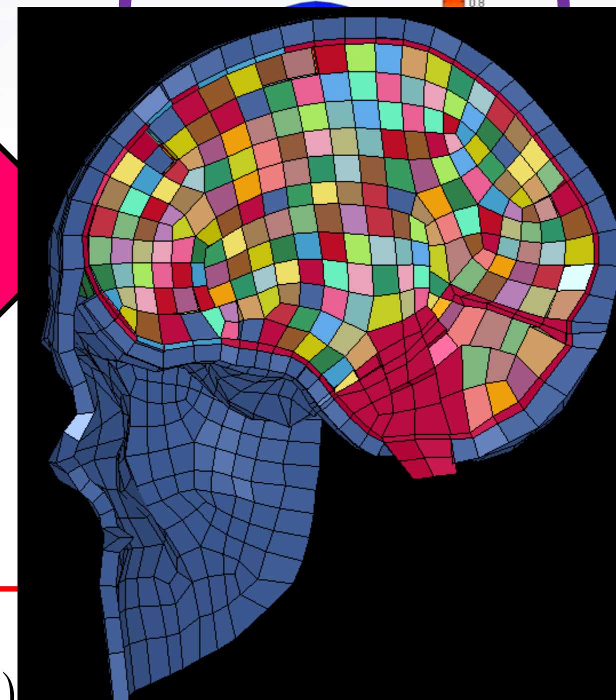


FRACTIONAL ANISOTROPY

102

New enhanced brain model





Heterogeneous and anisotropic brain model

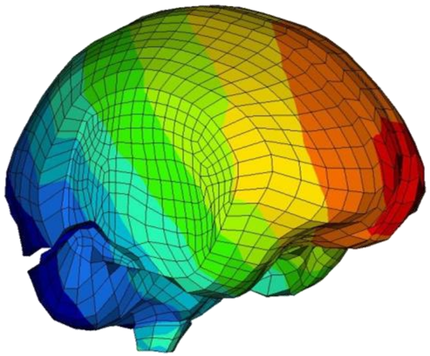
$$+\begin{cases} 0 & 0<\bar{\lambda}<1 \\ C_3\left(e^{C_4\left(\bar{\lambda}-1\right)}-1\right) & \bar{\lambda}\geq 1 \end{cases}$$

Fibers stress

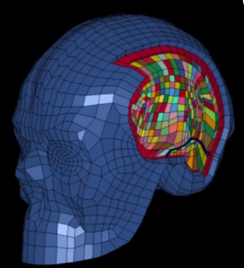
Anisotropic visco-hyperelastic brain model (Chatelin et al. 2012)

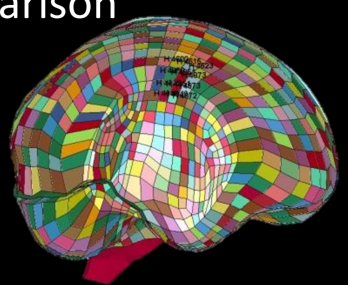
Validation of SUFEHM-14

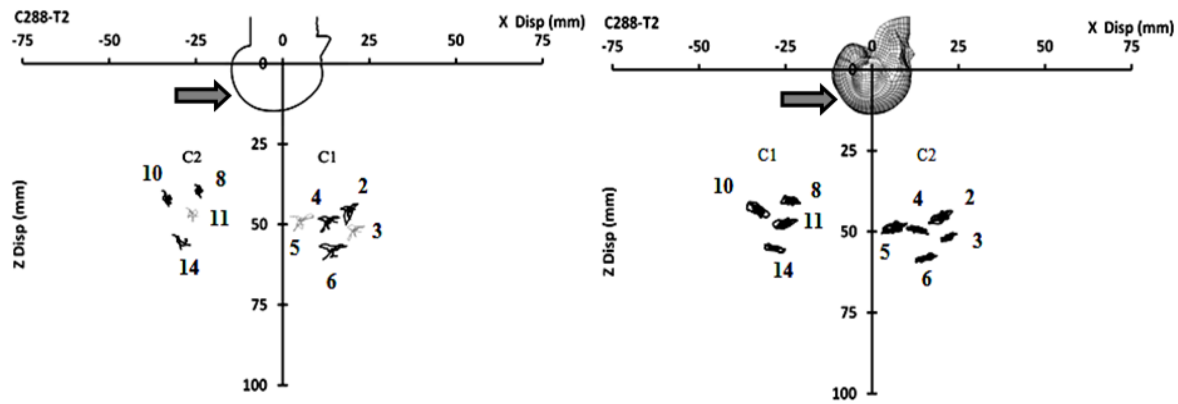
- New skull mechanical law was validated in frontal, vertex and lateral impacts
- Validation of brain model in terms of intracranial pressure against Nahum's and Trosseille's Experiments.
- Validation of brain behavior in terms of local brain motion was done by reconstruction of 11 Hardy's experiments.
- Parametric studies were performed which demonstrate the influence and importance of DTI data (Fractional anisotropy and Fiber orientation) .



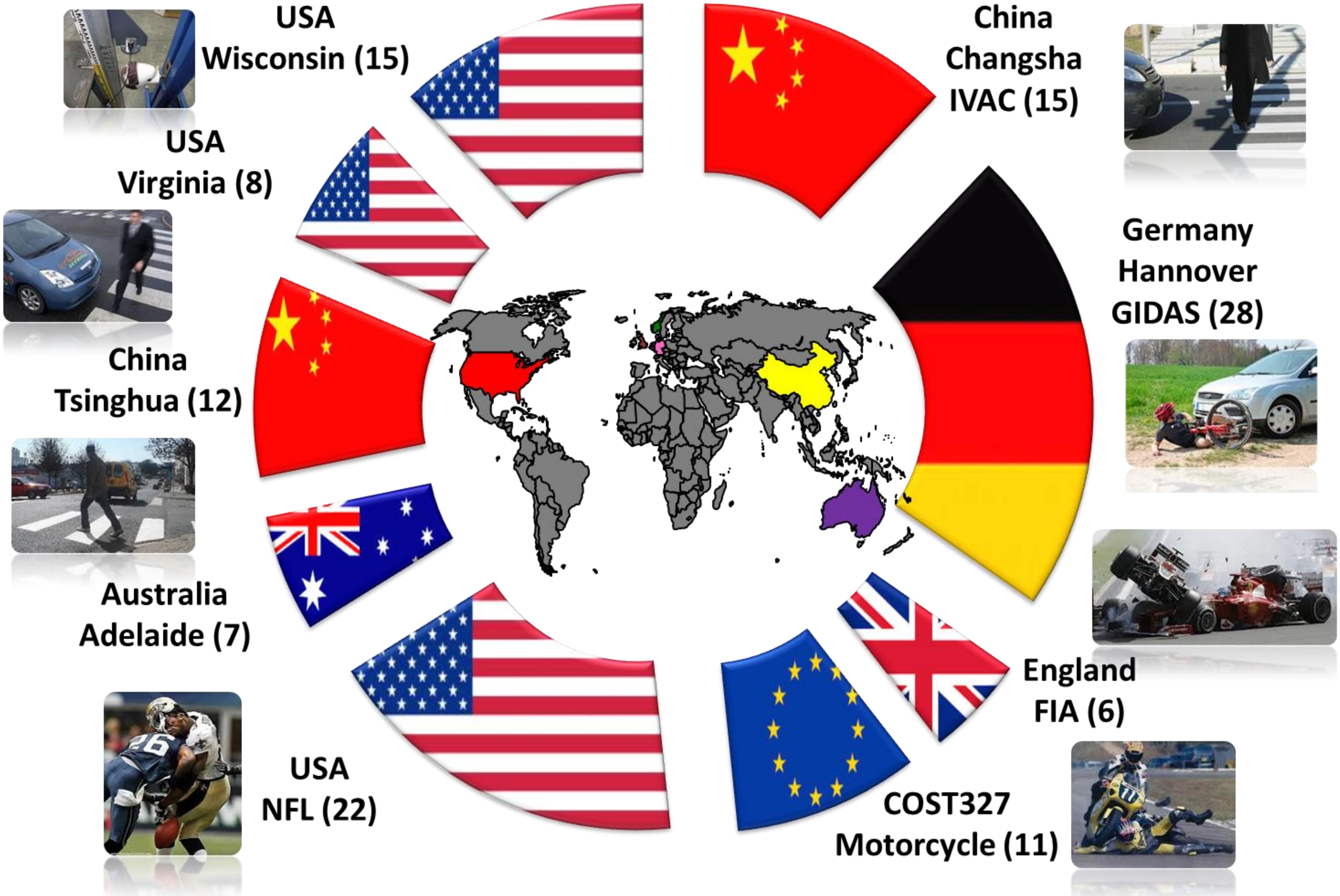
More than 100 NDT trajectories obtained from experiments for comparison



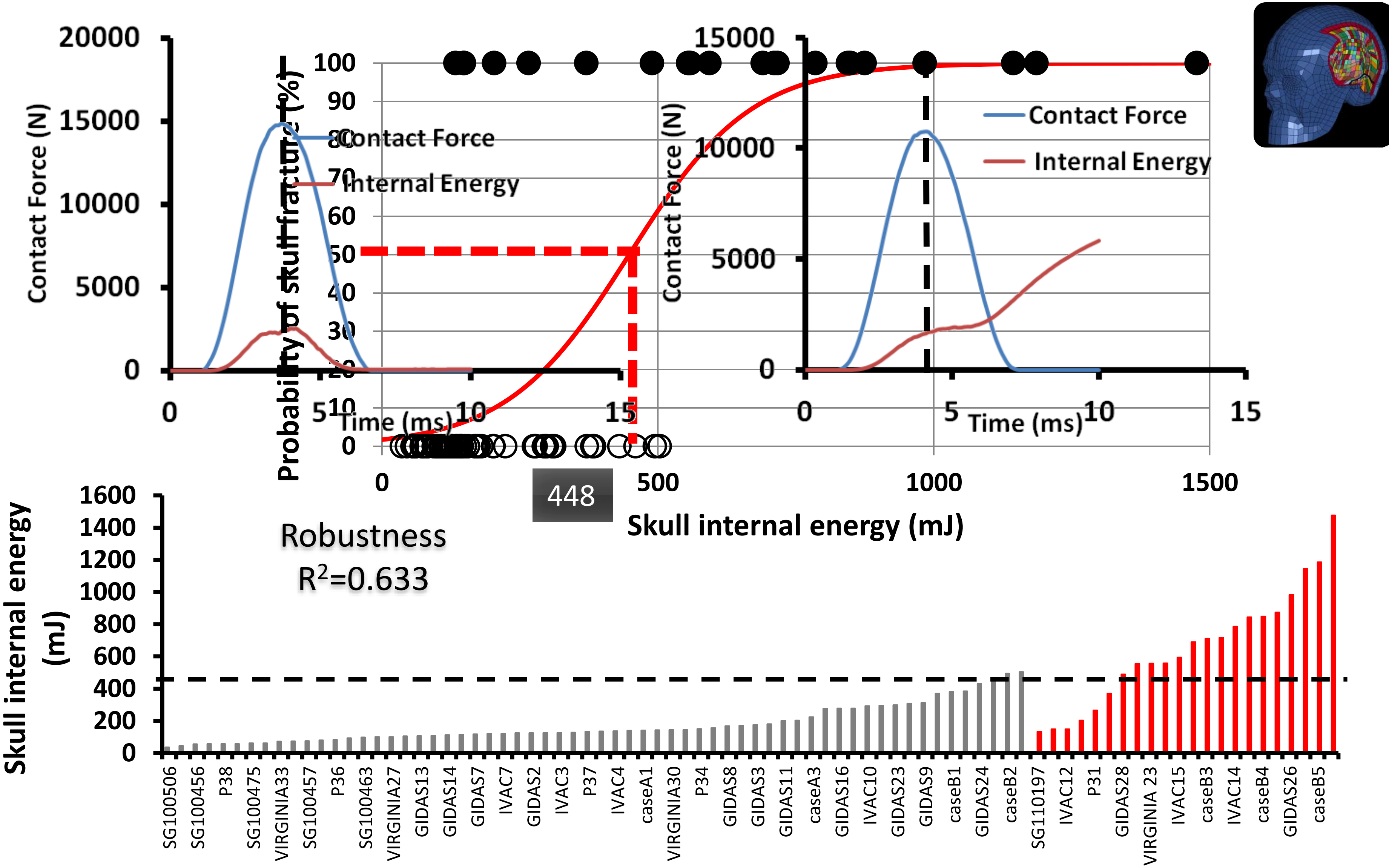




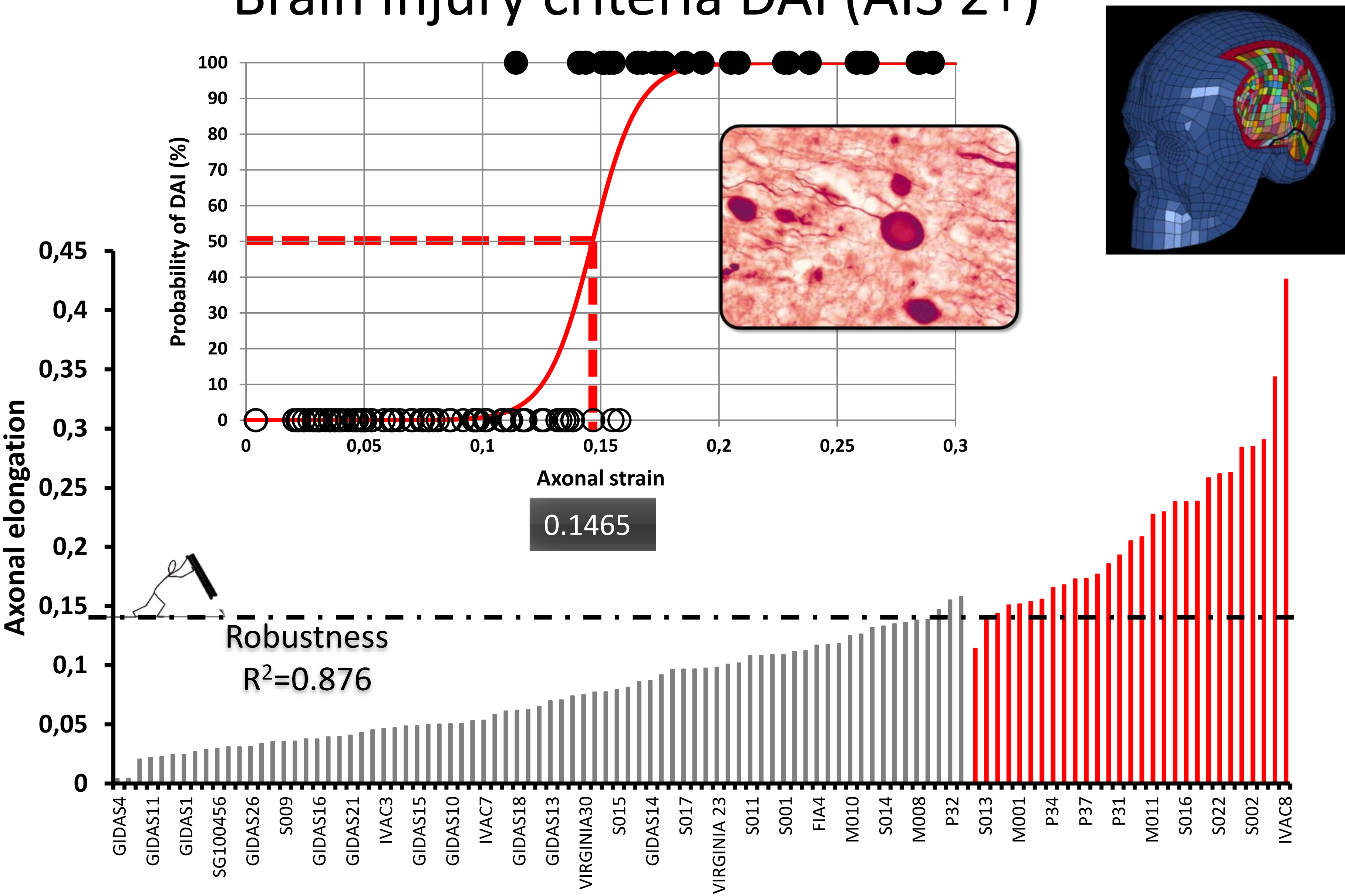
Database (125 cases)



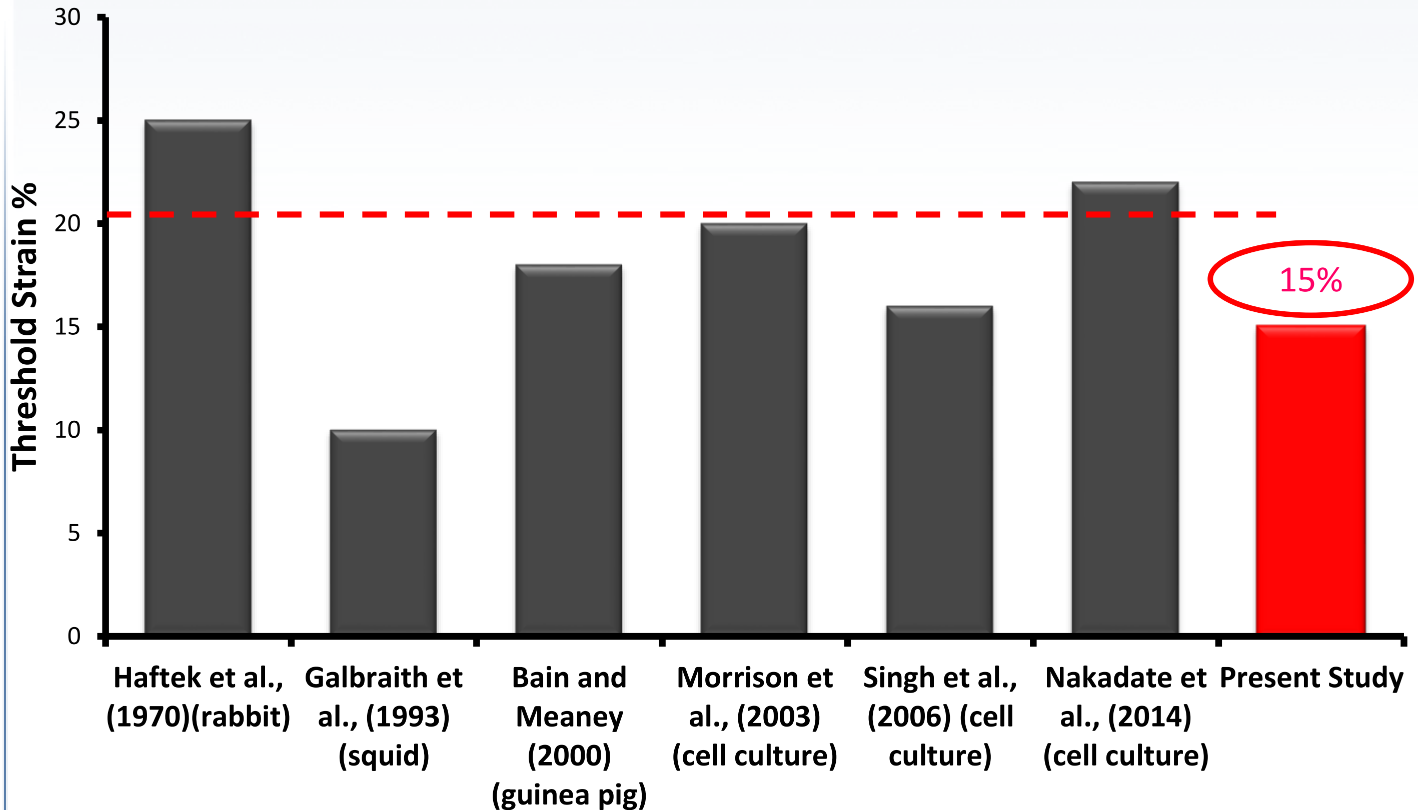
Skull fracture criteria

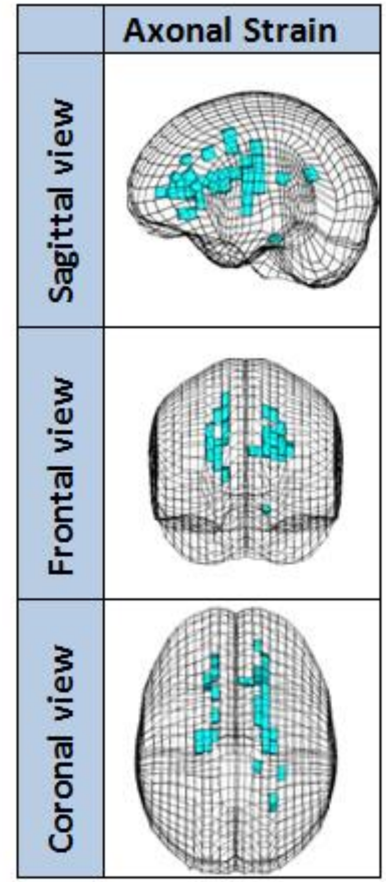


Brain Injury criteria DAI (AIS 2+)



AXON STRAIN IN THE LITTERATURE





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

CONCLUSION

- Critical aspects of today injury criteria
- State of the art head FE modeling
- Simulation of Real world head trauma
- Model based head injury criteria
- Head injury prediction tool for end user
- Application to Virtual Testing
- Experimental vs numerical test methods
- New helmet test methods
- Recent devlopments

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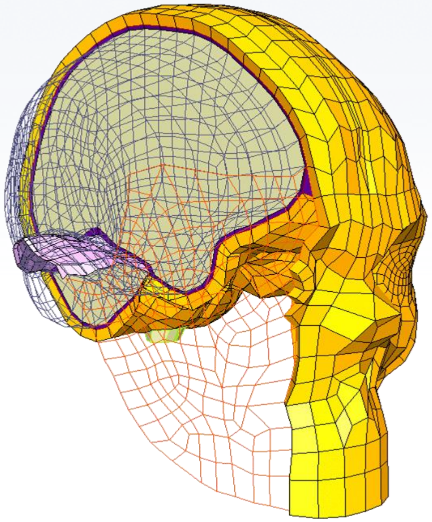

Thank you for you

Model based head injury criteria For Automotive Industry

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Presentations at standard bodies

- Strasbourg University Head Injury Criteria , *San Diego, October 2003 (ISO-doc N° 594)*
- HIC injury prediction capability versus Strasbourg criteria, *Nashville, October 2004 (Idoc N° 611)*
- HIC injury prediction capability vs Strasbourg criteria and SIMON, *Paris, June 2005 (doc N° 620)*
- State of the art head FE models and guidelines for validation, *Seoul, May 2007 (doc N° 680 & 681)*
- Improved Model Based Head Injury Criteria, *Madrid, January 2008 , EEVC WG 12 meeting*
- Improved Model Based Head Injury Criteria, ISO, WG6 ,*Paris, May 2009*
- Code and Model dependence of model based head injury criteria, *Stuttgart, June 2009 (EEVC-WG 12)*
- Towards new head protection standards, *Saint Louis, MO, USA, May 2010 (ASTM meeting)*
- *Model based Head Injury Criteria : Code, Model and Age Dependence, Paris June 2011, ISO WG6*
- New bicycle helmets test procedure, Milan October 2012, CEN TC158 WG11
- Brain injury criteria based on axon strain, Strasbourg, March 2015, CEN TC158 WG11
- Model based head injury criteria , Sept 2015 NTSEL, Tokyo
- New helmet test methode, Tampa, November 2015 (ASTM meeting)
- Model based head injury criteria, Leuven, June 2015 (EuroNcap)
- Towards New Motorcycle Helmet Test Method, Geneva, December 2018 (UN-ECE R22)

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KEY REFERENCES_1

- Peng Y, Chen Y, Yang J, Otte D, Willinger R : A study of pedestrian and bicyclist exposure to head injury in passenger car collision based on accident data and simulation. Safety Science 2012, 50 (9) 1749-1759.
- Bourdet N, Deck C, Carreira P, Willinger R : Head impact conditions in case of bicyclist falling. Sport Eng and Technology, 2012, 226(3/4), 282-289.
- Bourdet N, Deck C., Serre T, Perrin C., Llari M., Willinger R: In deep real world bicycle accident reconstruction. Int. J of Crashworthiness, 2013, DOI:10.1080/13588265.2013.805293
- Marjoux, D., Bourdet, N., and Willinger, R. . Computation of axonal elongations: towards a new brain injury criterion. International Journal of Vehicle Safety, 2009, Vol.4 No 4, pp.271-284.
- Chatelin S., Deck C., Renard F., Kremer S., Heinrich C., Armspach JP, Willinger R : Computation of axonal elongation in head trauma finite element simulation. J of Mech. Behavior of Biomed Material, V4, 2011, 1905-1919.
- Sahoo D., Deck C., Yoganandan N., Willinger R : Anisotropic composite human skull model and skull fracture validation against temporo-parietal skull fracture. Journal of the Mechanical Behavior of Biomedical Materials, 2013, vol 28, 340-353.
- Sahoo D., Deck C., Willinger R.: Development and validation of an advanced anisotropic visco-hyperelastic human brain FE model. Journal of the Mechanical Behavior of Biomedical Materials, 2014, vol.33, 24-42

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KEY REFERENCES_2

- Deck C., Willinger R. : Pass-fail criteria for helmet standard tests : CEN TC158-WG11 meeting, Strasbourg, March 2015.
- Deck C., Willinger R. : Head Injury Criteria : Consolidation of head trauma database and model based head injury criteria: ISO document SC36-WG6, Paris, June 2015.
- Sahoo D., Deck C., Willinger R. : Axonal strain as brain injury predictor, based on real world head trauma simulations. IRCOBI Conference, Lyon, Sept. 2015.
- Sahoo D., Deck C., Willinger R : Brain injury criteria expressed in terms of axon strains : Asian-Pacific Conf. on Biomech, Sapporo, Sept 2015.