TOWARDS ADVANCED BICYCLE HELMET TEST METHODS

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General Contexte

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CEN-TC 158 / WG11

Cost Action TU 1101
Towards Safer Bicycling Through Optimization of Bicycle Helmets and Usage

INTRODUCTION

- Current situation of head protection standards…and limitations
- Previous attempts
- Proposal of a new helmet test method
- Impact conditions
- Model Based Head Injury Criteria
- Conclusion

EXISTING BICYCLE TEST METHODS AND LIMITATIONS

STANDARDS FOR BICYCLE HELMETS

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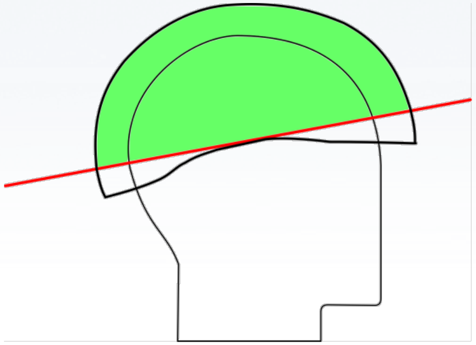
	NF EN 1078	ANSI Z90.4	CPSC	SNELL B-95	BS 6863	AS/NZS 2063	CAN/CSA D1132-M
Year	1997	1995	1999	1995	1997	1996	1996
Scope	EU	USA	USA	International	UK	Australia / NZ	Canada
Headform + helmet mass	5 kg	5 kg	5 kg	5 kg	5 kg	5 kg	5 kg
Tests	***3 tests*** •Drop •roll-off •retention system strength test	***2 tests*** •Drop •retention system strength test	***3 tests*** •Drop •roll off •retention system strength test	***3 tests*** •Drop •roll off •retention system strength test	***2 tests*** •Drop •retention system strength test		
Drop apparatus	Guided free fall	Twin wire drop rig	Guided free fall	Guided free fall	Twin wire drop rig	Twin wire drop rig	Twin wire drop rig
Conditioning	Hot +50°C Cold -20°C Wet	Ambient Hot +50°C Cold -10°C Wet	Ambient Hot +50°C Cold -20°C Wet	Ambient Hot +50°C Cold -15°C Wet		Ambient Hot +50°C Cold -5°C Wet	Ambient Hot +50°C Cold -10°C Wet
Impact on flat anvils	5,42 m/s (73J) at 1,5m	4,57 m/s	6,2m/s (98J) at 2m	110J (6,4 m.s) at 2,1m (limits for certification)	4,57 m/s	5.42m/s	5.7m/s
Impacts on hemispherical anvils			4,8 m/s (57J) at 1,2m	72 J 5,2 m/s at 1,4m (limits for certification)			Cylindrical 4.7m/s
Impacts on kerbstone anvils	4,57 m/s (52J) at 1,05m	4,57 m/s	57 J (4,8 m/s)	65 J (5,2 m/s) at 1,4m	4,57 m/s		
Homologation criteria	**< 250g**	**< 300g**	**< 300g**	**< 300g**	**< 300g**	**<300g <200g for 3ms <150g for 6ms**	**<250g <200g**

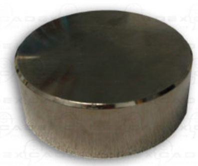
EN 1078 Standard Test

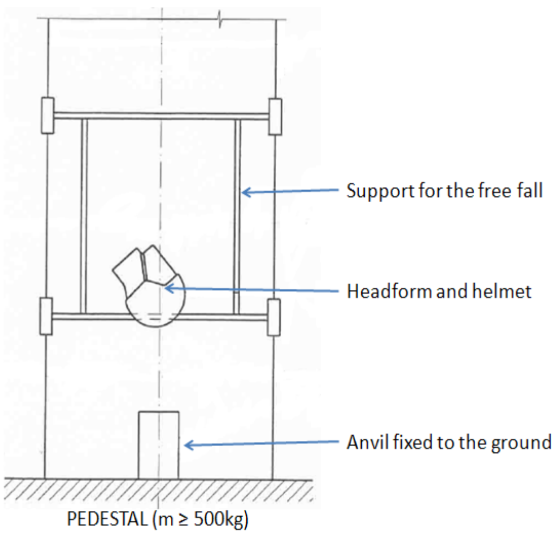
➢Shock absorbing capacity



- The helmet should protect the forehead, the occipital and parietal area of head

- Two kind of anvils (Kerstone, Flat)
  - $V_{kerbstone}$ =4.57 m/s (16.5 km/h)
  - V_{flat} = 5.42 m/s (19.5 km/h)

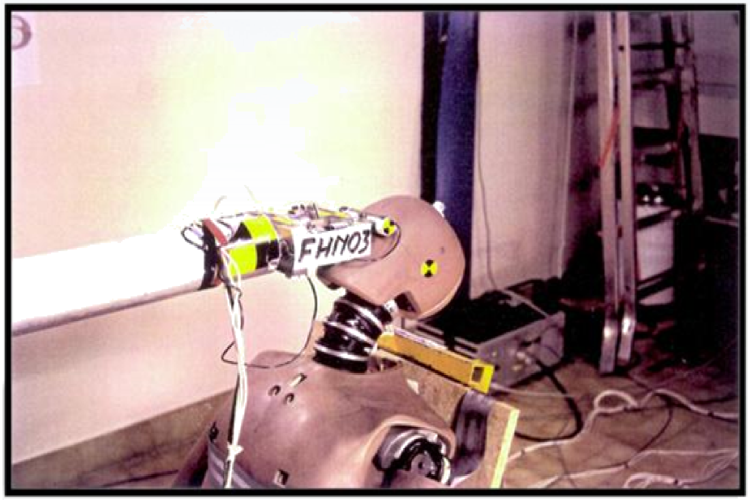




- Two temperatures (-20°C, +50°C) and one wet condition (+20°c)
- No ambient test

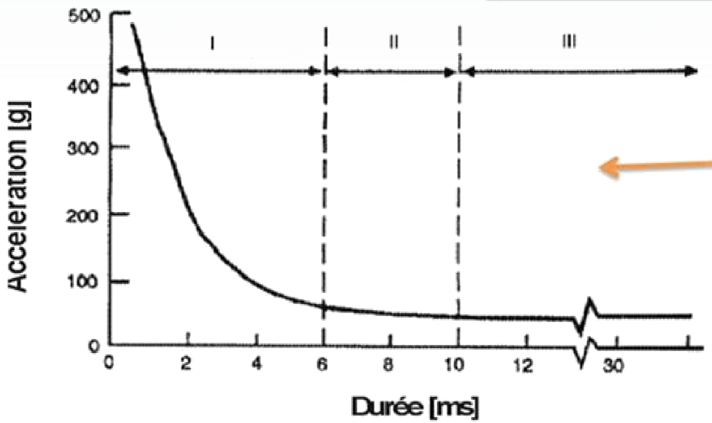
Approval criteria = acceleration < 250 G

HEAD INJURY CRITERIA (1972)



Partie I : cadaver tests, tests for which the fracture of the skull is chosen as a criterion of injury.

Partie II : intracranial pressure recorded on cadavers and animals correlated with concussions



Partie III :Tests on volunteers with whole body acceleration recorded and no injury.

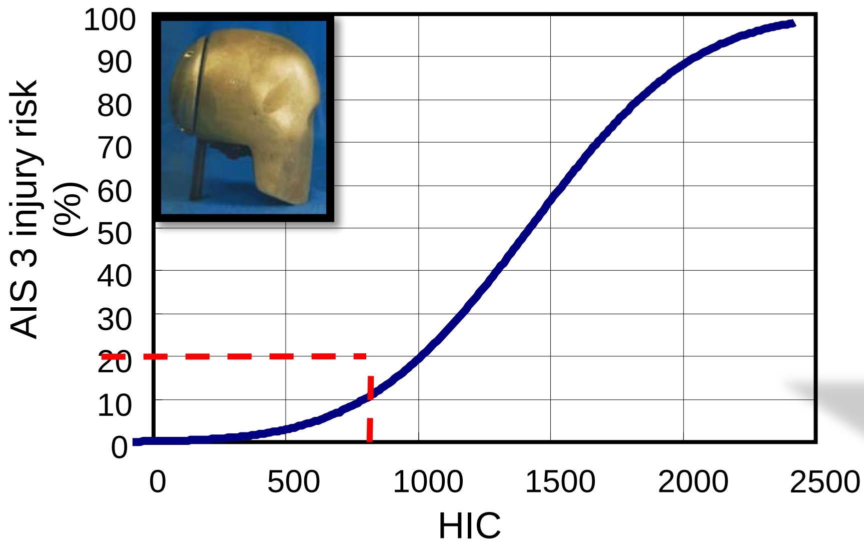
Head mass = 4.58 kg; HIC = 1000

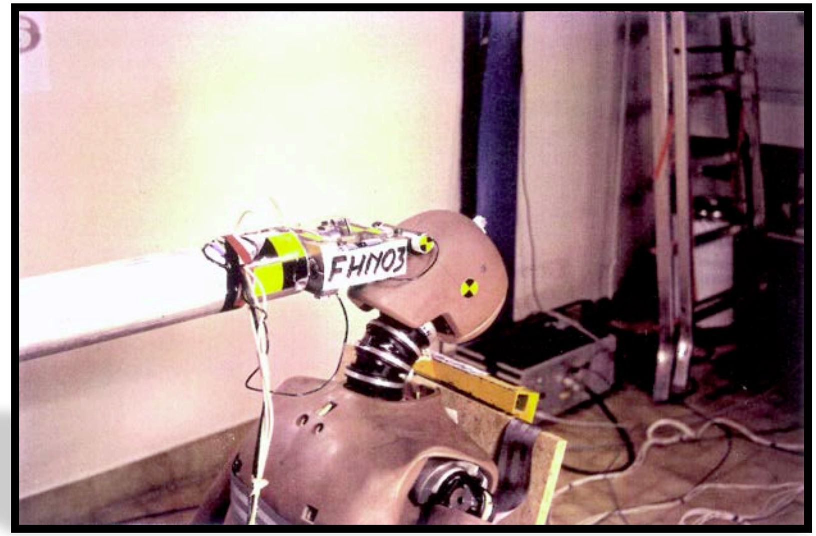
$$HIC = (t_2 - t_1)\left[\frac{1}{(t_2 - t_1)}\int_{t_1}^{t_2} a\,dt\right]^{2.5}$$

LIMITATIONS

- NO CONSIDERATION OF ROTATIONAL ACCELERATION
- NOT DIRECTION DEPENDANT
- NOT INJURY MECHANISM RELATED
- POOR CORRELATION WITH REAL WORLD OBSERVATION

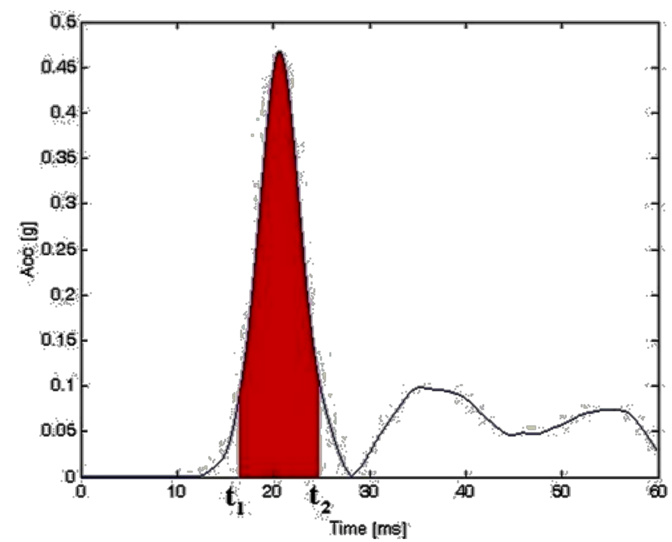
HEAD INJURY CRITERION (1972) : HIC





Head mass = 4.58 kg; HIC = 1000

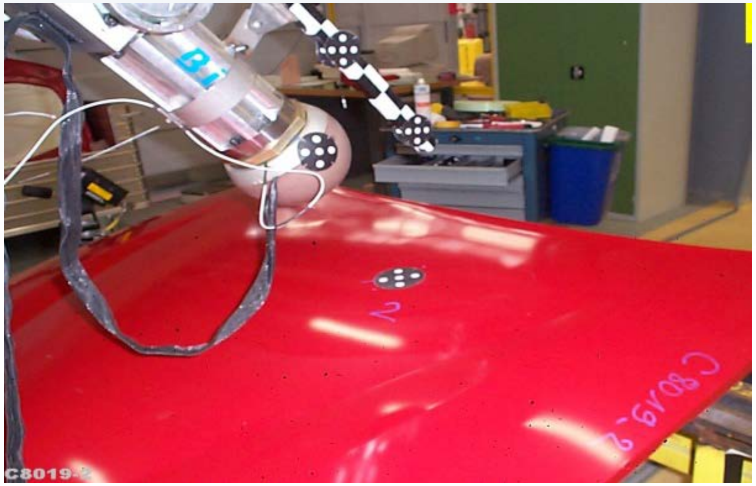
$$HIC = \max_{(t_1,t_2)}\left\{(t_2-t_1)\left[\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}\right\}$$



WHAT ABOUT STANDARDS?

- <u>Inside a car (1970)</u>
  - Dummy head; **HIC 1000**
- <u>Outside – pedestrian (2005)</u>
  - Headform; V=11 m/s ;
    e = 7 cm ; **HIC 1000 à 1700**
- <u>Motorcyclist (2002)</u>
  - Headform; V = 7.5 m/s ;
    e = 5 cm ; **HIC 2400** ; **Γ= 275G**
- <u>Cyclist</u>
  - Headform; V = 5.42 m/s ;
    e = 2.5 cm ; **Γ= 250G**

… for a same human head !

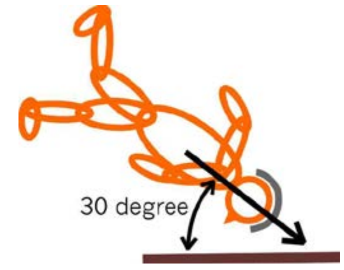


LIMITATIONS OF EXISTING STANDARDS

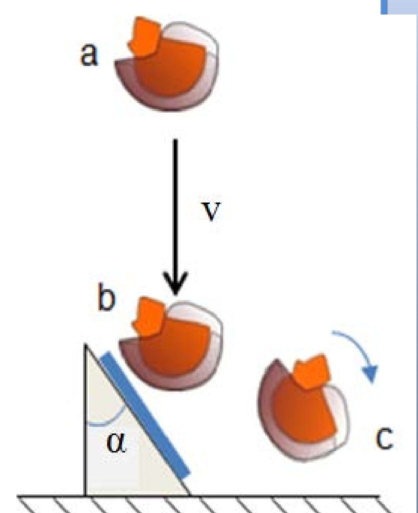
- Poor correlation with real world observation
- HIC was defined for a frontal impact
- Head injury criteria is direction dependant
- HIC is not injury mechanism related
- No consideration of rotational acceleration
- First proposals exist (4.5 krd/s2 to 8.5 krd/s2)
- What about rotation direction ?

Objectives

Define a method to measure rotational energy absorption in tangential impacts



- The first version of the test method is designed for *bike* and *equestrian* helmets.
- Impact conditions based on *real accident* data
  - 5-10m/s, 30-60degrees, hard impact surface
- The test must be *simple, robust and cost effective*.

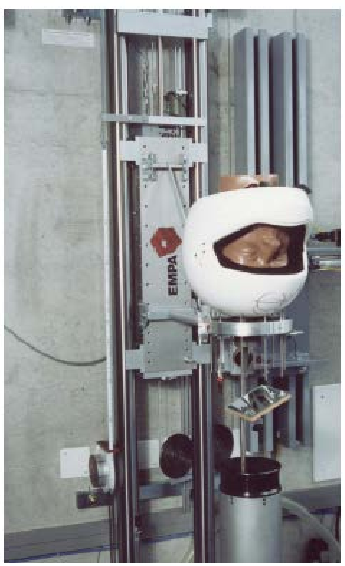


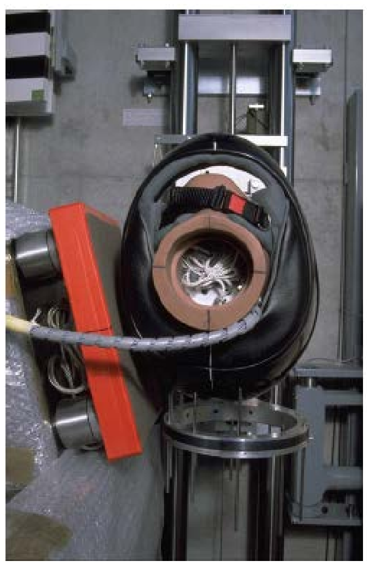
First attempts exist …

EXISTING TEST PROCEDURES

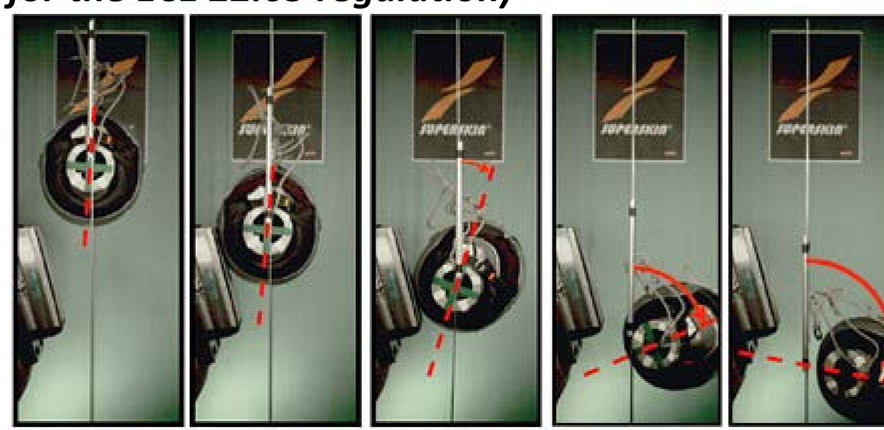
Despite this consolidated knowledge **no head protection standard are currently considering head rotational acceleration**. Only ECE R2205 EU and BS6658 motorcycle helmet standards consider a tangential impact condition but helmet evaluation is limited to the recording of the tangential force

COST 327





Impact tests on an anvil to test new helmet concept Philips Head Protection System (the inclined impact test, part of the approval tests for the ECE 22.05 regulation)

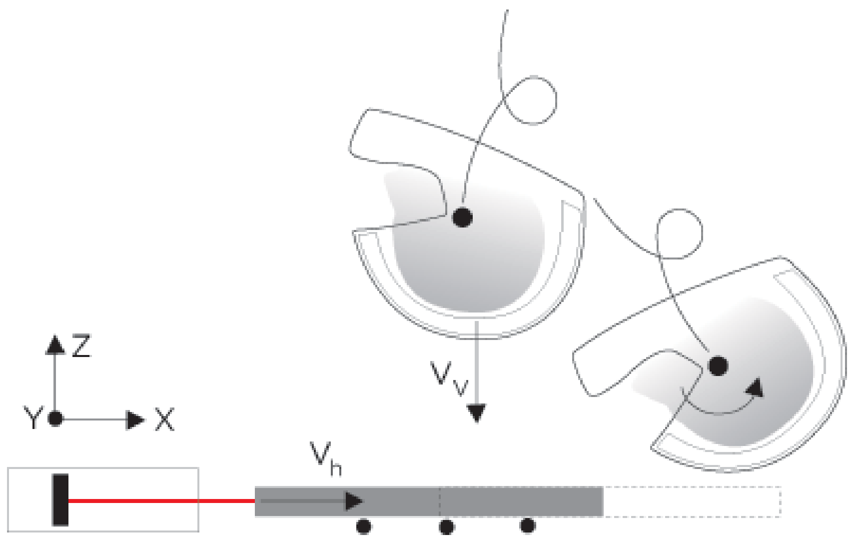


Oblique impact test (ECE 22.05) standard helmet: strong rotational force

EXISTING TEST PROCEDURES

Halldin et al. (2001)

- Simulate a fall from a motorcyclist on to the road surface
- A HIII headform falls vertically to impact a horizontally moving rigid rough.
- This rig was used to evaluate new helmet design (MIPS)



Pang et al. (2011)

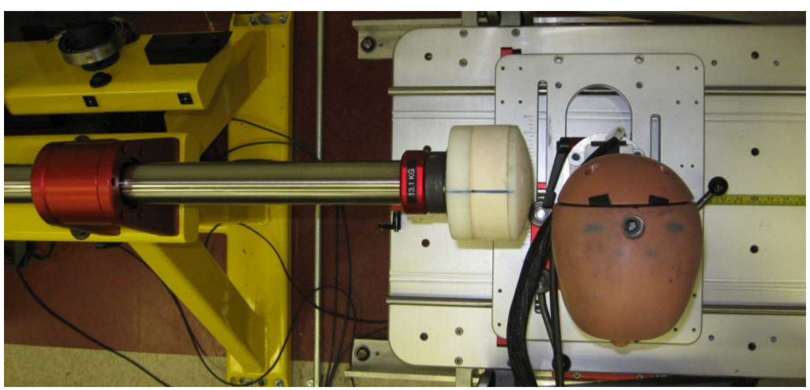
A novel laboratory test in order to investigate head and neck responses under oblique motorcycle helmet impacts.

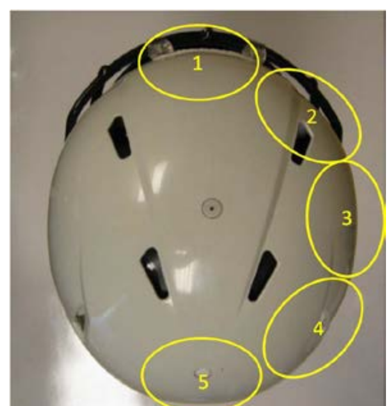
a helmeted Hybrid III head fitted to the Hybrid III neck

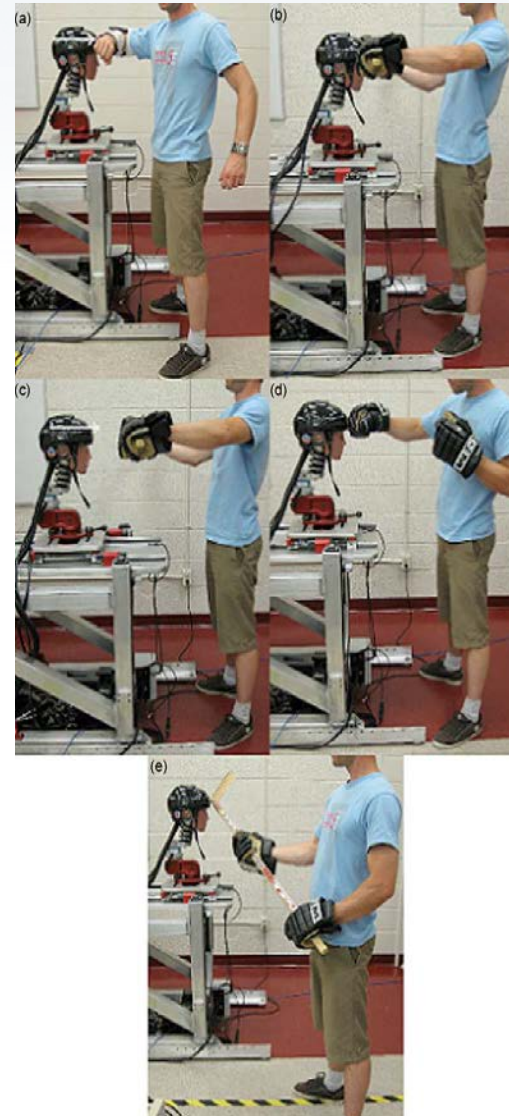
Existing test procedures

Gerberich *et al*. (1987), Flick *et al*. (2005), Coulson *et al (2009),* Rousseau et al (2009)
Walsh *et al*. (2009, 2010, 2011)

Test bench
Linear Impactor
- 50th percentile Hybrid III head- and neckform
- 3-2-2-2 accelerometer array
- Finite Element Model of the human head







Proposal of a new test method

- Impact conditions
  - Velocity vector,
  - Impact location,
  - Temperature, Humidity
  - Boundary conditions at neck
- Headform to be used
- Model Based Head Injury Criteria

HEAD IMPACT CONDITIONS_VELOCITY

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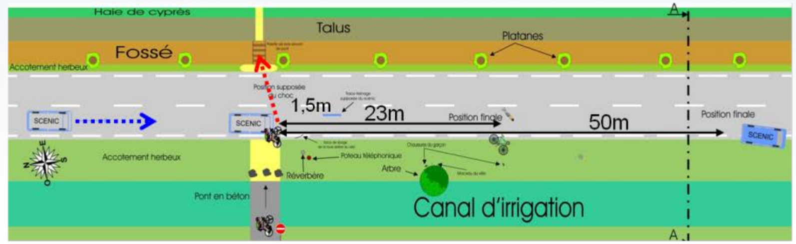
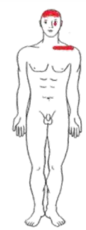
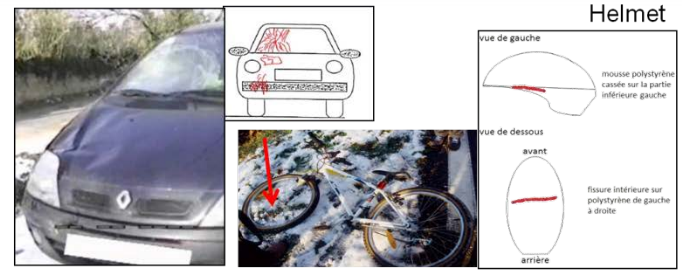
➢under real world accident reconstructions

A total of **26 real world accidents** involving a bicycle were reconstructed
Bourdet et al. (2012)





- Coma (Glasgow score =3)
- Several bleedings
- Intracranial Hypertension.
- Left clavicle fracture
- Left orbital contusion

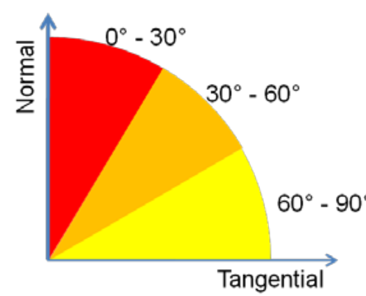


Head Impact conditions

Resultant Velocity	$\mathbf{V_{mean} = 6.8 \pm 2.7}$ **m/s**
Normal Velocity	$V_{mean} = 5.5 \pm 2.9$ m/s
Tangential Velocity	$V_{mean} = 3.4 \pm 2.0$ m/s

More often Moderately often Less often

Head Impact Area



Head Impact Angle

HEAD IMPACT CONDITIONS_VELOCITY

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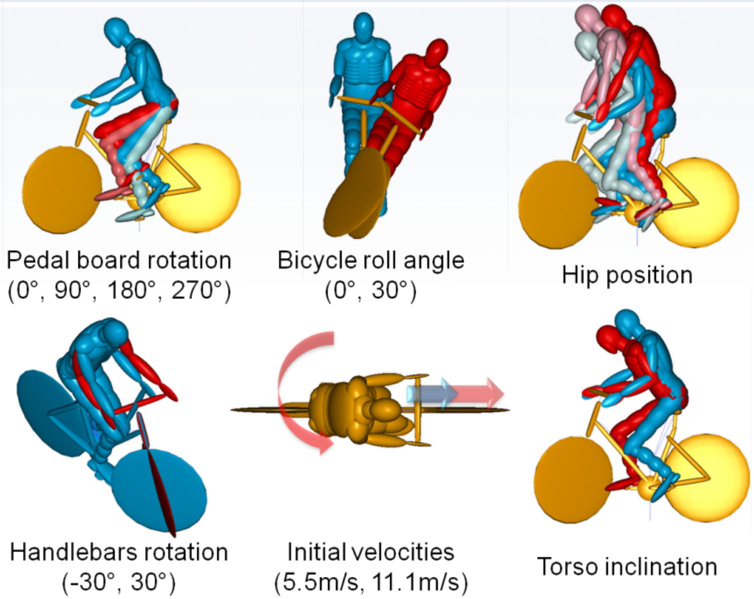
➢in case of bicyclist falling

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

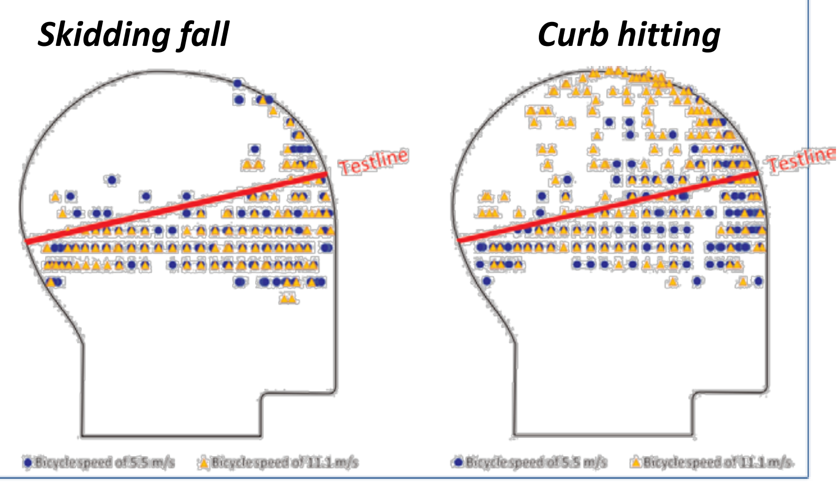


Head Impact conditions for a bicycle speed of ***5,5m/s*** *:*

	$V_{resultant}$ [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



HEAD IMPACT CONDITIONS_LOCATION

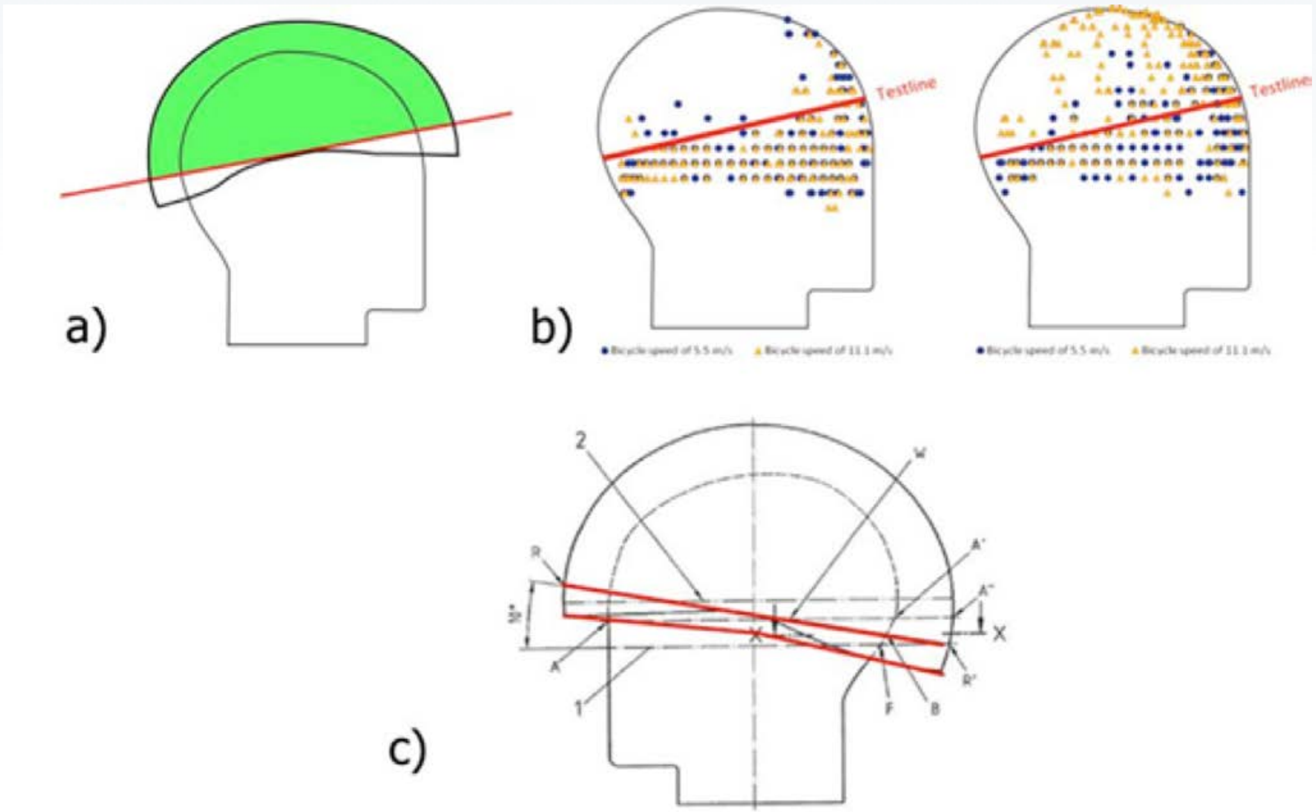
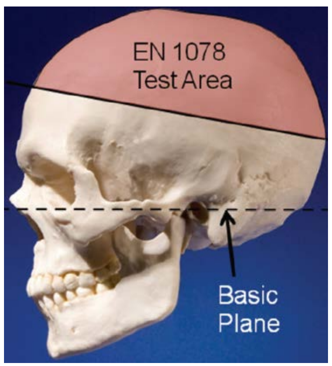
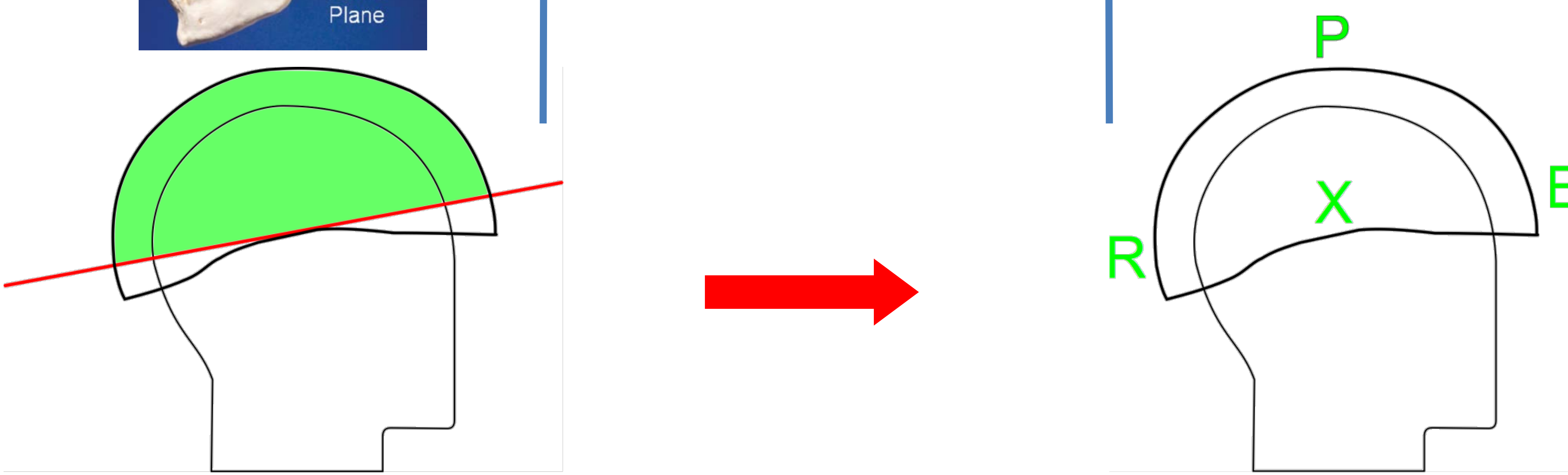


Illustration of current test line
Impact points to the head (Bourdet et al 2012
Proposal of new test line as from Otte et al 2013

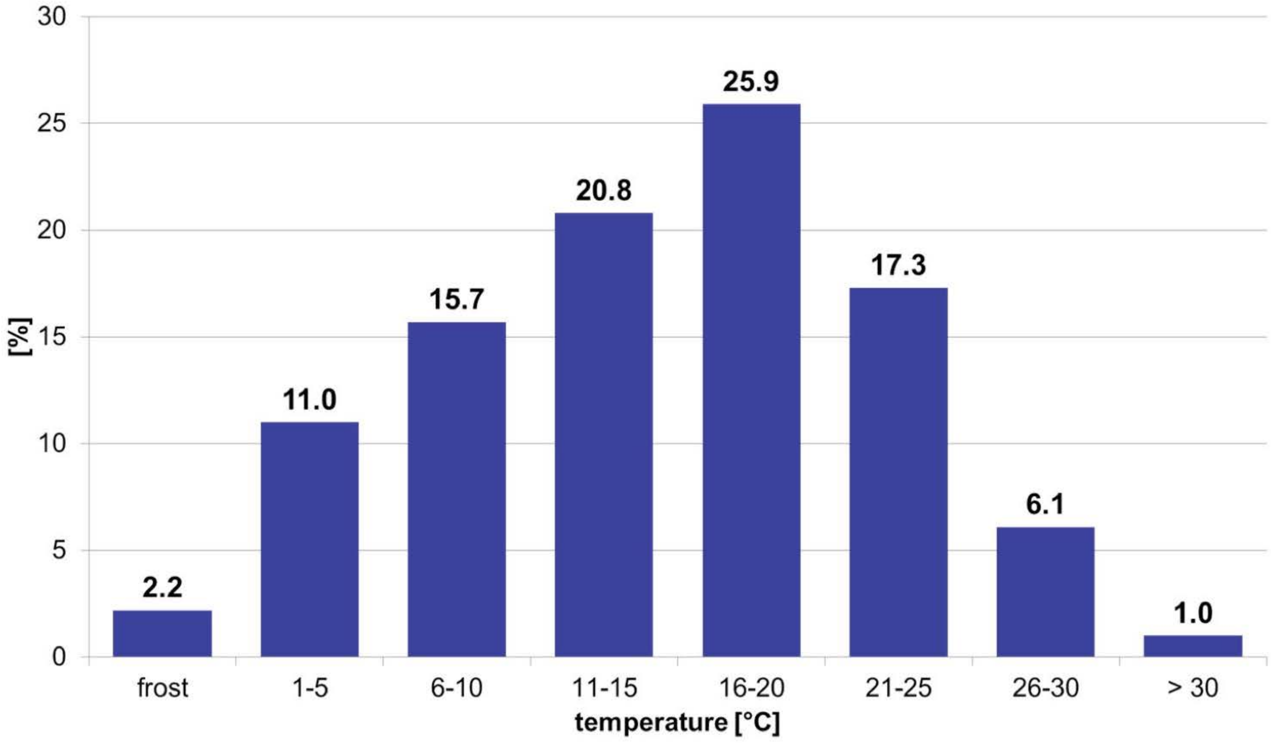
HEAD IMPACT CONDITIONS_LOCATION

Critical issue	Comments	Recommandations
Impact area upper RR' line	Sides of the helmets were the most frequently damaged regions	Suggested Points : B (frontal) P (vertex) R (rear) X (lateral)



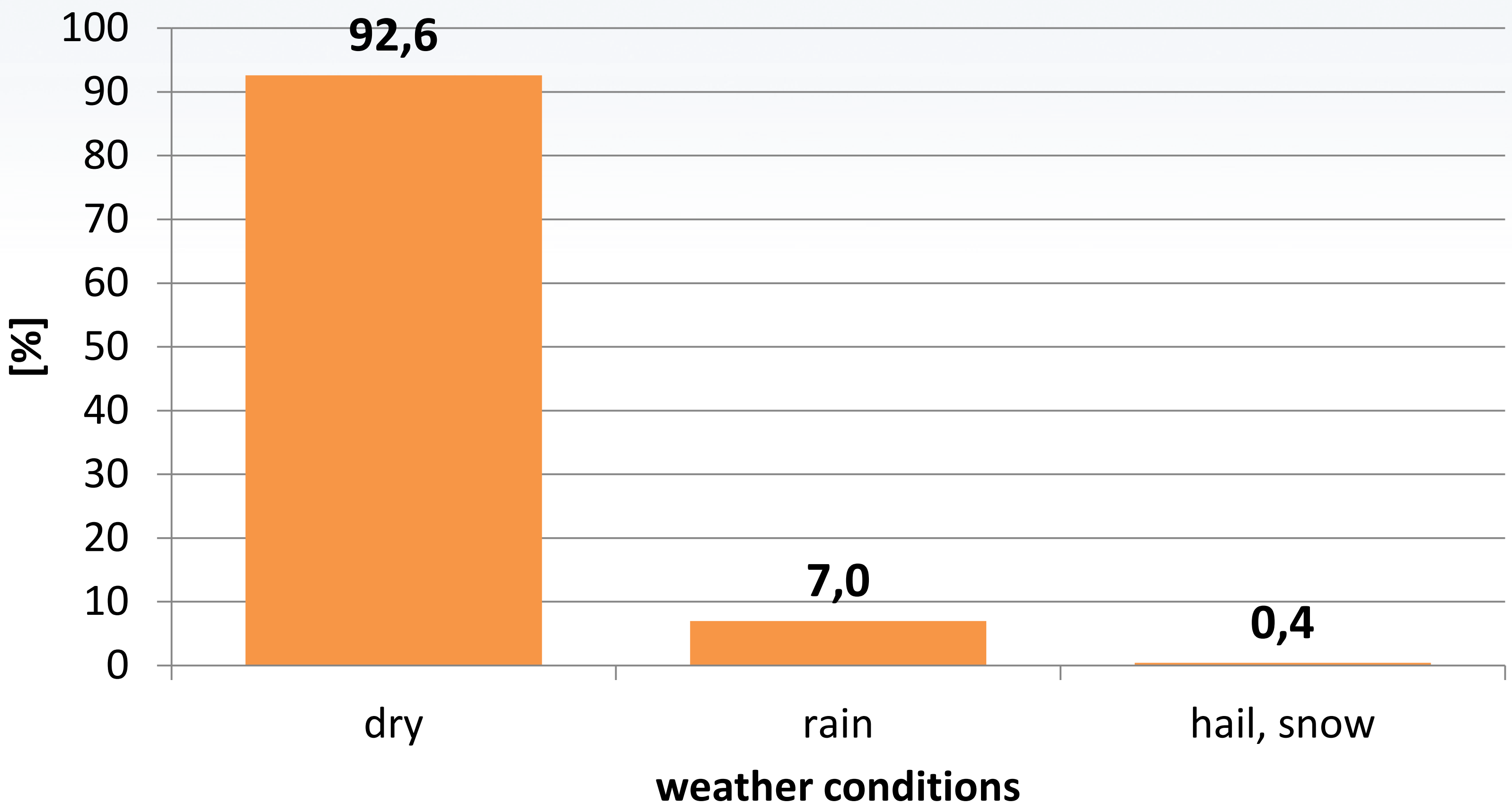


IMPACT CONDITIONS_TEMPERATURE



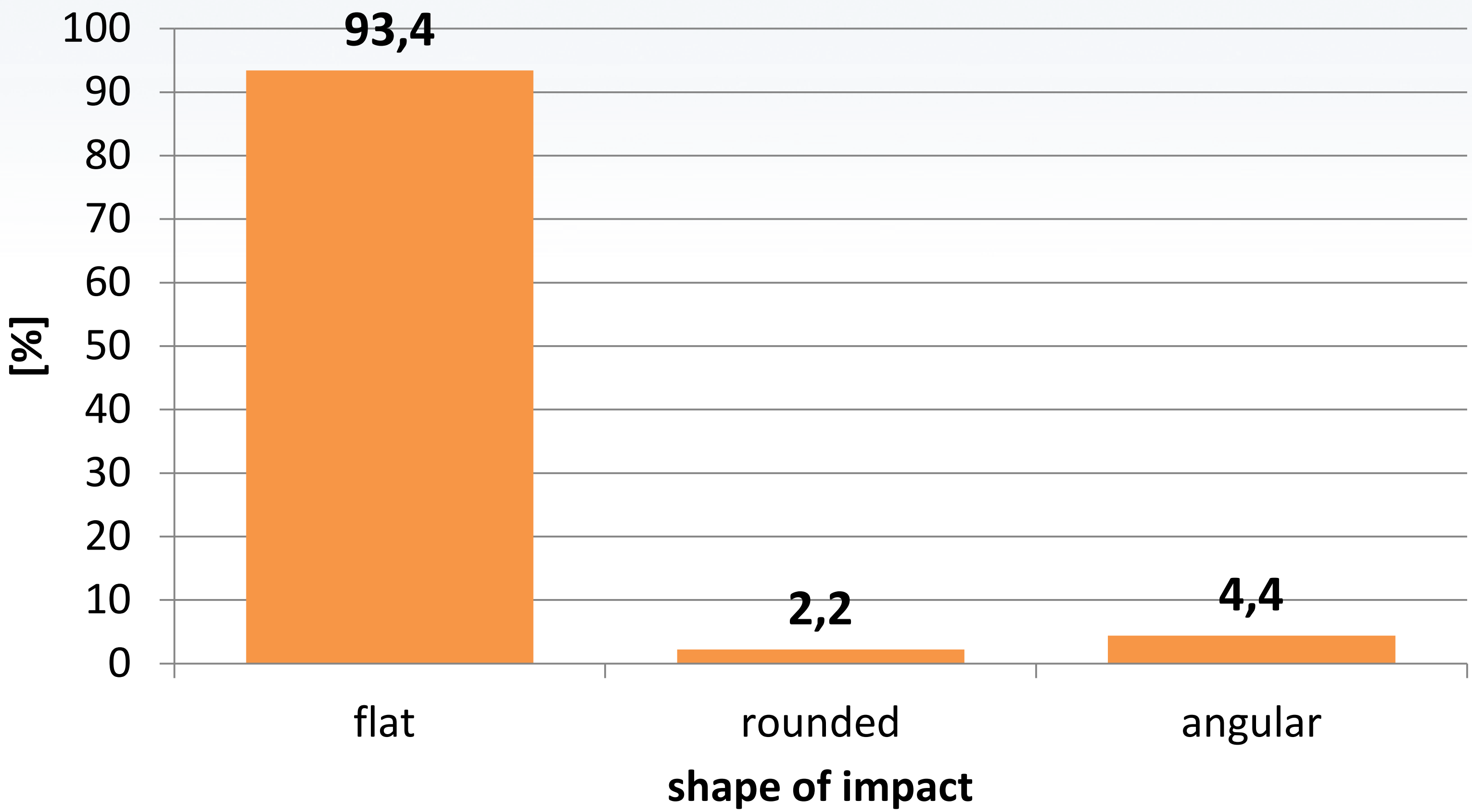
Results based on GIDAS and illustrating that 96.8% of the accidents occur between 1 and 30 °C (n=2412)

IMPACT CONDITIONS_HUMIDITY



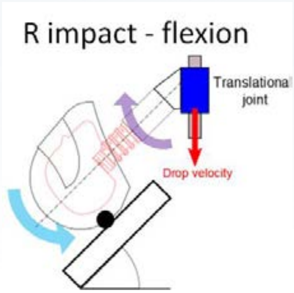
Results based on GIDAS and illustrating that 92,6 % of the accidents occur under dry weather onditions (n=2412)

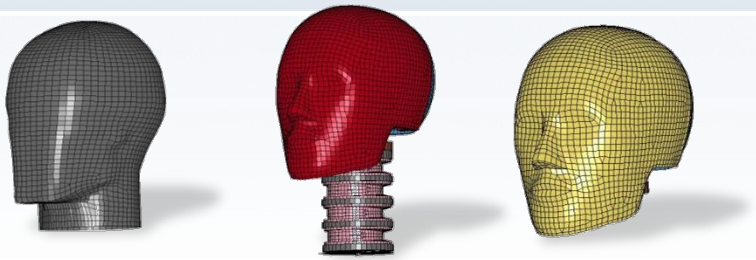
IMPACT CONDITIONS_IMPACTED SURFACE

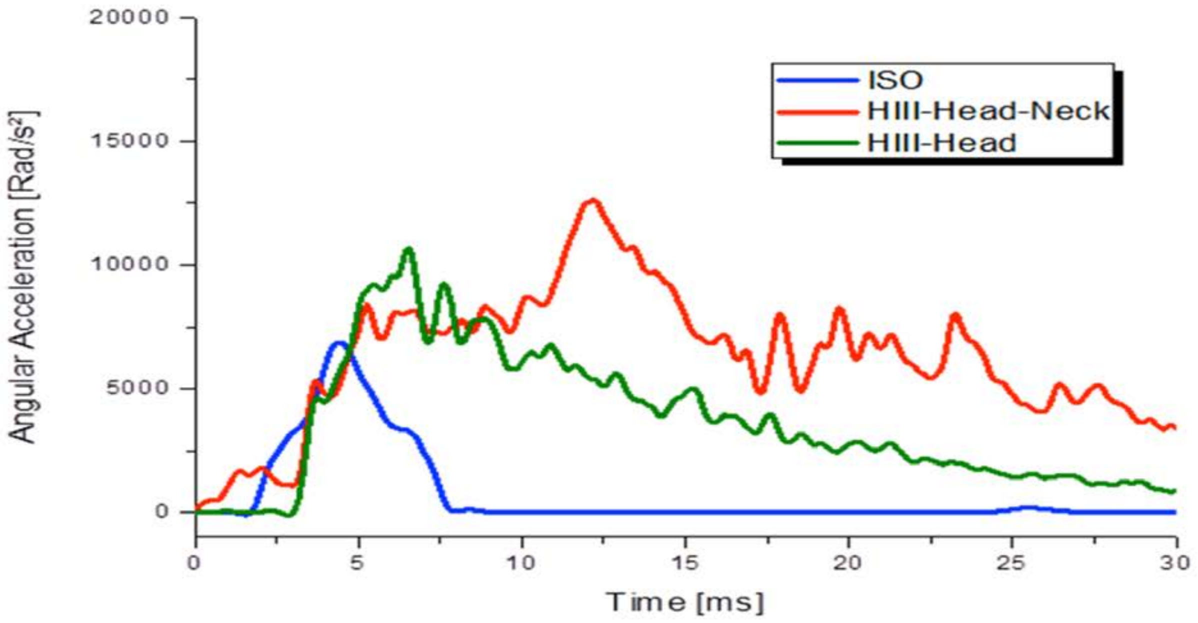


Results based on GIDAS and illustrating that 93.4 % of the head impacts are agains a flat surface (n=2412)

IMPACT CONDITIONS_AT NECK LEVEL







Rotational acceleration computed with thre different helmeted headforms and head boundary conditions under occipital impact against a 45° inclined anvil.

HEADFORM DEFINITION

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Critical issue	Comments	Recommandations
 Rigid Mass	The value of the mass includes “some” neck effects and its inertia is not controlled	Replacing ISO headforms by Hybrid III head o More realistic head mass o More realistic head inertia o Deformable skin o Easy link to Hybrid III neck o Possibility to fix rotational transducers

	Mass [kg]	I_{xx} [kg.m²]	I_{yy} [kg.m²]	I_{zz} [kg.m²]
ISO Pedestrian	4.5	11.10^{-3}	11.10^{-3}	$110.5.10^{-3}$
Hybrid III 50th	**4.5**	**$17.088.10^{-3}$**	**$18.872.10^{-3}$**	**$22.685.10^{-3}$**
SUFEHM	**4.5**	**$17.996.10^{-3}$**	**$18.360.10^{-3}$**	**$21.902.10^{-3}$**
ISO motor M	5.7		Not controlled	

The A, C, E, J, M and O sizes represent 95% of size used in global standards.

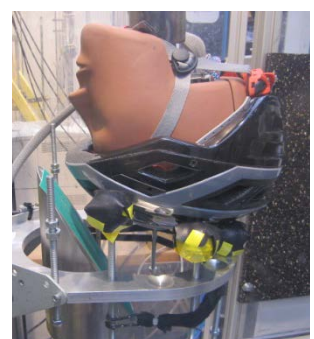
EN 960 headform size	Head circumference [mm]	Dummy model	Head circumference [mm]
A	500	Hybrid III 3 Year Old	508
C	520	Hybrid III 6 Year Old	520.7
E	540	Hybrid III 10 Year or 5th Female	538.5
J	570	Hybrid III 95th Large Male	584
M	600	Hybrid III 50th Male	597
O	620		

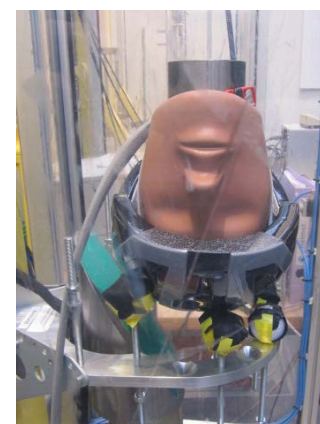
Head Impact Conditions & Headform

Critical issue	Comments	Recommandations
 Cold condition -20°C	Very few bicyclist's accident occur at temperatures as low as -20 °C Non realistic temperature	Cold conditioning -10°C
 Kerbstone anvil	Accident analysis shows that bicyclist heads only rarely impact kerbstone	~~Kerbstone anvil~~
 Head boundary conditions	1. Any linear impact, not strictly in line with the head-helmet center of mass leads to rotation 2. If tangential impacts are to be considered	Add a HIII neck ? 

Head Impact Conditions

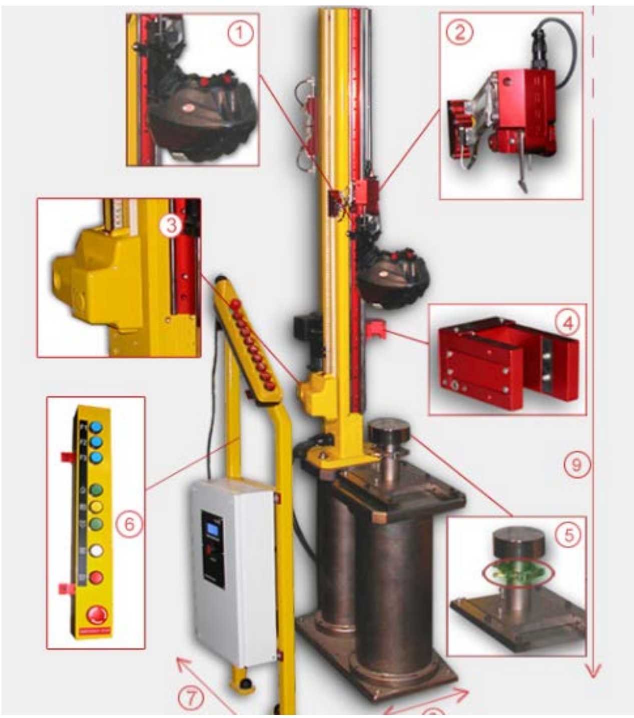
Critical issue	Comments	Recommandations
Linear Velocity 5.42 m/s	If the head initial velocity seems to be reasonable in regard of real world accident situation, and fall alone simulations, the fact that this velocity has only a normal component is not acceptable Velocity with only a normal component is not acceptable	Two tangential impacts characterized by : $-V_N = 5.42$ m/s $-V_T = 3.5$ m/s, $-V_R = 6.5$ m/s Frontal and lateral impacts

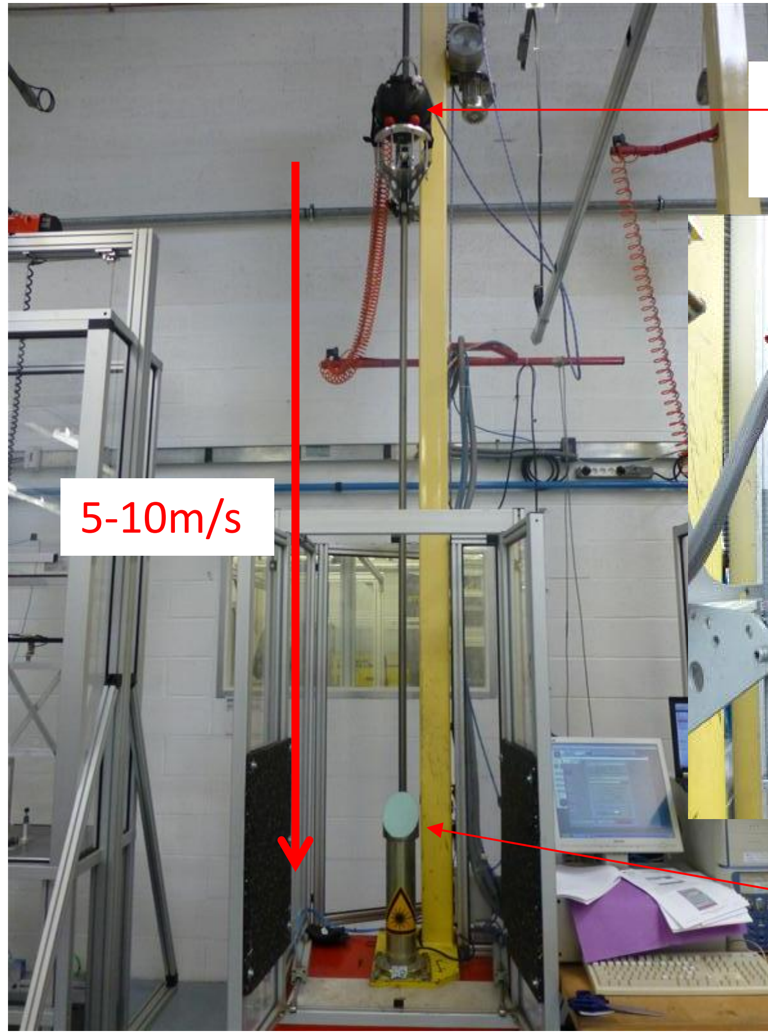




CEN-WG11 proposal for oblique test

Built around existing test rigs from AD Engineering or Cadex



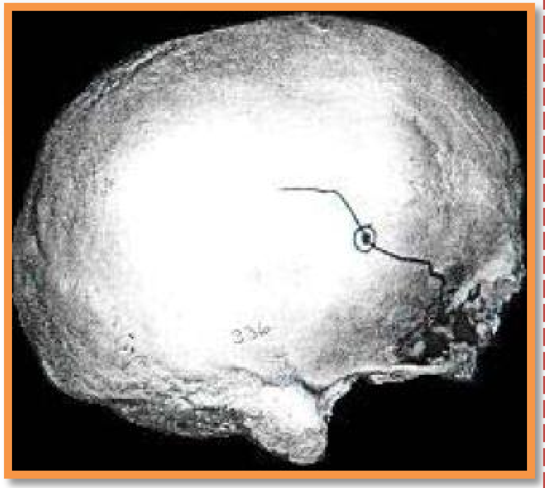


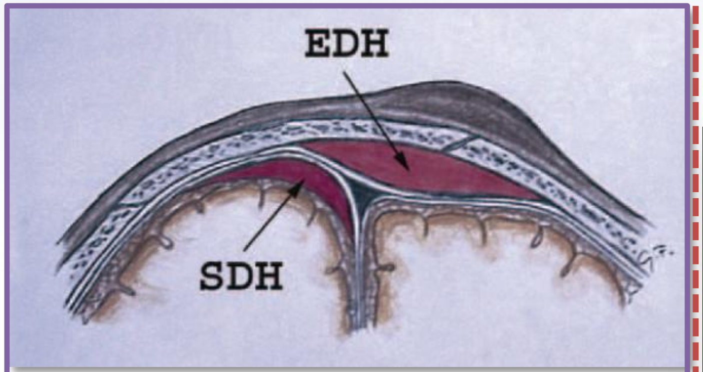
Hybrid III head form and helmet

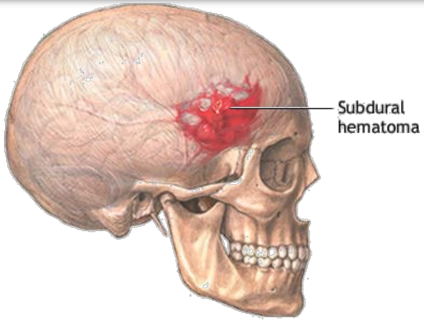
30-60° anvil with abrasive paper

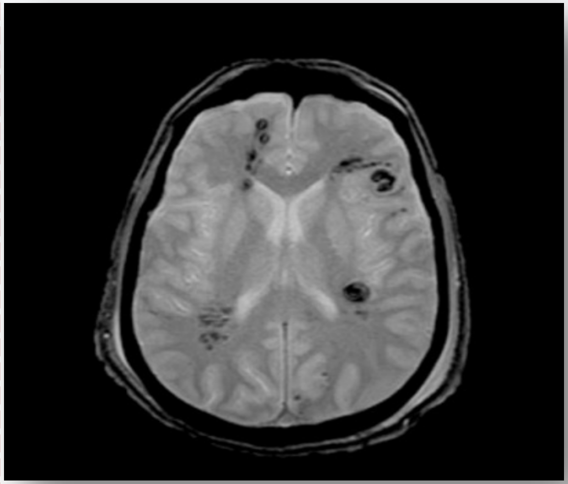
Standard helmet drop test machine adapted for rotational impact

ADVANCED HEAD INJURY CRITERIA









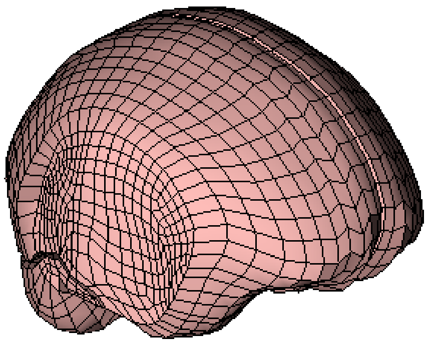
SKULL FRACTURES ↕ **SKULL DEFORMATION**

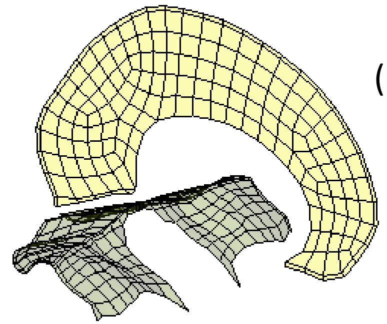
SUBDURAL AND SUBARACHNOIDAL HAEMATOMA ↕ **RELATIVE MOTION BETWEEN THE BRAIN AND THE SKULL**

DIFFUSE AXONAL INJURIES (DAI) ↕ **INTRACEREBRAL STRAINS/STRESS**

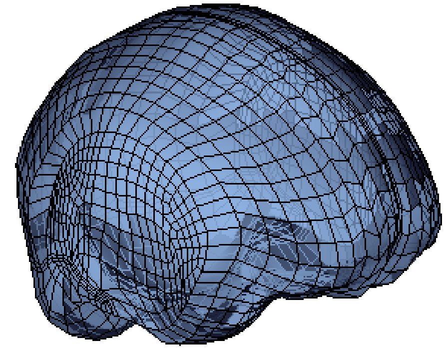
Strasbourg University FE Head Model

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

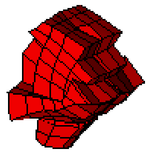




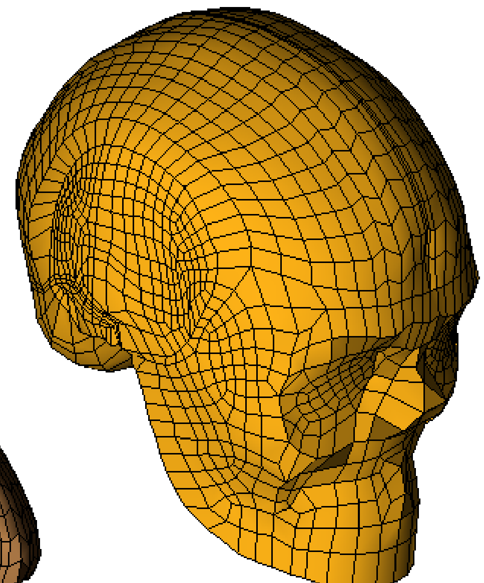
Membranes
(Elastic E=31.5MPa, γ=0.23)



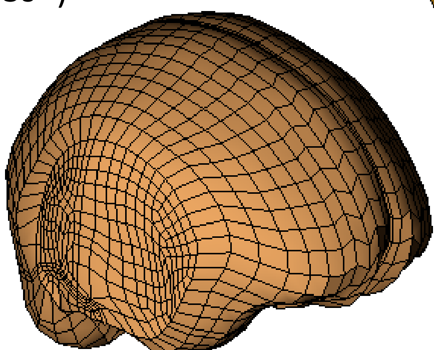
CSF
(Elastic E=12kPa, γ=0.49)



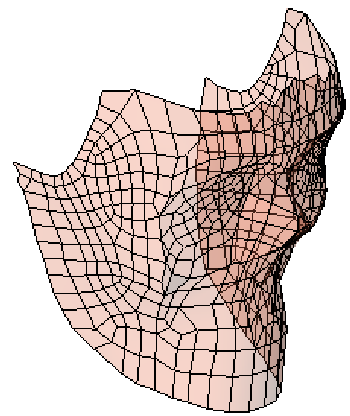
Brainstem
(Viscoelastic G_0=49kPa, G_∞=16.7kPa, β=145s^{-1})



Scalp
(Elastic E=16.7MPa, γ=0.42)



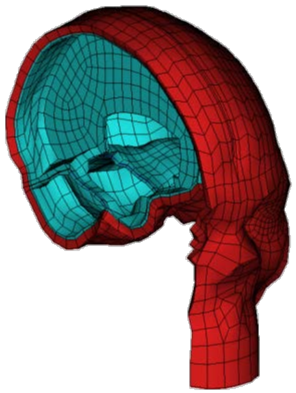
Skull
(Shell elements, composite law with failure criterion)

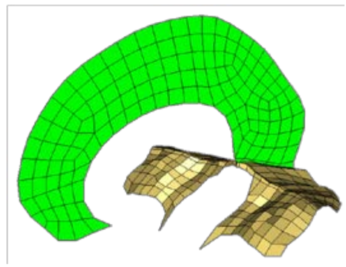


Face
(rigid)

SUFEHM_MECHANICAL PROPERTIES

PARTS

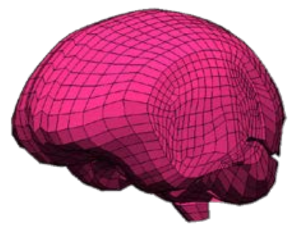




	ρ [kg.m⁻³]	E [MPa]	ν
Face	2500	5000	0.23
Scalp	1200	16.7	0.42
CSF	1040	0.012	0.49
Falx and tentorium	1140	31.5	0.45

BRAIN

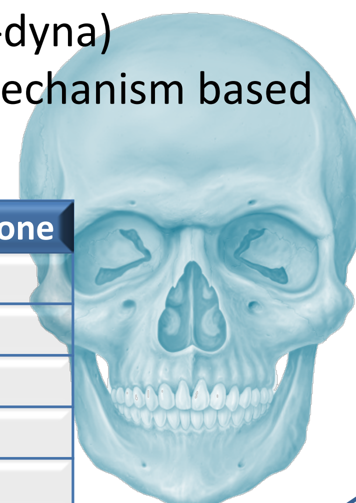
$$G(t) = G_\infty + (G_0 - G_\infty)e^{-\beta t}$$



	K [GPa]	G_0 [kPa]	G_∞ [kPa]	β [s^{-1}]
Brain	1.125	49	16.2	145

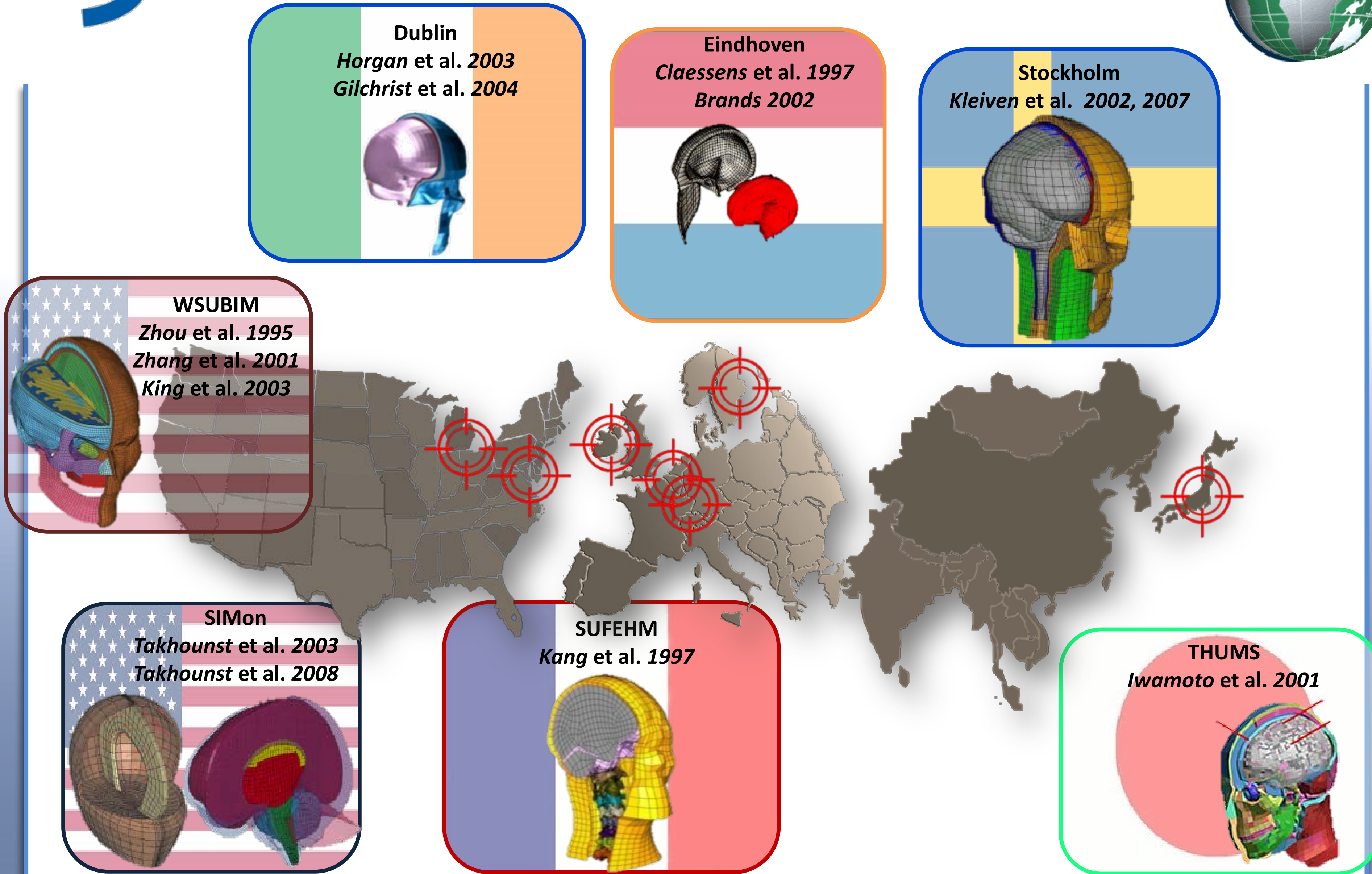
SKULL

- ❑ Skull material model =MAT55 _ENHANCED COMPOSITE_DAMAGE (Ls-dyna)
- ❑ Skull was modelled by a three layered composite shell and damage mechanism based on Tsai and Wu criterion(Tsai and Wu ,1971).

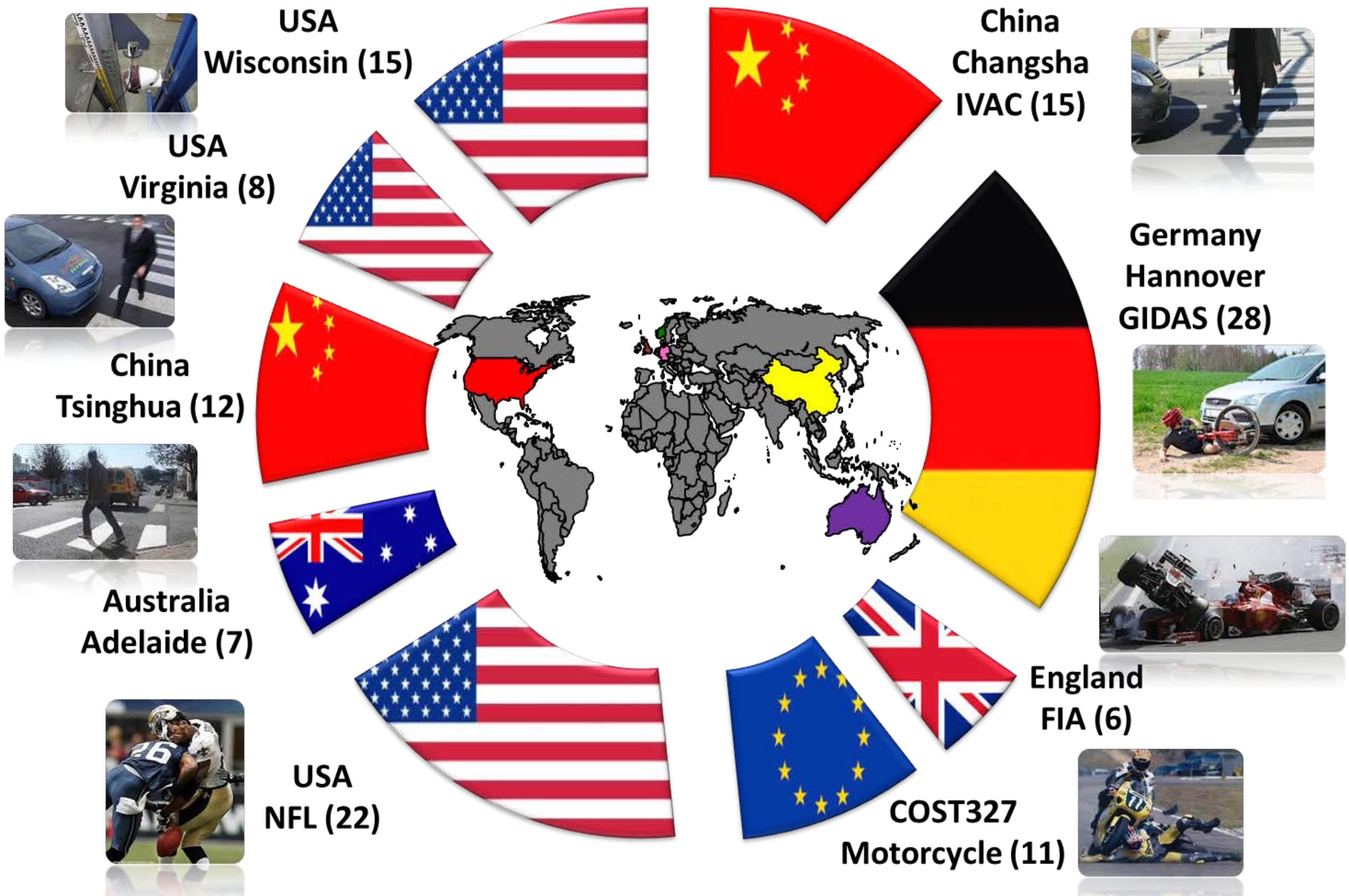


Parameters	Cortical bone	Diploe Bone
Mass density (Kg/m³)	1900	1500
Young's Modulus (Mpa)	15000	4665
Poisson's ratio	0.21	0.05
Longitudinal and transverse compressive strength(Mpa) Xc, Yc	132	24.8
Longitudinal and transverse Tensile strength (Mpa) X_t, Y_t	90	34.8

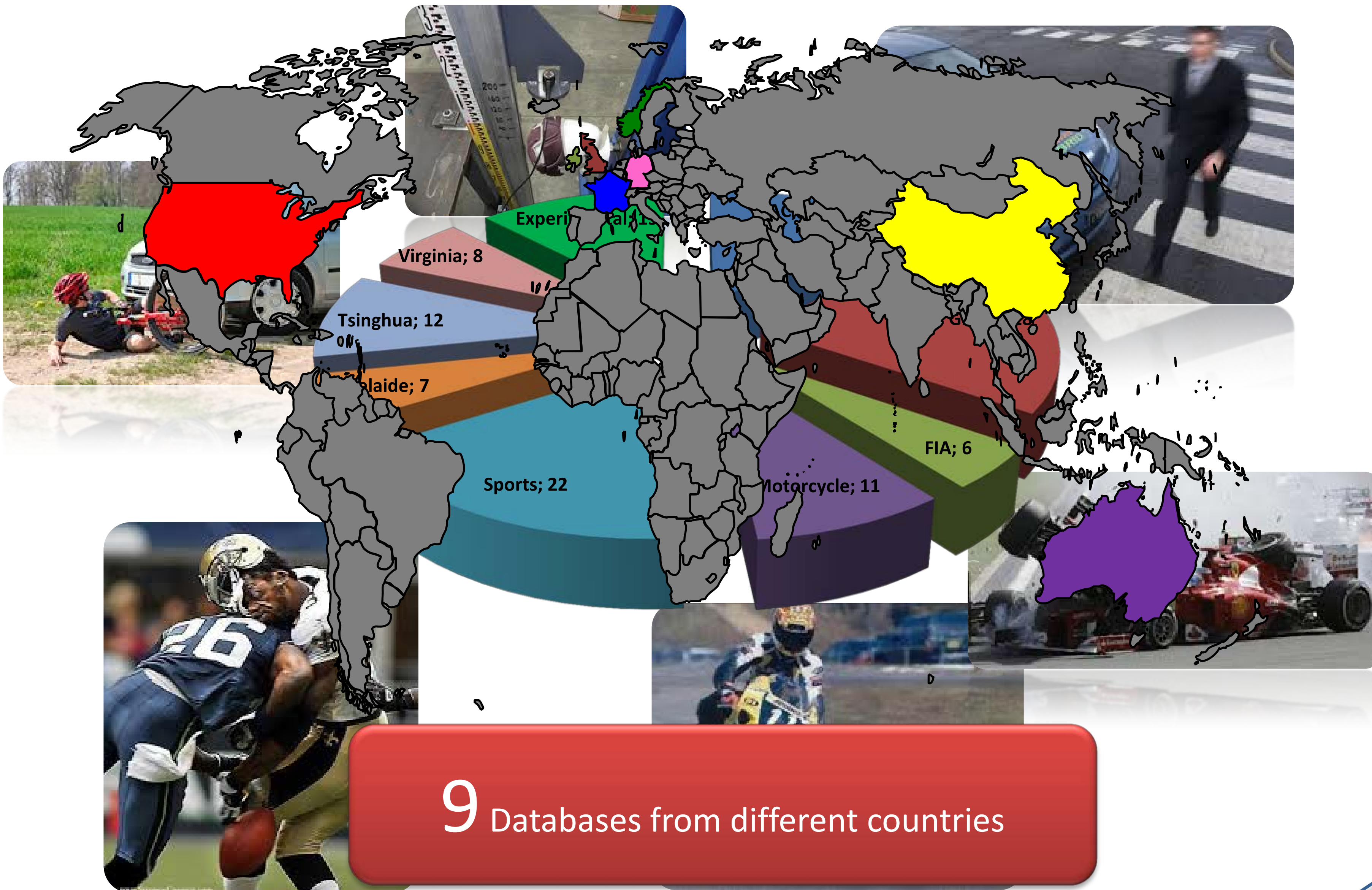
Head FEM around the World



Head Trauma database
(125 cases)



Head Trauma database (125 cases)



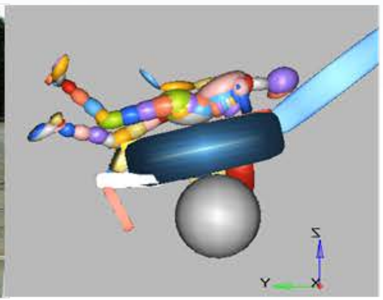
9 Databases from different countries

ACCIDENTS RECONSTRUCTIONS

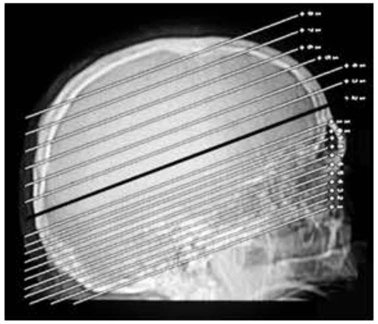
- **METHODOLOGY**

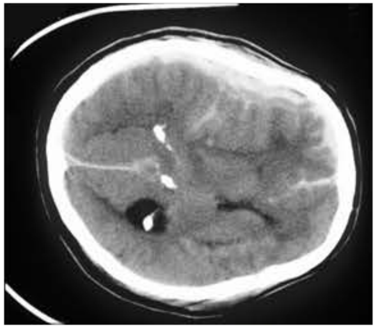
Experimental or analytical replication

Real accidents

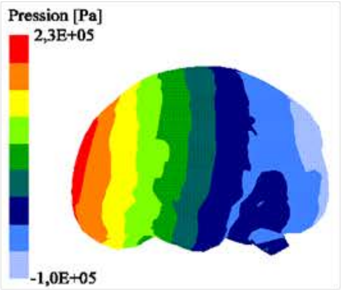


Detailed medical report





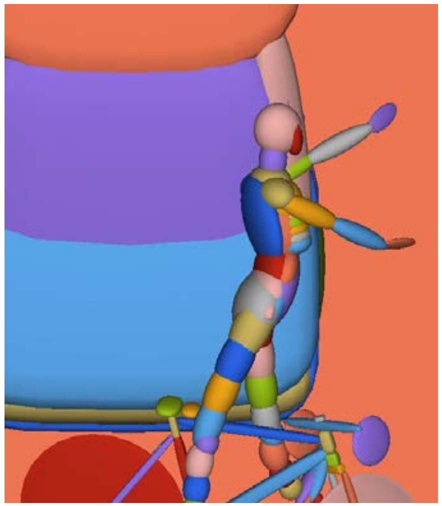
Numerical reconstruction

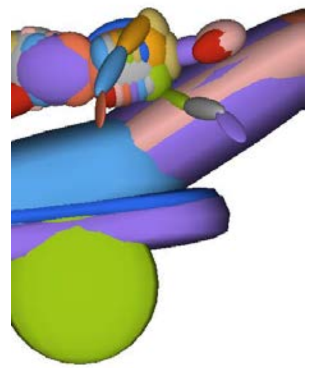


Injury mechanisms and tolerance limits

Bicyclist kinematics reconstruction

Unistra modeling

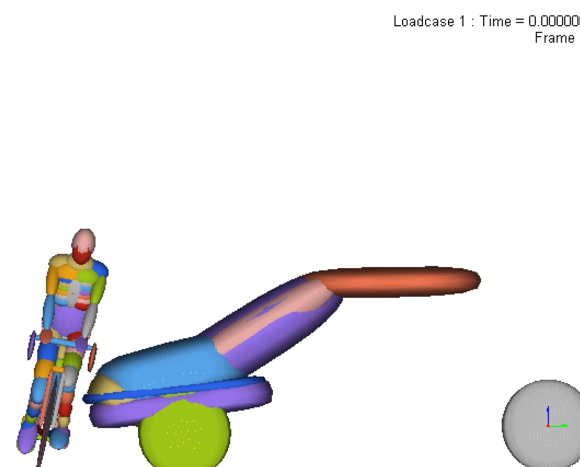




$V_{resultant} = 10.9$ m/s

$V_{normal} = 10.0$ m/s

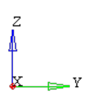
$V_{tangential} = 4.4$ m/s



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

Projection distance of 16.3 m

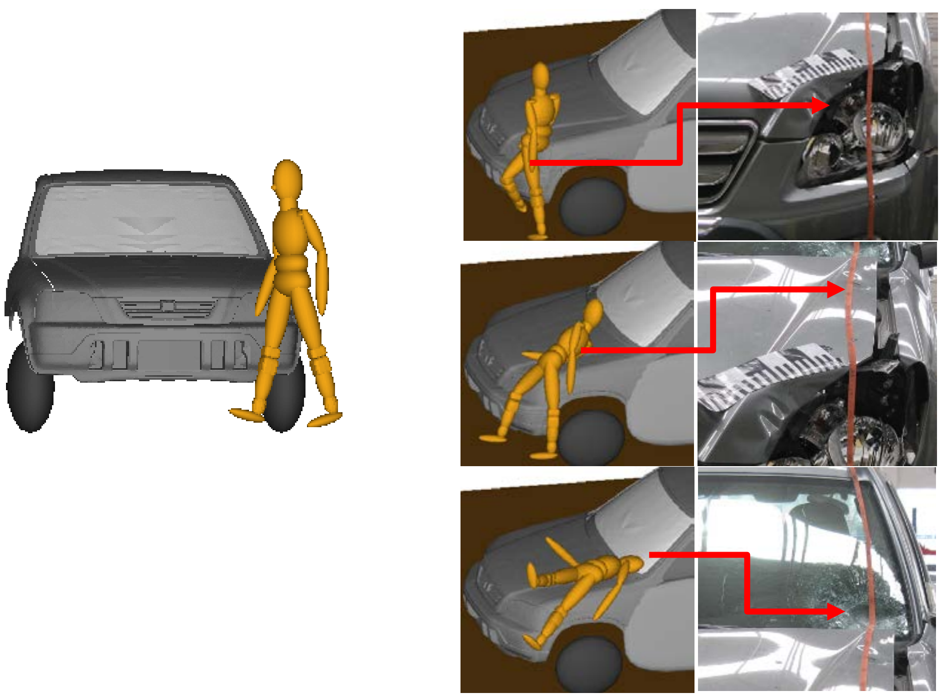
WAD of 2.10 m



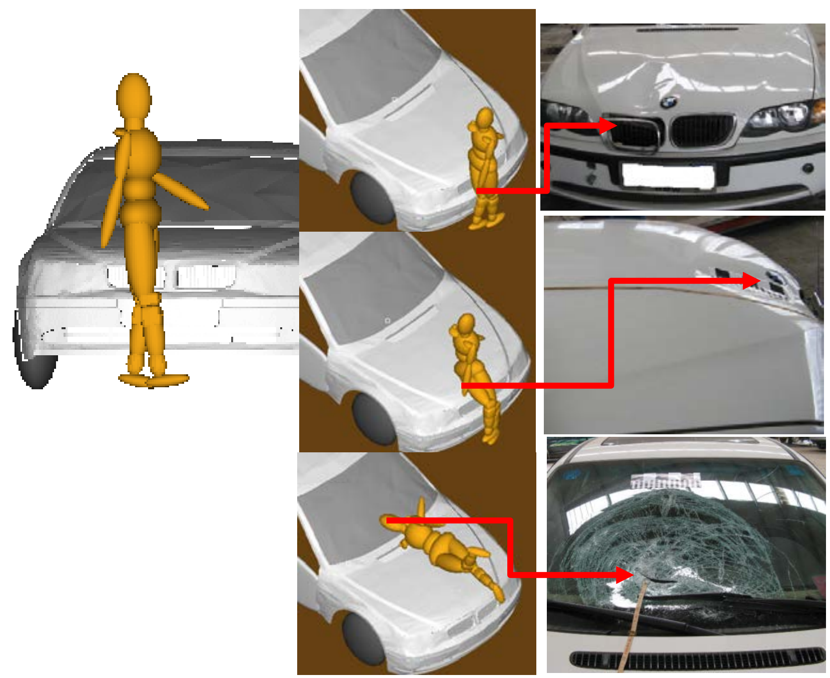
PEDESTRIAN KINEMATICS RECONSTRUCTION

➢ *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

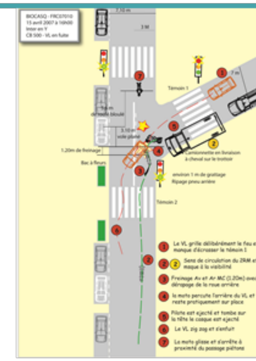
MOTORCYCLIST KINEMATICS

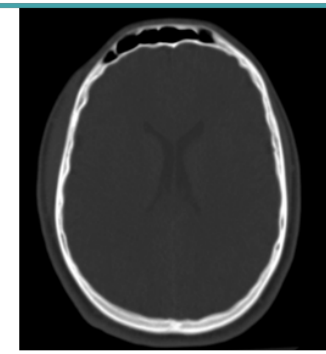
Case 2

Accident description

- Accident between a car and a motorcycle
- Doubt on helmet wearing

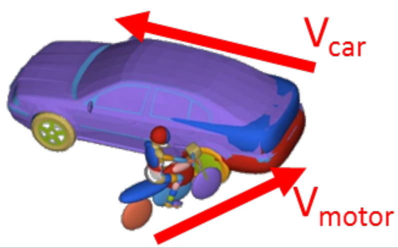
- Unconsciousness (Glasgow 7)
- AIS 3





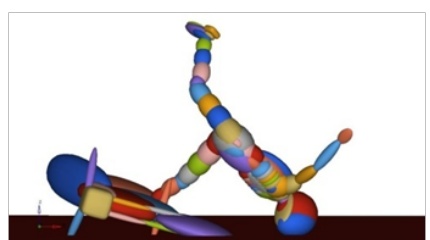
Accident reconstruction

Initial configuration



Impact kinematics

Extraction of head impact angle and velocity



Inputs for the helmeted headform under RADIOSS

SIMULATION OF THE HEAD TRAUMA

FIA

Motorcycles

Footballers

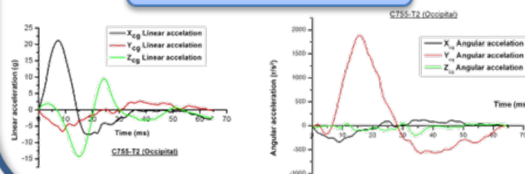
Total 125 accident cases

Pedestrians

Experiments

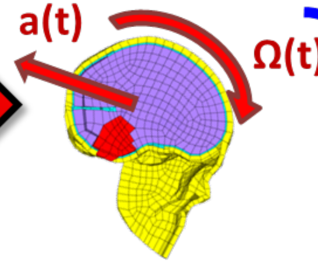
Experimental replications

6 accelerations

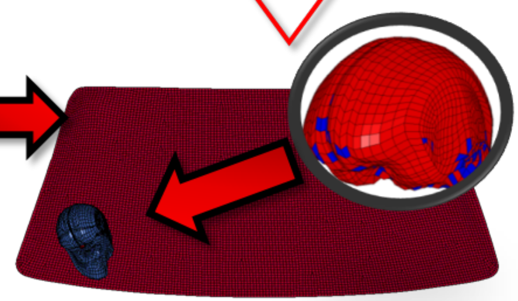


Numerical replications

Initial Head Velocity, Orientation Position



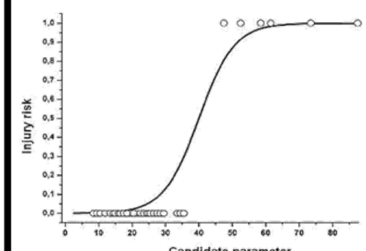
Numerical simulations



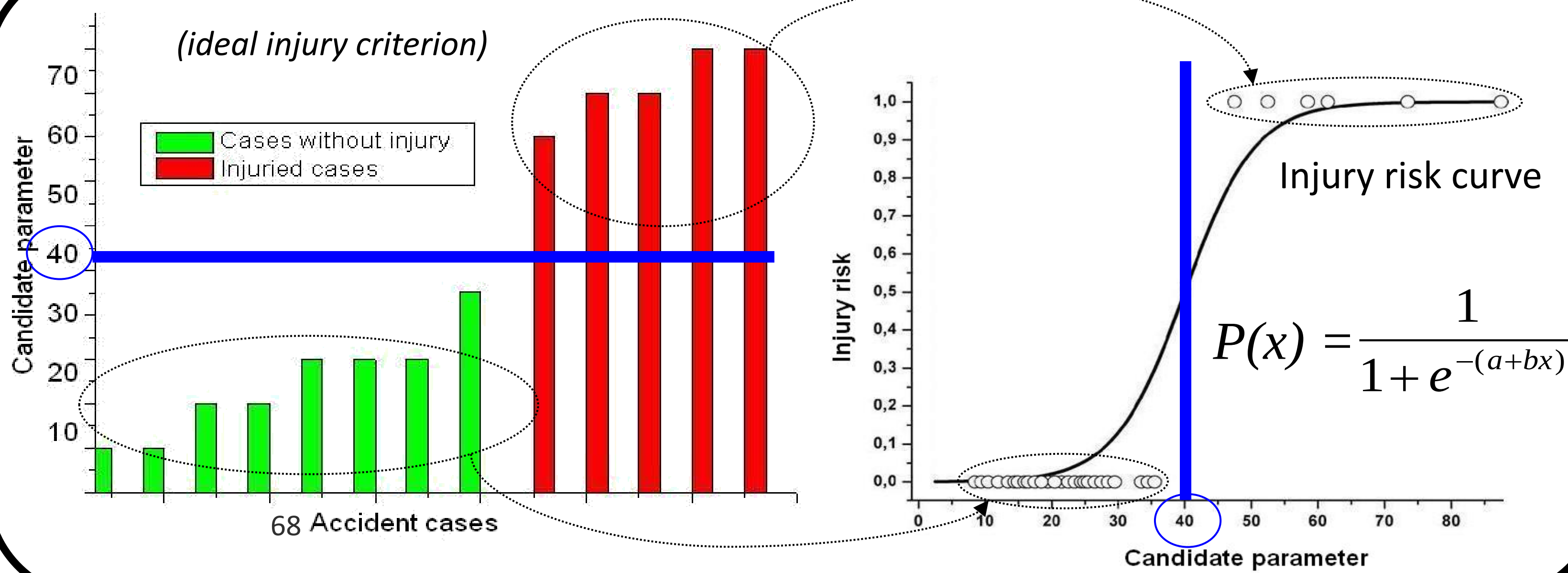
Injury Correlation

Statistical Analysis

Model Based Criteria



STATISTIC ANALYSIS : INJURY RISK CURVES



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

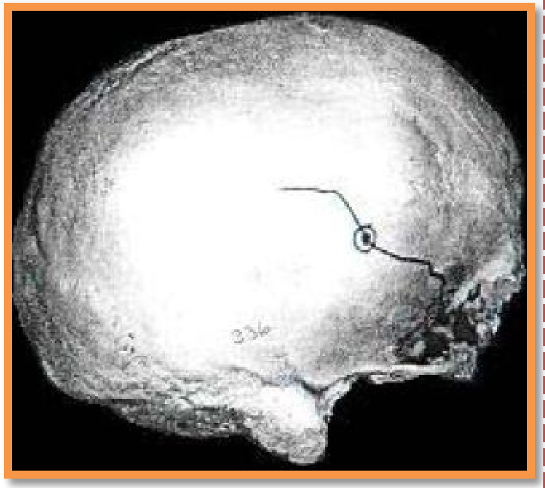
<u>*Modified likelihood method Nakahira et al. (2000)*</u>

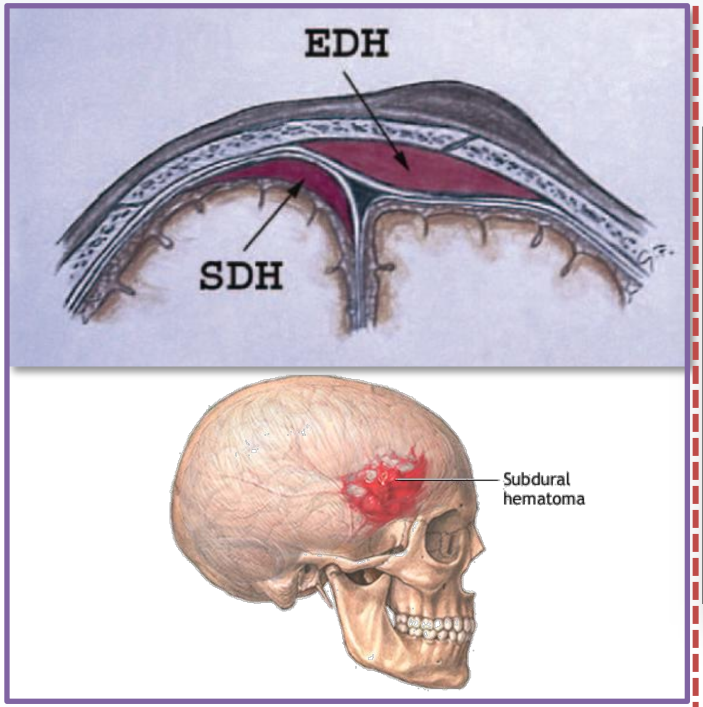
$$EB = \frac{1}{n} Log\left\{\prod_i P(x_i) \times \prod_j \left(1 - P(x_j)\right)\right\}$$

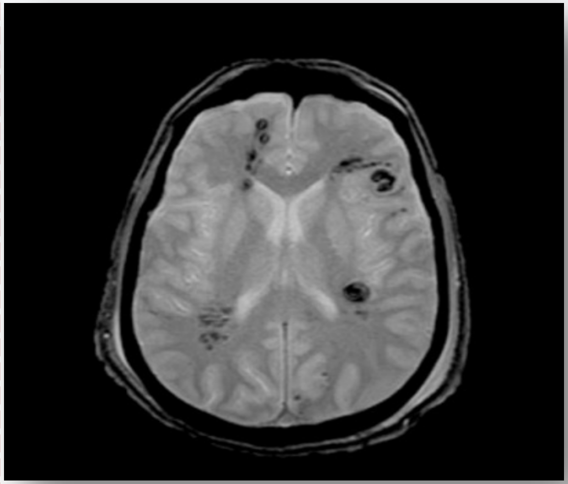
<u>*Binary logistic regression (SPSS v14.0)*</u>

we compared
the Nagelkerke R-sq statistic

Injury mechanisms and mechanical parameters







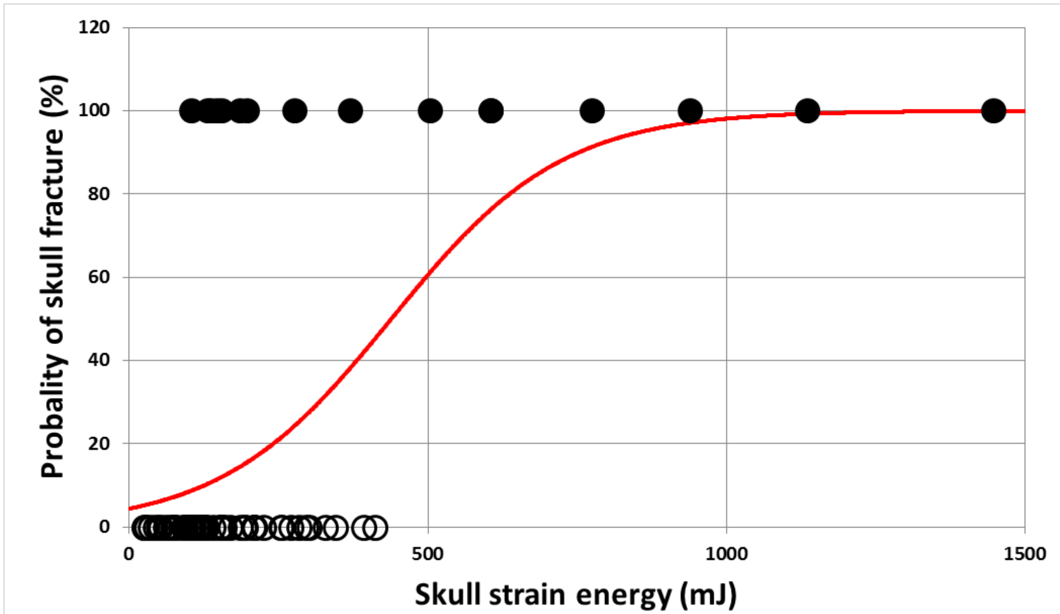
Skull fractures ↕ **Skull deformation**

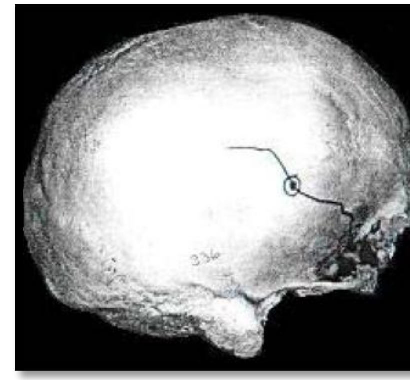
Subdural and subarachnoidal haematoma ↕ **Relative motion between the brain and the skull**

Diffuse Axonal Injuries (DAI) ↕ **Intracerebral strains/stress**

Skull fracture Criteria

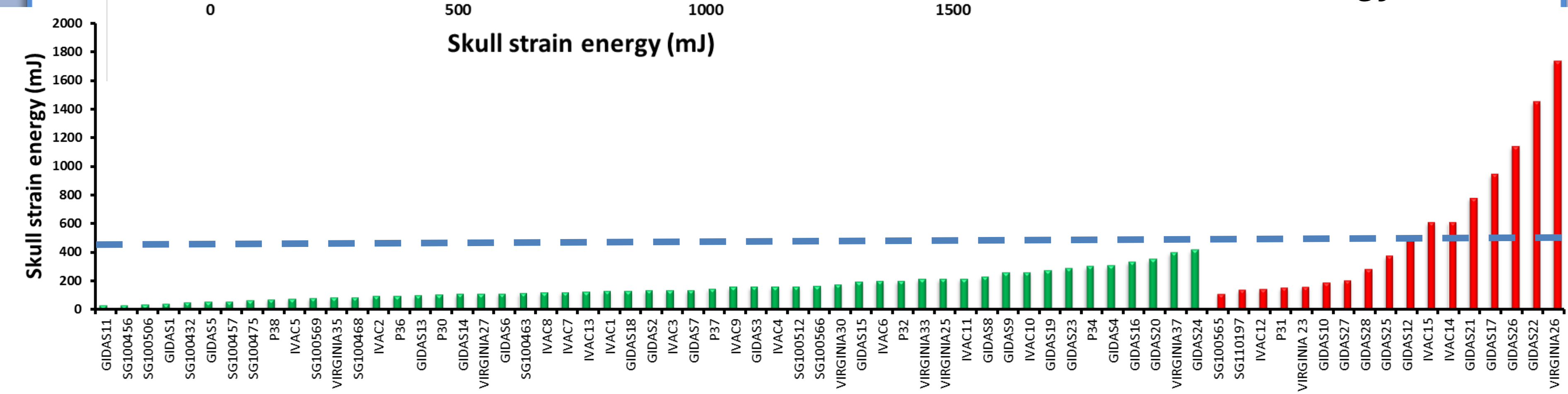
In terms of Skull Internal Energy :





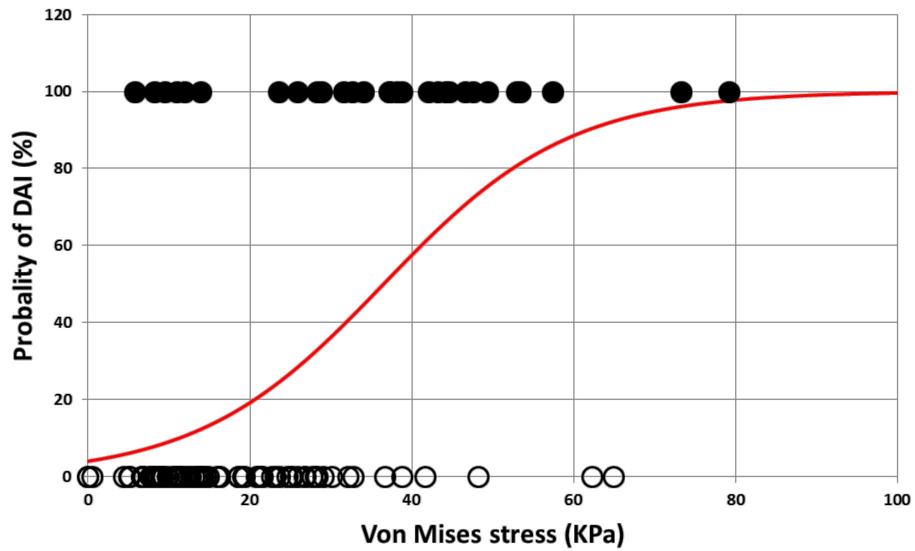
50% risk of skull failure:

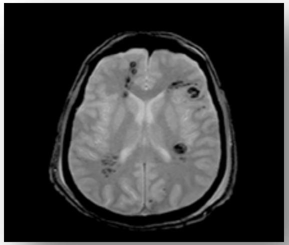
Skull Internal Energy=439mJ



Brain injury Criteria : AIS 2+

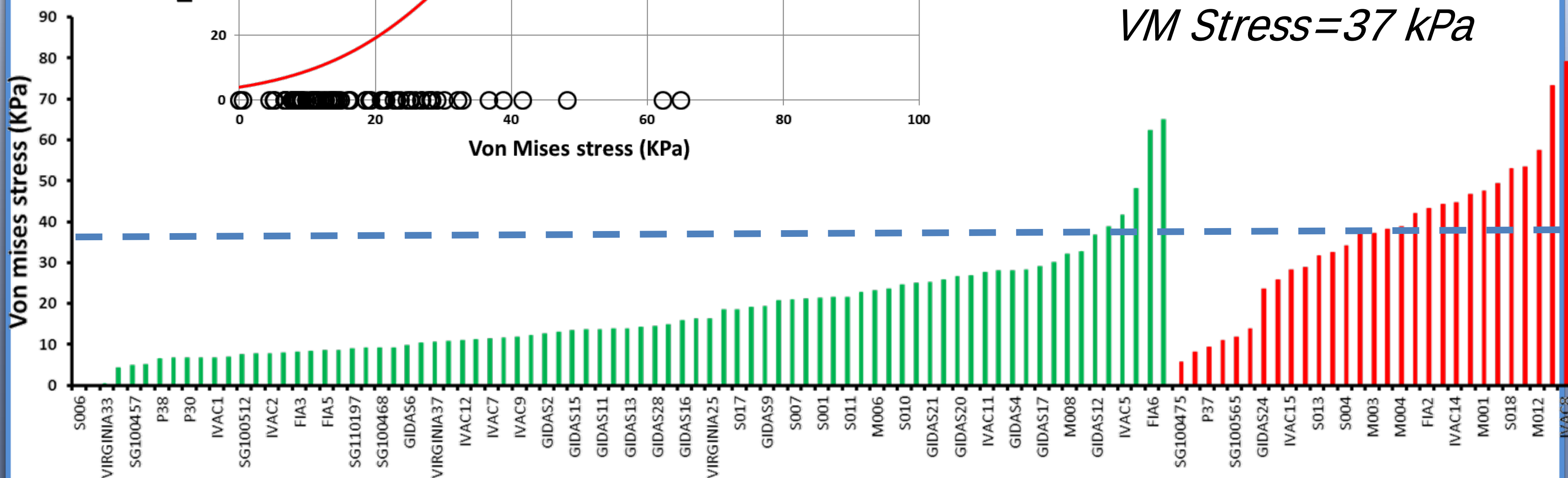
In terms of Brain VM Stress : R^2=0.36



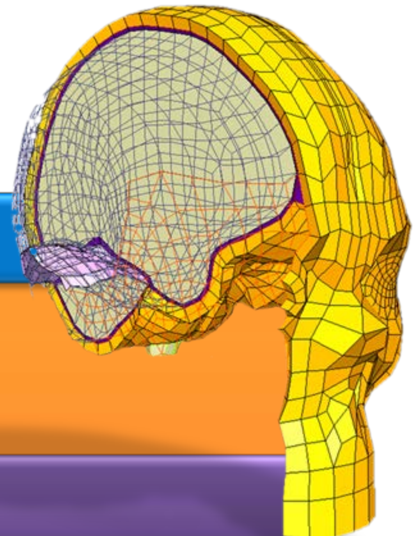


50% risk of DAI (AIS 2+):

VM Stress=37 kPa



Model based Head injury Criteria



SUB-ARACHNOIDAL HAEMATOMA (50% RISK)

- ✓ CSF Internal Energy : 4950 mJ

DAI (50% RISK) OF AIS 2+

- ✓ Intra-cerebral Von Mises stress : 37 kPa (previously 26-53kPa)

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

- ✓ Skull strain Energy : 439 mJ (previously 421 mJ)

INJURY CRITERIA FROM THE LITERATURE

UNIVERSITÉ DE STRASBOURG

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:

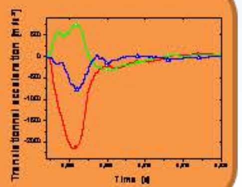
-Code dependance
-Age dependance

FROM RESEARCH TO END USERS

UNIVERSITÉ DE STRASBOURG

- PRE AND POST-PROCESSING USER INTERFACES :

ACCELERATION
- LINEAR
- ANGULAR



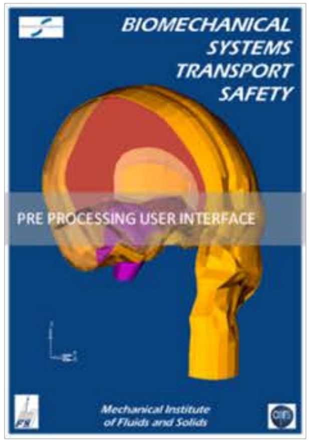
PRE PROCESSING USER INTERFACE

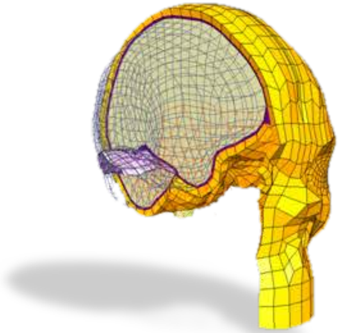
RADIOSS

LS DYNA

PAMCRASH

POST PROCESSING USER INTERFACE



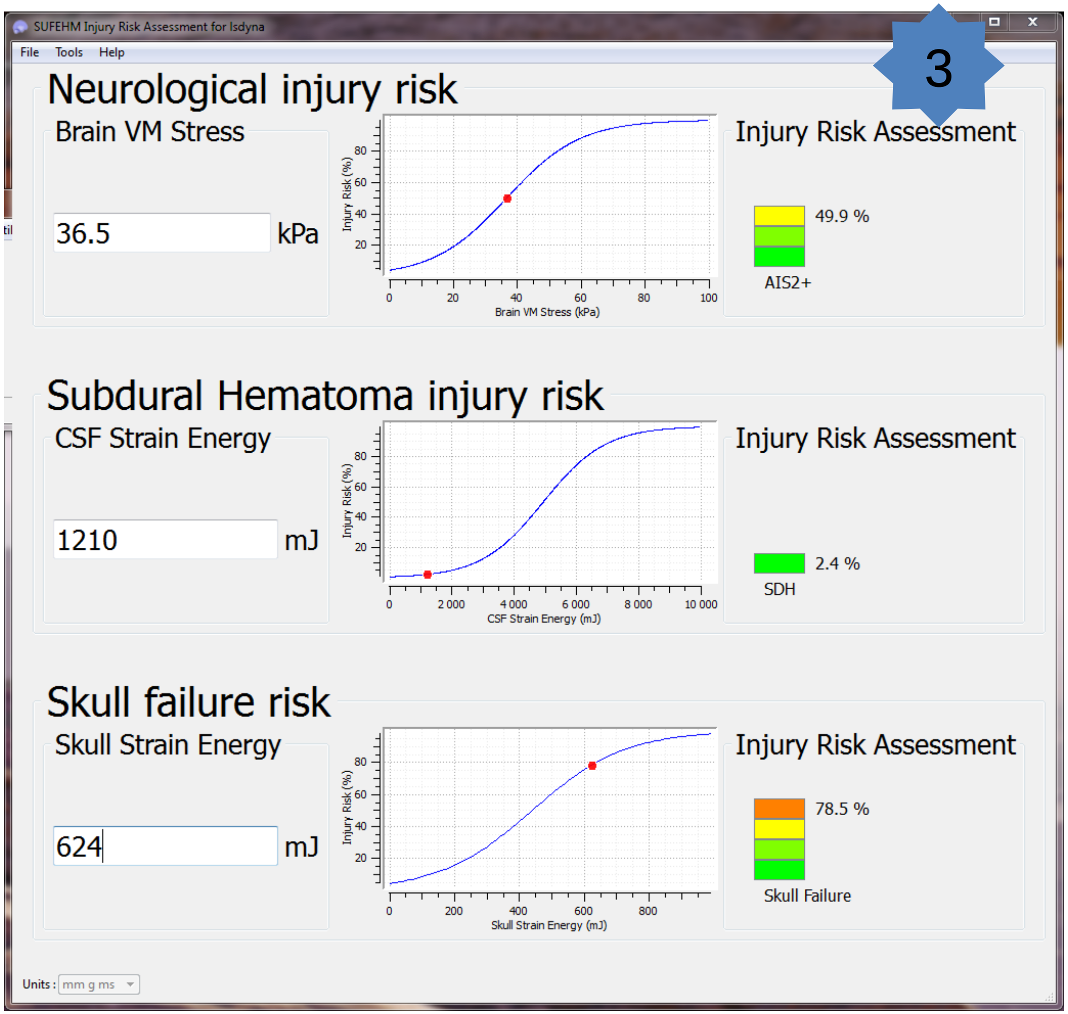


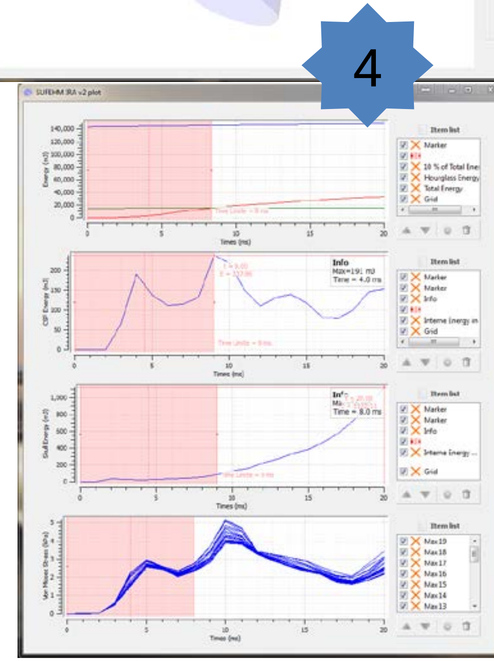
SUFEHM

INJURY PREDICTION
- DAI
- SDH

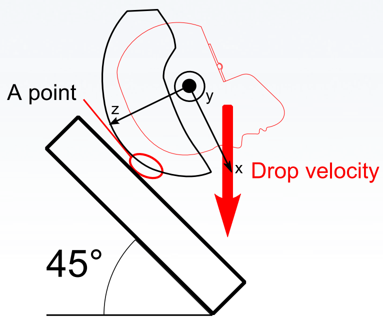
3D LOCALISATIONS

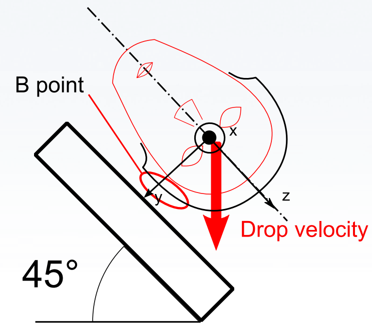
Head injury prediction tool

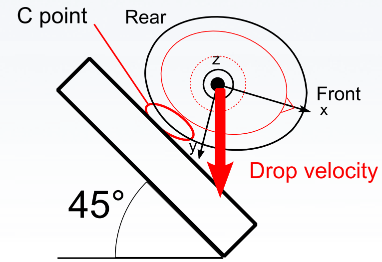




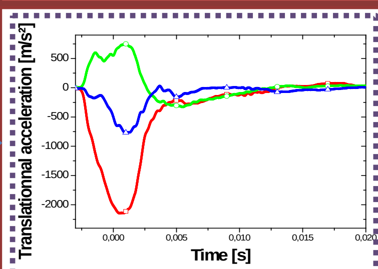
Head Injury Criteria in a new standard

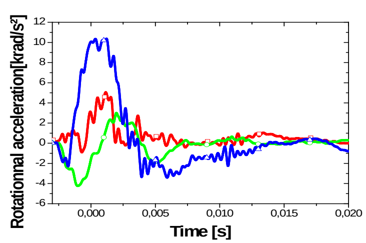






Linear and Rotational Accelerations



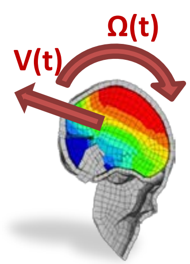


Standard Parameter

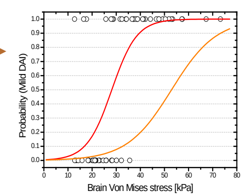
$$HIC = (t_2 - t_1)\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}$$

Improved Model based Head Injury Criteria

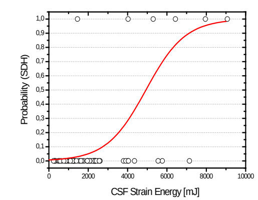
SUFEHM



Injury risk assessment for 3 injury mechanisms



Diffuse Axonal Injuries

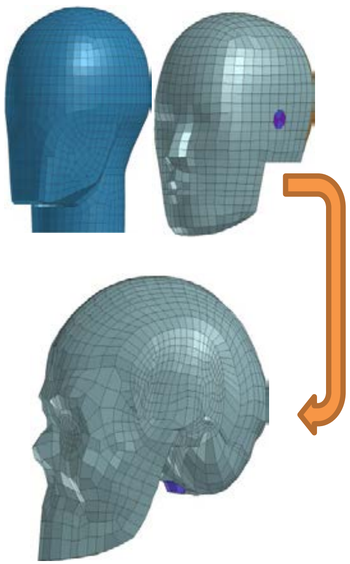


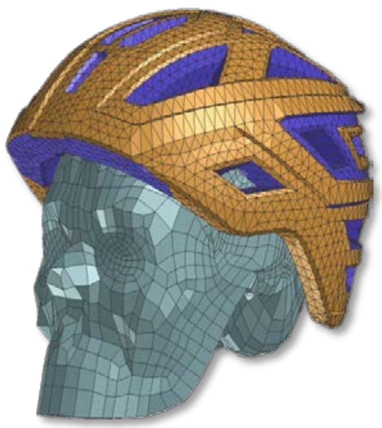
Subdural Hematoma

Feasability Study

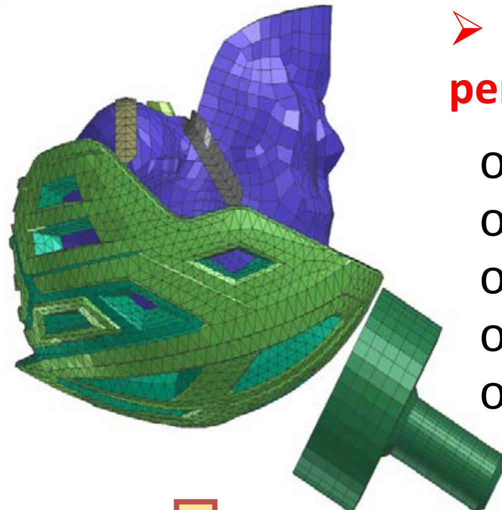
SUFEHM/Bicycle Helmet coupling

Coupling

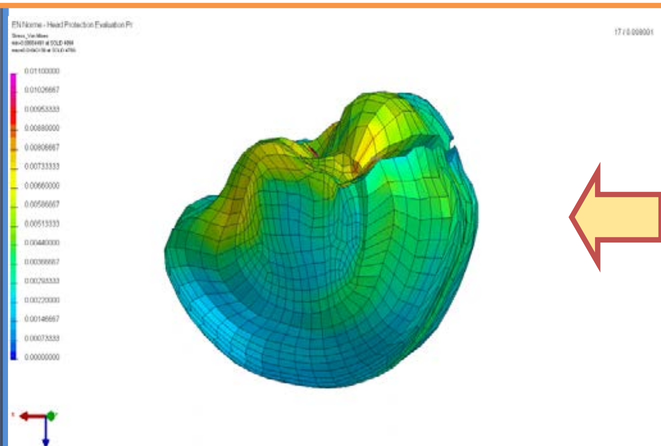


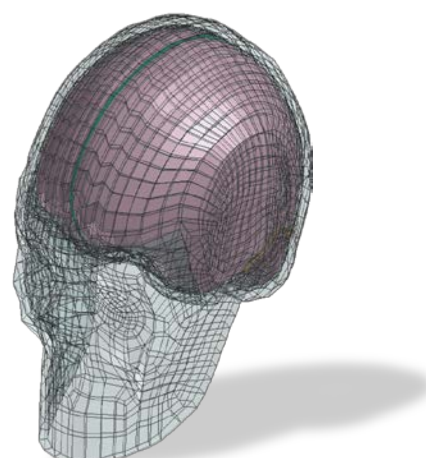


SUFEHM/Helmet
contact: Type 33, **FC=0.5**



- **39 simulations performed:**
  - o 2 test anvils: Flat, Kerbstone
  - o 8 (5) points on flat (kerbstone)
  - o Drop: Guided free fall
  - o 3 conditionings: -20°C, +50°C, H
  - o Impact velocities





- **2 simulations performed:**
  - o Head impact angle: 60°
  - o 2 impact locations: frontal, late
  - o Drop: Guided free fall
  - o Ambiant temperature
  - o v=5.42 m/s

CONCLUSIONS

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- A total of four key aspects have been reviewed in a critical way

  (head impact conditions, head surrogate, head impact location and head injury criteria)

- At head impact conditions level it is proposed to implement **tangential** head impact tests with a helmeted Hybrid III head.
- Further improvement concerns the impact location as the current test line excludes any impact to the temporal region.
- Simplified test conditions are proposed for impacted surface, temperature, humidity and neck boundary conditions
- A final key evolution concerns the assessment of the head injury risk for which a coupled experimental versus numeric method is proposed in order to introduce **model based head injury criteria**.

It is expected that the evolution of helmet standard test method will enable advanced helmet evaluation and optimization against biomechanical criteria

Institut de Mécanique des Fluides et des Solides - IMFS-UNISTRA
Equipe Biomécanique

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