French considerations on R22

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INTRODUCTION

• The needs of R22-improvements
• Head impact conditions
• Critical issue with current 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
• Towards advanced experimental vs numerical helmet test methods
• Conclusions
NEEDS OF R22 IMPROVEMENTS

More realistic head impact conditions: Consideration of Oblique impacts

Consideration of advanced head injury criteria

Proposal of an experimental versus numerical helmet test method

More general Context:

Similar progress exist within CEN TC158-WG11 (bycicle and equestrian helmets).

Progress also exist within FIM

Similar approach under progress within EuroNcap for car environment

Existing Helmet rating
TOWARDS NEW HELMET STANDARDS
It is **well known** that brain is sensitive to rotational acceleration since Holbourn (1943)

This phenomenon has essentially been addressed qualitatively with **animal** or physical **models**. Ommaya et al. (1967, 1968), Unterharnscheidt (1971), Ono et al. (1980), Gennarelli et al. (1982), Newman et al. (1999, 2000).....

By using **Finite Element Head Models** it was demonstrated and expressed quantitatively the **dramatic** influence of the rotational acceleration on intra-cerebral loading. Deck et al. (2007), Kleiven et al. (2007), Zhang et al. (2001)...
A number of studies focused 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)...

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
# Existing Attemps for Oblique Impact Tests

Submit by the expert from France

## Existing test procedures

<table>
<thead>
<tr>
<th>Authors</th>
<th>Helmet</th>
<th>Headform</th>
<th>$V_N$ (m/s)</th>
<th>$V_T$ (m/s)</th>
<th>$\ddot{\theta}$ (krad/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aldman et al., 1976</td>
<td>Motorcycle</td>
<td>Ogle-Opat + neck</td>
<td>5.2</td>
<td>8.3</td>
<td>[4.5 ; 14.5]</td>
</tr>
<tr>
<td>Aldman et al., 1978</td>
<td>Motorcycle</td>
<td>Ogle-Opat full dummy</td>
<td>4.4</td>
<td>8.3</td>
<td>[4.8 ; 19]</td>
</tr>
<tr>
<td>Mills &amp; Gilchrist, 1996</td>
<td>Motorcycle</td>
<td>Spherical</td>
<td>2.4</td>
<td>8.0</td>
<td>[10.4 ; 16.0]</td>
</tr>
<tr>
<td></td>
<td>Motorcycle</td>
<td>Spherical</td>
<td>3.1</td>
<td>8.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Motorcycle</td>
<td>Spherical</td>
<td>4.0</td>
<td></td>
<td></td>
</tr>
</tbody>
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<th>$\ddot{\theta}$ (krad/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halldin et al., 2001</td>
<td>Motorcycle</td>
<td>Ogle</td>
<td>5.0</td>
<td>5.0</td>
<td>[6.0 ; 14.0]</td>
</tr>
<tr>
<td>Mills &amp; Gilchrist, 2007</td>
<td>Bicycle</td>
<td>Ogle</td>
<td>4.5</td>
<td>3.6</td>
<td>[2.8 ; 6.2]</td>
</tr>
<tr>
<td>Pang et al., 2011</td>
<td>Motorcycle</td>
<td>Hybrid III + neck</td>
<td>6.26</td>
<td>3.13</td>
<td>[1.3 ; 10.9]</td>
</tr>
<tr>
<td></td>
<td>Motorcycle</td>
<td>Hybrid III + neck</td>
<td>7.67</td>
<td>5.42</td>
<td></td>
</tr>
</tbody>
</table>

<table>
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<tr>
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<th>Helmet</th>
<th>Headform</th>
<th>$V_N$ (m/s)</th>
<th>$V_T$ (m/s)</th>
<th>$\ddot{\theta}$ (krad/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Withnall &amp; Bayne, 2005</td>
<td>Football</td>
<td>Hybrid III + neck</td>
<td>5.4</td>
<td>0</td>
<td>Non precised</td>
</tr>
</tbody>
</table>

(Mills & Gilchrist, 1996)

(Harrison et al., 1996)

(US Patent, 2005)
THREE KEY ASPECTS TO BE CONSIDERED

New Test Method

- A more realistic 6D instrumented headform
- More realistic impact conditions
- More biofidelic injury criteria
HEAD IMPACT CONDITION VIA ACCIDENT SIMULATION

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HEAD IMPACT CONDITION FOR MOTORCYCLIST

Additional head impact condition

A total of 78 real world motorcycle accidents

\[ \begin{align*}
V_{\text{Resultant}} &= 13 \pm 7.2 \text{ m/s} \\
V_{\text{Normal}} &= 7.4 \pm 4.5 \text{ m/s} \\
V_{\text{Tangential}} &= 9.7 \pm 7.3 \text{ m/s}
\end{align*} \]

Comparison with drop velocity and angle from real accident cases gathered from literature

<table>
<thead>
<tr>
<th>Helmet</th>
<th>References</th>
<th>Drop velocity [m/s]</th>
<th>Anvil / Drop axis [deg]</th>
<th>Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motorcycle</td>
<td>Otte et al. 1999</td>
<td>12</td>
<td>&lt;30</td>
<td>Side of car or road</td>
</tr>
<tr>
<td>Equestrian</td>
<td>Mellor and Chinn 2006</td>
<td>9</td>
<td>37</td>
<td>Hard grass</td>
</tr>
<tr>
<td>Bike</td>
<td>Vershueren 2009</td>
<td>5.3</td>
<td>40</td>
<td>Road</td>
</tr>
<tr>
<td></td>
<td>Bourdet et al. 2013</td>
<td>6.8</td>
<td>60</td>
<td>Car</td>
</tr>
<tr>
<td></td>
<td>Bourdet et al. 2012</td>
<td>6.7</td>
<td>55</td>
<td>Road</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.2</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>Motorcycle</td>
<td>Real-world cases</td>
<td>11.1</td>
<td>44</td>
<td>Road and car</td>
</tr>
</tbody>
</table>
CONCLUSION

- The simulations of the victim kinematics in real world accident demonstrated the effectiveness of oblique head impact conditions.

- The human head is very sensitive to the rotational acceleration induced by this tangential component.

- It is important that the helmet presents protection capabilities against this loading.

Despite this consolidated knowledge, no head protection standard are currently considering head rotational acceleration.
From ISO EN960 to Hybrid III headform

- Mass in accordance with an average adult head
- More realistic inertial properties
- Deformable skin: soft contact between headform/helmet
- Further discussions undertaking progress within CEN TC158-WG11

<table>
<thead>
<tr>
<th>EN 960 headform size</th>
<th>Head circumference [mm]</th>
<th>Dummy model</th>
<th>Head circumference [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>500</td>
<td>Hybrid III 3 Year Old</td>
<td>508</td>
</tr>
<tr>
<td>C</td>
<td>520</td>
<td>Hybrid III 6 Year Old</td>
<td>520.7</td>
</tr>
<tr>
<td>E</td>
<td>540</td>
<td>Hybrid III 10 Year or 5th Female</td>
<td>538.5</td>
</tr>
<tr>
<td>J</td>
<td>570</td>
<td>Hybrid III 95th Large Male</td>
<td>584</td>
</tr>
<tr>
<td>M</td>
<td>600</td>
<td>Hybrid III 50th Male</td>
<td>597</td>
</tr>
<tr>
<td>O</td>
<td>620</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In collaboration with AD Engineering this test method is now operational

Certificated drop test device helmet testing absorption test

Anvil with a 45° inclined

ARS-06 and 06S Triaxial MHD Angular Rate Sensor Arrays from ATA sensors

PCB PIEZOTRONICs inc. accelerometers

500 g with a sensitivity of 10.00 mV/g, 10.02 mV/g and 10.05 mV/g respectively for x, y and z axes.

Instrumentation used for the 6D measurement of the headform
Motorcycle Helmet Test Method

- 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

- LX
- FY
- LZ

Submitted by the expert from France

Informal document GRSP-63-18
(63rd GRSP, 14-18 May 2018
agenda item 11)
BICYCLE HELMET TEST METHOD (WITHIN CEN)

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

**Linear Impacts**
Drop velocity = 5.5 m/s

**Oblique Impacts**
Drop velocity = 6.0 m/s \((V_N = 4.2 \text{ m/s})\)

- B
- R
- X
- LX
- FY
- LZ

Drop velocity = 25°

Drop velocity = 65°

Drop velocity = 66-68 mm
ILLUSTRATION OF OBLIQUE IMPACT

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agenda item 11)

LX Point  FY Point  LZ Point
PASS/FAIL CRITERIA FOR COMPLEX LOADING
Head tolerance curve proposed by Wayne State University given linear head accelerations versus time: WSUTC (1966).
Head injuries occur in the part upper the curve.

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

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

Part III: tests on human volunteers, no head impact, head kinematics recorded during sled tests.
HEAD INJURY CRITERION (1972) : HIC DEFINITION

Head mass = 4.58 kg; HIC = 1000

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

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

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

- **Motorcyclist (2002)**
  - Headform; $V = 7.5 \text{ m/s}$; $e = 5 \text{ cm}$; **HIC 2400**; $\Gamma = 275G$

- **Cyclist**
  - Headform; $V = 5.42 \text{ m/s}$; $e = 2.5 \text{ cm}$; $\Gamma = 250G$

... 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...)
ADVANCED TISSU LEVEL INJURY CRITERIA
STATE OF THE ART
HEAD FE MODEL AND VALIDATION
Skull Model Improvement

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

50th percentile adult skull

SUFEHM 98
Accident reconstructions
Tolerance limits

Digitalisation

[Deck, 2004]

[Kang, 1997]
Brain
(Viscoelastic $G_0 = 49$ kPa, $G_\infty = 16.7$ kPa, $\beta = 145$ s$^{-1}$)

Brainstem
(Viscoelastic $G_0 = 49$ kPa, $G_\infty = 16.7$ kPa, $\beta = 145$ s$^{-1}$)

Skull
(Shell elements, composite law with failure criterion)

Membranes
(Elastic $E = 31.5$ MPa, $\gamma = 0.23$)

CSF
(Elastic $E = 12$ kPa, $\gamma = 0.49$)

Scalp
(Elastic $E = 16.7$ MPa, $\gamma = 0.42$)

Face
(rigid)
**Intra-cranial behaviour validation**

Nahum & Trosseille (1977) (1992)
Impact area: front
Impactor: Cylinder with padding
Impact velocity: 6.3 m/s
Duration: 6.2 ms

Yoganandan (1994)
Impact area: vertex
Impactor: Rigid sphere
Impact velocity: 7.3 m/s
Duration: 2 ms

**Skull validation**

Hardy (2001)
Impact area: occipital
Impactor: Cylinder
Impact velocity: 2 m/s
Duration: 20 ms

Sarron (1999)
Back face effect
Under Ballistic conditions
**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**

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

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**Input:**

- IMPACTOR MASS 5.6Kg
- $E=13.6$ Mpa
- $\nu=0.16$

---

**Graph:**

- Interaction force between the head and the impactor

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*Experimental*
• Impact force, head acceleration

Some oscillations can appear in head acceleration results
STATE OF THE ART NUMERICAL HEAD MODEL

Submitter: Expert from France

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(63rd GRSP, 14-18 May 2018
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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
MODEL BASED BRAIN INJURY CRITERIA
REAL WORLD HEAD TRAUMA SIMULATION
**ACCIDENTS RECONSTRUCTIONS**

Submitted by the expert from France

**METHODOLOGY**

- Experimental or analytical replication
- Numerical reconstruction
- Real accidents
- Detailed medical report
- Injury mechanisms and tolerance limits

Informal document GRSP-63-18
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Database (125 cases)

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USA
Wisconsin (15)

USA
Virginia (8)

China
Tsinghua (12)

Australia
Adelaide (7)

USA
NFL (22)

China
Changsha IVAC (15)

Germany
Hannover GIDAS (28)

England
FIA (6)

COST327
Motorcycle (11)
Detailed Accident Reconstruction
Example: Description of Accident Case

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
**EXAMPLE: KINEMATICS RECONSTRUCTION**

Unistra modeling

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

\[ V_{\text{resultant}} = 10.9 \, \text{m/s} \]
\[ V_{\text{normal}} = 10.0 \, \text{m/s} \]
\[ V_{\text{tangential}} = 4.4 \, \text{m/s} \]
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

<table>
<thead>
<tr>
<th>Example 1</th>
<th>Example 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accident</strong></td>
<td><strong>Simulation</strong></td>
</tr>
<tr>
<td>Throw distance (m)</td>
<td>12.4</td>
</tr>
<tr>
<td>WAD (mm)</td>
<td>2000</td>
</tr>
<tr>
<td>Velocity (km/h)</td>
<td>60</td>
</tr>
</tbody>
</table>
MODEL BASED HEAD INJURY CRITERIA
Binary logistic regression (*SPSS v14.0*)

we compared
the Nagelkerke R-sq statistics
Brain injury Criteria : AIS 2+

- 50% risk of DAI (AIS 2+): VM Stress = 37 kPa

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### SUFEHM Head injury Criteria

<table>
<thead>
<tr>
<th>Injury Type</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sub-arachnoidal Haematoma (50% Risk)</strong></td>
<td>✓ CSF Internal Energy: -135 kPa</td>
</tr>
<tr>
<td><strong>DAI (50% Risk) of AIS 2+</strong></td>
<td>✓ Intra-cerebral Von Mises stress: 37 kPa</td>
</tr>
<tr>
<td><strong>Skull Fracture Injuries (50% Risk) of AIS 2+</strong></td>
<td>✓ Skull strain Energy: 439 mJ</td>
</tr>
</tbody>
</table>

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HEAD INJURY PREDICTION TOOL FOR END USERS
FROM RESEARCH TO END USERS

Submitted by the expert from France

PRE-POST-PROCESSING USER INTERFACES:

- ACCELERATION
  - LINEAR
  - ANGULAR

- RADIOSS

- LS DYNA

- PAMCRASH

- SUFEHM

INJURY PREDICTION
- DAI
- SDH

3D LOCALISATIONS
Experimental vs Numerical Test Method

The 18 impact tests are simulated using SUFEHM

Linear Accelerations

Rotational Accelerations

Standard Parameters

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

Improved Model Based Head Injury Criteria

Assessment of Brain Injury Risk
SUFEHM Injury Risk Assessment Tool

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INJURY RISK ASSESSMENT

Neurological injury risk
Brain VM Stress
36.5 kPa

Injury Risk Assessment
49.9 %
AIS2+

Subdural Hematoma injury risk
CSF Strain Energy
1210 mJ

Injury Risk Assessment
2.4 %
SDH

Skull failure risk
Skull Strain Energy
624 mJ

Injury Risk Assessment
78.5 %
Skull Failure
HELMET RATING
RATING BASED ON BRAIN INJURY RISK

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HELMET RATING: STIFTUNGWAHRENTEST 2017

CRATONI  CASCO  LAZER  ALPINA  ONEAL

LIMAR  PROPHETE  GIRO  BELL  B’TWIN

ABUS  UVEX  KED  POC  OVERADE
Rating of 21 bicycle helmets
# Le critère de la sécurité avant tout

Le nombre de collisions est nettement supérieur aux accidents dus à la faute humaine.

| Matière plastique | Acétate de polyvinyle | Béton | Acier | Aluminium | Propane | Polymères | Silice | Triacétylsulfone
|-------------------|----------------------|-------|-------|-----------|---------|-----------|-------|----------------|
| Hauteur (mm)      | 150                  | 100   | 50    | 200       | 200     | 200       | 100   | 150
| Rayon de courbure | 100                  | 50    | 10    | 200       | 300     | 300       | 200   | 200
| Espacement (mm)   | 100                  | 50    | 10    | 200       | 300     | 300       | 200   | 200

La connaissance des données et la maîtrise des techniques sont cruciales pour la sécurité des consommateurs.
20 MOTORCYCLE HELMETS

Submitted by the expert from France

Under progress ...

Informal document GRSP-63-18
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• Needs of R22 improvements
• Importance of oblique impact conditions and need of protection against rotational acceleration.
• Advanced Brain injury prediction tool for end user are available
• Proposal of a novel test method
• Consumer tests & Helmet rating
Remerciements :

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Strasbourg University
Laboratoire des sciences de l'ingénieur, de l'informatique et de l'imagerie (Icube)
Equipe Matériaux multi-échelles et Biomécanique (MMB)
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)
- 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 method, Tampa, November 2015 (ASTM meeting)