IRCOBI

International Research Council on Biomechanics of Injury

IRCOBI-NOCSAE-Snell-PDB TBI Workshop
September 8, 2015, Lyon

Presentations:

1. Thomas A. Gennarelli: What do we know about angular head motions (AHM)?
2. James A. Newman: The Evolution (and demise?) of Kinematic Brain Injury Metrics
3. Daniel J. Thomas: Impact Injury of the Head and Spine
4. Narayan Yoganandan: Strain Distributions in the Brain with Varying Pulse Separations
5. Warren N. Hardy: Angular Measures in Testing and their Implications
6. Cameron R .'Dale' Bass: Measuring Impact Severity for in Vivo Biomechanics
7. M. Panzer: Evaluation of Kinematic Predictors for Brain Injury in Multiple Crash Modes
8. Rémy Willinger: 6D Brain Injury Metric Based on Axon Elongation
9. Svein Kleiven: Importance of Angular Head Motions for Brain Injury Prediction
10. Erik G. Takhounts: BrIC Update: Does BrIC Depend on the Signal Time Duration?
11. Blaine Hoshizaki: Measuring Head Motions in Sports Helmet Testing
12. D. Halstead: National Operating Committee on Standards for Athletic Equipment
13. Elizabeth McCalley: Angular Head Motion with and without Head Contact: Implications for Brain Injury
14. Jeff Crandall: 2015 Performance Testing of Football Helmets
15. Lyndia C. Wu: Head Acceleration Sensing: Valid or Invalid?
16. E. Becker: Snell Impact Testing
17. Luca Cenedese: Regulation ECE22/05 - Test for projections and surface friction
18. Terry Smith: Motocross Helmets and Concussion Risk Reducing Technologies Do They Work?
19. Peter Halldin: Proposal for a new test method measuring the head kinematics in angled helmeted impacts

What do we know about angular head motions (AHM)?

IRCOBI-NOCSAE-Snell-PDB TBI Workshop

September 8, 2015, Lyon

Thomas A. Gennarelli, M.D.

Emeritus Professor of Neurosurgery, Medical College of Wisconsin
Clinical Professor of Neurosurgery , George Washington University

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Speakers

- Keep on time !!!
- Introduce yourself and your unit: but be humble, like our US presidential contender DT
- Keep on time !!!
- There is time mostly for main points, add whatever you want to your submission
- DIM, Keep on time !!!

Goals and purposes of this workshop

- to bring together important scientists who have worked in AHM
- to discuss contemporary issues regarding AHM
- to discuss methods of how best to measure AHM in several venues (sport, vehicular, helmet, etc.)
- to develop relationships between performance standards and injury risk
- to memorialize the workshop by having it transcribed and placed on our websites after [illegible]ng : Elisabet Agar

Angular Head Motions

- Is there a crisis regarding AHM?

- Is it of our own creation because of shifting definitions of the clinical problem?

The “Truths”

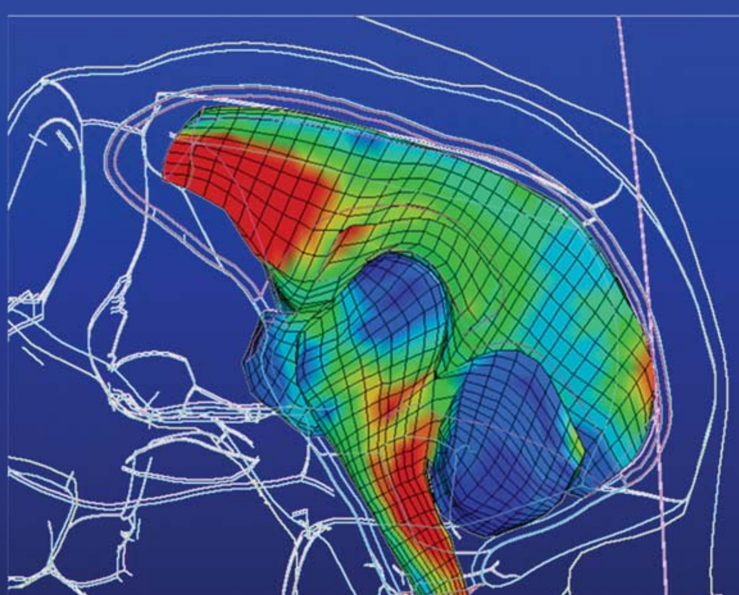
- Concussion and diffuse brain injuries are due to angular motions

- Translational motions don’t produce high brain strain

The Truths

- **Concussion and diffuse brain injuries are due to angular motions…are they?**
- **Translational motions don't produce high brain strain…don't they?**

Maximum principal strains in Translational Acceleration



(In red strains above 0.25)

Jacobo Antona-Makoshi et al., IRCOBI 2012

Gama 1835

- First experiments: used gel filled flasks with embedded black threads
- “fibers as delicate as those of which the organ of the mind is composed are liable to break” as a result of violence to the head.

Gama, J.-P. (1835). *Traité des Plaies de Tête et de l’Encéphalite,* Crochard, Paris.

The Frist really comprehensive experimental concussion paper

BRAIN

VOL. 64, PARTS 2 and 3.

EXPERIMENTAL CEREBRAL CONCUSSION.

BY D. DENNY-BROWN and W. RITCHIE RUSSELL.

(From the Laboratory of Physiology, Oxford.)

Brain 64:93-164, 1941

It is necessary to distinguish clearly between "acceleration concussion" and "compression concussion." As has been emphasized, acceleration concussion depends on the skull being subjected to a sudden change of velocity, as occurs in most human injuries, and the effect produced is directly proportional to velocity of the striking object, where other factors are constant. Under certain circumstances, however, as we have described in many of the above experiments, compression concussion may occur owing to severe distortion of the skull. For example, the ex-

Denny-Brown and Russell Brain 64:93-164, 1941

Considerable confusion arises from differing uses of the term concussion. Many clinicians use the term to indicate a mild head injury with impaired consciousness lasting for less than one hour, while when there is more prolonged loss of consciousness the diagnosis of "cerebral contusion" is postulated: it may at once be stated that in this latter group there is often no certain clinical evidence of an area of contusion, so that

If, as the deductions from our investigations indicate, concussion is the direct effect of physical stress on neurones, and contusion the effect of stress on supporting vascular structure

The mechanism by which the neurones are damaged in acceleration concussion must be of great complexity.

Denny-Brown and Russell Brain 64:93-164, 1941

MECHANICS OF HEAD INJURIES

A. H. S. HOLBOURN, M A EDIN, D PHIL OXFD

Brought angular motions to attention

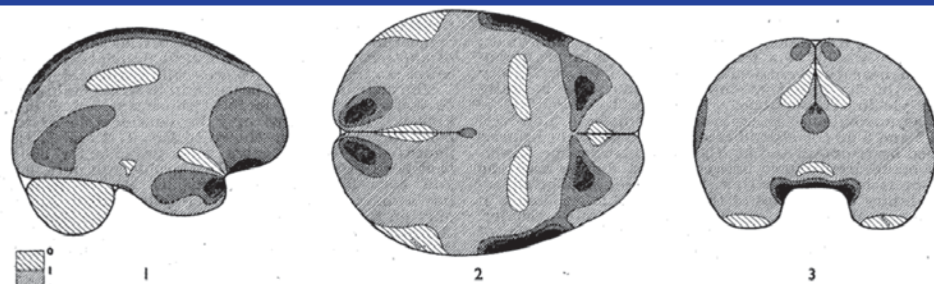


Fig. 1—Intensity of the shear-strains resulting from a forwards rotation caused by a blow on the occiput.
Fig. 2—Intensity of the shear-strains due to a rotation in the horizontal plane caused by a blow near the upper jaw or temples.
Fig. 3—Intensity of the shear-strains due to a rotation in the coronal plane caused by a blow above the ear.

Key—Scale of maximum shear-strain (= distortion) in arbitrary units of shear. The units differ in the three diagrams.

An attractive feature of HOLBOURN'S presentation of the effects of shear is that it offers a clear mechanical explanation for the observations of DENNY BROWN and RITCHIE RUSSELL on cerebral concussion. Much remains

Lancet, pp. 438-441, Oct 9, 1943

Lancet editorial, pp. 449-450, Oct 9, 1943

If there is no rotation or only a very small or slow one, there is no rotational injury. Thus, if the head is so well fixed that it cannot rotate at all when it receives a blow, there will be no rotational injury. Denny-Brown and Ritchie Russell[4] found that it was very difficult to produce concussion in cats when the head was fixed, but easy when it was free to move. This points to the fact that concussion is a rotational injury. One would

On this assumption there are two main causes of injury: (1) deformation of the skull with or without fracture; and (2) sudden rotation of the head which is responsible for the so-called contrecoup injuries, for some intracranial hæmorrhages and probably for concussion.

The change-over from one law of injury to the other occurs gradually somewhere in the region between 1/5 and 1/500 sec.

Experiments are in progress to find a more accurate value for the critical duration of the blow.

Holbourn uses the word "concussion" three times, he was mainly talking about coup and contra-coup hemorrhages and the importance of shear

Gurdjian and Lissner respond to Holbourn

It is not clear why tensile strains may not be the important factor in the causation of lesions instead of shear strains.

In dynamic head injury with a blow lasting a fiftieth of a second or less, producing linear acceleration, there is a steep pressure gradient through the brain in the direction of the blow. This will cause shear strains. This is not comparable to hydrostatic or equal three-dimensional pressures which may obtain with blows of long duration.

Lancet 243:389-390, 3/18/44

Holbourn fights back…agreeably

They say "it is not clear why tensile strains may not be the important factor in the causation of lesions instead of shear strains." Since any unilateral tensile strain is mathematically equivalent to a dilatation combined with a pair of shear strains, the unilateral tensile strains are just as much the cause of lesions as are shear strains.

Lancet p. 483, 4/8/44

Holbourn's letter to Sabina Strich

14, The Chenonry,
Old Aberdeen

13th. Oct. 56.

Dear Dr. Strich,

I did consider doing the experiment on a cat when I was in Oxford. A strong metal box rather larger than the cat's head would have to be made and attached to the axis of rotation. The cat's head would be put in the box and plaster of Paris poured into the gap between head and box. An arm projecting out from the axis would be moved in such a way as to produce a constant rotational acceleration. I got as far as making the metal box when I was in Oxford.

HAD-II (Stapp: 670905 1967)

A Device for the Investigation of Head Injury Effected by Non-Deforming Head Accelerations

Lawrence S. Higgins and Robert A. Schmall
Life Sciences Div., Technology Inc.

Abstract

The major contribution of this effort to the investigation of head injury is the design and construction of a machine having the following functional goals:

1. Delivery of a reproducible acceleration-time profile to a primate head.
2. Capability of increasing the acceleration magnitude while retaining a similar acceleration-time profile.
3. The path traversed by the head must be constrained during the acceleration.
4. The forces applied to the head must be distributed so as not to produce gross damage to the brain or skull.

The machine that has evolved is designated as the Head Acceleration Device II (HAD-II). Basically, this machine consists of an axial cam cut on the face of a

HAD-II Stapp 1971, 1972

Comparison of Translational and Rotational Head Motions in Experimental Cerebral Concussion

T. A. Gennarelli and A. K. Ommaya
Surgical Neurology Branch, National Institute of Neurological Diseases and Stroke National Institutes of Health, U.S. Public Health Service

L. E. Thibault
Biomedical Engineering and Instrumentation Branch, Division of Research Services National Institutes of Health, U.S. Public Health Service

720970

Pathophysiologic Responses to Rotational and Translational Accelerations of the Head

T. A. Gennarelli, L. E. Thibault, and A. K. Ommaya
National Institute of Health and Georgetown University

Stapp 1987

872197

Directional Dependence of Axonal Brain Injury due to Centroidal and Non-Centroidal Acceleration

Thomas A. Gennarelli
Dept. of Neurosurgery and
Dept. of Bioengineering

Lawrence E. Thibault
Dept. of Bioengineering
Univ. of Pennsylvania
Philadelphia, PA

G. Tomei, R. Wiser, D. Graham, and J. Adams
Dept. of Neuropathology
Univ. of Glasgow
Glasgow, U.K.

Hypothesis of Concussion and Prolonged Traumatic coma

Cerebral Concussion and Traumatic Unconsciousness—Correlation of Experimental and Clinical Observations on Blunt Head Injuries

AYUB K. OMMAYA AND T. A. GENNARELLI

[*Reprinted from* BRAIN, *Vol. 97, Part IV, 1974, pp. 633–654*]

MEDICAL COLLEGE OF WISCONSIN

Hypothesis of Concussion and Prolonged Traumatic coma

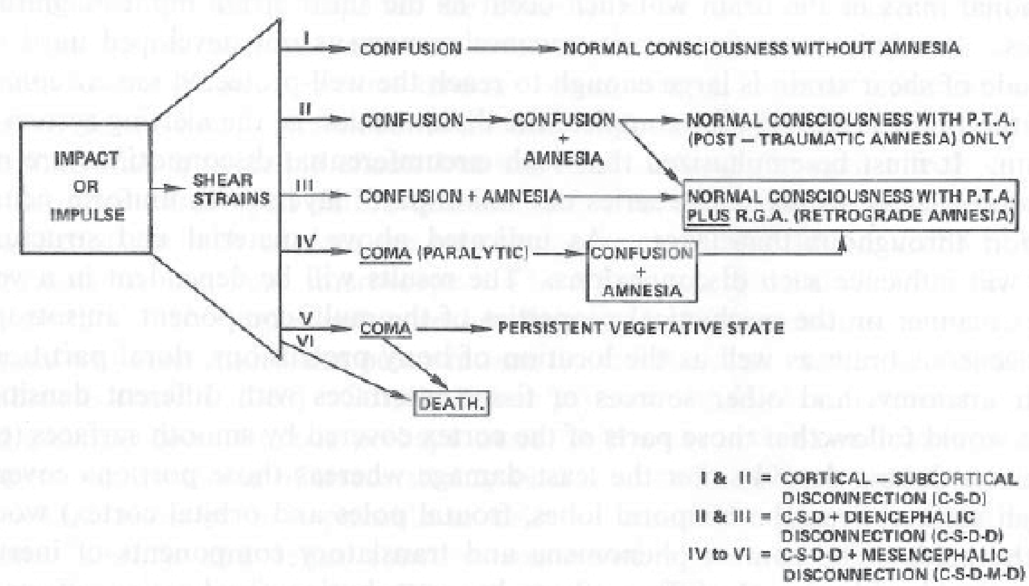


FIG. 2.—Diagrammatic description of our hypothesis for the syndromes of cerebral concussion with increasing severity of primary injury causing more extensive disconnexions between the cortex and the mesencephalic-diencephalic "core" of the brain. Note that Grade IV cerebral concussion is the state of traumatic unconsciousness which may be further subdivided according to duration of coma or severity of neurological sequelæ.

Ommaya and Gennarelli Brain 1974

First CT Description of DAI

[Reprinted from RADIOLOGY, Vol. 127, No. 2, Pages 393–396, May, 1978.]

Computed Tomography of Shearing Injuries of the Cerebral White Matter[1]

Robert A. Zimmerman, M.D., Larissa T. Bilaniuk, M.D., and Thomas Genneralli, M.D.

Changes secondary to shearing injury of the cerebral white matter can be demonstrated on CT. These consist of eccentric hemorrhage in the corpus callosum, diffuse cerebral swelling, subarachnoid hemorrhage and less frequently, hemorrhage around the third ventricular region and in the cerebral white matter. These CT findings are associated with acute severe neurologic deficits and sequelae. Eight cases with this injury pattern were encountered in 286 acute head injuries. All 8 patients were involved in automobile accidents.

INDEX TERMS: Brain, injuries, 1[0].400 • Computed tomography, head, 1[0].1211 • (Supratentorial brain laceration, 1[3].439)

Radiology 127:393–396, May 1978

Large Pathological Description of DAI

Diffuse Axonal Injury Due to Nonmissile Head Injury in Humans: An Analysis of 45 Cases

J. Hume Adams, FRCPath,* D. I. Graham, MRCPath,* Lilian S. Murray, BSc,† and Grace Scott, MBChB*

Forty-five cases of diffuse axonal injury (DAI) brought about by nonmissile head injury in humans are analyzed and compared with 132 cases of fatal head injury without DAI. All cases were subjected to a comprehensive neuropathological study. In the patients with DAI a statistically significant lower incidence of lucid interval, fracture of the skull, cerebral contusions, intracranial hematoma, and evidence of high intracranial pressure were found, with a higher incidence of head injury due to road traffic accident. Brain swelling and hypoxic brain damage were not statistically different in the two groups. The features of DAI in humans are compared with the DAI that has been produced in subhuman primates by pure inertial loading brought about by angular acceleration of the head. The available evidence indicates that DAI in human beings occurs at the time of head injury and is not due to complicating factors such as hypoxia, brain swelling, or raised intracranial pressure.

Adams JH, Graham DI, Murray LS, Scott G: Diffuse axonal injury due to nonmissile head injury in humans: an analysis of 45 cases. Ann Neurol 12:557–563, 1982

First Experimental reproduction of DAI

PROLONGED TRAUMATIC COMA WITHOUT MASS, HYPOXIA OR ISCHEMIA

Immediate, prolonged unconsciousness unaccompanied by mass lesions occurs in almost half of severely head injured patients and is associated with 35% of all deaths from injury [21]. Although the coma in such injuries has in the past been regarded as the result of the primary brainstem injury, evidence gained from human postmortem material fails to support the presence of brainstem injury in the absence of hemispheric damage [37, 46]. The more common neuropathological pattern includes diffuse microscopic damage to innumerable axons throughout the brain as well as focal lesions in the corpus callosum and in the dorsolateral quadrants of the rostral brainstem [2, 6–8]. The cause of this axonal injury has been proposed, but not proved, to be due to shear strain [26, 27, 50]. The term *shear*, however, connotes a specific injury mode to the biomechanician, so that we prefer the descriptive term *diffuse axonal injury* (DAI) for this entity rather than the numerous designations currently in use [8, 28, 42,

Diffuse axonal injury and traumatic coma in the primate.
Ann Neurol 12:564–574, 1982
Gennarelli TA, Thibault LE, Adams JH, Graham DI, Thompson CJ, Marcincin R

Clinical Classification of DAI

Acta Neurochirurgica, Suppl. 32, 1—13 (1983)

Division of Neurosurgery, University of Pennsylvania, Philadelphia, Pennsylvania, U.S.A.

Head Injury in Man and Experimental Animals: Clinical Aspects

By

T. A. Gennarelli

THE GEORGE WASHINGTON UNIVERSITY

MEDICAL COLLEGE OF WISCONSIN

DAI is usually, but not always, associated with immediate coma

Table 1. The relationship between diffuse axonal injury (DAI) and fracture of skull, type of injury and the occurrence of a lucid interval as defined in the text

	Cases with DAI ($n=122$)	Cases without DAI ($n=312$)	P value
Fracture of skull	70 (57%)	254 (81%)	<0.001
Road traffic accident	84 (69%)	157 (50%)	<0.005
Fall	22 (18%)	122 (39%)	<0.001
Lucid interval	17 (14%)	119 (59%)	<0.001

Table 2. The relationship between diffuse axonal injury (DAI) and some other types of brain damage resulting from a head injury

	With DAI ($n=122$)	Without DAI ($n=312$)	P value
Gliding contusions	71 (58%)	65 (21%)	<0.001
Raised intracranial pressure	85 (70%)	253 (81%)	<0.01
Moderate/severe hypoxic brain damage	60 (49%)	171 (55%)	NS
Large intracranial haematoma	32 (26%)	182 (58%)	<0.001
Basal ganglia haematoma	23 (19%)	24 (8%)	<0.001
Swelling	49 (40%)	169 (54%)	<0.01

Adams DAI in head injury: definition, diagnosis, grading. Histopathol 15:49 1989

PHENOTYPES OF TRAUMATIC HEAD INJURY

- SCALP LACERATIONS
- SKULL FRACTURES
- TRAUMATIC BRAIN INJURY
  - FOCAL BRAIN INJURIES
    - CONTUSION, LACERATION
    - HEMORRHAGE: EDH, SAH, SDH, ICH
  - DIFFUSE BRAIN INJURIES
    - CONCUSSION SYNDROMES
      - Civilian non-sport
      - Civilian sport related
      - Military
    - DIFFUSE AXONAL INJURY
    - Brain Swelling: unilateral or bilateral
  - PENETRATING INJURIES
- BLAST-EXPLOSIVE INJURIES and PTSD
- CTE

THE GEORGE WASHINGTON UNIVERSITY · NOBIS · DEUS · FIDUCIA · 1821

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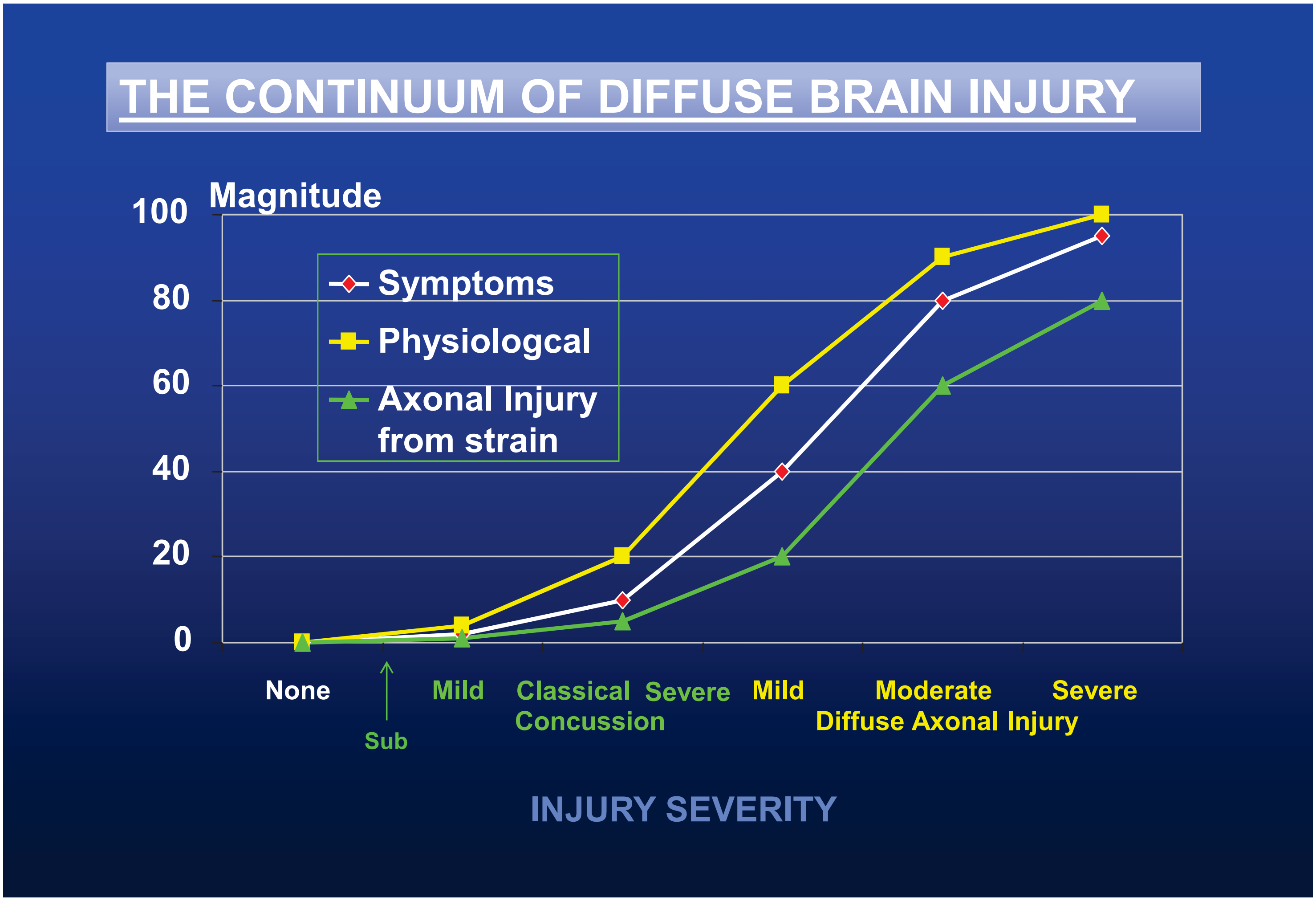
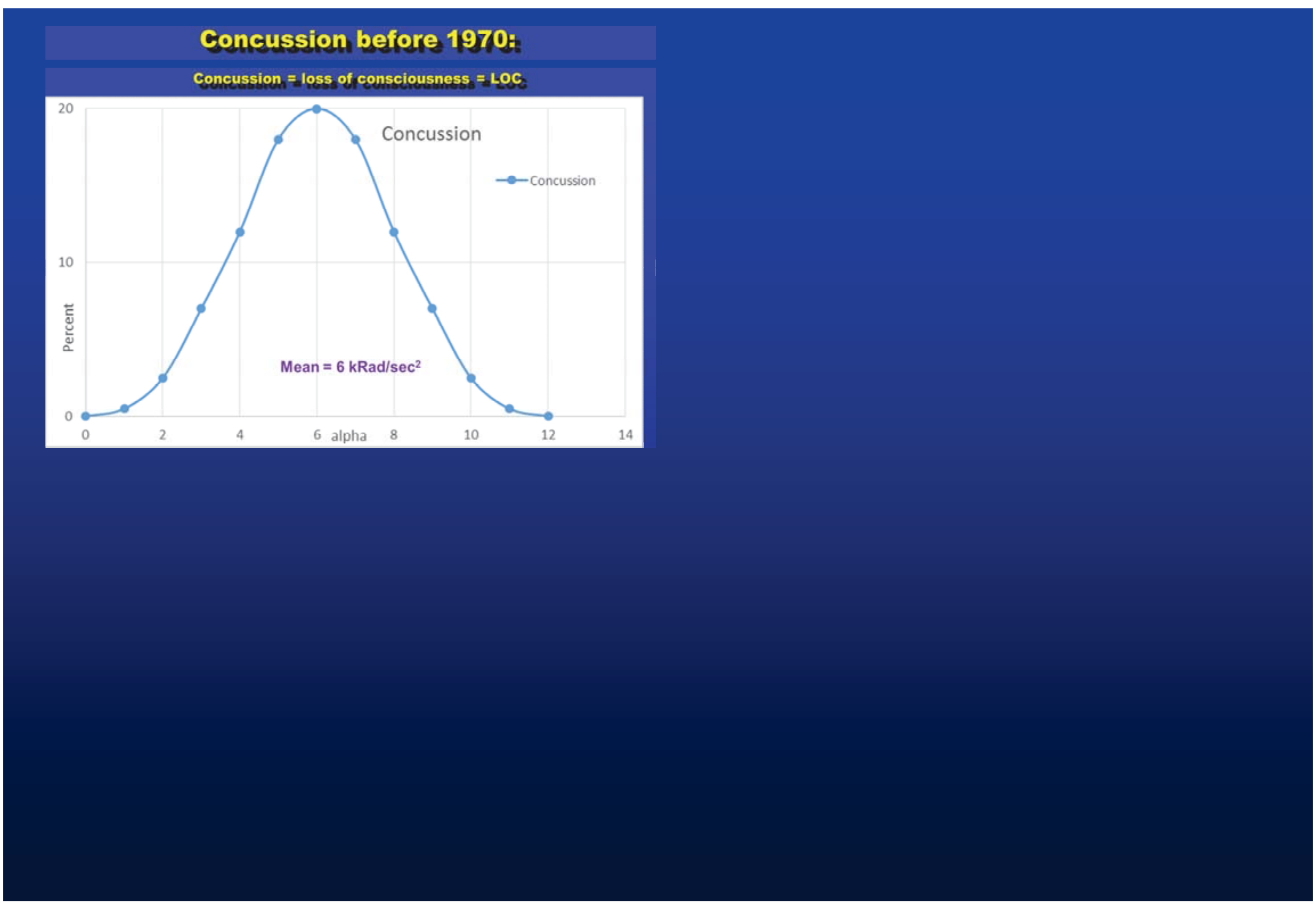
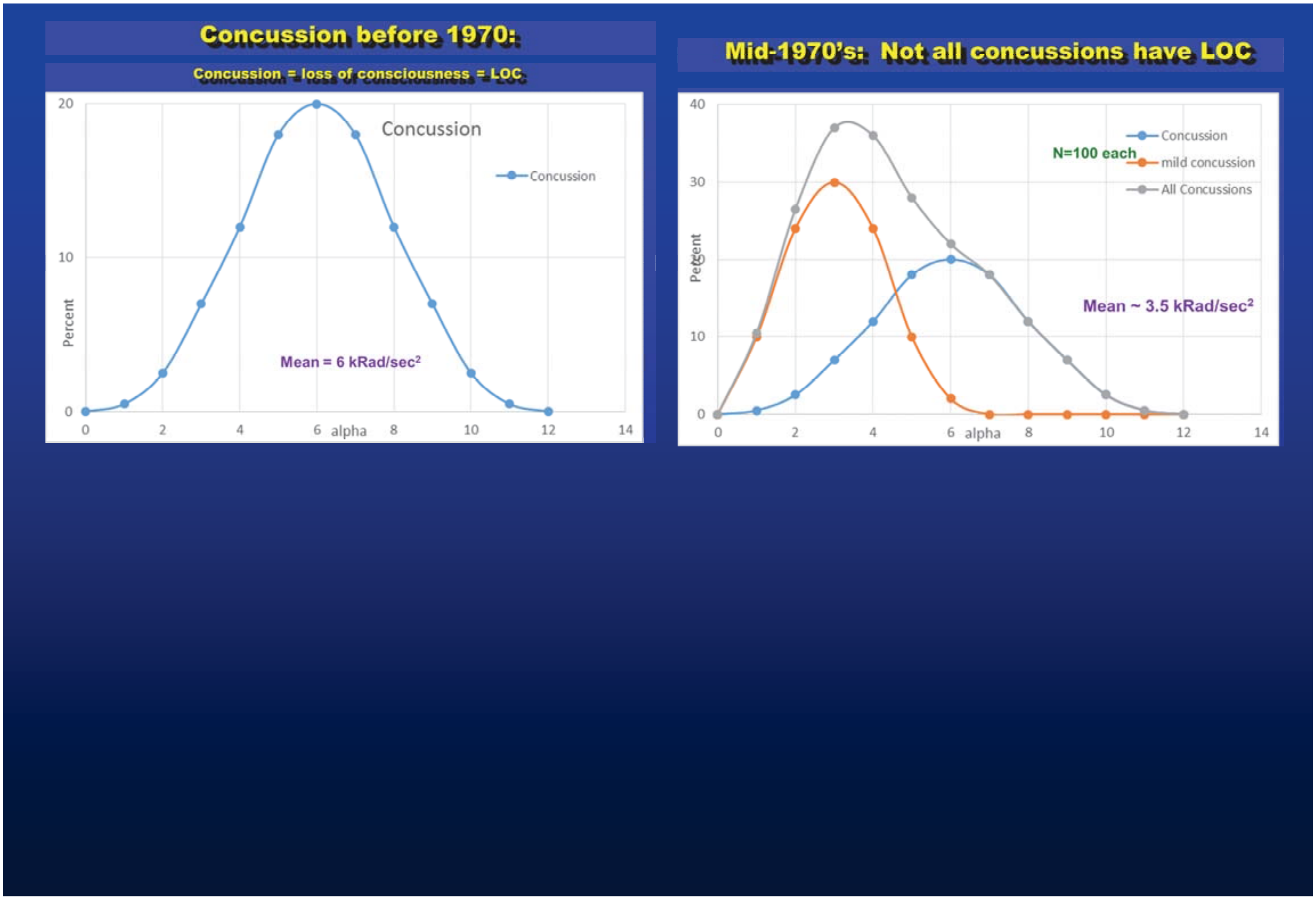
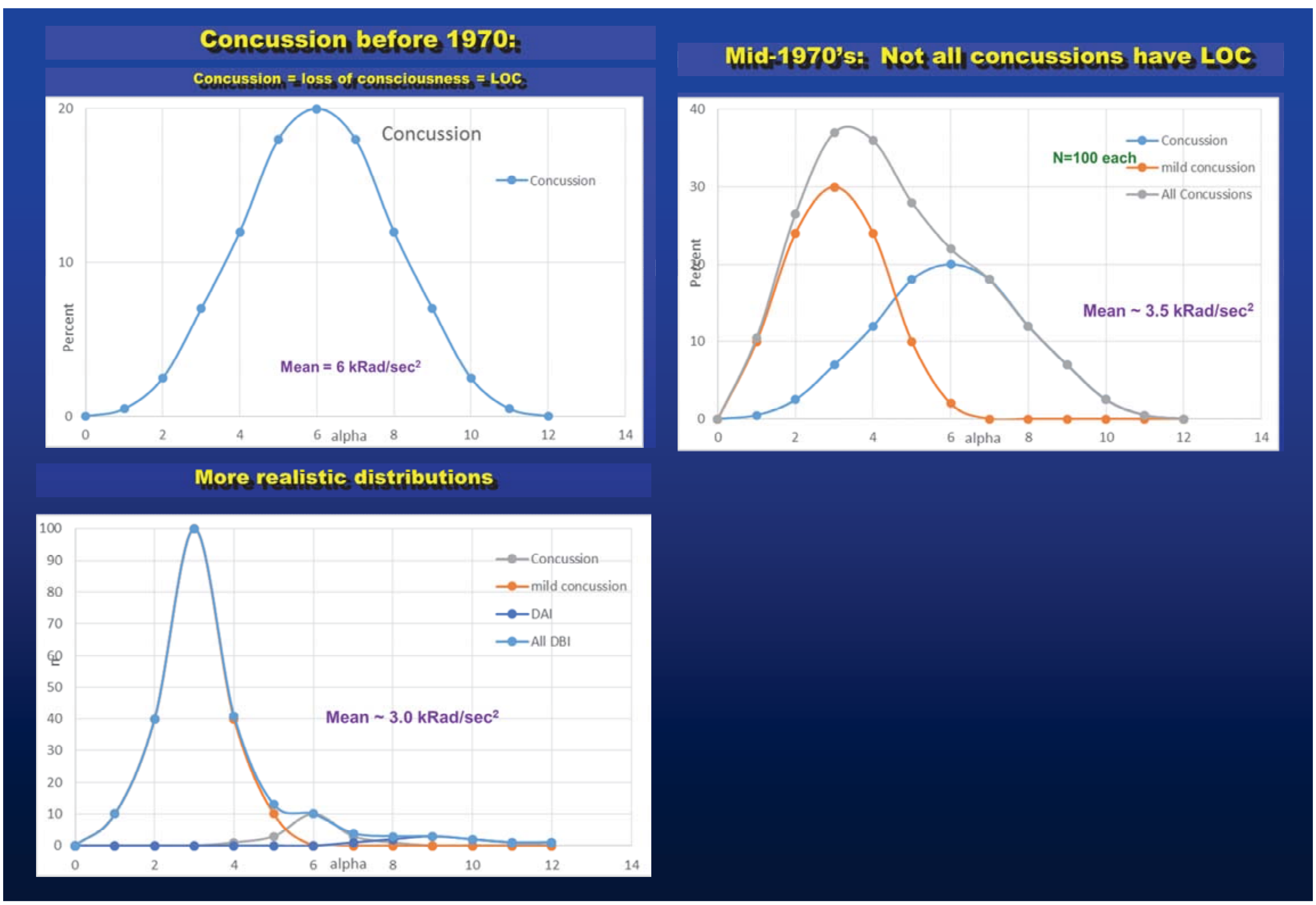
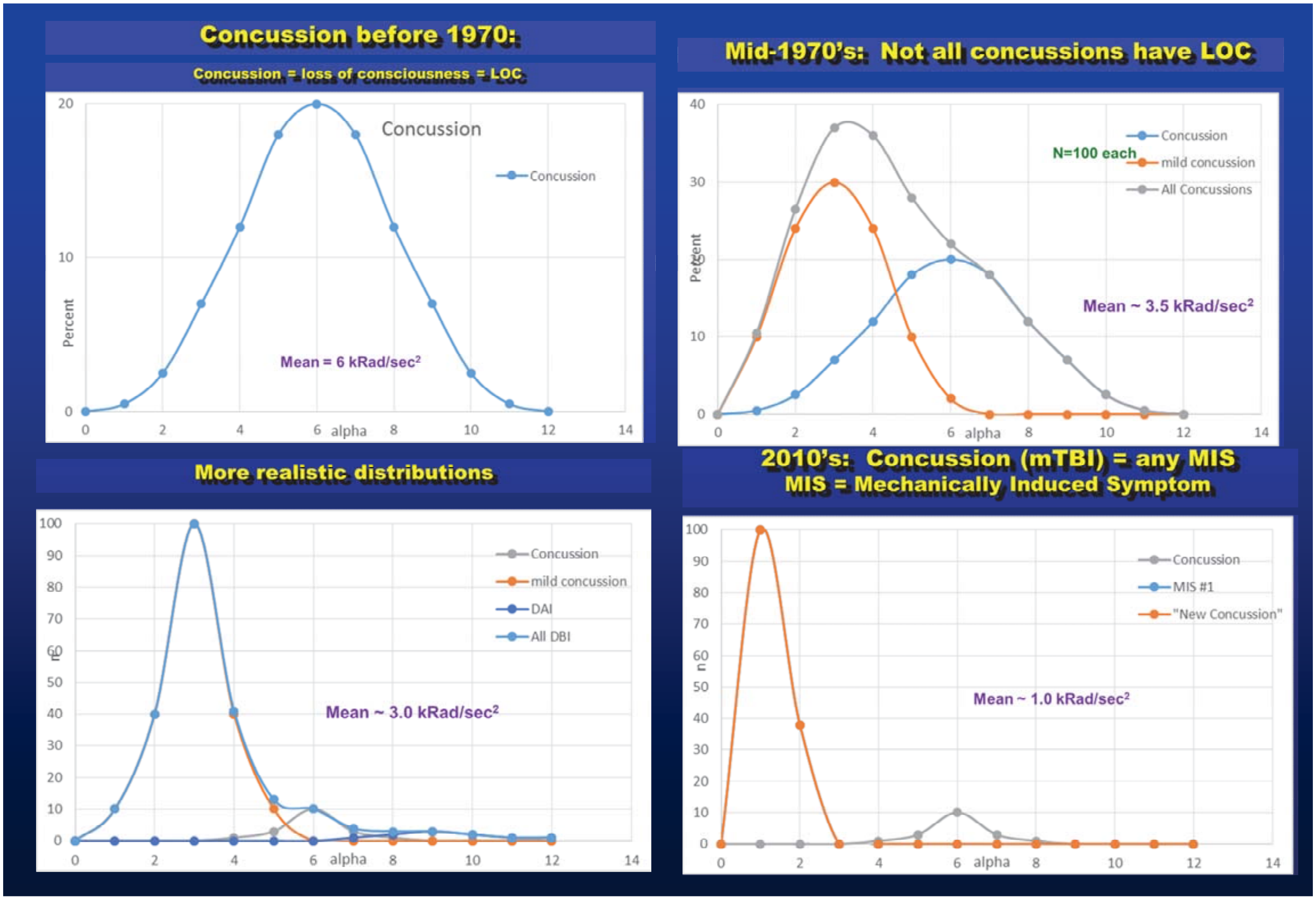

THE CONTINUUM OF DIFFUSE BRAIN INJURY
Magnitude
100
80
60
40
20
0
Symptoms
Physiologcal
Axonal Injury from strain
None
Sub
Mild
Classical Concussion
Severe
Mild
Moderate
Severe
Diffuse Axonal Injury
INJURY SEVERITY

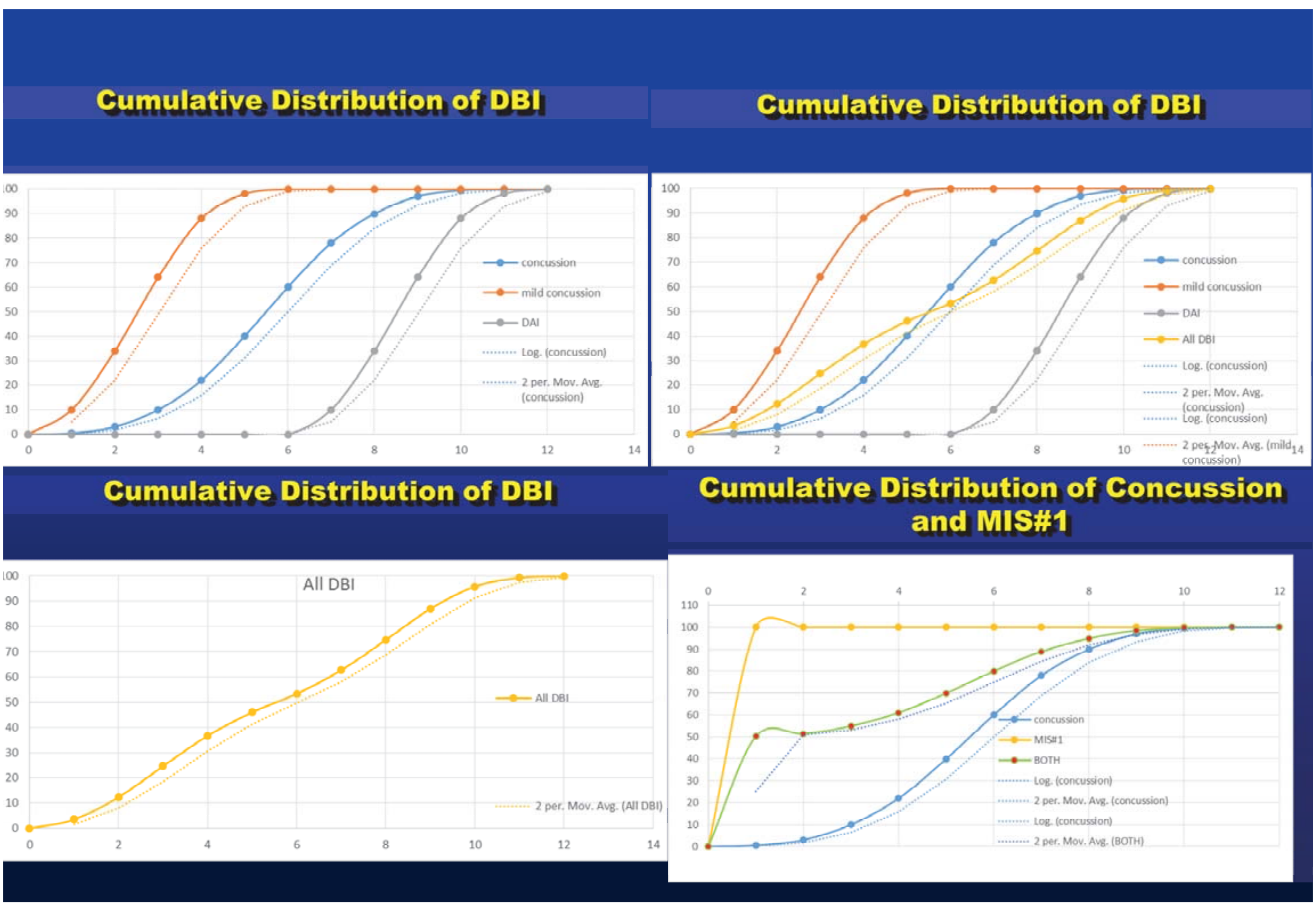

Concussion before 1970:
Concussion = loss of consciousness = LOC
Concussion
Concussion
20
10
0
Percent
Mean = 6 kRad/sec²
0
2
4
6
alpha
8
10
12
14


Concussion before 1970:
Concussion = loss of consciousness = LOC
Concussion
Mean = 6 kRad/sec²
Percent
alpha
Mid-1970's: Not all concussions have LOC
N=100 each
Concussion
mild concussion
All Concussions
Mean ~ 3.5 kRad/sec²
Percent
alpha


Concussion before 1970:
Concussion = loss of consciousness = LOC
Concussion
Mean = 6 kRad/sec²
Percent
alpha
Mid-1970's: Not all concussions have LOC
N=100 each
Concussion
mild concussion
All Concussions
Mean ~ 3.5 kRad/sec²
Percent
alpha
More realistic distributions
Concussion
mild concussion
DAI
All DBI
Mean ~ 3.0 kRad/sec²
alpha



Concussion before 1970:
Concussion = loss of consciousness = LOC
Concussion
Concussion
Percent
Mean = 6 kRad/sec²
alpha
Mid-1970's: Not all concussions have LOC
Concussion
mild concussion
All Concussions
N=100 each
Percent
Mean ~ 3.5 kRad/sec²
alpha
More realistic distributions
Concussion
mild concussion
DAI
All DBI
Mean ~ 3.0 kRad/sec²
alpha
2010's: Concussion (mTBI) = any MIS
MIS = Mechanically Induced Symptom
Concussion
MIS #1
"New Concussion"
Mean ~ 1.0 kRad/sec²
alpha



Cumulative Distribution of DBI
concussion
mild concussion
DAI
Log. (concussion)
2 per. Mov. Avg. (concussion)
Cumulative Distribution of DBI
concussion
mild concussion
DAI
All DBI
Log. (concussion)
2 per. Mov. Avg. (concussion)
Log. (concussion)
2 per. Mov. Avg. (mild concussion)
Cumulative Distribution of DBI
All DBI
All DBI
2 per. Mov. Avg. (All DBI)
Cumulative Distribution of Concussion and MIS#1
concussion
MIS#1
BOTH
Log. (concussion)
2 per. Mov. Avg. (concussion)
Log. (concussion)
2 per. Mov. Avg. (BOTH)

The new concussion:

any symptom after a head hit

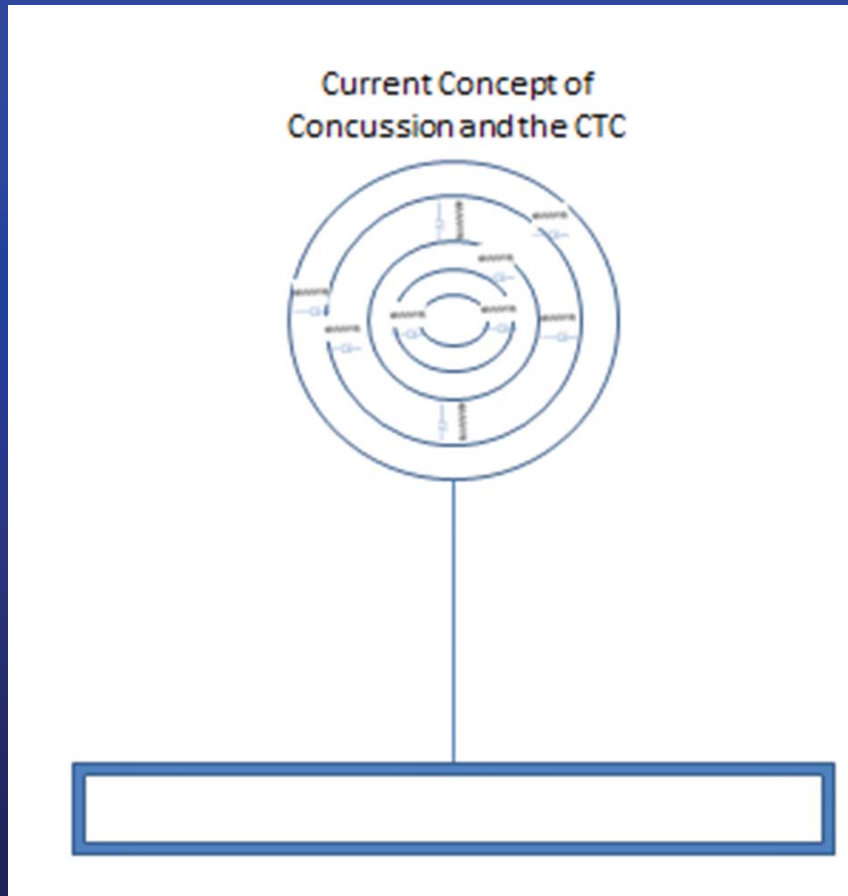
(or not hit)

The new concussion:

any symptom after a head hit

(or not hit)

The theories of concussion have lagged far behind the publications



Today’s new “concussion”

- No longer is “concussion” the same as “cerebral concussion” or “commotio cerebri” because many symptoms currently ascribed to “concussion” or its (more) confusing moniker mild traumatic brain injury (mTBI) are arguably not of cerebral or even of brain origin.
- These include headache, dizziness, seeing “stars”, tinnitus, fuzzy or blurred vision, fatigue, neck pain, photophobia, taste or smell disorders, sensitivity to noise, etc.
- Currently, the term “cerebral” concussion is being replaced by virtually any symptom arising after head motion whether it arises from the cerebrum or not..
- Thus, a Symptomcentric Concept of the Concussions is proposed whereby symptoms from various sites arise in response to a mechanical stimulation of the brain or other individual anatomic s

What other brain structures can respond to mechanical Stimuli?

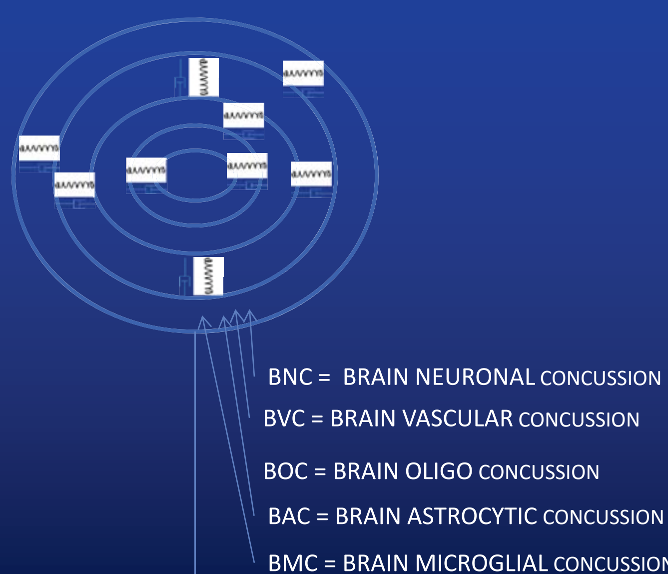
What other brain structures can respond to mechanical Stimuli?

- **Neurons:** axons, soma, dendrites, synapses, networks
- **Blood vessels:** arterial, venous, capillary
- **Oligodendrocytes**
- **Astrocytes**
- **Microglia**

Brain Mechanical Responses

Mechanically Induced Symptoms = MIS

- **Neurons:** axons, soma, dendrites, synapses, networks
- **Blood vessels:** arterial, venous, capillary vasoconstriction or vasodilatation
- **Oligodendrocytes:** demyelination, altered electrical transmission
- **Astrocytes:** gliosis
- **Microglia:** inflammation



What else can be concussed besides the brain?

Are there other structures that respond to mechanical stimulation? What is concussible?

What else can be concussed besides the brain?

Are there other structures that respond to mechanical stimulation? What is concussible?

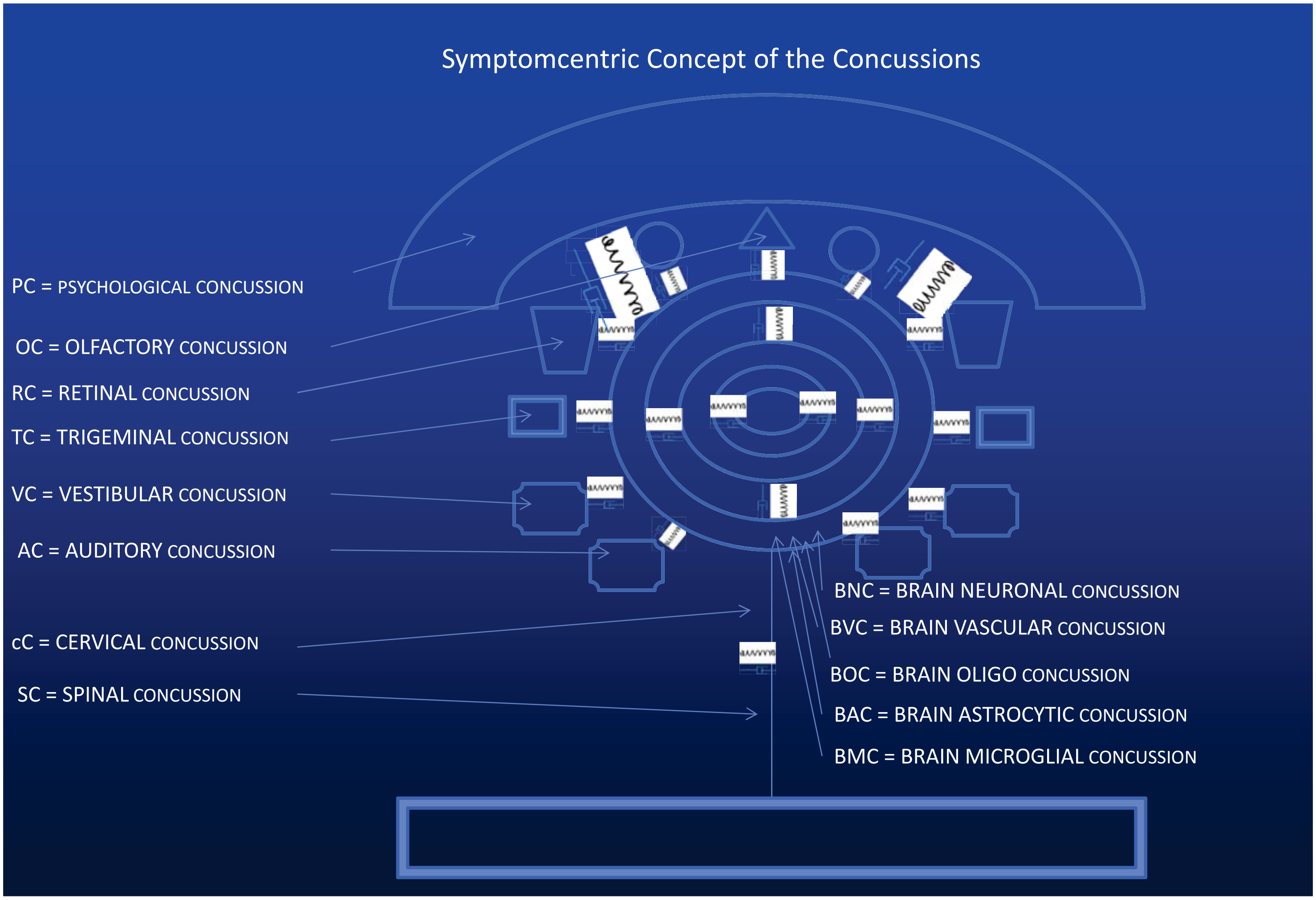
- **Olfactory nerves, tract**
- **Retina, optic nerves**
- **Trigeminal: Face, scalp, skin**
- **Vestibular apparatus:** semicircular canals
- **Auditory apparatus:** cochlea
- **The neck:** muscles, ligaments, joints, vessels
- **Cervical spinal cord**

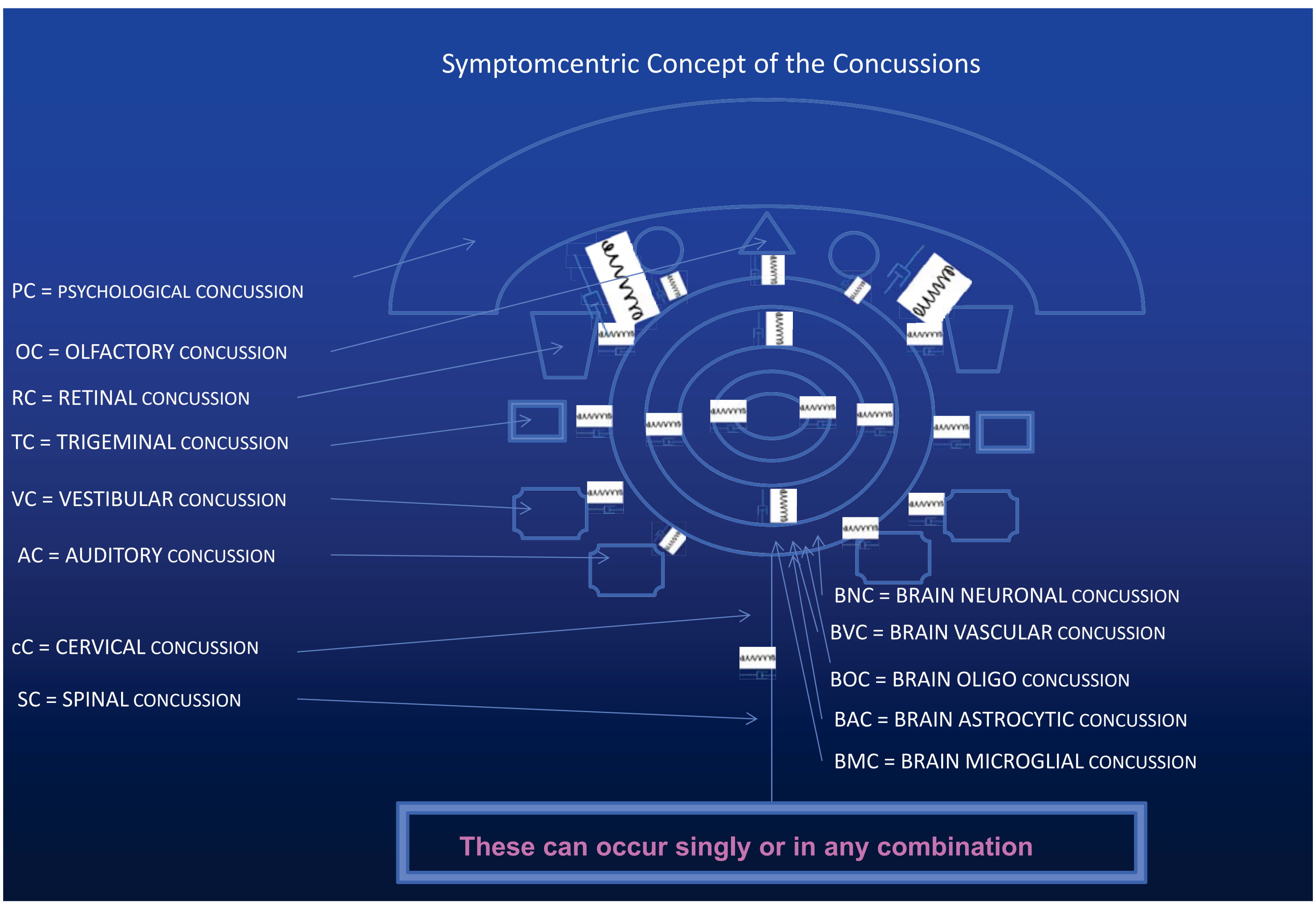
Mechanically Induced Symptoms = MIS

- **Olfactory concussion**: posttraumatic symptoms arising from the olfactory nerves, bulbs or tracts such as diminished or exaggerated smell.
- **Retinal concussion**: posttraumatic symptoms arising from retinal motions or from traumatic alterations of the electroretinogram such as diminished, dim or "fuzzy" vision, photophobia or visual aberrations.
- **Trigeminal concussion**: posttraumatic symptoms arising from stimulation or depression of the branches of the trigeminal nerve such as headache, facial pain or numbness.
- **Vestibular concussion**: posttraumatic symptoms arising from semicircular canal dysfunction such as dizziness, balance problems, lightheadedness.
- **Auditory Concussion**: posttraumatic symptoms arising from cochlear dysfunction such as hyper or hypoacousis, sensitivity to noise.

Mechanically Induced Symptoms = MIS

- **Cervical concussion**: posttraumatic symptoms arising from the nerves, muscles, joints, ligaments or blood vessels in the neck such as neck pain, numbness/pain in posterior portion of head, lightheadedness.
- **Spinal concussion**: posttraumatic symptoms arising from the cervical spinal cord such as tingling, numbness, weakness.
- **Psychological Concussion**: posttraumatic symptoms arising from the influence of mechanical energy on one's overall psychological state. This is a more abstract "injury", the magnitude and expression (symptoms) of which depend on not only the magnitude of the mechanical input but also on the pre-existing personality "strength".


Symptomcentric Concept of the Concussions
PC = PSYCHOLOGICAL CONCUSSION
OC = OLFACTORY CONCUSSION
RC = RETINAL CONCUSSION
TC = TRIGEMINAL CONCUSSION
VC = VESTIBULAR CONCUSSION
AC = AUDITORY CONCUSSION
cC = CERVICAL CONCUSSION
SC = SPINAL CONCUSSION
BNC = BRAIN NEURONAL CONCUSSION
BVC = BRAIN VASCULAR CONCUSSION
BOC = BRAIN OLIGO CONCUSSION
BAC = BRAIN ASTROCYTIC CONCUSSION
BMC = BRAIN MICROGLIAL CONCUSSION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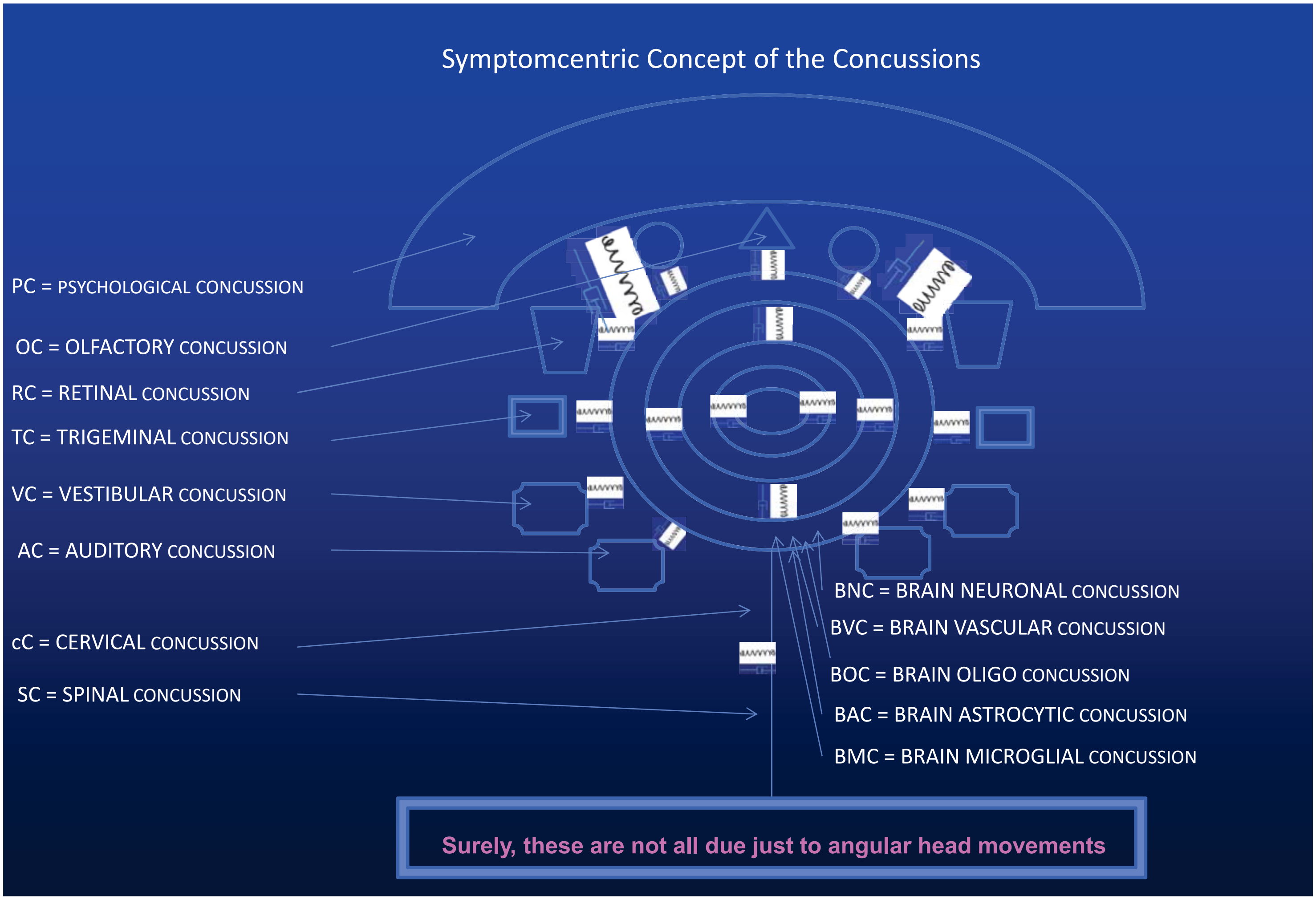
BAC = BRAIN ASTROCYTIC CONCUSSION
BMC = BRAIN MICROGLIAL CONCUSSION
These can occur singly or in any combination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BNC = BRAIN NEURONAL CONCUSSION
BVC = BRAIN VASCULAR CONCUSSION
BOC = BRAIN OLIGO CONCUSSION
BAC = BRAIN ASTROCYTIC CONCUSSION
BMC = BRAIN MICROGLIAL CONCUSSION
Surely, these are not all due just to angular head movements


Now, the rest is in your hands!

The Evolution (and demise?) of Kinematic Brain Injury Metrics

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NBEC Inc.
Edmonton, Alberta, Canada

ANGULAR MOTION BRAIN INJURY WORKSHOP

SMF/NOCSAE/PDB/IRCOBI Workshop
Lyon, France, September 8, 2015

Our Premise.

Closed brain injury is caused by head motion.

The severity/probability of head injury is somehow related to the way in which the head/skull moves.

There is a relationship between brain injury and head kinematics.

In the Beginning…….

- 1943 Holbourne — MAXIMUM ANGULAR VELOCITY
- 1946 Gurdjian — LINEAR ACCELERATION, DURATION
- 1956 Snively — MAXIMUM LINEAR ACCELERATION
- 1960 Patrick — LINEAR ACCELERATION PLUS "DWELL TIMES".

A. Holbourne 1943

"Mechanics of Head Injury." Lancet

" For very short duration blows, (brain) injury is proportional to the change of rotational velocity not the rate of change – i.e. acceleration."

E. Gurdjian, J. Webster, H. Lissner 1943 - 1970

"Experimental Head Injury with Special Reference to the Mechanical Factors in Acute Trauma."

"When a linear fracture was obtained in the human cadaver, a moderate to severe concussion could be deduced."

Skull fracture coincided with head translational acceleration of about 250Gs.

Helmet Impact Twin Wire Test Setups

Crash

Athletic

ASA Z90.1 – 1966

"Headform acceleration in excess of 200G shall not persist for longer than 2msec and at 150Gs for no longer than 4msec."

NHTSA DoT 218 - 2015

Motorcycle Helmet Standard – DoT 218, 1973

The MONORAIL

…in the middle……

1966 Gadd	Severity Index
1967 Versace	SI correction
1972 NHTSA	HIC
1980 Ommaya et al	Max ang velocity and max ang acceleration

Acceleration “data” circa 1966

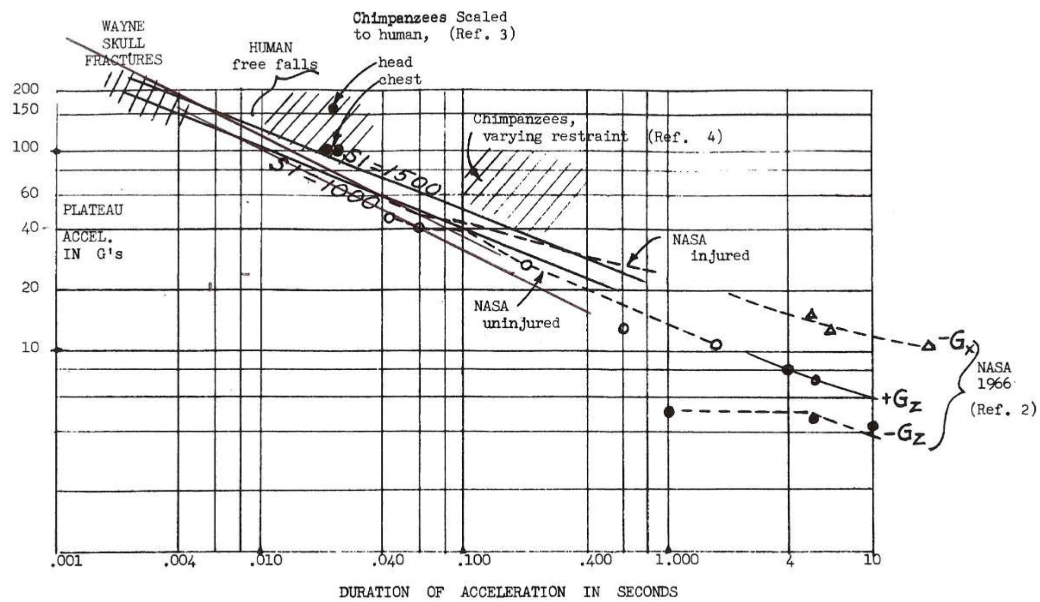


Fig. 1 - NASA 1959 and 1966 literature summaries for tolerable plateau accelerations, harnessed, with other data superimposed

NOCSAE Severity Index

$$\bar{a}^{2.5} T < 1{,}000$$

$$\mathrm{SI} = \int_T \mathrm{a}^{2.5} dt < N$$

Versace 1971

$$\bar{a}^{2.5}T < 1{,}000$$

$$[1/T\int_T a(t)dt]^{2.5}T < 1{,}000$$

Head Injury Criterion

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

Ommaya et al 1966 - 1981

"no convincing evidence has to this date been presented which relates brain injury and concussion to translational motion of the head…" - 1972

Thibault & Gennarelli - primate scaling

concussion	8,000 rad/s^2	@ 75 rad/s
subdural hematoma	12,500 rad/s^2	@ 60 rad/s
diffuse axonal injury	15,000 rad/s^2	@150 rad/s

Toward the End.

1985 Newman	GAMBIT
2000 Newman et al	HIP
2003 Klieven	PI
2007 Newman	NSI
2011 Takhounts et al	BrIC
2013 Takhounts et al	Max angular velocity

Generalized Acceleration Model for Brain Injury Tolerance - 1985

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

Head Impact Power - 2000

- $HIP = ma_x \int a_x dt + ma_y \int a_y dt + ma_z \int a_z dt +$
- $I_x \alpha_x \int \alpha_x dt + I_y \alpha_y \int \alpha_y dt + I_z \alpha_z \int \alpha_z dt$

New Severity Index - 2007

$$NSI = \left(\frac{m_k}{m_r}\right)^{1/3} \left(\frac{A_m \Delta V}{A_t V_i}\right) \leq 1.0$$

Brain Rotational Injury Criterion - 2011

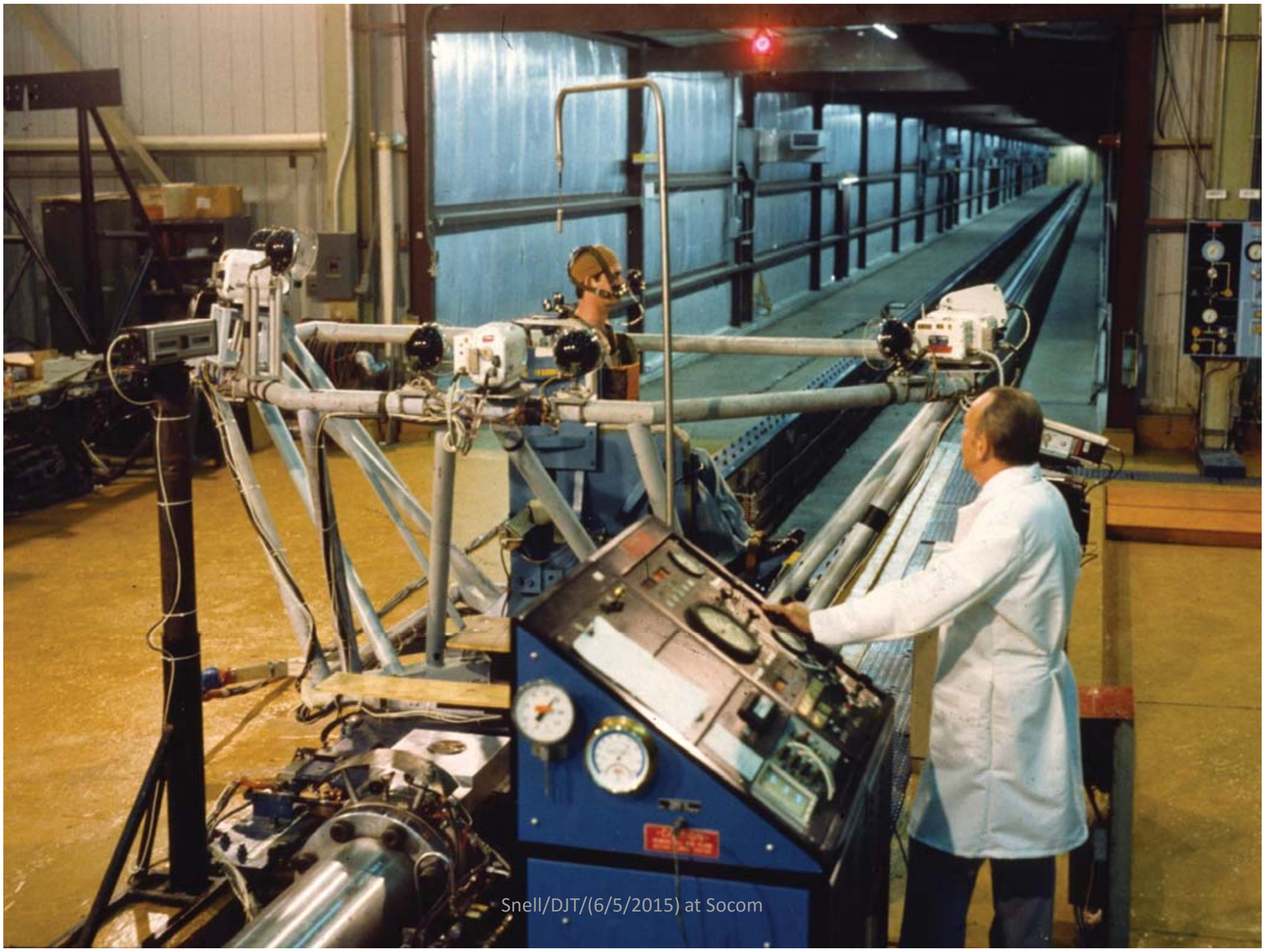
$$BRIC = \frac{\omega_{max}}{\omega_{cr}} + \frac{\alpha_{max}}{\alpha_{cr}}$$

Brain Injury Criteria (BrIC) - 2013

rotational velocity (not rotational acceleration) is the mechanism for brain injuries . (See Holbourne 1943).

And in the end………..

Kinematic correlations will no longer be required when mathematical (FE) brain models can quickly and accurately predict brain tissue distortion characteristics (eg CSDM) for various head impact scenarios.



- <u>Impact Injury of the Head and Spine</u>

Chapter5:"Experimental Head and Neck Injury"

Daniel J. Thomas and

M. Eugene Jessop

Illustration: p. 213

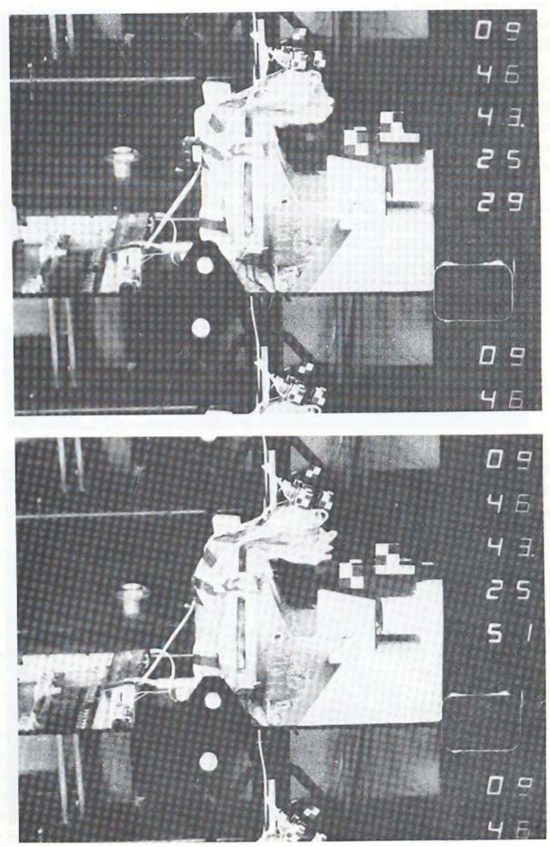


Figure 5-24. Side photographs (500 frames per second) of two successive positions in LX1893 animal A03924, which encompass the time of peak head angular and linear accelerations shown in Figures 5-15 and 5-16. The camera was laboratory mounted.

Snell/DJT/(6/5/2015) at Socom

- <u>Impact Injury of the Head and Spine</u>

Chapter5:"Experimental Head and Neck Injury"

Daniel J. Thomas and

M. Eugene Jessop

Illustration: p. 210

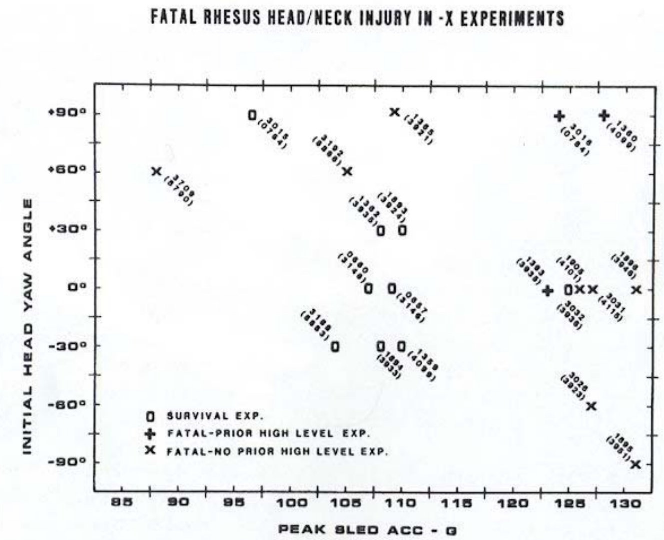


Figure 5-23. Illustration of the effect of peak sled acceleration and initial head yaw angle on the threshold for fatal anatomical disruption in the Rhesus monkey.

Concussion and Angular Acceleration

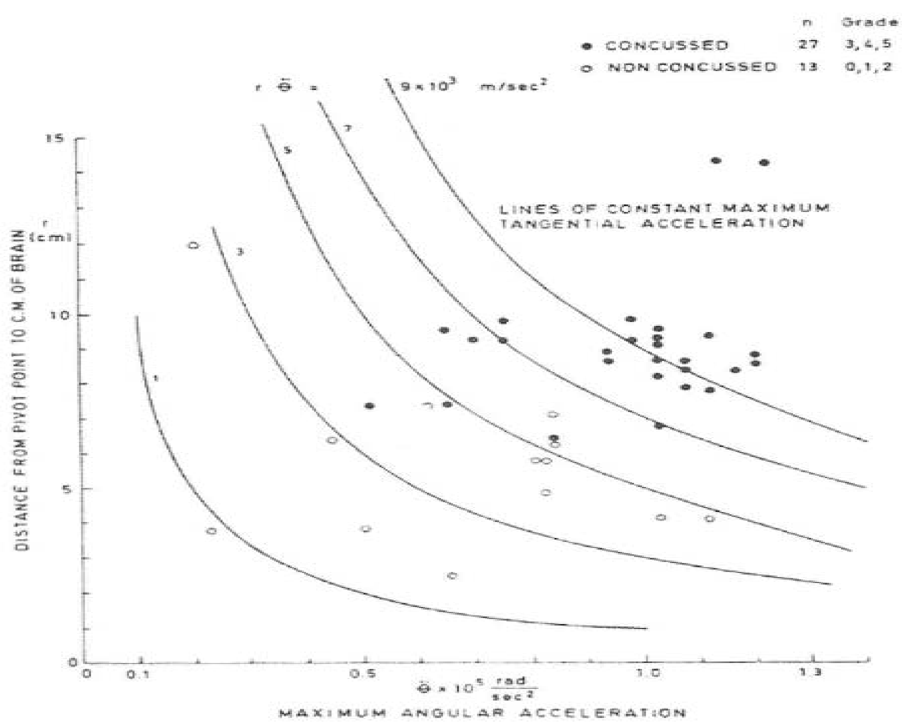


Fig. 7 - Concussion as function of r,θ̈

22nd Stapp - 1978 – Gennarelli

A Statistical Analysis of -X Rhesus Head Kinematics

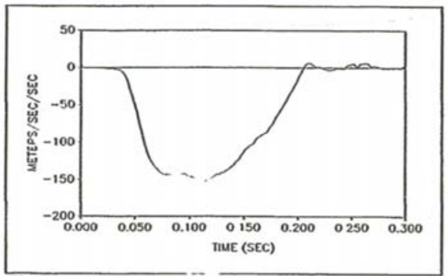


Figure 1. Sled acceleration profile for 15 g, -X human NUCU run.

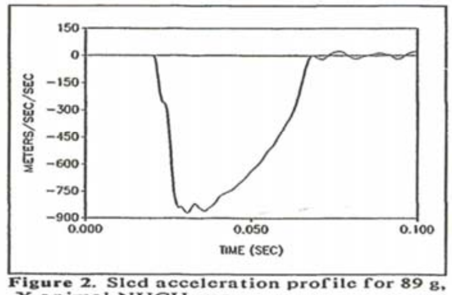


Figure 2. Sled acceleration profile for 89 g, -X animal NUCU run.

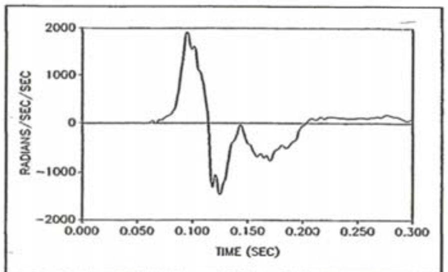


Figure 3. Head angular acceleration (Y-axis) for 15 g, -X human NUCU run.

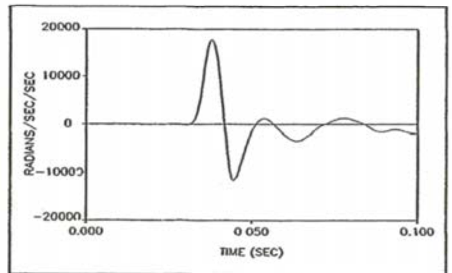


Figure 4. Head angular acceleration (Y-axis) for 89 g, -X animal NUCU run.

Human vs. Rhesus Head Kinematics Comparison

B-1

Important Lessons Learned

1. Primate species can be used to experimentally and exactly replicate known critical human injury
2. (– X) Head neck separation Man-Rhesus-Baboon, about 100 G
3. Initial conditions of head and neck critical to threshold for injury
4. (+ X) Head neck separation at same level. More complicated
5. No concussion, no microscopic brain tissue effects using 1982 technique
6. Head neck restraint solutions work (motorsport-Hans by Hubbard, and Downing
7. Sensory Evoked Potential changes in animal can guide safe human research

Helmet Testing Issues

Head Device

Neck/No Neck

3D Response

Retention Performance

Fit

Multiple Hits in a Single Event

Force Applicator

Neck Brace?

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Strain Distributions in the Brain with Varying Pulse Separations

Narayan Yoganandan, PhD

Department of Neurosurgery

Medical College of Wisconsin

Milwaukee WI, USA

Brain Injury Mechanisms

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- Head contact-based
  - Epidural hematoma
  - Coup contusion
- Head motion-based
  - Concussion
  - Subdural hematoma
  - Contrecoup contusion
  - Diffuse axonal injuries

Genneralli, Snell, 2005

CIREN Data
Head Contact Loading Regions

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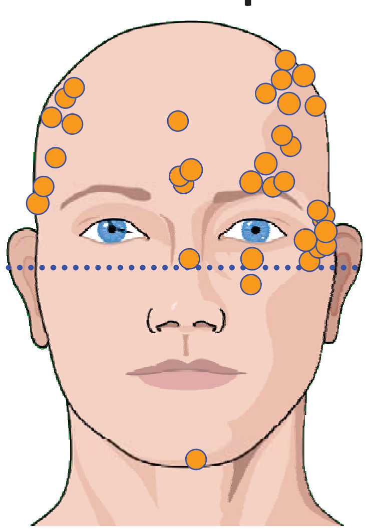
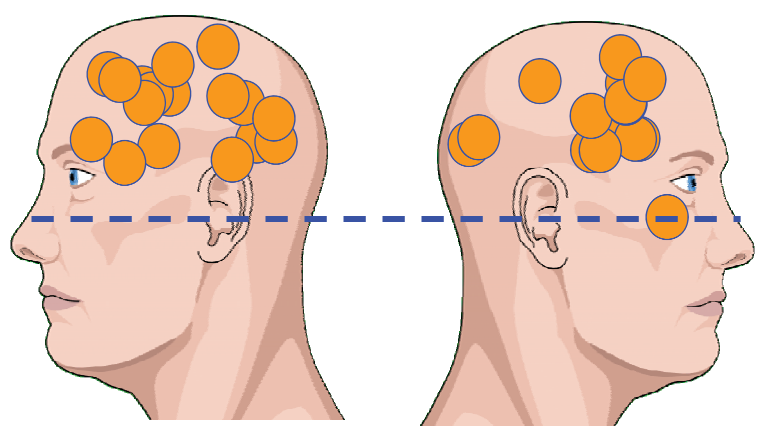
Frontal impacts



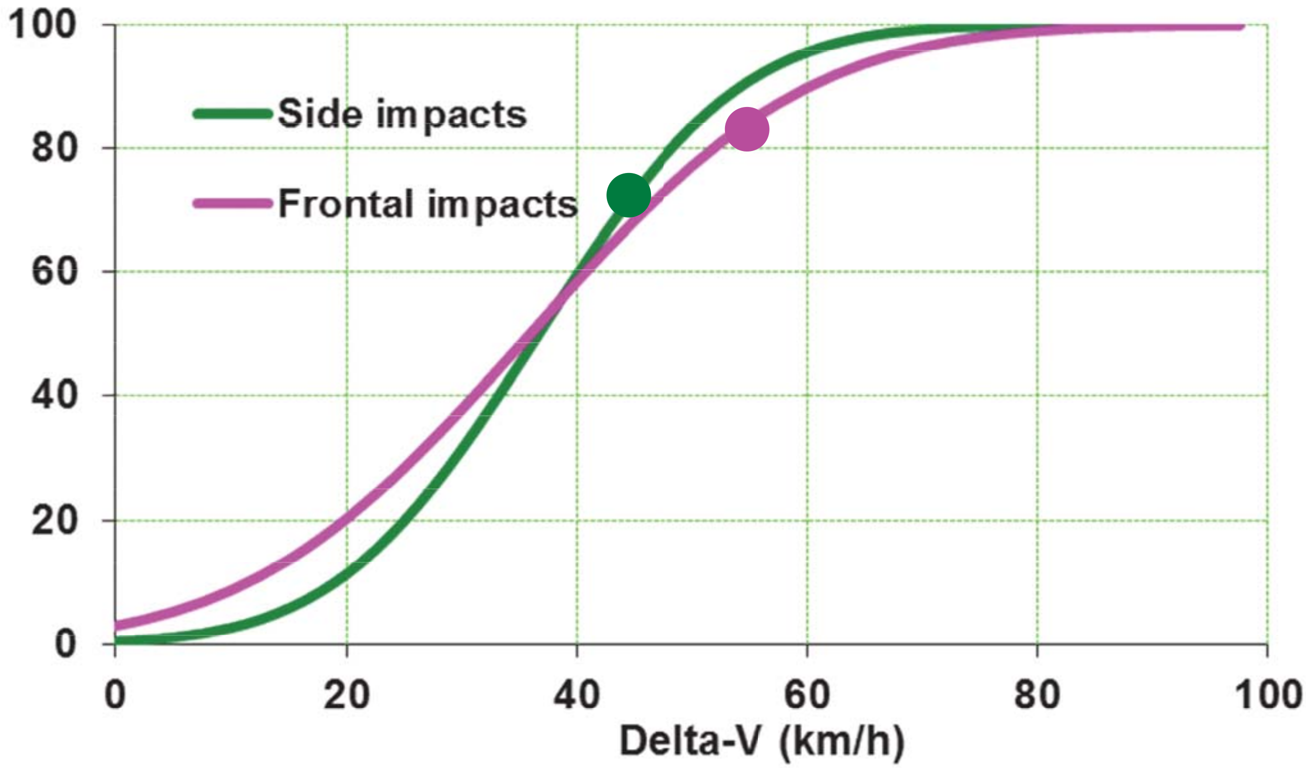
Nearside impacts

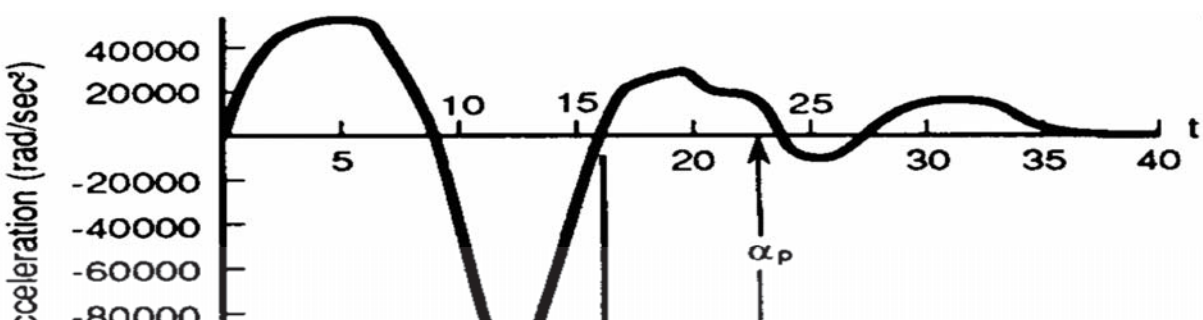


A majority of contacts occur away from the head cg: Implications ⇔ angular acceleration

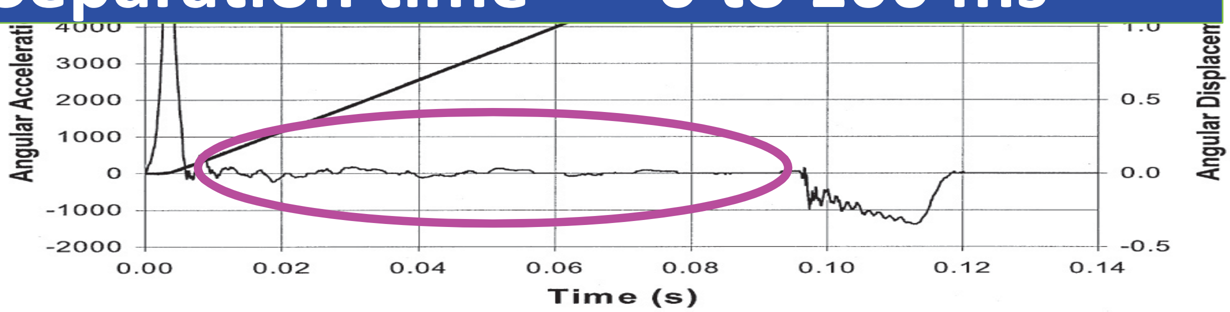
Yoganandan et al, AAP, 2010

Cumulative Frequency (%) Distribution





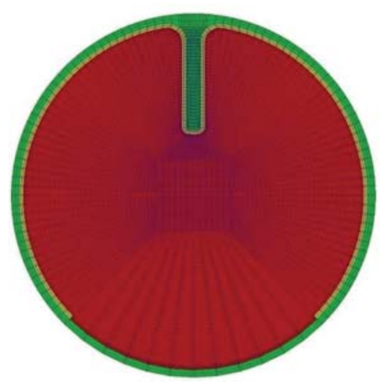
Acceleration	4 to 210 krad/s^2
Deceleration	1 to 170 krad/s^2
Separation time	0 to 100 ms

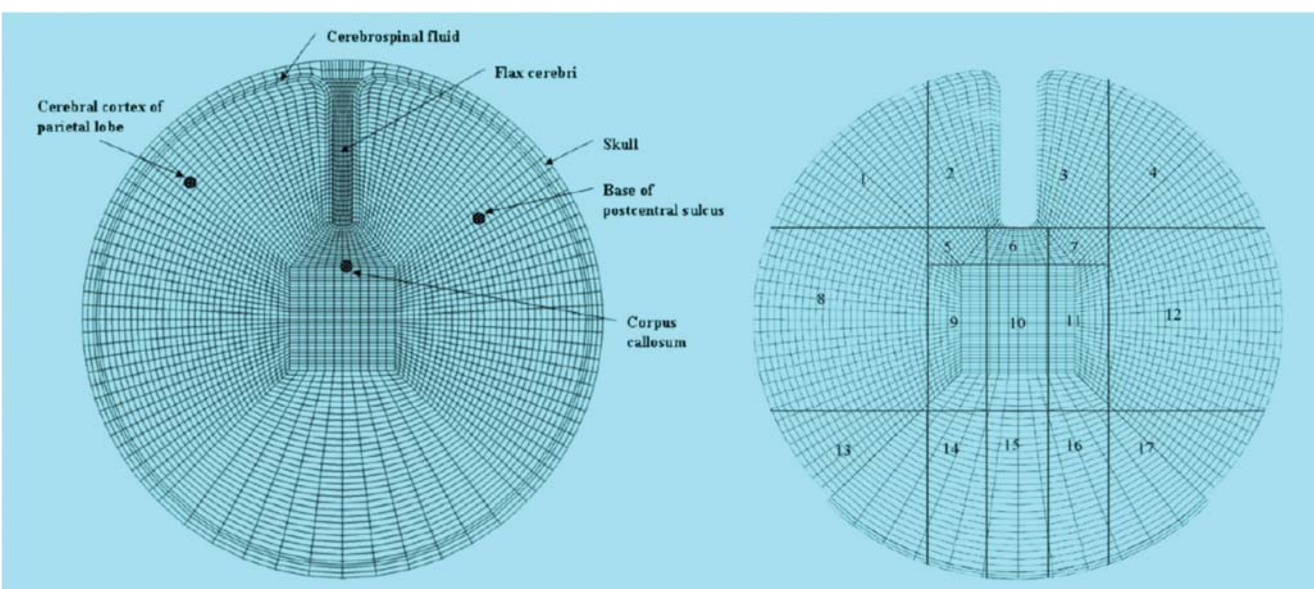


Strain Fields in different Brain Regions

- **Delineate the role of:**
  - ❖acceleration pulses,
  - ❖deceleration pulses,
  - ❖alone or in combination, and
  - ❖with varying separation times
- **Using a finite element model**

Finite Element Model





Experimental Study

FE model

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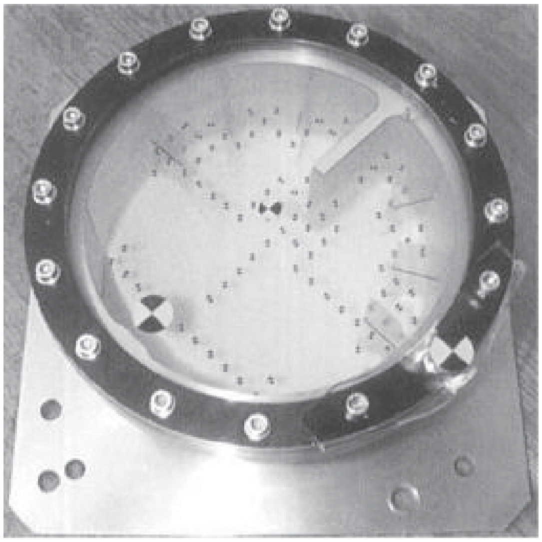
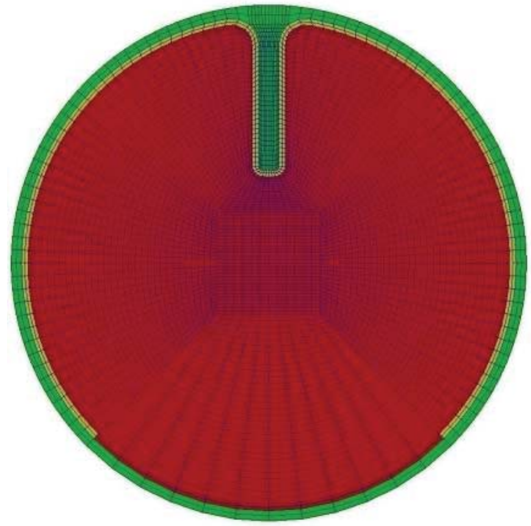




Skull – cylindrical aluminum vessel

CSF – liquid paraffin layer

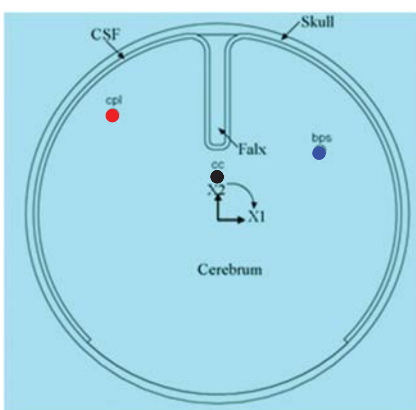
Cerebrum – silicone gel

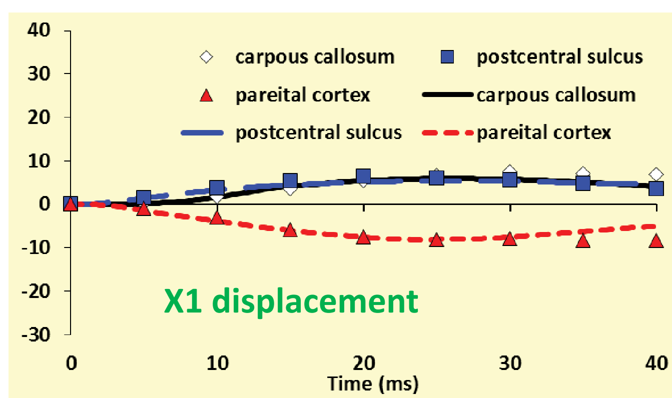
Angular acceleration loading

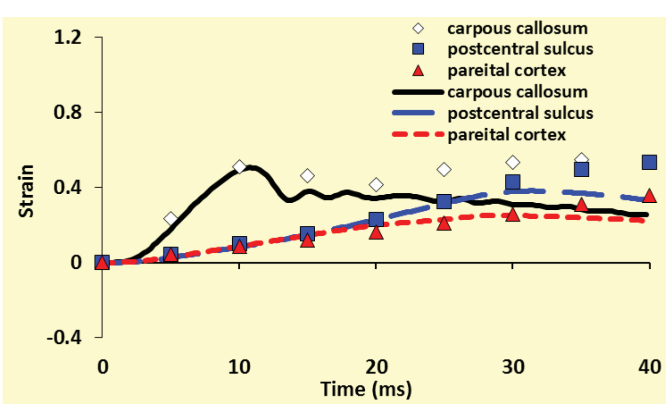
Bradshaw et al. 2001

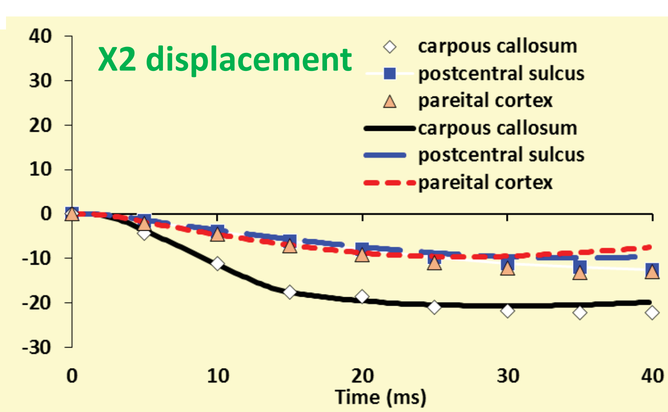
Validation: Displacement (mm), ε

MEDICAL COLLEGE OF WISCONSIN





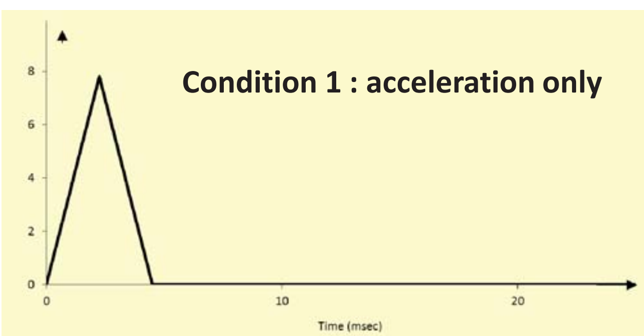


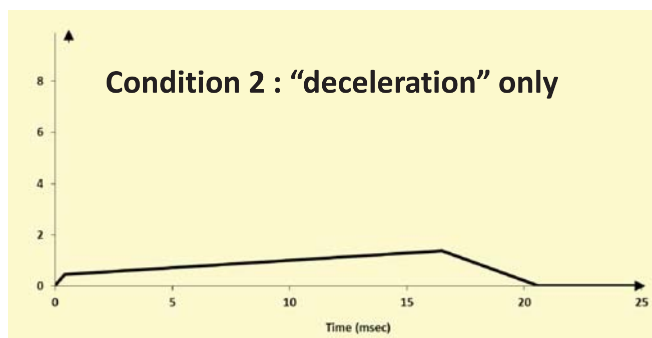


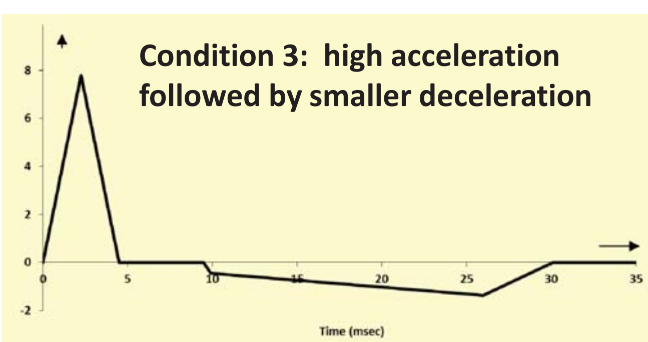
Strains with varying Pulses

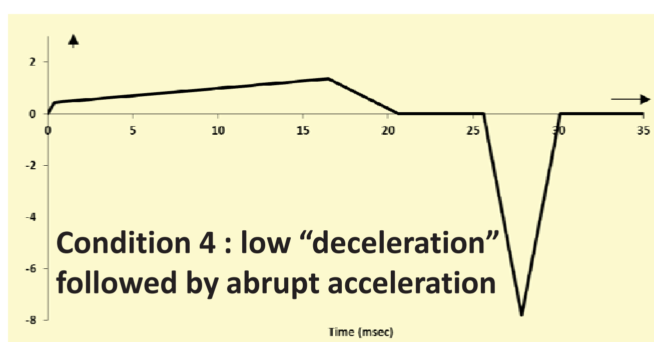
1. Acceleration only vs deceleration only
   - ➢ effect of pulse shape at same velocity
2. Acceleration and then deceleration
   - ➢ effect of dual pulses
3. Acceleration and then deceleration
   - ➢ with varying separation times
4. Deceleration and then acceleration
   - ➢ with varying separation times

Acceleration-deceleration Pulses



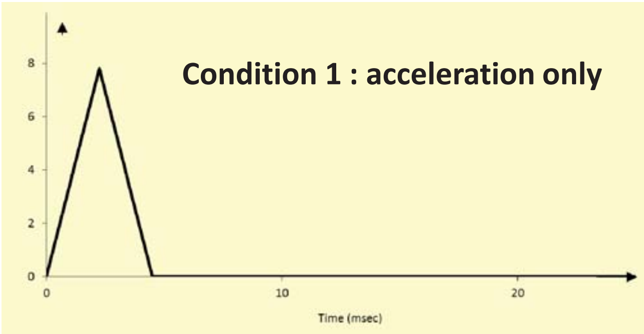


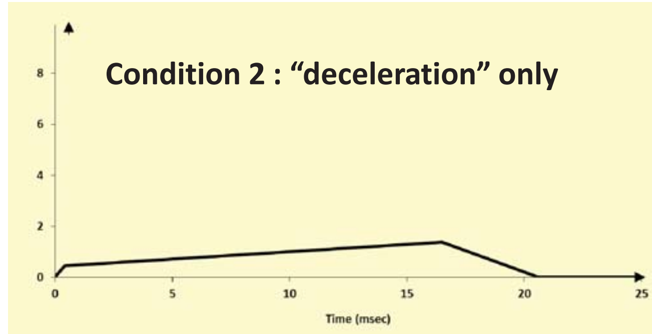




1. Acceleration versus deceleration:

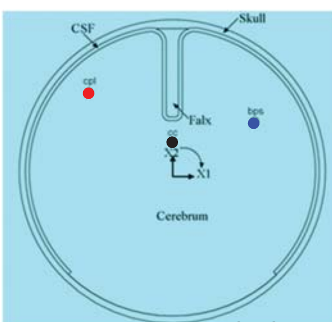
-Effect of pulse shape



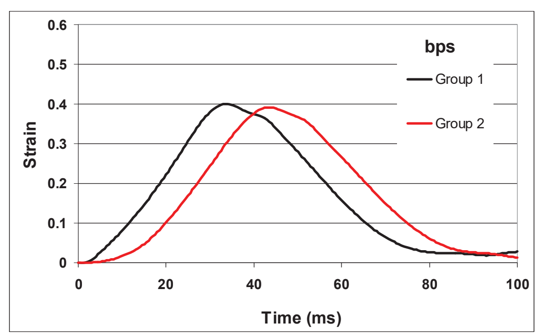


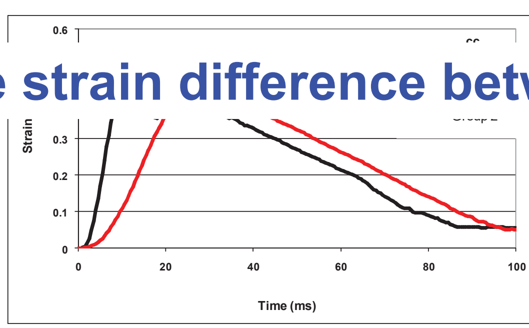
Two pulses have same change in angular velocity

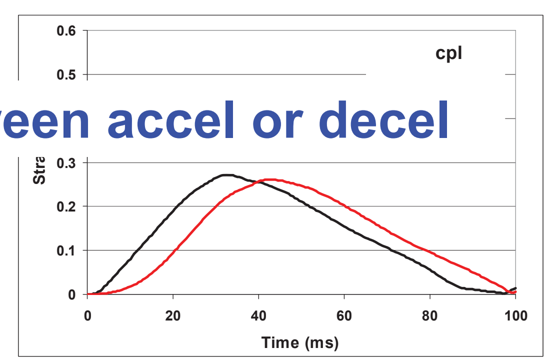
Strain Histories in Several Brain Regions



corpus callosum (cc),
base of postcentral sulcus (bps),
and cortex of the parietal lobe (cpl)



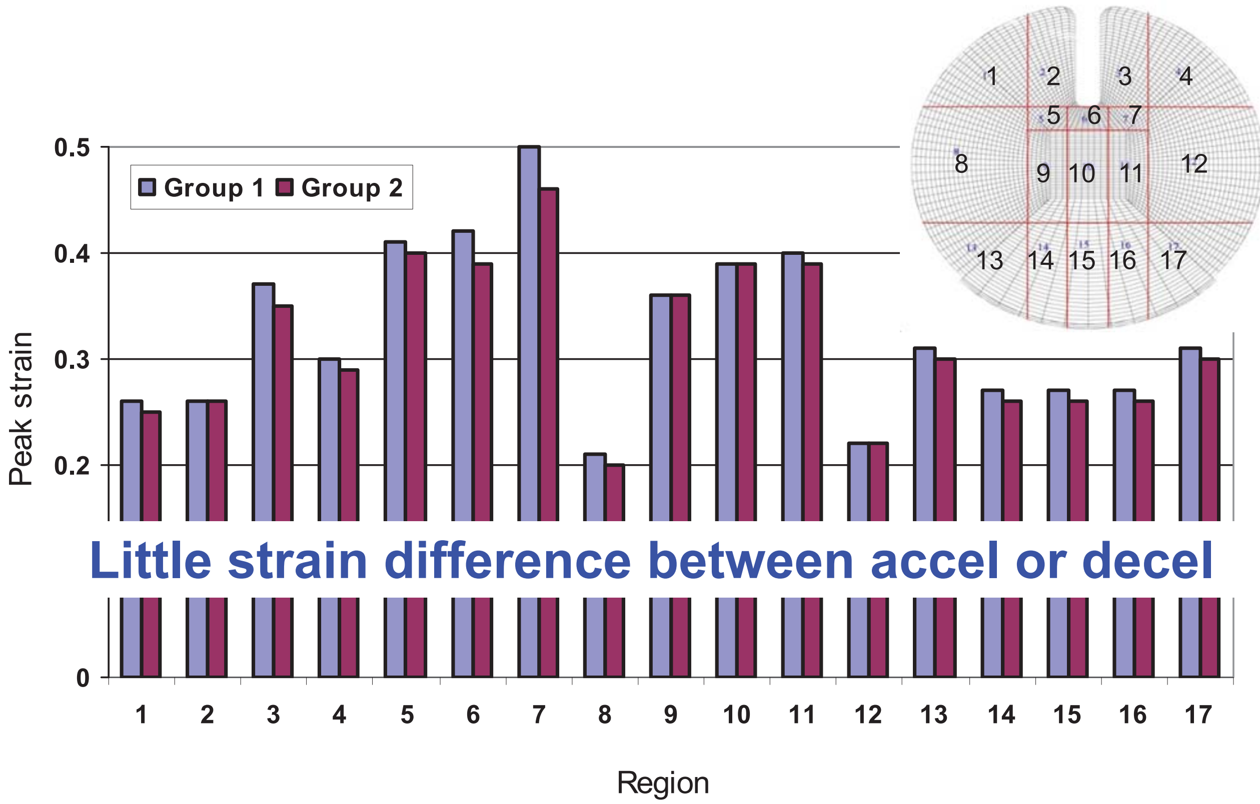




Little strain difference between accel or decel

Condition/group 1 = acceleration only
Condition/group 2 = deceleration only

Peak Average Strains in 17 Regions



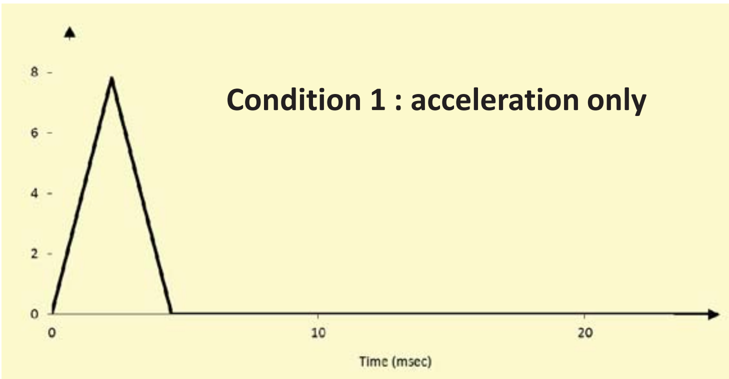
Condition/group 1 = acceleration only

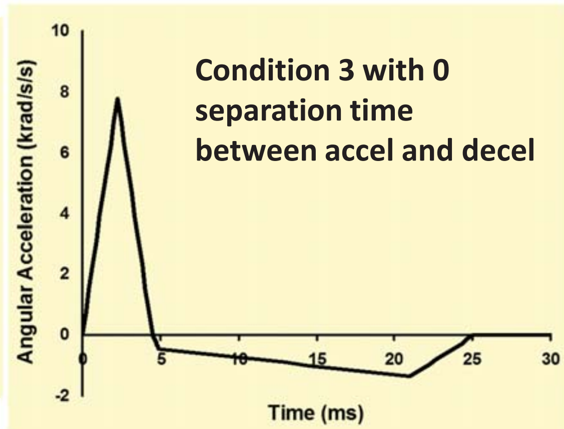
Condition/group 2 = deceleration only

Summary

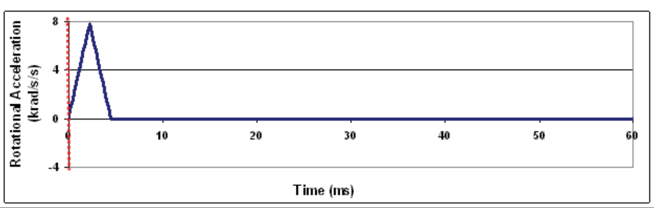
- At the same angular velocity, the magnitude of acceleration does not produce different strain fields

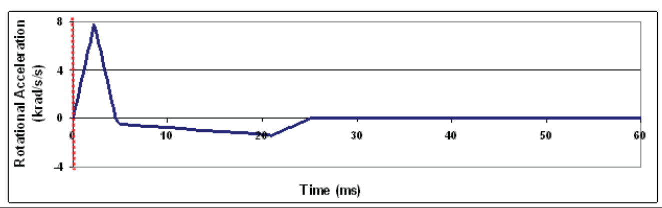
2: Combined Loading:
Effect of presence of deceleration pulse

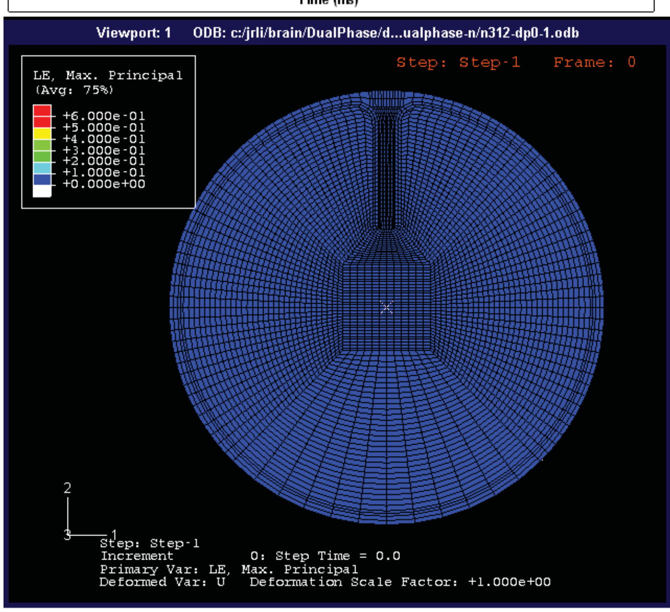


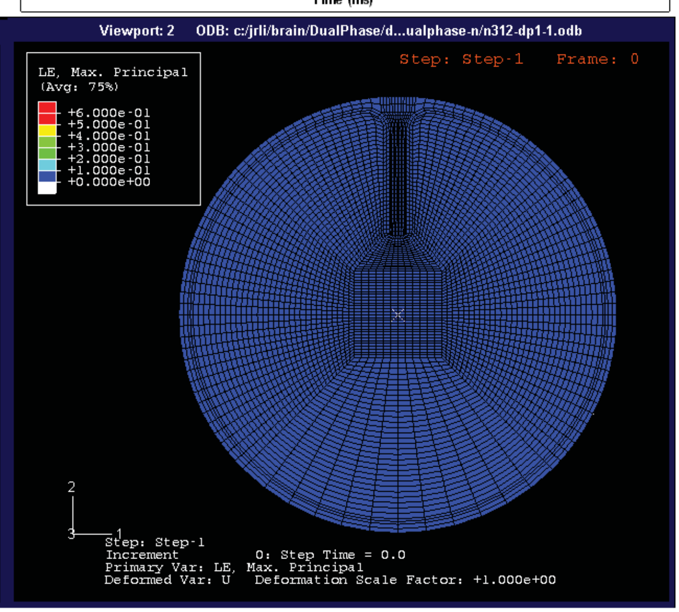


Effect of Deceleration on Brain Strains

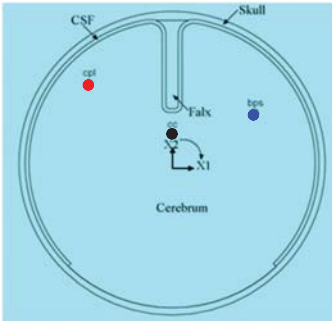






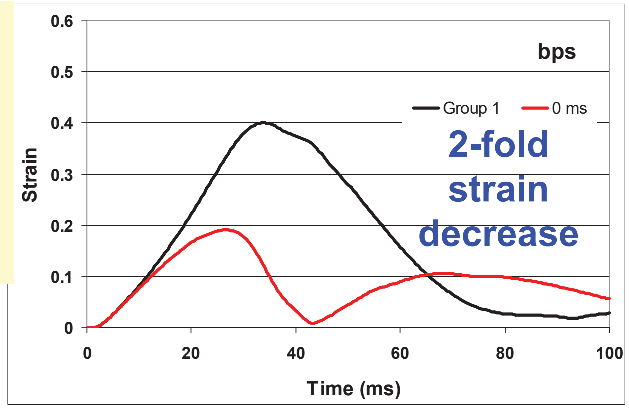


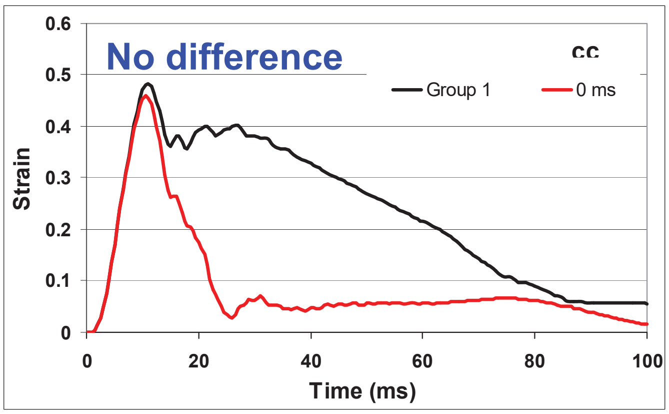
Strain Histories: Conditions 1 & 3 simulations

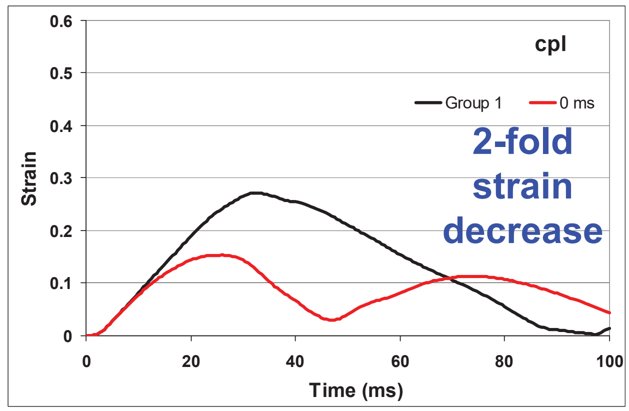


Condition/group 1 = accel only Versus No separation between accel and decel

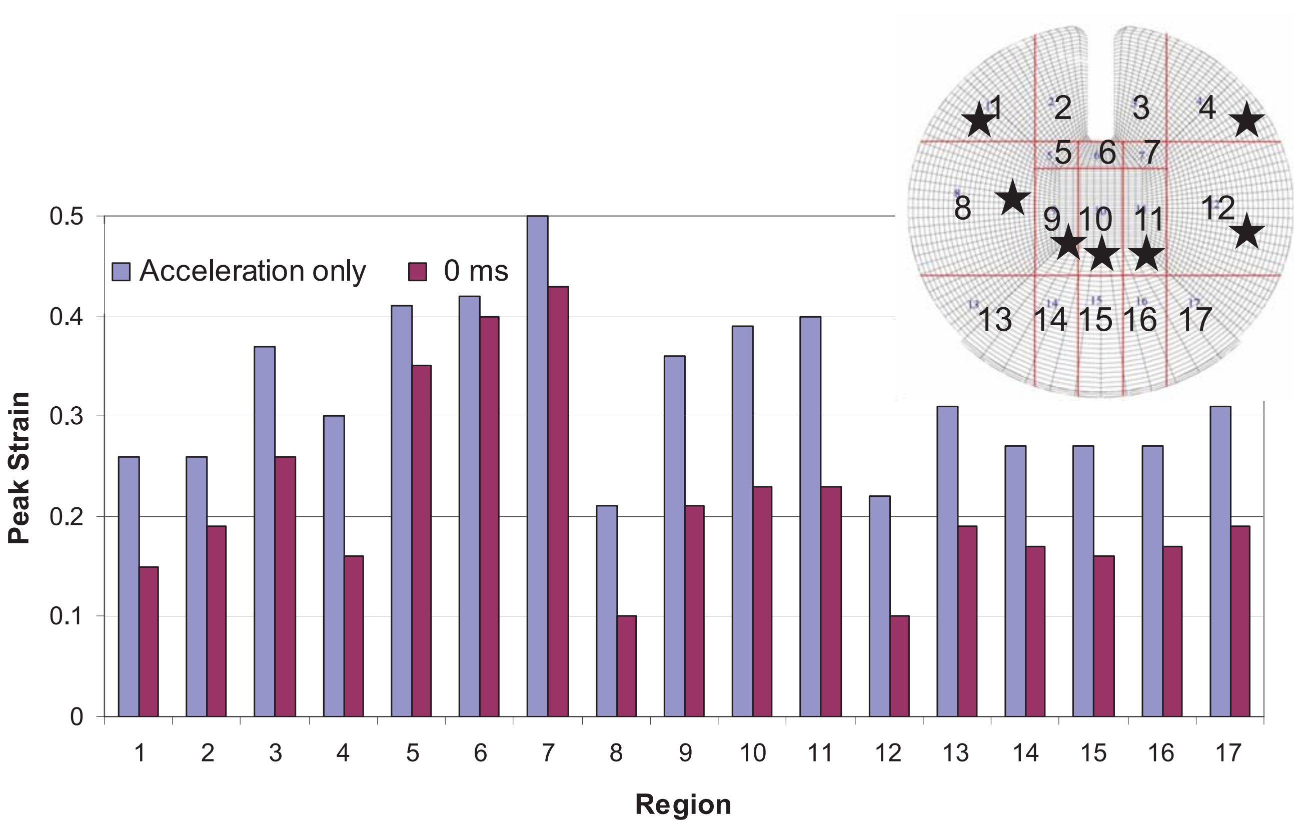
corpus callosum (cc),
base of postcentral sulcus (bps),
and cortex of the parietal lobe (cpl)







Peak Mean Regional Strains: Conditions 1 & 3:

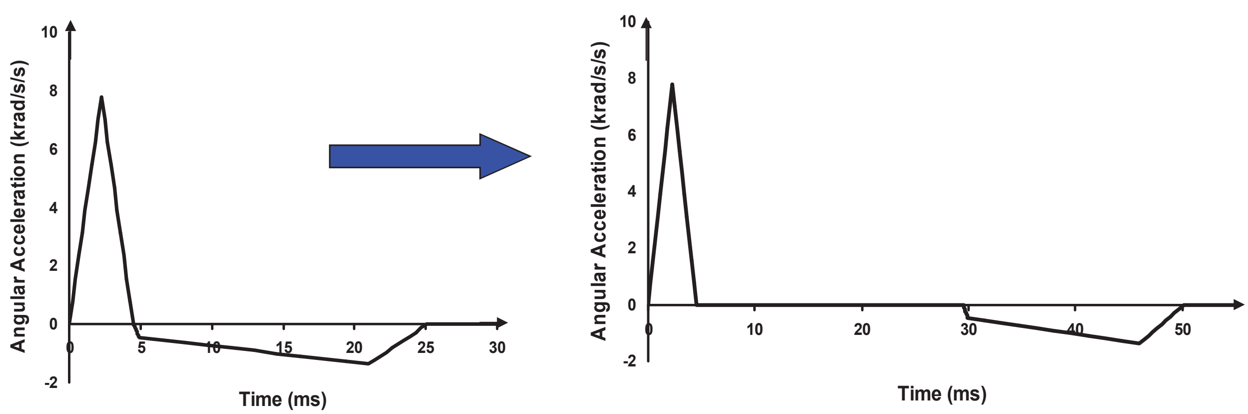


Condition/group 1 = acceleration only
Condition/group 3 = 0 ms separation

Summary

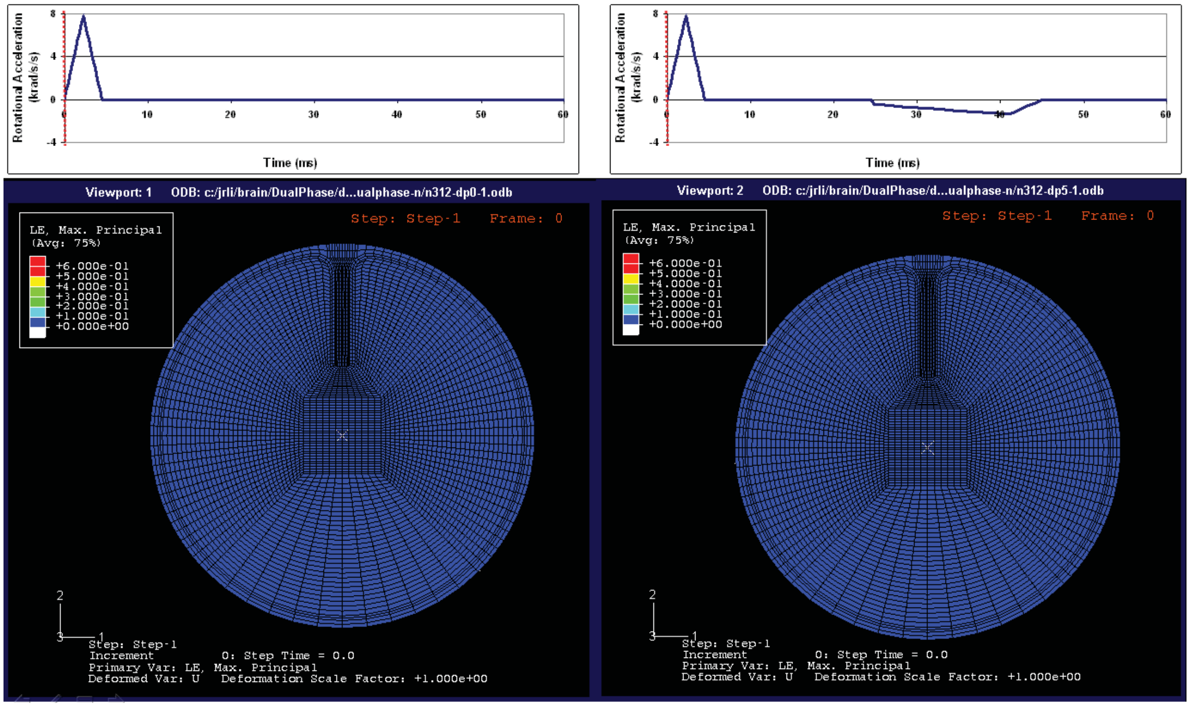
- At same angular velocity, the magnitude of acceleration does not produce different strain fields
- Under combined loading
  - ❖No separation time: peak strains are smaller compared to single acceleration

C: Combined Loading: Effect of changing separation time



separation time: 0, 5, 10, 15, 20, 25 ms

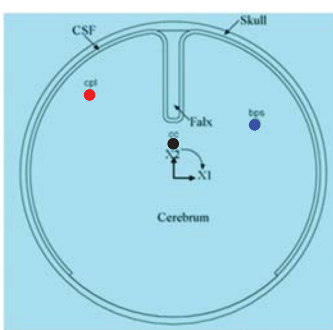
Long Separation: Equivalent to Single Pulse



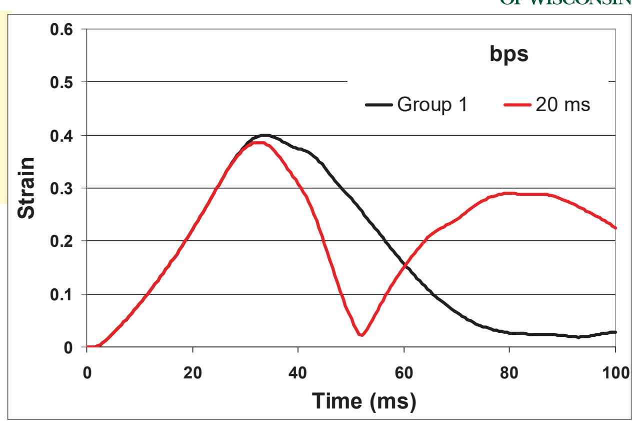
20 ms

Very little differences at 20 ms+

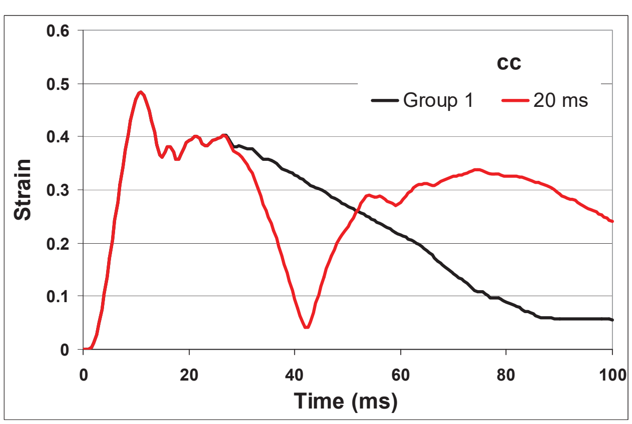
Strain-time Histories: Single vs 20 ms A &D

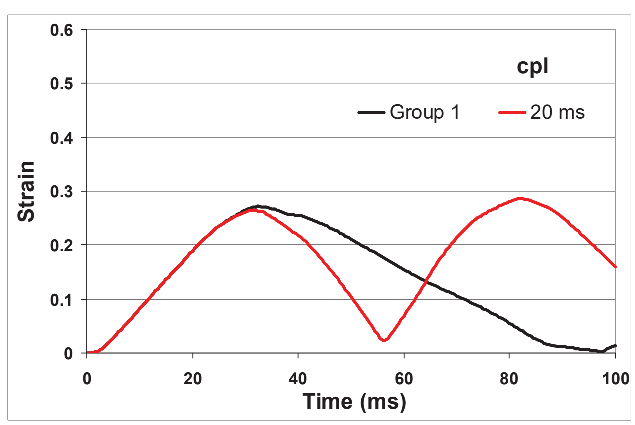


Group1 = accel only Versus 20 ms separation



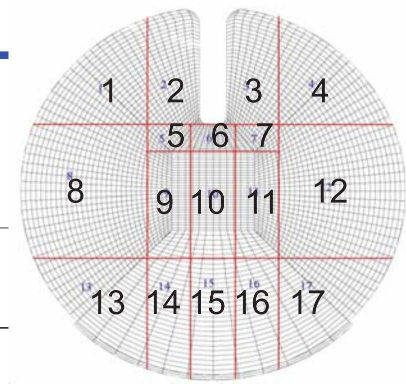
corpus callosum (cc),
base of postcentral sulcus (bps),
and cortex of the parietal lobe (cpl)

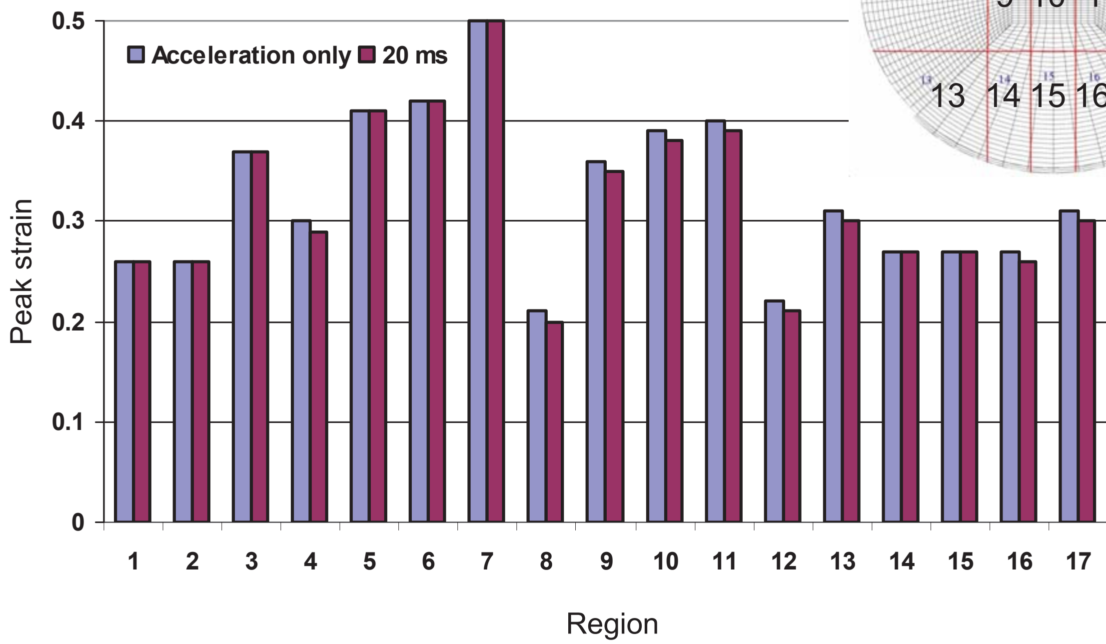




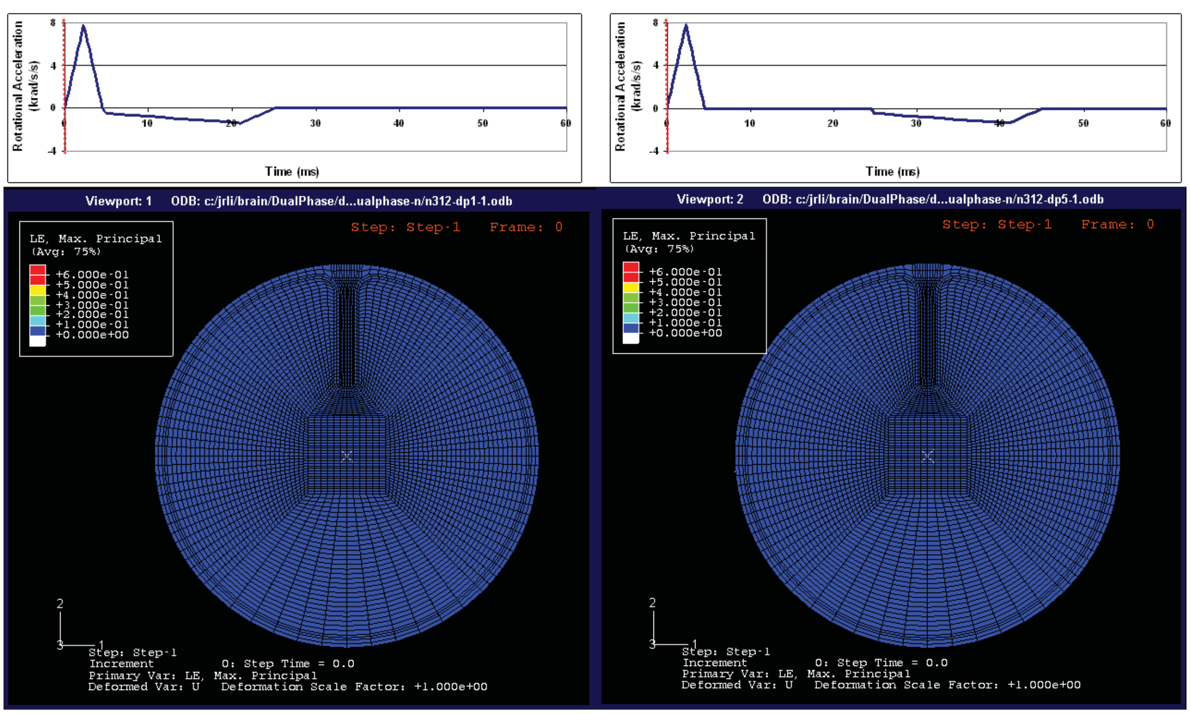
Peak mean regional strains: Conditions 1 & 3:

Very little differences at 20 ms+





Effects of Separation Times on Brain Strain

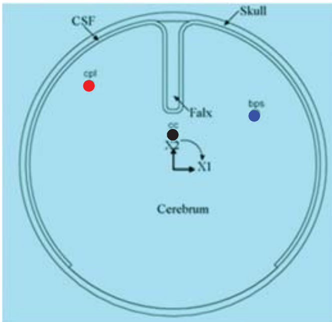


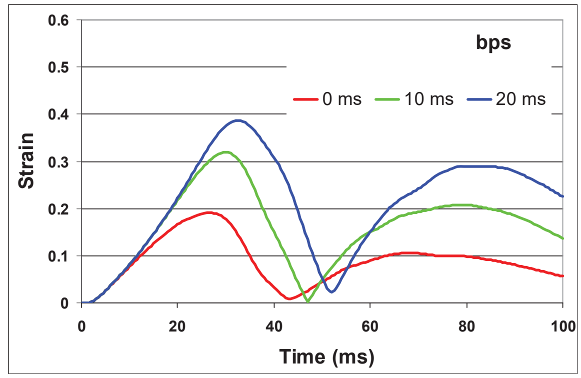
0 ms

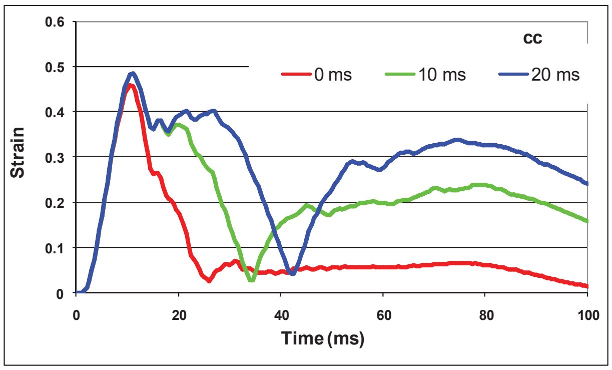
20 ms

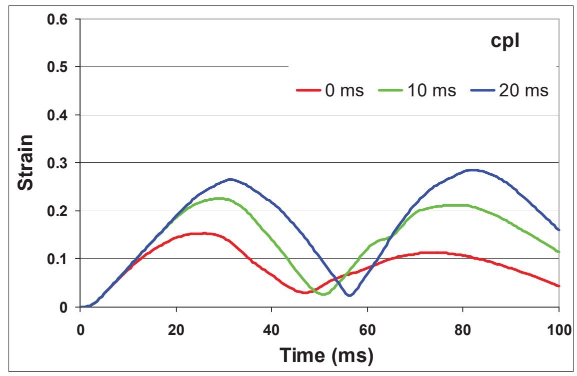
Strain increases as separation increases

Strain Histories with Increasing Separation Times (A &D)



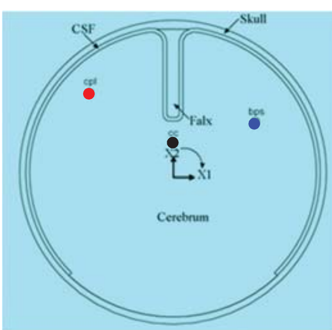


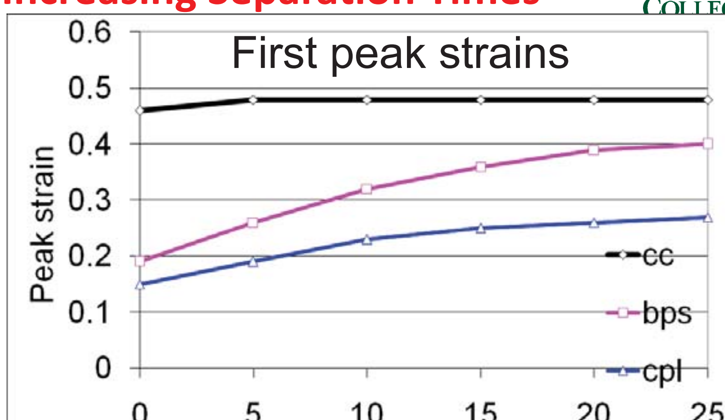


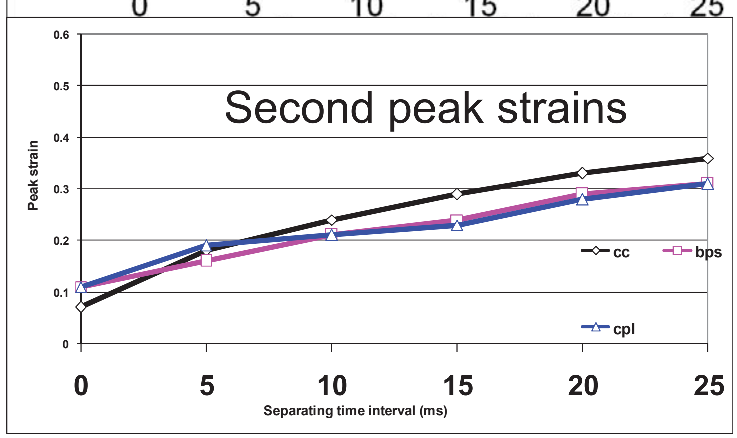


Strain increases as separation increases

1st and 2nd Peak Strains with Increasing Separation Times

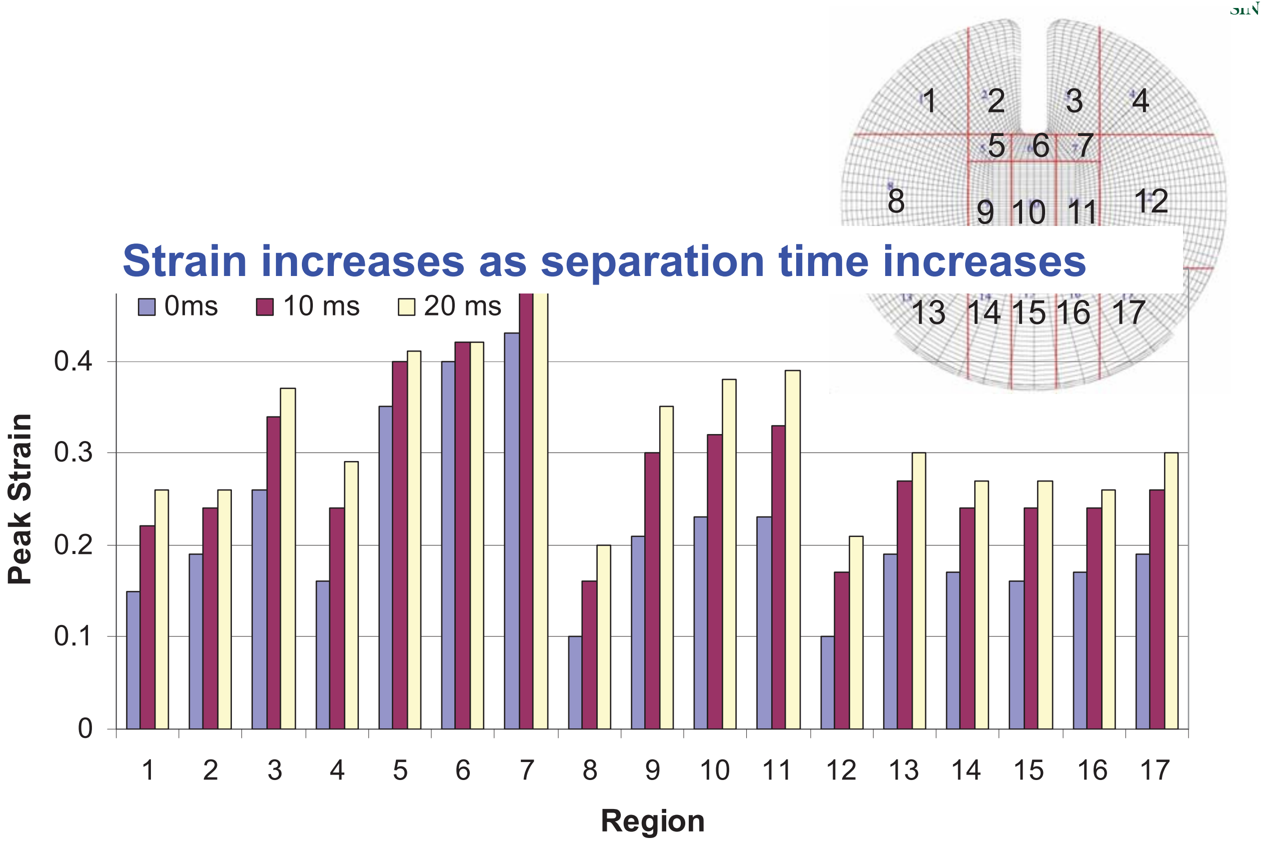






Strain increases as separation increases

Peak mean regional strains: Conditions 1 & 3:

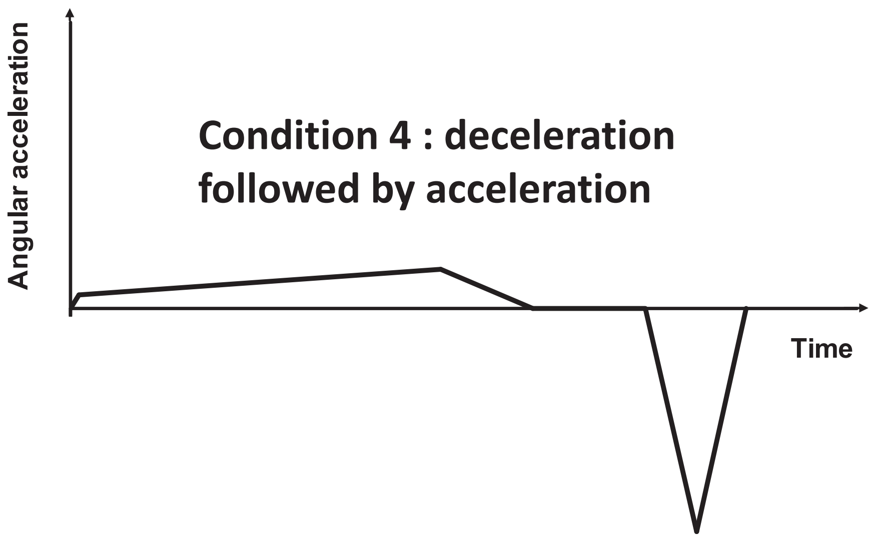


Summary

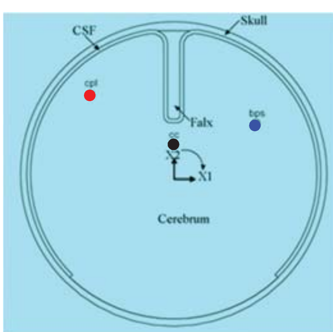
MEDICAL COLLEGE OF WISCONSIN

- At the same angular velocity, the magnitude of acceleration does not produce different strain fields
- Under combined loading
  - ❖No separation time: peak strains are smaller compared to single acceleration
  - ❖Increasing separation time increases strain in most regions

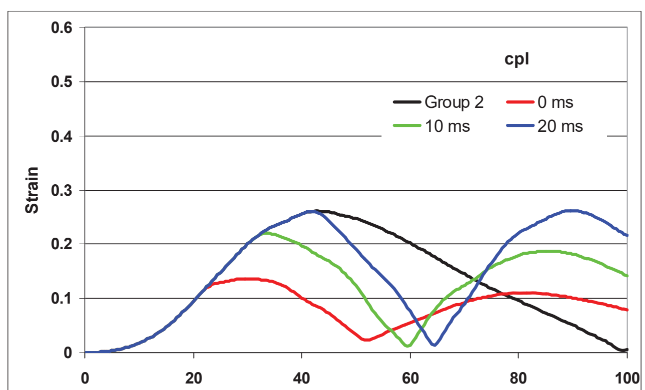
D. Results of Condition 4 simulations

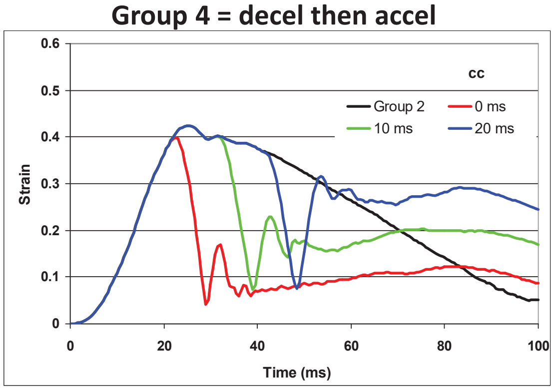


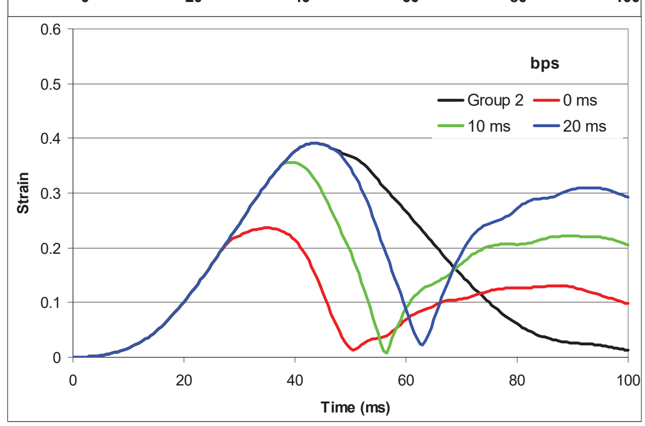
Strain Histories with Deceleration 1st and D& A



Group 2 = decel only
Group 4 = decel then accel



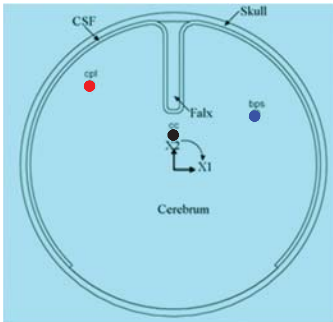


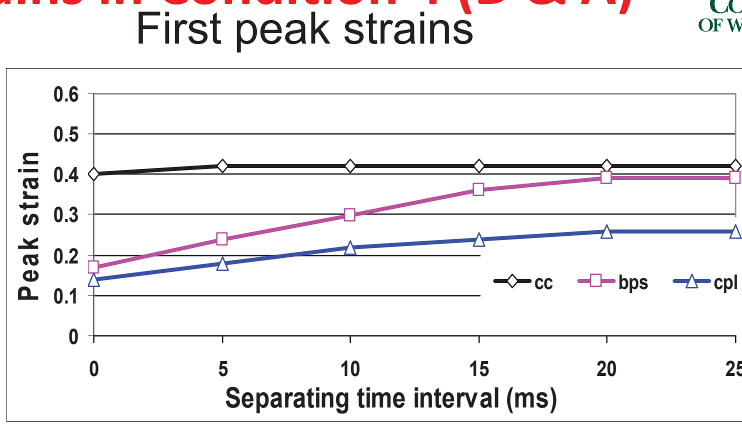


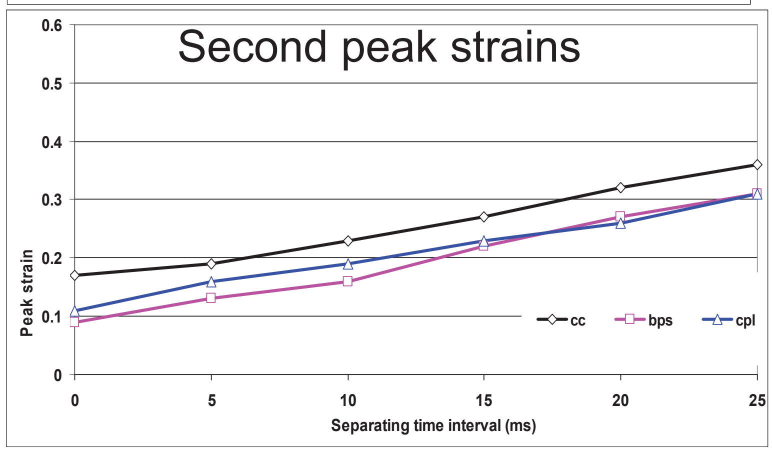
Strain increases 2-fold from no separation

1st and 2nd Peak Strains in Condition 4 (D & A)

MEDICAL COLLEGE OF WISCONSIN







Summary

MEDICAL COLLEGE OF WISCONSIN

- At the same angular velocity, the magnitude of acceleration does not produce different strain fields
- Under combined loading
  - ❖No separation time: peak strains are smaller compared to single acceleration
  - ❖Increasing separation time increases strain in most regions
- Deceleration followed by acceleration: similar trends

Conclusions

- At the same angular velocity, magnitude of acceleration does not produce different strain fields
- Under combined loading
  - ❖No separation time: peak strains are smaller compared to single acceleration
  - ❖Increasing separation time increases strains in most regions
- Deceleration followed by acceleration - similar trends
- Brain demonstrates regional and pulse-specific responses to angular accelerations
- Regional strain distributions depend on pulse shape

Acknowledgements

MCW Department of Neurosurgery

VA Medical research

Thank you

Warren N. Hardy
Virginia Tech
Center for Injury Biomechanics

Angular Measures in Testing
and their implications

8 September 2015, Lyon, France

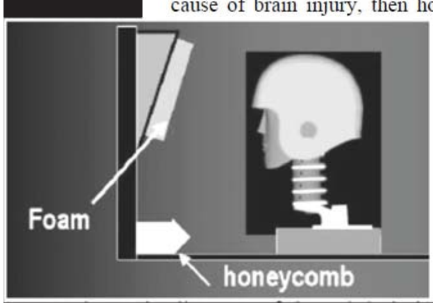
Linear vs. Angular Acceleration

IS HEAD INJURY CAUSED BY LINEAR OR ANGULAR ACCELERATION?

Albert I. King, King H. Yang, Liying Zhang and Warren Hardy
Bioengineering Center, Wayne State University
David C. Viano
Mild Traumatic Brain Injury Subcommittee, National Football League

ABSTRACT

Currently, angular acceleration is believed to be more damaging to the brain than linear acceleration, even though both are present in any head impact. In a recent experiment, it was found that a helmeted head sustained the same degree of angular acceleration as the unhelmeted head for the same impact, but its linear acceleration was decreased significantly. So, if angular acceleration is the cause of brain injury, then how is the brain protected by the helmet? This paper proposes a new ... suggests that input acceleration limits should be replaced by response

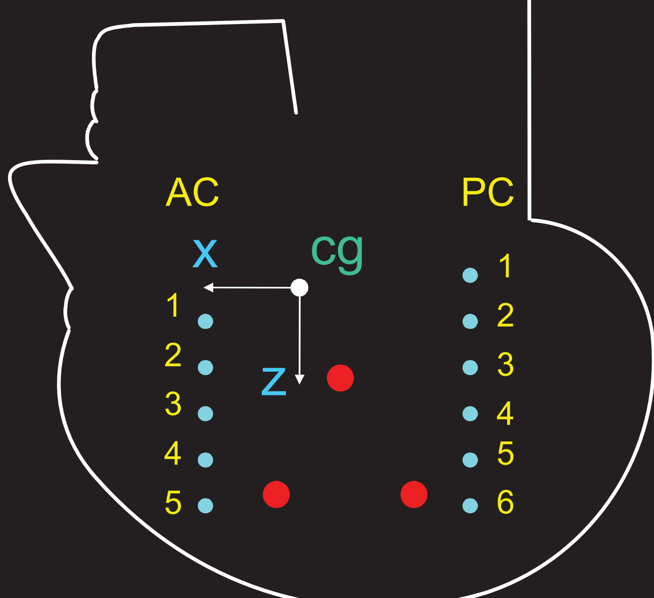


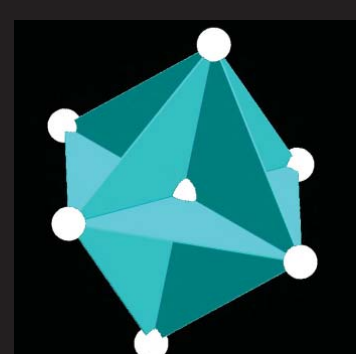
Relative Brain/Skull Motion

- **High-speed x-ray -**
  - **Hodgson et al. (1966)**
  - **Shatsky et al. (1973, 1976)**
  - **Stalnaker et al. (1977)**
  - **Nusholtz et al. (1984)**
  - **Hardy et al. (1997)**
  - **Hardy et al. (2001)**
  - **Hardy et al. (2007)**

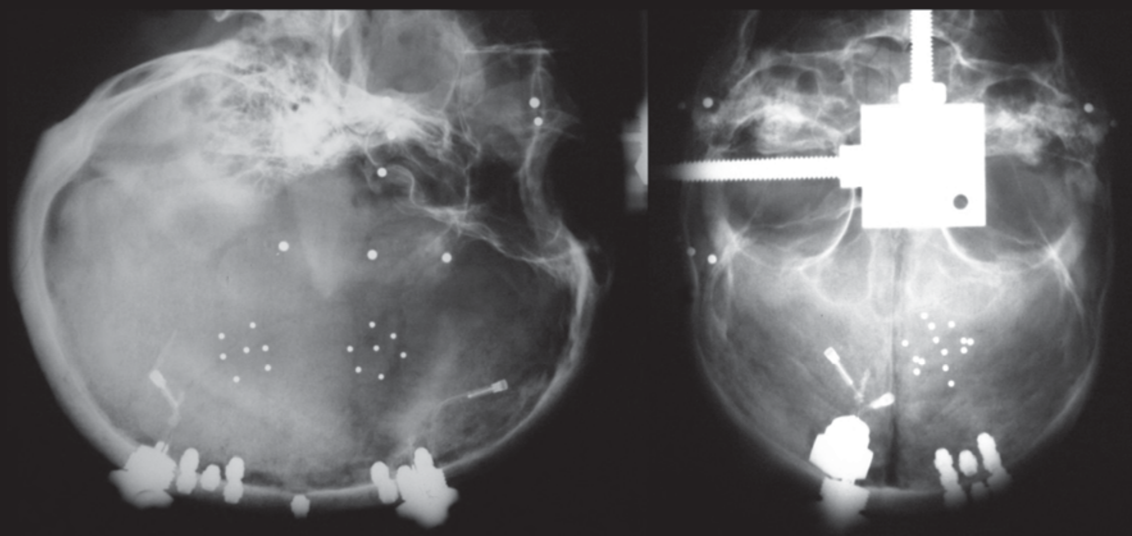
Neutral Density Targets

Column Approach



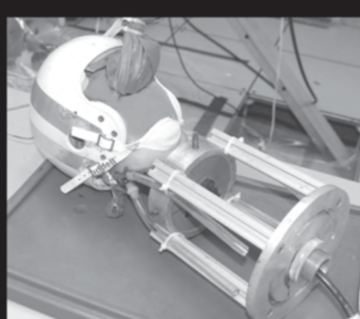


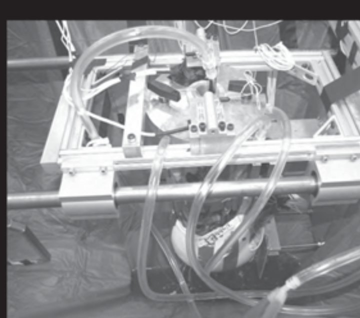
Prepared Specimen



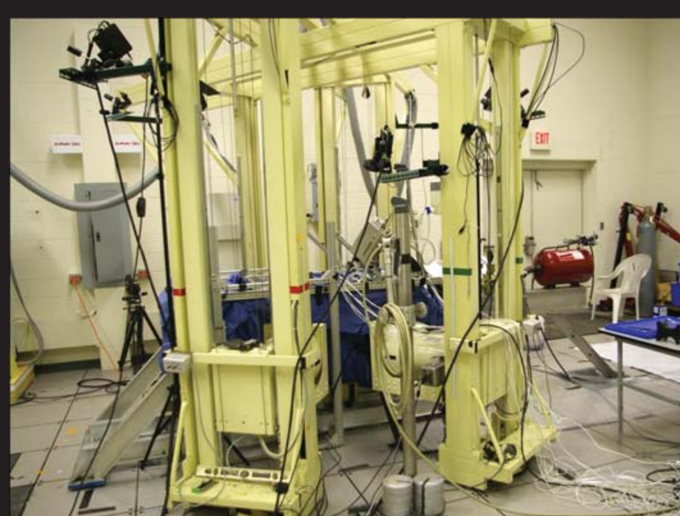
C288

Specimen Testing

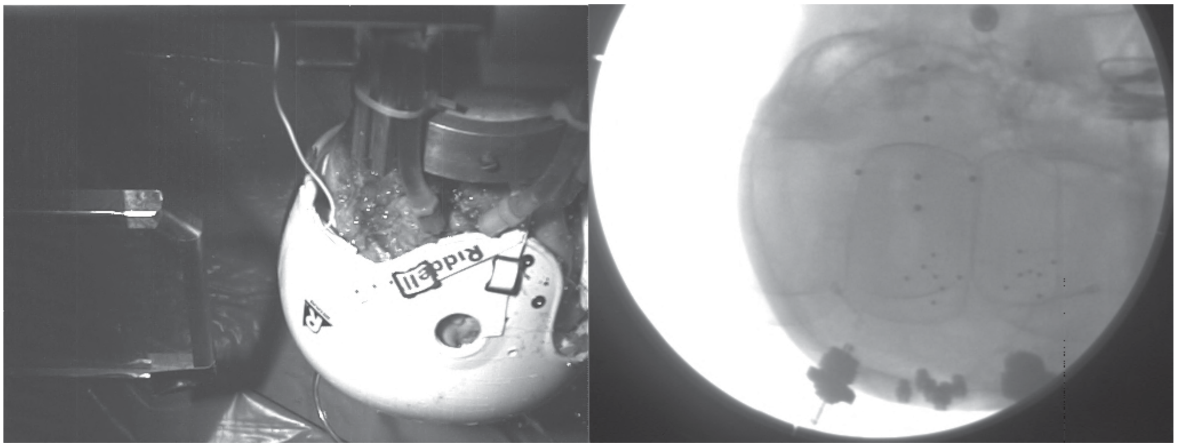




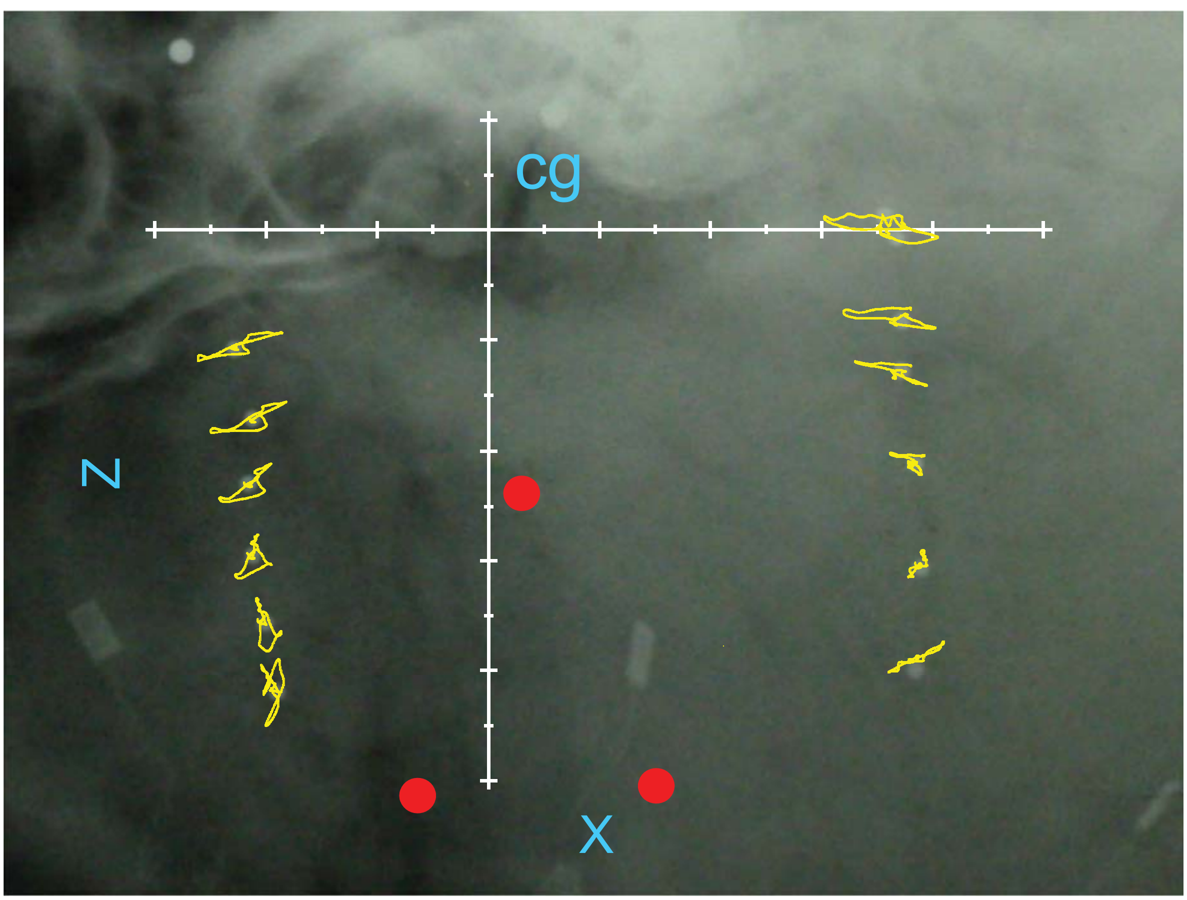
- High-speed biplane x-ray
- Riddell VSR4

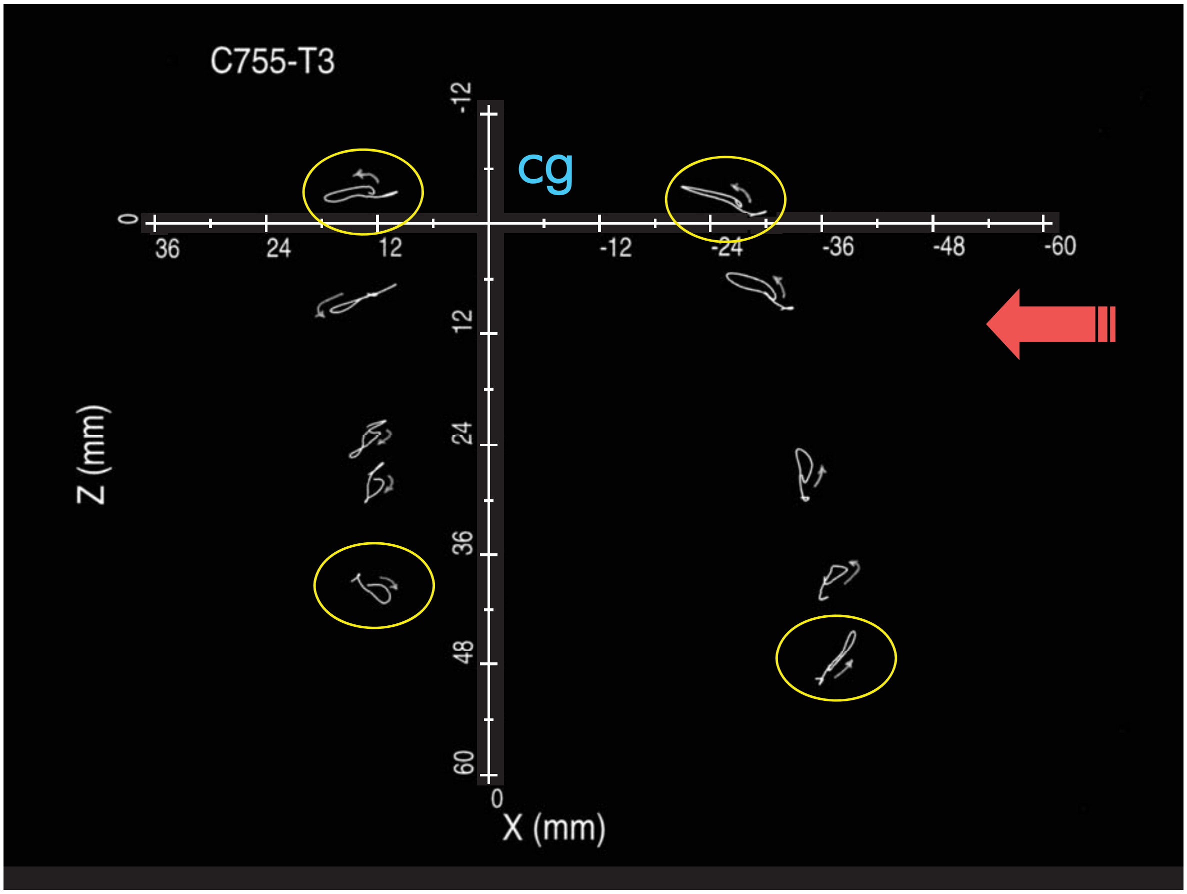


Test C288-T1

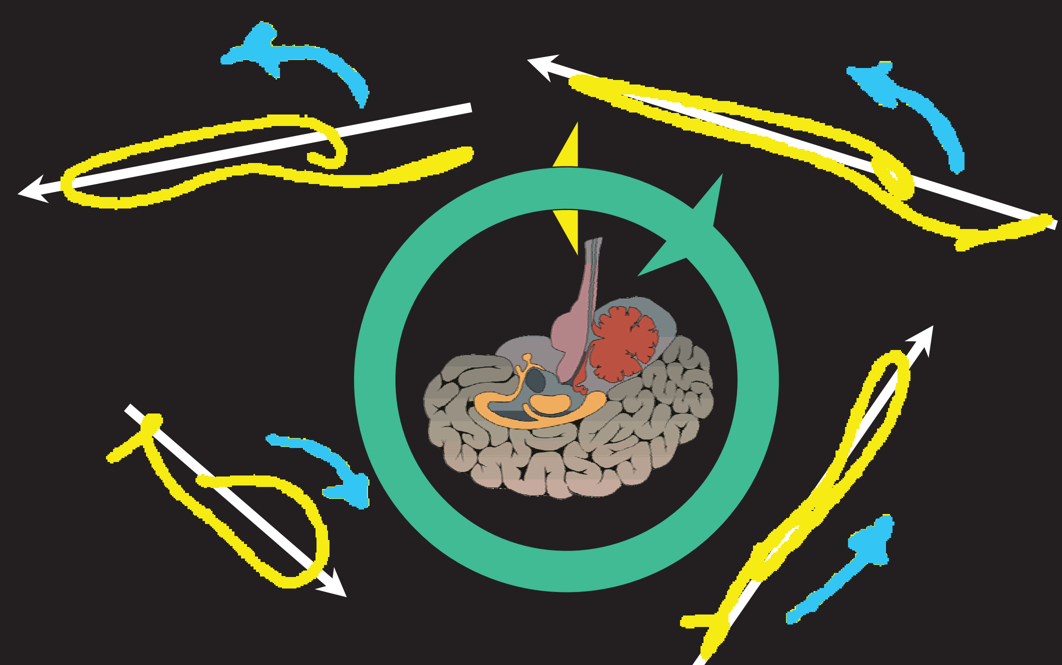


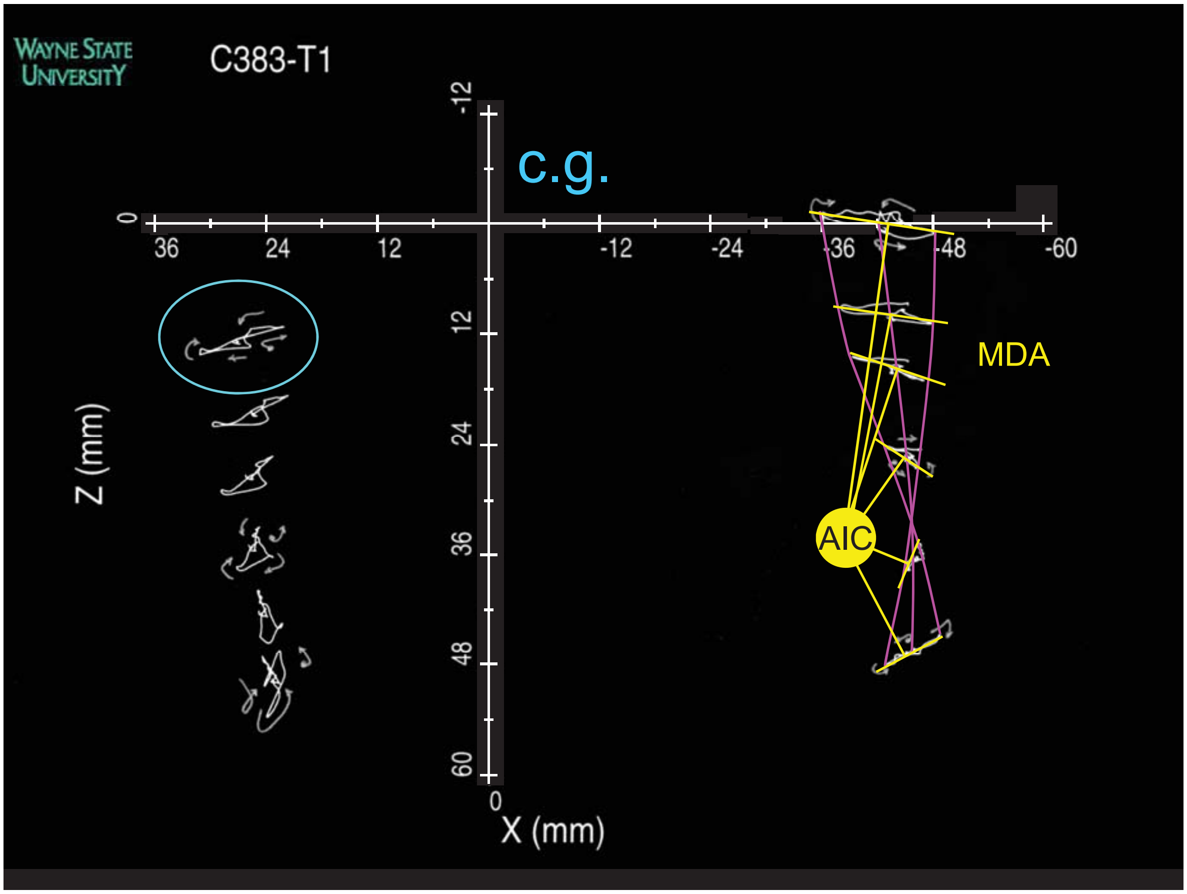
Aligned occipital impact in the median plane using a helmet



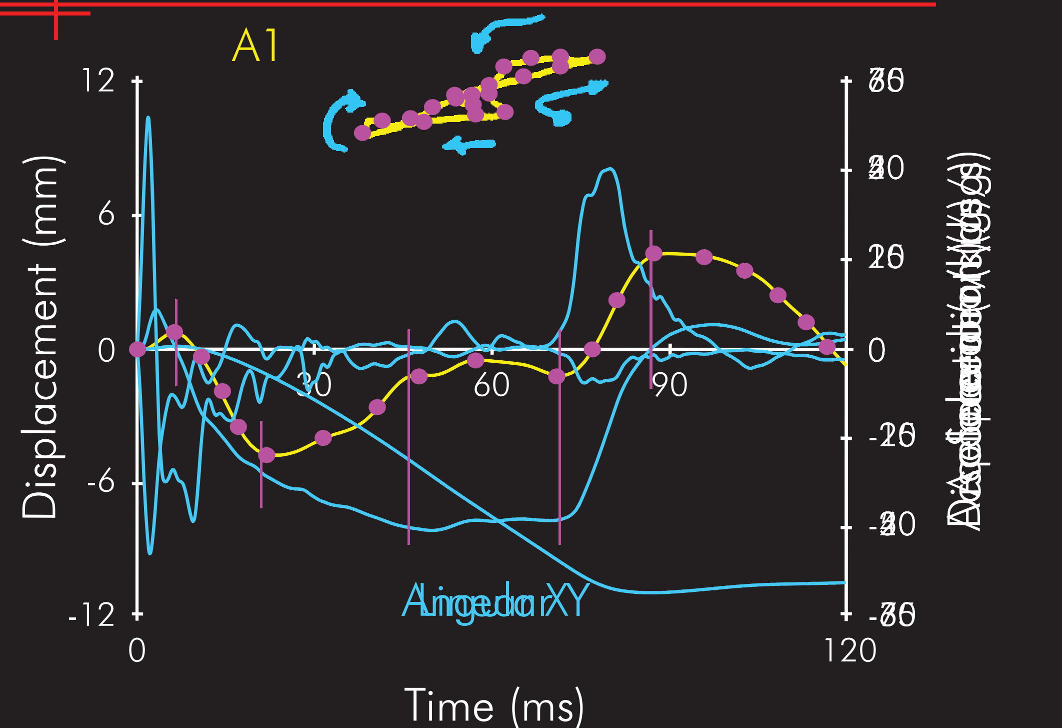


NDT Displacements

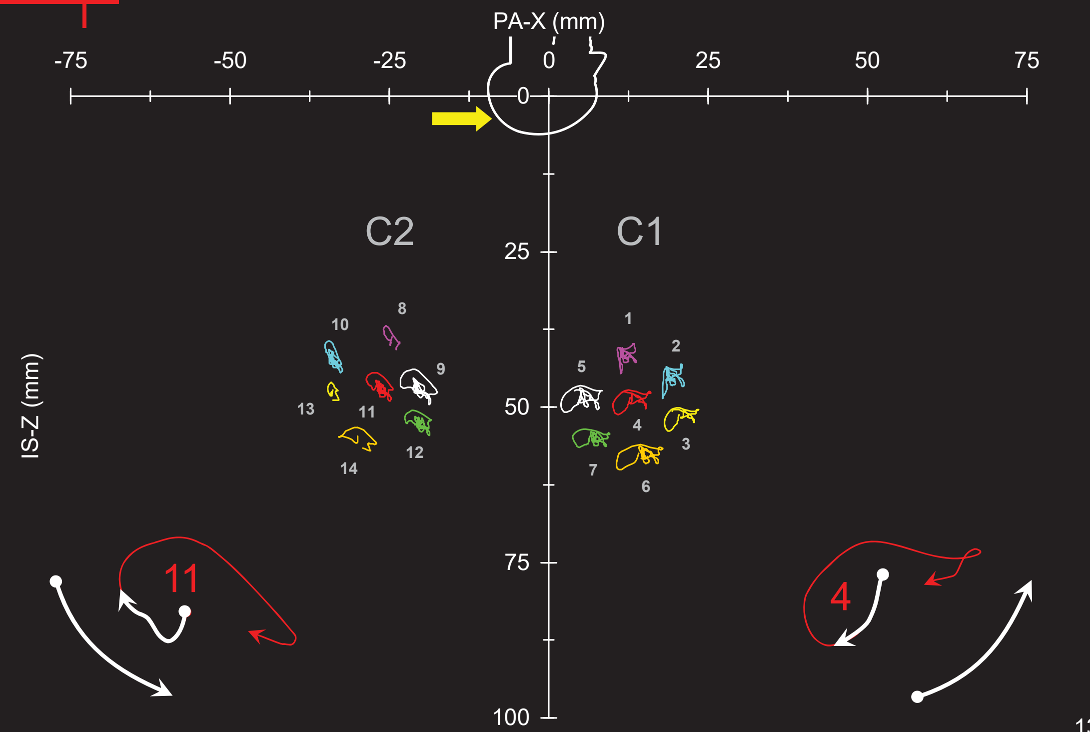




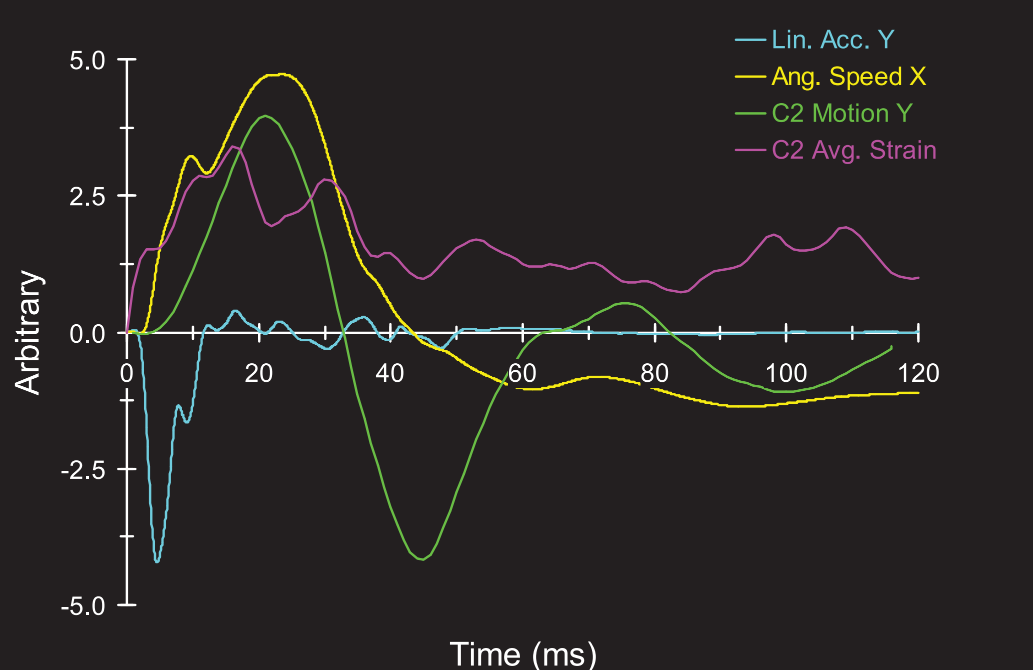
C383-T1 Kinematics



C288-T3 Motion Patterns



C380-T1 Comparisons



Kinematics and Helmet Use

Head Responses		No Helmet Mean	No Helmet Std. dev.	Helmet Mean	Helmet Std. dev.	p
Linear Acc.	(g)	124	38	75	34	0.0009
Angular Acc.	(krad/s/s)	10.6	5.4	5.9	3.8	0.0093
Angular Speed	(rad/s)	21	6	20	5	0.5890

$p < 0.05$

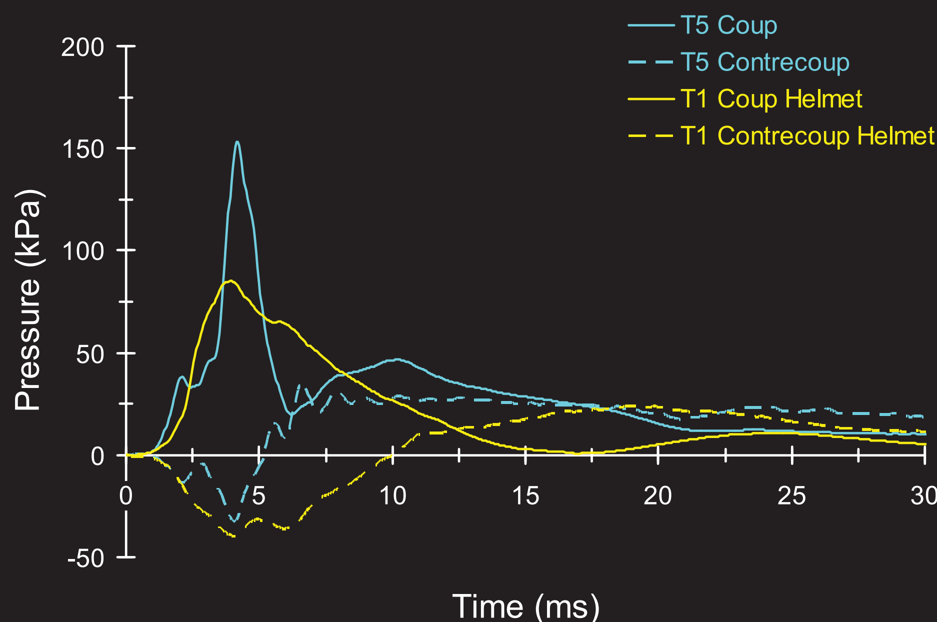
Brain Motion and Helmet Use

Peak Average Responses		No Helmet Mean	No Helmet Std. dev.	Helmet Mean	Helmet Std. dev.	p
Total Excursion	(mm)	6.9	3.8	6.4	1.9	0.6669
Max. Princ. Strain	-	0.025	0.016	0.039	0.023	0.0138
Max. Shear	-	0.022	0.009	0.037	0.021	0.0013
Max. Princ. Rate	(s^{-1})	25	15	28	21	0.5950
Max. Shear Rate	(s^{-1})	24	17	29	24	0.4221
Max. Princ. * Rate	(s^{-1})	0.184	0.201	0.331	0.328	0.0559
Max. Shear * Rate	(s^{-1})	0.132	0.153	0.314	0.312	0.0100

$p < 0.05$

Pressure and Helmet Use

C241 Pressure

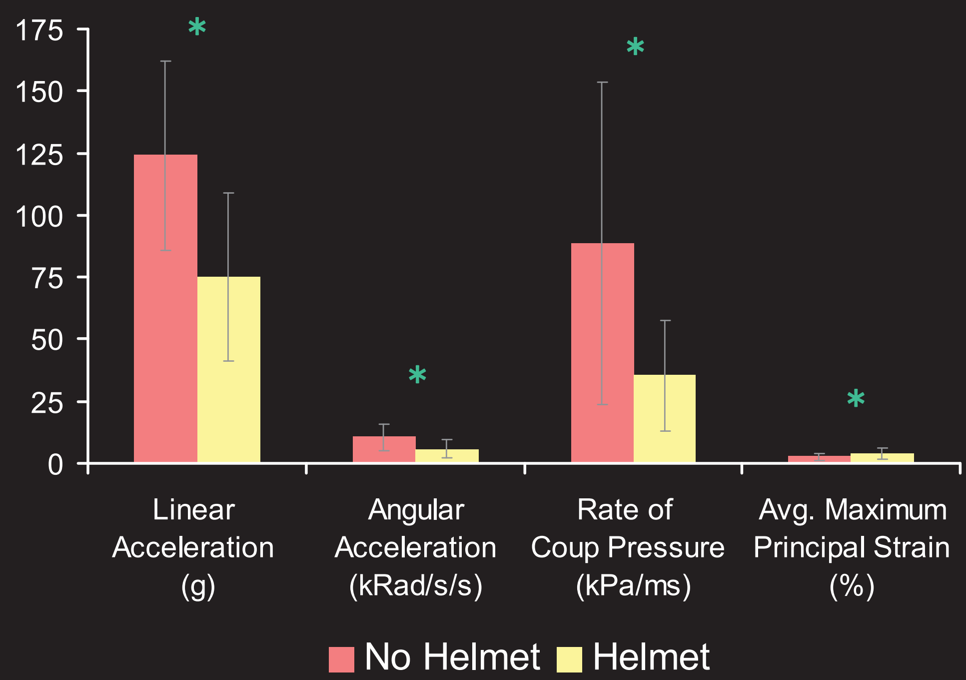


Pressure and Helmet Use

Coup Responses		No Helmet Mean	No Helmet Std. dev.	Helmet Mean	Helmet Std. dev.	p
Peak	(kPa)	68	48	59	22	0.5952
Duration	(ms)	16	18	22	19	0.5204
Rate	(kPa/ms)	89	65	35	22	0.0304
Impulse	(kPa*ms)	374	307	394	173	0.8708

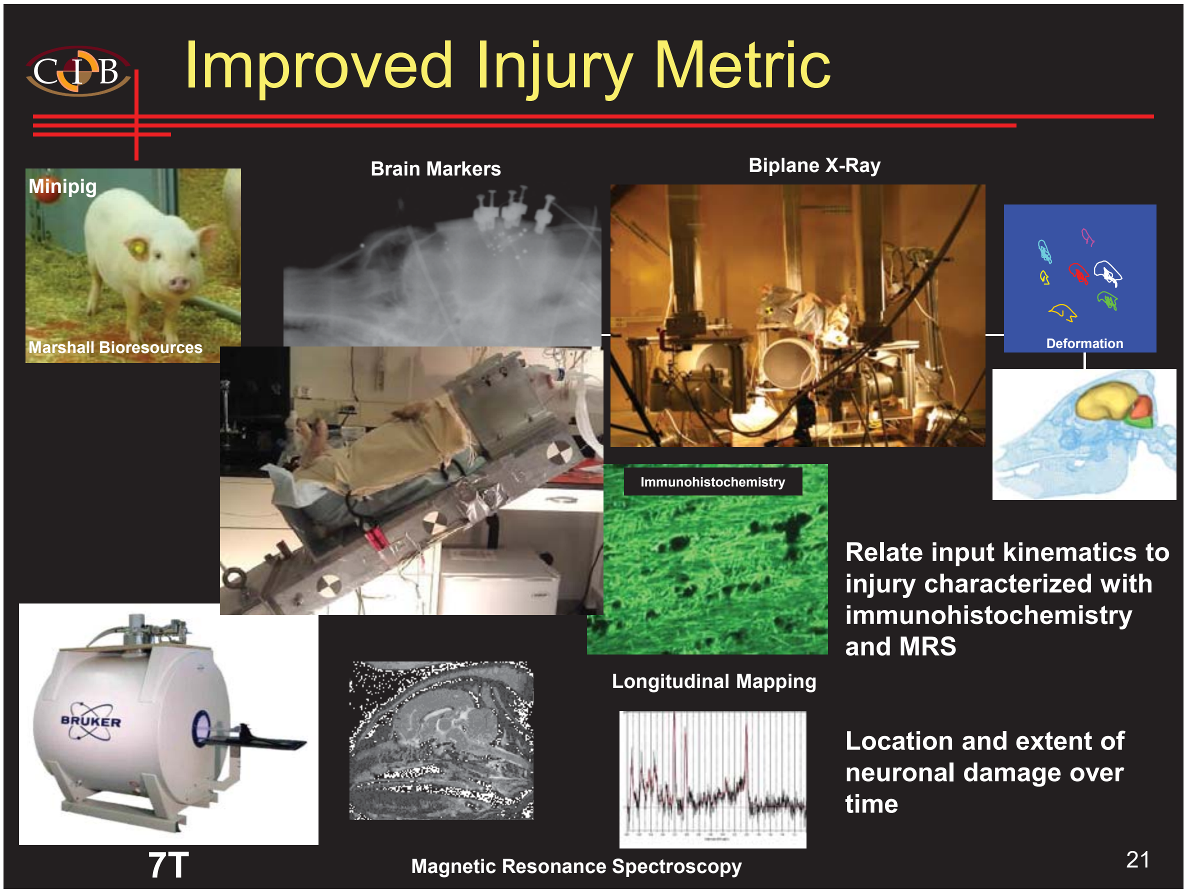
$p < 0.05$

Effect of Helmet Use

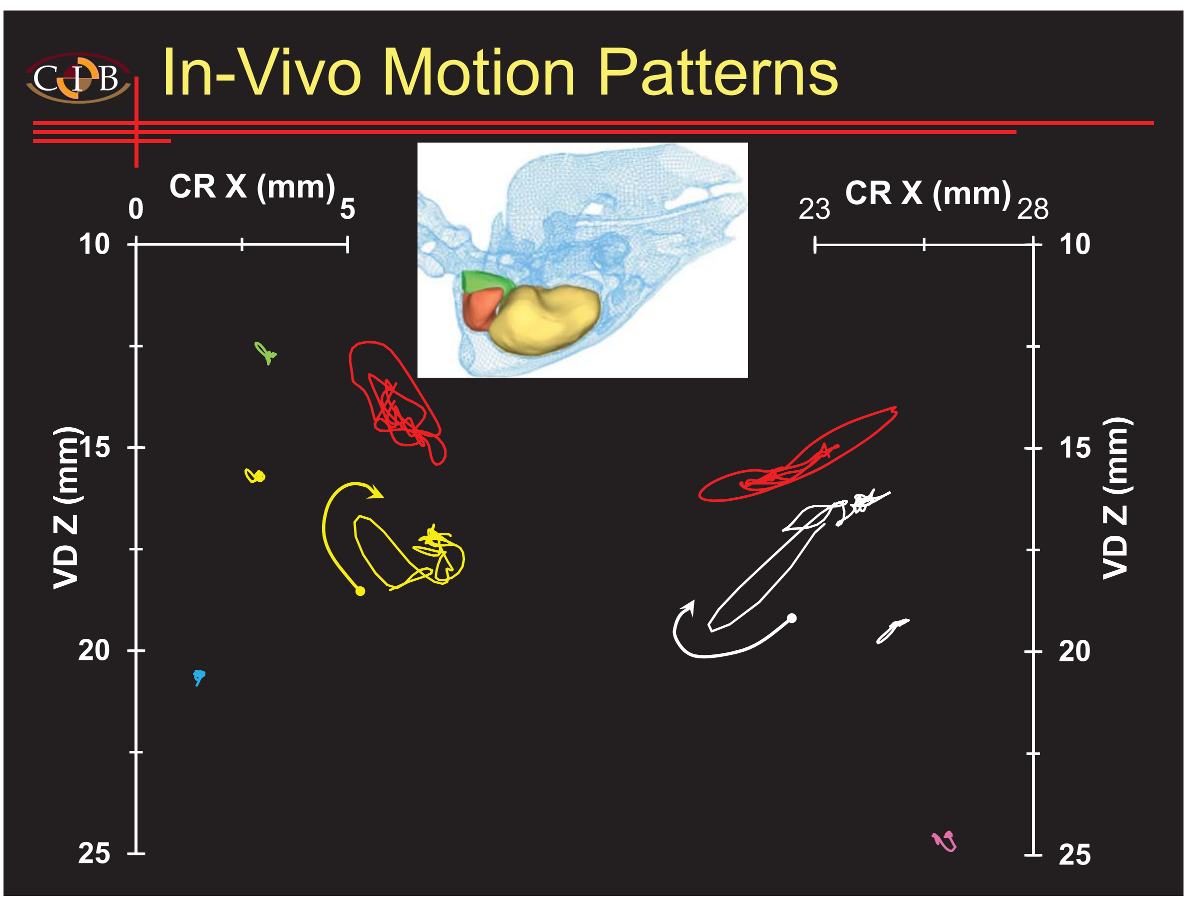


Summary: Helmet Effects

- **Linear and angular acceleration of the head are reduced with use of a helmet,**
- **Angular speed is not reduced significantly with use of a helmet,**
- **Helmet use did not influence the extent of relative brain displacement,**
- **Peak average maximum principal strain and peak average maximum shear strain increase for helmet use*.**



CIB
Improved Injury Metric
Minipig
Marshall Bioresources
Brain Markers
Biplane X-Ray
Deformation
Immunohistochemistry
Relate input kinematics to injury characterized with immunohistochemistry and MRS
BRUKER
7T
Longitudinal Mapping
Location and extent of neuronal damage over time
Magnetic Resonance Spectroscopy
21



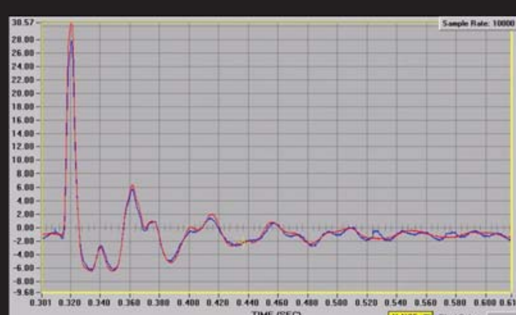
CIB
In-Vivo Motion Patterns
CR X (mm)
0
5
10
15
20
25
VD Z (mm)
CR X (mm)
23
28
10
15
20
25
VD Z (mm)

Summary: In-Vivo Testing

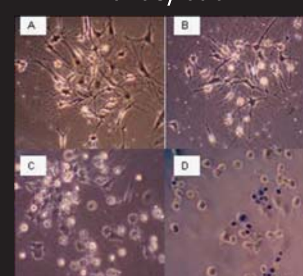
- Increases in light and heavy neurofilament
- Similar metabolite changes suggest myelin damage or inflammation
- Unique metabolite changes suggesting energy crisis in the GABA shunt system and Glu excitotoxicity

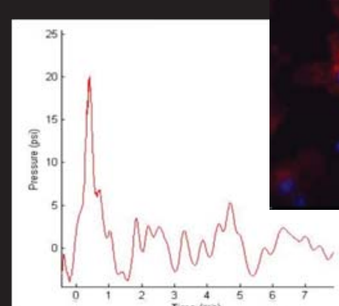
Findings suggest distinct underlying mechanisms

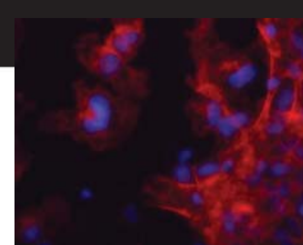
Impulse & Shock Wave Generator



Astrocytosis

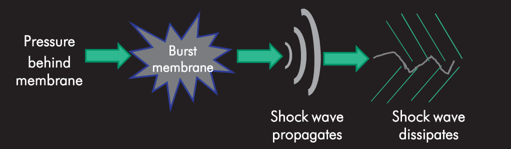


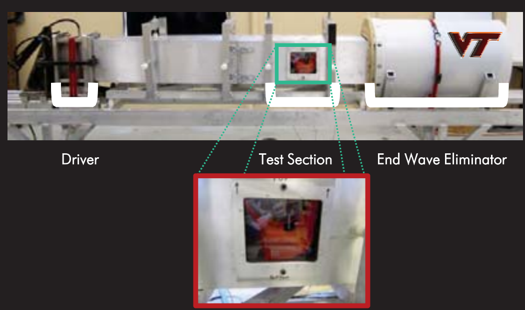


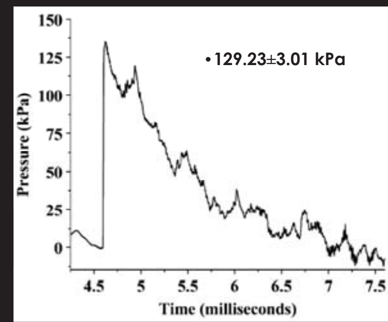


Actin Damage

Blast-Induced Neurotrauma





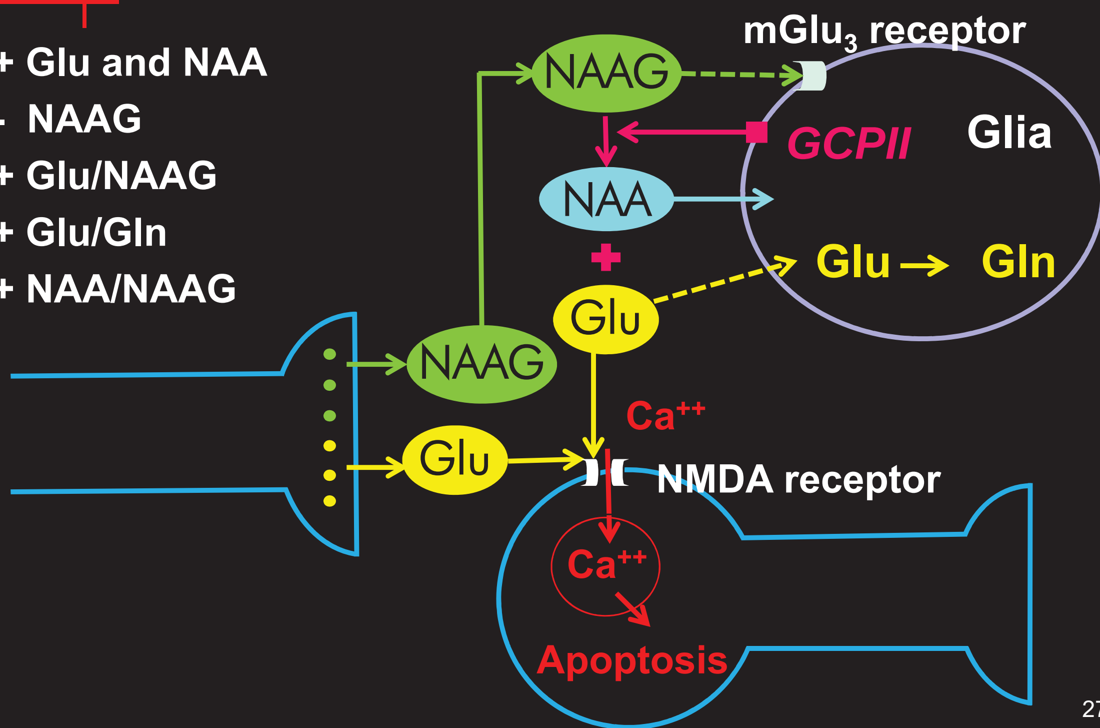


Oxidative stress
Neuroinflammation
Neuronal loss
Neurochemical changes

Thank You

Combined Metabolite Pathway

- \+ Glu and NAA
- \- NAAG
- \+ Glu/NAAG
- \+ Glu/Gln
- \+ NAA/NAAG

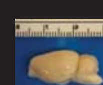


Animal Model

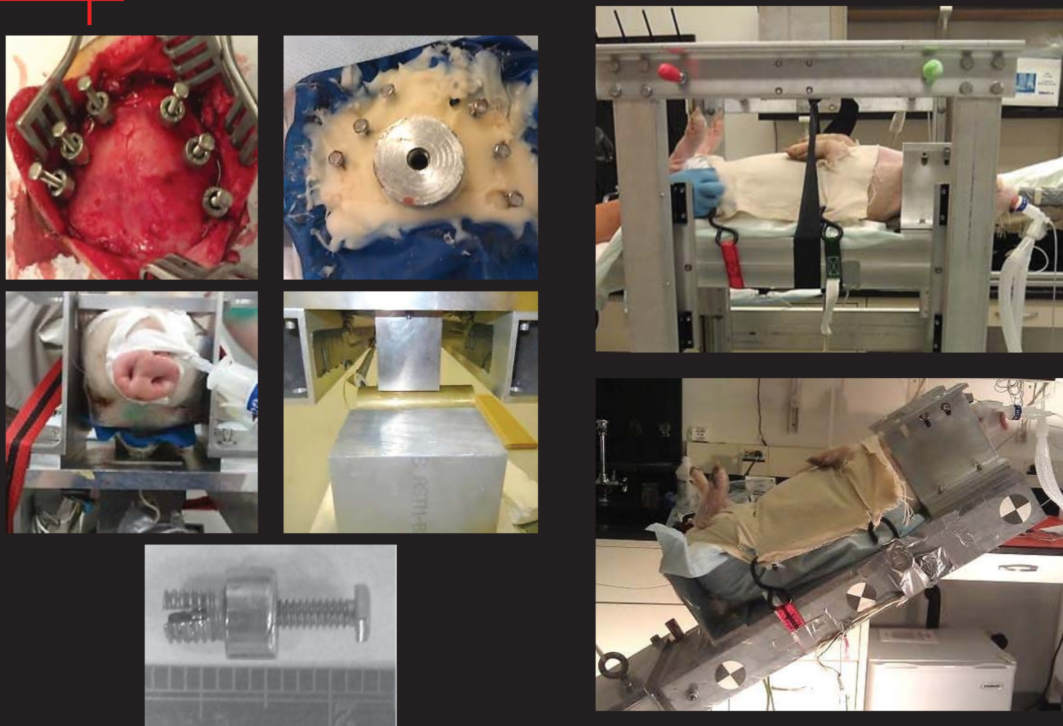
Human

Minipig

Rat

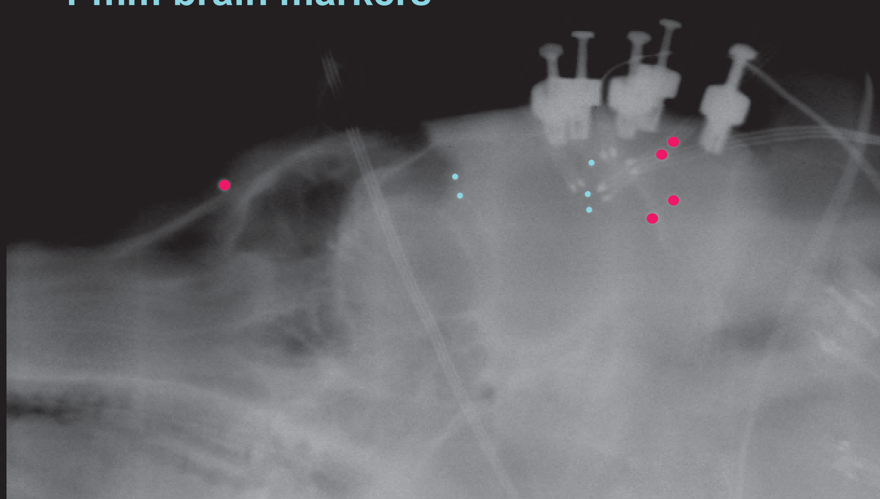


Animal Methods

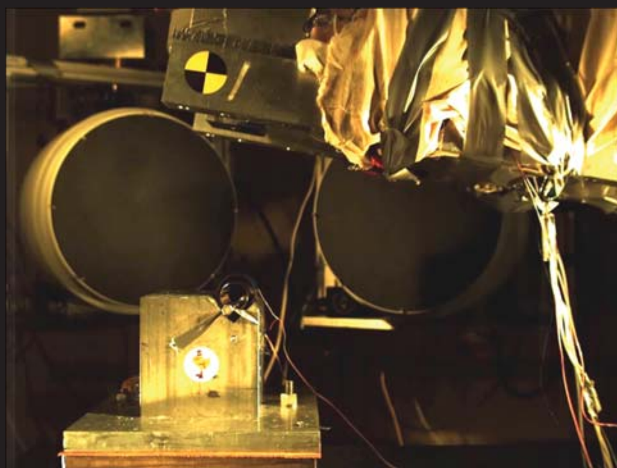


Minipig Instrumentation

- **Radio-opaque markers**
  - **2 mm skull markers**
  - **1 mm brain markers**



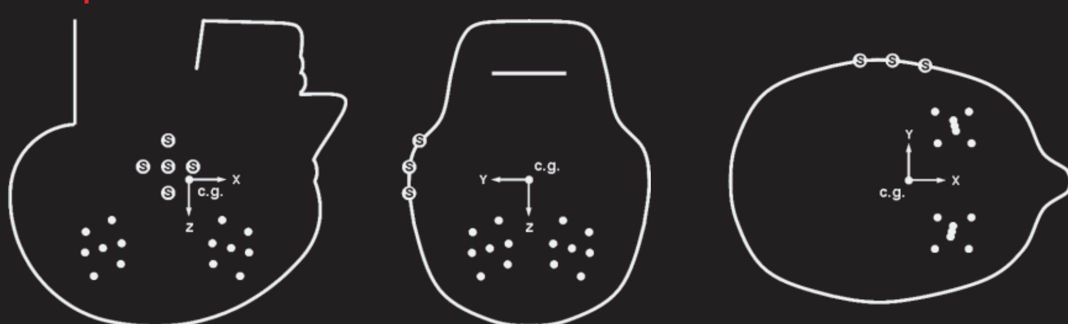
High-Speed Biplane X-Ray

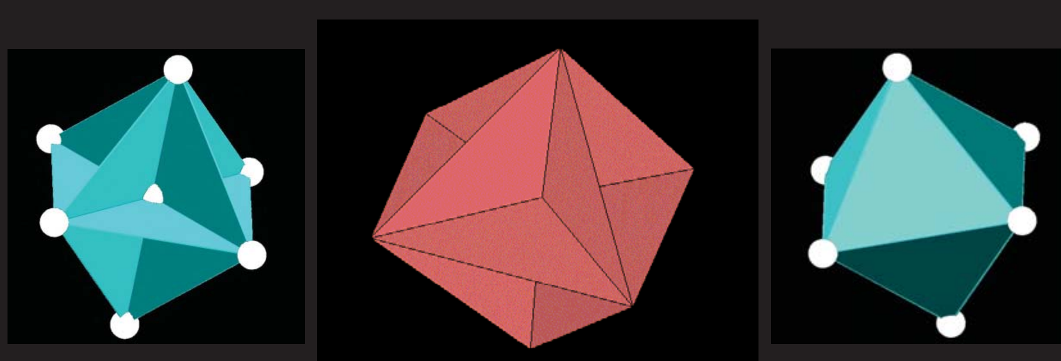


Combined input device

All animals were dropped from an angle of 25° to vertical

NDT Cluster Configurations





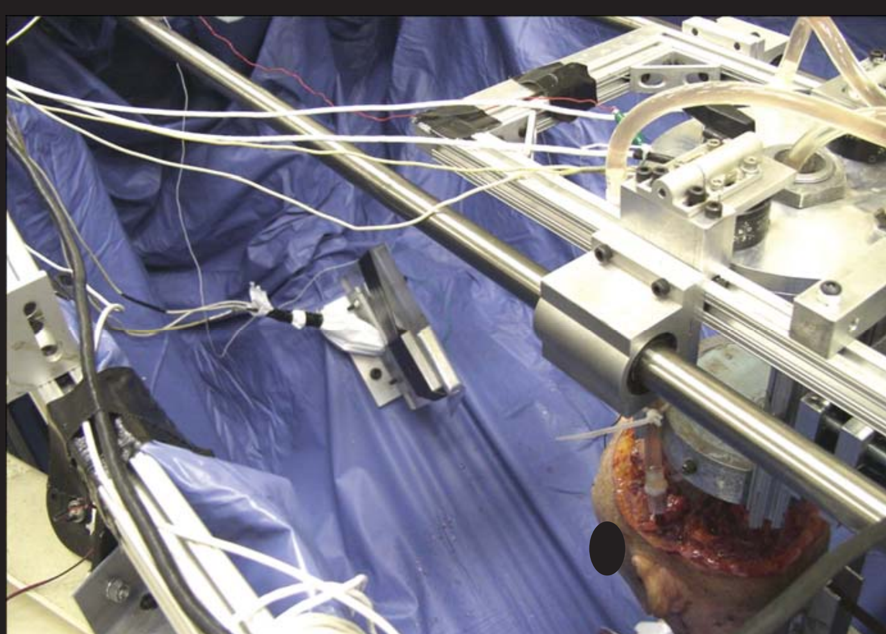
Injury Characterization Summary

Range of Peak Kinematics Parameters		
Parameter	Translation	Combined
Impact Speed (m/s)	2.7 - 3.5	2.6 - 4.3
Impact Duration (ms)	13.0 - 23.0	13.6 - 19.9
Linear Acceleration (g)	27.5 - 70.1	40.1 - 95.9
Angular Acceleration (rad/s^2)	NA	1014.5 - 3814.9
Angular Speed (rad/s)	NA	7.2 - 10.8

- Physical Damage: Axonal disruption identified with light and heavy neurofilament
- Metabolite changes: glutamate excitotoxicity or an energy crisis along with inflammation and axonal/myelin damage

• Fievisohn et al. 2014

Impact Procedures



Measuring Impact Severity for *in Vivo* Biomechanics

Jason F. Luck, Jay K. Shridharani, Kyle A. Matthews
Jason R. Kait, Cameron R. 'Dale' Bass

Injury and Orthopaedic Biomechanics Laboratory
Department of Biomedical Engineering, Duke University

September 8, 2015

Problem?

- Head Impact/Traumatic Brain Injury
  - Major societal problem, across ages, sex, no particular need to convince this audience
- Problem:

Are there mechanical correlates (6DOF rigid) with 'mild' TBI?

If so, what are they?

Assumption?

- An Assumption is Often Made that Some 'Rigid Body' Impact Characteristics of the Skull are Associated with Human Changes in Mentation

Is This True?

Also?

Don't We Already Have Successful Ways to Measure Exposure?

(i.e. Head Impact, Acceleration, etc.)

So?

Don't We Already Have Successful Ways to Measure Exposure?

Yes.

So?

Don't We Already Have Successful Ways to Measure Exposure?

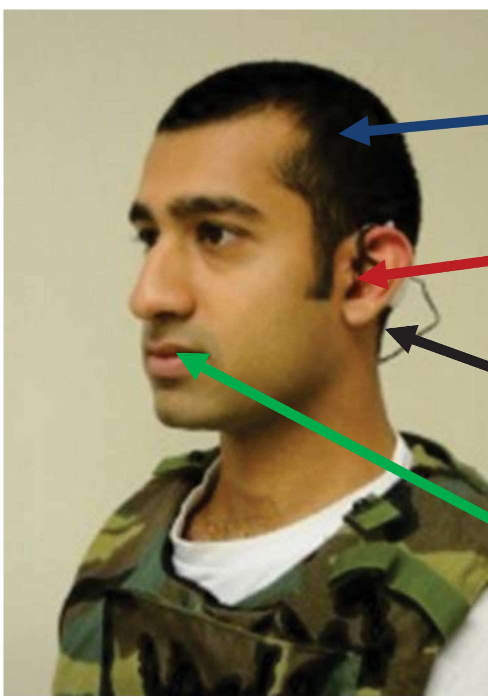
Yes. In cadavers with screws.

So?

Don't We Already Have Successful Ways to Measure Exposure?

At higher severities, living humans are more difficult.

Options (Examples)



Helmet - Sprung against head - HITS (Duma,2005)

In Ear - DASHR, Motor sports (Knox, 2009, Panzer, 2009)

Skin Surface, X2

In Mouth – Attached to Teeth/Mouthguard, X2, I1 (Camarillo, 2013)

DUKE BME

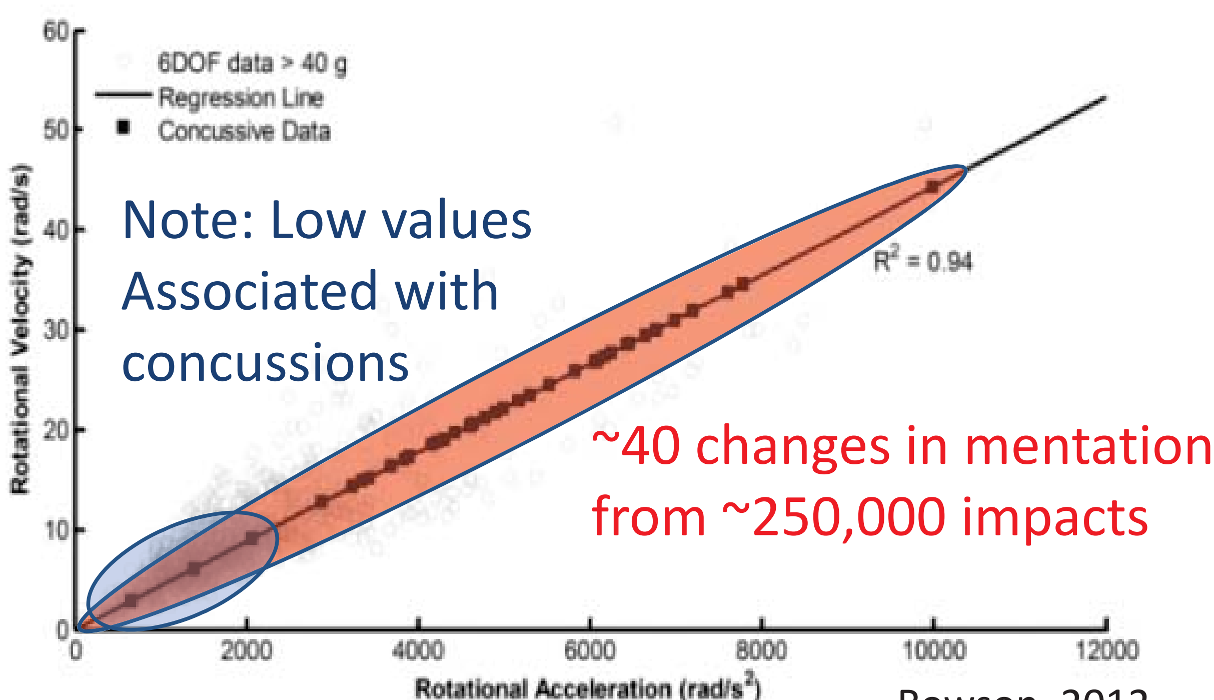
Example of the Difficulties

- HITS System
  (E.g. Duma, 2005, Rowson, 2011, 2012)
  - Football helmet-based accelerometers
  - In contact with head
  - Has been used to reconstruct 6DOF accel

Riddell, 2014

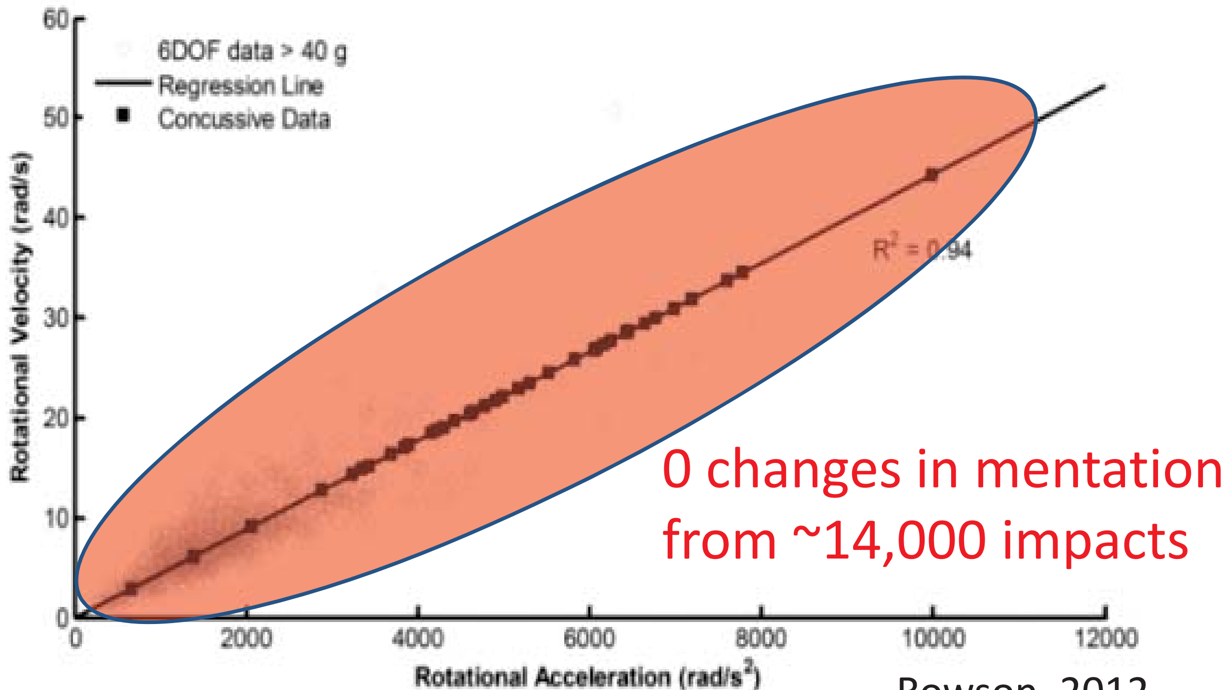
DUKE BME

HITS – VA Tech- Concussion Data



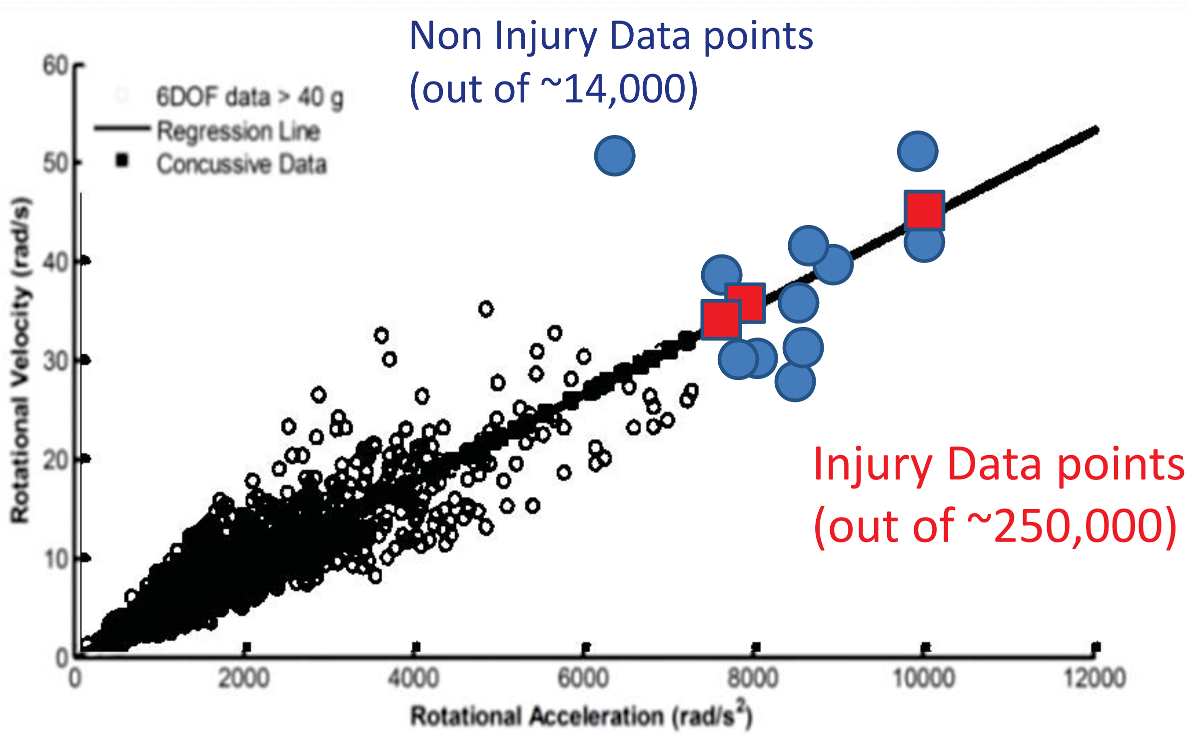
Rowson, 2012

HITS – VA Tech
6DOF Data



Rowson, 2012

HITS – VA Tech
Close Look at Data



DUKE BME

HITS – VA Tech

Close Look at Data

At highest values,

11 non injuries (out of ~14,000)

for the 3 injuries (out of ~250,000)

So, simply putting them on the same basis (i.e. out of ~250,000), there are:

196 non injuries for every 3 injuries at the highest ‘severity’

DUKE BME

So.

Is impact rotation/acceleration simply not well associated with change of mentation?

(e.g. sensitivity/specificity, other genetic, phylogenetic etc. factors?)

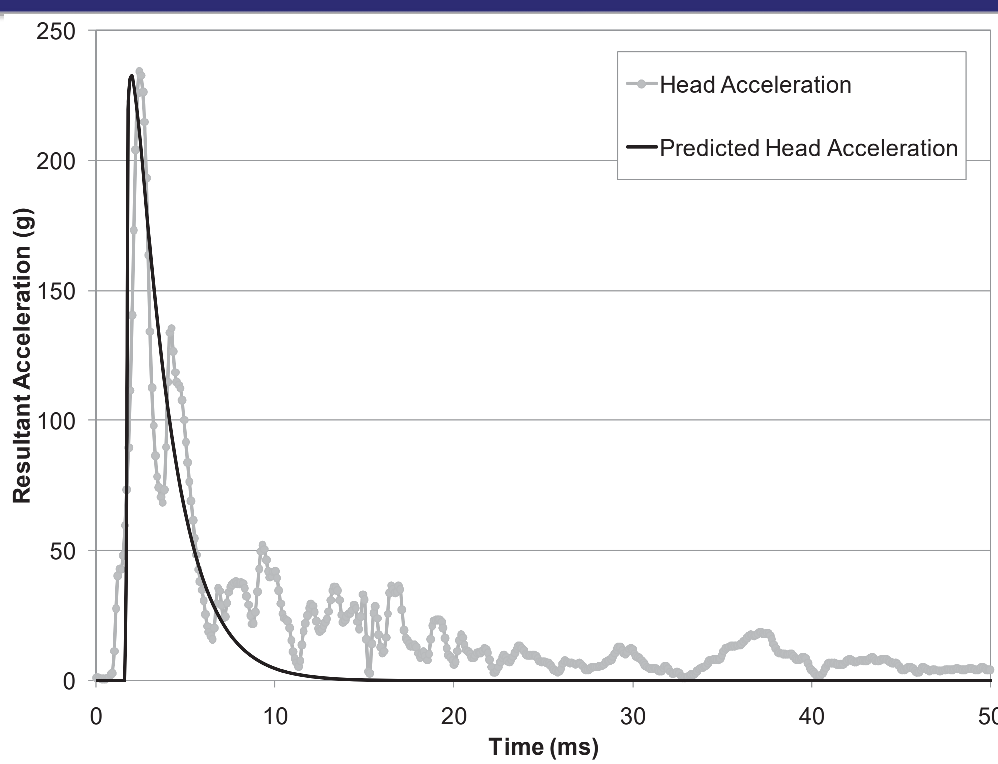
So.

Is impact rotation/acceleration simply not well associated with change of mentation?

Unknown, but our Hypothesis: Probably Coupling/Analysis Issues.

Ear Coupling –

(Panzer, 2009; Salzar, 2008)



Our Previous Work
Why is it not good enough

- Ear Accerometers Circa 2009
  - *Relies on post-test modeling*
  - ~$8000 sensors (6)
  - Too much coupling to the EAM, heavy resin (e.g. Begeman, 2006)
  - No one manufactured the sensors, we had a few triax units.

New Design - DASHR

Data **A**cquisition **S**ystem - **H**ead **R**esponse

Concept:
In bony canal of one ear (3 accel, 3 ARS)

System Characteristics

Advantage: *Strong biomechanical coupling with low mass and compact earpiece design*

- Earpiece/sensor/board < 4 g

- Small electronics package (~16 x 24 mm)
  - > 200 g peak accel
  - ~ 4000 deg/sec angular velocity
  - > 100 kS/s/Ch for 7 channels (typical 10 k)
  - Heart rate/RR (though heart rate)

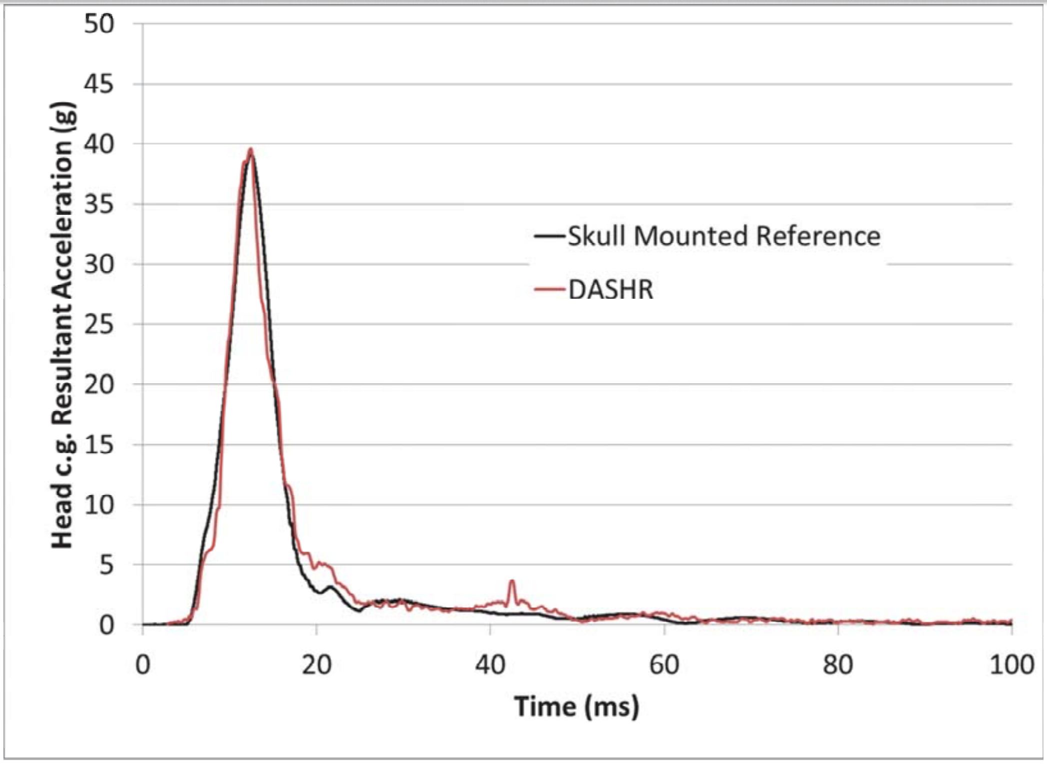
- Battery life – depends on battery, application

Biomechanical Data

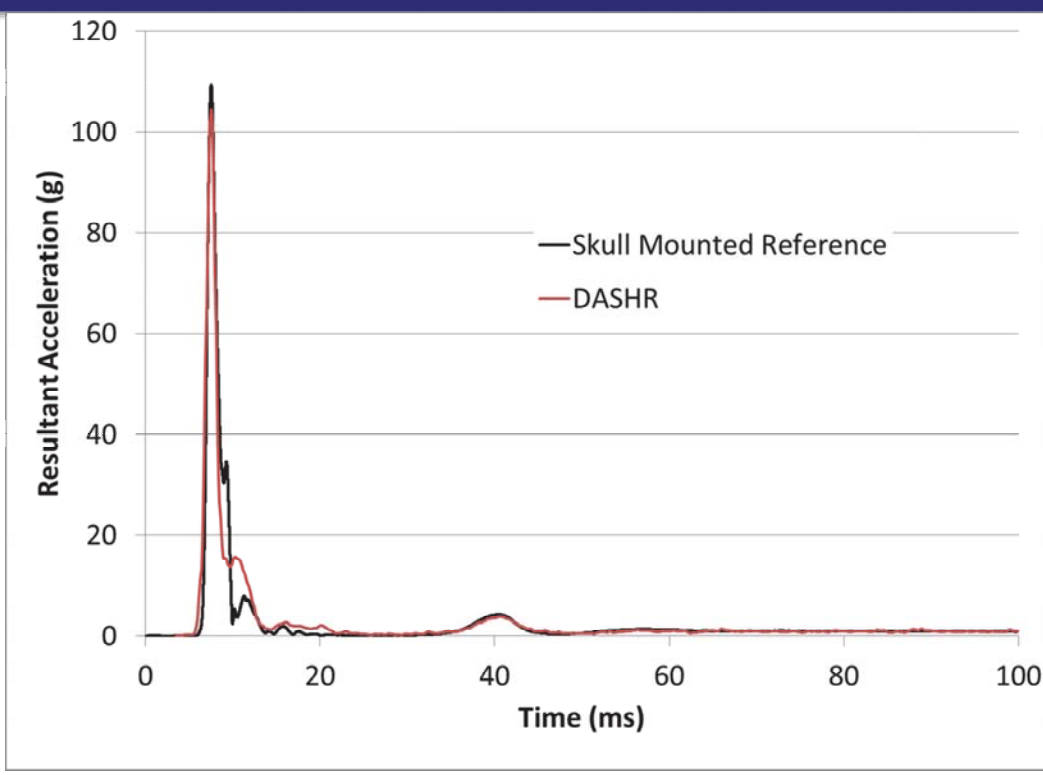
Some Validation Data from Cadaver Head Test – Drop Tests

- Cadaver, ~ midsize adult male
- Hard surface impacts
- No helmet – to 3-25 cm
- Helmet – to 10-100 cm
- Impacts to ~180 g - Vertex, Frontal, Frontal Oblique, Occipital, Occipital Oblique, Parietal
- Reference sensor screwed to occiput

Typical Time History – Helmet

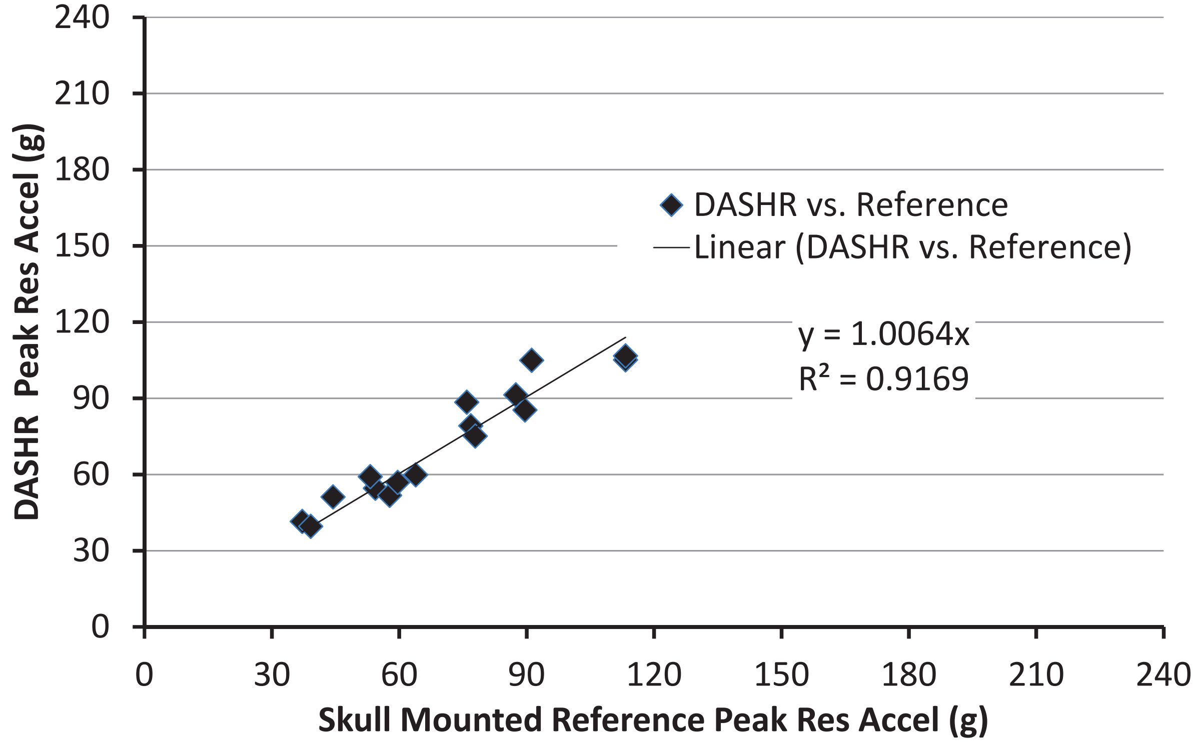


Typical Time History – No Helmet



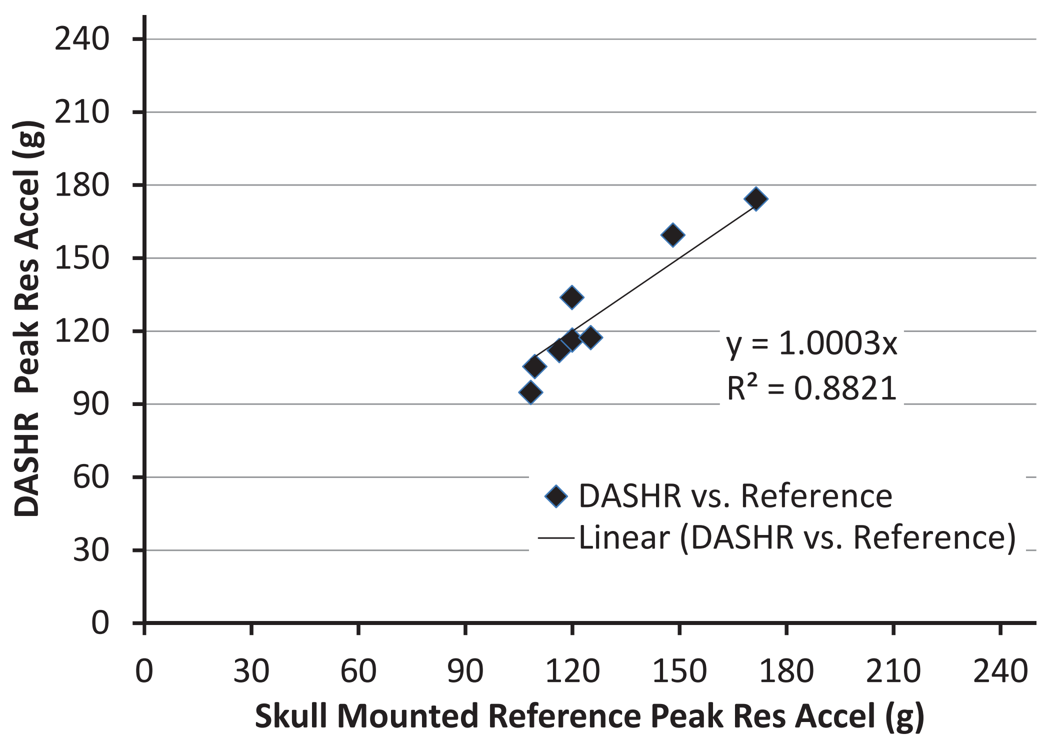
DUKE BME

Accel - With Helmet

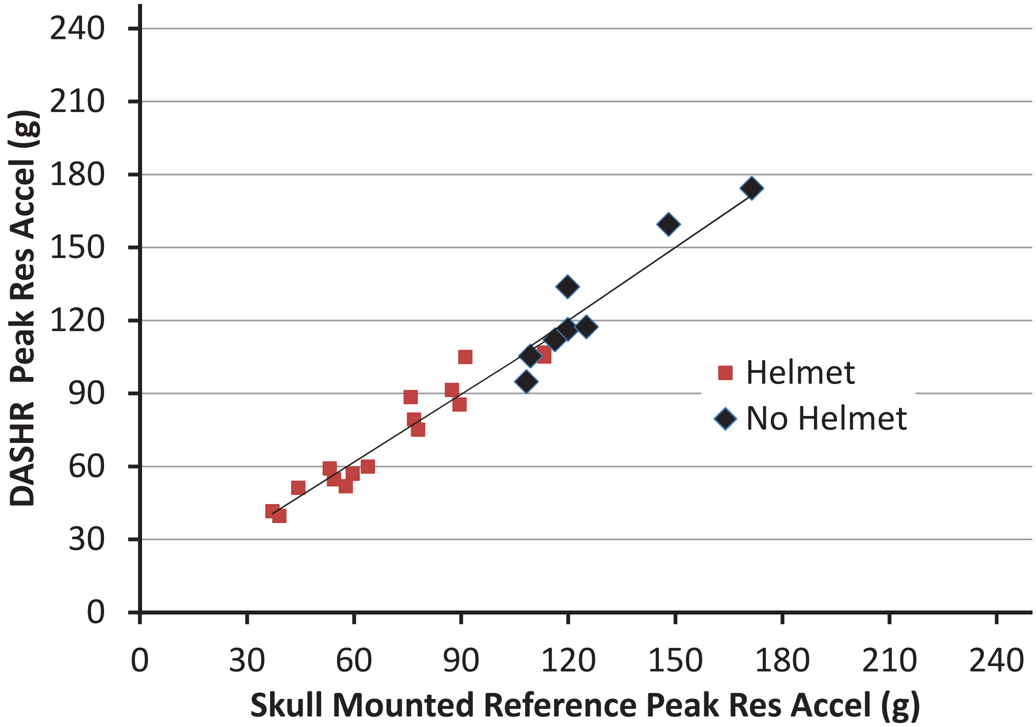


DUKE BME

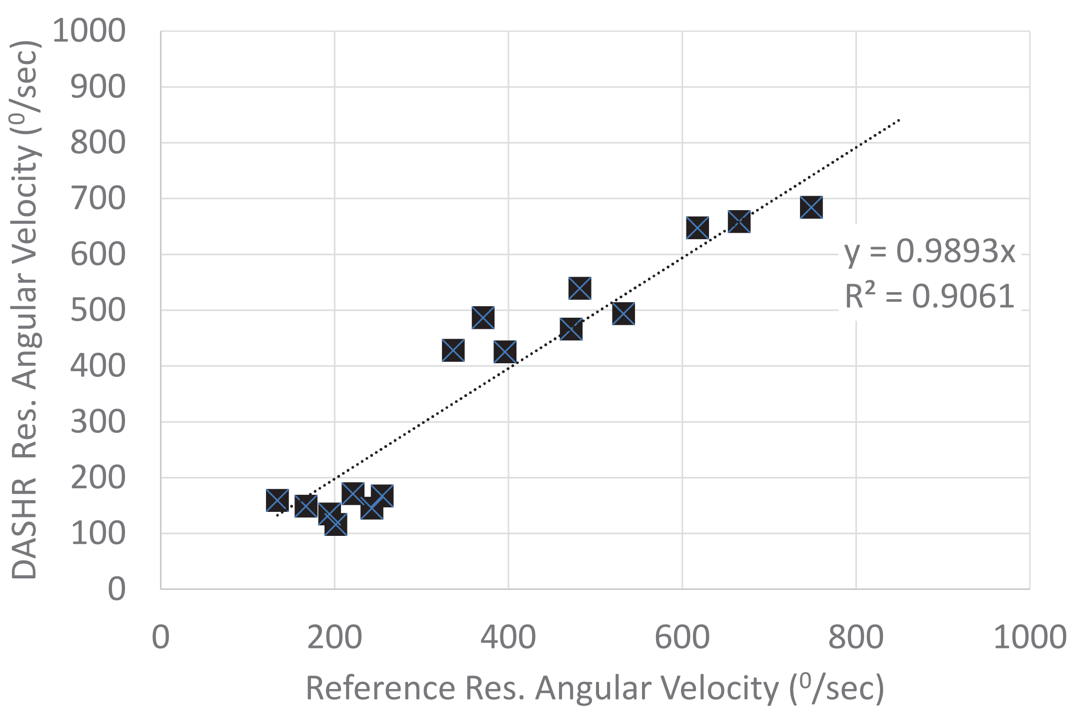
Accel - No Helmet



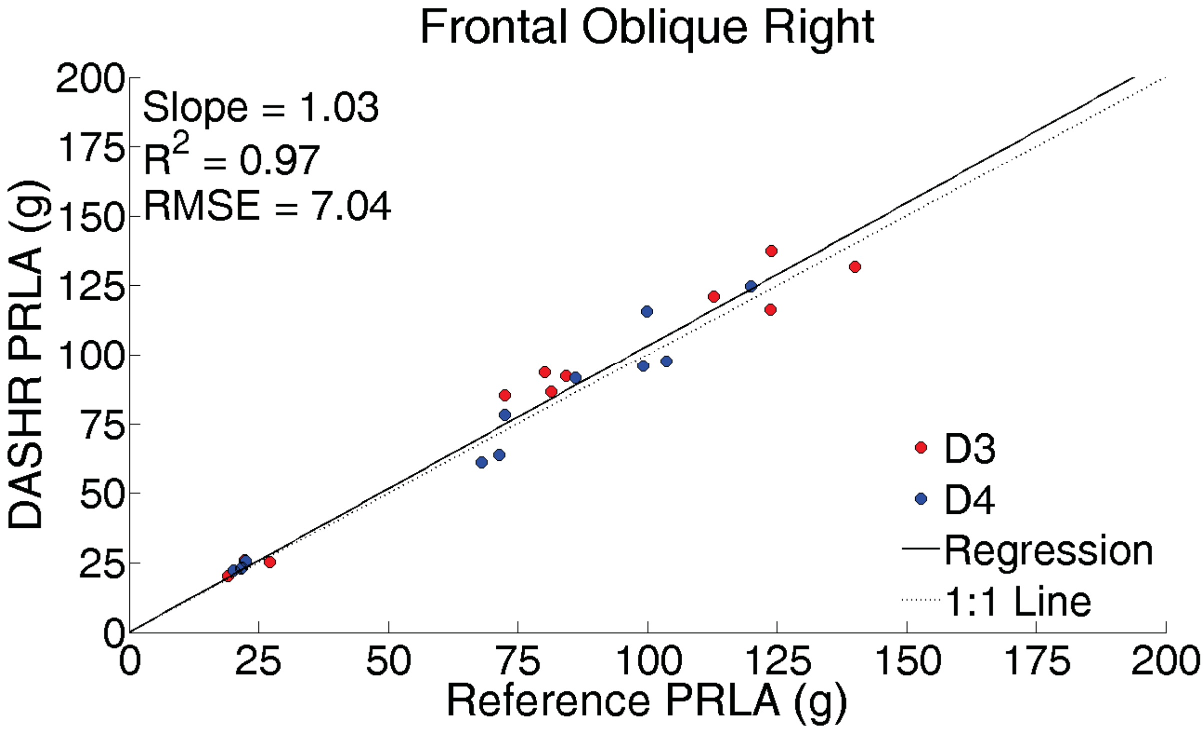
Linear Accelerations



Angular Rate – Both



Different Earpiece Design - Example



DASHR Bottom Line

- New System for Assessing Head Impact
  - Good preliminary validation
  - Both linear and rotational acceleration for typical impact directions
  - Both helmeted and non-helmeted
  - Addresses coupling issues in other techniques
  - Ergonomics of use refinements
    - e.g. Earpiece, electronics unit, compliance

DASHR Bottom Line

- Previously Used
  - Epidemiological Study of Military Head Impact (~100 Subjects with ~200 units) and Other Assessments
- Currently Being Used
  - Sports assessments (~50 Subjects with ~50 Units)

Acknowledgements

- The DASHR System Was Developed with Internal Funds from Bass Laboratory – Duke University
- The Authors Gratefully Acknowledge ARO (U Penn-Prime) under MURI W911NF-10-1-0526 and the US Navy for experimental use of the DASHR.

Source

This presentation has been produced by staff of

Injury Biomechanics Laboratory
Biomedical Engineering – Duke University

Duke
DEPARTMENT OF
Biomedical Engineering

Eruditio et Religio

Measuring Head Impact Severity for *In Vivo* Biomechanics

Jason F. Luck, Jay K. Shridharani, Kyle A. Matthews
Jason R. Kait, Cameron R. 'Dale' Bass

Injury and Orthopaedic Biomechanics Laboratory
Department of Biomedical Engineering, Duke University

September 8, 2015

Evaluation of Kinematic Predictors for Brain Injury in Multiple Crash Modes

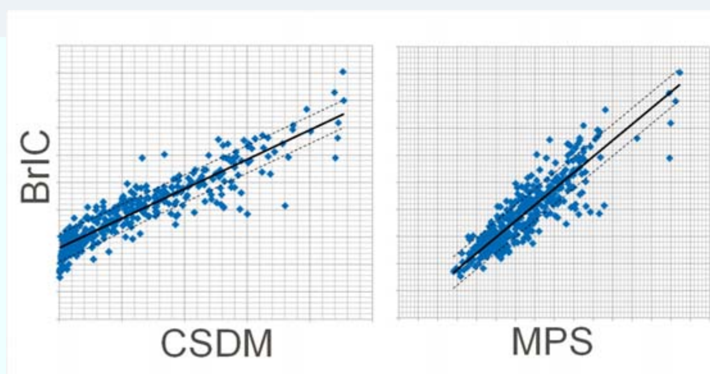
M.B. Panzer
L.F. Gabler
J.R. Crandall

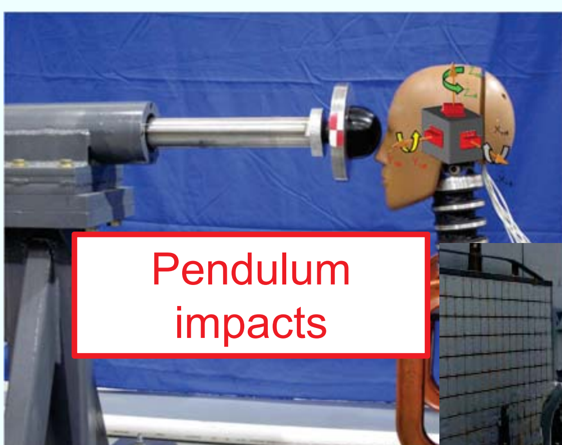
IRCOBI-NOCSAE-PDB-Snell
Workshop on Angular Head Motions
September 8th, 2015
Lyon, FR

UNIVERSITY of VIRGINIA
Mechanical and Aerospace Engineering

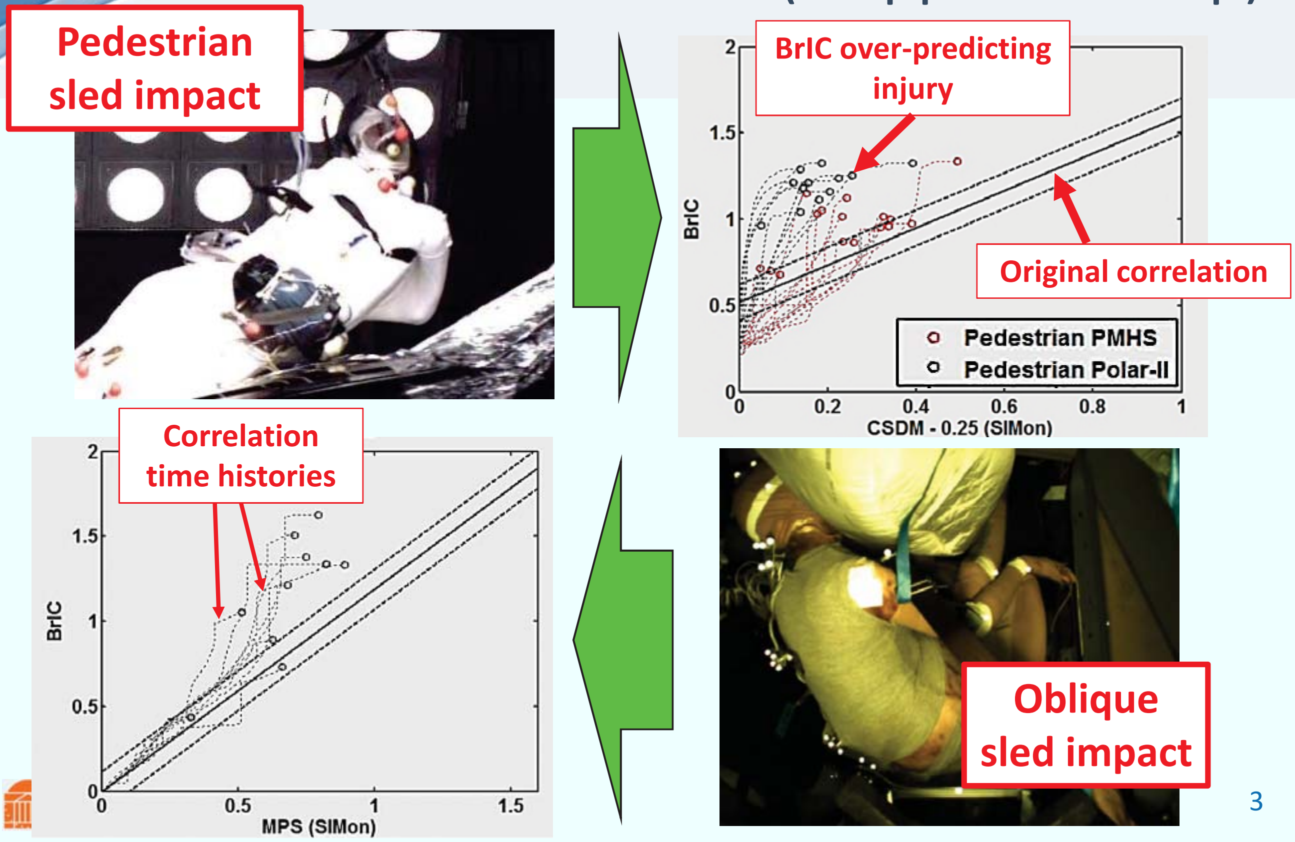
Takhounts et al. 2013

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





Gabler et al. 2014 (Stapp Workshop)



Gabler et al. 2014 (Stapp Workshop)

- BrIC correlations compared to Takhounts et al., 2013
  - Qualitative assessment using SIMon

Condition	Early history (Inertial dominated)	Full history (Impact dominated)
Pedestrian	Inconsistent (BrIC high)	Consistent
Frontal	Consistent	Consistent
Oblique	Inconsistent (BrIC high)	Inconsistent (BrIC high)

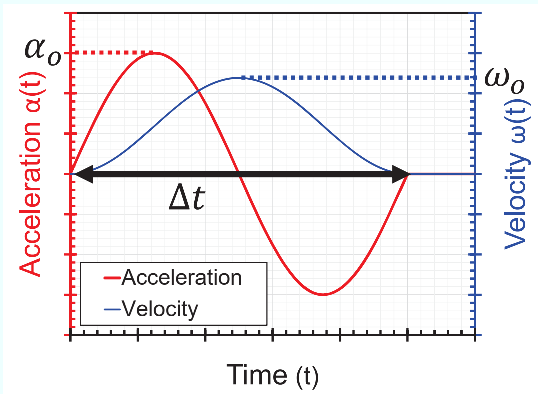
- BrIC was overestimating brain deformation for longer-duration responses

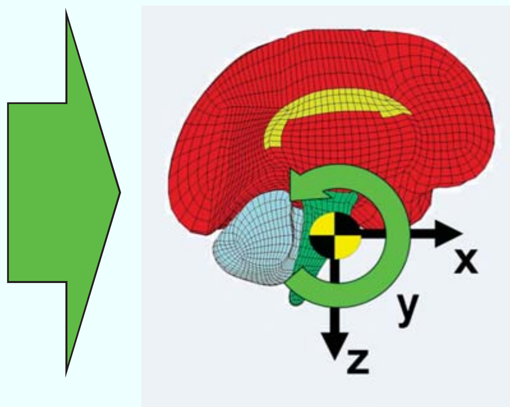
Gabler et al. 2015 (JSAE)

- Investigated effect of impact duration (Δt) on strain response
- Preliminary study using sagittal plane kinematics

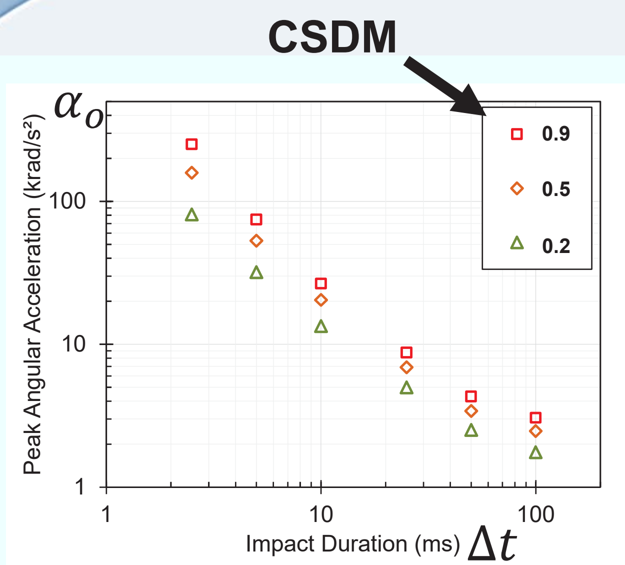
$$\alpha(t) = \alpha_o \sin\left(\frac{2\pi}{\Delta t} t\right)$$

$$\omega(t) = \frac{\omega_o}{2}\left[1 - \cos\left(\frac{2\pi}{\Delta t} t\right)\right]$$

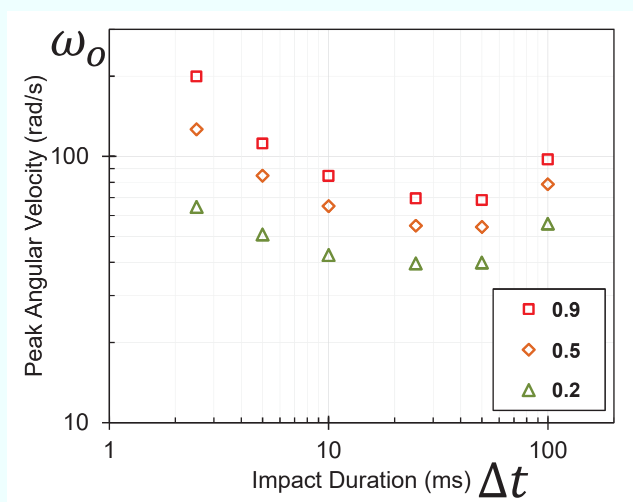




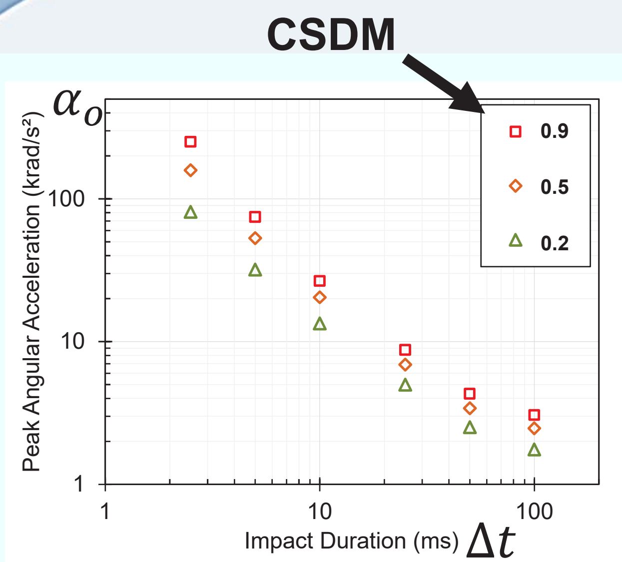
Gabler et al. 2015 (JSAE)



$$\omega_o = \frac{\alpha_o \Delta t}{\pi}$$

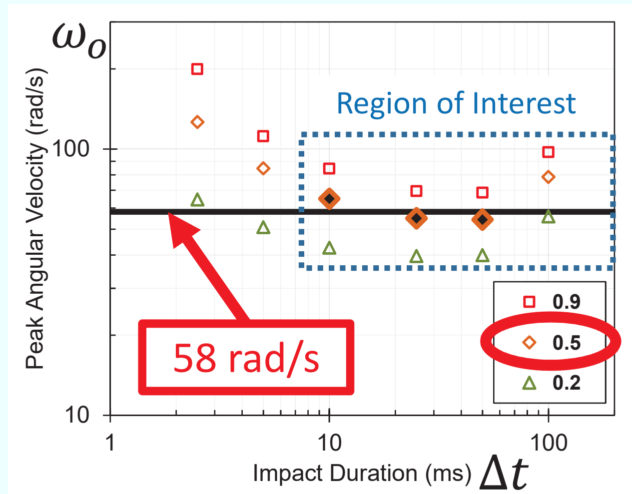


Gabler et al. 2015 (JSAE)



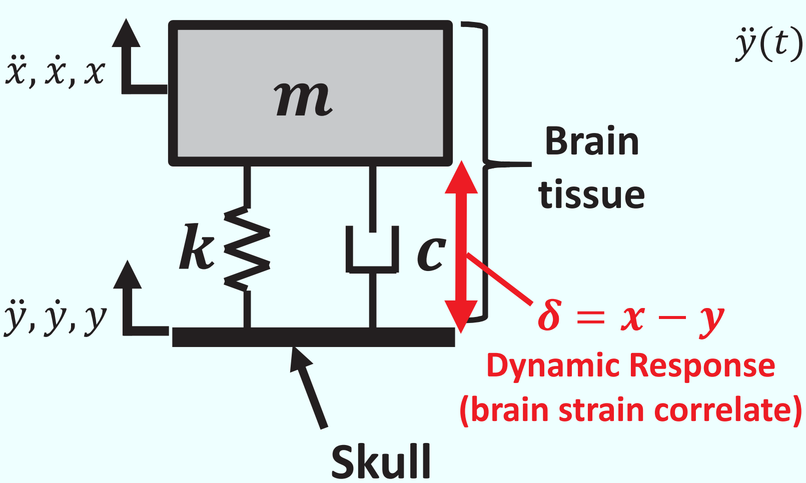
$$\omega_o = \frac{\alpha_o \Delta t}{\pi}$$

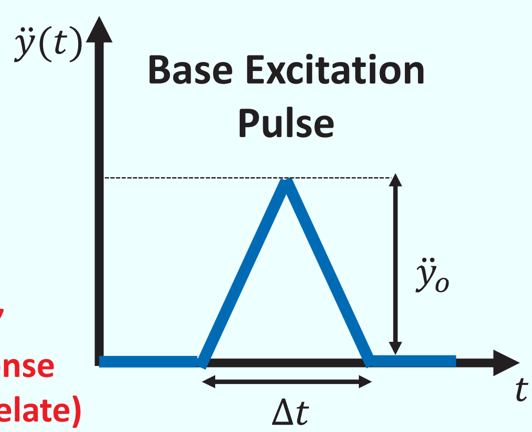
59 rad/s
(Takhounts et al. 2013)



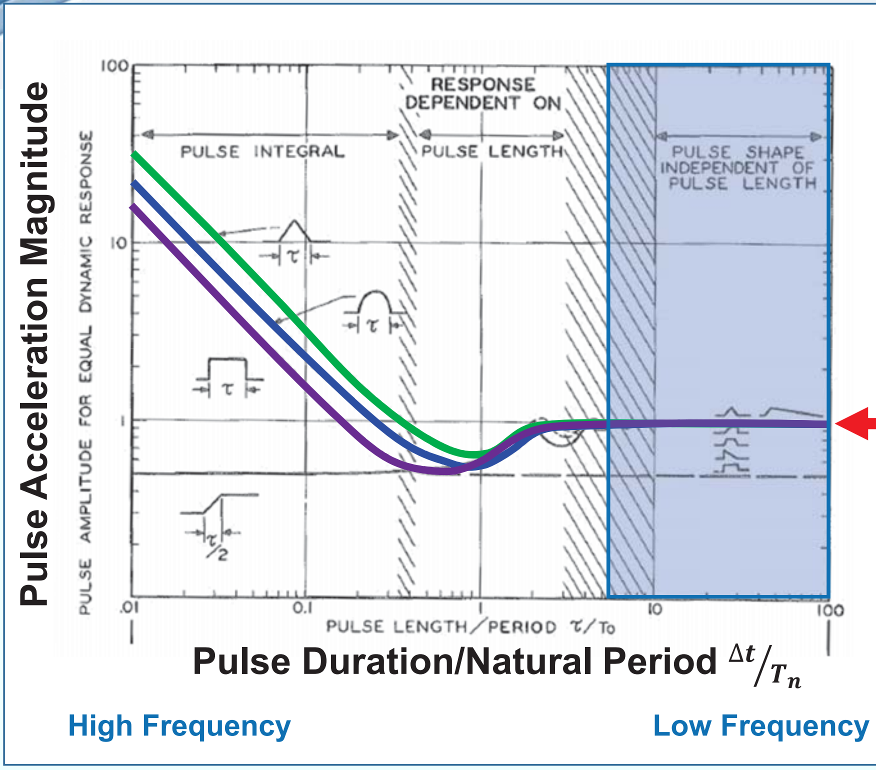
Theoretical Considerations

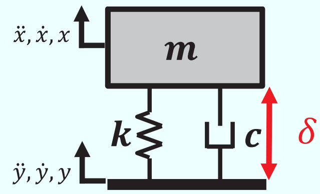
- Consider 1DOF dynamic system with base excitation.





Theoretical Considerations

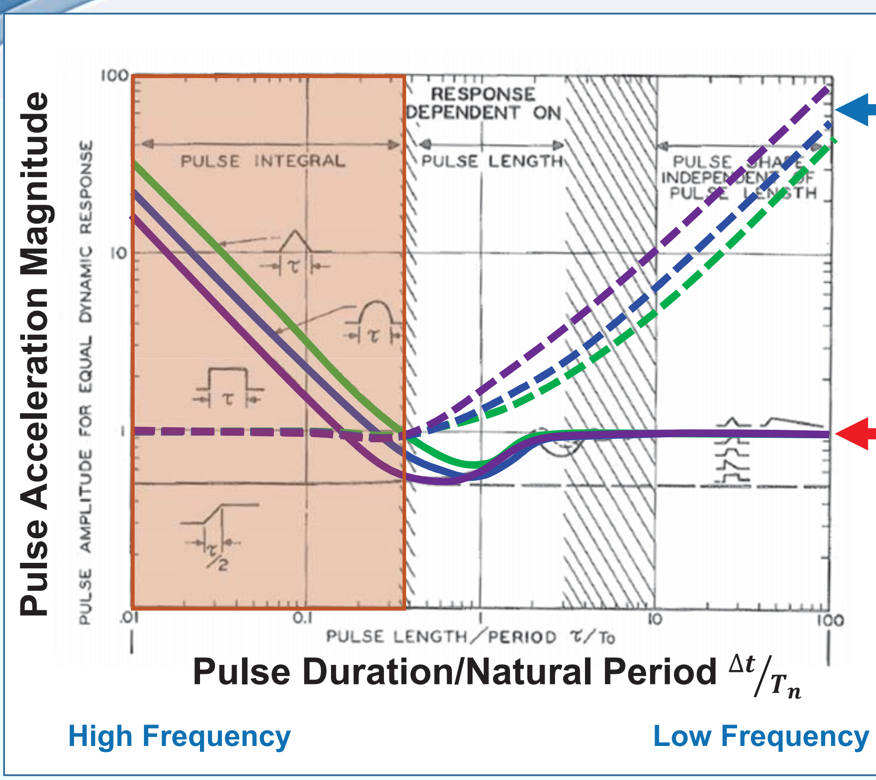




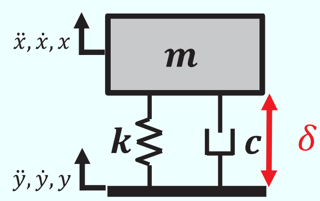
δ_{max} = Constant

Longer durations:
$\delta_{max} \propto \ddot{y}_{max}$
Response depends only on acceleration magnitude!

Theoretical Considerations



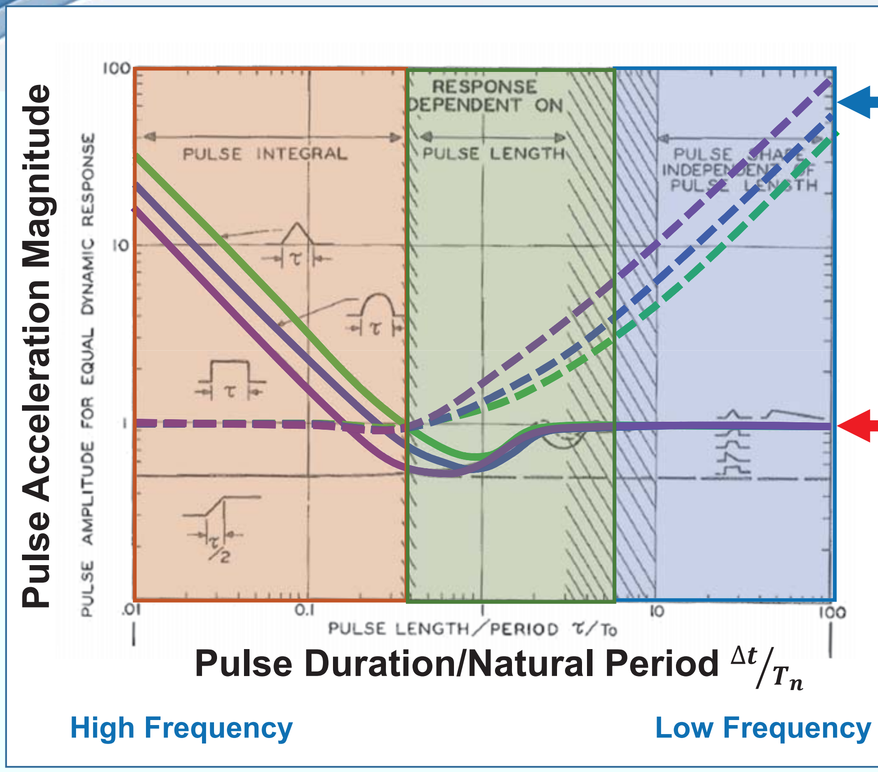
$\dot{y}_{max}$ curves



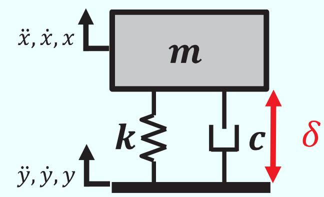
δ_{max} = Constant

Shorter durations:
$\delta_{max} \propto \dot{y}_{max}$
Response depends only on velocity magnitude!

Theoretical Considerations



$\dot{y}_{max}$ **curves**

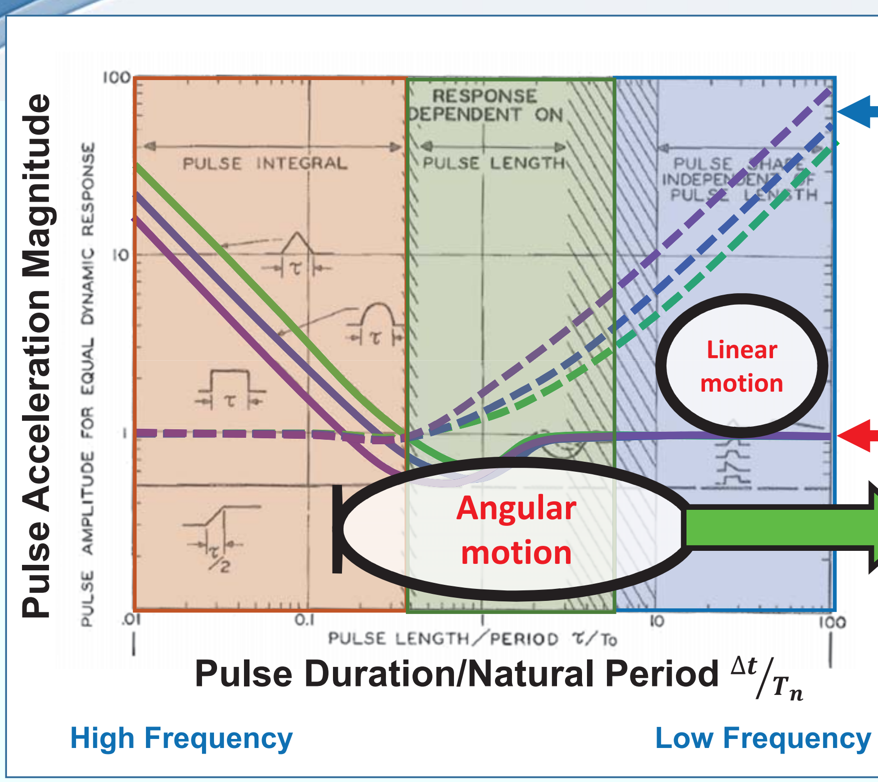


δ_{max} **= Constant**

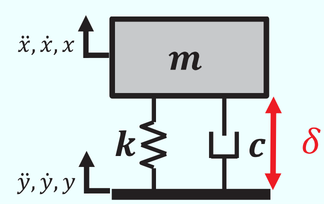
Moderate durations:
$\delta_{max} \propto \ddot{y}, \dot{y}, \Delta t$
Response depends on acceleration, velocity or duration!

von Gierke, H. "Transient acceleration, vibration and noise problems in space flight." Bioastronautics. Macmillan NY, 1964. 27-75.

Theoretical Considerations



$\dot{y}_{max}$ **curves**



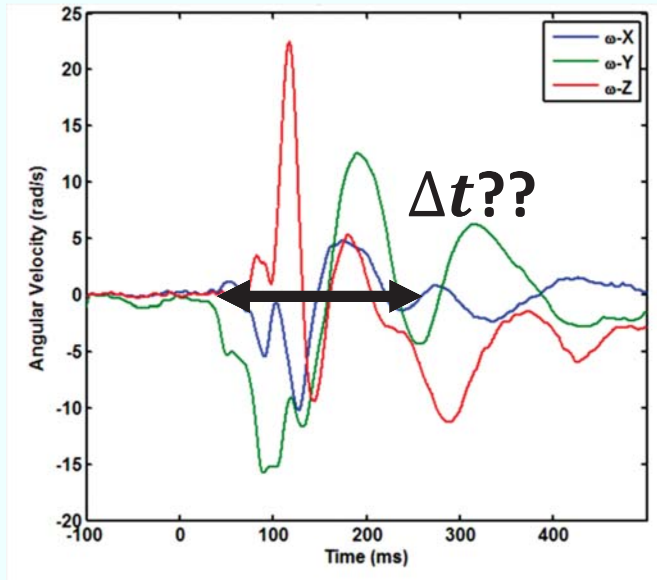
δ_{max} **= Constant**

Moderate durations:
$\delta_{max} \propto \ddot{y}, \dot{y}, \Delta t$
Response depends on acceleration, velocity or duration!

von Gierke, H. "Transient acceleration, vibration and noise problems in space flight." Bioastronautics. Macmillan NY, 1964. 27-75.

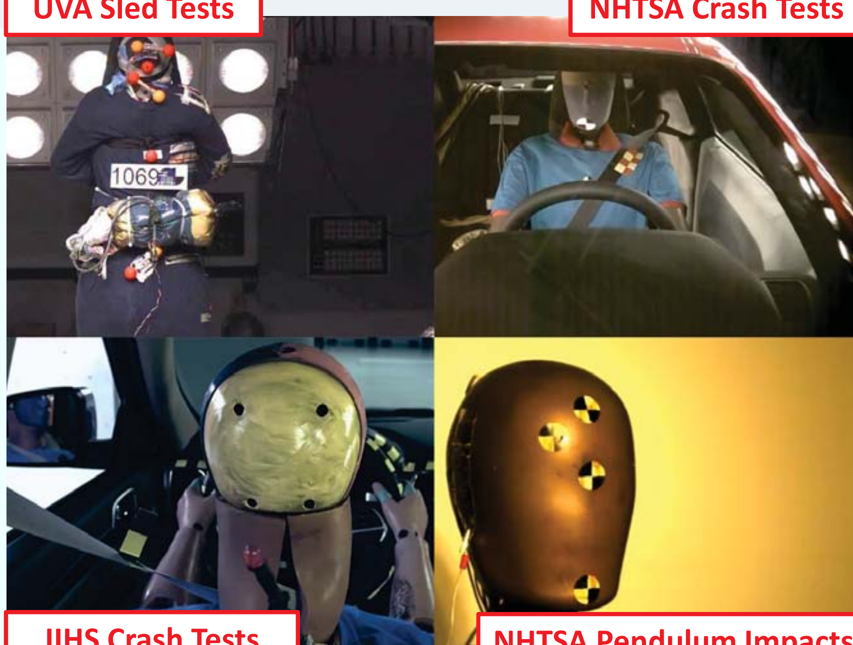
Impact Duration

- Difficult to define Δt
  - Multiple DOF
  - Rotational vs. translational
- Our approach is to define a relationship between α & ω based on mechanics



Head Impact Database

Crash Modes	Total # of Impacts (n = 593)
FRONTAL†	274
OBLIQUE‡	166
SIDE	125
PEDESTRIAN	28

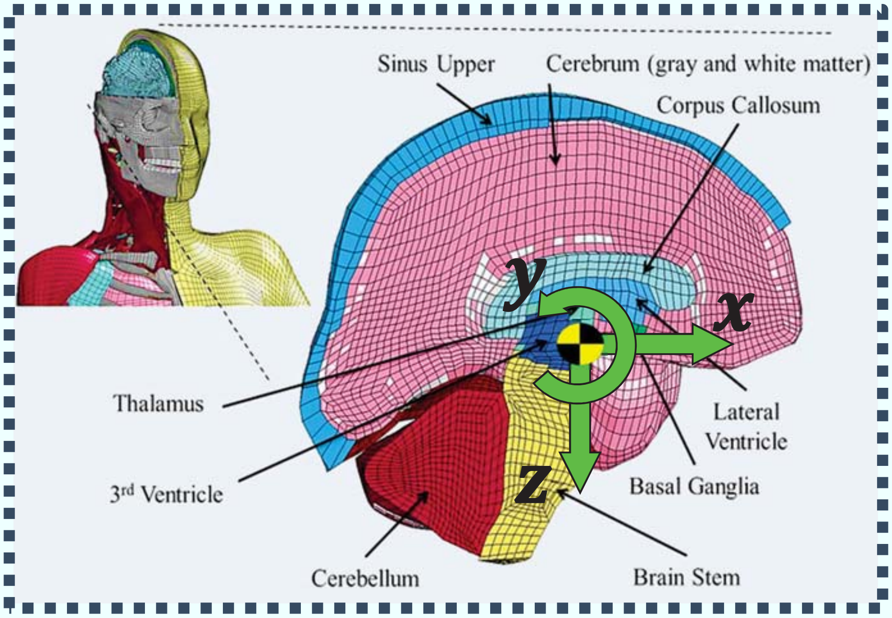


†Includes Small Overlap Tests
‡Includes 7°,15°,20°,& 60° impacts

GHBMC FE Head Model

GHBMC v4.3

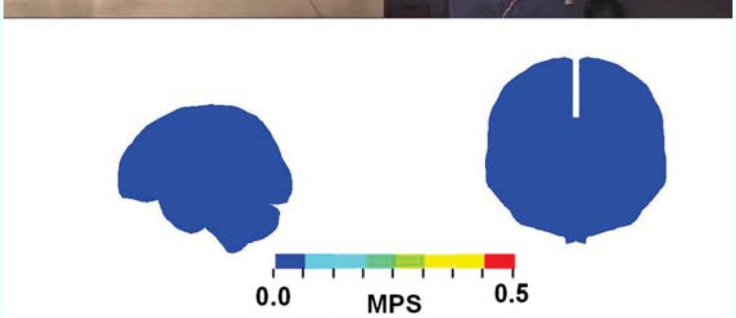
- Adult 50th male
- ~120,000 elements
- 25 sub-structures
- Intracranial responses validated for 6DOF



Strain Measures

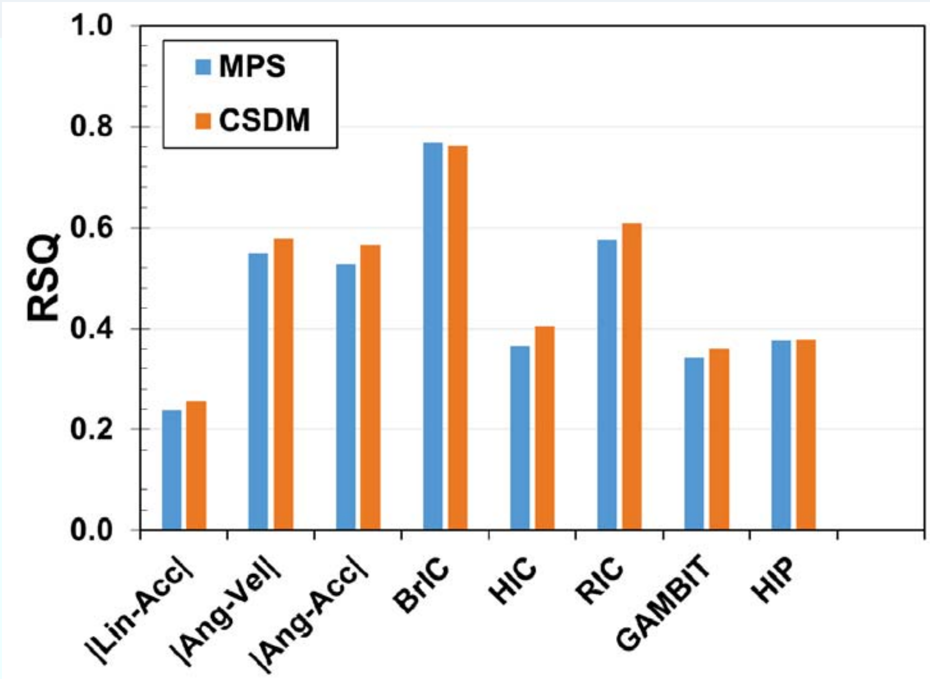
NHTSA Frontal NCAP

Pedestrian Sled



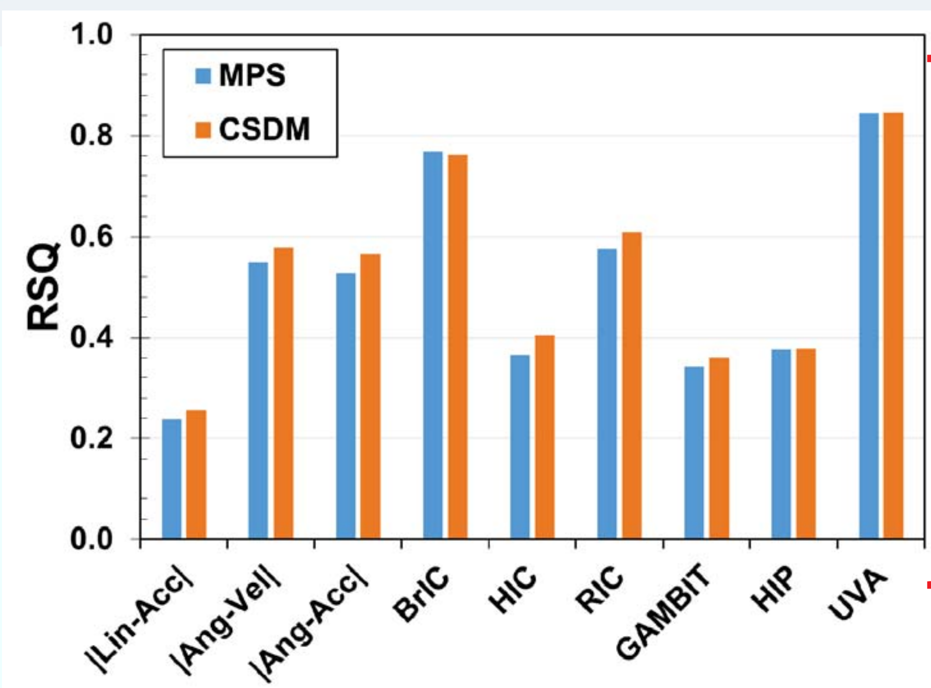
- MPS – Maximum Principal strain
- CSDM – Cumulative Strain Damage Measure

Correlation with Existing Metrics



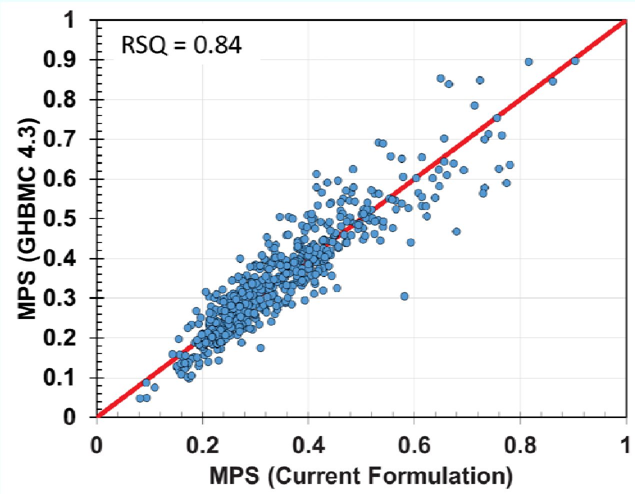
BrIC is the best correlate to FE model results

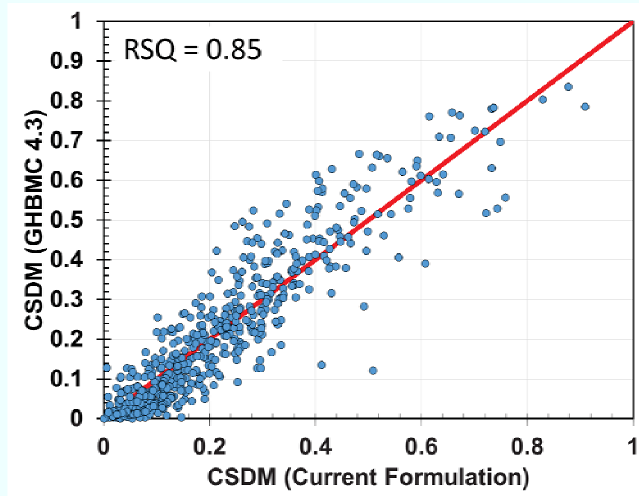
Correlation with Proposed Metric



Current UVA formulation based on mechanics

Correlation with Proposed Metric





Acknowledgements

- Partnership for Dummy Technology and Biomechanics (PDB)

PARTNERSHIP FOR DUMMY TECHNOLOGY AND BIOMECHANICS

- National Highway Traffic Safety Administration (NHTSA)

NHTSA NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION

- Insurance Institute for Highway Safety (IIHS)

IIHS HLDI Insurance Institute for Highway Safety Highway Loss Data Institute

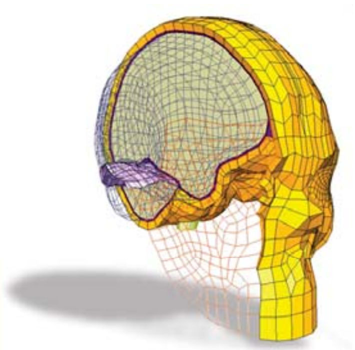
Thank you !

UNIVERSITÉ DE STRASBOURG

IRCOBI-NOCSAE-PDB-Snell Workshop

cnrs

6D Brain Injury Metric Based on Axon Elongation



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Caroline DECK
Debasis SAHOO

Strasbourg University, Strasbourg France.

INTRODUCTION

- Introduction and context
- Advanced brain FE modelling
- Real world head trauma database
- 6D brain injury metric based on axon strain
- Head injury prediction tool for end user
- Application in automotive and helmet industry
- Conclusion

CONTEXT

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

since Holbourn (1943)

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

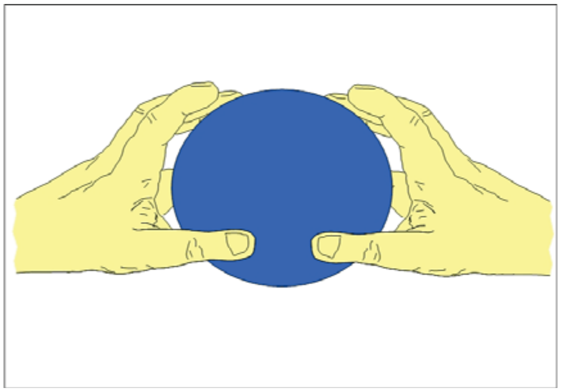
Ommaya et al. (1967, 1968), Unterharnscheidt (1971), Ono et al. (1980), Gennarelli et al. (1982), Newman et al. (1999,2000).....

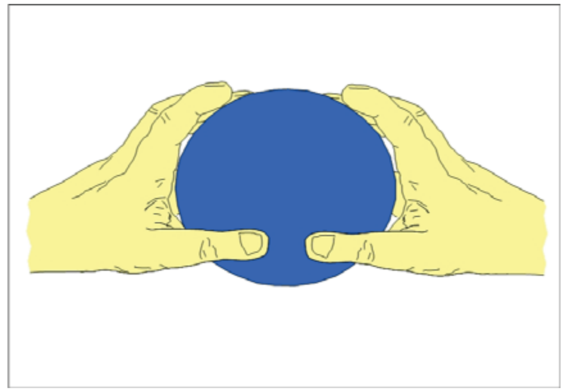
By using **Finite Element Head Models** it was expressed quantitatively how dramatic the influence of the rotational acceleration is on intra-cerebral loading.

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

HEAD ROTATION AND BRAIN SHEARING

- Low shearing modulus of soft biological tissue





shear

- Evidence in volunteer head shaking
- A very simple test

CONTEXT

A number of studies focussed on the victim kinematics in **real world accident** and demonstrated the effectiveness of tangential 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

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

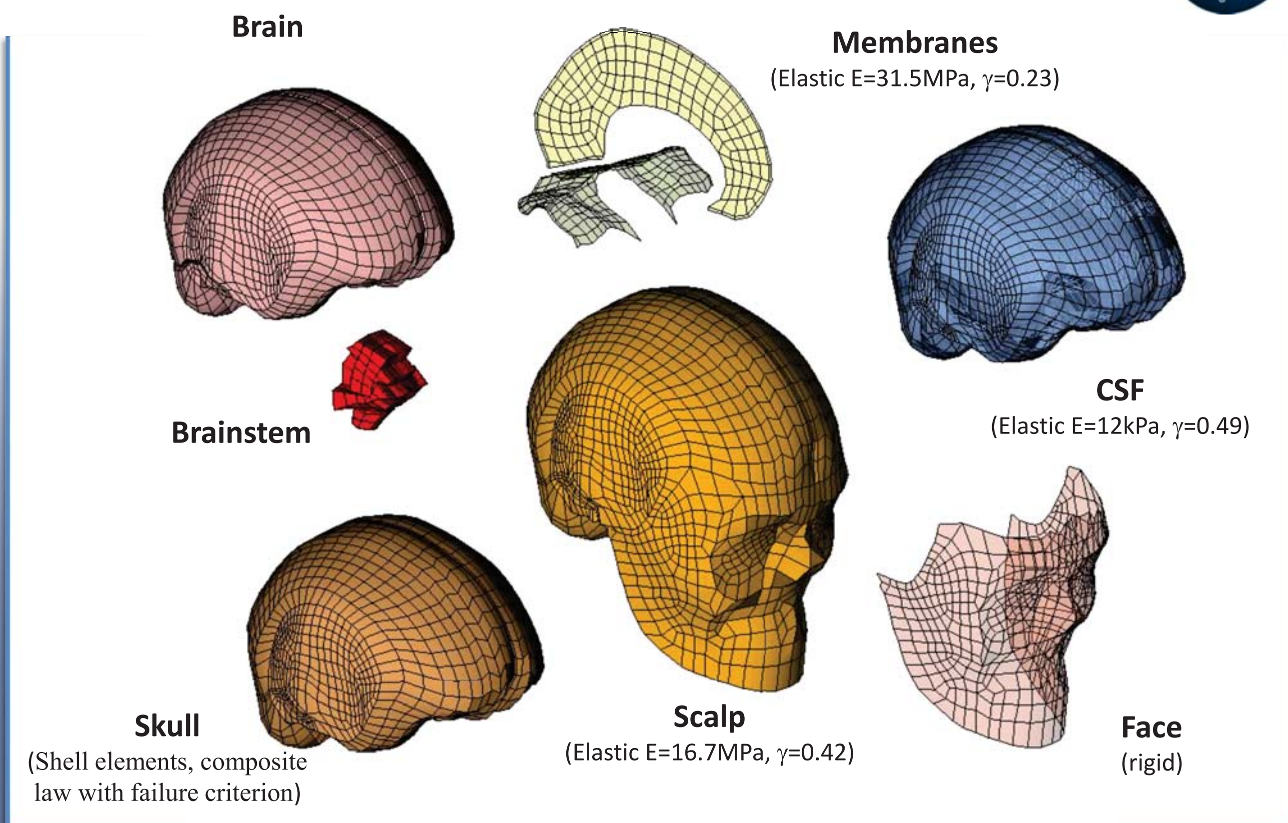
RECENT LITERATURE

- Marjoux, D., Bourdet, N., and Willinger, R. 2009 . Computation of axonal elongations: towards a new brain injury criterion. International Journal of Vehicle Safety, Vol.4 No 4, 271
- Chatelin S., Deck C., Renard F., Kremer S., Heinrich C., Armspach JP, Willinger R : 2011 Computation of axonal elongation in head trauma finite element simulation. J of Mech. Behavior of Biomed Material, V4, 1905-1919.
- Cloots, R.J.H., van Dommelen, J.A., Nyberg, T., Kleiven, S., Geers, M.G., 2011. Micromechanics of diffuse axonal injury: influence of axonal orientation and anisotropy. Biomechanics and Modeling in Mechanobiology. 10, 3, 413-422.
- Wright R, K Ramesh : 2011, An axonal strain injury criterion for traumatic brain injury, Biomechanics and Modeling in Mechanobiology, , 1-16.
- Cloots RJH, van Dommelen JAW, Kleiven S, Geers M, 2013. Multi-scale mechanics of traumatic brain injury: predicting axonal strains from head loads. Biomechanics and Modeling in Mechanobiology, 12(1):137-150.
- Giordano, C, Kleiven, S, 2014. Evaluation of Axonal Strain as a Predictor for Mild Traumatic Brain Injuries Using Finite Element Modeling. Stapp Car Crash Journal, Vol. 58
- Sahoo D., Deck C., Willinger R.:2014 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
- Sahoo D., Deck C., Willinger R.:2015 Axonal strain as brain injury predictor based on real world head trauma simulation. IRCOBI 2015

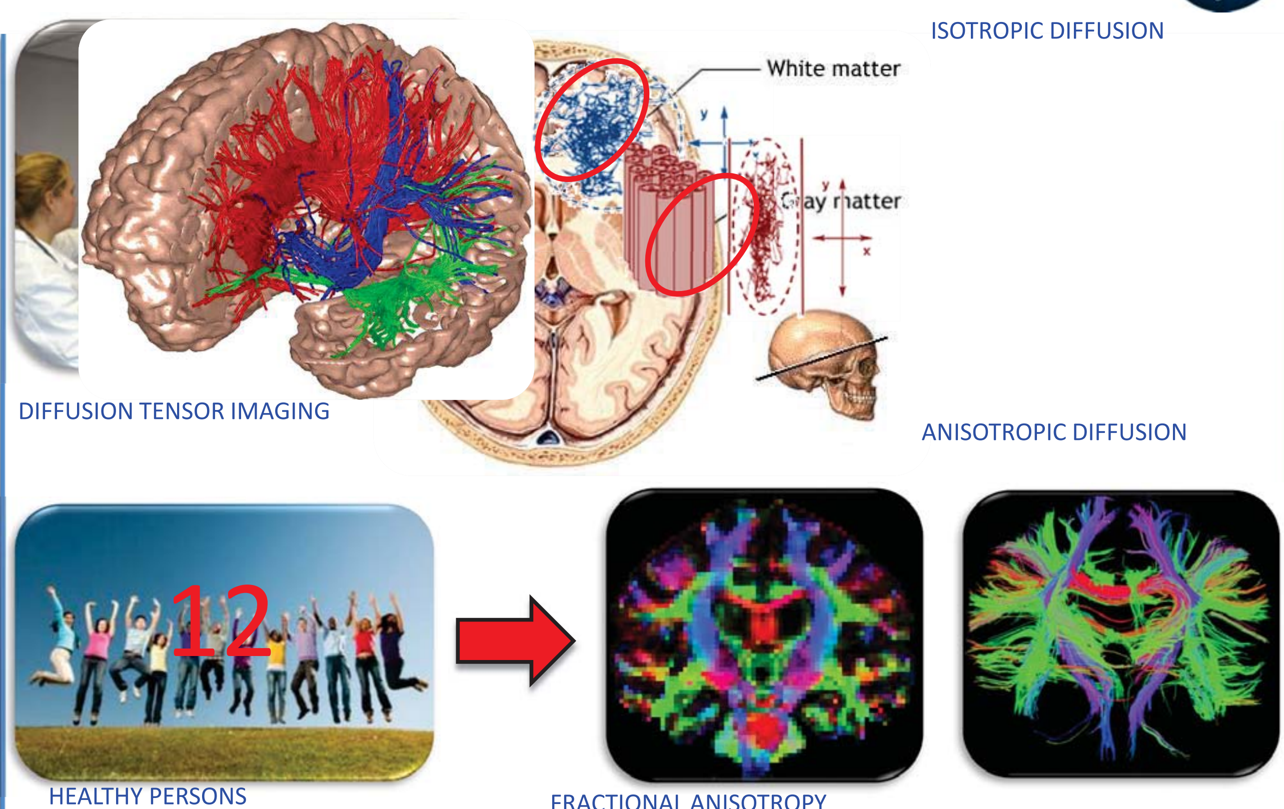
STRASBOURG UNIVERSITY FINITE ELEMENT MODEL

(SUFEHM)

SUFEHM Presentation



DTI of the Brain



Coupling of DTI data

Diffusion Parameters

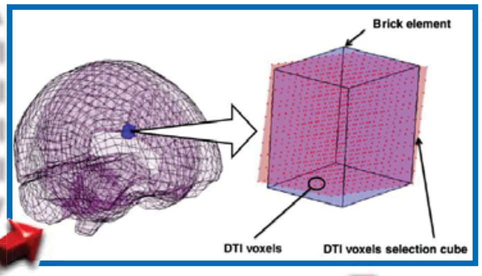
$$FA = \sqrt{\frac{3}{2}\frac{\sum_i(\lambda_i - \frac{1}{3}tr(D))^2}{\sum_i(\lambda_i)^2}}$$

Fractional Anisotropy

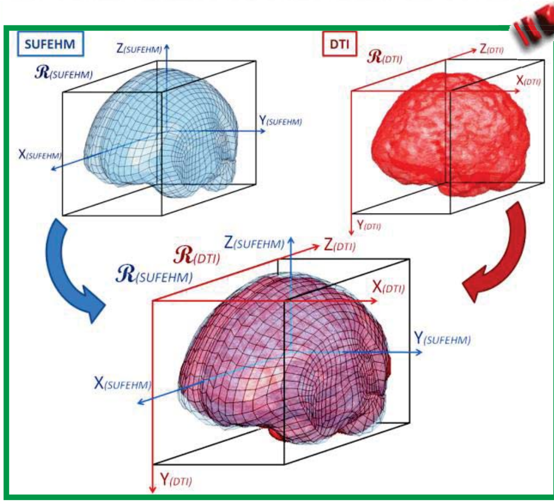
$$\vec{l} = FA \times \overrightarrow{e_{j|\lambda_j=\max(\lambda_i)}}$$

Fibers orientation

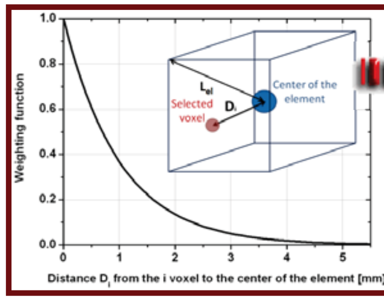
[Papadakis *et al.*, 1999; LeBihan *et al.* , 2001]



Voxel selection



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



Assign Weighting function

Fractional Anisotropy

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

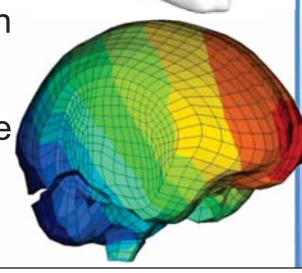
Anisotropy vector

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

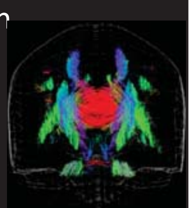
Validation of SUFEHM

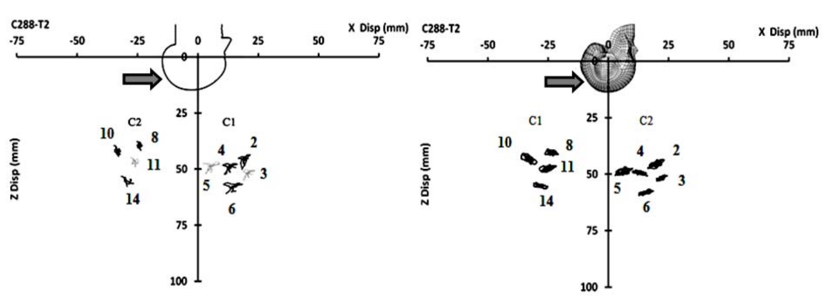
(Sahoo et al 2014)

- ✓ 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 Fiber orientation .



More than 100 NDT trajectories obtained from experiments for comparison

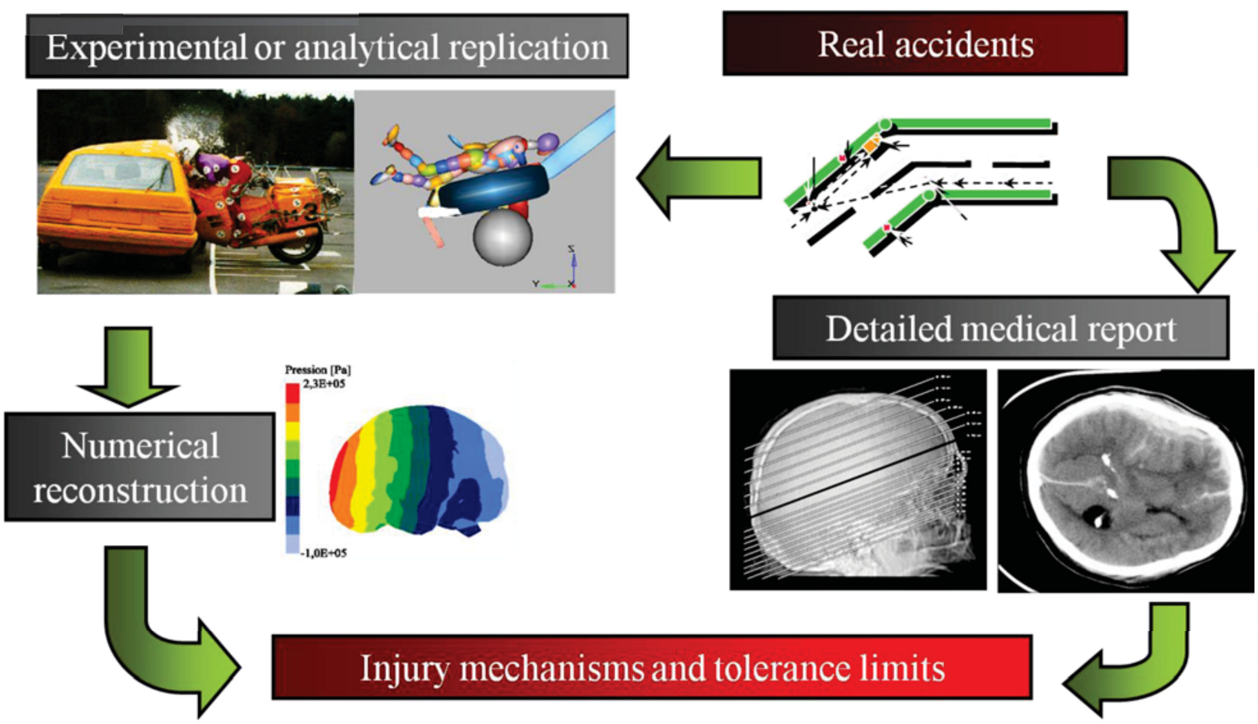




HEAD TRAUMA DATABASE

Accidents reconstructions

- **METHODOLOGY**



CONSOLIDATED HEAD TRAUMA DATABASE

DETAILED ACCIDENT RECONSTRUCTION

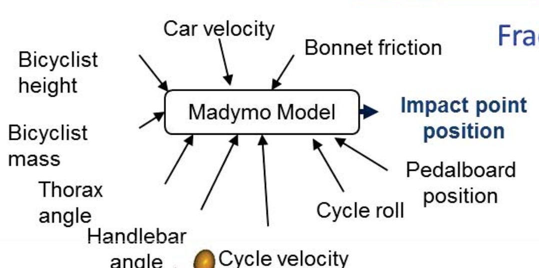
EXAMPLE : RECONSTRUCTION METHODOLOGY

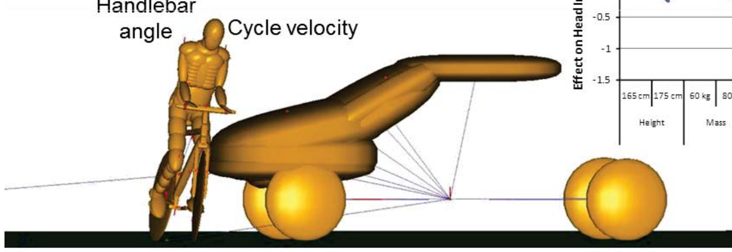
Unistra modeling

Parametric study

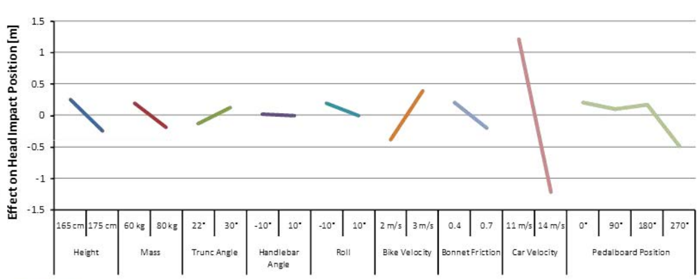
(~16 simulations)

	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





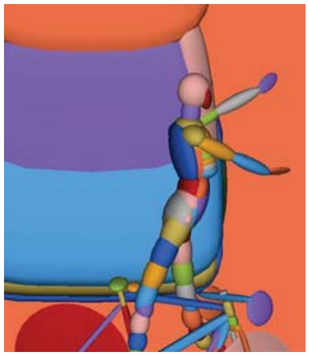
Fractional orthogonal array L16 (12 factors at two levels and a factor with 4 levels)

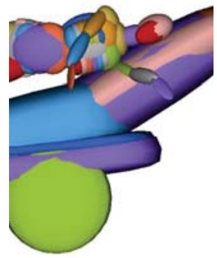


Evaluation function F versus car velocity and bicyclist position

EXAMPLE : KINEMATICS RECONSTRUCTION

Unistra modeling





$V_{resultant}$ = 10.9 m/s

V_{normal} = 10.0 m/s

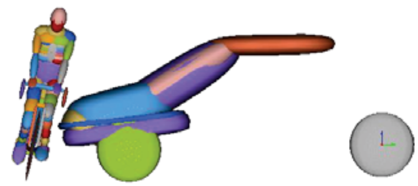
$V_{tangential}$ = 4.4 m/s

Loadcase 1 : Time = 0.000000
Frame 1

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

Projection distance of 16.3 m

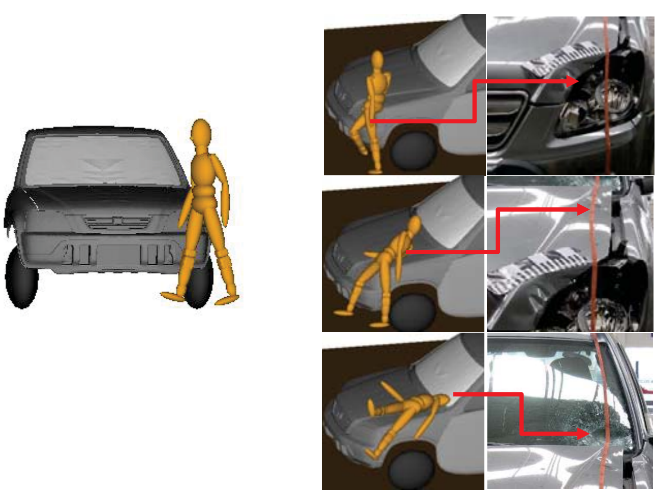
WAD of 2.10 m



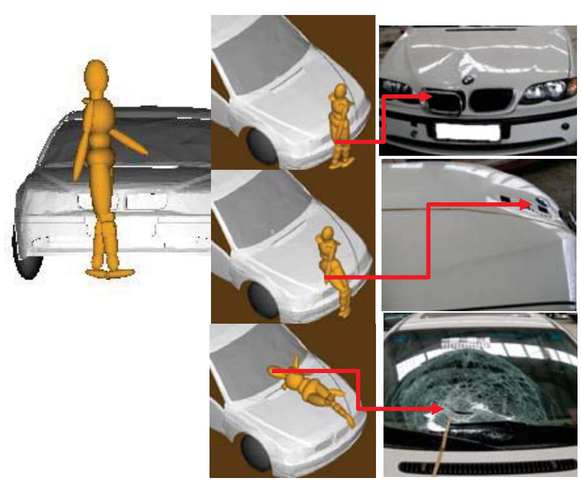
ACCIDENT DATA COLLECTION AND RECONSTRUCTION

➢ *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

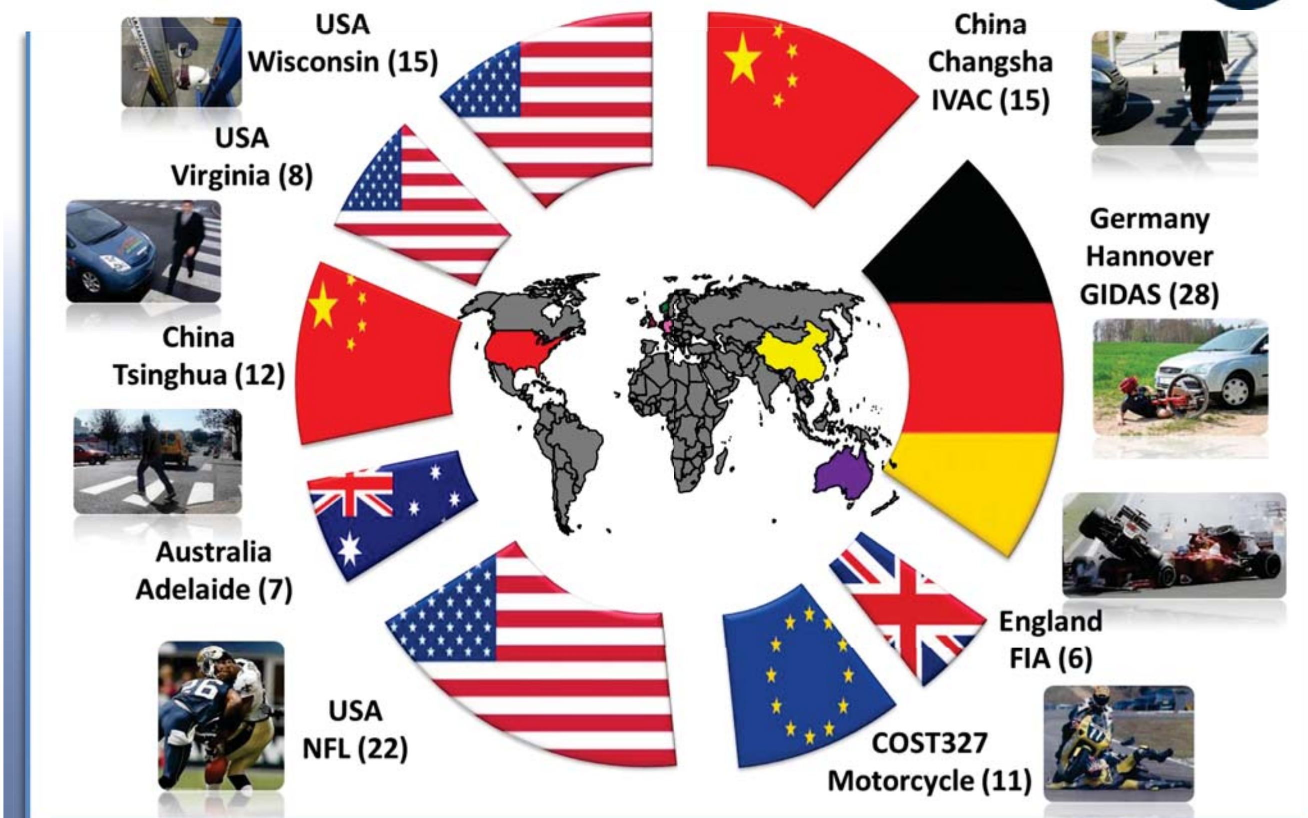


Example 1



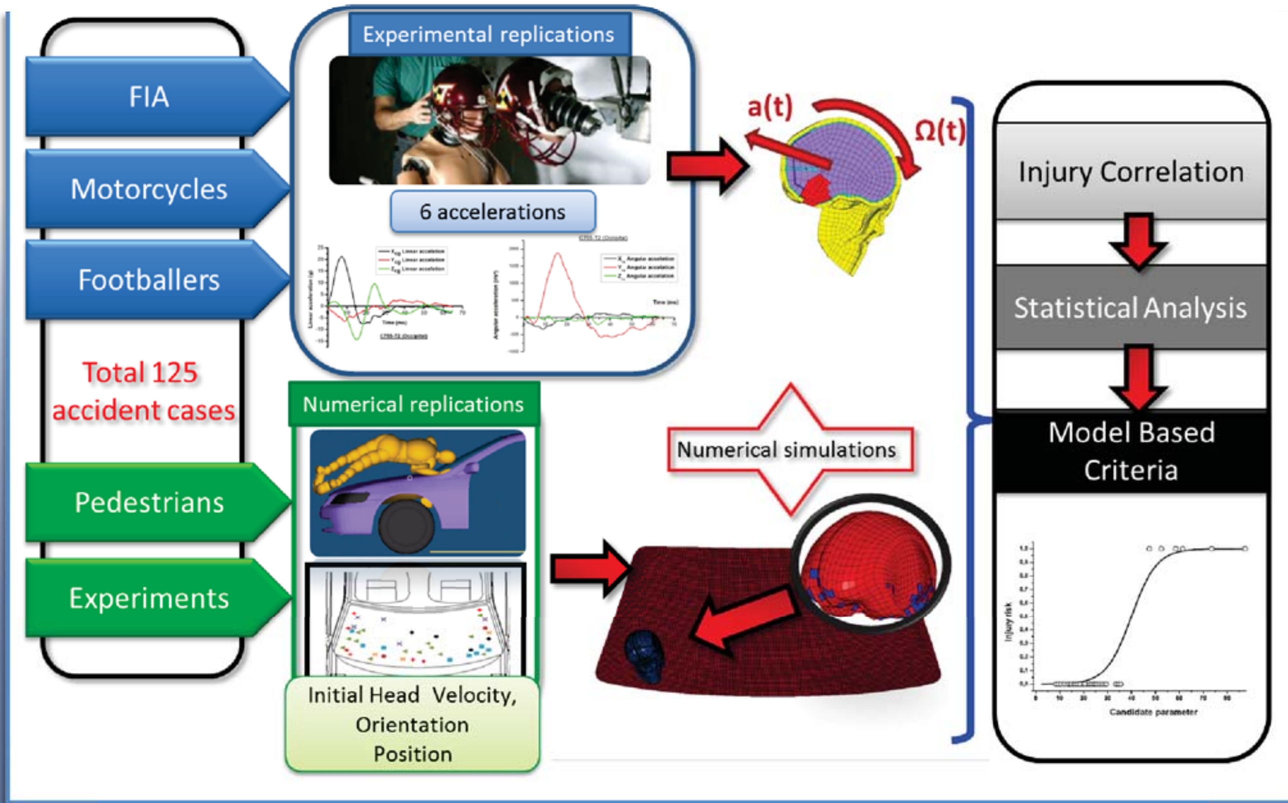
Example 2

Database (125 cases)

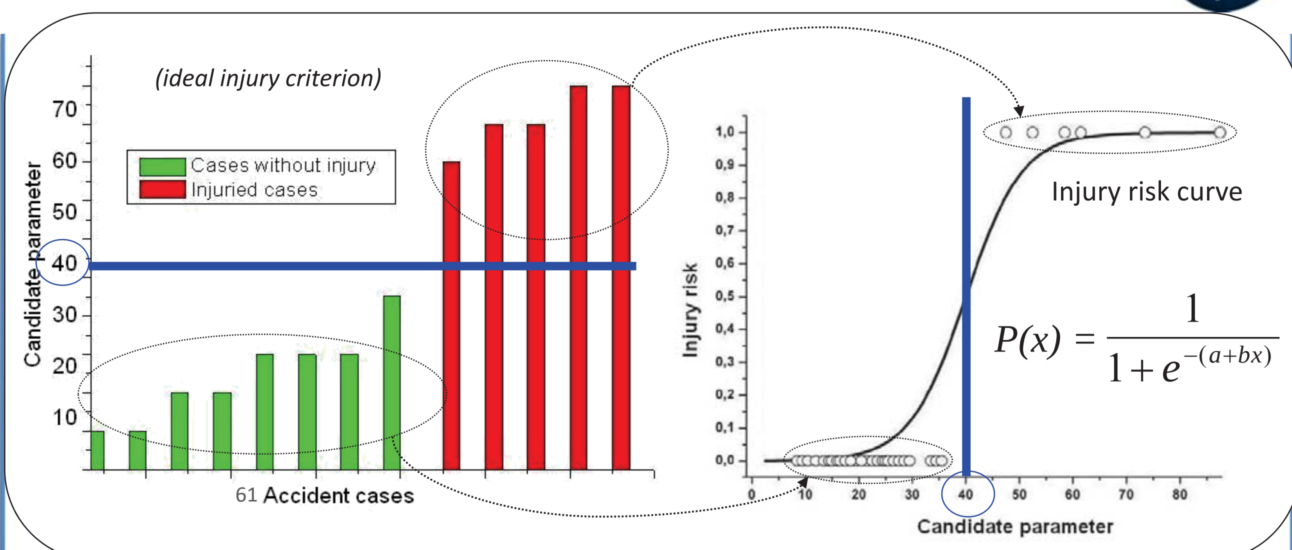


MODEL BASED HEAD INJURY CRITERIA

Head trauma simulation



Two statistical methods



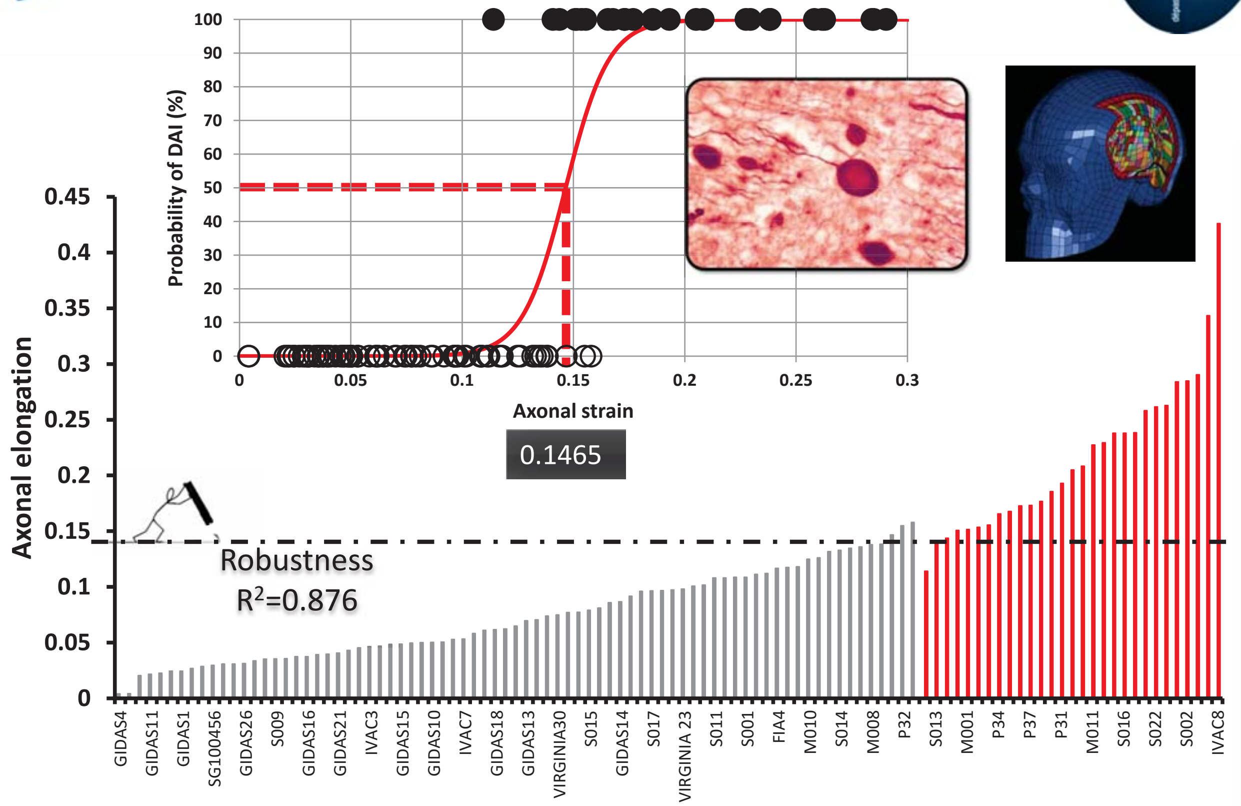
<u>*Modified likelihood method Nakahira et al. (2000)*</u>

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

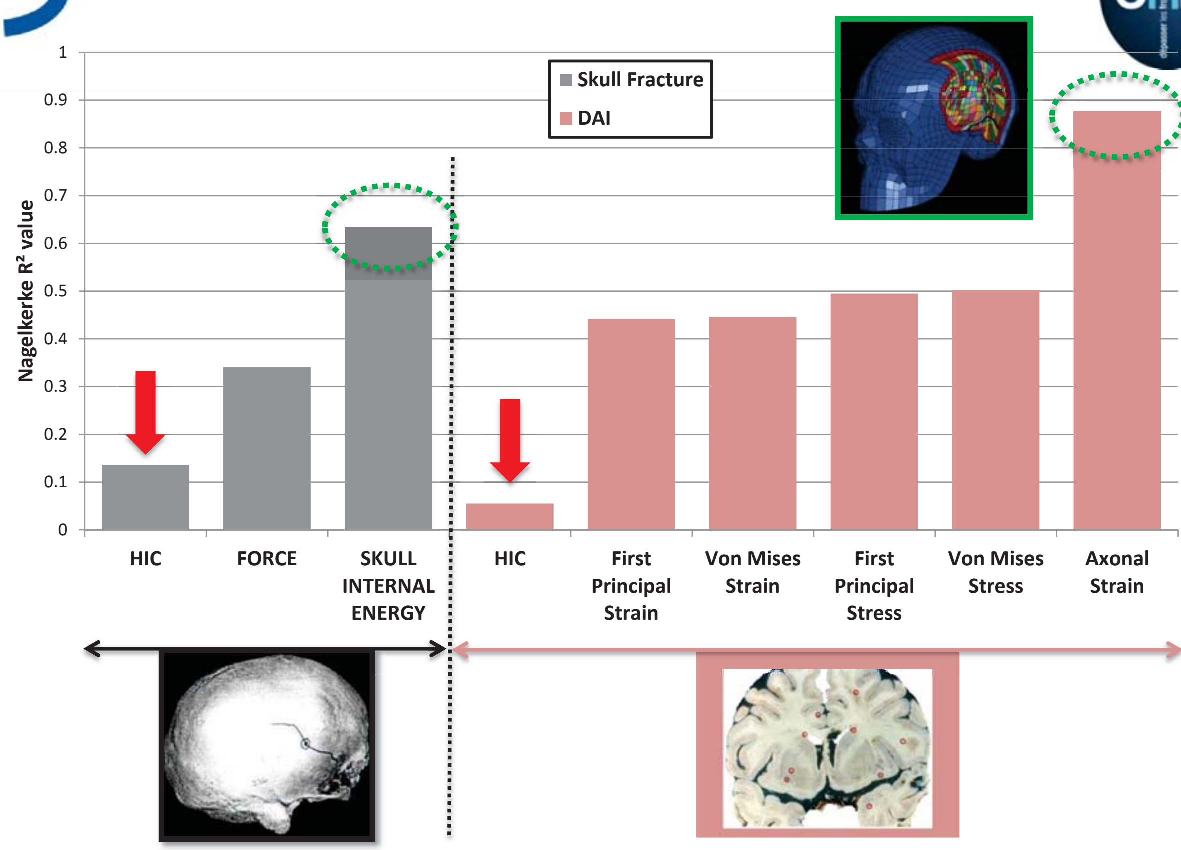
<u>*Binary logistic regression (SPSS v14.0)*</u>

Nagelkerke <u>R-sq</u> statistic

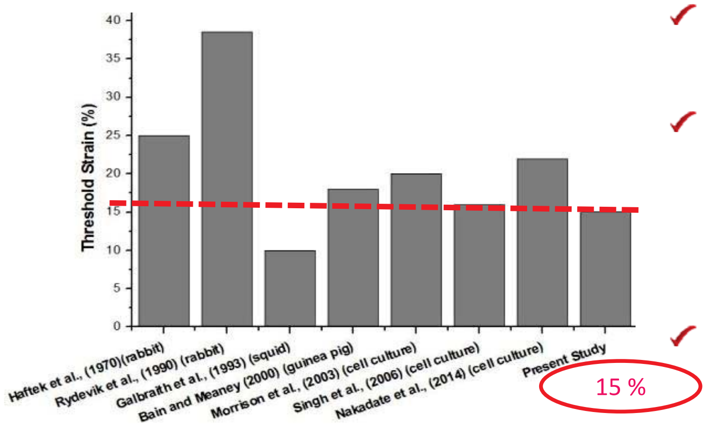
Brain Injury criteria DAI (AIS 2+)



Evaluation of existing Head Injury Criteria

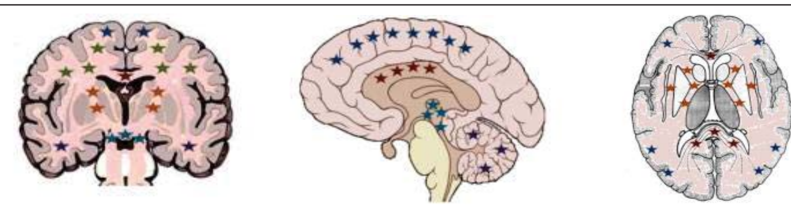


Axon strain in the literature



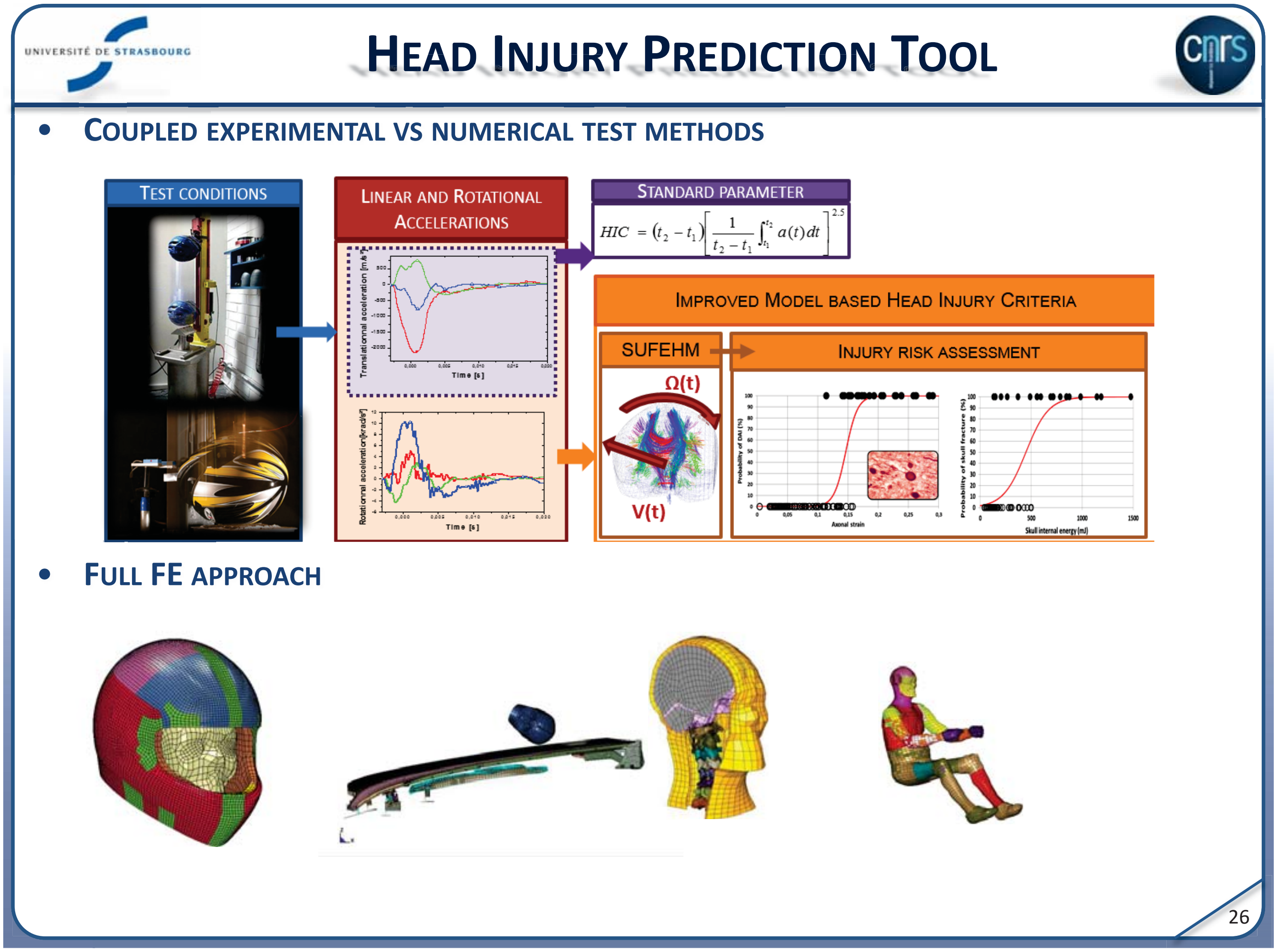
- ✓ Experimental data based on cell culture lead to similar axon strain threshold.
- ✓ A similar approach based on NFL data simulated with KTH model lead to 7% to 15 % depending on the brain region (Kleiven et al 2014)
- ✓ General DAI description shows injury within main axon bundles.

★ Interface white/gray matter
★ Corpus callosum
★ Corona radiata
★ Internal capsule
★ Cerebellum
★ Others



[Gennarelli *et al.*, 1982] [Gentry *et al.*, 1988] [Ng *et al.*, 1994] [Graham and Gennarelli, 1997] [Arfanakis *et al.*, 2002]

HEAD INJURY PREDICTION TOOL FOR END USERS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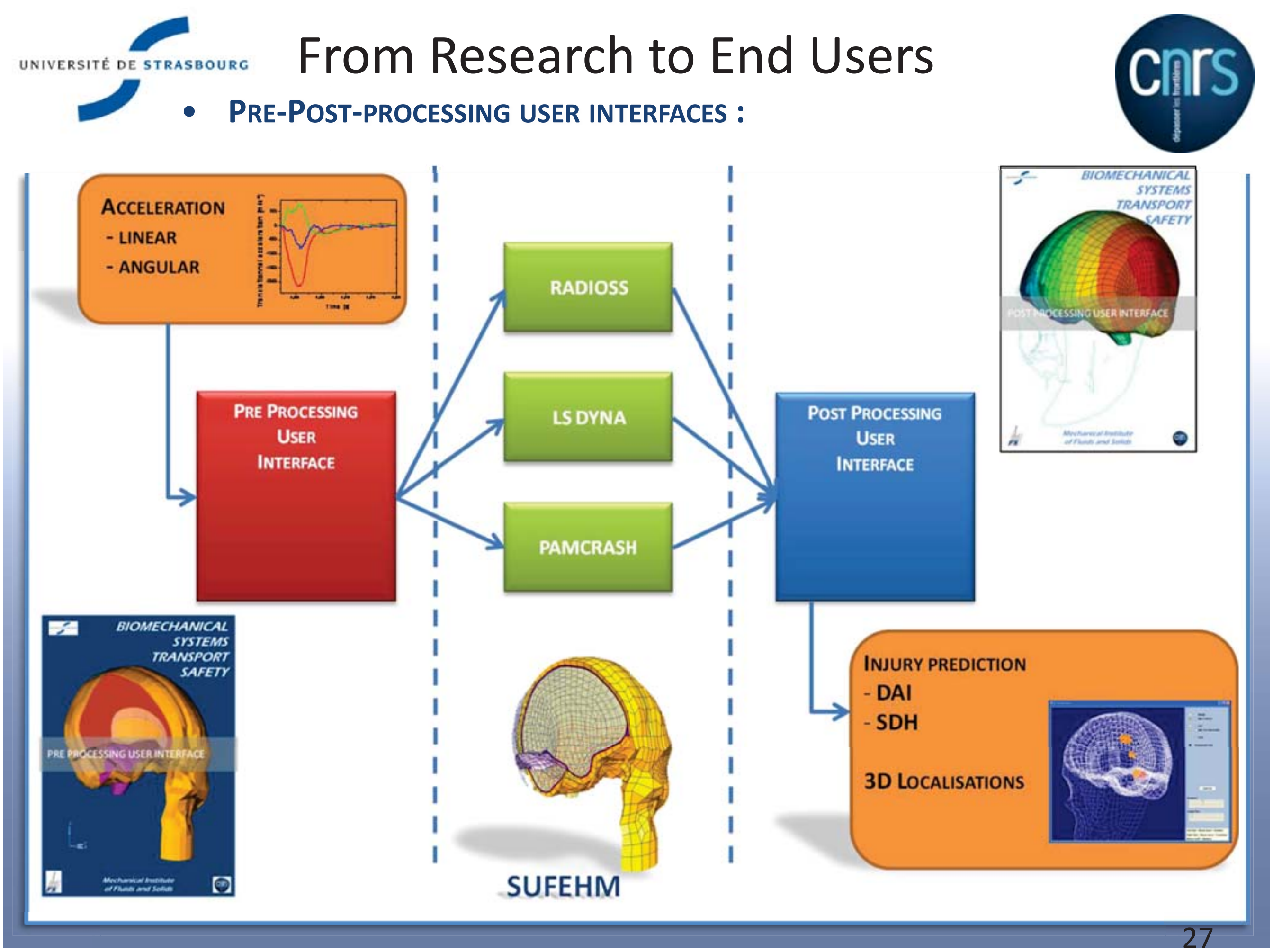
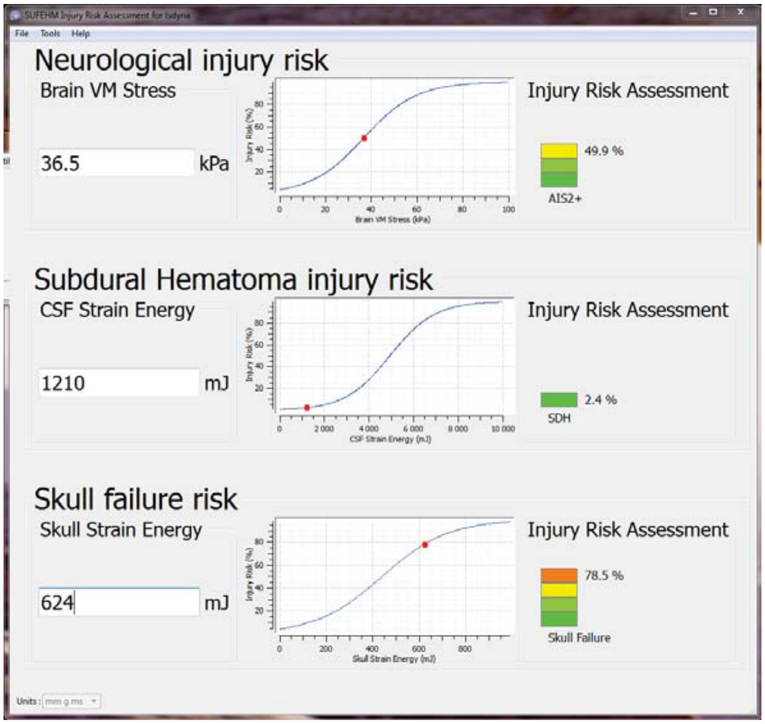
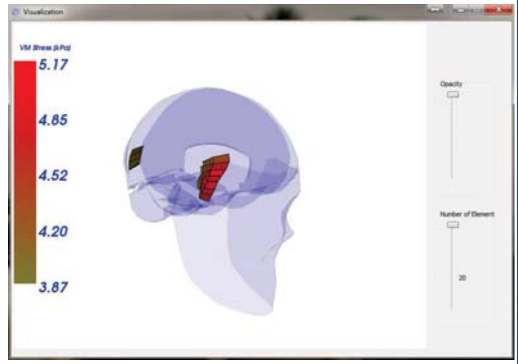
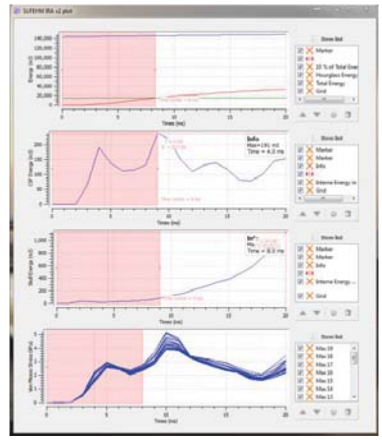
HEAD INJURY PREDICTION TOOL
cnrs
COUPLED EXPERIMENTAL VS NUMERICAL TEST METHODS
TEST CONDITIONS
LINEAR AND ROTATIONAL ACCELERATIONS
STANDARD PARAMETER
$HIC = (t_2 - t_1)\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)\,dt\right]^{2.5}$
IMPROVED MODEL BASED HEAD INJURY CRITERIA
SUFEHM
INJURY RISK ASSESSMENT
Ω(t)
V(t)
Time [s]
FULL FE APPROACH
26


UNIVERSITÉ DE STRASBOURG
From Research to End Users
cnrs
PRE-POST-PROCESSING USER INTERFACES :
ACCELERATION
- LINEAR
- ANGULAR
PRE PROCESSING USER INTERFACE
RADIOSS
LS DYNA
PAMCRASH
POST PROCESSING USER INTERFACE
BIOMECHANICAL SYSTEMS TRANSPORT SAFETY
POST PROCESSING USER INTERFACE
BIOMECHANICAL SYSTEMS TRANSPORT SAFETY
PRE PROCESSING USER INTERFACE
INJURY PREDICTION
- DAI
- SDH
3D LOCALISATIONS
SUFEHM
27

HEAD INJURY RISK ASSESSEMENT TOOL







COMPUTATION OF SUFEHM CRITERIA VIA WEB SIMULATION

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FAISABILITY AND FIRST APPLICATIONS

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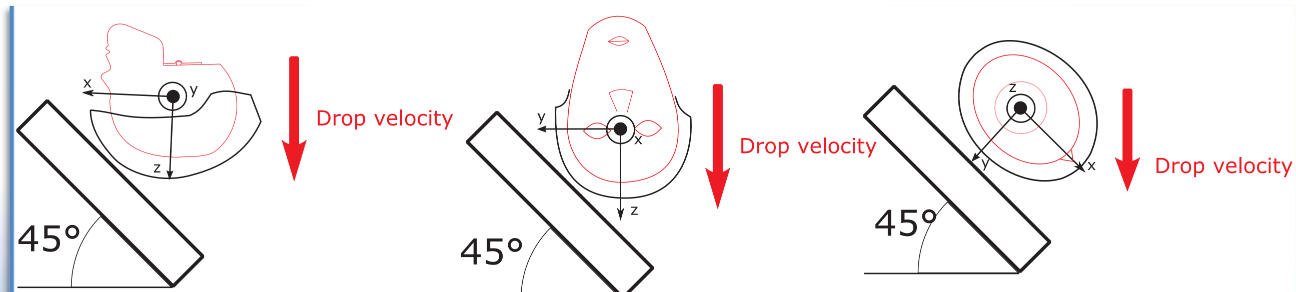
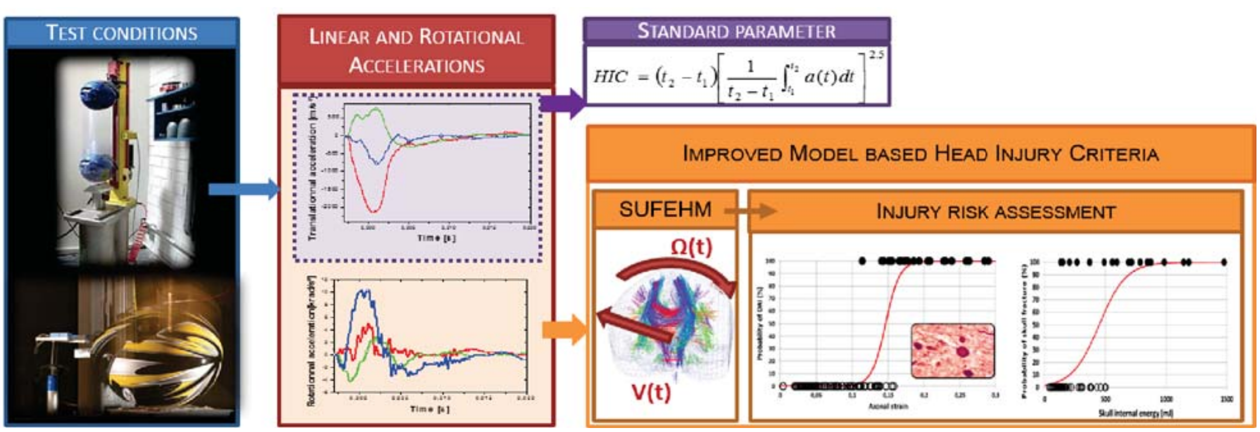
Head Injury Criteria in helmet test method (CEN TC 158-WG11)

cnrs





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Helmet Consumer tests

- 35 bicycle helmets and 12 motorcycle helmets
- Linear and tangential impact tests
- Using Hybrid III head and 6D acceleration curves
- Rating according to axon strain
- Published in journals and web

- EuroNcasque project

UNIVERSITÉ DE STRASBOURG

Helmet Consumer tests

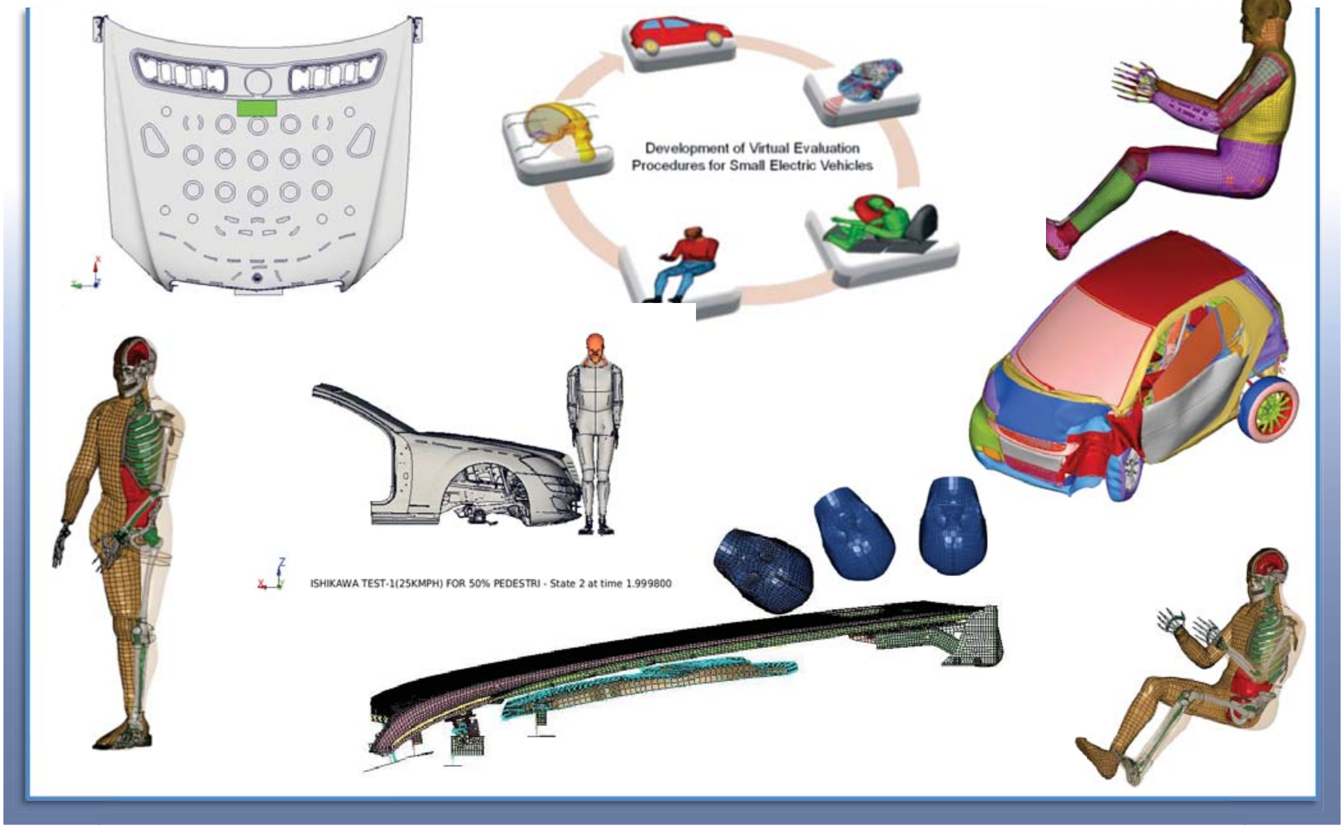

Le critère de la sécurité avant tout

60 Millions de consomateurs (F)
August 2015

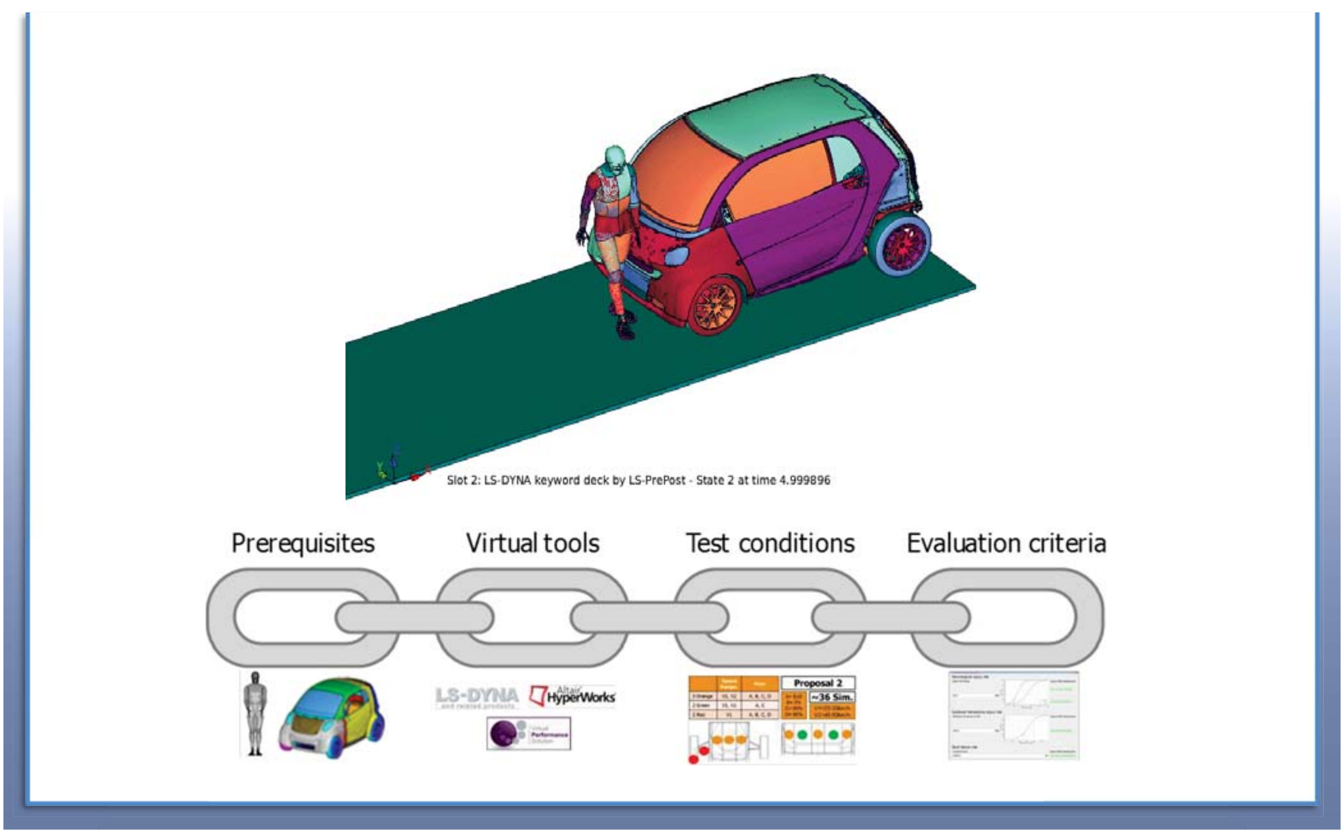
Stiftung Warentest (D)
August 2015

FOLKSAM (S)
Under progress

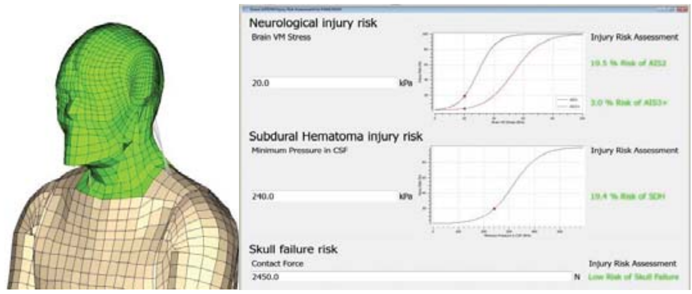
Virtual testing in automotive environment (Safe-EV)



Safe-EV project
Pedestrian Passive Safety



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



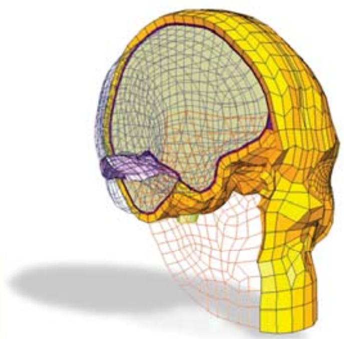
- Further possible injury risk indicators (based on max. strain analysis)

CONCLUSION-1

- Angular acceleration exist and is critical for brain
- Advanced brain FE models
- Computation of axon strain
- Consolidated head trauma database with 125 cases.
- Very high Nagelkerke R^2 value (R^2=0.876) for brain injury

- Best candidate parameter for brain injury is axon strain
- The model based head injury criteria are:
- Axon strain for brain AIS2+ (ε_a= 15%)
- Skull strain energy for fracture (0.5 J)

6D Brain Injury Metric Based on Axon Elongation



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Importance of Angular Head Motions for Brain Injury Prediction

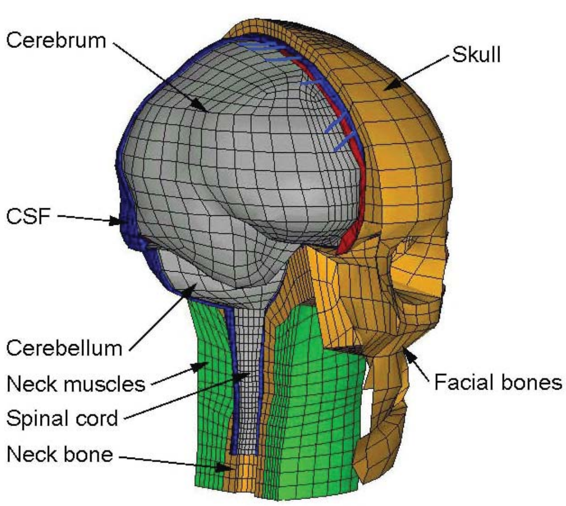
Svein Kleiven, Madelen Fahlstedt, Chiara Giordano
Xiaogai Li, Victor S. Alvarez, Peter Halldin

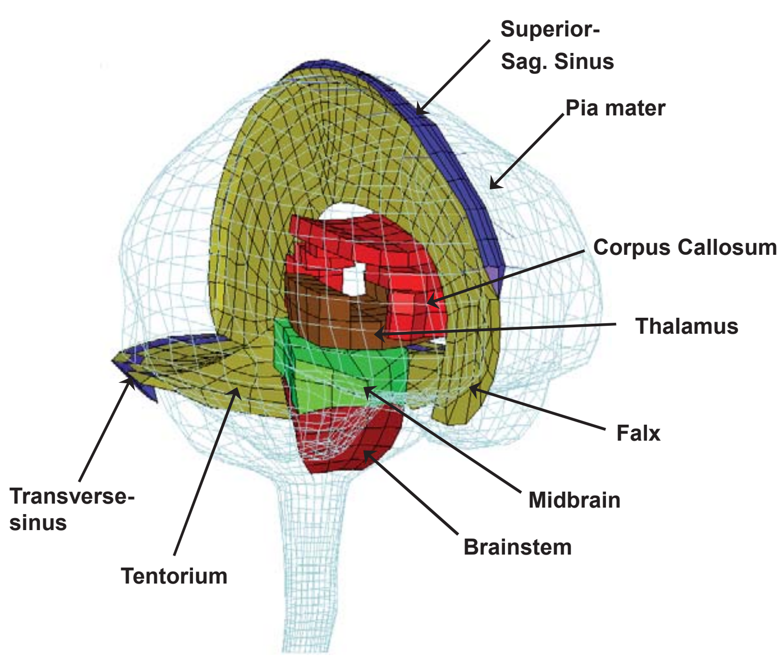
KTH Technology and Health

Overview of the presentation

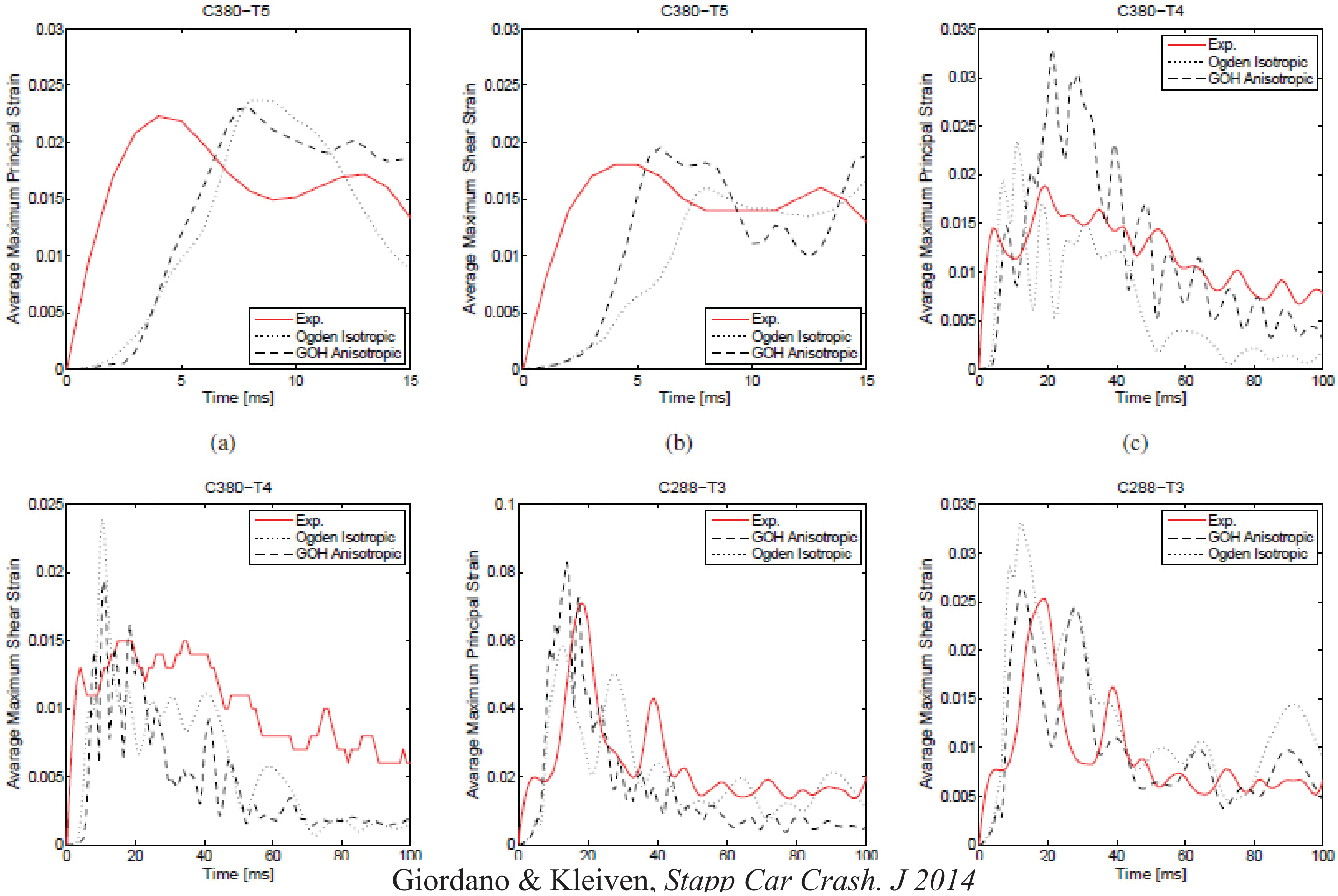
- FE modelling of the human head
- Injurious strains induced by angular motion
- Influence of impact direction
- Angular velocity as a predictor of strain
- Axonal injury prediction

The KTH head model





Comparison with experimental strain data



Giordano & Kleiven, *Stapp Car Crash. J 2014*

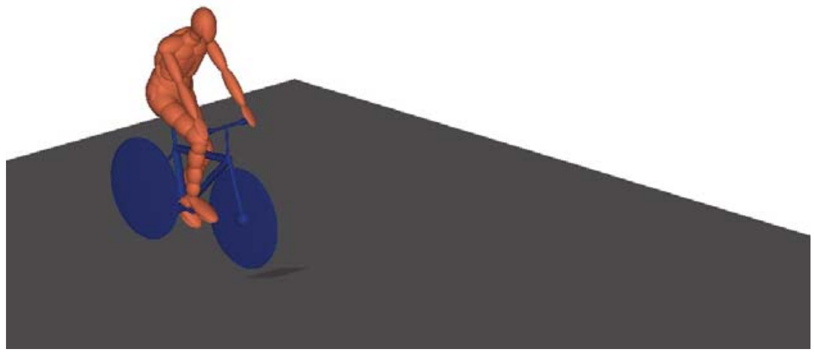
Overview of the presentation

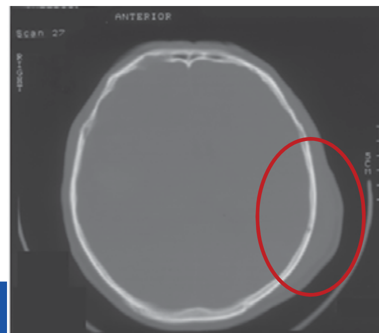
- FE modelling of the human head
- **Injurious strains induced by angular motion**
- Influence of impact direction
- Angular velocity as a predictor of strain
- Axonal injury prediction

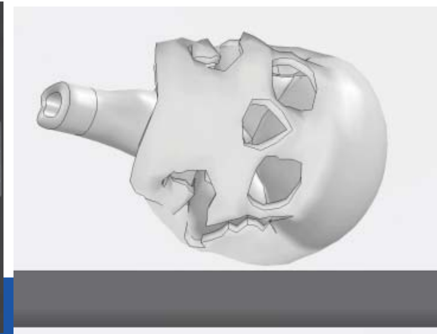
KTH VETENSKAP OCH KONST

Bicycle Accident Reconstruction

- Elderly man
- Uneven ground
- Skull fracture
  Contusion
- No Helmet

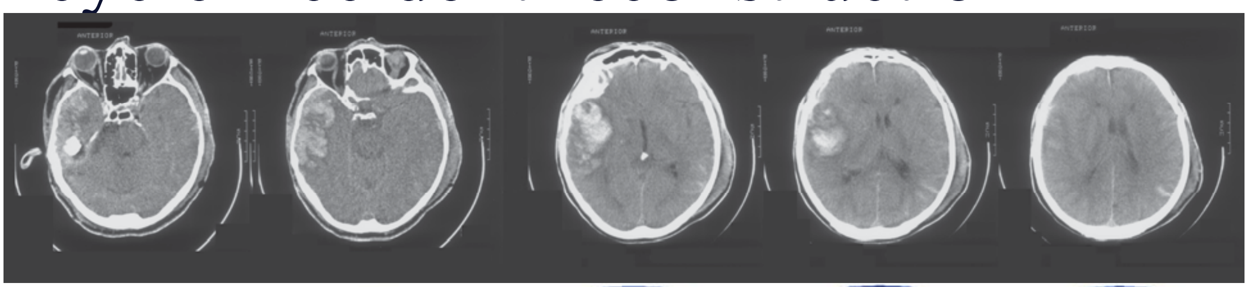


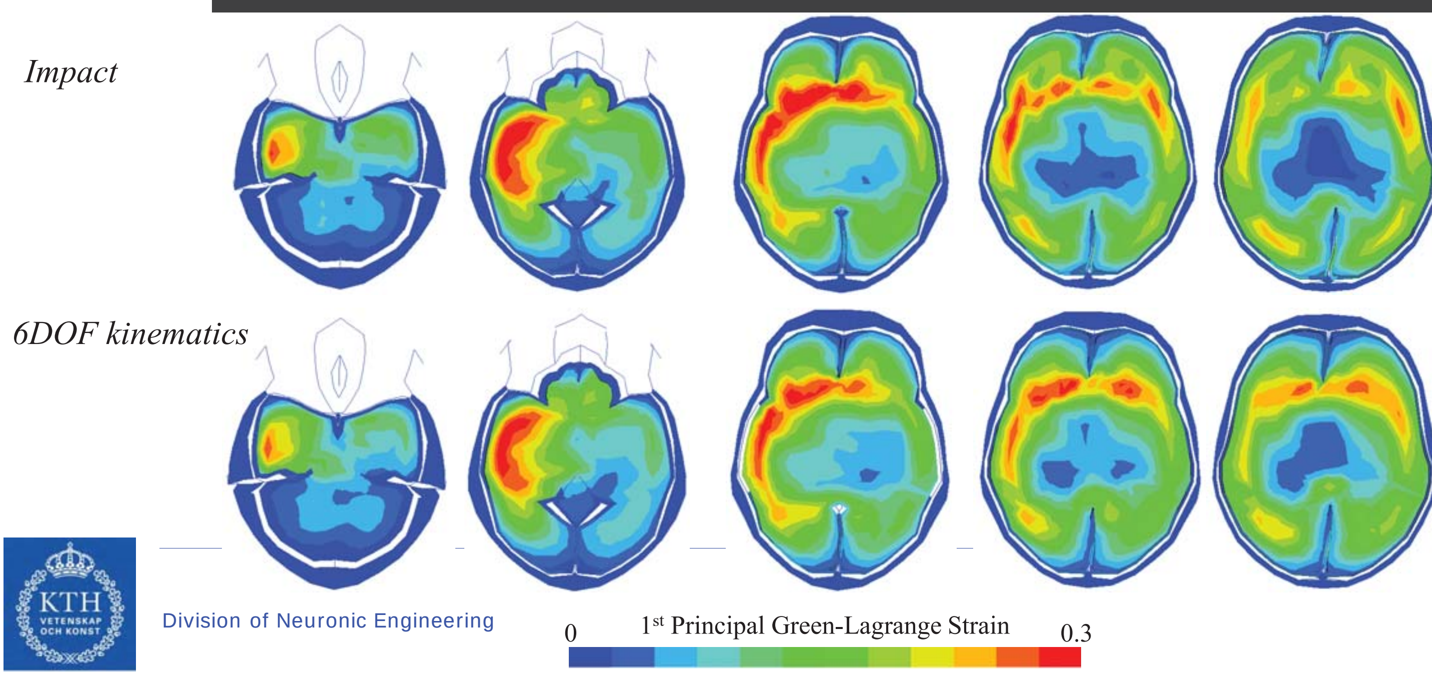




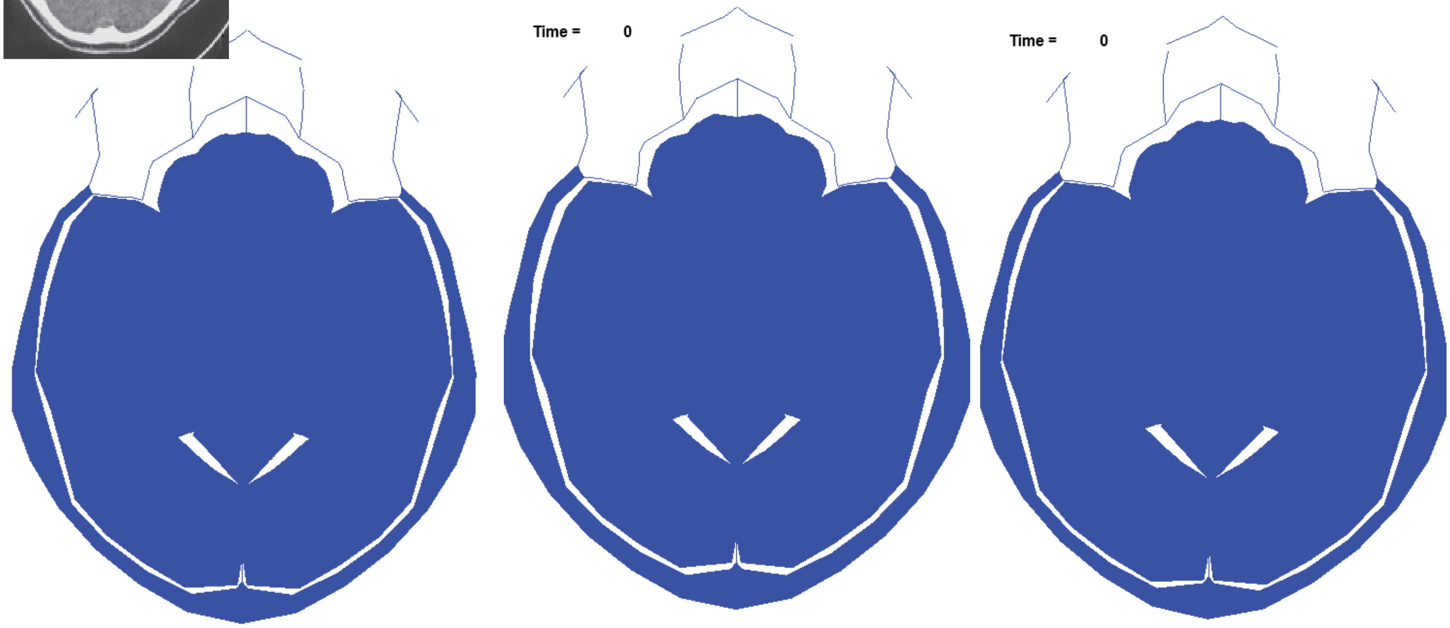
(Fahlstedt et al. J.Biomech. 2015)

Bicycle Accident reconstruction





Bicycle Accident reconstruction

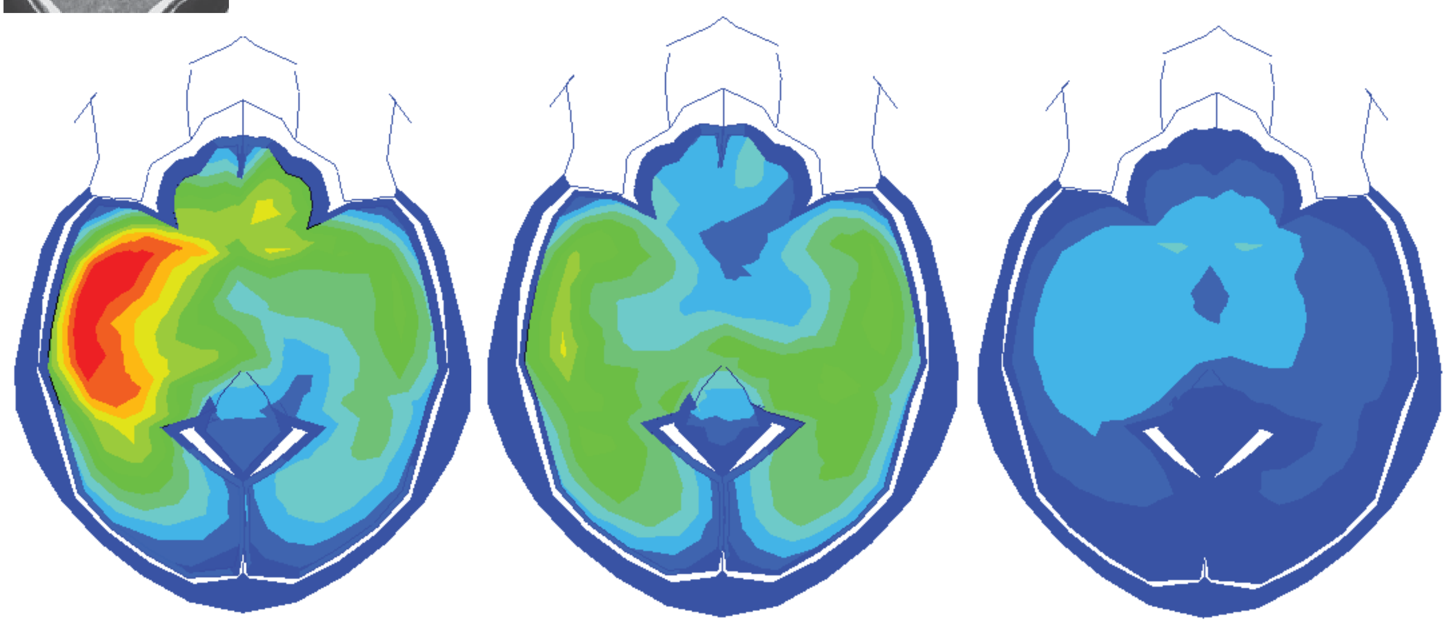


Impact *Only angular* *Only linear*

Division of Neuronic Engineering

0 1st Principal Green-Lagrange Strain 0.3

Bicycle Accident reconstruction

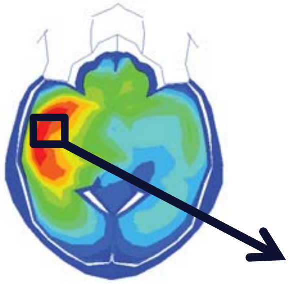


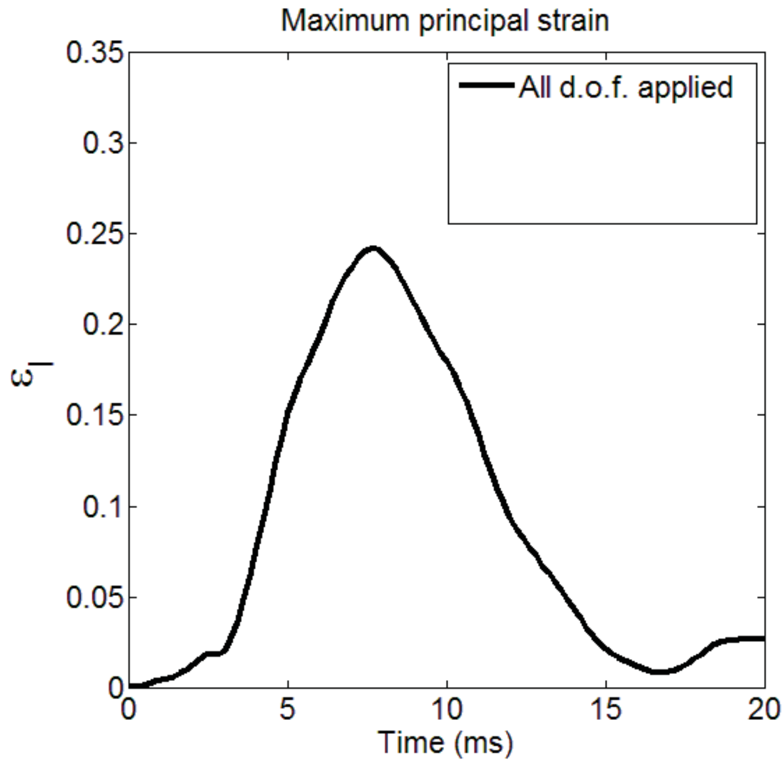
Impact *Only angular* *Only linear*

Division of Neuronic Engineering

0 1st Principal Green-Lagrange Strain 0.3

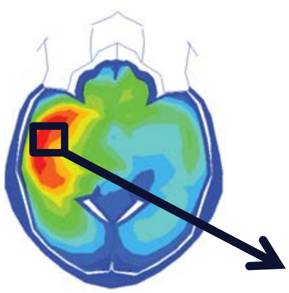
Bicycle Accident reconstruction

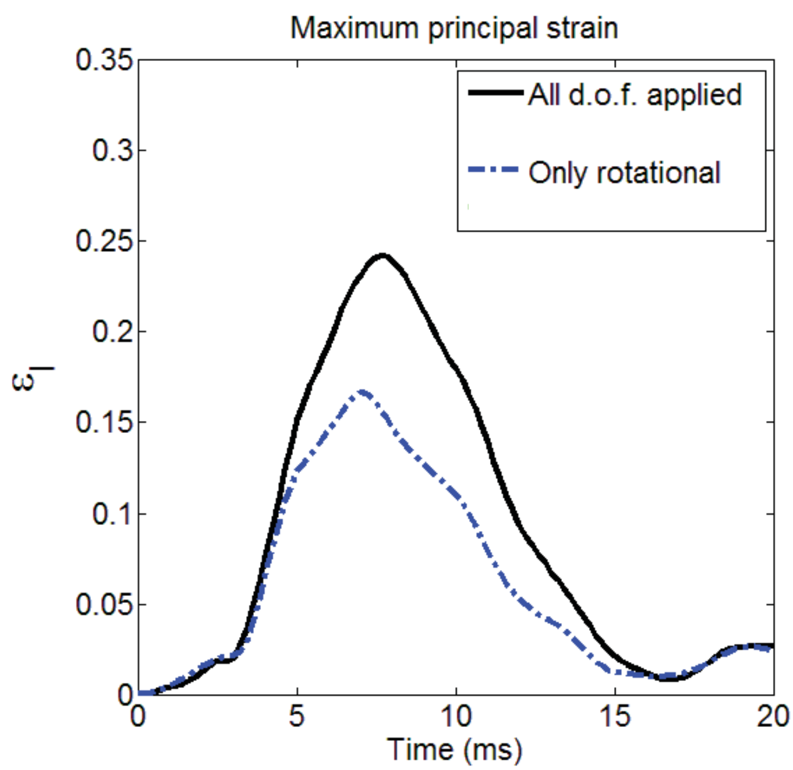




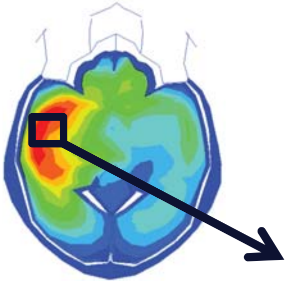
Division of Neuronic Engineering

Bicycle Accident reconstruction

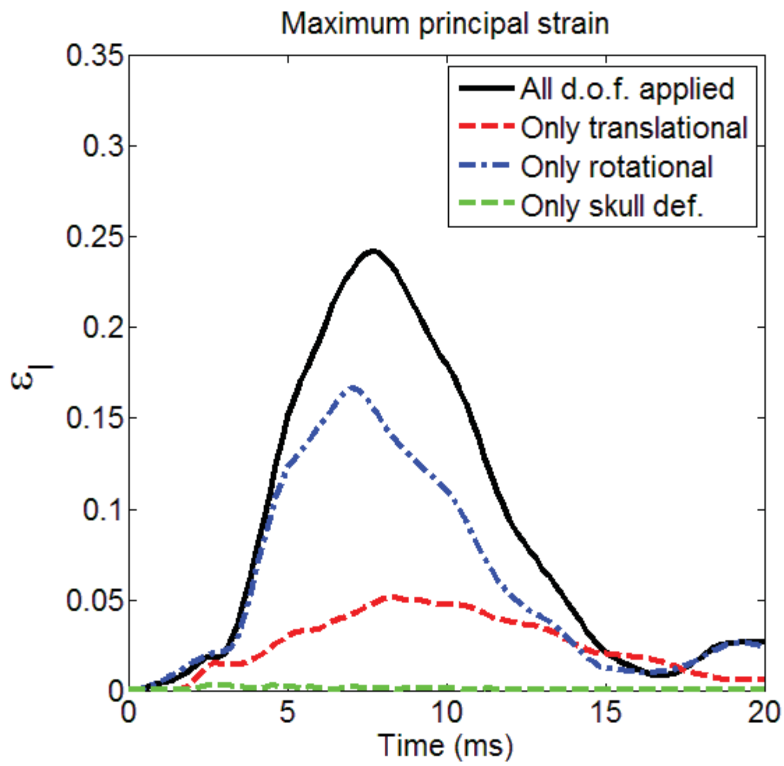




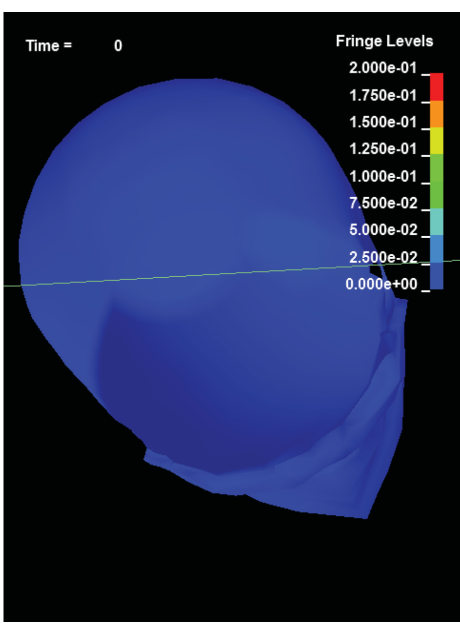
Division of Neuronic Engineering



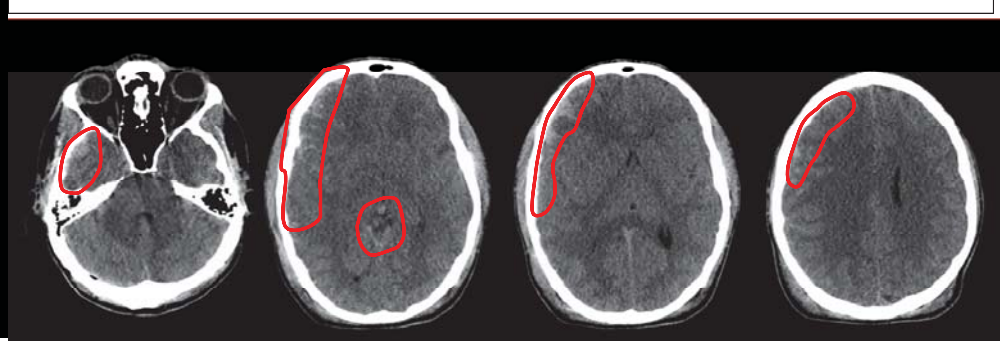
Bicycle Accident reconstruction



Fall Accident reconstruction

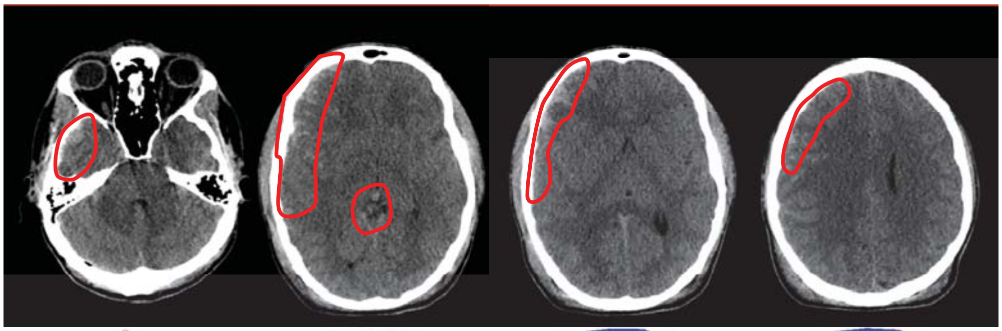


Medical record:
Fall accident from 4 meters.
Wound on the right eyebrow.
CT images show multiple contusions at frontal, parietal and temporal lobe at right hemisphere.



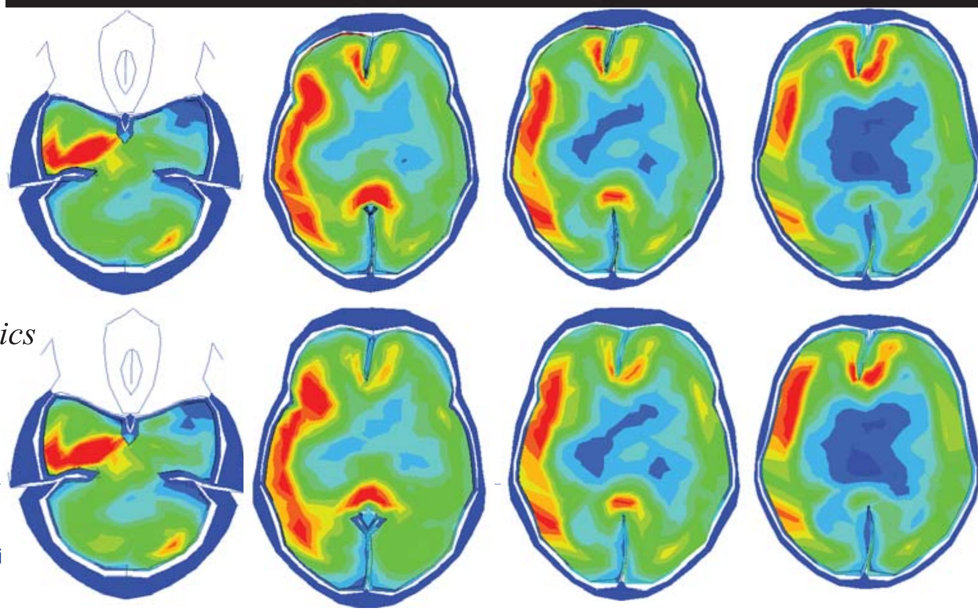
Division of Neuronic Engineering

Fall Accident reconstruction



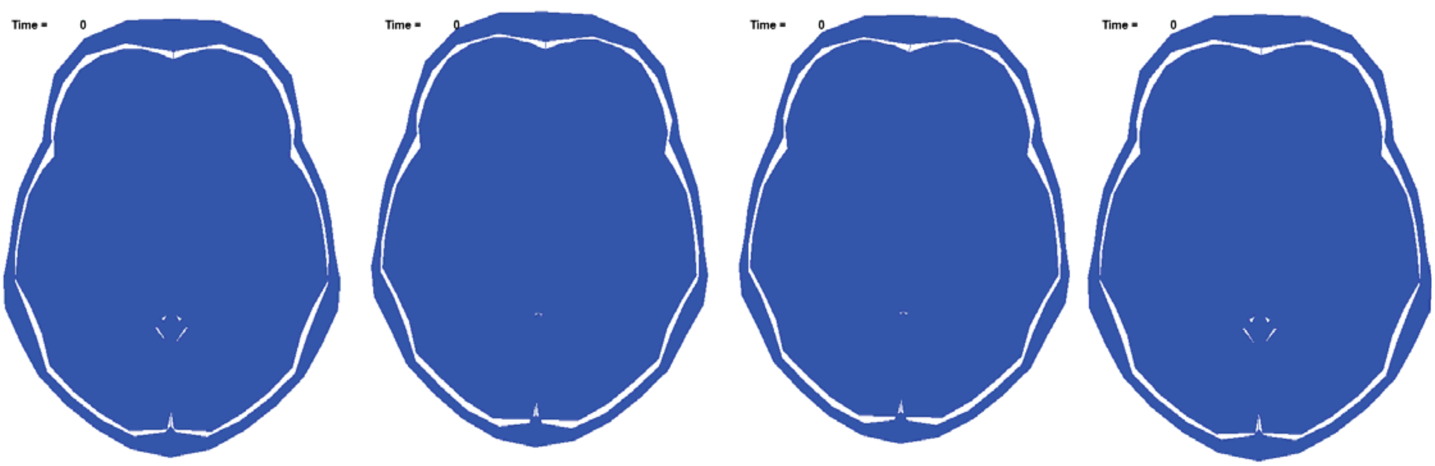
Impact

6DOF kinematics



Divisi

Fall Accident reconstruction



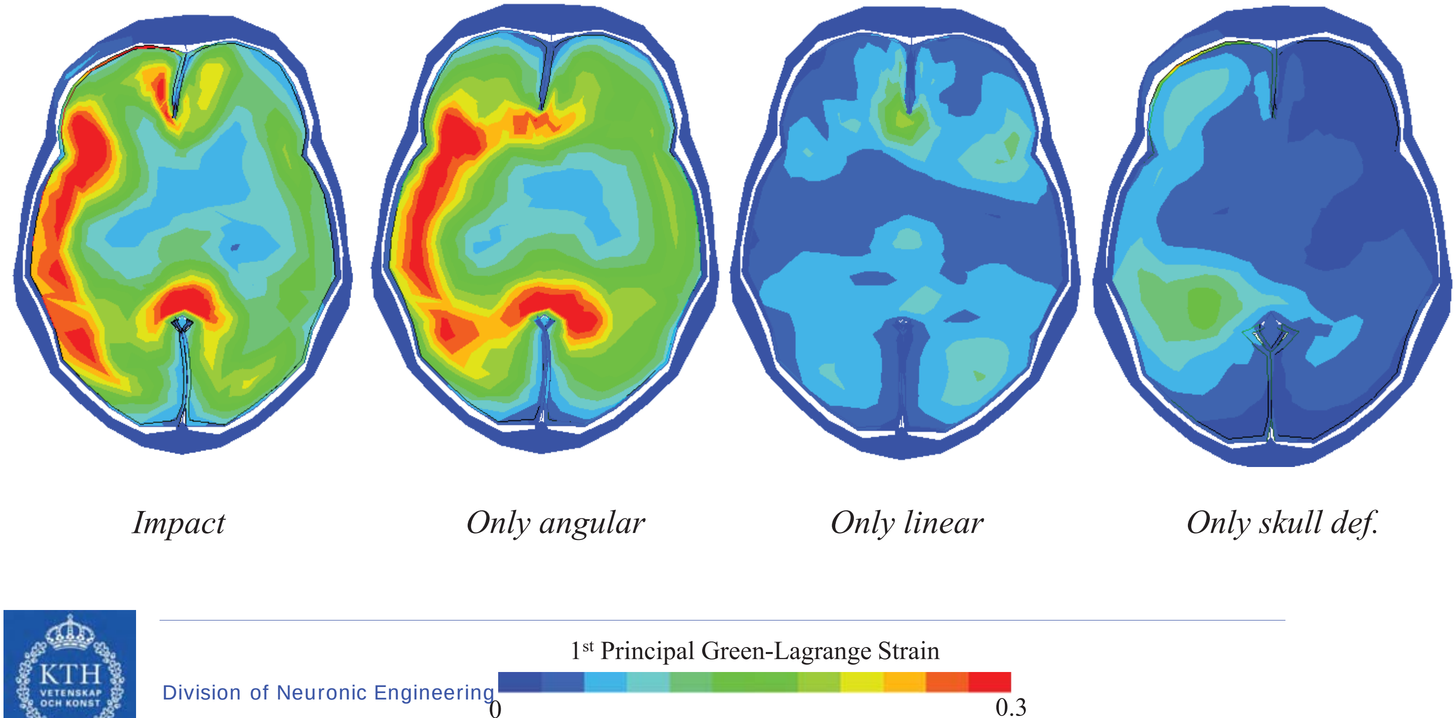
Impact *Only angular* *Only linear* *Only skull def.*

1st Principal Green-Lagrange Strain

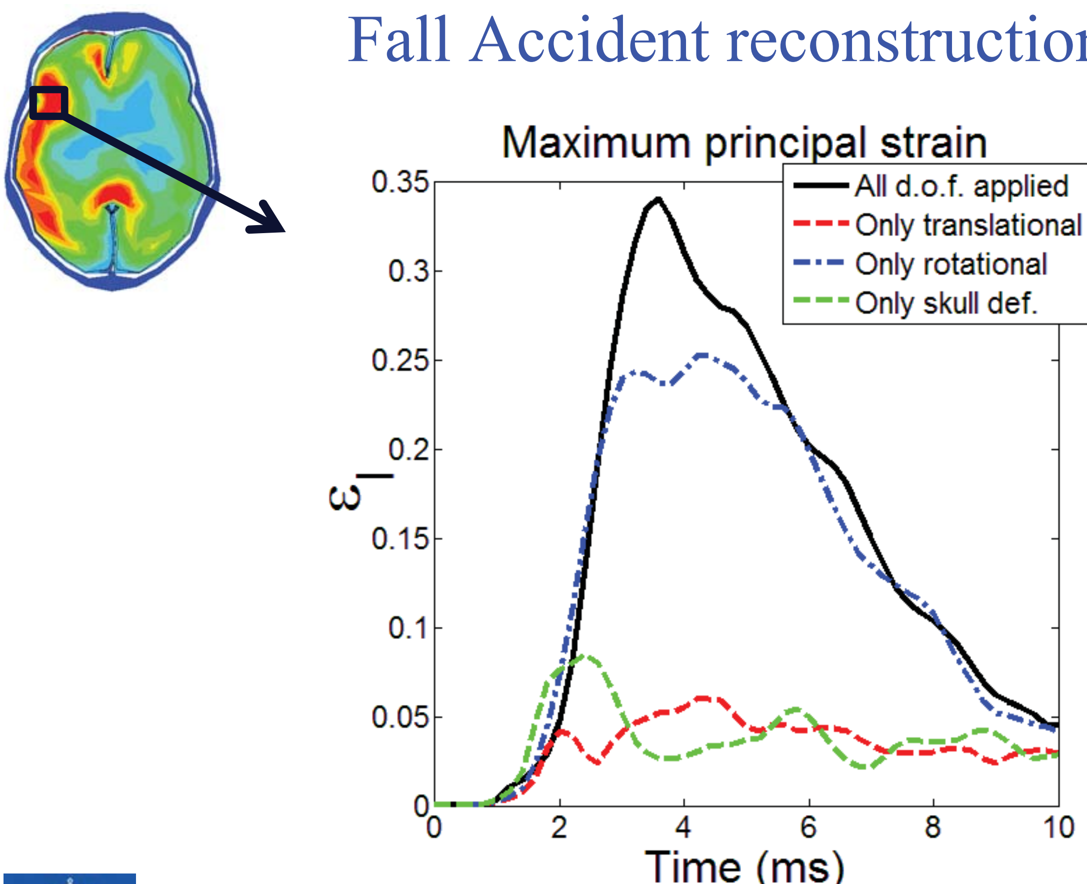
0 0.3

Division of Neuronic Engineering

Fall Accident reconstruction



Fall Accident reconstruction



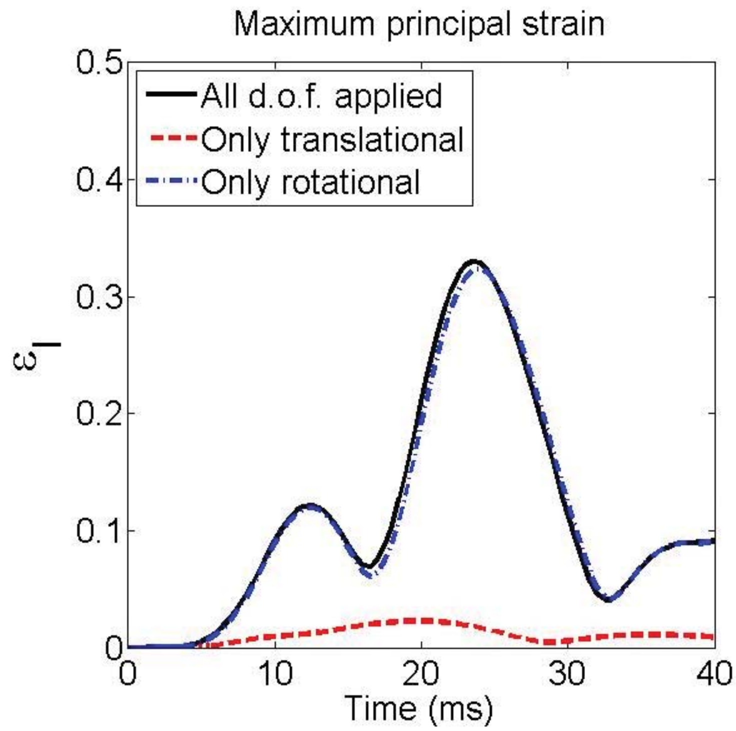
Reconstruction of 58 NFL accidents

Kleiven, *Stapp Car Crash Journal 2007*

Influence of rotational and translational kinematics

Only translational kinematics ***Only rotational kinematics*** ***All kinematics applied***

Influence of rotational and translational kinematics



Overview of the presentation

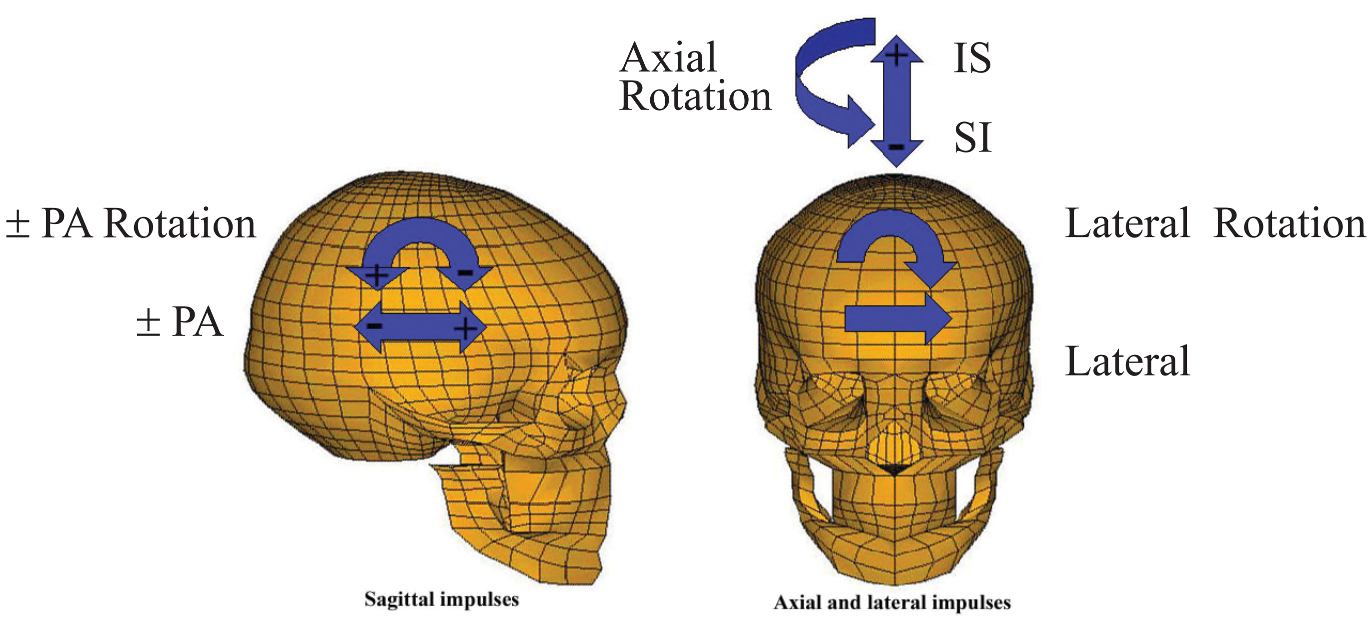
- FE modelling of the human head
- Injurious strains induced by angular motion
- **Influence of impact direction**
- Angular velocity as a predictor of strain
- Axonal injury prediction

Study of directional influence

Variation in Impact Direction gives a Change in Intracranial Response which are not predicted by existing Head Injury Criteria.

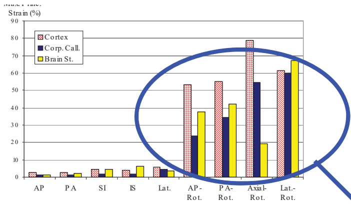
Kleiven, *J. Neurotrauma, 2003; IJCrash worthiness 2006*

Applied Impulses

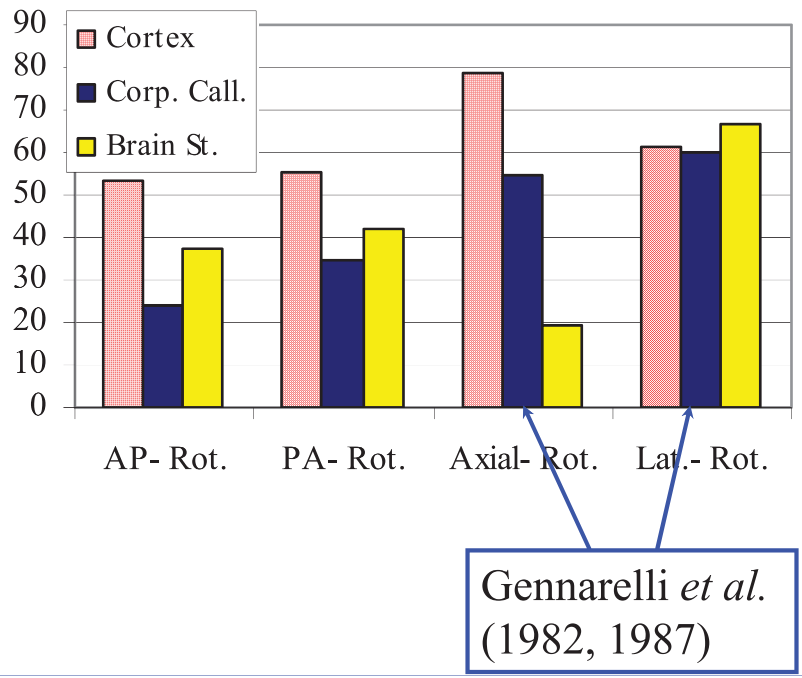


Kleiven, *J. Neurotrauma, 2003; IJCrash worthiness 2006*

Rotational impulses



Max. Princ.
Strain (%)



Overview of the presentation

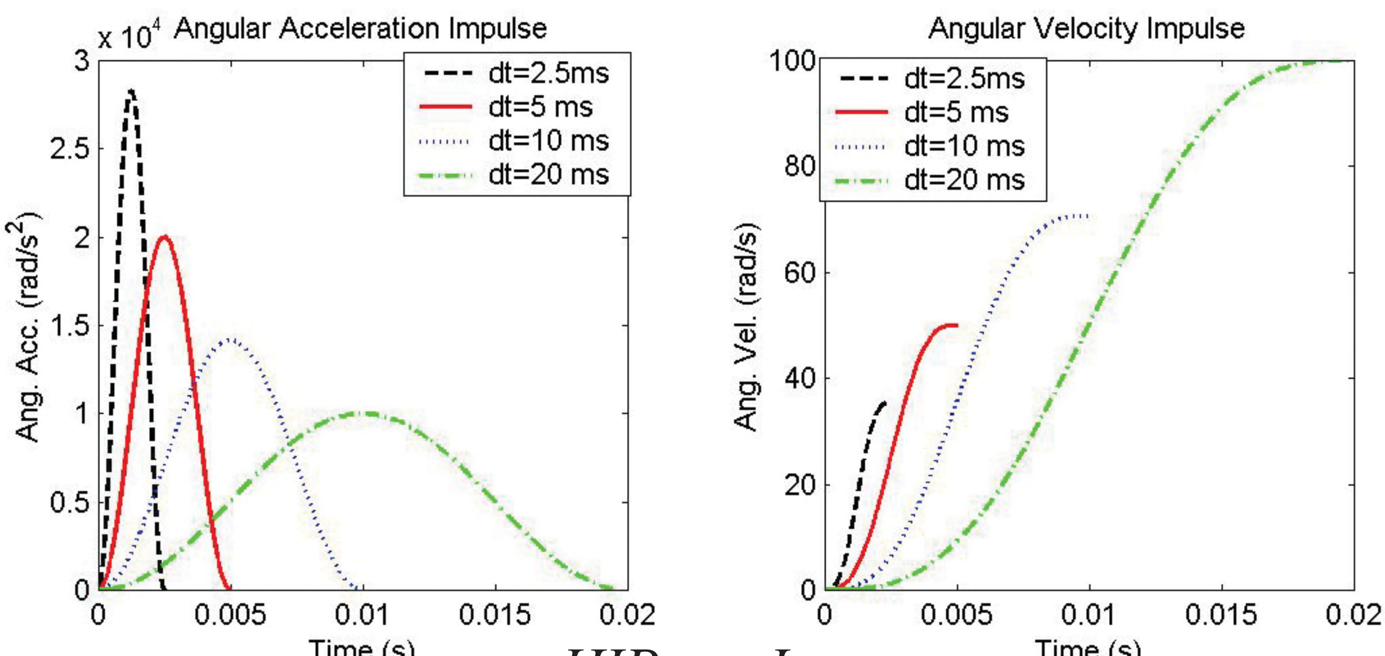
- FE modelling of the human head
- Injurious strains induced by angular motion
- Influence of impact direction
- **Angular velocity as a predictor of strain**
- Axonal injury prediction

Evaluation of global injury measures

Keeping the measures constant and varying the impulse duration. If the measure is correlating with strain, applying a constant value of the injury measure would result in a constant strain in the model.

Kleiven, *WCB-2002, IJCrash worthiness 2006*

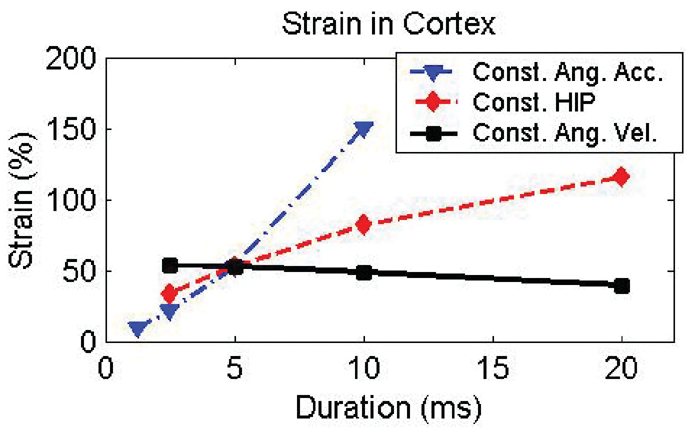
Same HIP but varied duration

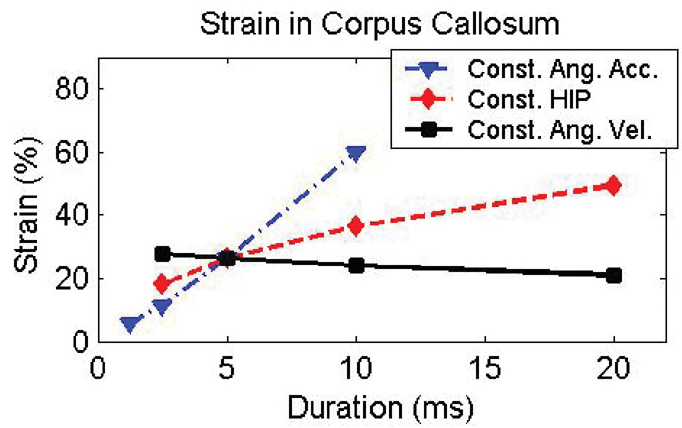


$$HIP_{rot} = I\alpha \cdot \omega$$

Newman et al. (2000)

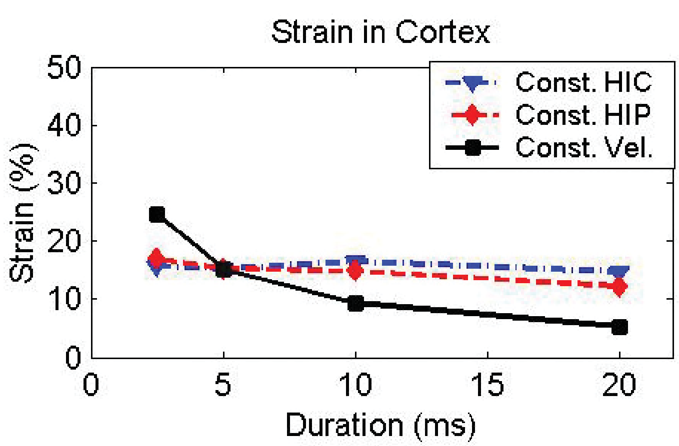
HIP, α and Δω for rotational kinematics

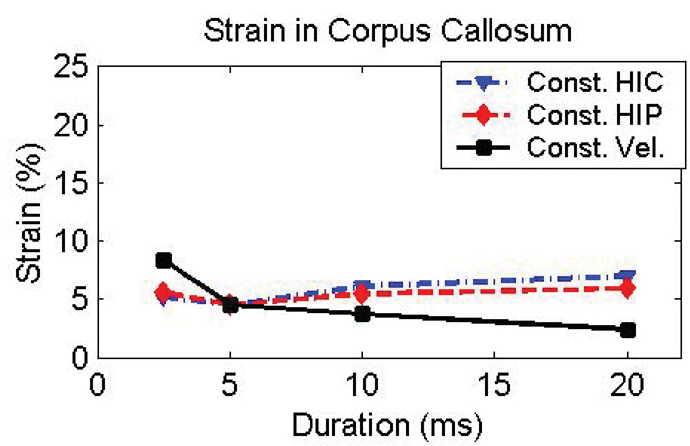




Kleiven, *WCB-2002, IJCrash worthiness 2006*

HIC, HIP and ΔV for translational kinematics





Kleiven, *WCB-2002, IJCrash worthiness 2006*

Reconstruction of NFL concussions

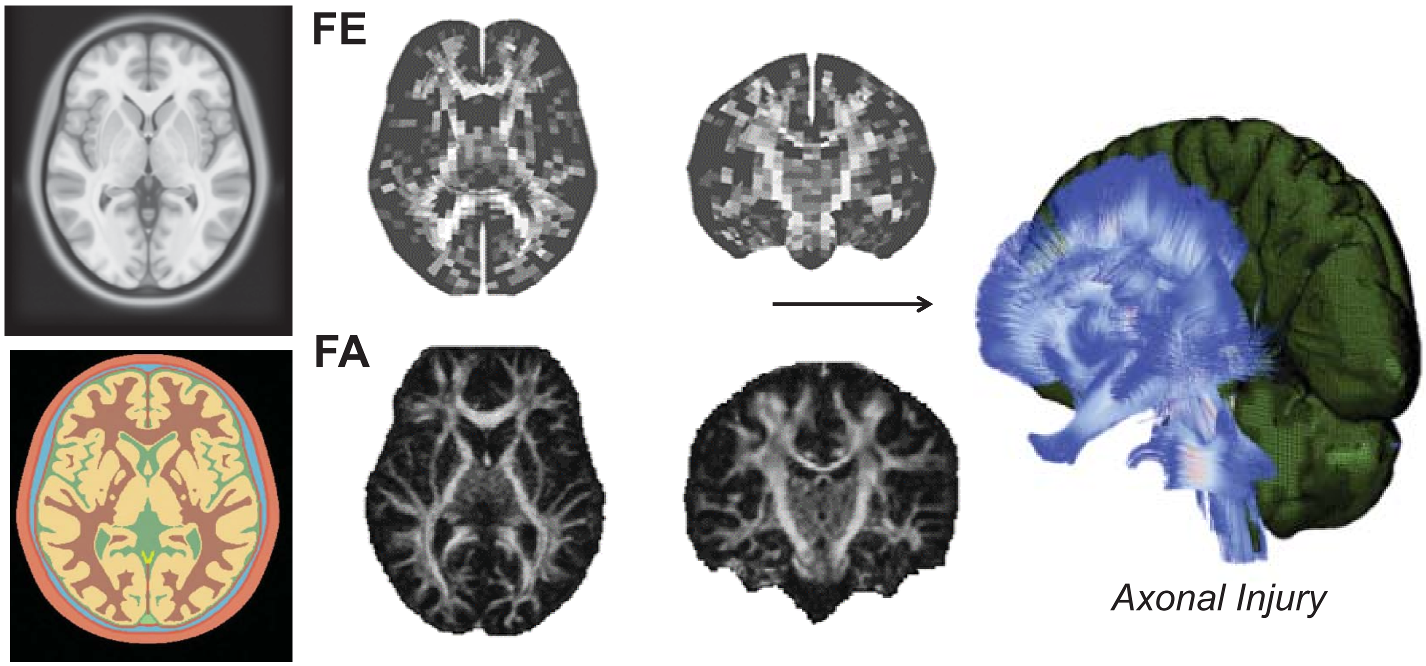
	-2 log likelihood ratio Statistic	p-value	p-value Hosmer-Lemeshow	Nagelkerke pseudo R^2	Perc. Correct classification
Resultant translational acc.	28,457	<0.001	0,315	0,52	74,1
Resultant roational acc.	25,439	<0.001	0,391	0,48	79,3
Resultant rotational vel.	14,193	<0.001	0,437	0,29	74,1
HIP	16,403	<0.001	0,587	0,33	77,6
HIC	31,528	<0.001	0,955	0,56	82,8
Transl. Acc + Rot. Acc.	32,875	<0.001	0,348	0,58	82,8
Transl. Acc + Rot. Vel.	33,119	<0.001	0,097	0,58	84,5
HIC + Rot. Acc.	35,477	<0.001	0,816	0,61	86,2
HIC + Rot. Vel.	35,856	<0.001	0,582	0,62	87,9
HIC + Rot. Vel. X, Y, Z	41,847	<0.001	0,466	0,69	87,9

Kleiven, *Stapp Car Crash Journal 2007*

Overview of the presentation

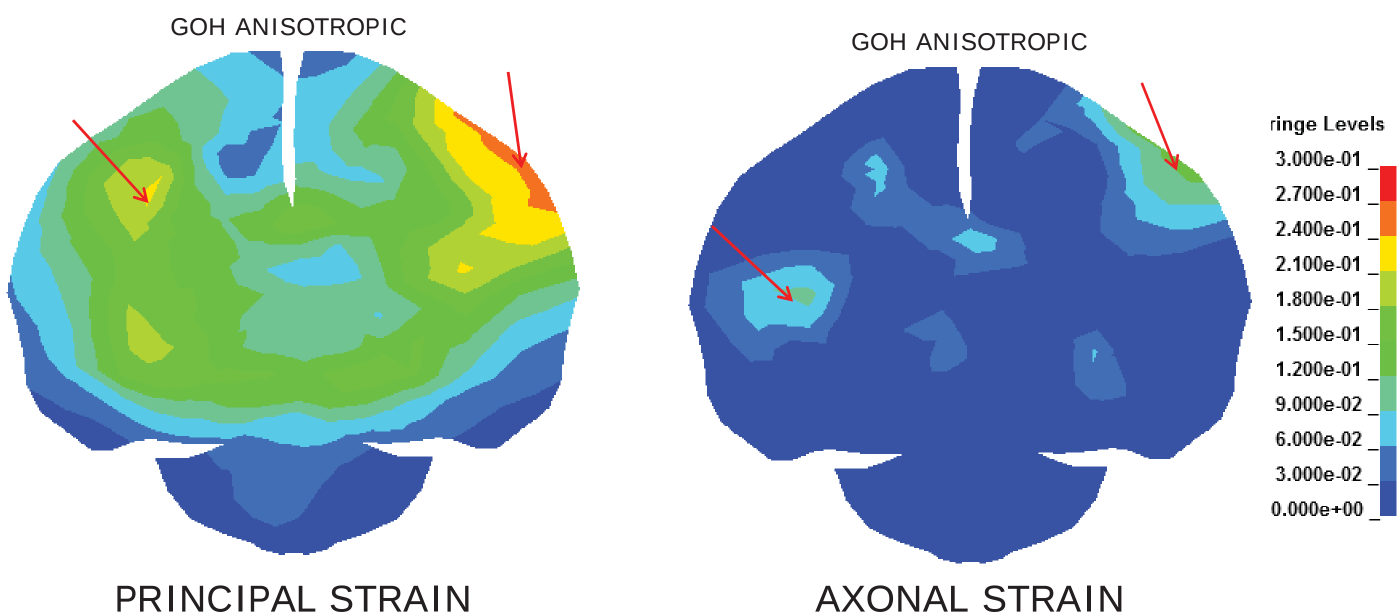
- FE modelling of the human head
- Injurious strains induced by angular motion
- Influence of impact direction
- Angular velocity as a predictor of strain
- **Axonal injury prediction**

Connecting FA with mechanical anisotropy



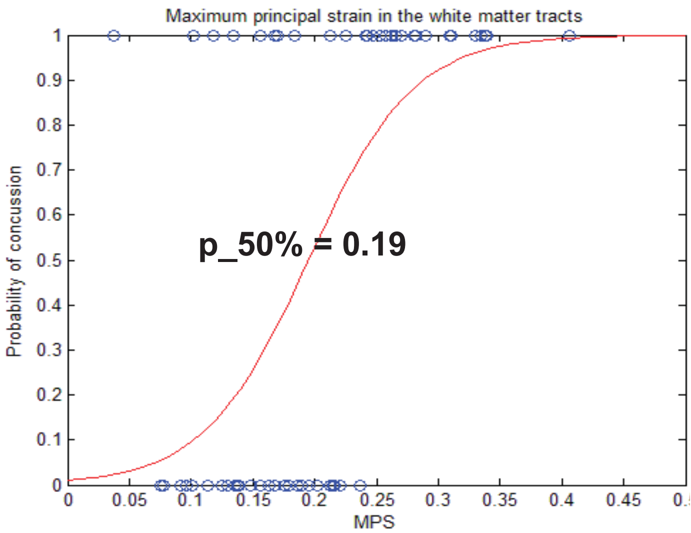
Giordano & Kleiven, *Roy.Soc.Int. 2014*

Maximum principal strain is an overprediction of axonal strain

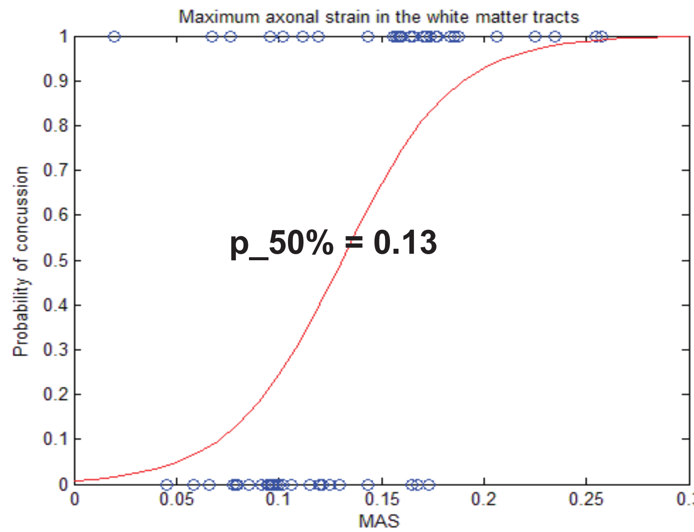


Giordano *et al.* J. Biomech. 2014

Axonal strains better predict concussion



74 % of concussions are correctly classified



81 % of concussions are correctly classified

Giordano & Kleiven, *Stapp Car Crash. J 2014*

Conclusions

- Strain fringes is similar to injury patterns of contusions and hematoma in several accident reconstruction cases
- Injurious strains are mainly induced by angular motion
- Angular velocity is proportionate to strain
- Axonal strains better predict concussion than other predictors

Tissue level predictor or global predictor?

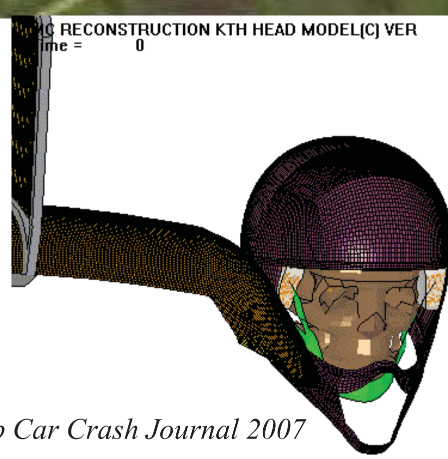
- If choosing a tissue level predictor (e.g. FEM)[1]:
  - Brain responses are different for each head FE model.
  - Lack of a standard adopted for successful validation.
  - Establish a set of criteria for model qualities such as mesh element qualities, numerical stability, mesh convergence, hourglass energy, etc.
- Bench-marking of models.

[1]Ji S. et al. (2013). Parametric Comparisons of Intracranial Mechanical Responses from Three Validated Finite Element Models of the Human Head.

Tissue level predictor or global predictor?

- If choosing a global predictor:
  - Load direction has to be accounted for
  - Angular velocity is more important for strain & injury than angular acceleration (Holbourn)
  - Has to reflect injury mechanism and severity

MC accident reconstruction



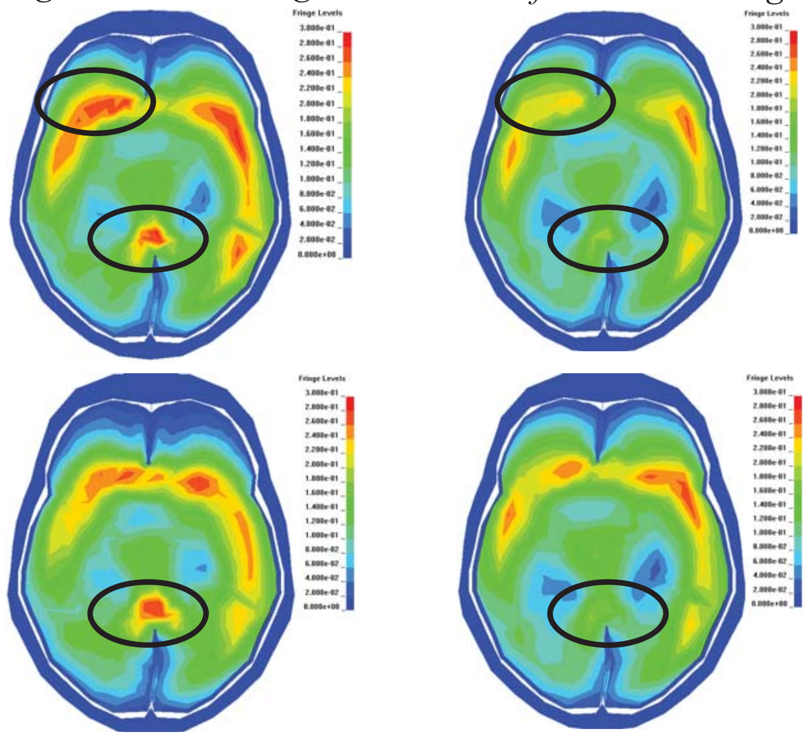
Kleiven, *Stapp Car Crash Journal 2007*

Helmet design for rotational protection

Hematoma in the frontal lobe

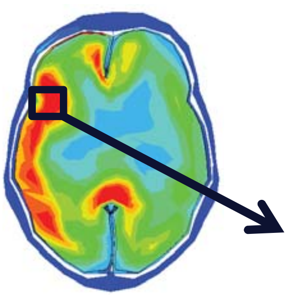
Hematoma in the rear part of the brain

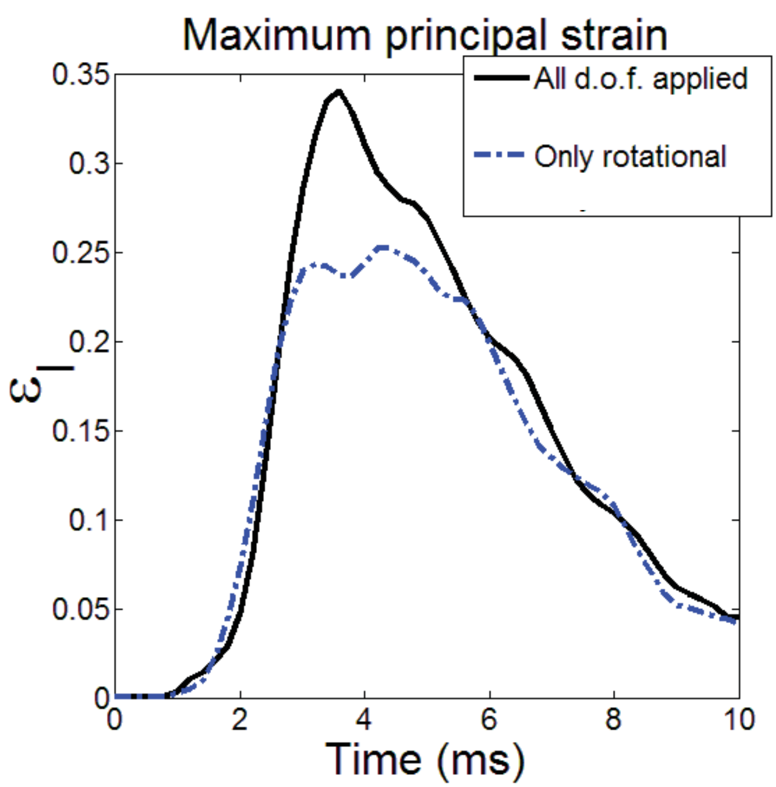
Regular helmet design *Modified helmet design*



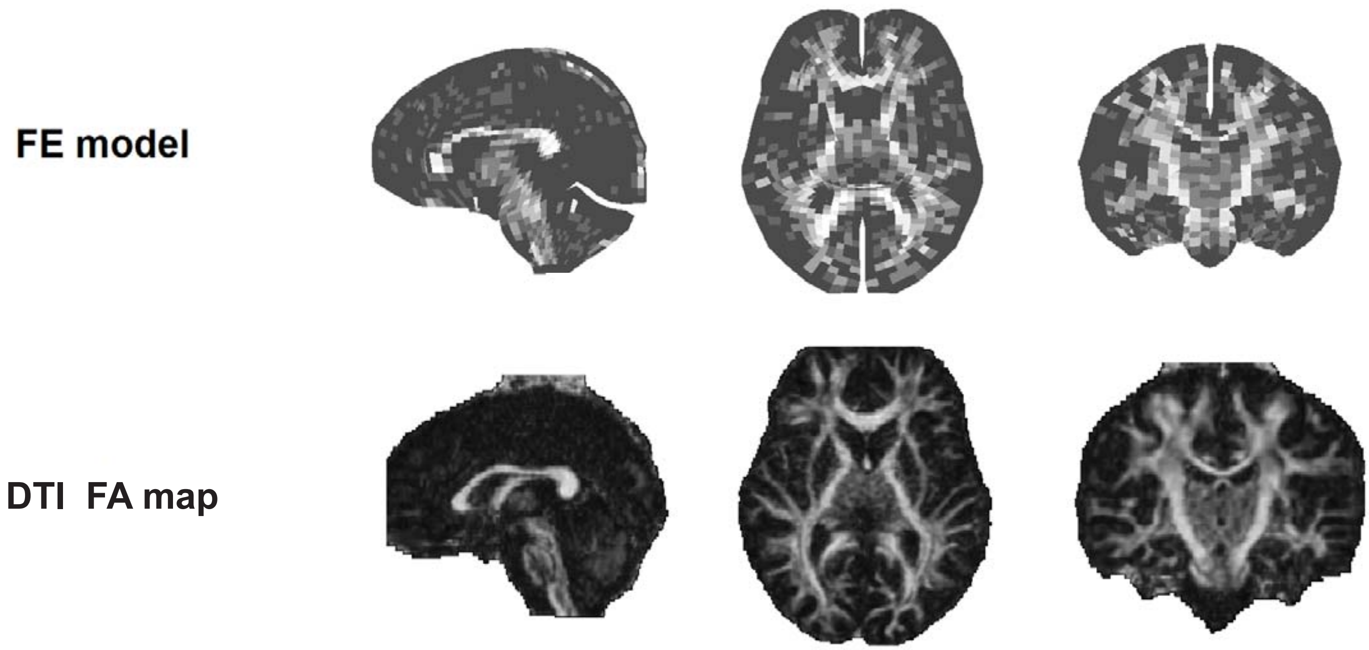
Halldin, Aare, Kleiven, von Holst, *Improved helmet design and test methods to reduce rotational induced brain injuries,* Proc. Int. Conf. on Closed Head Trauma, 2003.

Fall Accident reconstruction





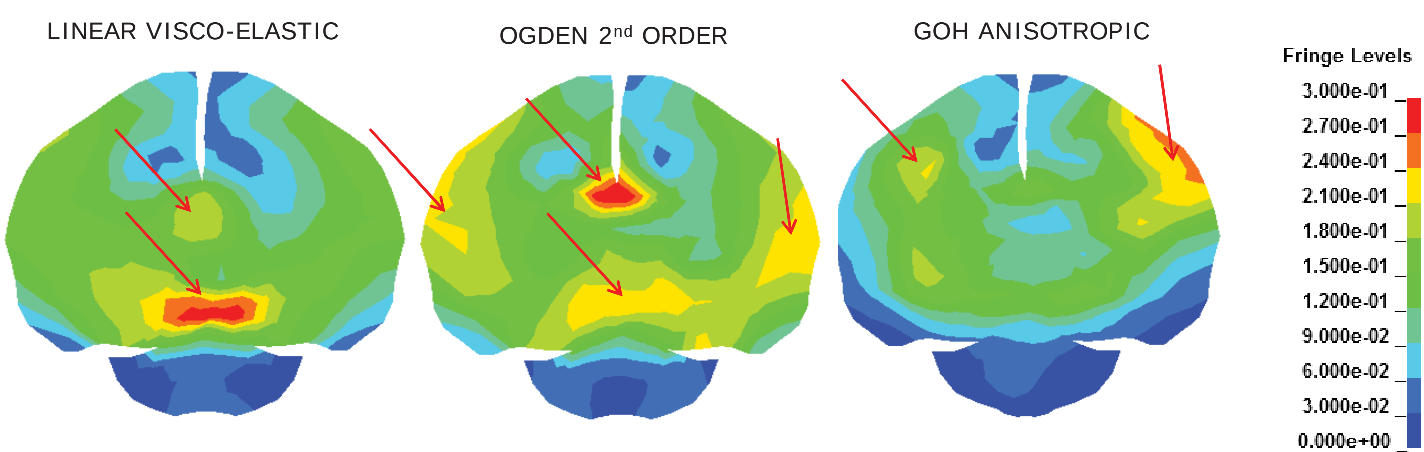
Connecting FA with mechanical anisotropy



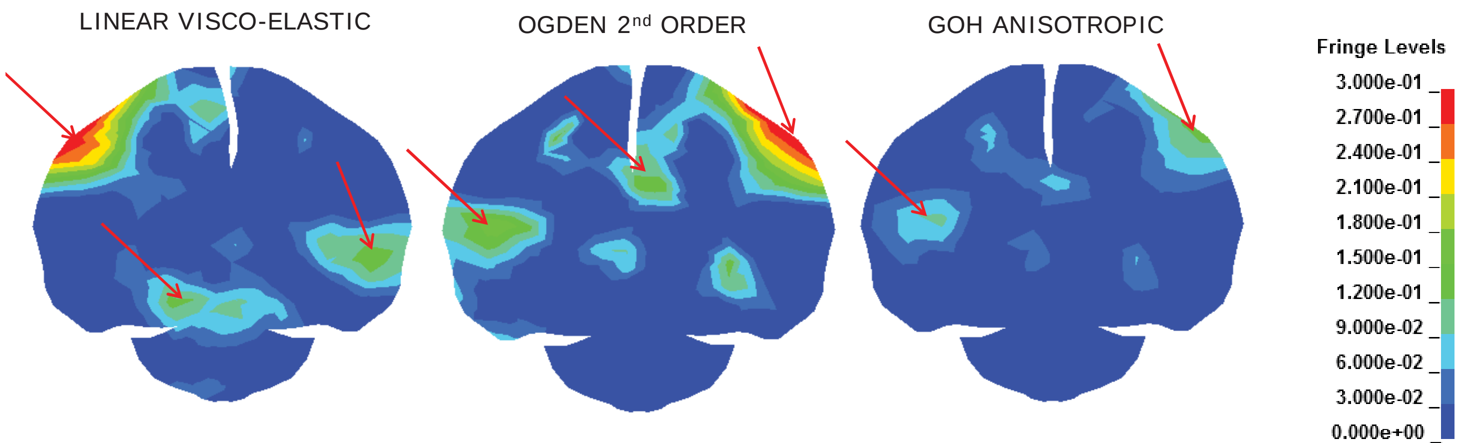
Giordano & Kleiven, *Roy.Soc.Int. 2014*

ROYAL INSTITUTE OF TECHNOLOGY

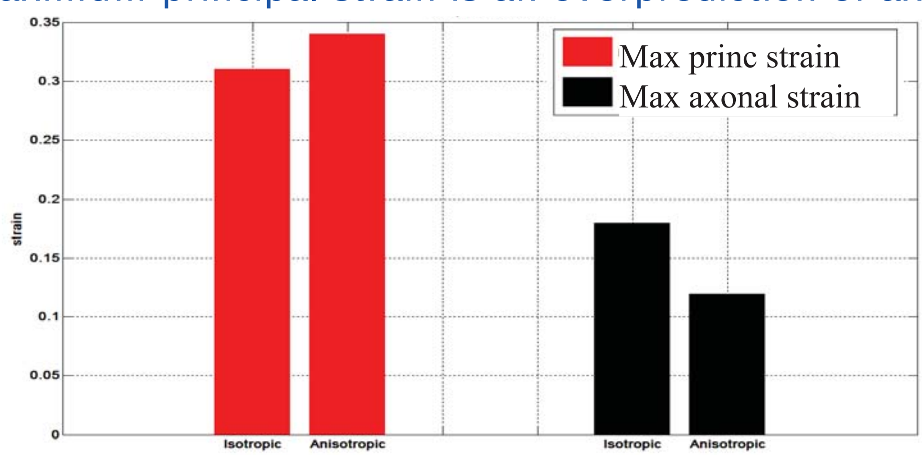
CONCUSSIVE CASE PRINCIPAL STRAIN

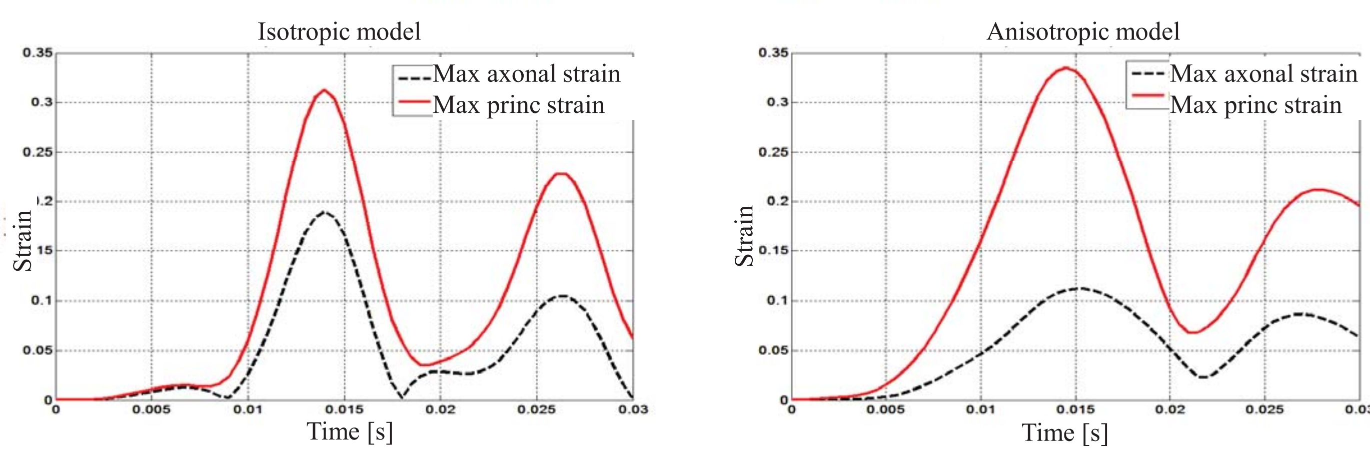


CONCUSSIVE CASE AXONAL STRAIN



Maximum principal strain is an overprediction of axonal strain





Giordano, Cloots, Van Dommelen & Kleiven, *J. Biomech. 2014*

AVERAGE	
Predictor	AUC
MPS	0.82
MAS	**0.92**
AESM	0.89
CSDM 10%	0.83
HIC	0.85
BrIC	0.86

Conclusions benchmark of DSNM, SIMon & WSU

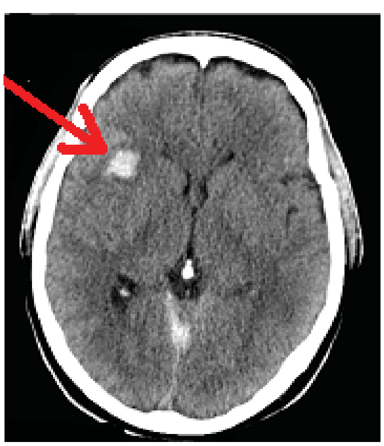
- Differ in mesh geometry and material properties.
- Significant disparities in brain responses ($p<0.05$) in both magnitude and spatial distribution.
- Model-predicted brain responses from one study should not be compared with or extended to other studies in which a different head FE model is utilized.
- Injury tolerance thresholds from a specific model also should not be generalized to other studies when a different model is used.
- Limited experimental data available for partial but incomplete model validation, and lack of a standard adopted for successful validation.
- Establish a set of criteria for model qualities such as mesh element qualities, numerical stability, mesh convergence, hourglass energy, etc.

Ji S. et al. (2013). Parametric Comparisons of Intracranial Mechanical Responses from Three Validated Finite Element Models of the Human Head.

Strain & pressure pattern in the brain

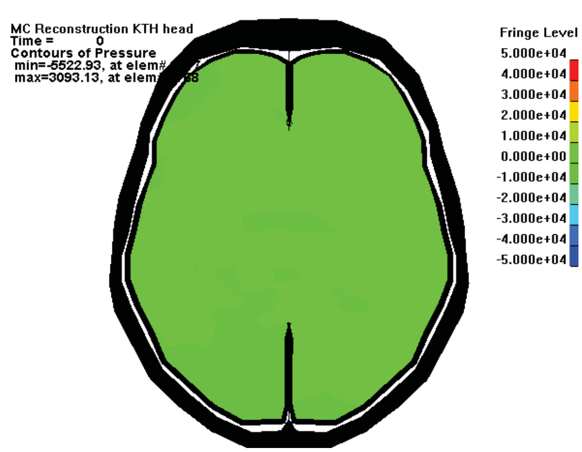
Hematoma in
the frontal lobe

FEM-simulations



CT image

Strain

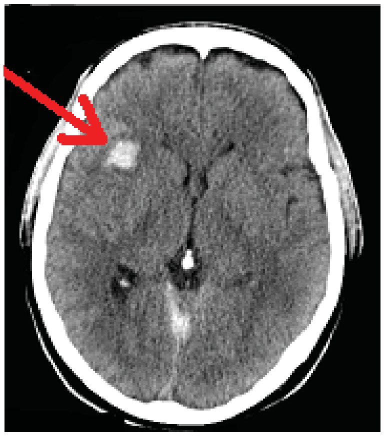


Pressure

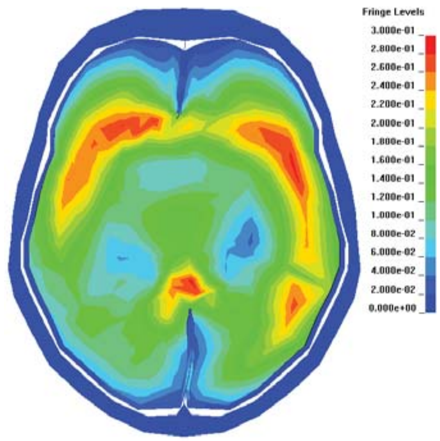
Strain & pressure pattern in the brain

Hematoma in
the frontal lobe

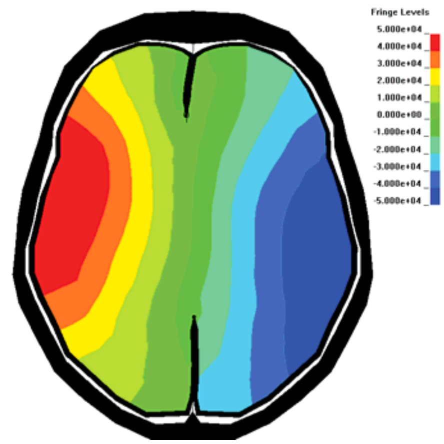
FEM-simulations



CT image



Strain

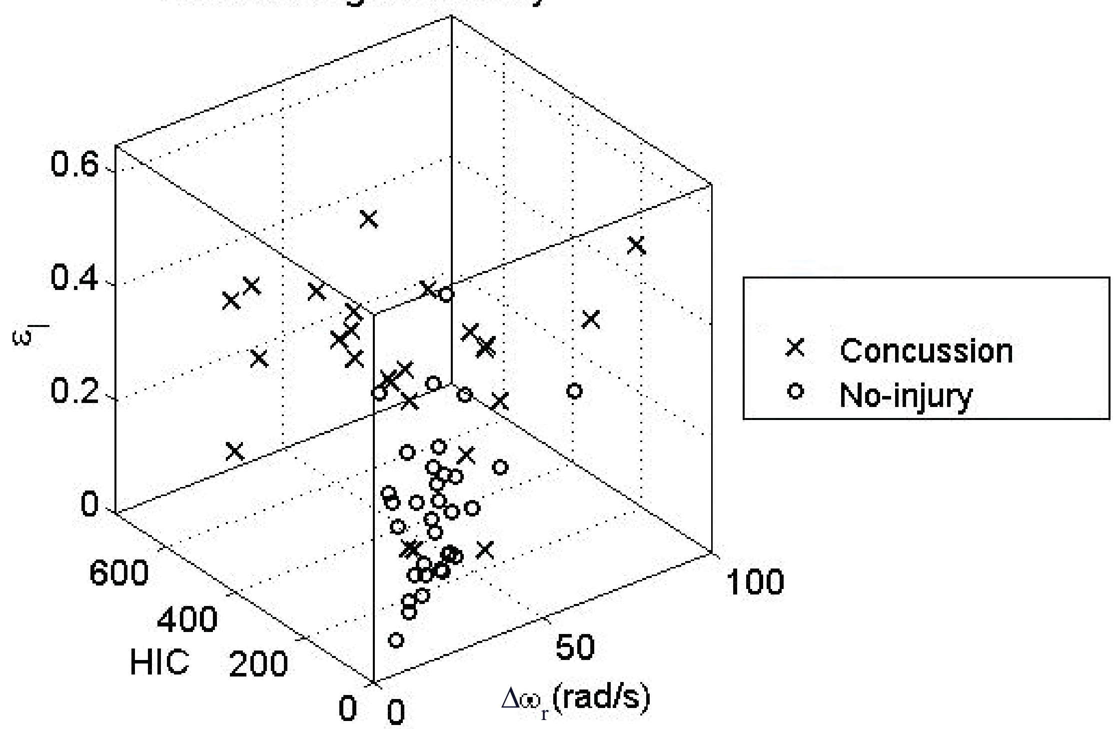


Pressure

Kleiven, *Stapp Car Crash Journal 2007*

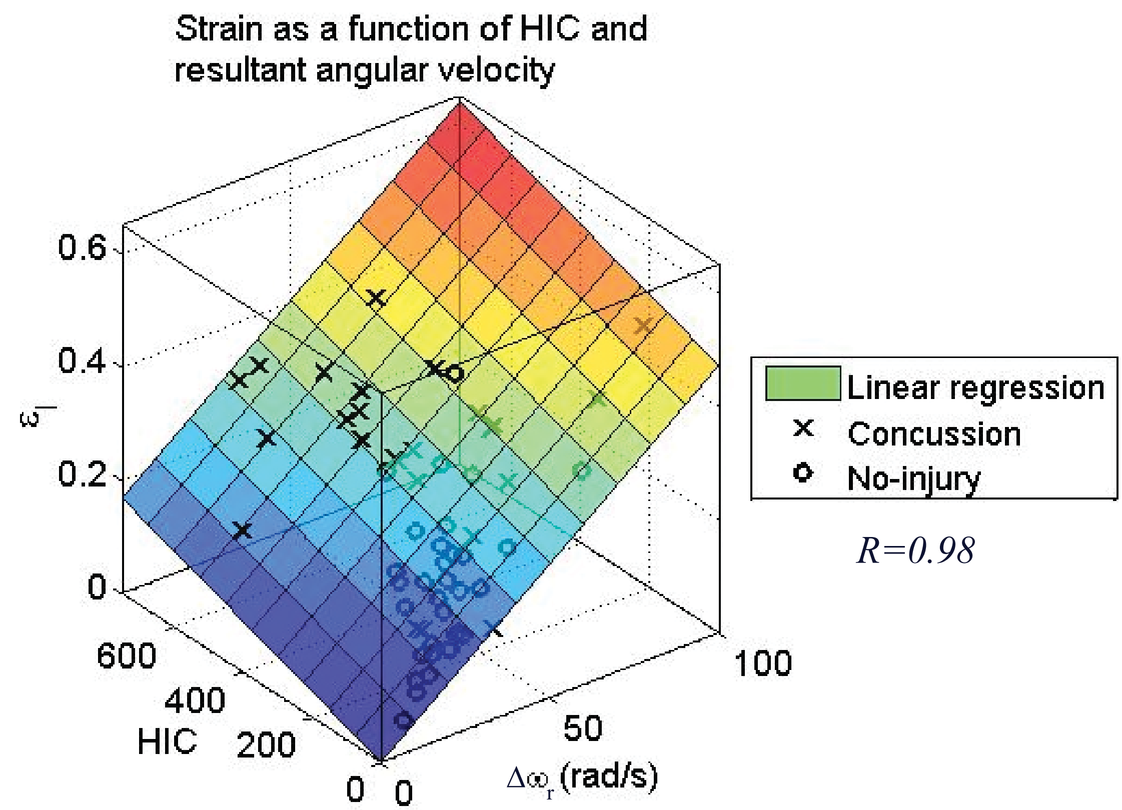
Division of Neuronic Engineering

Strain as a function of HIC and resultant angular velocity



$$\varepsilon_I(\Delta\omega_r, HIC) = 0.004718 \cdot \Delta\omega_r + 0.000224\, HIC$$

Kleiven, *Stapp Car Crash Journal 2007*

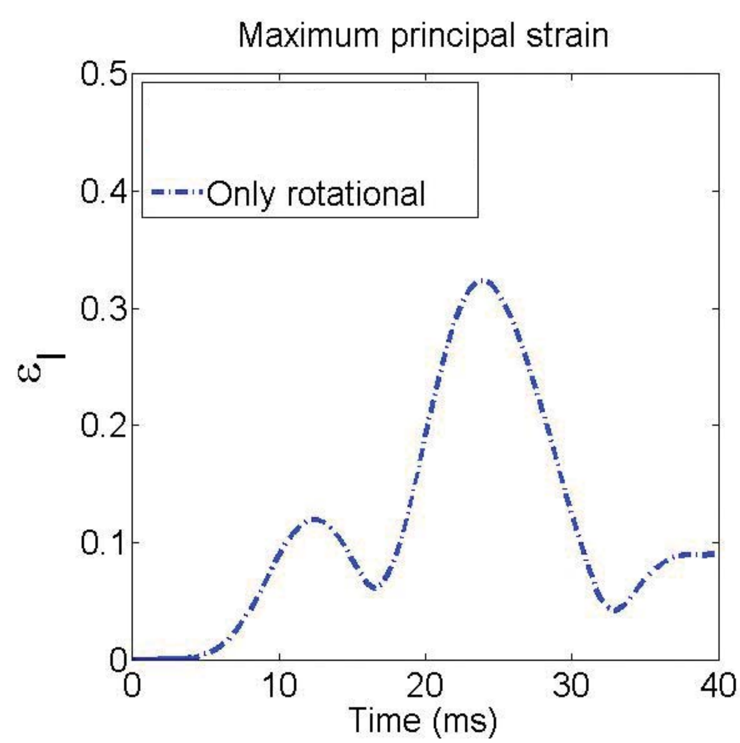


R=0.98

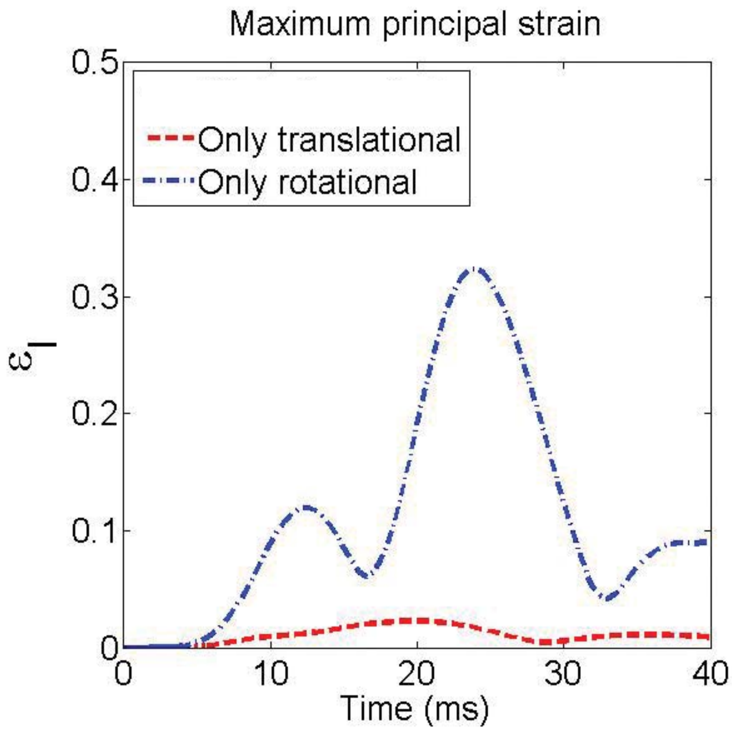
$$\varepsilon_I(\Delta\omega_r, HIC) = 0.004718 \cdot \Delta\omega_r + 0.000224 \cdot HIC$$

Kleiven, *Stapp Car Crash Journal 2007*

Influence of rotational and translational kinematics



Influence of rotational and translational kinematics



Divisi

Summary

- Existing criteria (HIC) only accounts for a translational motion
- HIC is a good predictor for translational motion
- Rotational motion give higher strain in the brain due to its low shear modulus/high bulk modulus
- $\Delta\omega$ (rotational velocity) is a good predictor for rotational motion
- Load direction has to be accounted for

BrIC

Takhounts et al. 2013

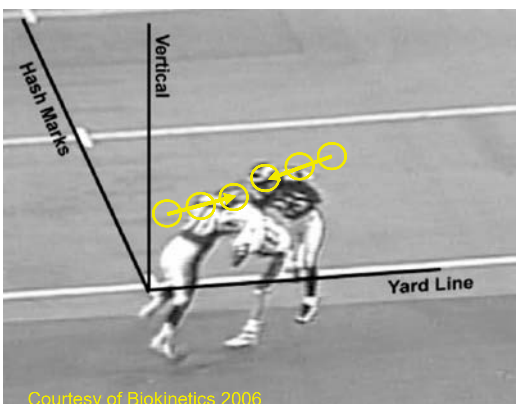
$$BrIC = \sqrt{\left(\frac{w_x}{w_{xc}}\right)^2 + \left(\frac{w_y}{w_{yc}}\right)^2 + \left(\frac{w_z}{w_{zc}}\right)^2}$$

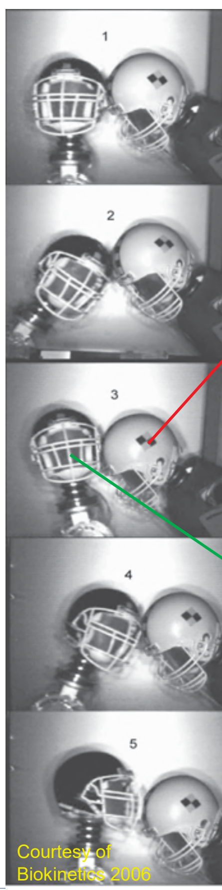
evaluates the effect of angular velocity components on brain damage. The criterion is based on angular velocities in different directions as the mechanism for brain injury.

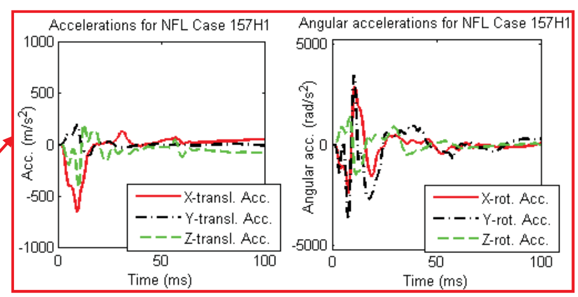
w_{xc}, w_{yc}, and w_{zc} : critical angular velocities

SiMON head model:
66.3, 53.8 and 41.5 rad/s

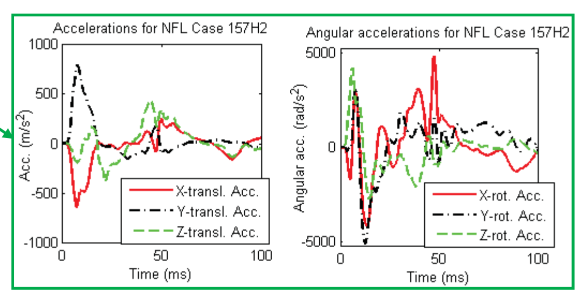
KTH head model:
45.2, 40.1 and 27.5 rad/s





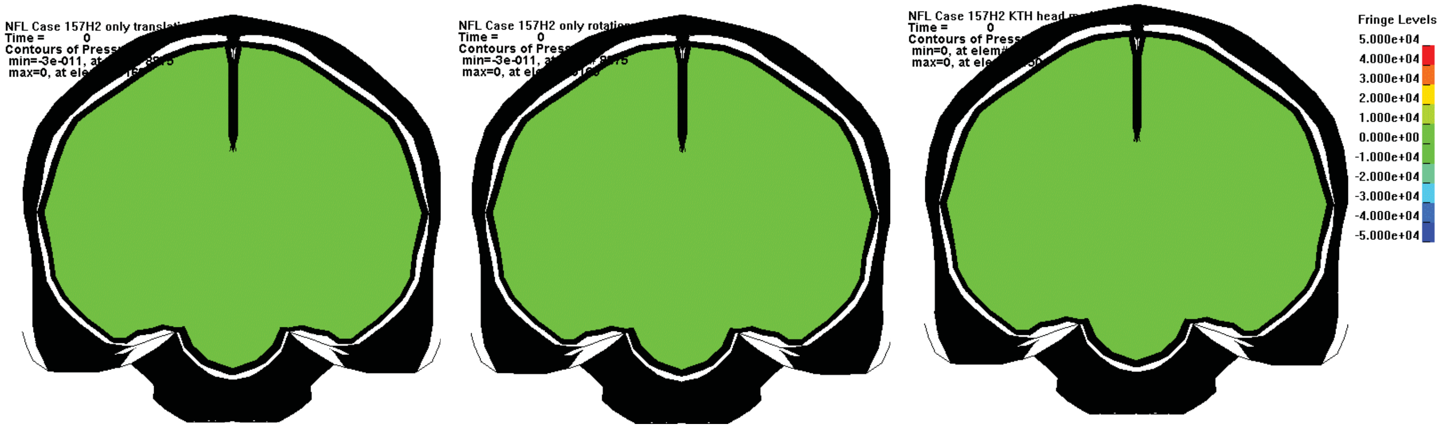


Striking player (H1)



Struck player (H2)

Influence of rotational and translational kinematics



Only translational kinematics *Only rotational kinematics* *All kinematics applied*

Automatic generation of finite element models from DTIs

Aim :

To create a patient specific FE-model

Input :

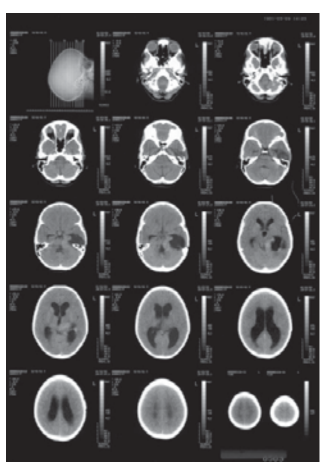
DTI / MR from the patient

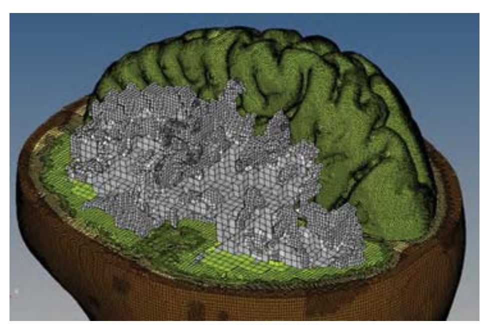
Procedure:

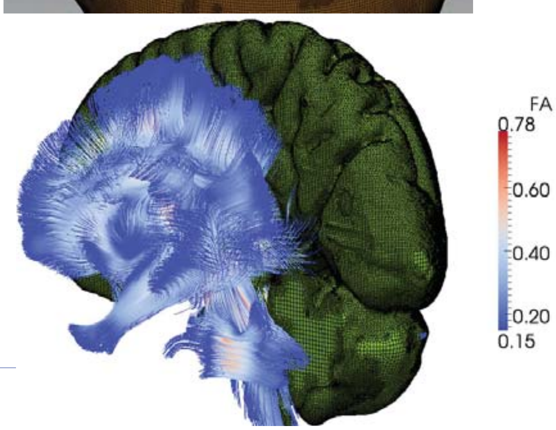
Anatomy & anisotropy is extracted

Result :

Authentic model

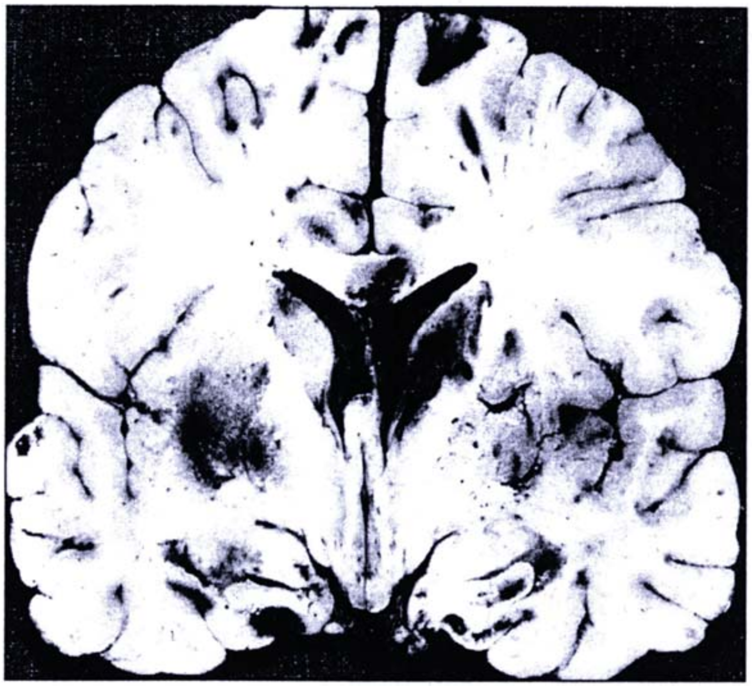


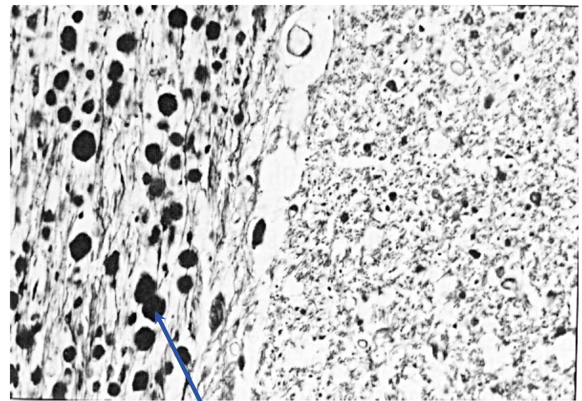




Giordano & Kleiven, Roy.Soc.Int. 2014; Giordano *et al.* J. Biomech. 2014

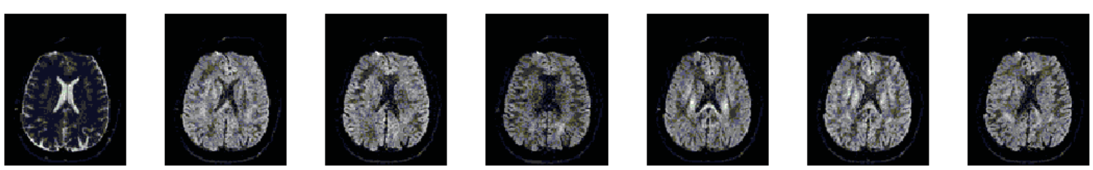
Diffuse Axonal Injury

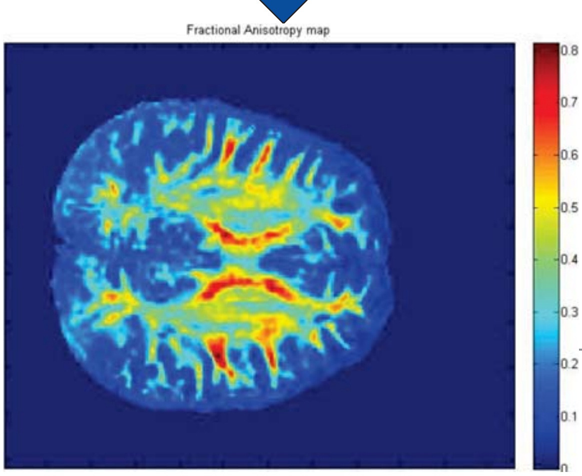




Axonal swelling (left)
360 X Amplif.

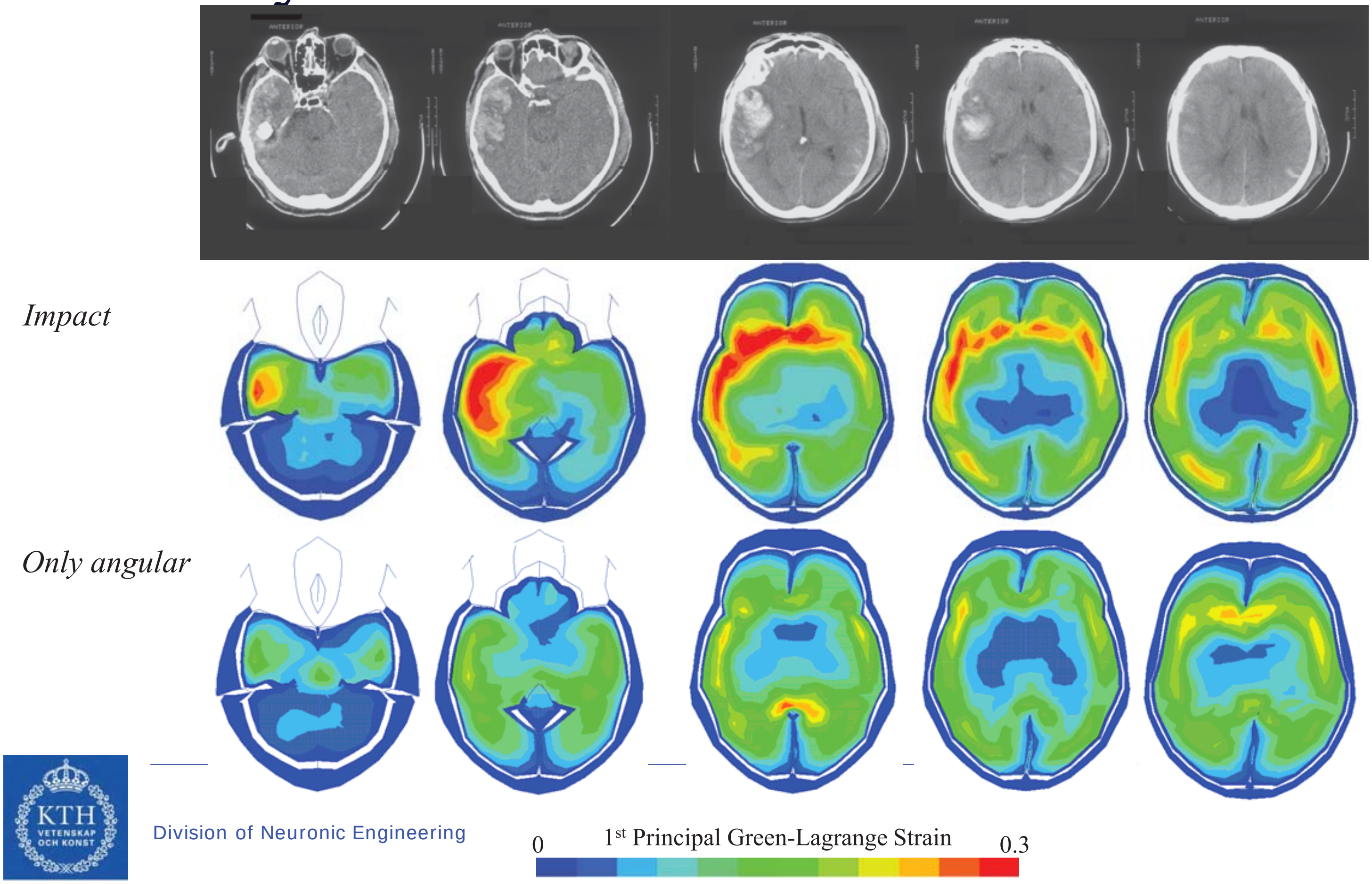
Diffusion Weighted Images





Diffusion Tensor Imaging (DTI) is a MRI technique that can delineate macroscopic axonal organization in brain tissue.

Bicycle Accident reconstruction



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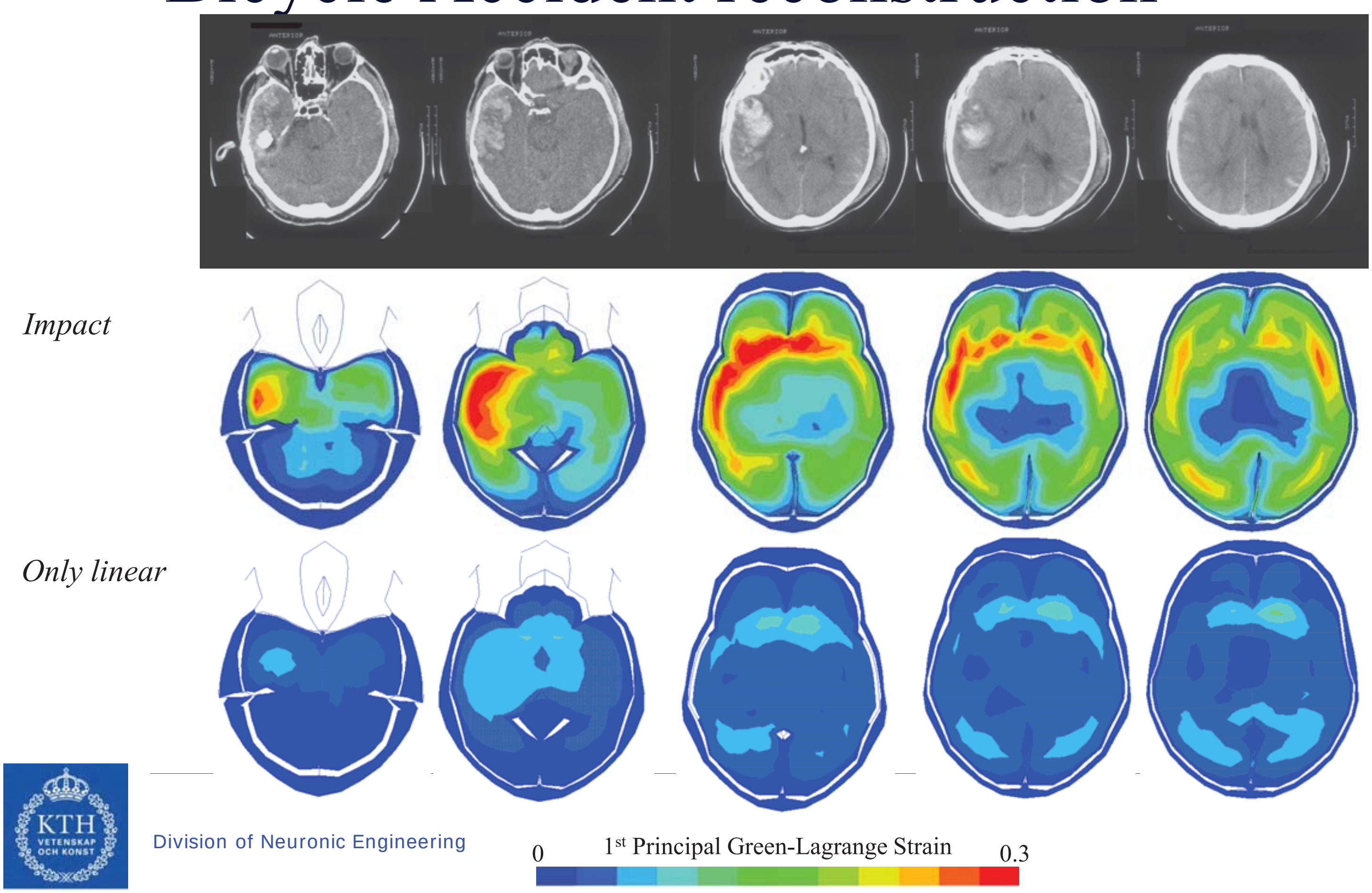
Bicycle Accident reconstruction



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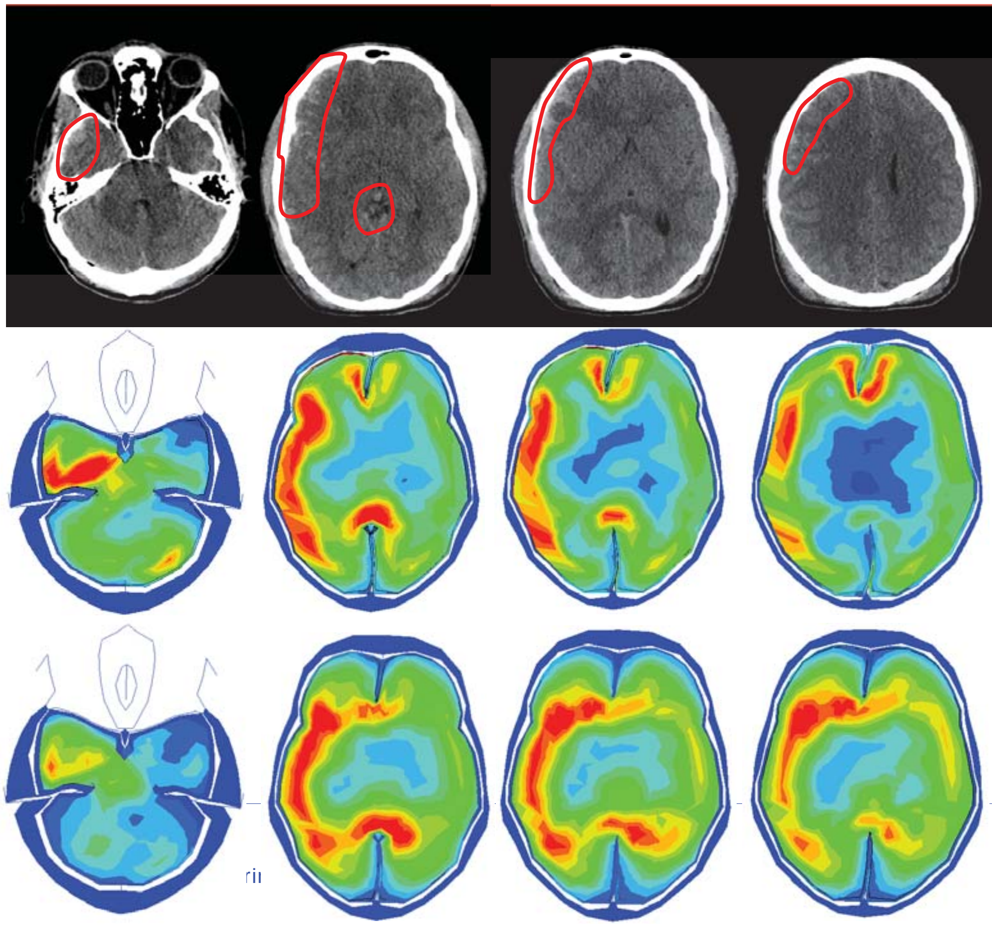
Fall Accident reconstruction

Impact

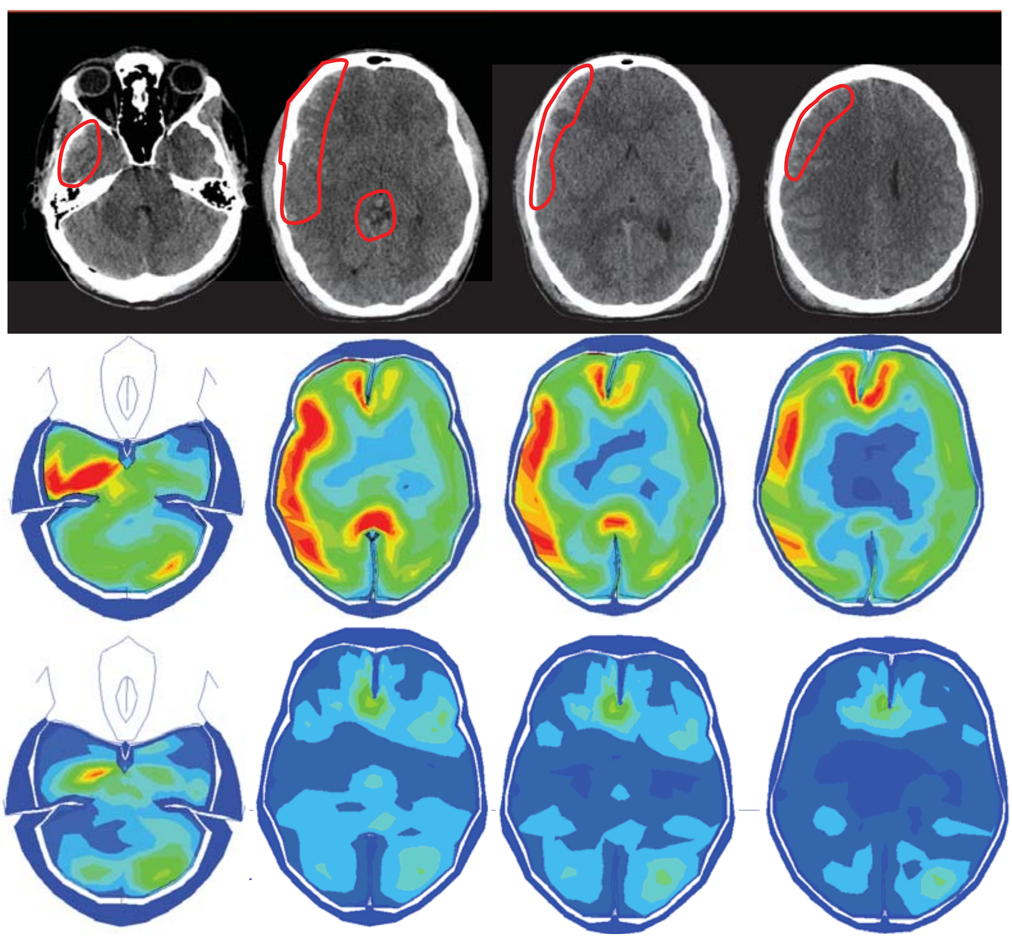
Only angular



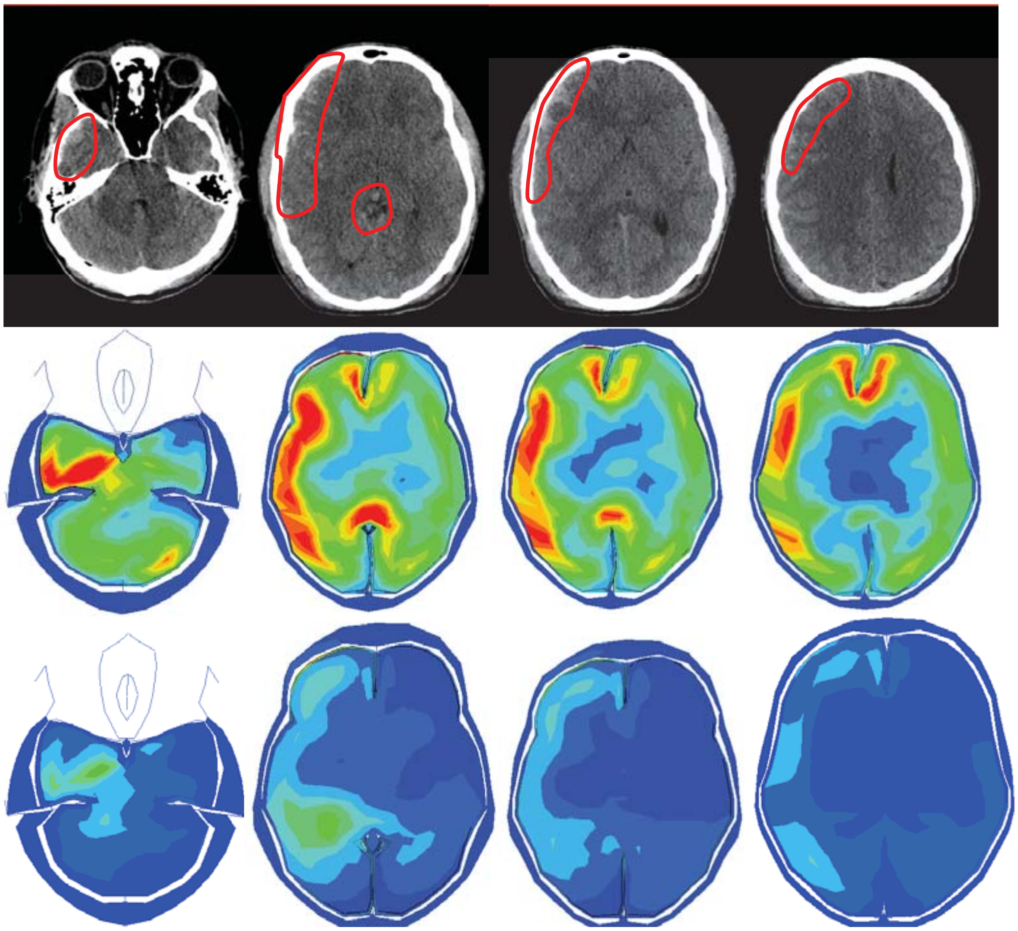
Fall Accident reconstruction

Impact

Only linear



Fall Accident reconstruction



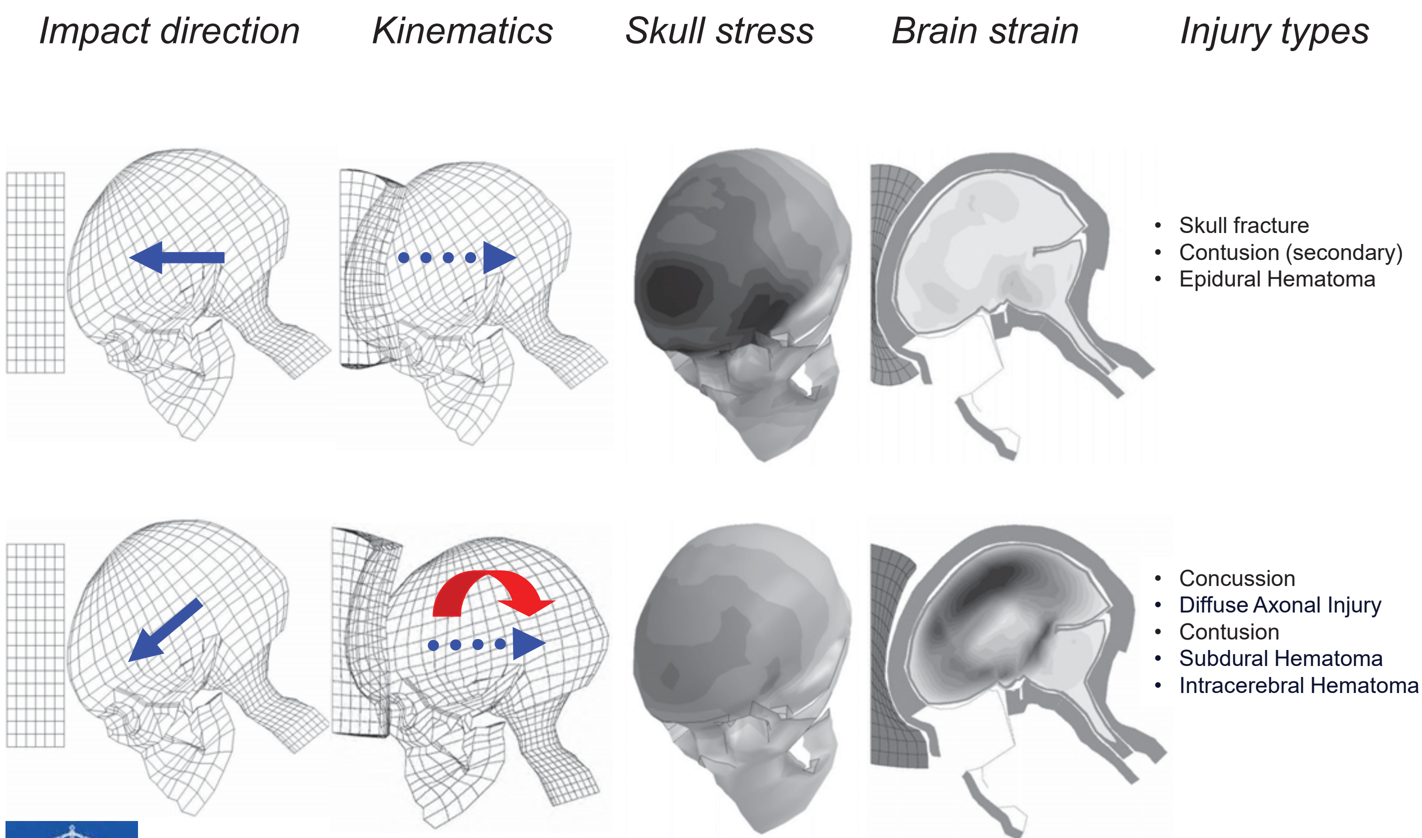
Impact

Only skull def.

Material properties of brain tissue

- Average experimental Shear modulus (G_0) around 2.0 *kPa*
- Bulk modulus around 2.0 *GPa* (as water)

$$\boxed{K \approx 10^6 \cdot G}$$



Impact direction
Kinematics
Skull stress
Brain strain
Injury types
Skull fracture
Contusion (secondary)
Epidural Hematoma
Concussion
Diffuse Axonal Injury
Contusion
Subdural Hematoma
Intracerebral Hematoma

BrIC Update:
Does BrIC Depend on the Signal Time Duration?

Erik G. Takhounts

The views expressed here are my own and not necessarily those of DOT

Current Formulation (Takhounts et al., 2013)

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

$\boldsymbol{\omega_{xC}}$	**66.25 rad/s**
$\boldsymbol{\omega_{yC}}$	**56.45 rad/s**
$\boldsymbol{\omega_{zC}}$	**42.87 rad/s**

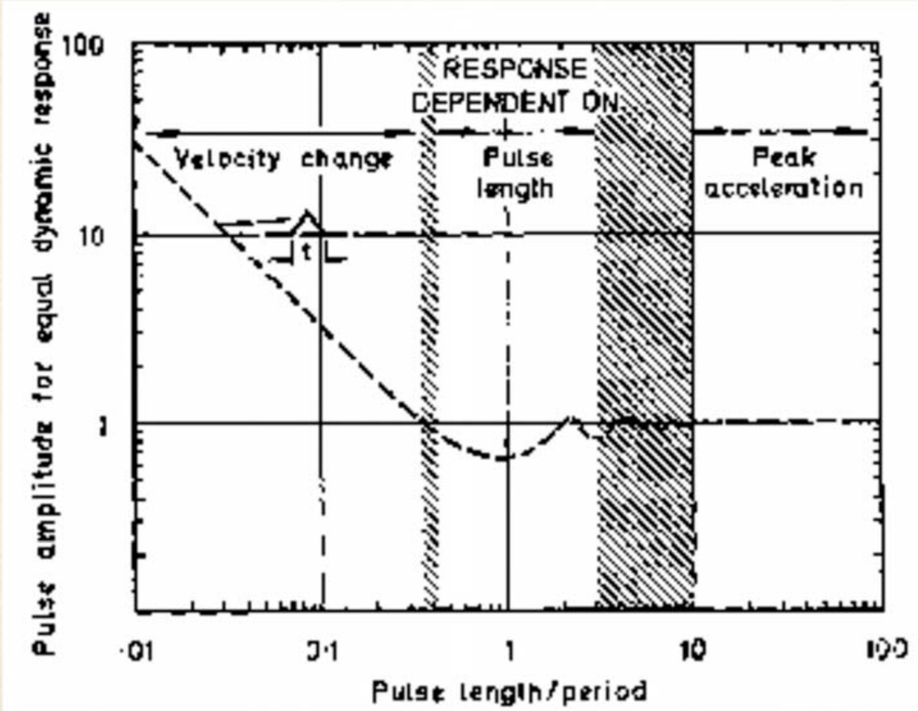
Motivation
Holbourn (1943)

“For blows of long duration the shear strains in the brain are proportional to the force, hence the injury is proportional to the acceleration, or the rate of change of velocity of the head.”

“For very short blows the injury is proportional to the force multiplied by the time for which it acts, hence the injury is proportional to the change of velocity of the head…”

The switchover occurs between 2 and 200 ms.

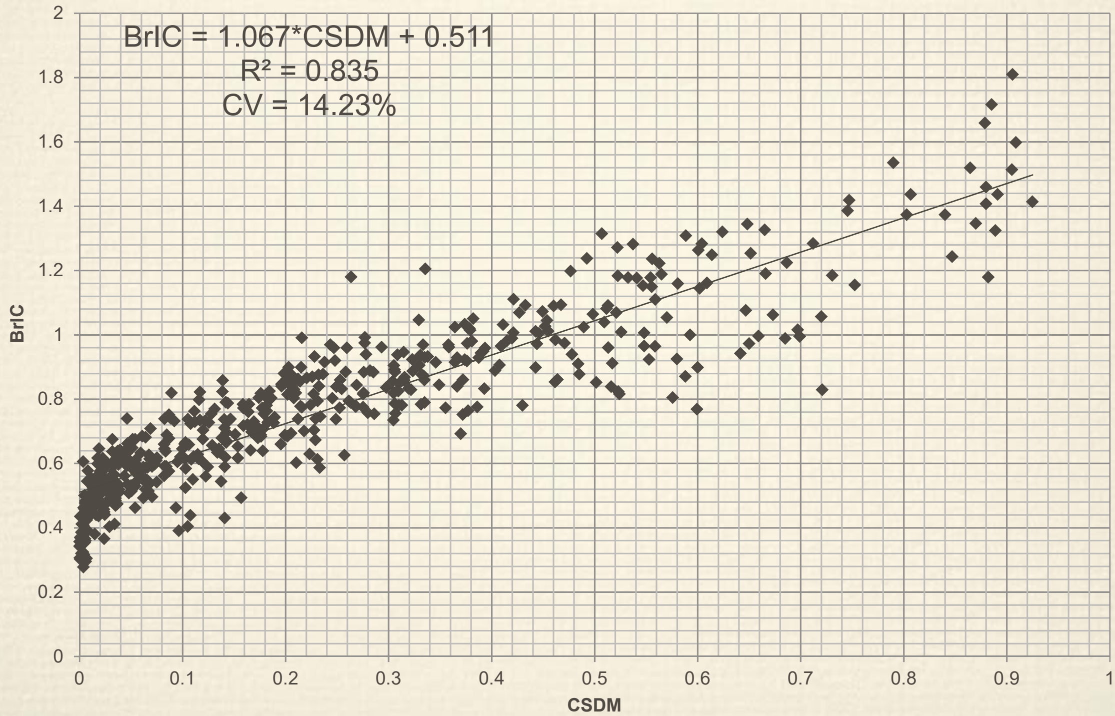
Glaister (1975) after H.E. von Gierke (1964)



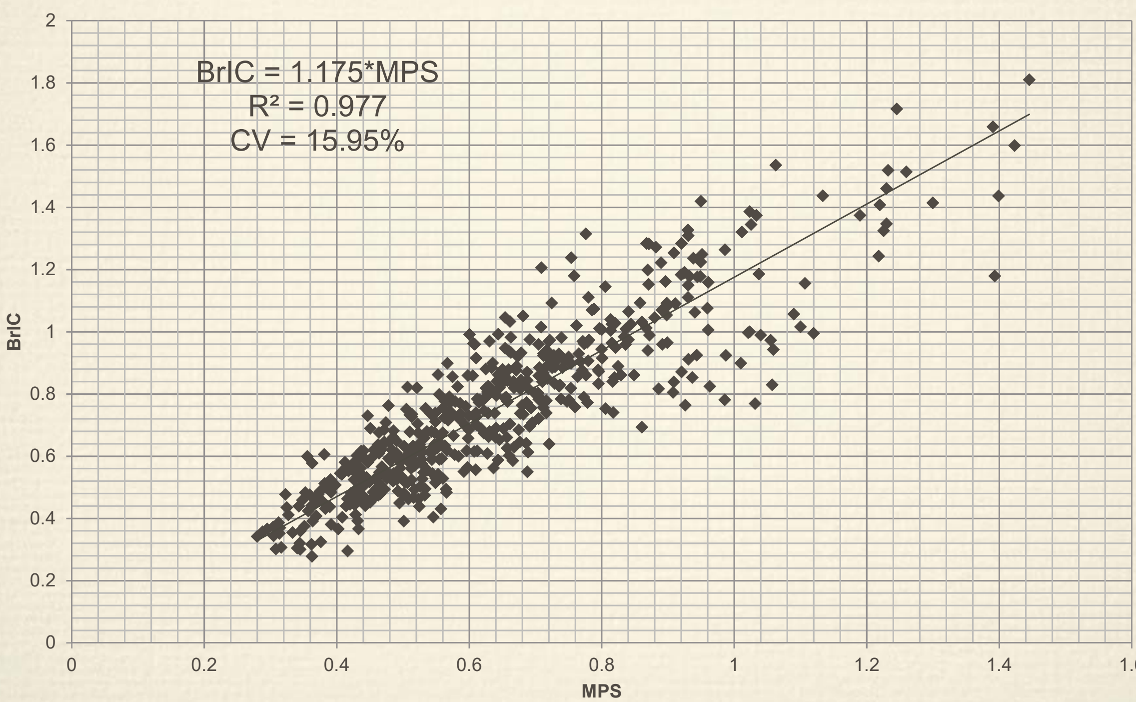
Research Question

Does BrIC depend on the time duration of the angular velocity signal?

“Original BrIC” is a Correlate for CSDM (543 tests)



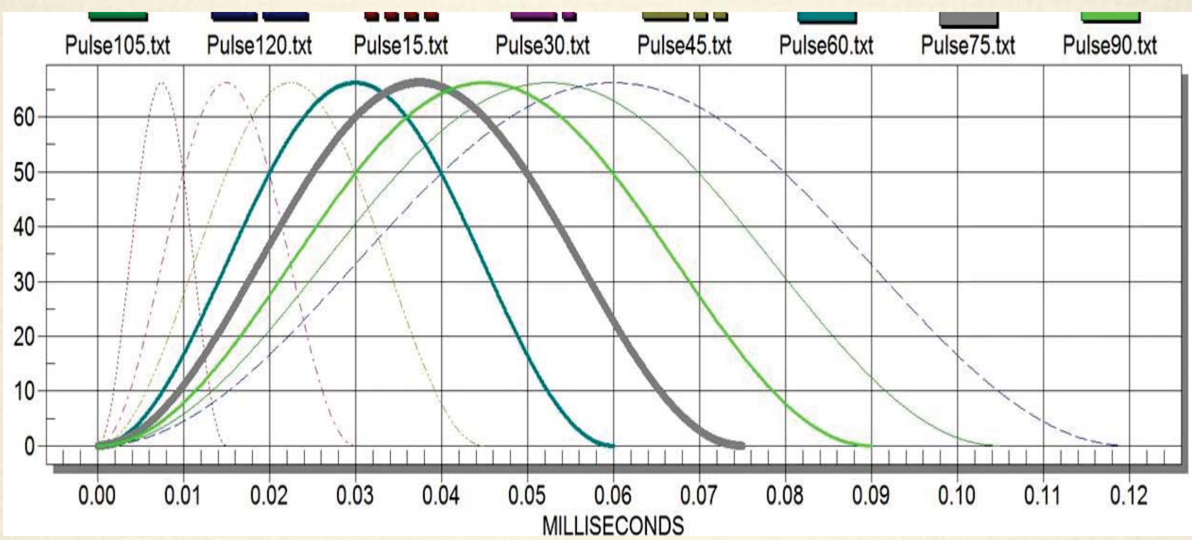
“Original BrIC” is a Correlate for MPS (543 tests)



Research Question (slightly modified)

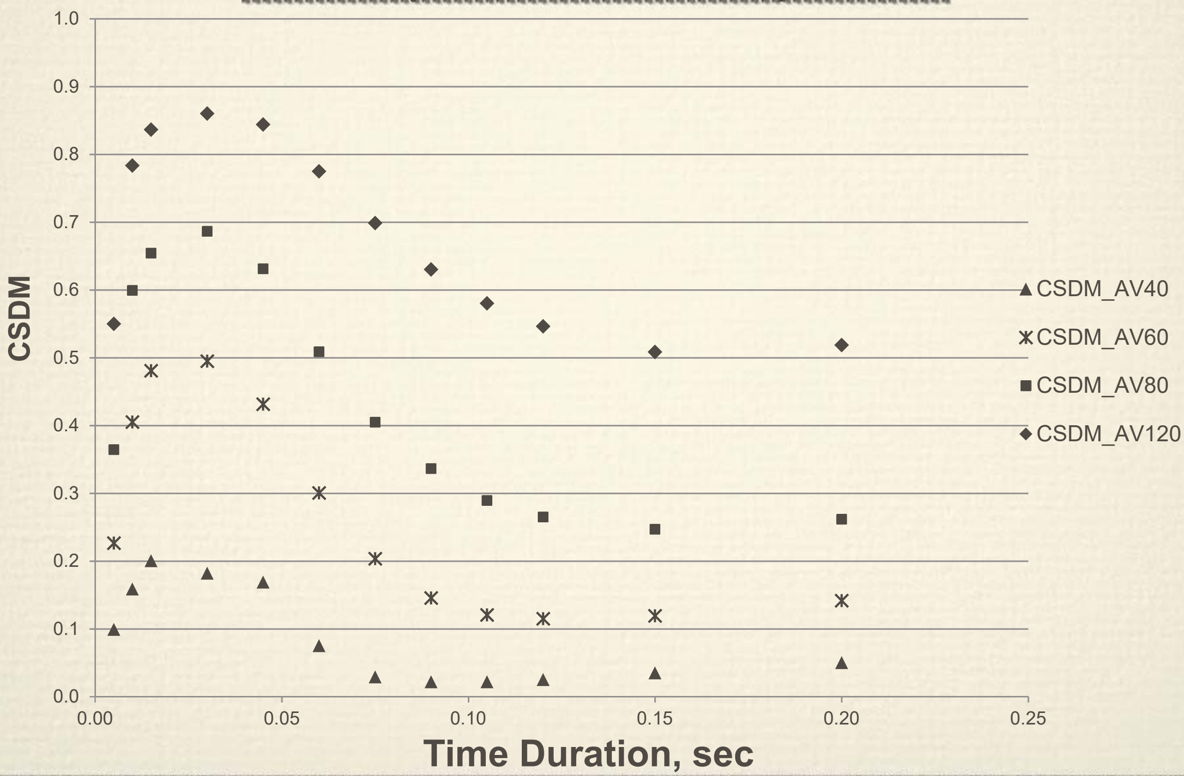
Does the CSDM depend on the time duration of the angular velocity signal?

Angular Velocity Input Signals to the SIMon FE Model

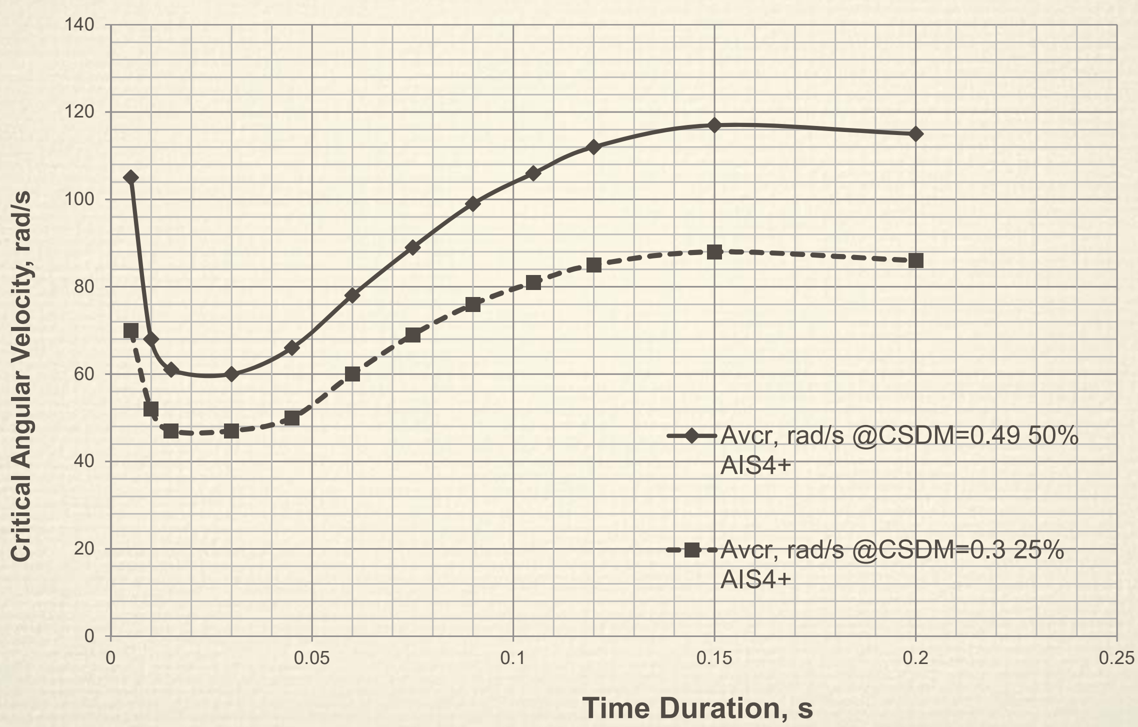


Magnitude range from 20 to 120 rad/s with 10 rad/s interval
Time duration range from 5 to 200 ms with 15 ms time interval

Results: CSDM vs Time Duration (X-direction)



Results: Critical Angular Velocity vs Time Duration (X-direction)

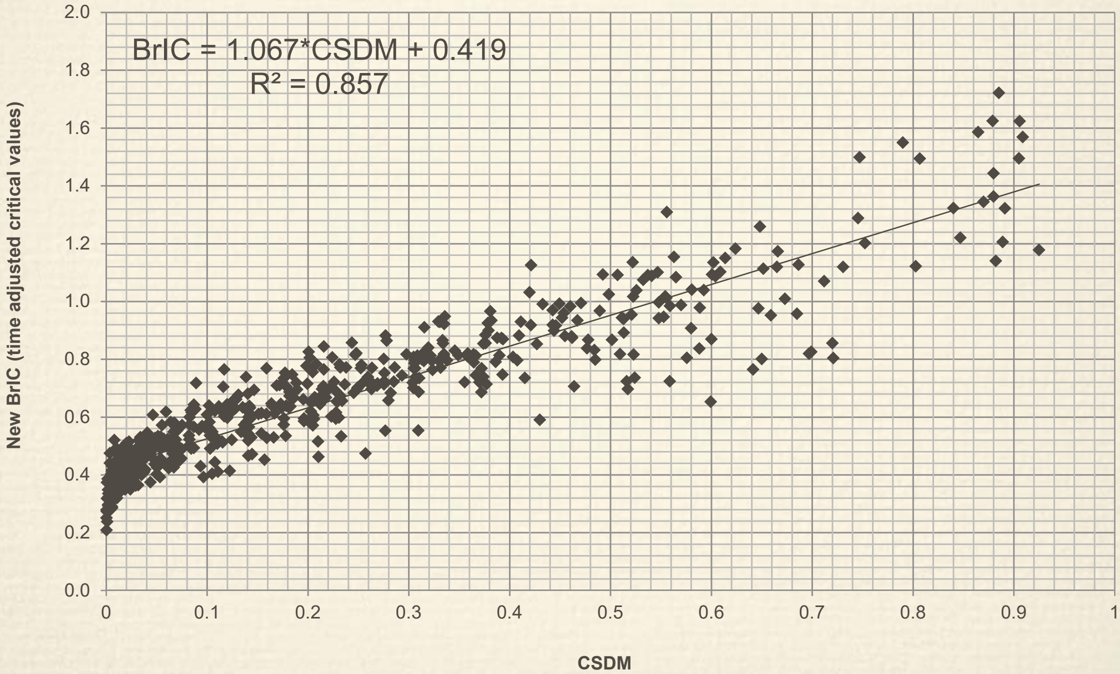


Results: Critical Angular Velocities for Each Time Duration

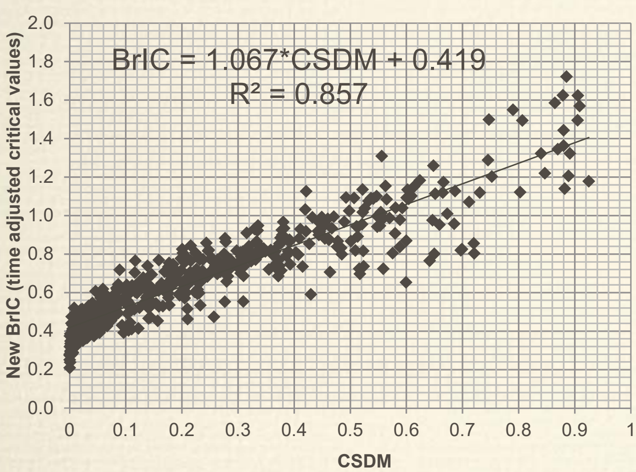
	X-direction		Y-direction		Z-direction	
Time, s	Avcr, rad/s @CSDM=0.49 50% AIS4+	Avcr, rad/s @CSDM=0.30 25% AIS4+	Avcr, rad/s @CSDM=0.49 50% AIS4+	Avcr, rad/s @CSDM=0.30 25% AIS4+	Avcr, rad/s @CSDM=0.49 50% AIS4+	Avcr, rad/s @CSDM=0.30 25% AIS4+
0.005	105	70	92	65	99	57
0.010	68	52	66	52	60	39
0.015	61	47	59	49	46	34
0.030	60	47	58	48	42	32
0.045	66	50	54	46	39	31
0.060	78	60	59	51	50	38
0.075	89	69	68	57	64	49
0.090	99	76	74	62	73	57
0.105	106	81	80	65	81	63
0.120	112	85	84	68	87	68
0.150	117	88	89	70	95	74
0.200	115	86	93	70	100	78

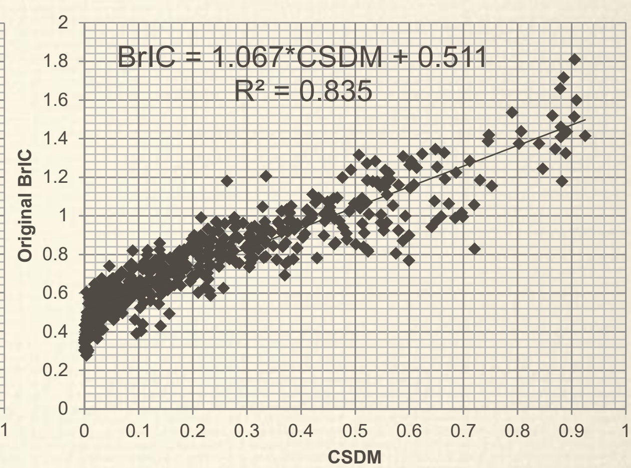
Devised three methods of calculating time duration for an arbitrary signal and recalculated BrIC (New BrIC) with the time adjusted critical values

"New BrIC" as a Correlate for CSDM (543 tests)



"New BrIC" vs "Original BrIC"





For CSDM = 0.49, BrIC = 0.94

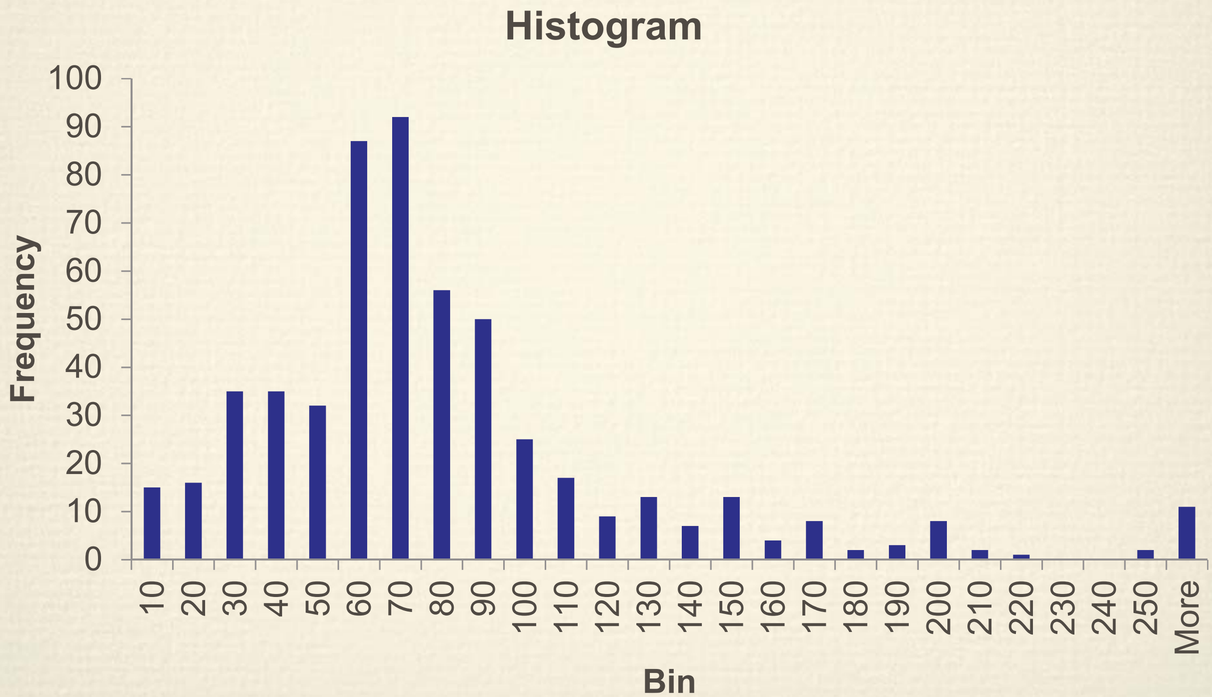
For CSDM = 0.49, BrIC = 1.03

Conclusions

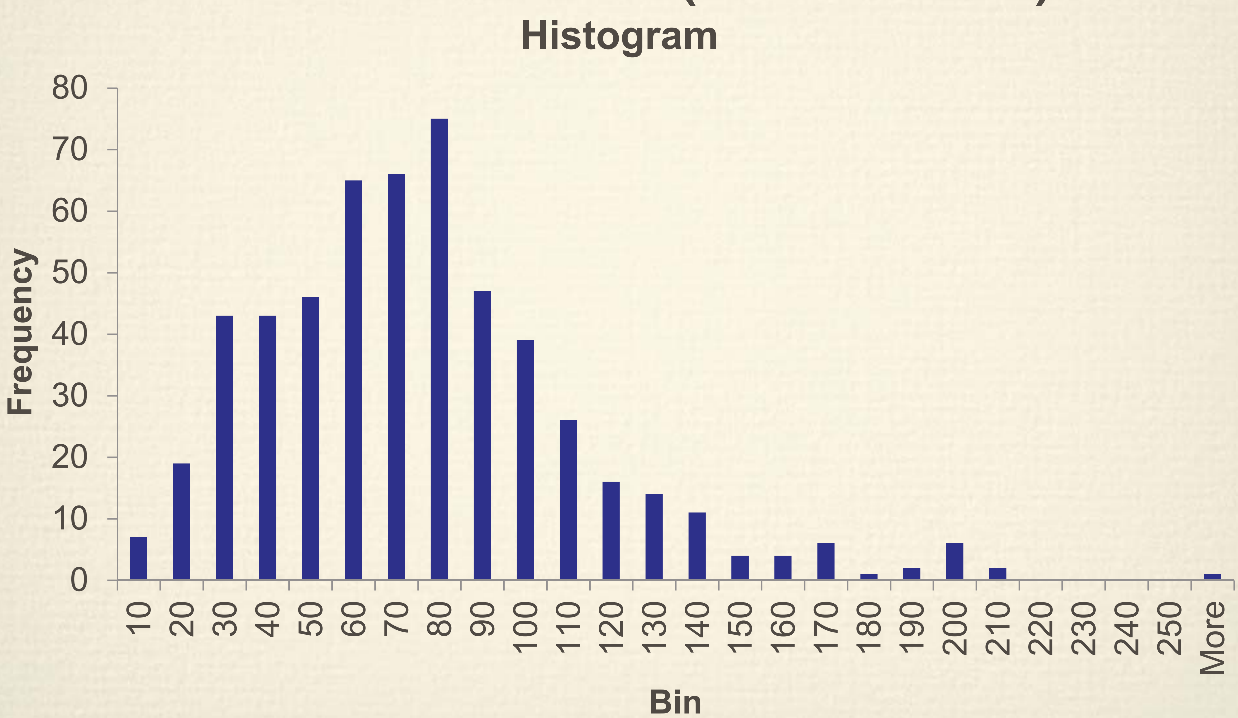
- No clear advantage for using the time adjusted BrIC – New BrIC – for evaluating brain injury risk for car passengers
- For pedestrians, where the pulse time duration is much longer than those seen in car occupants, the time adjusted BrIC may be useful

The End

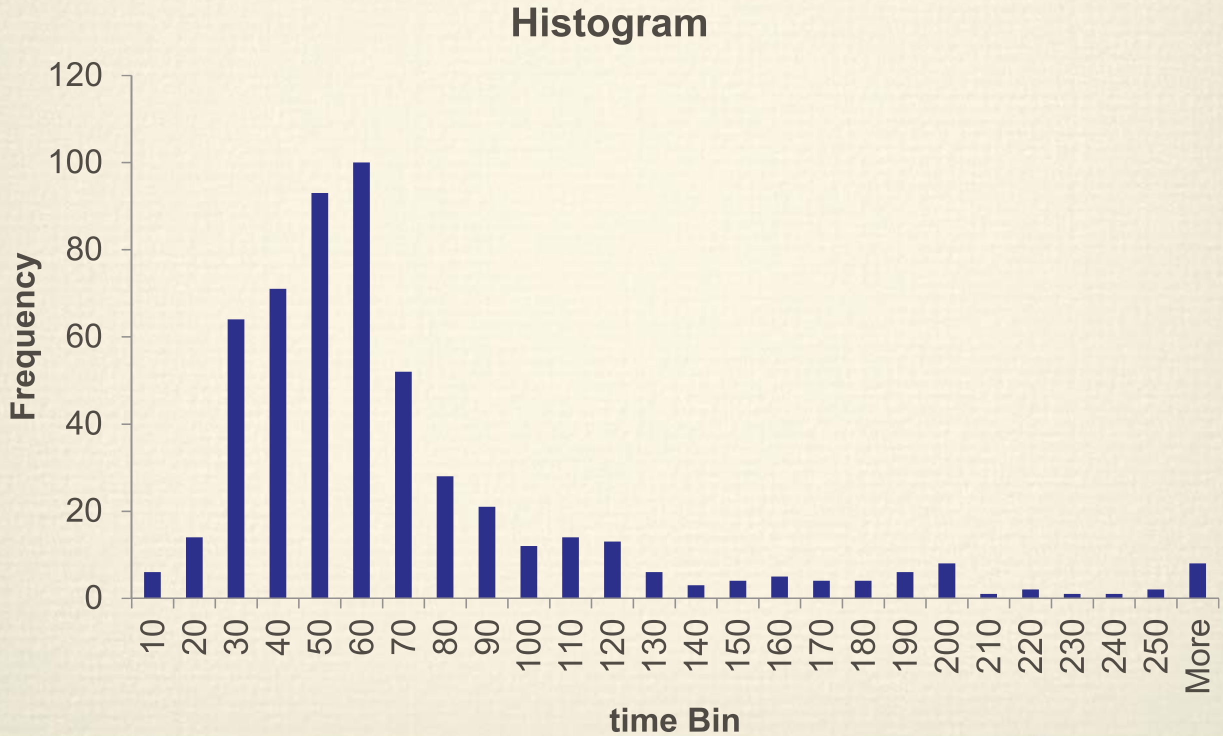
Signal Time Duration Distribution in X-direction (543 tests)



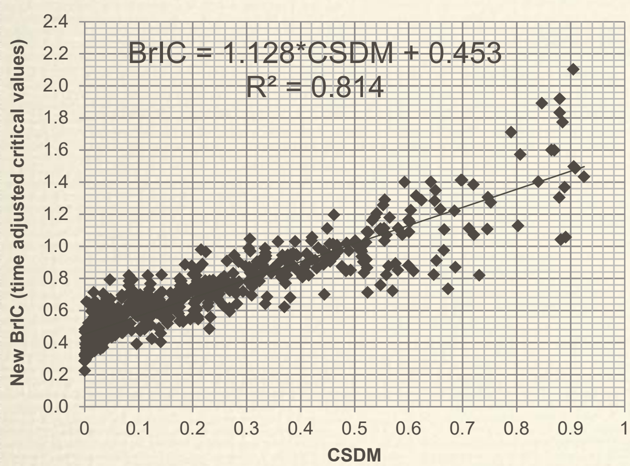
Signal Time Duration Distribution in Y-direction (543 tests)

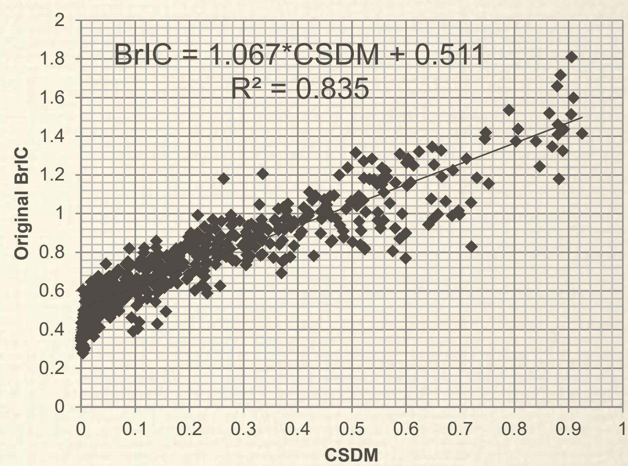


Signal Time Duration Distribution in Z-direction (543 tests)



"New BrIC" vs "Original BrIC"



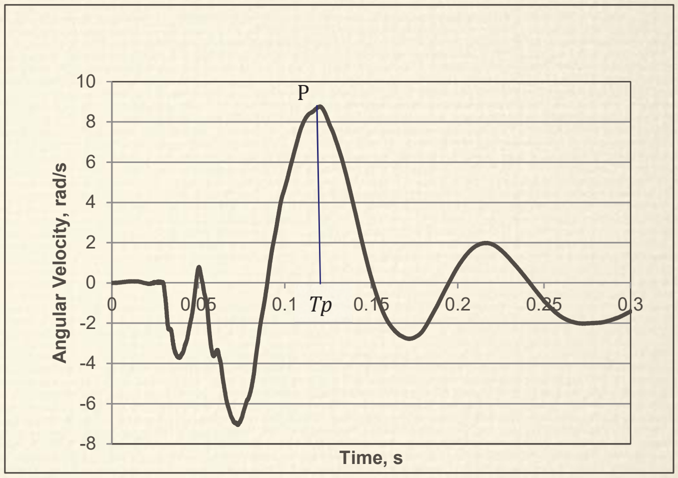


For CSDM = 0.49, BrIC = 1.01

For CSDM = 0.49, BrIC = 1.03

Algorithm #1

- Find Peak (point *P*)
- Find time to peak (*Tp*)
- Set time step (*dt*)
- Move to the left and right of *Tp* by *dt* and compute areas under the curve
- Find *T_left* and *T_right* when respective areas reach max
- If peak *P* is too close to zero and the area doesn't reach max then *T_left* is time = zero
- If peak *P* is too close to end and the area doesn't reach max then *T_right* is time = end
- DeltaT = *T_left* + *T_right*

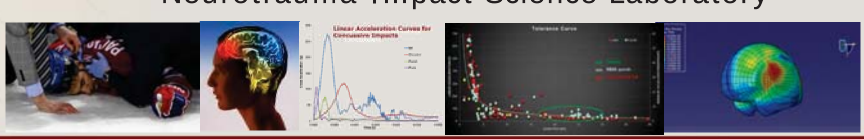


Université d'Ottawa | University of Ottawa

Measuring Head Motions in Sports
Helmet Testing

IRCOBI 2015
Lyon France

Blaine Hoshizaki PhD
Neurotrauma Impact Science Laboratory



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Helmet Performance

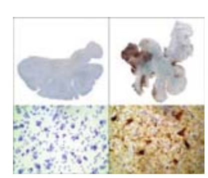
1. Head injuries in sport.
2. Mechanisms for head injury in sport.
3. Dynamic response curves for concussion.
4. Dynamic response and impact duration for concussive impacts.
5. Concussive head impacts comparing four sports.
6. Helmet performance for four injury mechanisms.

Head injuries in sport are ill defined and complex.

1. Traumatic
    1. Skull fractures (linear)
    2. Intracranial bleeds (linear)
    3. Subdural bleeds (rotational)
    4. Diffuse axonal injury (rotational)

2. Concussive injuries (levels of severity of concussion)
    1. Transient (symptoms). (linear/rotation)
        1. Typically concussions resolve in the first three days.
        2. Disability from concussion is hard to predict?
    2. Persistent (linear/rotation)
        1. May result in serious and permanent disability.

3. Repetitive brain injuries
    1. cerebral traumatic encephalopathy, (CTE) (?)
    2. Serious and long term neurological disability (Depression/Parkinson) (?)

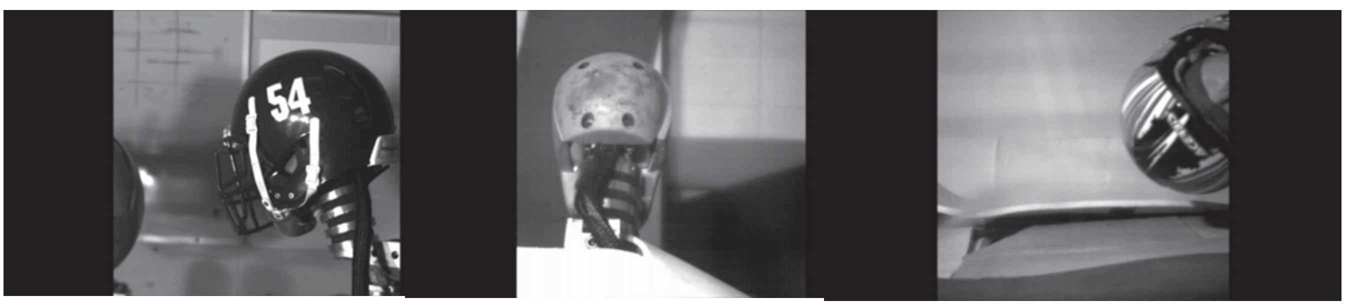


High Velocity Impact Knee Shoulder

Head Injury Events

Fall Elbow Punch

Neurotrauma Impact Science Laboratory



Helmet Knee High Velocity Impact

Velocity - Location - Angle - Mass - Compliance - Mechanics

Shoulder Fall Punch

Injury Reconstructions

Impact parameters that create injury risk

Velocity –influences magnitude and duration

Location –influences linear, angular magnitude and direction.

Angle –influences linear, angular acceleration

Mass – influences magnitude and duration

Compliance – influences magnitude and duration

Mechanics – influences linear, angular magnitude and duration.

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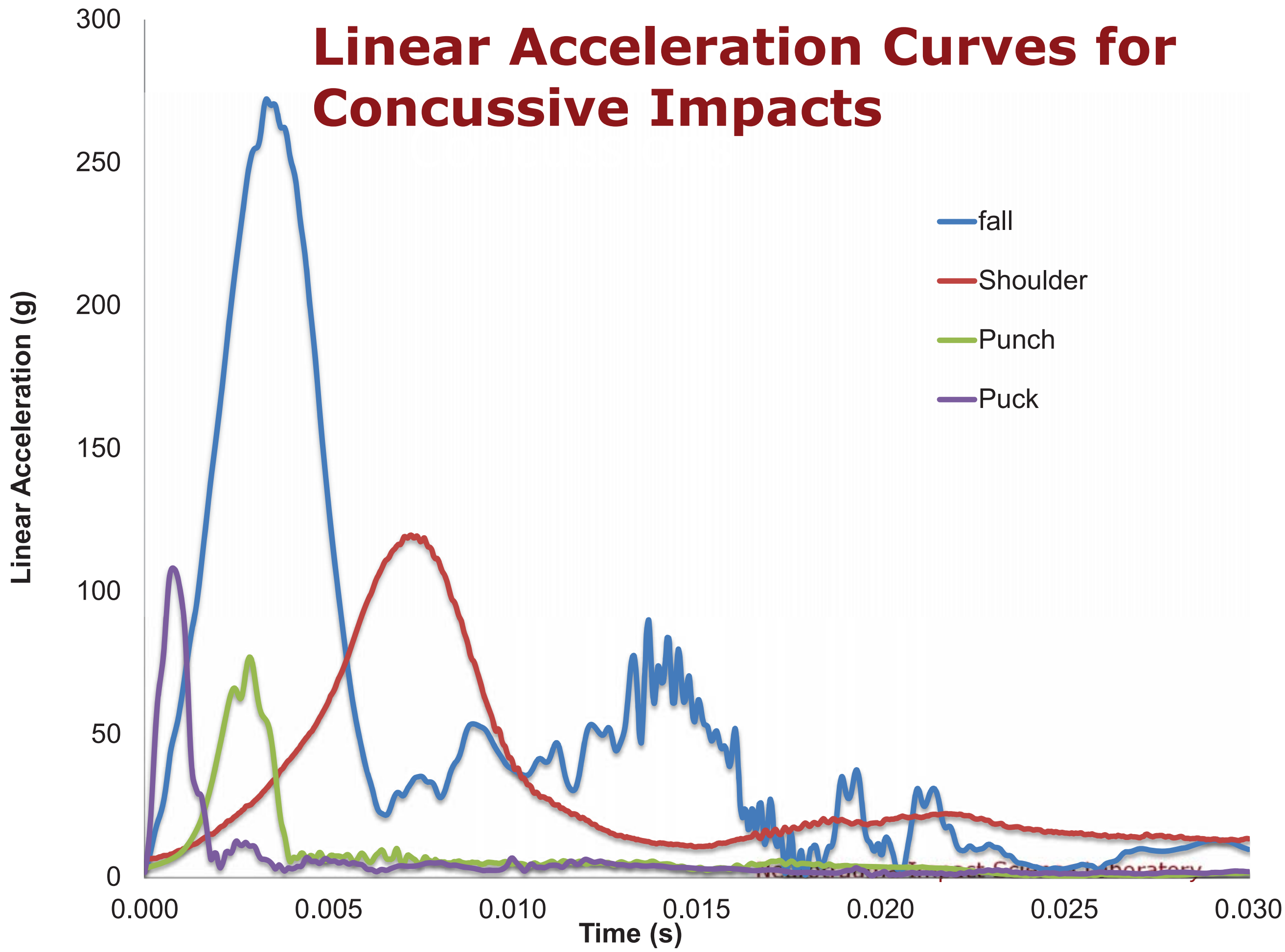
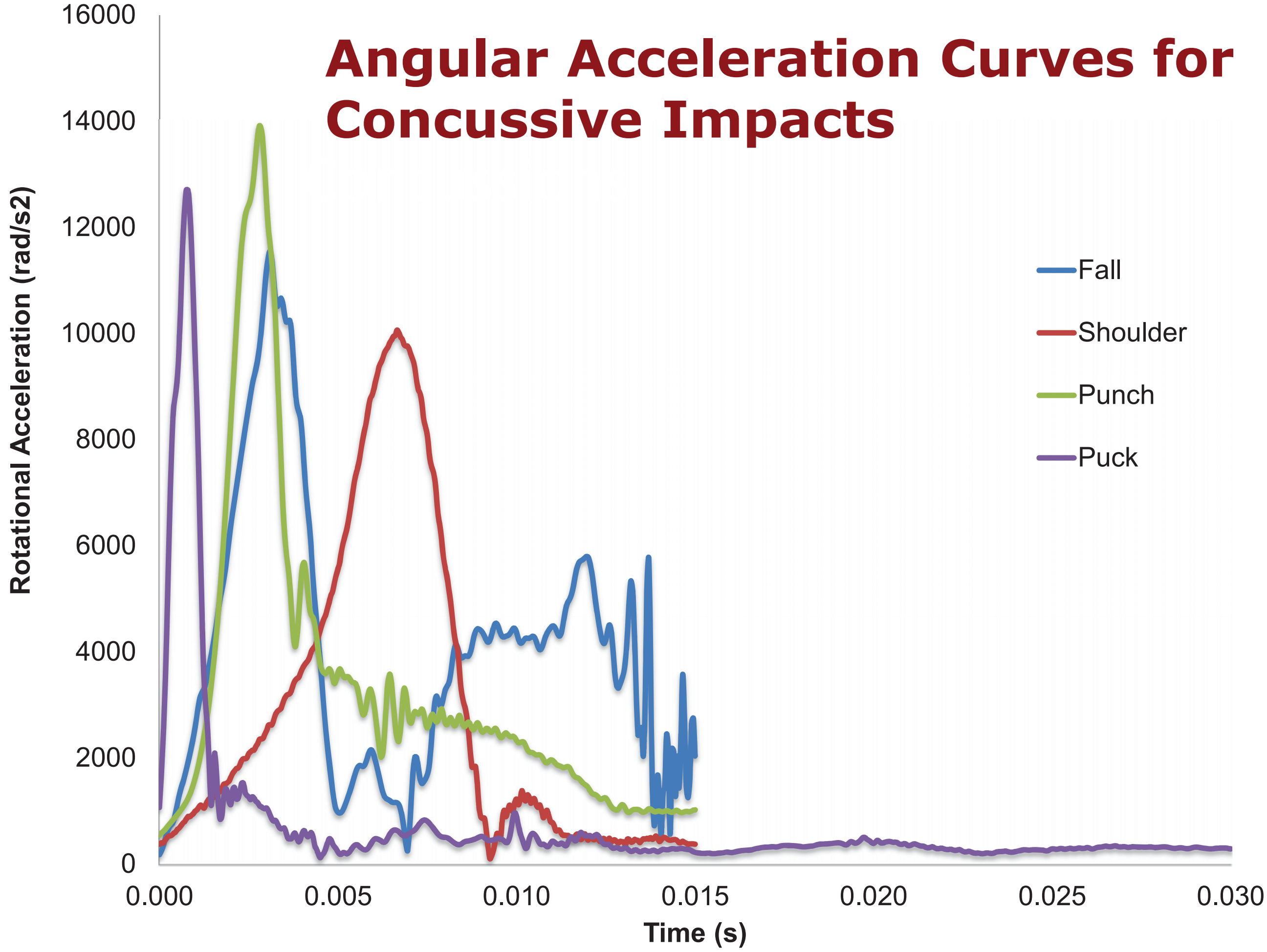
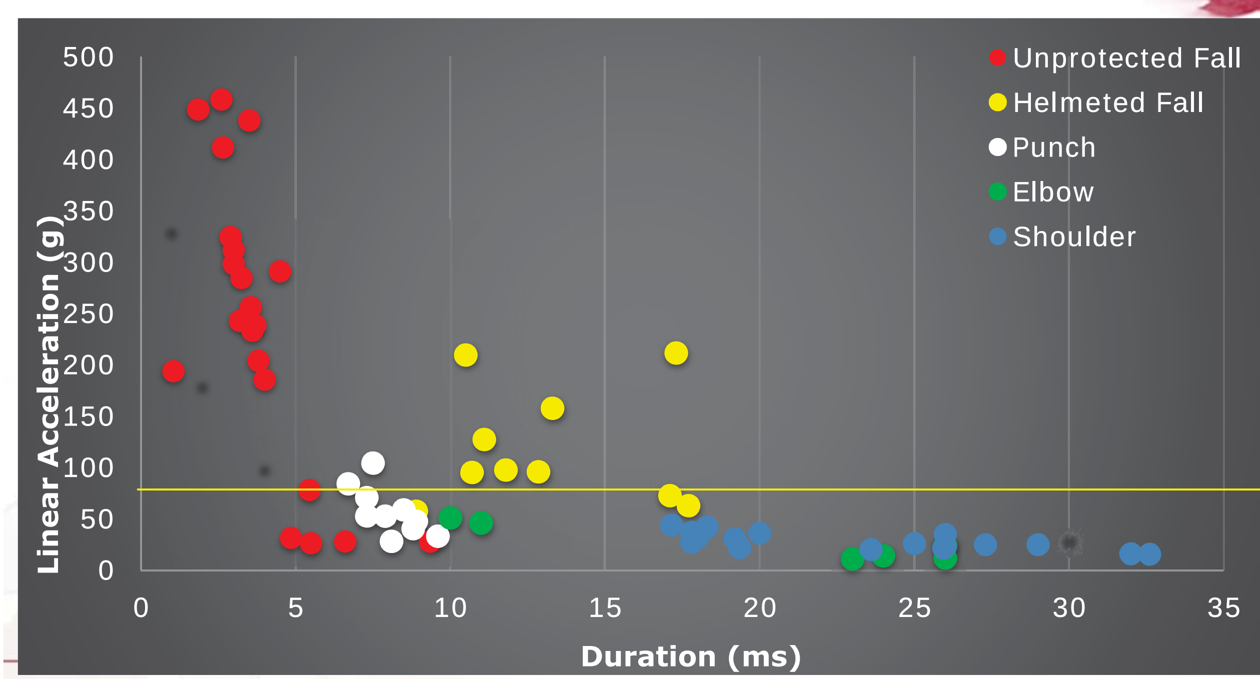
Linear Acceleration Curves for Concussive Impacts



Angular Acceleration Curves for Concussive Impacts



Linear Acceleration – Duration: Tolerance curve for Concussive Impacts



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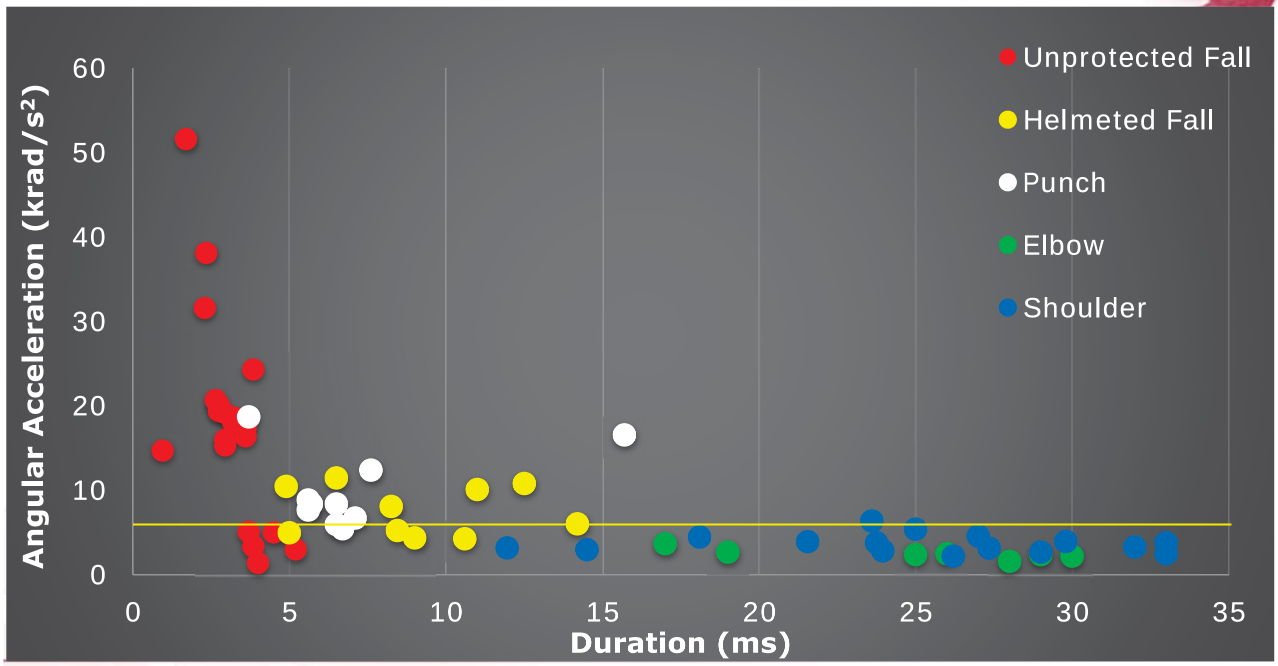
Angular acceleration – Duration: Tolerance curves for Concussive Impacts



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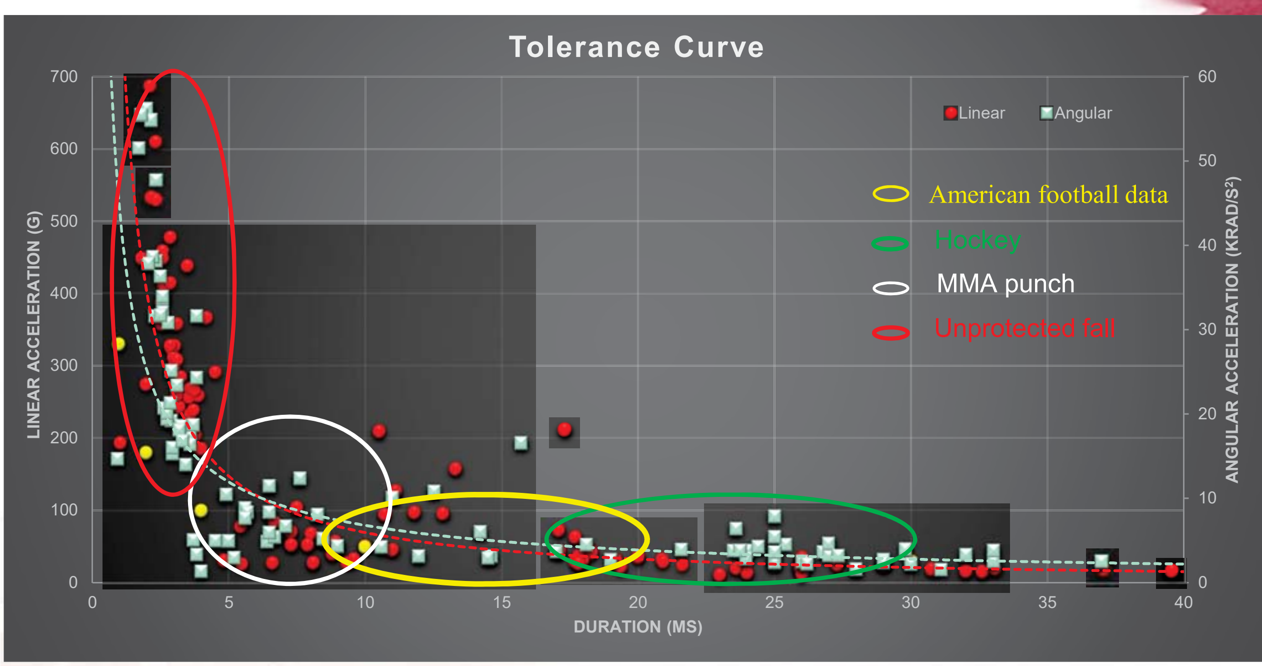
Line of best fit for linear and rotational acceleration and time for concussion events



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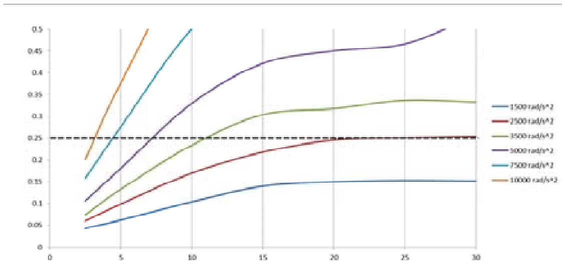
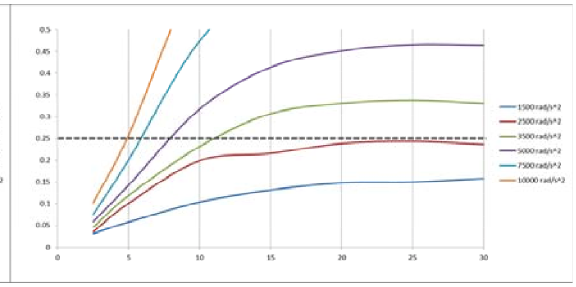
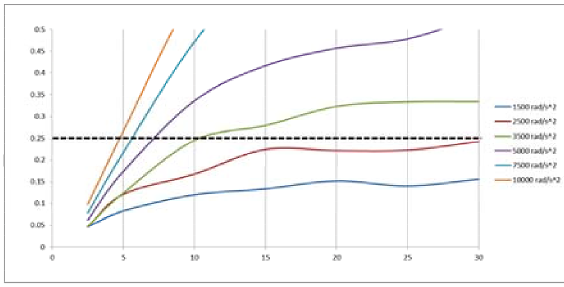


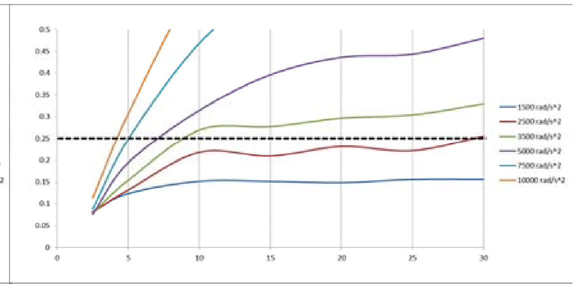
Rotational input only



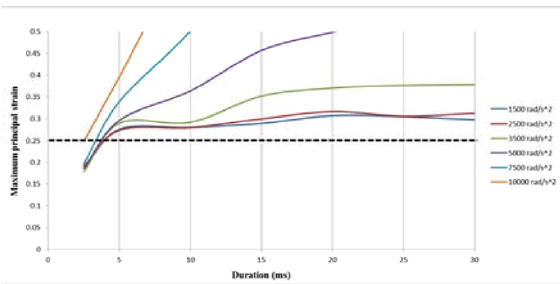
Rotational acceleration with 20g linear input



Rotational acceleration with 50g linear input



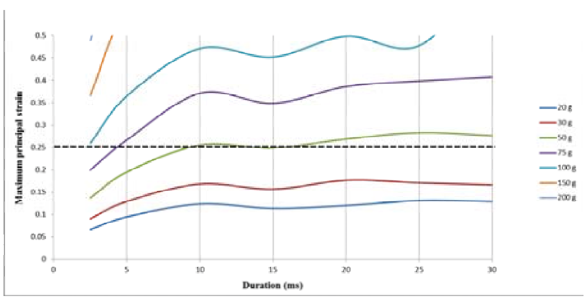
Rotational acceleration with 100g linear input



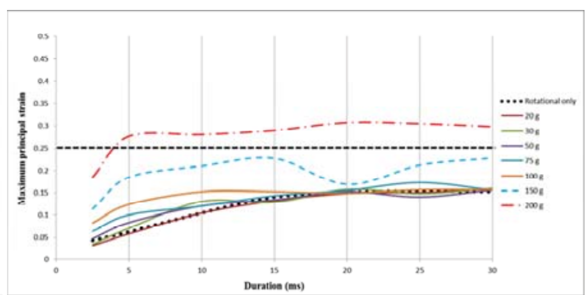
Rotational acceleration with 200g linear input

Maximum Principle Strain for Rotational Acceleration for White matter (UCD FEM)

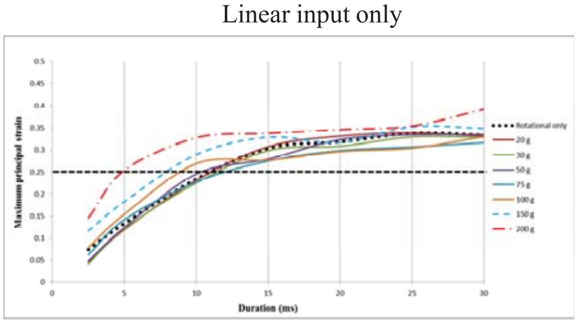
Neurotrauma Impact Science Laboratory



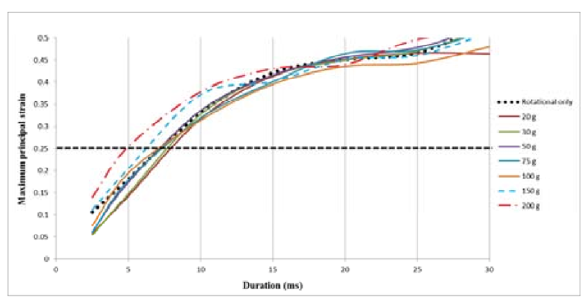
Linear input only



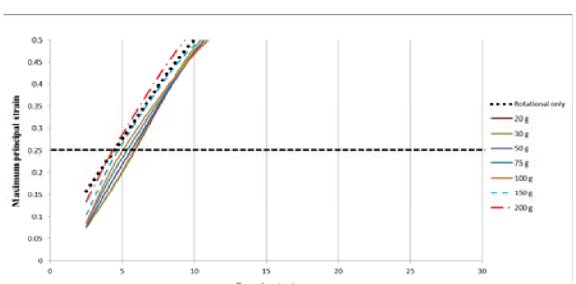
Linear acceleration with 1500 rad/s^2 rotational accel.



Linear acceleration with 3000 rad/s^2 rotational accel.



Linear acceleration with 5000 rad/s^2 rotational accel.



Linear acceleration with 10000 rad/s^2 rotational accel.

Maximum Principle Strain for Linear Acceleration for White matter (UCD FEM)

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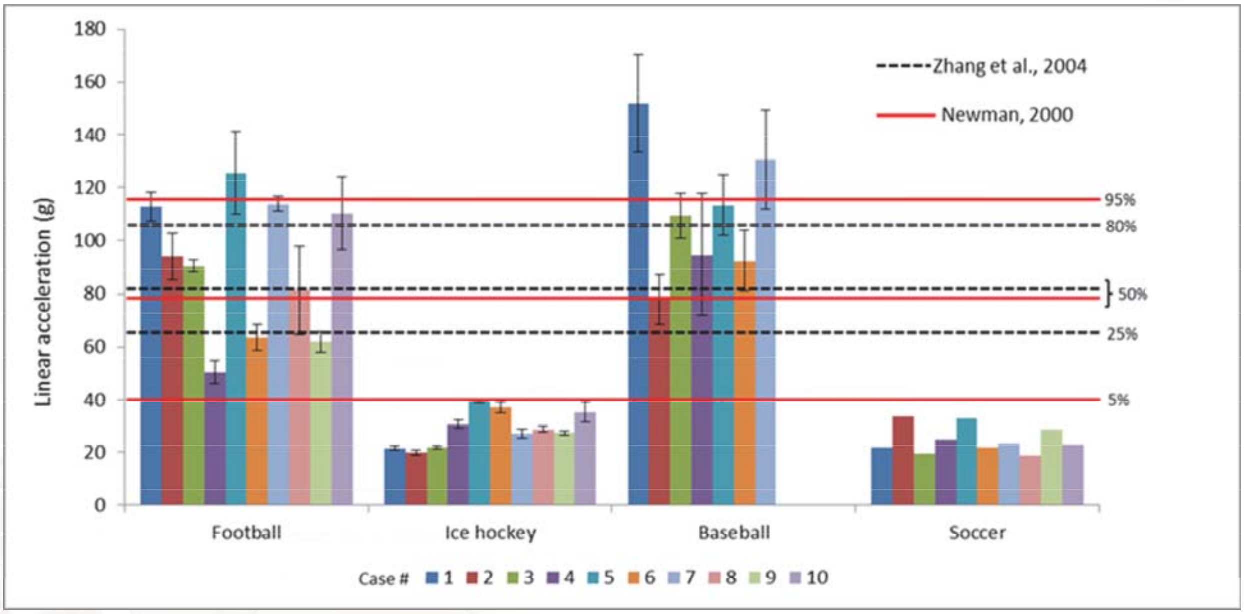
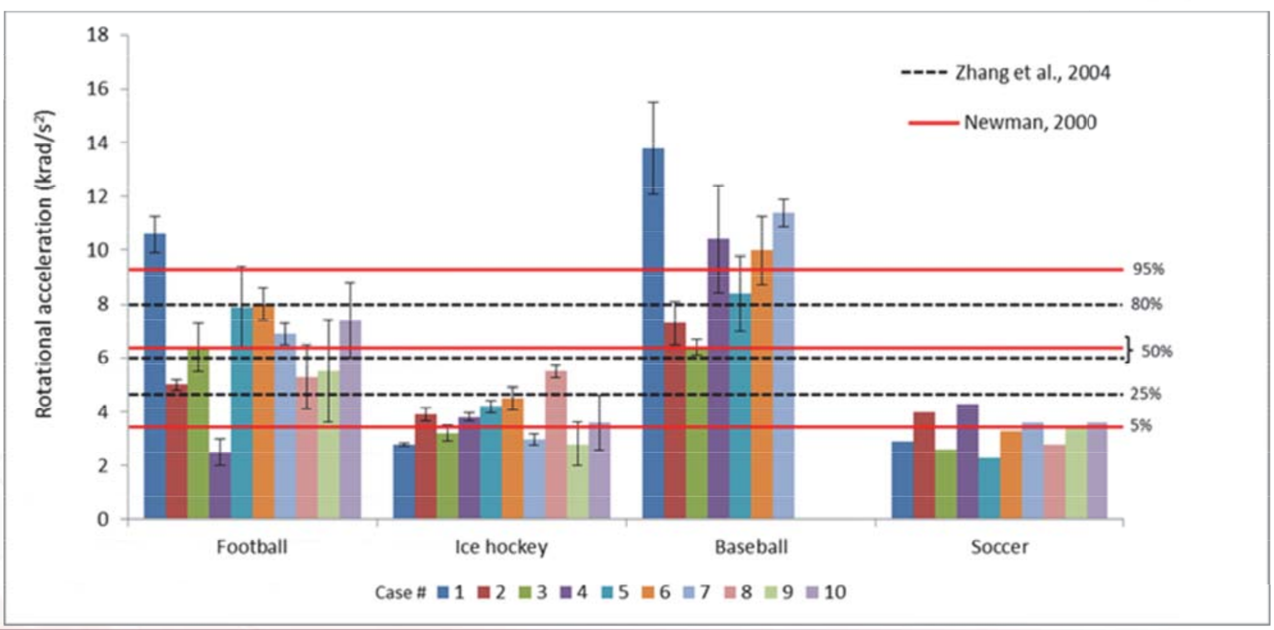
Linear acceleration for Concussive impacts for four Impact mechanisms.



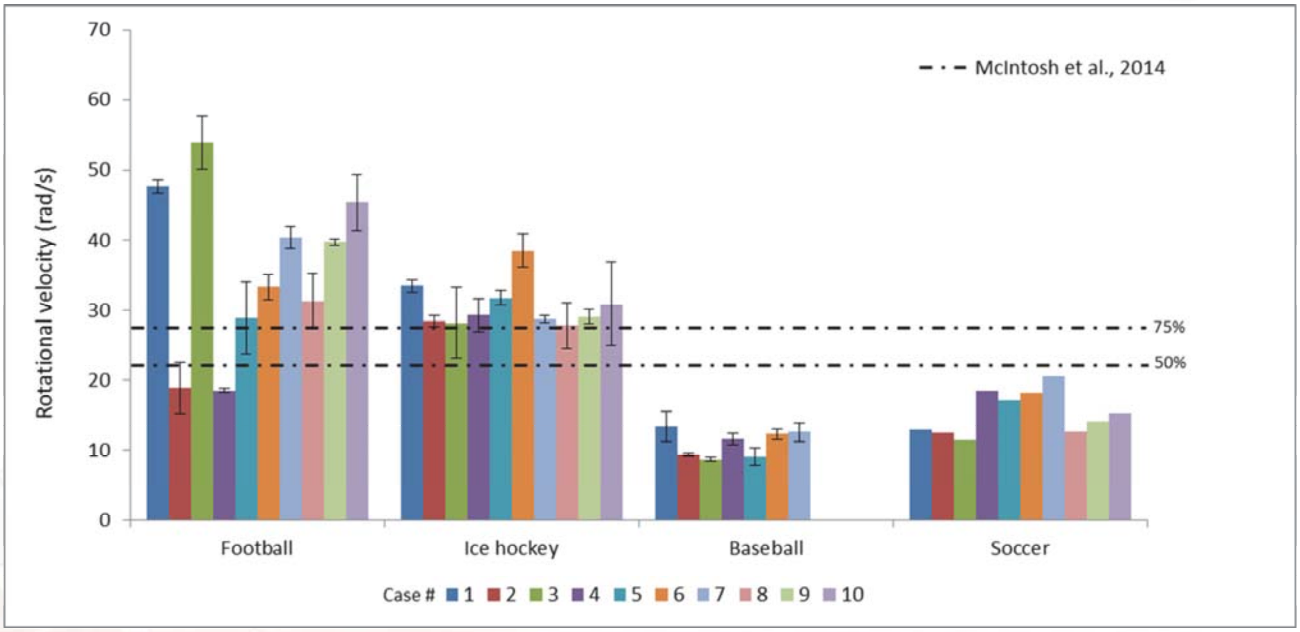
Football - helmet to helmet
Ice hockey - shoulder to helmet
Baseball - ball to helmeted head
Soccer - ball to head

Rotational acceleration for Concussive impacts for four Impact mechanisms.



Football - helmet to helmet
Ice hockey - shoulder to helmet
Baseball - ball to helmeted head
Soccer - ball to head

Rotational velocity for Concussive Impacts for Four Impact Mechanisms.



Football - helmet to helmet
Ice hockey - shoulder to helmet
Baseball - ball to helmeted head
Soccer - ball to head

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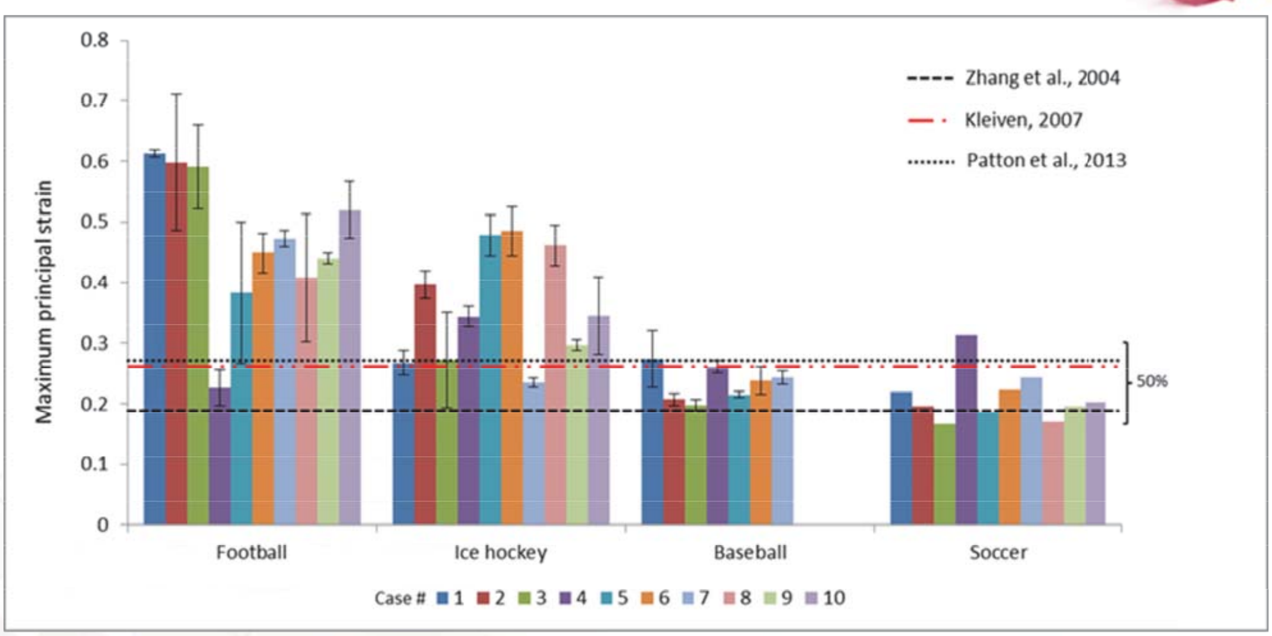
Maximum Principal Strain for Concussive Impacts for Four Impact Mechanisms



Football - helmet to helmet
Ice hockey - shoulder to helmet
Baseball - ball to helmeted head
Soccer - ball to head

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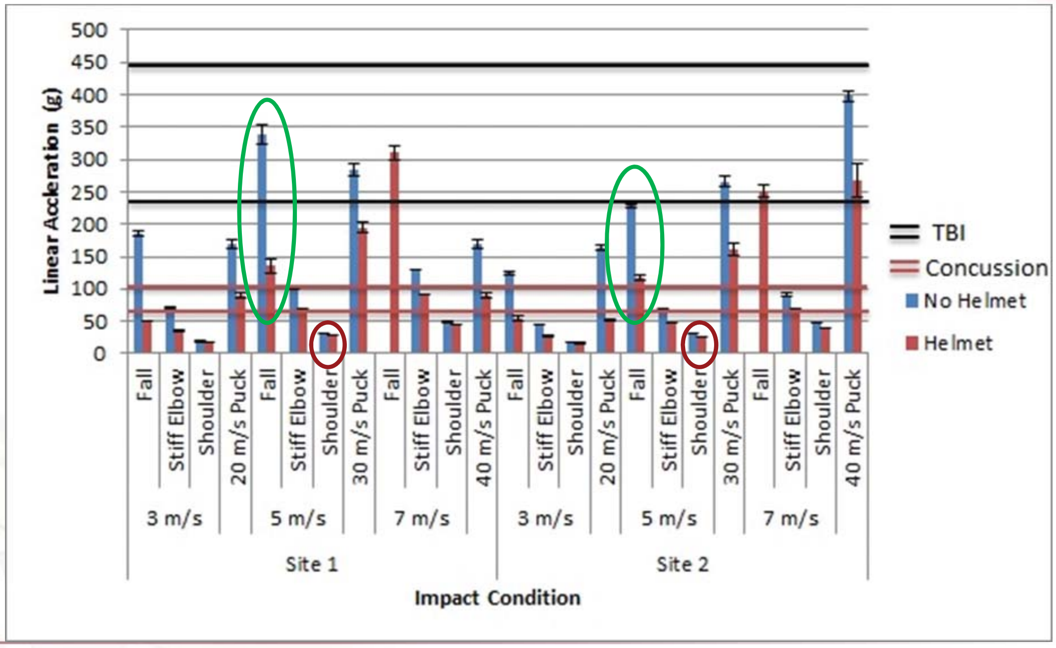
Linear acceleration for hockey helmet and no helmet conditions for Fall, Elbow, Shoulder & Puck Impacts.



Clark 2015

Hockey helmet

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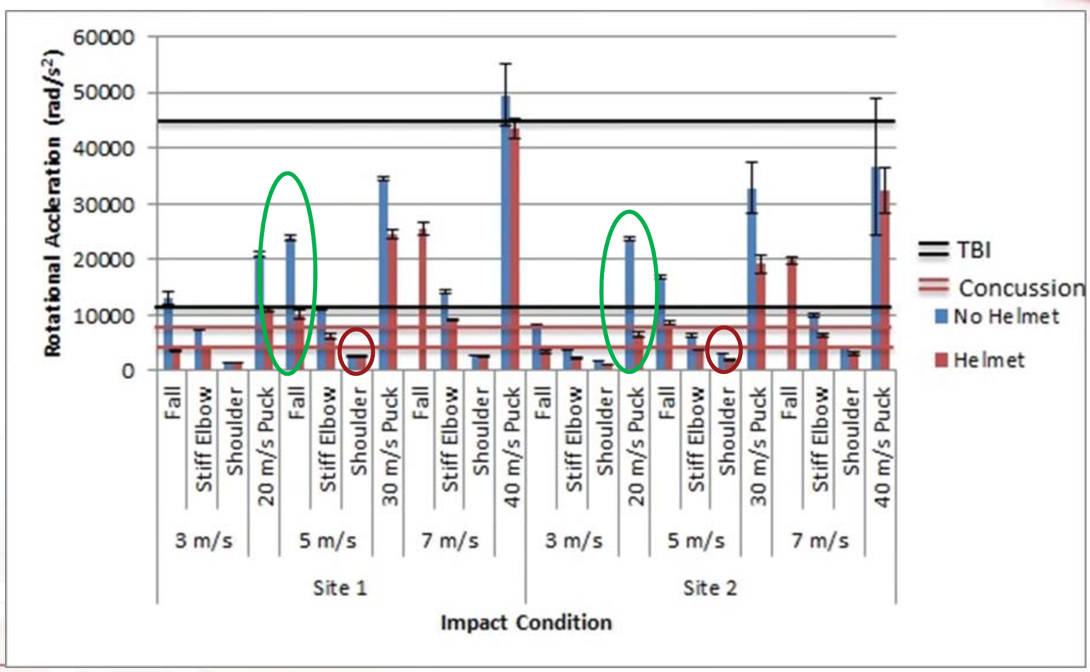
Rotational acceleration for hockey helmet and no helmet conditions for Falls, Elbow, Shoulder & Puck Impacts.



Clark 2015

Hockey helmet

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Summary

1. Defining the event(s) creating the risk of concussion for the activity is critical. In order to effectively measure the capacity of a helmet to mange rotational head motions the injury event has to be defined.
2. Injury event impact characteristics: Velocity – Location – Angle – Compliance – Mass – Mechanics interact to predict the dynamic response characteristics associated with concussions.
3. Helmet Rotational head motions have to be considered with all parameters when developing a test method.
4. Evidence supports the importance of rotational head motions in predicting concussions in longer duration impacts.

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Thank you

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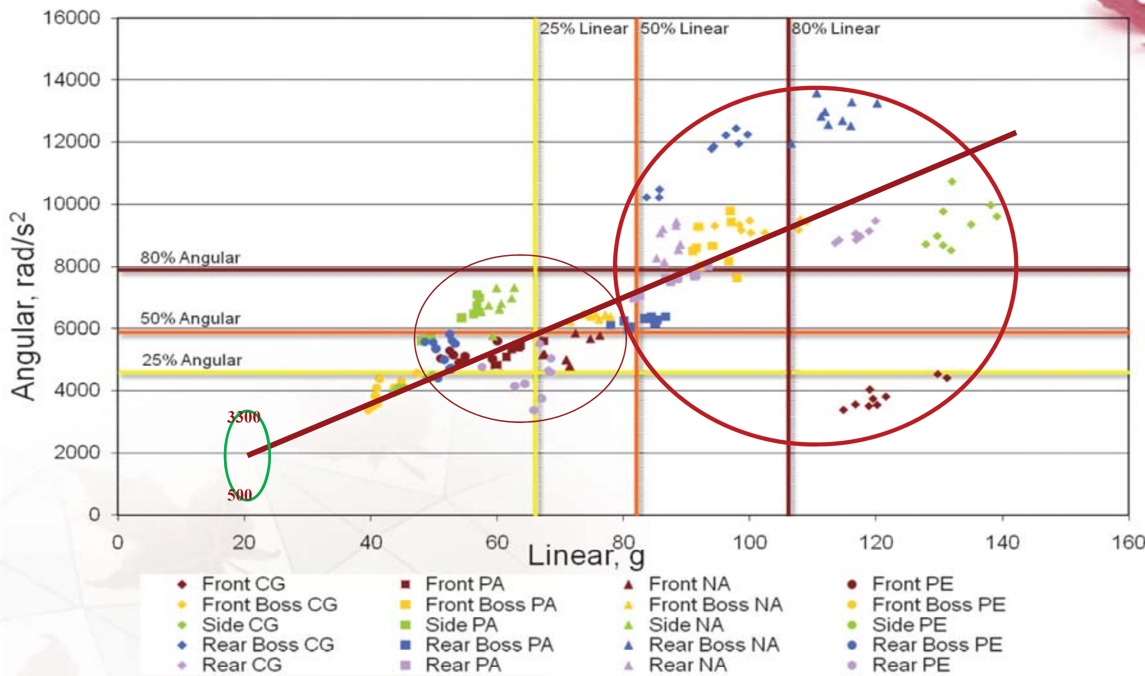
Contributions by: Andrew Post PhD
Michio Clark MSc.

The relationship between peak linear and peak rotational acceleration



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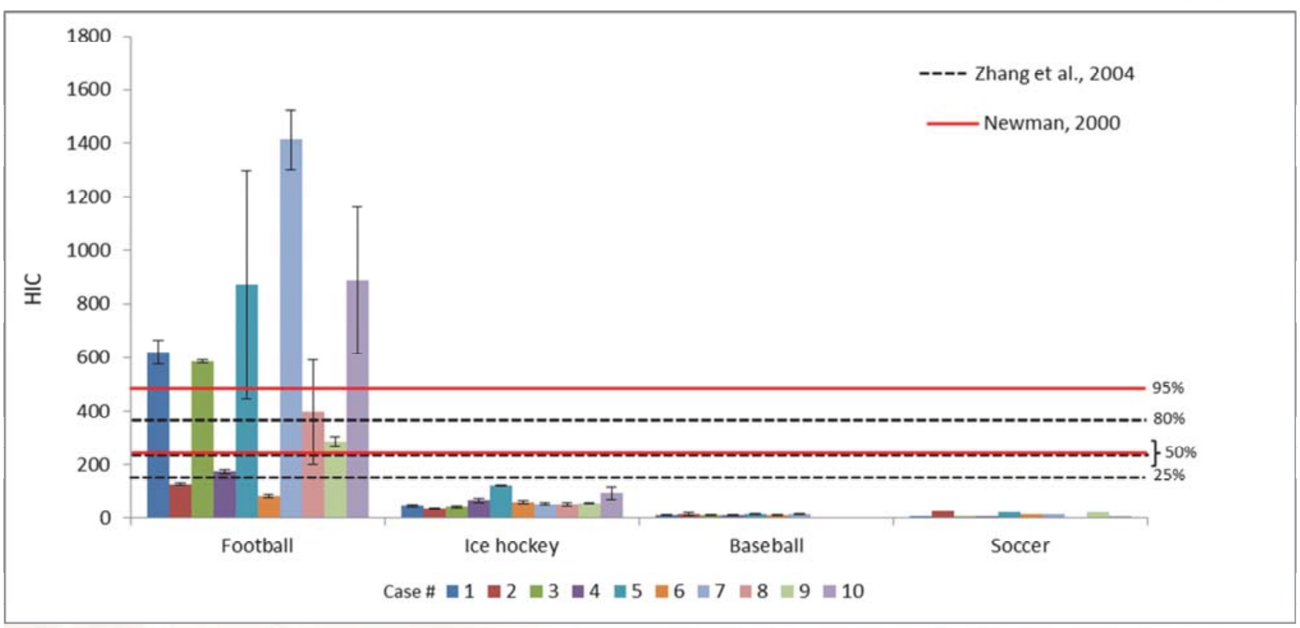
NiSL

HIC_{15} (HIC_{36} for ice hockey) for Concussive Impacts for Four Impact Mechanisms.



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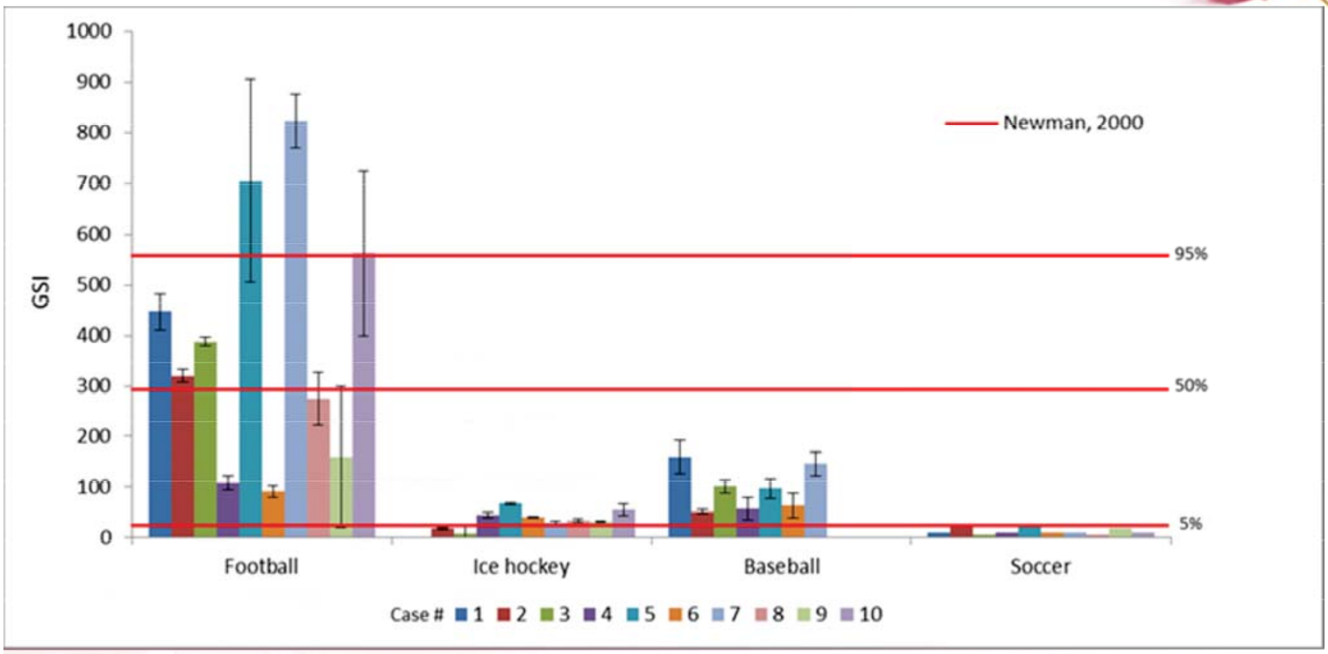
Football - helmet to helmet
Ice hockey - shoulder to helmet
Baseball - ball to helmeted head
Soccer - ball to head

GSI for Concussive impacts for four Impact mechanisms.



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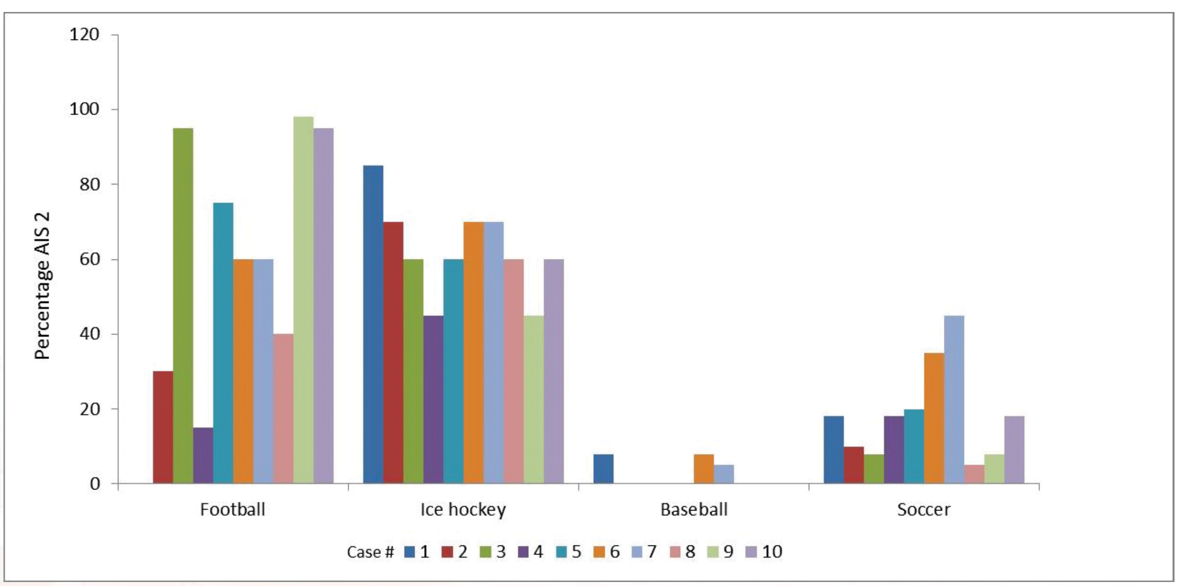
Football - helmet to helmet
Ice hockey - shoulder to helmet
Baseball - ball to helmeted head
Soccer - ball to head

BrIC - AIS 2 for Concussive Impacts for Four Impact Mechanisms.



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Concussive Impacts in Ice Hockey

MECHANISM	Acceleration Linear (g)	 Rotational (rad/s^2)	Duration	Input type	Grey matter Maximum principal strain
Puck	145.1	19813.6	5 ms	LIN + ROT	0.2832
				LIN	0.2363
				ROT	0.1781
Puck	253.4	24487.5	5 ms	LIN + ROT	0.2985
				LIN	0.3555
				ROT	0.2275
Puck	108.9	11353	5 ms	LIN + ROT	0.1261
				LIN	0.1468
				ROT	0.1104
Puck	71.1	9878	5 ms	LIN + ROT	0.2152
				LIN	0.1619
				ROT	0.1815
Shoulder	25.8	3919.7	25 ms	LIN + ROT	0.438
				LIN	0.168
				ROT	0.4101
Shoulder	24.8	3815.8	25 ms	LIN + ROT	0.3621
				LIN	0.125
				ROT	0.3607
Shoulder	19.9	3753.6	25 ms	LIN + ROT	0.419
				LIN	0.1269
				ROT	0.4241

NOCSAE

- National Operating Committee on Standards for Athletic Equipment.
  - **Purpose: To commission research on and establish standards for protective athletic equipment.**

NOCSAE History

- Formed in 1969 through efforts of American College Health Association, NCAA, National Federation of State High Schools Associations, & Sporting Goods Manufacturers Association
- Formed to conduct research directed toward injury reduction and prevention
- Development of human headform which mimics human head response to impact accelerations
- First football helmet standard was published in 1973
- 1998 changed criterion to 1200 SI from 1500 SI

NOCSAE Board of Directors

- American College Health Association
- American College of Sports Medicine
- American Orthopaedic Society for Sports Medicine
- Athletic Equipment Managers Association
- College Football Association
- National Association of Secondary School Principals
- NATA
- NAERA
- SGMA

NOCSAE Standards Process

Step 1: Standard Requested

- Test method/performance standard/procedural guide

Step 2: Investigate

- Is the standard necessary?
- What does the data support?

Step 3: Write Standard

- Draft -> Proposed -> Final Document

Step 4: Modify/Revise as needed

NOCSAE
Test Methods

- Helmets
  - Football
  - Baseball/Softball Batting/Catchers
  - Lacrosse
  - Field Hockey
- Baseballs/Softballs
- Lacrosse Face Masks
- Football Face Masks

- Fund research into the mechanics of head injuries. One key goal is gender and age differences to be incorporated in standards.

System Improvements

- NOCSAE system modifications are many and include
  - Reduced system friction
  - Increased system rigidity
  - Modified coupler system
  - Improved calibration procedures

- Consistency between NOCSAE and other systems
  - Better than with non bio-fidelic head form systems

System Repeatability

- Standards must be repeatable to be a standard
- NOCSAE Test methods are separate from Performance requirements.
- NOCSAE DOC 001 Drop test method
- NOCSAE DOC 021 Projectile test method
- NOCSAE DOC 081 Pneumatic Ram Impact test method

  The Pneumatic Ram test is a complex system with many compliant interactions beside the test specimen headgear

  Preliminary Round Robin Inter Laboratory testing and previous limited lab to lab studies have been positive.

Performance Specifications

- NOCSAE has specific performance requirements when tested in accordance with the required test method.
- Multiple inputs and Pass/Fail requirements.
  - Low level vs max impact
- Demanding QC/QA requirments
- Independent third party certification required.

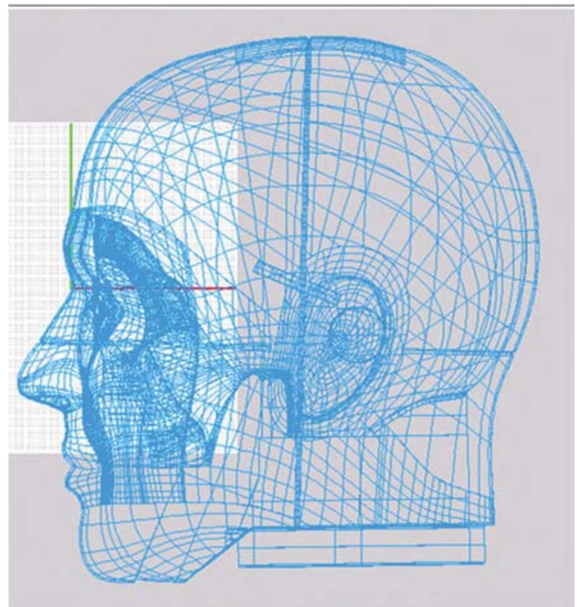
NOCSAE Testing

- Football helmets -
  - Proposed Pneumatic Ram test
- Batting helmets -
- Lacrosse helmets -
- Field Hockey Headgear-
- Projectiles-
  - Base balls, LAX balls, Field Hockey balls
- Various Face protectors-

Head Form Development

The Heart of The NOCSAE System

NOCSAE Headforms



Southern Impact Research Center

Anthropometrical References used in the development of the new NOCSAE head model.

The Farkas references refer to the following:

"Anthropometry of the Head and Face"
2nd Edition, Raven Press, NY
Editor: Leslie G. Farkas, M.D., C.Sc., D.Sc., FRCS (C)
Assoc. Prof., Dept. of Surgery
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"Anthropometry of the Head and Face"
1st Edition, Raven Press, NY
Editor: Leslie G. Farkas, M.D., C.Sc., D.Sc., FRCS (C)
Assoc. Prof., Dept. of Surgery
University of Toronto

The HFN references refer to an unpublished notebook based on the following data:

Anthropometry: The individual and the Population
Cambridge Studies in Biological Anthropology
Editors: S. J. Ulijaszek & C. G. N. Mascie – Taylor
Department of Biological Anthropology
University of Cambridge, Cambridge, UK

Anthropometric Methods: Designing To Fit The Human Body
J. A. Roebuck, JR
Human Factors and Ergonomics Society
PO Box 1369 Santa Monica, CA 90406

Anthropometry of the Head, Neck and Face
MIT Press

SAE publication on Human Anthropometry

Halstead Study Of Facial And Cranial Features In Athletes, 1987
Unpublished

The Reicho data is from that individual's ongoing, as yet unpublished, data on eye and face anthorpometry.

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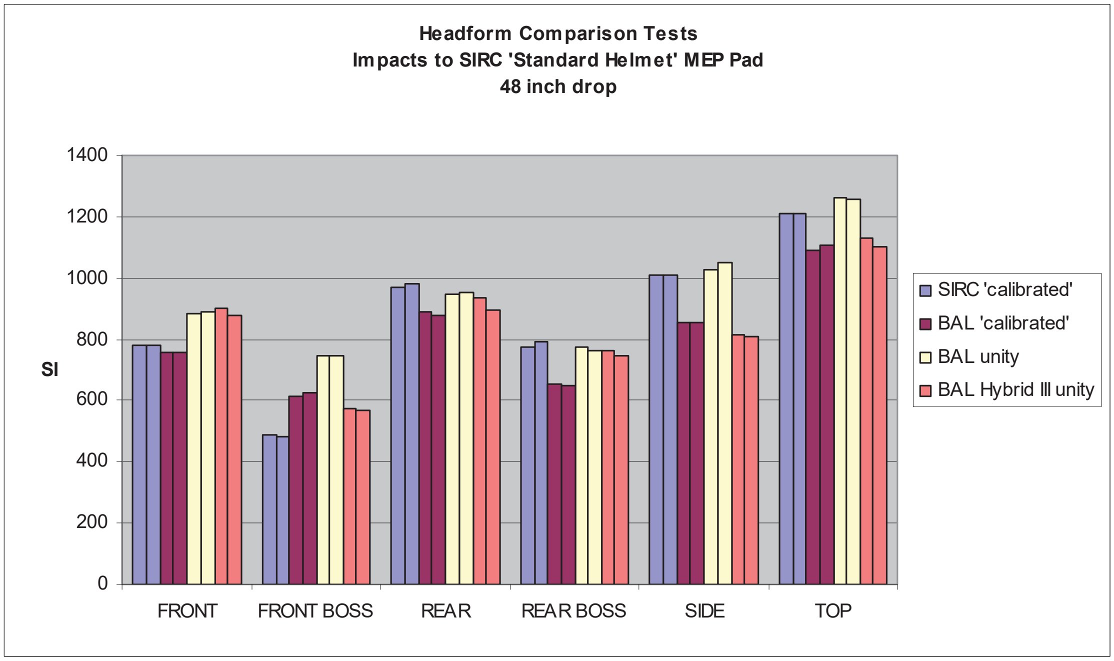
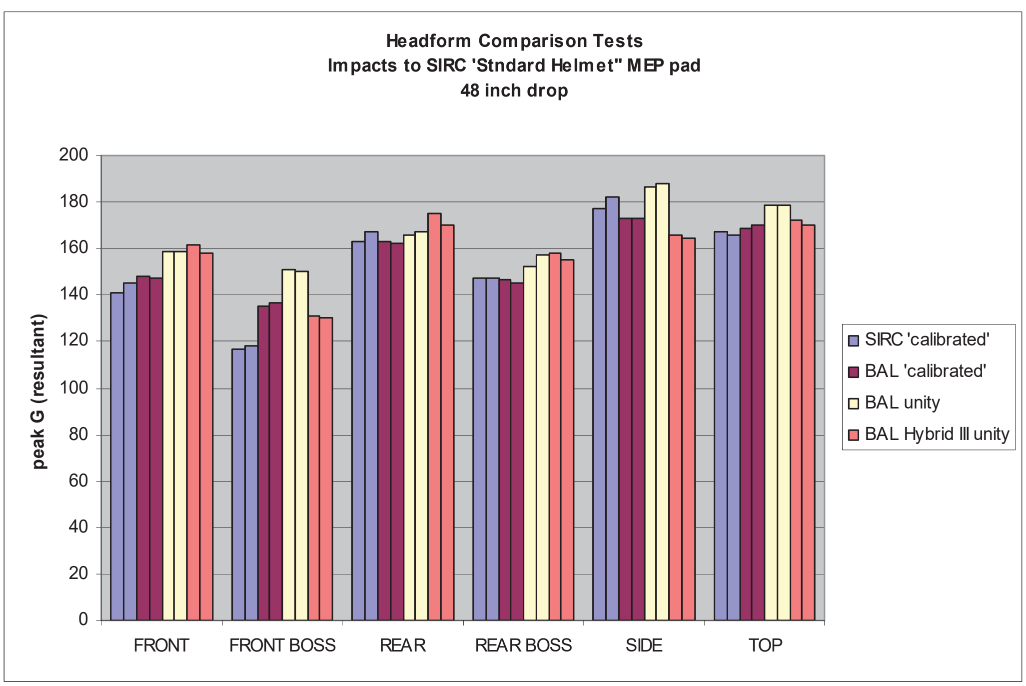
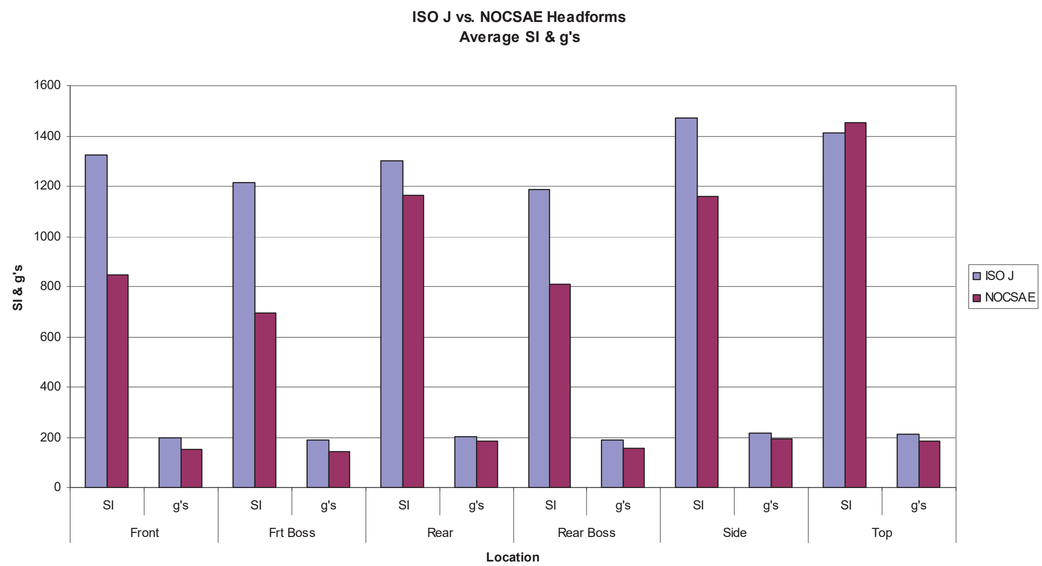
NOCSAE v Hybrid III



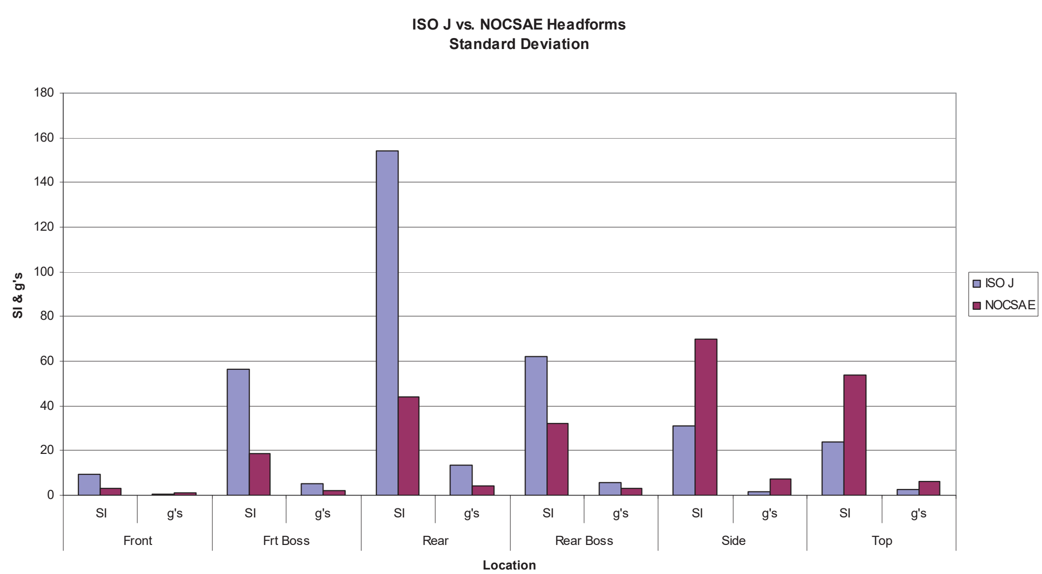
NOCSAE v Hybrid III



ISO vs. NOCSAE Headform Average SI and g



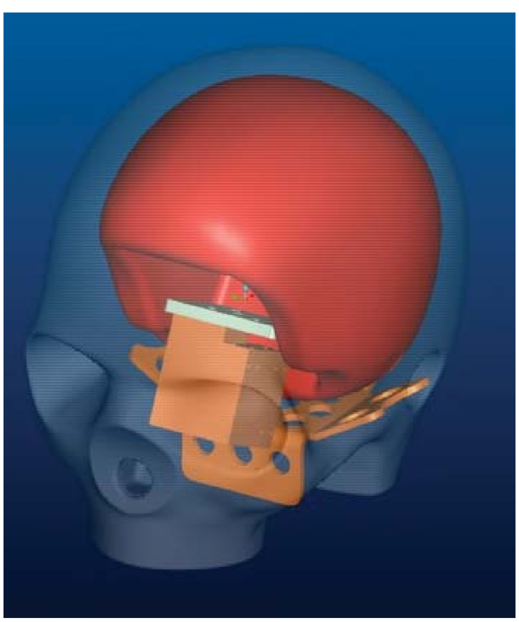
ISO vs. NOCSAE Headform Standard Deviation

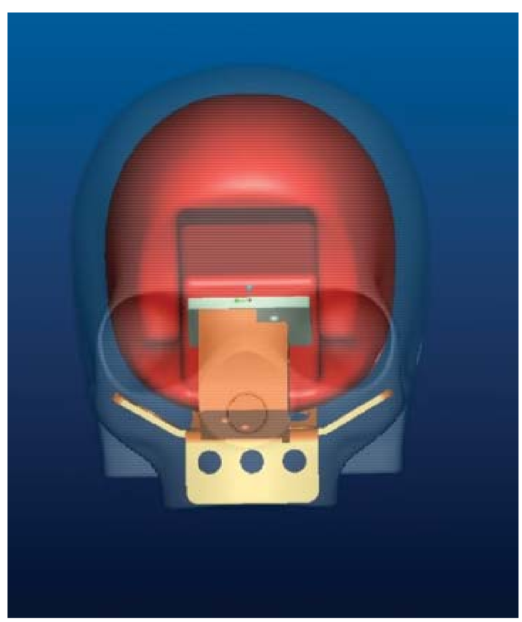


Headform Sizes

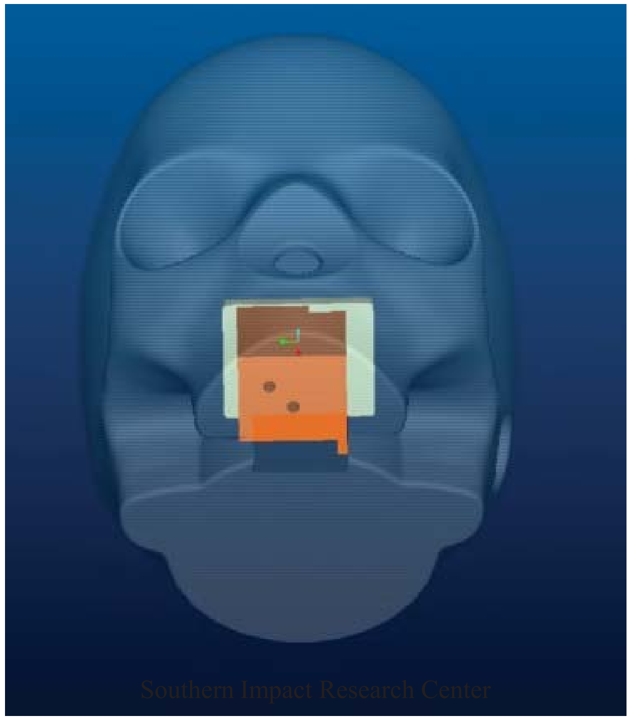
- NOCSAE headforms are available in three sizes, based on significant anthropometric work
- 5% male head form (50% 10 year old male)
- 50% male head form
- 95% male head form
- Mass is size variable
- This creates challenges in performance across sizes.

3-2-2-2 placement

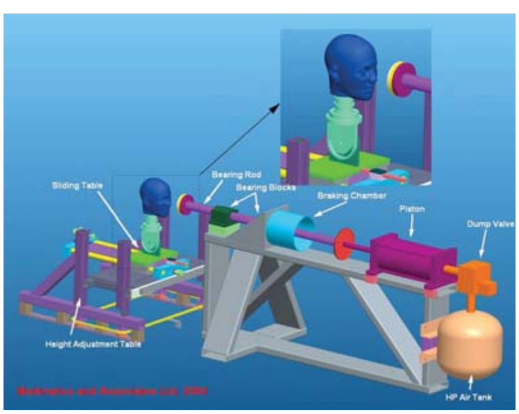


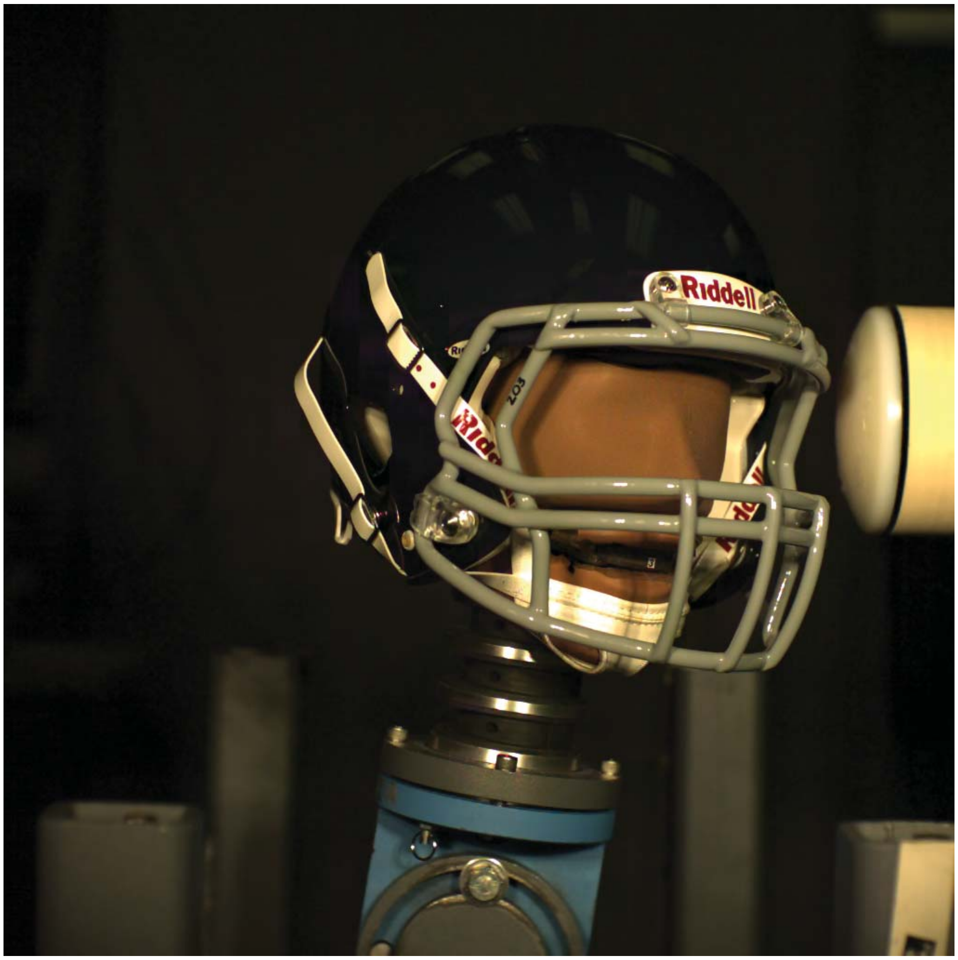


3-2-2-2 placement



Pneumatic Ram





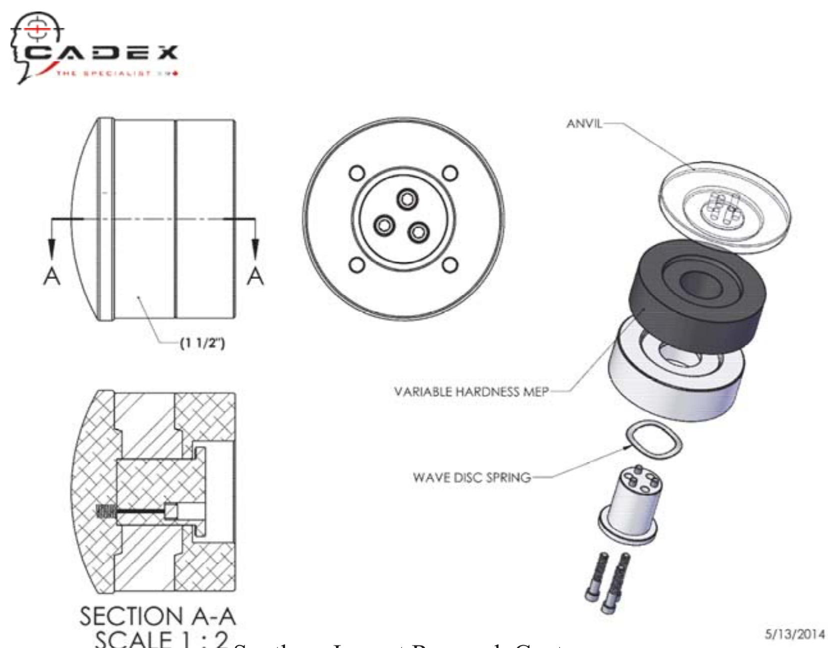
Pneumatic Ram Test Method – ND 081

Current status: Proposed

<u>History</u>

- Draft document goes back to 2005
- 7.4, 9.3, and 11.2 m/s velocities were investigated
- Pass/Fail criteria based on Severity Index
- Impact locations were directed through the CG
- Vinyl Nitrile end cap with nylon impactor face

New Modular Elastomer Programmer [MEP] End Cap



MEP End Cap

PROS

- MEP stiffness can be specified
- Material properties can be tracked with a drop test and can be replaced when necessary
- Uniform deformation during impacts
- End cap is bolted onto the ram so all impact energy is transferred to the test helmet

Cons

- Increased impactor mass
- Increased Stiffness compared to VN
- Reduction of on-field helmet to helmet impact replication

Current Proposed Parameter

NOCSAE Document 081 – PR Test Method

Inter-laboratory Study Specifications

- 6 standard impact locations + 1 random
- New MEP/Aluminum Striker
- Impact velocity: 6.0 m/s [+/- 2%]

NOCSAE Document 002 – FB Performance Spec.

- Pass/fail criteria 6,000 rad/s^2

Pneumatic Ram Test Method – ND 081

- Proposed Impact Locations
  - 4 locations are related to the locations impacted during NOCSAE drop testing but are not directed through the cg of the headform
  - 2 impact locations designed to create high rotational accelerations
  - 1 random location will give the test technician the opportunity to expose a weakness for a particular model

1348108940ND08104m04LinearImpactTestMethod.pdf

1396898424ND00213m13MfrdFBHelmetsStandardPerformance.pdf


QUESTIONS?

Angular Head Motion With and Without Head Contact: Implications for Brain Injury

ELIZABETH MCCALLEY

SOUTHERN IMPACT RESEARCH CENTER

Angular Head Motion With and Without Head Contact – Implications for Brain Injury

- Hybrid III headform and neck with NAP
- Mounted onto a monorail drop tower
- 48” drop height
- Rear impact location
- Three different helmet types (bicycle, football, hockey)
- 3 impacts per configuration (new helmet each impact)
- Fixtures installed to induce one of three different head motions
  - Indirect Loading – head rotation, no head impact
  - Direct Loading – no pre contact head rotation, linear impact onto flat anvil
  - Combined Loading – pre contact head rotation, impact onto 45 degree anvil

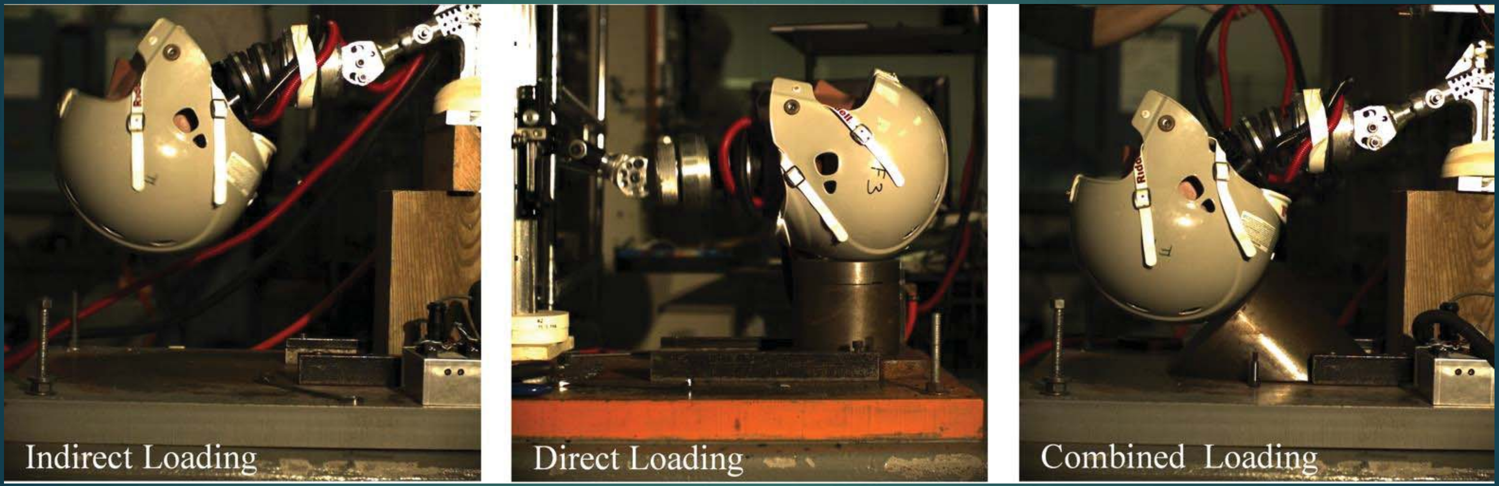
Methodology

DATA COLLECTION

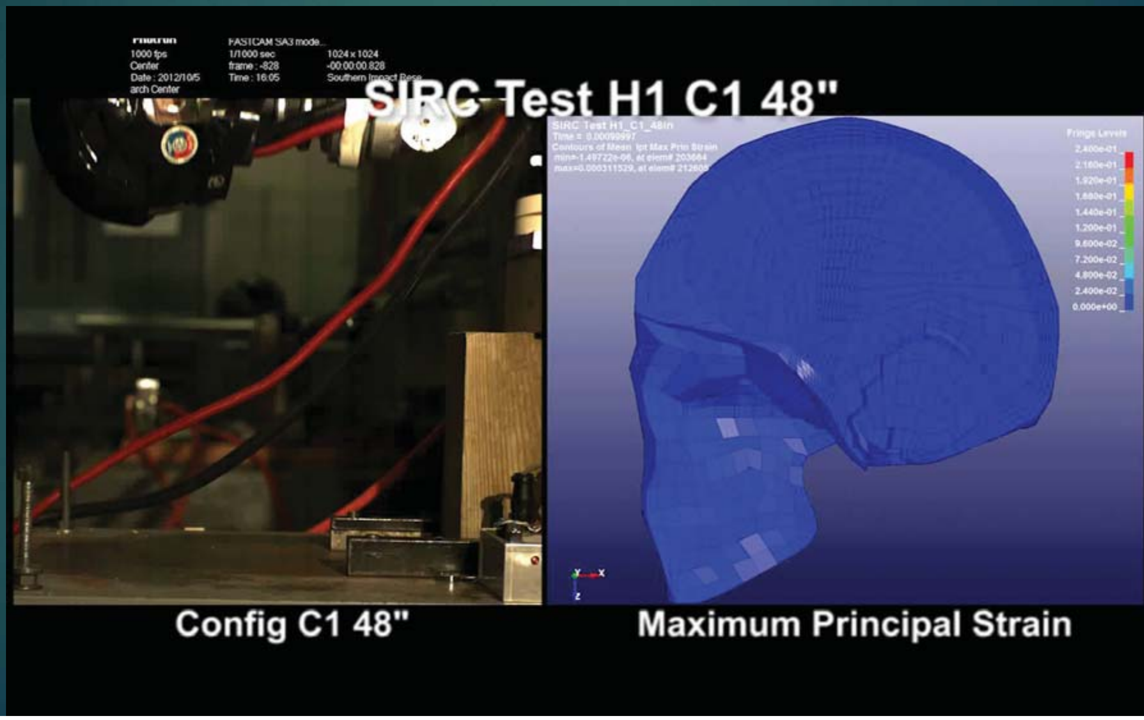
- 10 kHz data sampling per channel
- Anti-aliasing and SAE J211 Filter (Class 1000)
- Computation of linear and angular accelerations for all three directions
- Convert data into SAE sign convention for input into UCD Brain Injury Model

MODELING

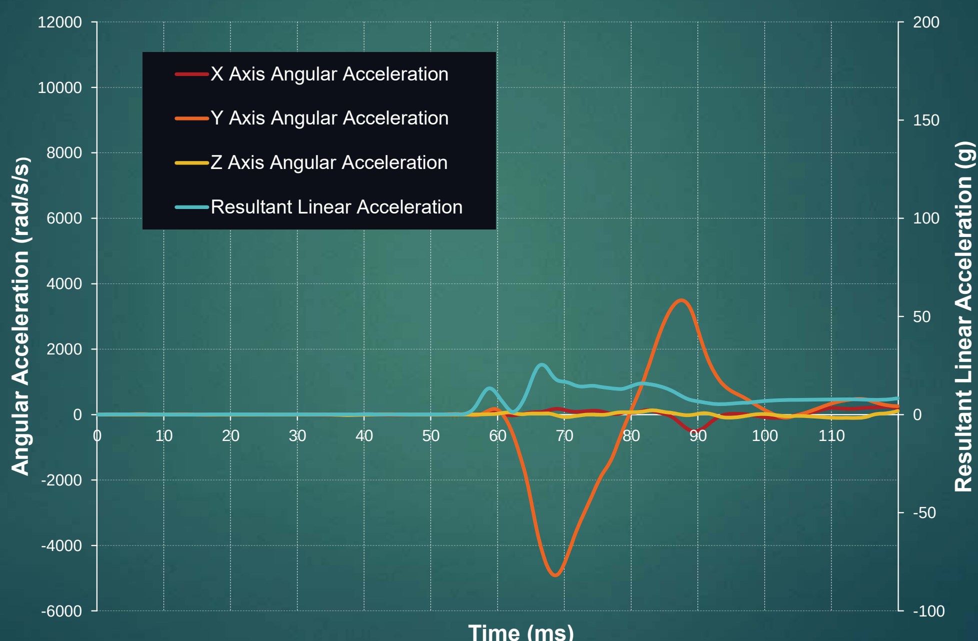
- Skull and brain model developed by University College Dublin
- Consists of 18,448 solid elements and 7,877 shell elements
- 13 different anatomical components
- Validated using data from Nahum et al. (1977)
- Output from SIRC testing used as an input to drive the skull (modeled as a rigid shell)



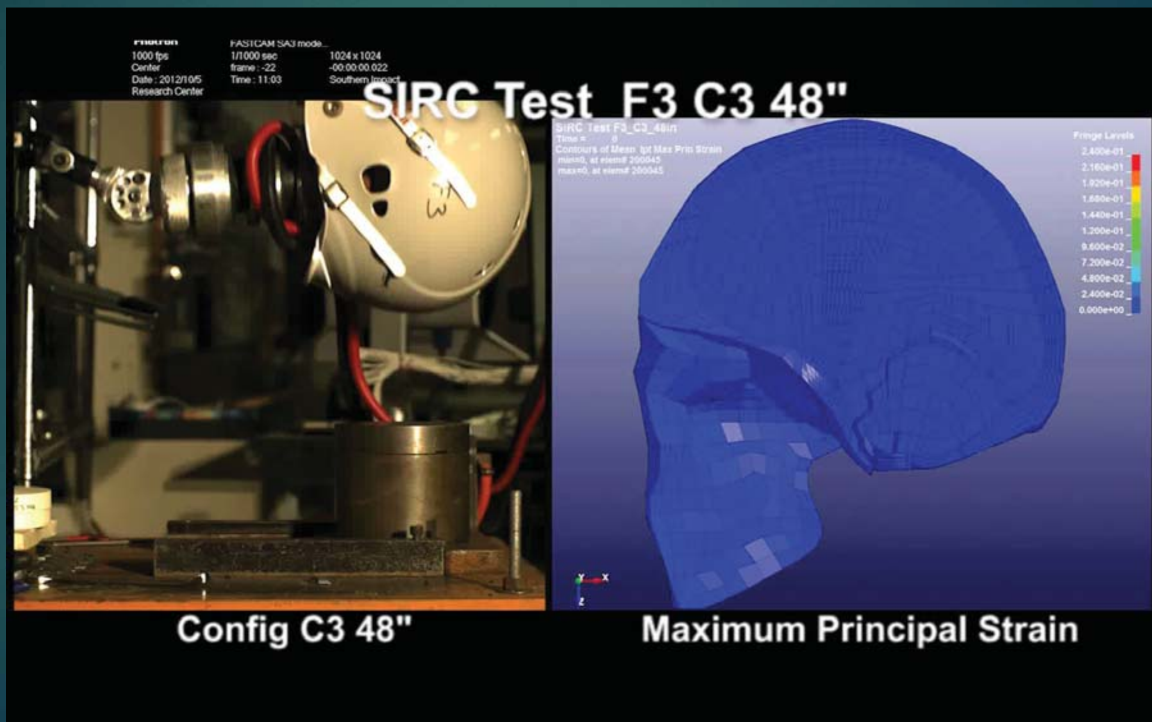
Indirect Loading



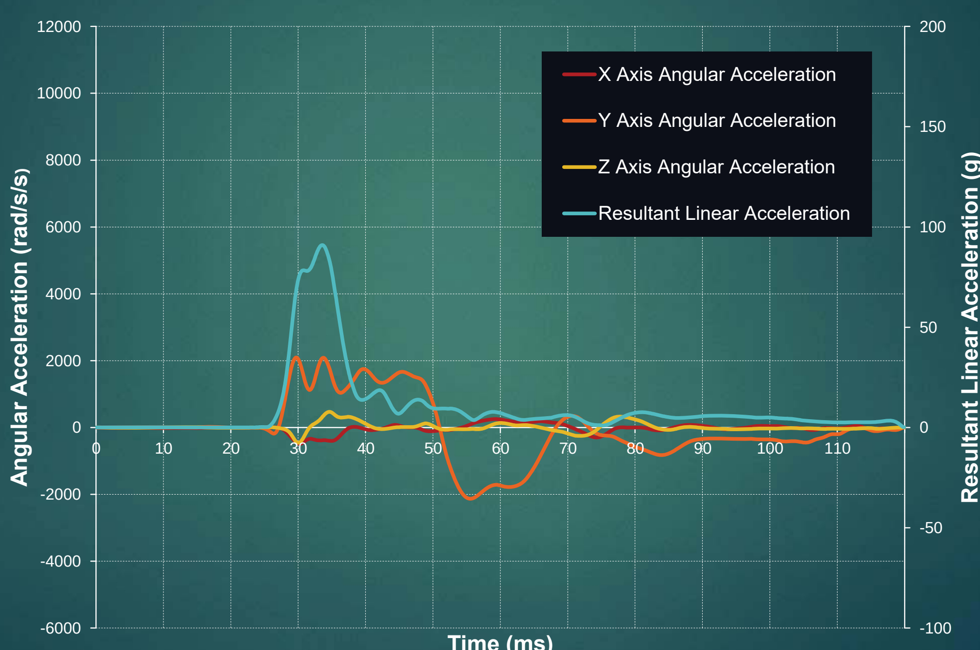
Results – Indirect Loading



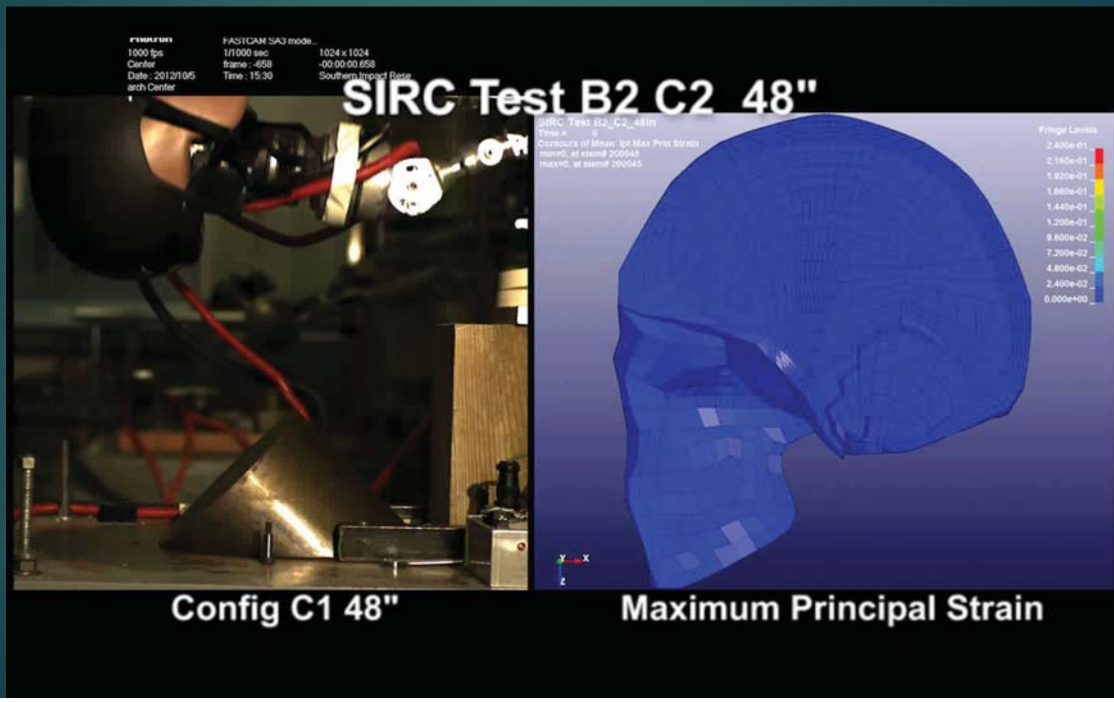
Direct Loading



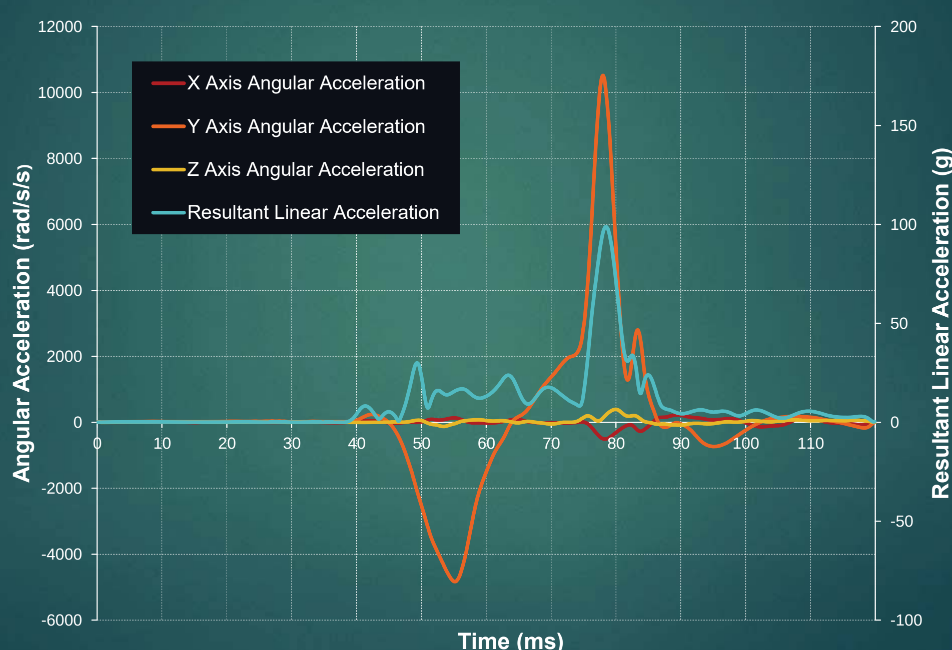
Results – Direct Loading

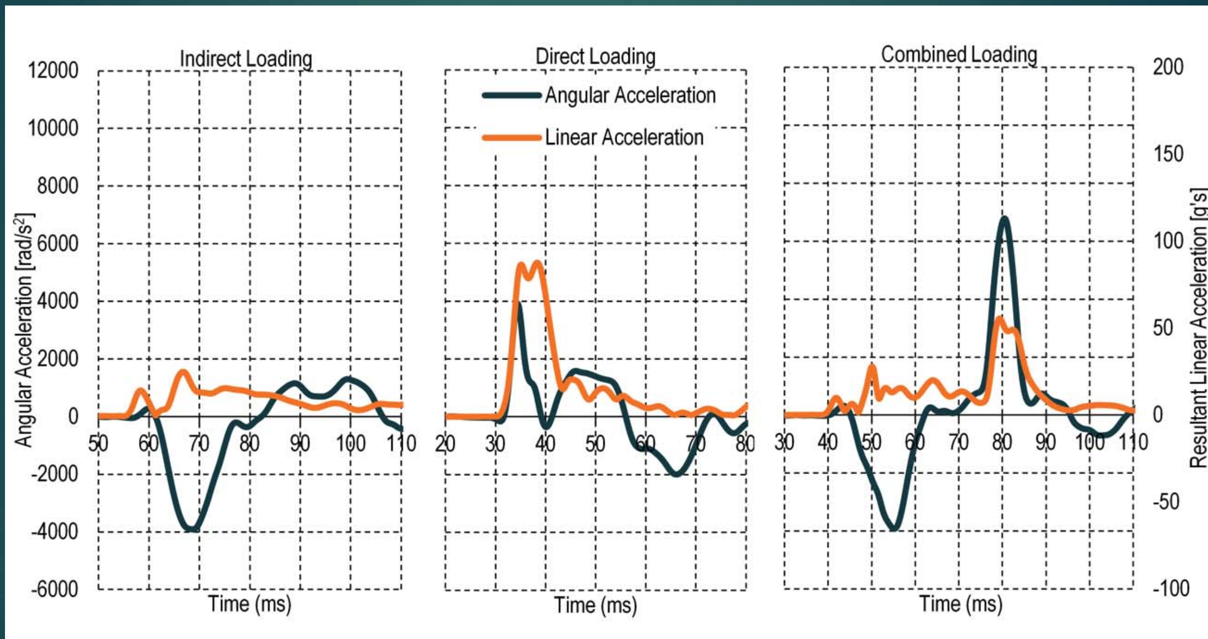


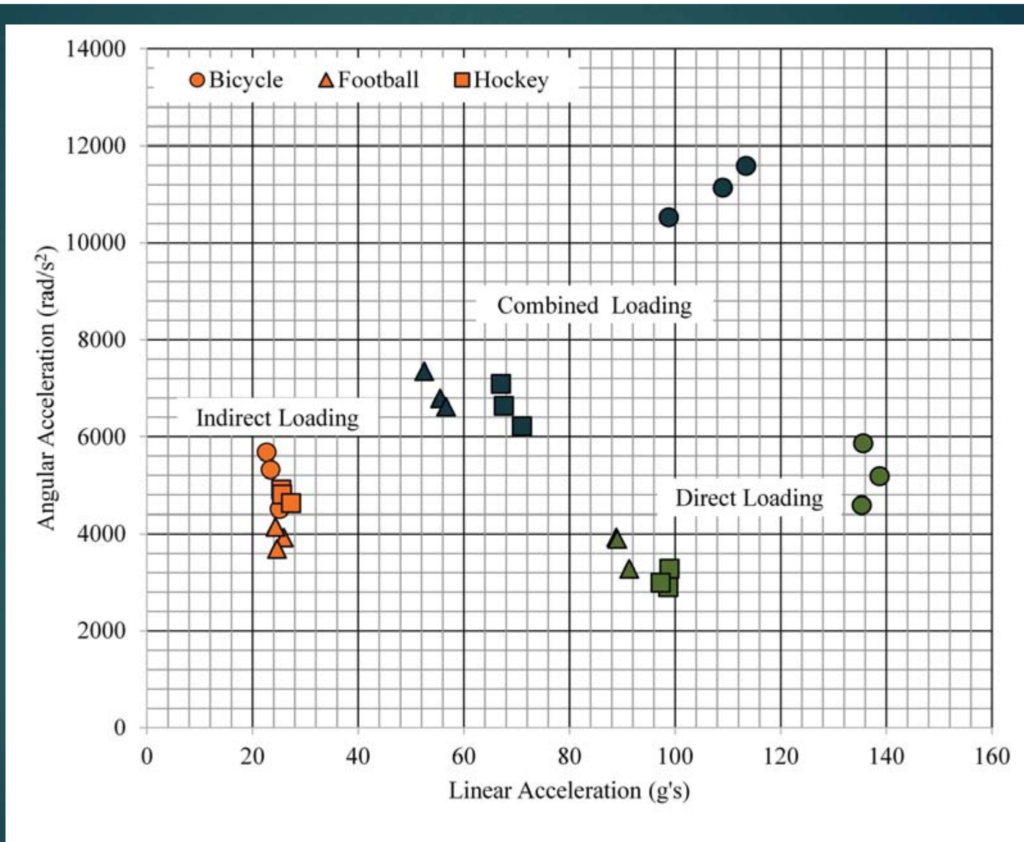
Combined Loading

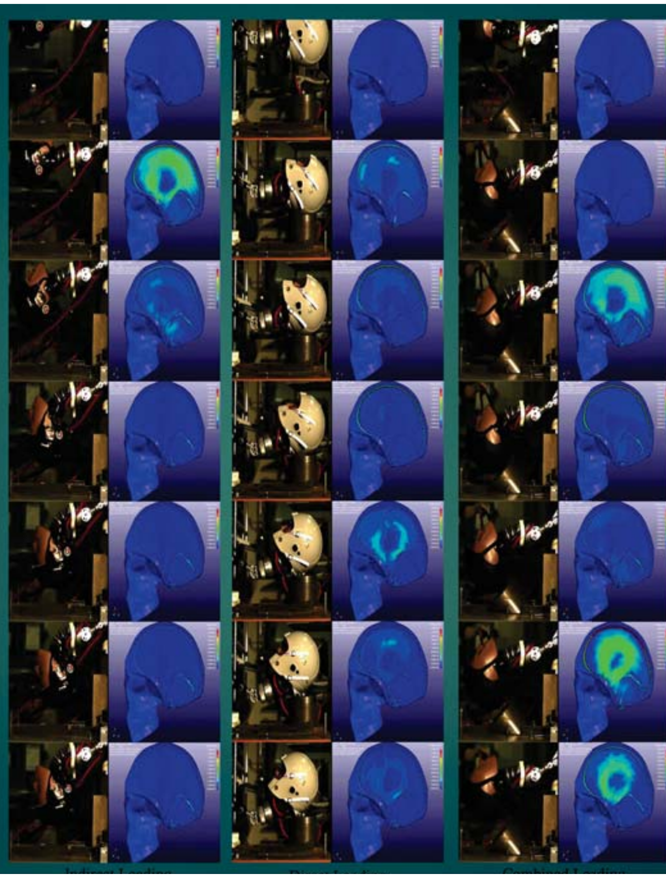


Results – Combined Loading




Indirect Loading
Direct Loading
Combined Loading
Angular Acceleration
Linear Acceleration
Angular Acceleration [rad/s²]
Resultant Linear Acceleration [g's]
Time (ms)
Time (ms)
Time (ms)


Bicycle
Football
Hockey
Combined Loading
Indirect Loading
Direct Loading
Angular Acceleration (rad/s²)
Linear Acceleration (g's)



Results: Peak Linear and Angular Acceleration

Peak Linear Resultant Acceleration (g)*

	Indirect	Combined	Direct
Bicycle	23.8 (1.3)	107.1 (7.5)	136.6 (1.9)
Football	25.0 (0.8)	54.9 (2.1)	89.7 (1.4)
Hockey	26.1 (1.0)	68.6 (2.2)	98.3 (0.9)

Peak Angular Resultant Acceleration (krad/s^2)*

	Indirect	Combined	Direct
Bicycle	5.2 (0.6)	11.1 (0.5)	5.2 (0.6)
Football	3.9 (0.2)	6.9 (0.3)	3.7 (0.4)
Hockey	4.8 (0.2)	6.6 (0.4)	3.1 (0.2)

* Significant across helmet type, test condition and helmet X test condition (alpha = .05)

Results: MPS and VMS

Maximum Principal Strain in Gray Matter (%)*

	Indirect	Combined	Direct
Bicycle	18.4 (1.6)	31.2 (1.9)	20.8 (2.2)
Football	14.9 (0.3)	24.2 (1.0)	14.2 (0.6)
Hockey	17.6 (0.6)	17.8 (0.7)	10.3 (0.3)

Maximum Von Mises Stress in Gray Matter (kPa)*

	Indirect	Combined	Direct
Bicycle	9.8 (0.9)	17.7 (1.2)	11.7 (1.2)
Football	7.9 (0.2)	14.0 (0.5)	1.7 (0.5)
Hockey	9.4 (0.3)	9.5 (0.3)	5.6 (0.2)

* Significant across helmet type, test condition and helmet X test condition (alpha = .05)

Results: Brain Volume Under Strain

Gray Matter Volume at 15% Strain Threshold (% volume)*

	Indirect	Combined	Direct
Bicycle	0.6 (0.4)	7.7 (2.2)	0.8 (0.3)
Football	0.0 (0.0)	6.5 (2.5)	0.0 (0.0)
Hockey	0.4 (0.2)	2.7 (0.1)	0.0 (0.0)

Gray Matter Volume at 20% Strain Threshold (% volume)*

	Indirect	Combined	Direct
Bicycle	0.0 (0.0)	1.1 (0.7)	0.1 (0.1)
Football	0.0 (0.0)	0.4 (0.2)	0.0 (0.0)
Hockey	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)

Summary and Conclusions

- Head/neck kinematics prior to impact play a significant role in the resulting linear and angular accelerations
- This research has identified a kinematic profile and injury mechanism that may explain those cases involving low level linear acceleration and concussion
- Impacts involving pre-contact angular head acceleration and contact result in higher levels of strain in the gray matter and a greater volume of gray matter tissue undergoing strain
- The role of the helmet in cases involving angular acceleration and contact is very limited
- Future research needs to focus on the entire kinematic sequence, including pre-contact linear and angular head motion

2015 Performance Testing of Football Helmets

J. Crandall, J. Funk

NFL Head, Neck and Spine Engineering Subcommittee

K. Arbogast, B. Myers

NFL PA Consultants

C. Withnall, M. Wonnacott

Biokinetics

IRCOBI-NOCSAE-SNELL-PDB Workshop, September 8, 2015

Purpose of Testing

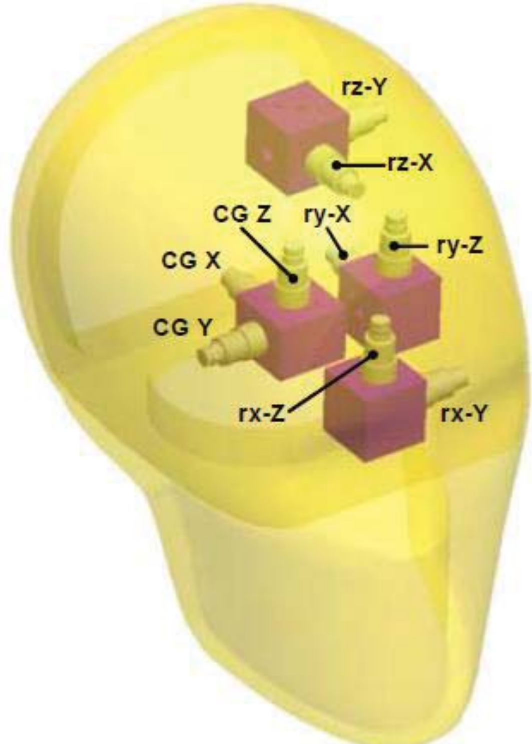
- To evaluate contemporary helmet performance in laboratory impacts replicating open-field hits of NFL players

Test Apparatus

- Test protocol comparable to previous NFL testing of helmets (Viano et al. 2012)
- Linear impactor strikes a helmeted Hybrid III head and neck mounted to a slider (head translation and rotation)
- Meant to replicate on-field impacts in the NFL based on video reconstructions

Test Apparatus

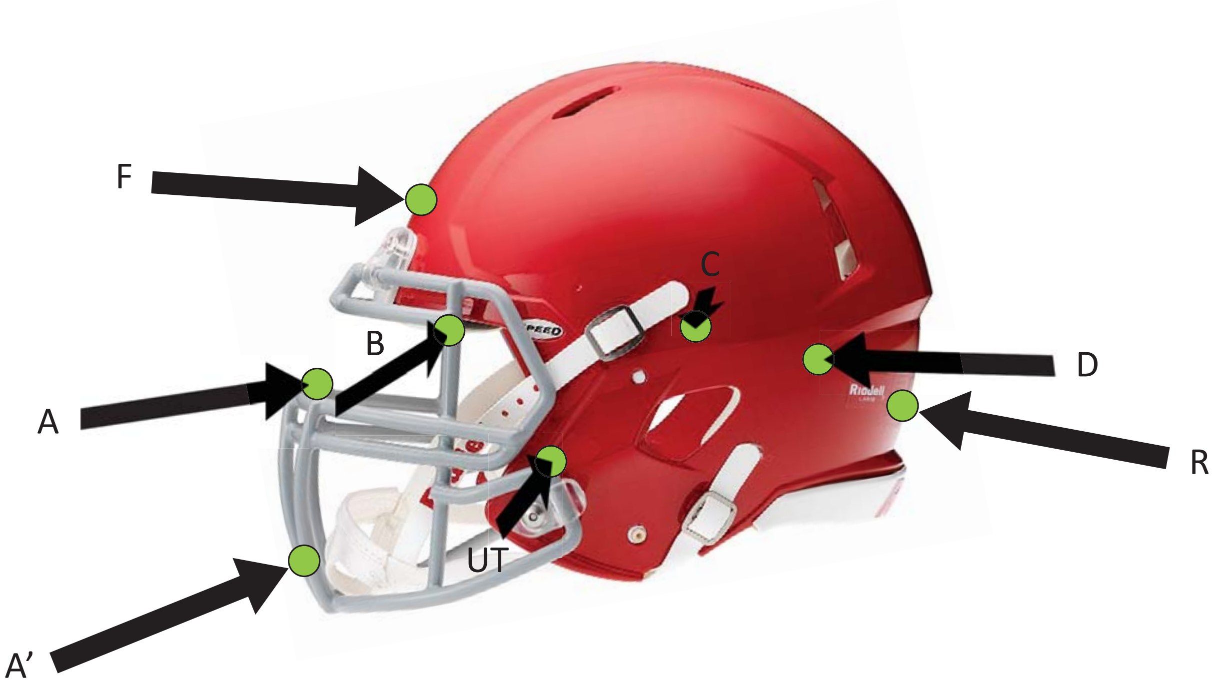
- Impactor mass = 14 kg
  - Effective mass of striking player
- Vinyl nitrile end cap
  - Meant to replicate shape and stiffness of striking player’s helmet
- 50^{th} male Hybrid III head and neck
- 2 layers of nylon stockings on head
- EGOP facemask (or similar)
- Soft chinstrap



Methodology

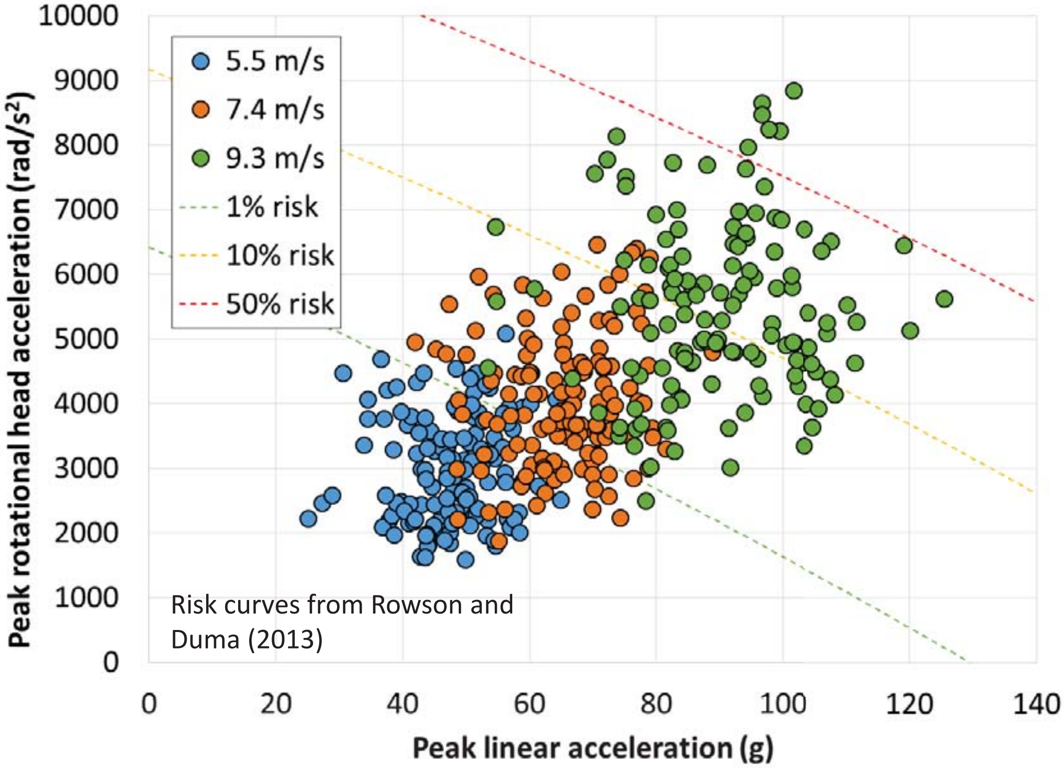
- Full test matrix: 3 factors -helmet, speed, location
- 17 helmet models (representing >95% of NFL player’s helmets)
- 3 test speeds
  - 9.3 m/s = average closing speed of concussive impacts in the NFL
  - 7.4 m/s = average – 1 sd
  - 5.5 m/s = average – 2 sd
- Ambient temperature

Helmet Impact Locations



Test Matrix

Test purpose		Performance			Repeatability	Reproducibility	
					(same helmet)	(different helmet)	
Manufacturer	**Model**	**5.5 m/s**	**7.4 m/s**	**9.3 m/s**	**7.4 m/s**	**9.3 m/s**	# tests
Riddell	Revolution Speed Classic	X	X	X	X	X	40
Riddell	Revolution Speed	X	X	X			24
Riddell	Revolution	X	X	X			24
Riddell	SpeedFlex	X	X	X	X	X	40
Riddell	VSR-4	X	X	X			24
Schutt	Air XP	X	X	X	X	X	40
Schutt	Air XP Pro	X	X	X			24
Schutt	Vengeance DCT	X	X	X			24
Schutt	Vengeance VTD	X	X	X			24
Schutt	Vengeance VTD II	X	X	X			24
Rawlings	Impulse	X	X	X	X	X	40
Rawlings	Impulse +	X	X	X			24
Rawlings	NRG Quantum	X	X	X			24
Rawlings	NRG Tachyon	X	X	X			24
Xenith	Epic Varsity	X	X	X	X	X	40
Xenith	X2E	X	X	X			24
SG	Varsity	X	X	X	X	X	40
Total		17	17	17	6	6	504

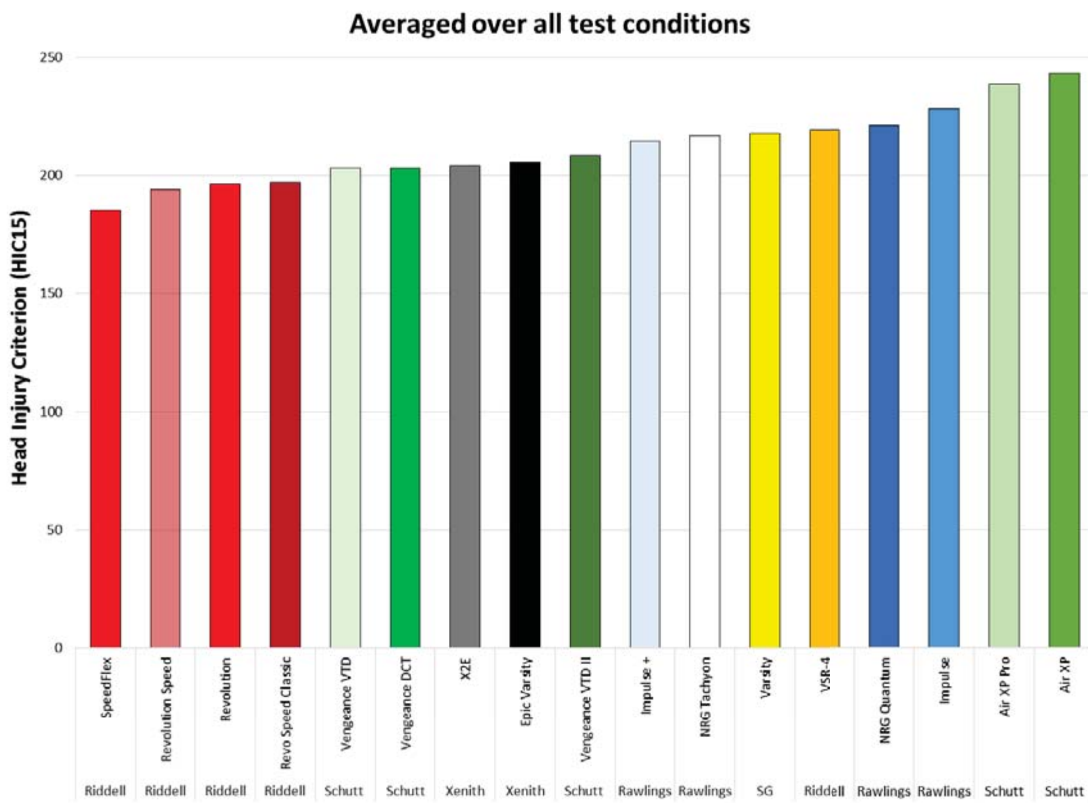


Results

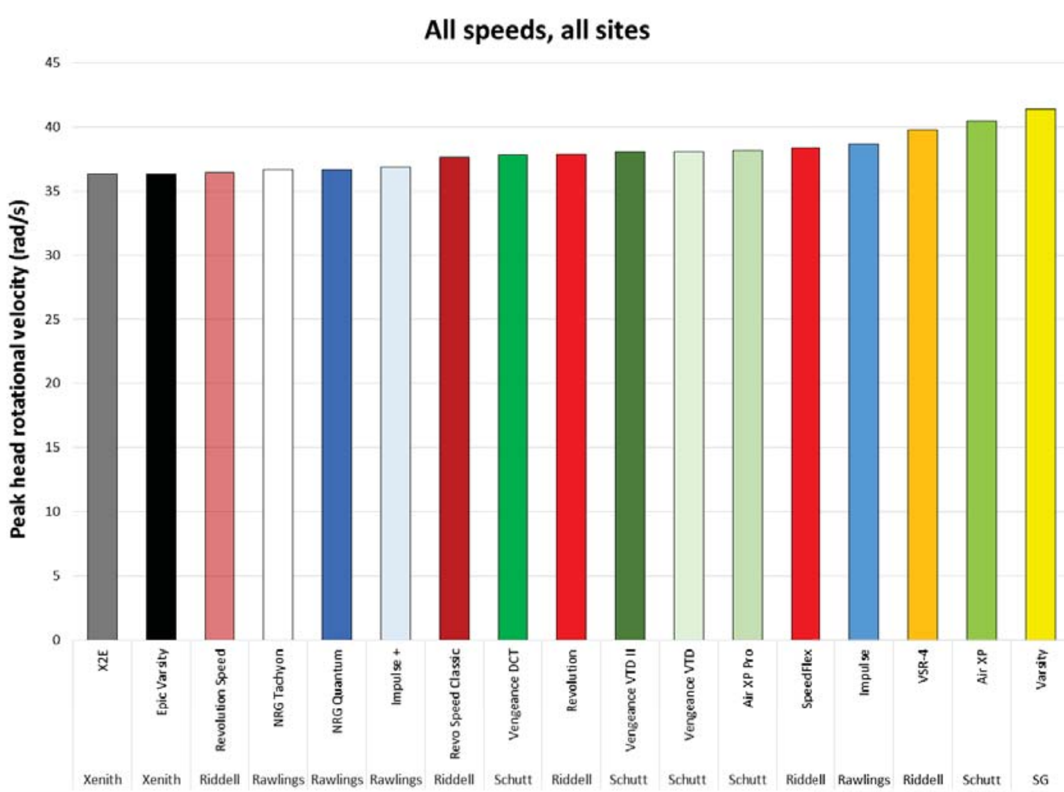
- No sensor failures or test equipment failures
- No helmet failures, but some post-test damage

Cracking and compression of liner in SG Varsity

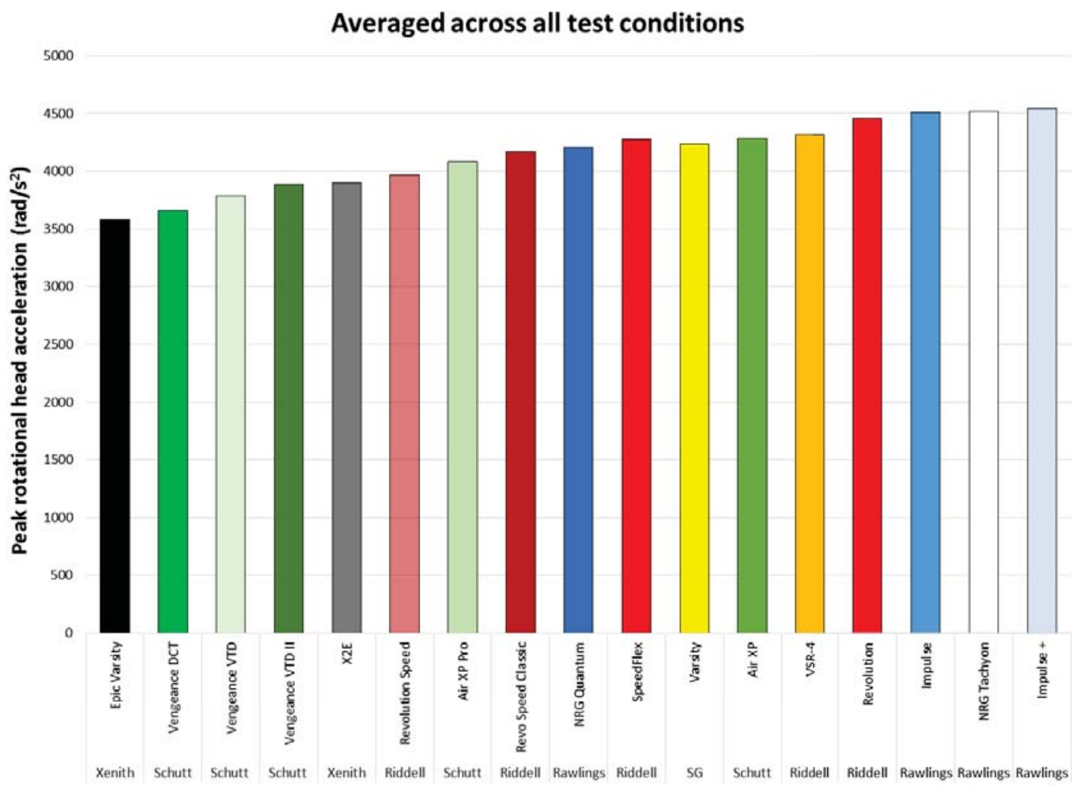
Broken facemask clip on Xenith X2E

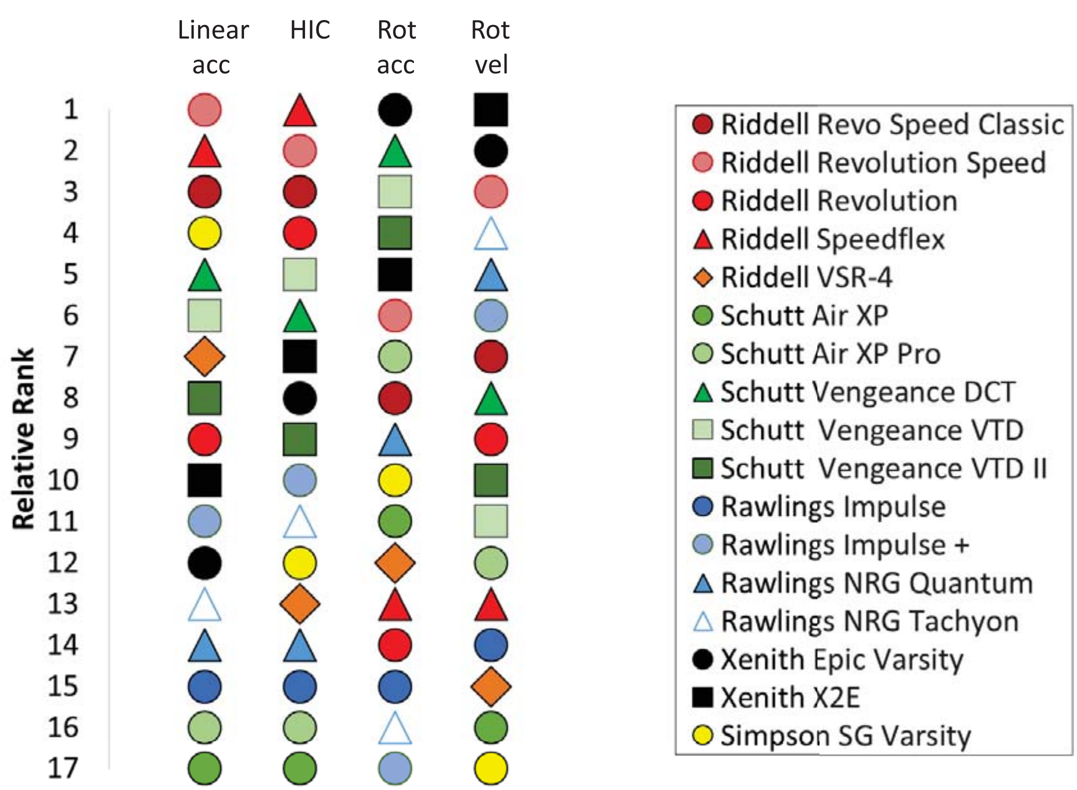


Averaged over all test conditions
Head Injury Criterion (HIC15)
250
200
150
100
50
0
SpeedFlex
Revolution Speed
Revolution
Revo Speed Classic
Vengeance VTD
Vengeance DCT
X2E
Epic Varsity
Vengeance VTD II
Impulse +
NRG Tachyon
Varsity
VSR-4
NRG Quantum
Impulse
Air XP Pro
Air XP
Riddell
Riddell
Riddell
Riddell
Schutt
Schutt
Xenith
Xenith
Schutt
Rawlings
Rawlings
SG
Riddell
Rawlings
Rawlings
Schutt
Schutt



All speeds, all sites
Peak head rotational velocity (rad/s)
45
40
35
30
25
20
15
10
5
0
X2E
Epic Varsity
Revolution Speed
NRG Tachyon
NRG Quantum
Impulse +
Revo Speed Classic
Vengeance DCT
Revolution
Vengeance VTD II
Vengeance VTD
Air XP Pro
SpeedFlex
Impulse
VSR-4
Air XP
Varsity
Xenith
Xenith
Riddell
Rawlings
Rawlings
Rawlings
Riddell
Schutt
Riddell
Schutt
Schutt
Schutt
Riddell
Rawlings
Riddell
Schutt
SG


Averaged across all test conditions
Peak rotational head acceleration (rad/s²)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Epic Varsity
Vengeance DCT
Vengeance VTD
Vengeance VTD II
X2E
Revolution Speed
Air XP Pro
Revo Speed Classic
NRG Quantum
SpeedFlex
Varsity
Air XP
VSR-4
Revolution
Impulse
NRG Tachyon
Impulse +
Xenith
Schutt
Schutt
Schutt
Xenith
Riddell
Schutt
Riddell
Rawlings
Riddell
SG
Schutt
Riddell
Riddell
Rawlings
Rawlings
Rawlings


Linear acc
HIC
Rot acc
Rot vel
Relative Rank
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
Riddell Revo Speed Classic
Riddell Revolution Speed
Riddell Revolution
Riddell Speedflex
Riddell VSR-4
Schutt Air XP
Schutt Air XP Pro
Schutt Vengeance DCT
Schutt Vengeance VTD
Schutt Vengeance VTD II
Rawlings Impulse
Rawlings Impulse +
Rawlings NRG Quantum
Rawlings NRG Tachyon
Xenith Epic Varsity
Xenith X2E
Simpson SG Varsity

Relationship between Metrics (Correlation Matrices and Scatterplot)

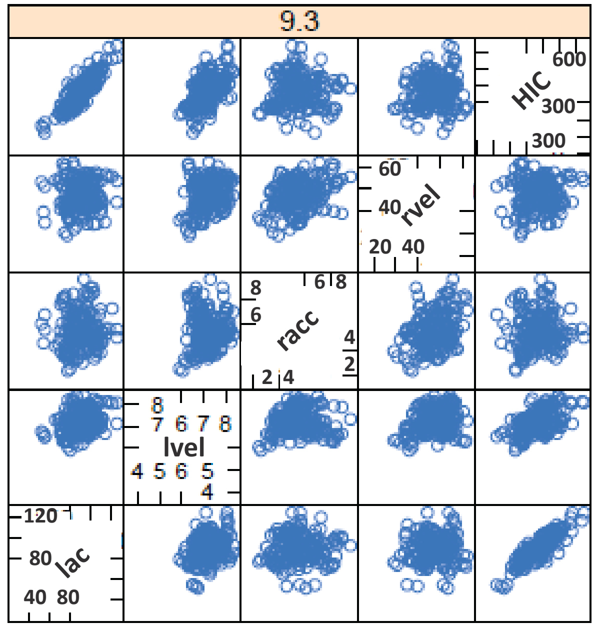
HIC, Maximum Resultant Accelerations and Velocities

5.5 m/s	linacc	rotacc	rotvel	HIC15
linacc	1.000	0.068	0.217	0.878
rotacc	0.068	1.000	0.292	0.100
rotvel	0.217	0.292	1.000	0.306
HIC15	0.878	0.100	0.306	1.000

7.4 m/s	linacc	rotacc	rotvel	HIC15
linacc	1.000	0.065	0.137	0.885
rotacc	0.065	1.000	0.343	0.112
rotvel	0.137	0.343	1.000	0.215
HIC15	0.885	0.112	0.215	1.000

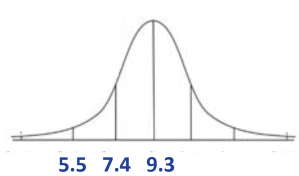
9.3 m/s	linacc	rotacc	rotvel	HIC15
linacc	1.000	0.046	0.048	0.893
rotacc	0.046	1.000	0.348	0.040
rotvel	0.048	0.348	1.000	0.101
HIC15	0.893	0.040	0.101	1.000

Pearson's Correlation Coefficient (r)

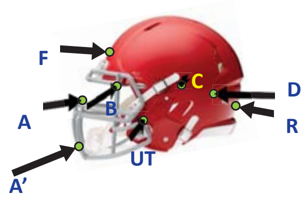


lacc (g), lvel (m/s), rvel (rad/s), racc (krad/s^2)

Helmets Compared with Linear ANOVA models



Impact Speed (m/s)



Impact Locations (8)

Helmet Models (17)

$$Metric\ = \mu + Helmet + Speed + Location + \ \epsilon$$

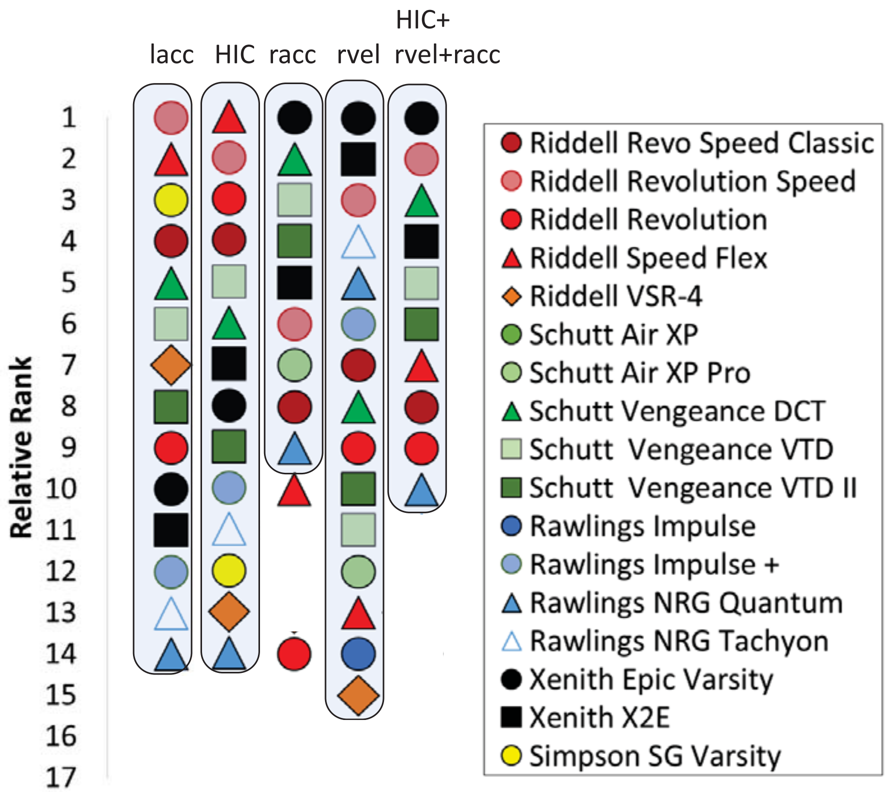
Independent Variables

μ – average performance across all helmets (17)
Helmet – accounts for differential performance across helmets
Speed – categorical variable to account for nonlinearities
Location – accounts for differential performance in impact location
ϵ – random variable incorporating all other variation in data

Dependent Variables (Metrics)
(Maximum Values)

lacc	resultant linear acceleration
HIC	Head Injury Criterion (15)
racc	resultant rotational acceleration
rvel	resultant rotational velocity
HIC + rvel + racc	normalized sum with equal weighting of individual metrics

ANOVA and Tukey's HSD methodology originally used in "Independent Review and Evaluation of NFL Helmet-Testing Program" by D. Meaney and B. Myers (July 2010)

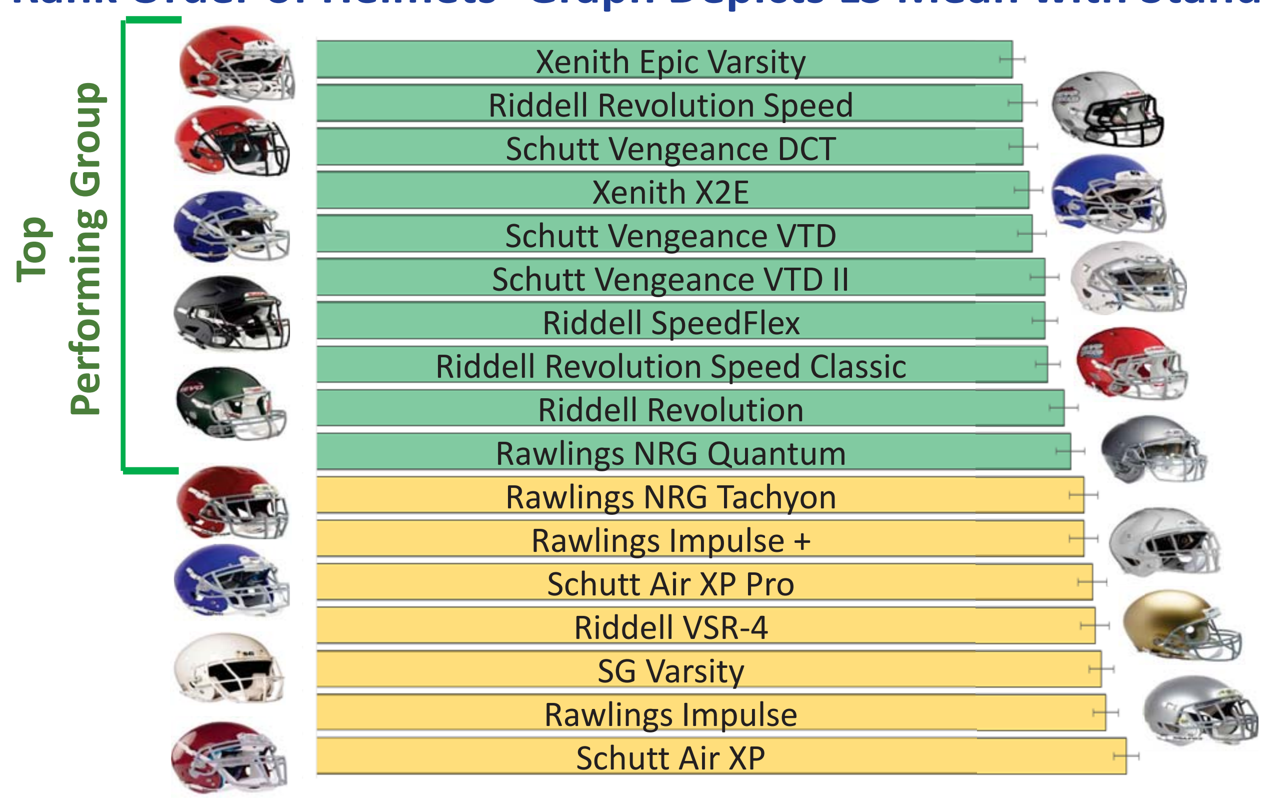


With a few exceptions for rotational acceleration (racc), the helmets in the top group of the combined metric were also in the top groups of all the individual metrics

Tukey's HSD
Dependent Variable Metrics
(maximum variable)

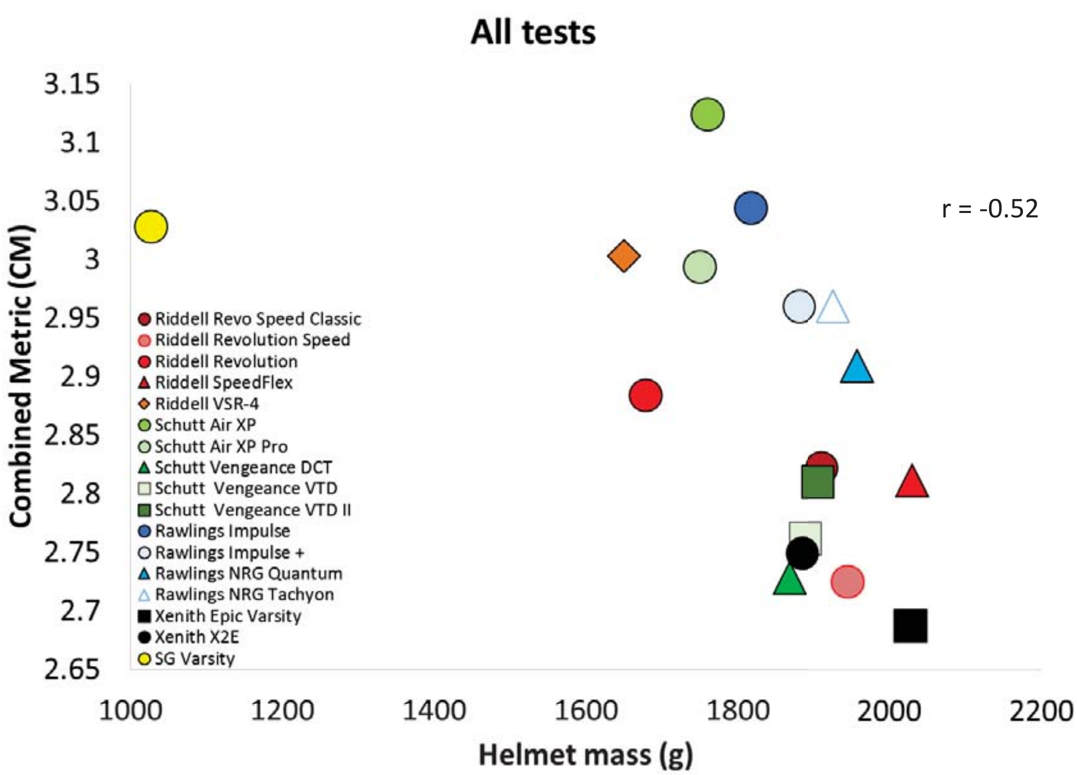
lacc	linear acceleration
HIC	Head Injury Criterion (15)
racc	rotational acceleration
rvel	rotational velocity
HIC + rvel + racc	normalized sum with equal weighting of individual metrics

Rank Order of Helmets- Graph Depicts LS Mean with Standard Error

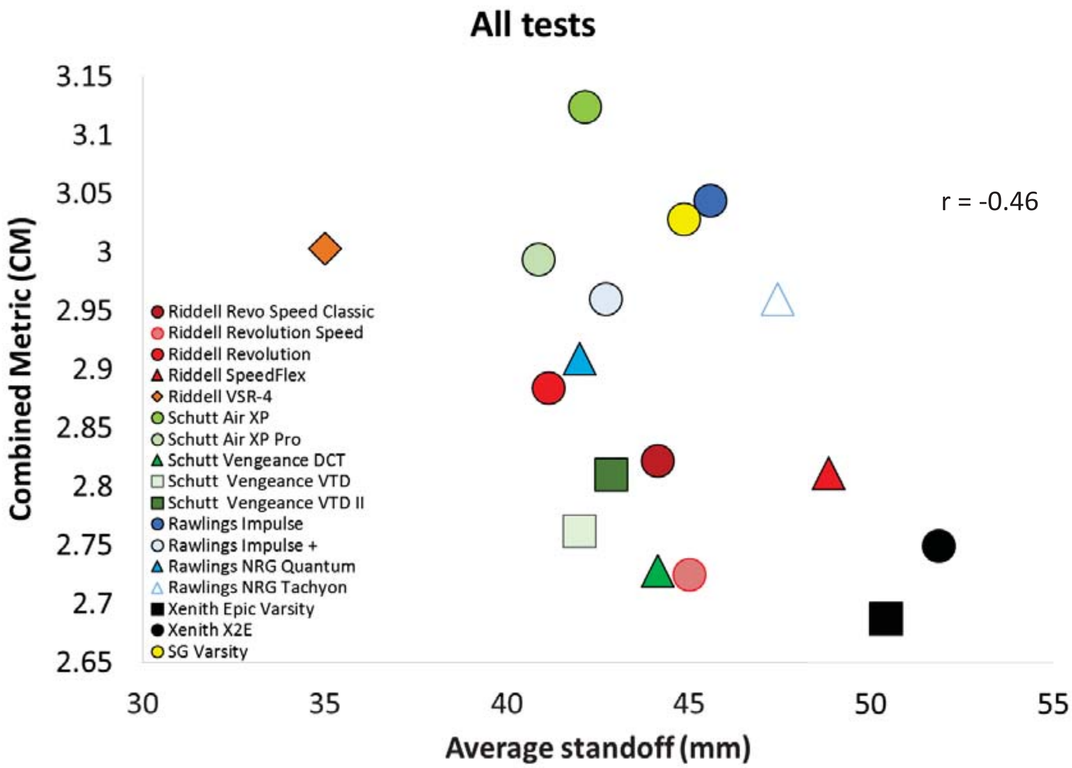


Limitations

- Test-to-test variability
  - Repeatability testing (same helmet): RMS error = 6% - 9%
  - Reproducibility testing (different helmet): RMS error = 8% - 13%
- Higher Speed Tests (11.2 m/s) not conducted
- Current state of biomechanical knowledge
- No consensus on injury criteria for concussion, i.e. risk levels associated with a particular injury metric
  - Multiple Rotational Metrics (velocity, acceleration)
  - Relative Ranking



Moment of Inertia Measurements to be completed by 12/2015

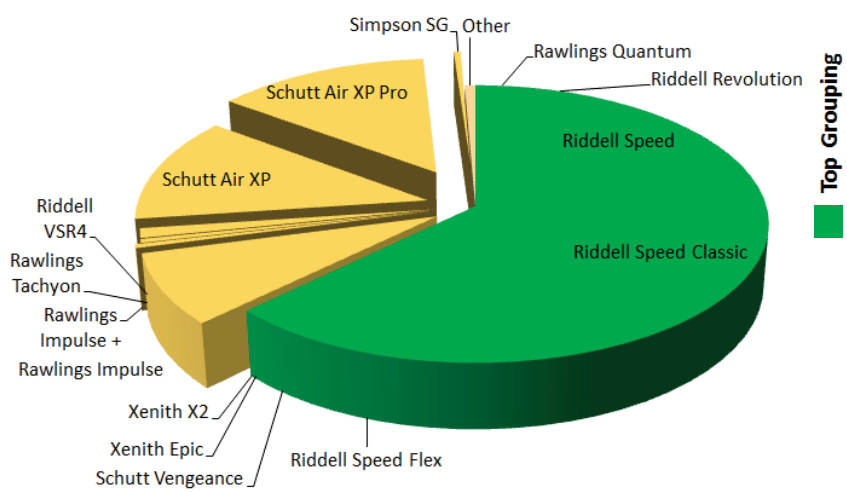


PLAYER HELMET SIZE FORM

	PLAYER	
	HEIGHT	
	WEIGHT	
	POSITION	
	HEAD CIRCUMFERENCE Measure approximately 1" above the eyebrows at the widest part of the head 	
HELMET	MANUFACTURER	
	MODEL	
	SIZE	
	JAW PADS	
	CROWN SIZE, FRONT PAD, LINER, ETC.	
	SHIMS (IF APPLICABLE)	
FACEMASK	MANUFACTURER	
	MODEL	
	MATERIAL (CARBON STEEL, TITANIUM, ETC.)	
CHINSTRAP	MANUFACTURER	
	HARD/SOFT	
	CUP SIZE (MEDIUM, DEEP, ETC.)	
	Items worn under helmet (Skull Cap, etc. - leave blank if nothing)	
COMMENTS ON HELMET FIT		
	Name of person filling out form	
	Date	

2015 Helmet Survey

Helmet information collected on all players during season, entered in NFL Injury Surveillance System when a head injury occurs



Helmet Models Not separated from pie are in top performing group (62.7%)
Helmet Models separated from pie are not in the top performing group (37.3%)

2015 Performance Testing of Football Helmets

J. Crandall, J. Funk
NFL Head, Neck and Spine Engineering Subcommittee
K. Arbogast, B. Myers
NFL PA Consultants
C. Withnall, M. Wonnacott
Biokinetics

IRCOBI-NOCSAE-SNELL-PDB Workshop, September 8, 2015

HEAD ACCELERATION SENSING: VALID OR INVALID?

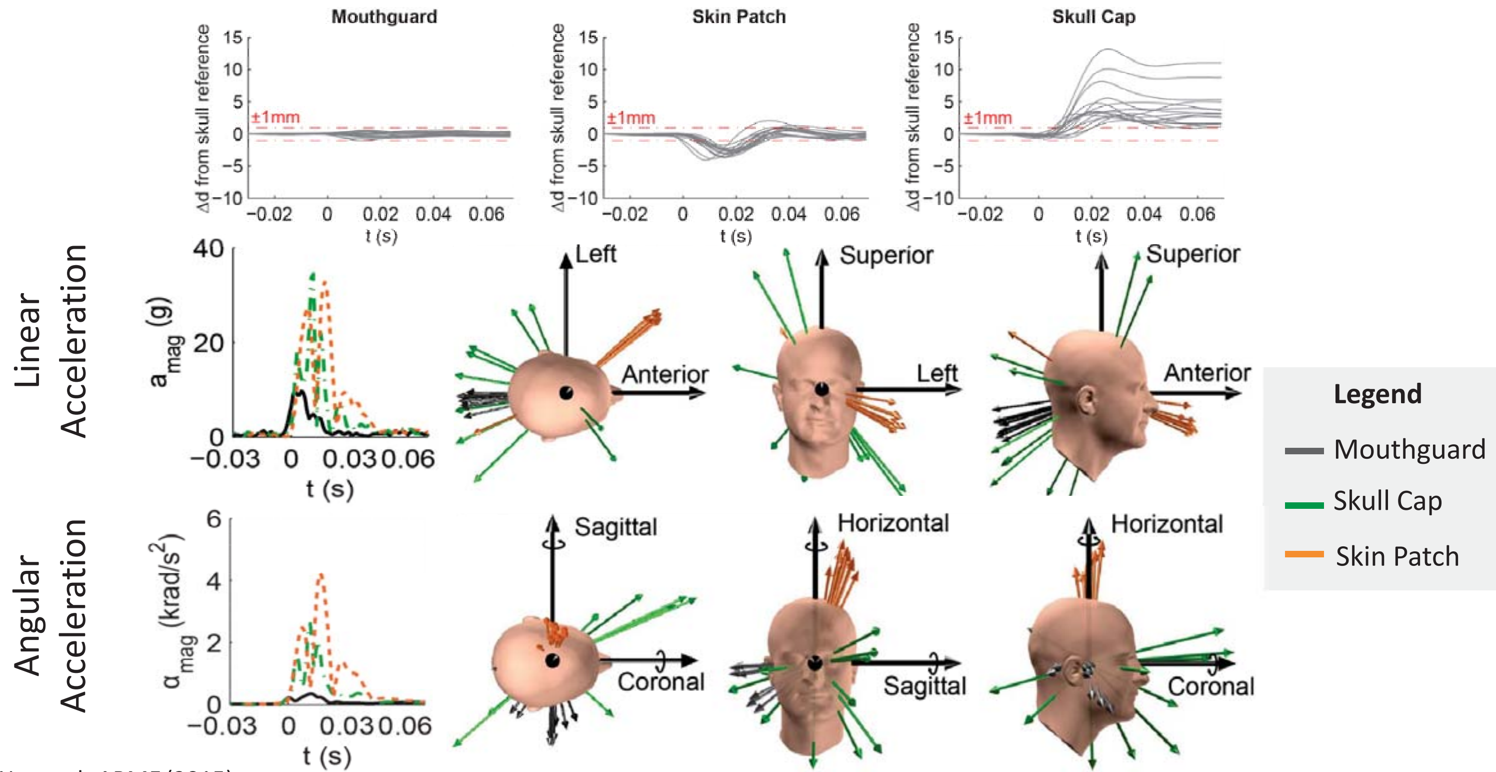
Lyndia C. Wu
Camarillo Lab, Stanford University
Bioengineering Department

Head sensing options

Sensor motion during *In vivo* soccer header

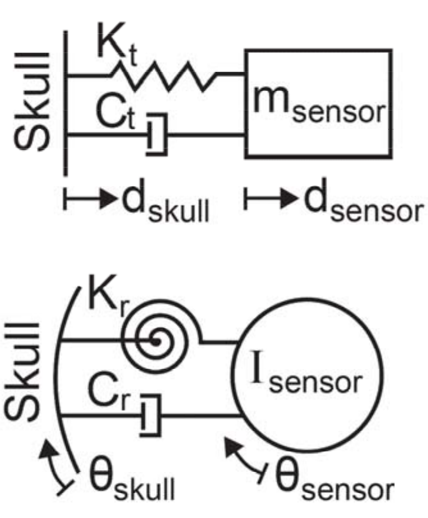
Wu, et al. *ABME* (2015).

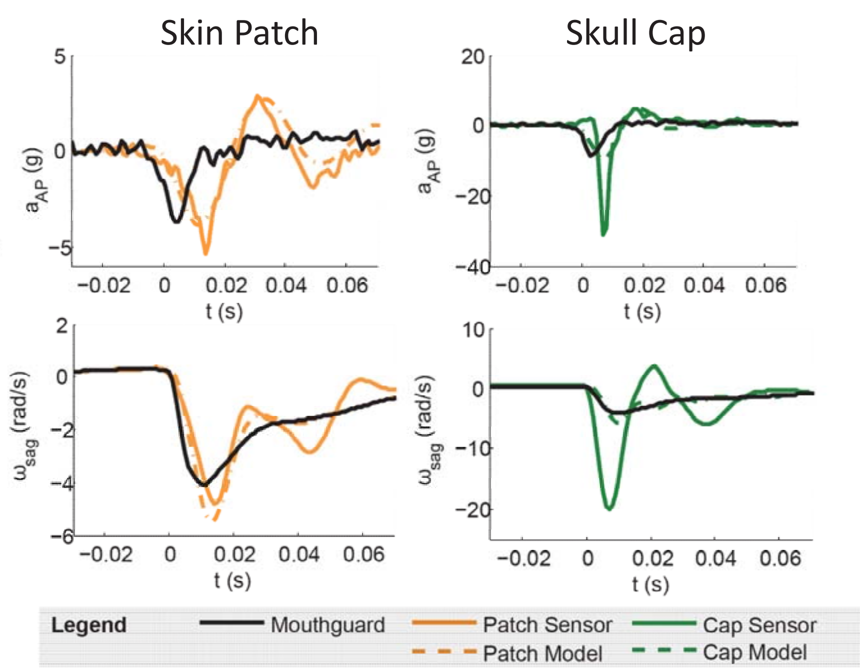
Displacement errors, acceleration differences



Wu, et al. *ABME* (2015).

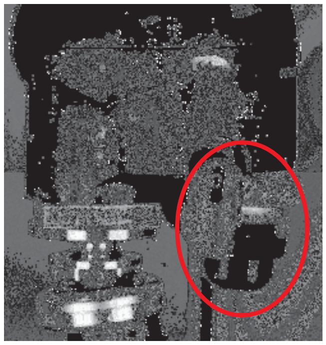
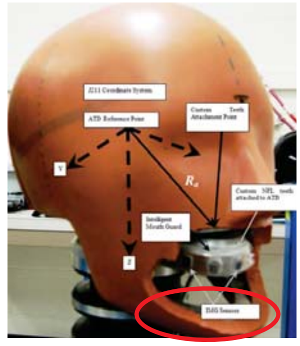
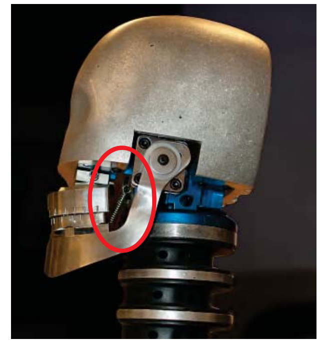
Semi-modelable errors





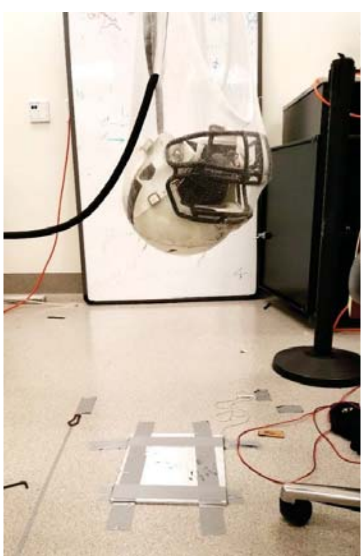
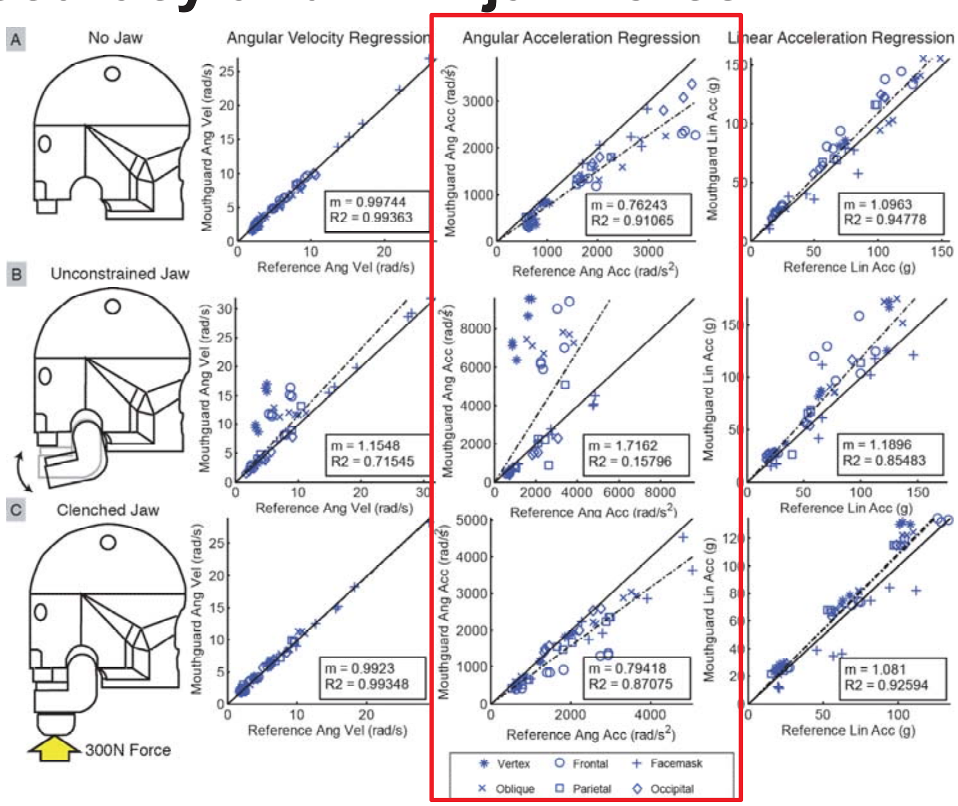
Wu, et al. *ABME* (2015).

Mouthguard Evaluations

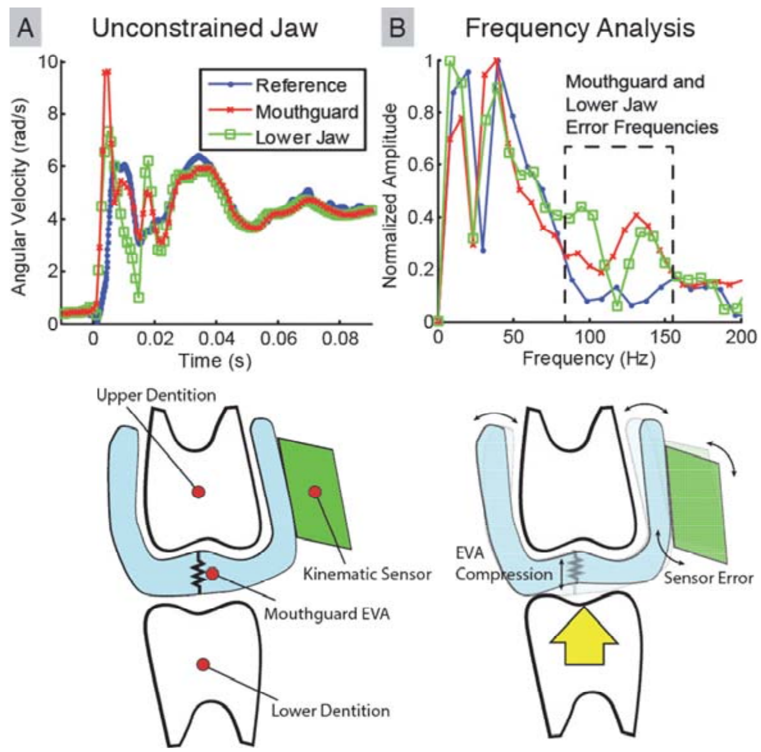
	Camarillo et. al. 2013, ABME	Bartsch et. al., 2014, Stapp	Seigmund et. al., 2015, ABME
Linear Acceleration	m=1.01, R^2=0.96	m=1.01, R^2=0.99	m=0.90, R^2=0.90
Angular Acceleration	m=0.90, R^2=0.89	m=1.00, R^2=0.99	m=1.30, R^2=0.56

Mouthguard accuracy and ATD jaw force

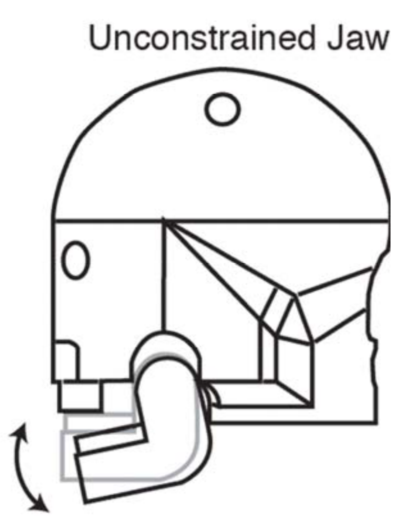



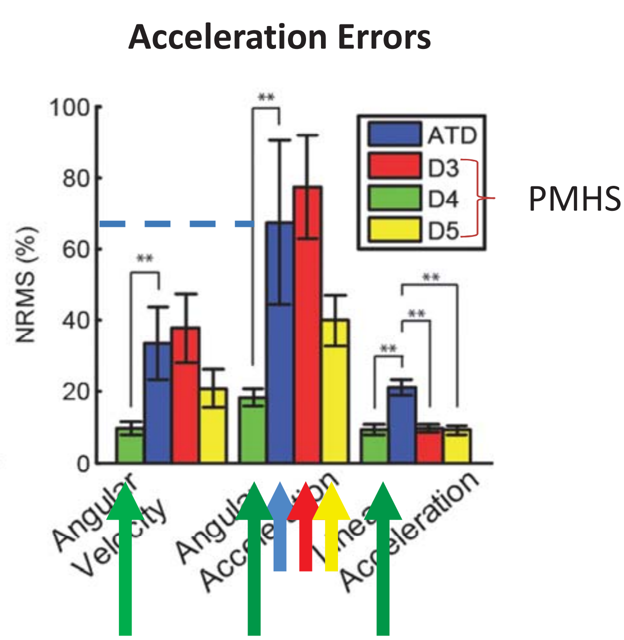
Kuo et al., unpublished

Modeling Mouthguard Error

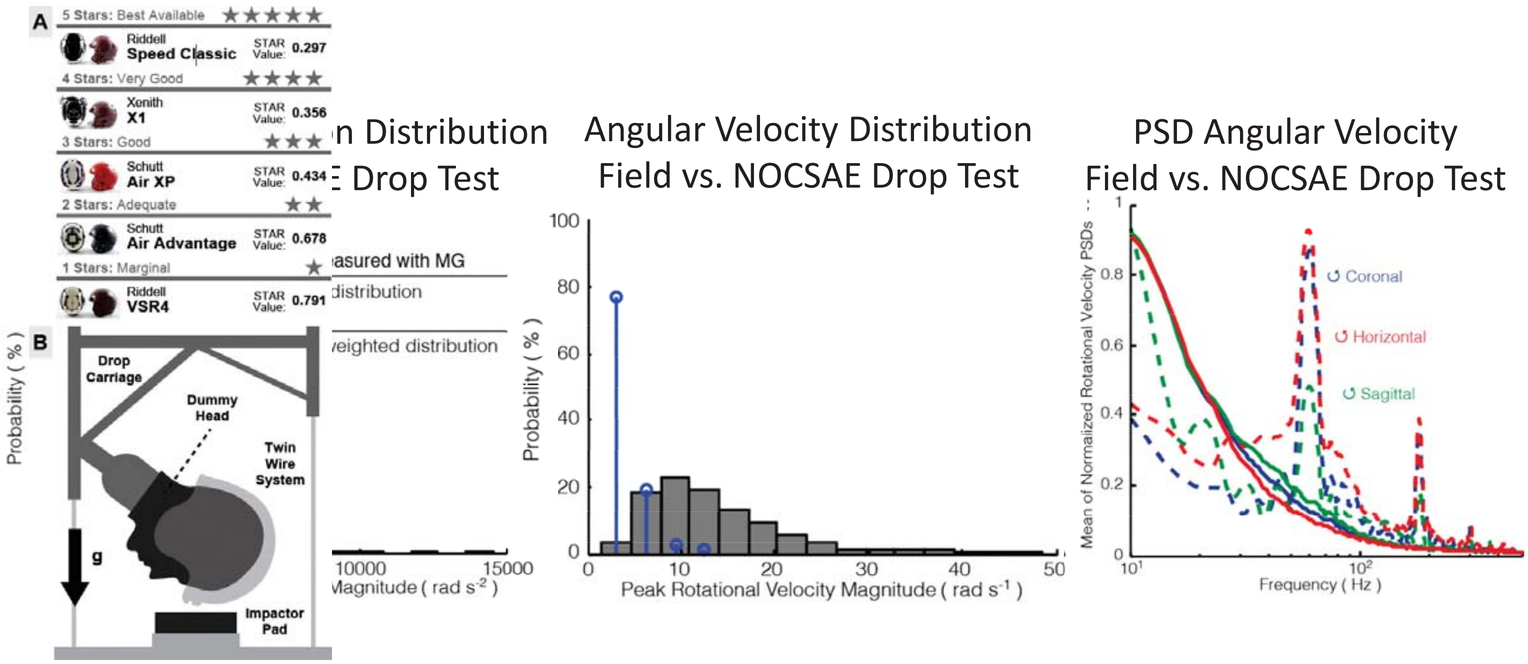


PMHS evaluation





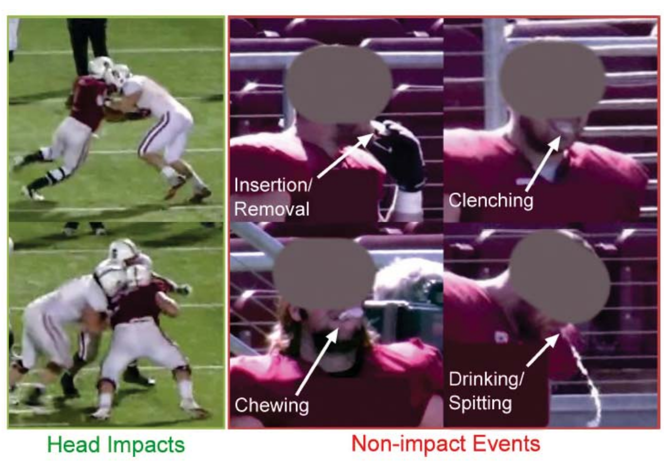
Collegiate football rotation and NOCSAE/STAR



Hernandez, et al. *J Biomech* (2015).

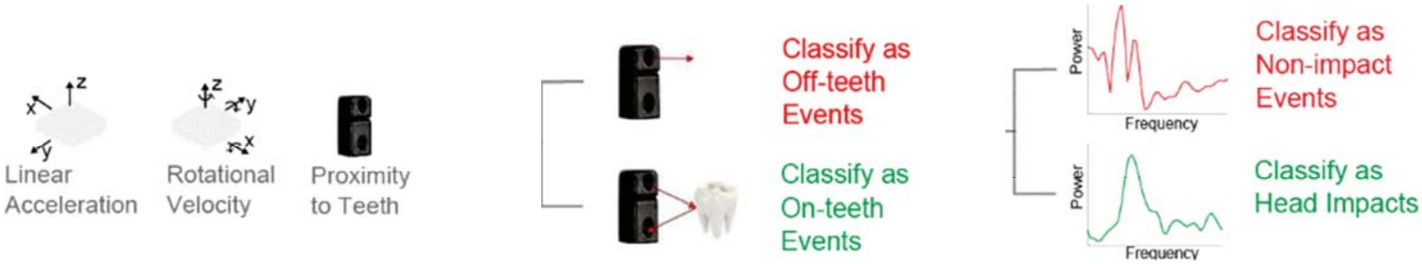
Impact Detection

- Any medical screening: false positive -> unnecessary care
- False positives are also scary
- US Lystedt Law – any suspected concussion needs care



Wu, et al. *IEEE Trans. Biomed. Eng.* 61.11 (2014)

Impact Detection



Detect an impact:
10g threshold

Classify as on mouth:
IR proximity sensing

Classify as impact:
SVM classifier

	10 g Threshold Only	10 g Threshold + Proximity	SVM Alone	SVM + Proximity
Sensitivity	0.92	0.92	0.98	0.98
Precision	0.37	0.93	0.97	0.9998
Specificity	0.58	0.96	0.99	0.9999
Accuracy	0.65	0.94	0.99	0.99
Area Under ROC	0.780 (0.031)	0.979 (0.005)	0.998 (0.001)	1 (0.000)

Wu, et al. *IEEE Trans. Biomed. Eng.* 61.11 (2014)

Acknowledgements

- Dr. Dale Bass's group at Duke
- X2 for donating skin patch
- Stanford Athletics for continual support

NSF
STANFORD BIO-X
NSERC CRSNG
NIH National Institutes of Health
the David & Lucile Packard FOUNDATION
Stanford MEDICINE | Child Health Research Institute

Workshop on Rotation

September 8, 2015

Snell Impact Testing

- Drop Testing – Guided Fall
  - Shock Directed Through the Center of Gravity
  - Specified Velocity & Impact surfaces
  - Rotational Input deliberately minimized
- Uniaxial Accelerometer Measures
  - Parallel to the force vector – as much as possible
- Peak G Criterion
  - No attention to pulse shape
  - That is: no SI, HIC or Time Duration limits

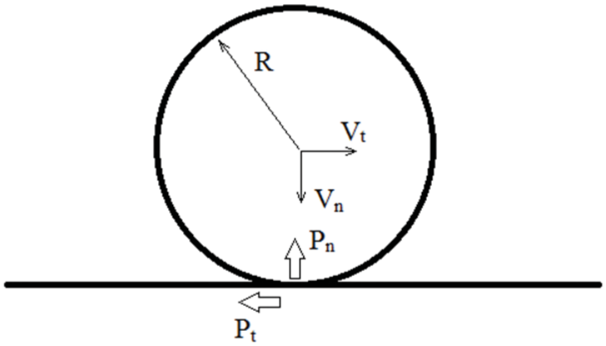
...And No Angular Acceleration

- We do inspect for shell projections etc.
- But the concerns are mostly post impact
  - Neck Injury
    - Sliding Forces and Torques
    - Helmet kept from sliding with rest of body

Rotational Acceleration Limiters

- SuperSkin®
  - Appears to be compatible with Snell M2015
  - Minimal increase in helmet dimensions
  - Slip Plane at the outside shell
- 6D – Omni Directional Suspension
  - Also appears compatible
  - Slip plane about half-way through the liner
- MIPS®
  - Currently present in some Snell certified helmets
  - Slip plane on inner surface of liner
- No Extra Credit at Snell But No Outright Rejection
  - Maybe some of these will be proven in the field

Simple Model



$$\omega \leq \frac{R * (1 + C_r) * V_N * M * C_f}{I}$$

Table 3. Summary of test results from flat coupon structures

Sample	Normal force [N]	Coefficient of friction (μ)	
		Peak	Sliding
Polycarbonate	1,900	0.77	0.42
Carbon fibre *(CS-01)*	2,000	0.17	0.12
Sacrificial layer	1,900	0.10	0.09

Mellor and StClair, Advanced Motorcycle Helmets, TRL Ltd. UK, 2005.

Some Parameters

23-4 *The Biomedical Engineering Handbook, Second Edition*

TABLE 23.1 Average Male Head Mass

Reference	No. of Subjects	Average Body Mass (kg)	Average Head Mass (kg)
Walker et al., 1973	16	67.1	4.49
Hubbard and McLeod, 1974	11		4.54
Reynolds et al., 1975	6	65.2	3.98
Adjusted per HMRTF	6	76.9	4.69
Beier et al., 1980	19	74.7	4.32
McConville et al., 1980	31	77.5	4.55*
Robbins, 1983	25	76.7	4.54†

* Based on adjusted head volume of 95% of the reported head volume (4396 cm^3) and a head specific gravity of 1.097.
† Based on an estimated head volume of 4137 cm^3 and a head specific gravity of 1.097.

TABLE 23.2 Average Mass Moments of Inertia* of the Male Head ($kg \cdot m^2 \times 10^{-3}$)

Reference	I_{xx}	I_{yy}	I_{zz}
Walker et al., 1973		23.3	
Hubbard and McLeod, 1974	17.4	16.4	20.3
Adjusted per HMRTF	22.6	21.3	26.3
Beier et al., 1980 (16 male subjects only)	20.7	22.6	14.9
McConville et al., 1980	20.4	23.2	15.1
Adjusted by sp. gr. 1.097	22.4	25.5	16.6
Robbins, 1983	20.0	22.2	14.5
Adjusted by sp. gr. 1.097	22.0	24.2	15.9

* The mass moments of inertia given are about the *x*, *y*, or *z* anatomic axes through the center of gravity of the head.

C_r	0.2
V_n (DOT)	6.0 m/sec
R	15 cm
I - Helmet	0.015 kg-m^2
M - Helmet	1500 grams
Wall Thickness	4 cm

Estimated Outcomes

Material	Delta ω rad/sec	ω*R Rolling Speed	ω/2*0.01 secs Travel?	ω/0.01 secs Avg Rot Acc?
Polycarbonate	129	19.35 m/sec	37°	12.9 krad/s^2
Carbon Fiber	28.4	4.26 m/sec	8°	2.84 krad/s^2
Sacrificial Layer	16.7	2.5 m/sec	5°	1.67 krad/s^2

- Presumably
  - Angular velocity times R won't exceed the final tangential velocity
  - Completely Effective Slip Planes might reasonably be expected to manage the anticipated angular velocity divided by two and times the pulse duration
    - (10 msecs)

Implications

- Current Test Methods Ameliorate Angular Accelerations (At least somewhat)
  - They limit normal forces
    - Which limit tangential forces & torques
- Total Angular Momentum Transfer
  - Depends on impact velocity
  - And not shock attenuation
- Slip Zones may have to afford considerable travel
  - High Friction surfaces and high tangential velocities may lead to considerable angular displacements

$$HIC = C_{pulse} V_0^4 / (X_0^{1.5} g^{2.5})$$

- $C_{ramp} = 0.75872$ $\quad A = \frac{8V_0^3}{9gX_0^2} t\,,\ 0 \le t \le \frac{3X_0}{2V_0}$
- $C_{half\ sine} = 0.65132$ $\quad A = \frac{V_0^2}{gX_0} Sin\left(\frac{V_0}{X_0} t\right),\ 0 \le t \le \frac{\pi X_0}{2V_0}$
- $C_{square\ wave} = 0.35355$ $\quad A = \frac{V_0^2}{2gX_0}\ ,\ \ 0 \le t \le \frac{2X_0}{V_0}$

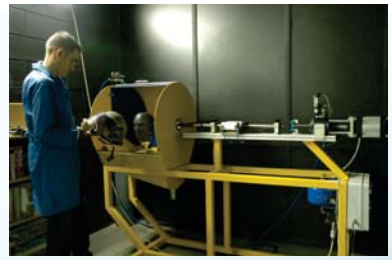
- $C_{minimal} = 0.22964$ $\quad A = 0.6[\frac{HIC}{t}]^{0.4},\ 0 \le t \le \frac{8X_0}{3V_0}$

Regulation ECE22/05

Test for projections and surface friction

NEWTON TESTING


- Head Protection
- Face and eye protection
- Body Protection
- Automotive

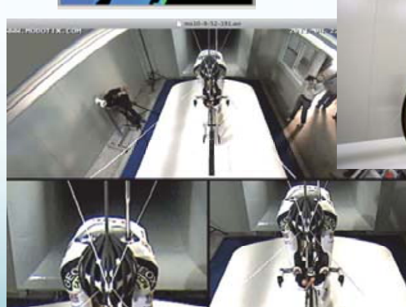


NEWTON: WIND TUNNEL


- Aerodynamics
- Acoustics
- Termodynamics







REGULATION ECE22/05

Rev. 4 addendum 21@20 February 2002:
UNIFORM PROVISIONS CONCERNING THE APPROVAL OF PROTECTIVE HELMETS AND THEIR VISORS FOR DRIVERS AND PASSENGERS OF MOTOR CYCLES AND MOPEDS

UNITED NATIONS

ECE symbol	*Contracting Parties*	*Date of application*
E 1	Germany	07.05.84
E 2	France	16.05.95
E 3	Italy	03.06.77
E 4	Netherlands	01.06.72
E 5	Sweden	15.06.73
E 6	Belgium	01.06.72
E 7	Hungary	23.11.79
E 8	Czech Republic	26.05.95
E 9	Spain	03.12.76
E 10	Serbia	27.04.92
E 11	United Kingdom[5]	30.06.00
E 12	Austria	28.07.87
E 13	Luxembourg	01.05.83
E 14	Switzerland	02.07.82
E 16	Norway	21.02.88
E 17	Finland	13.02.78
E 18	Denmark	20.12.76
E 19	Romania	06.05.96
E 20	Poland	13.11.92
E 21	Portugal[1]	24.03.98
E 22	Russian Federation	17.02.87
E 23	Greece[1]	24.03.98
E 24	Ireland[1]	24.03.98
E 25	Croatia	08.10.91
E 26	Slovenia	15.01.88
E 27	Slovakia	14.01.97
E 28	Belarus	01.09.03
E 29	Estonia	25.07.99
E 31	Bosnia and Herzegovina	06.03.92
E 32	Latvia	18.01.99
E 34	Bulgaria[4]	01.01.07
E 35	Kazakhstan	
E 36	Lithuania	29.03.02
E 37	Turkey	07.07.00
E 39	Azerbaijan	
E 40	The Former Yugoslav Republic of Macedonia	17.09.91
E 42	European Union[2]	24.03.98
E 43	Japan	
E 45	Australia	
E 46	Ukraine	
E 47	South Africa	
E 48	New Zealand	19.03.02
E 49	Cyprus[3]	01.05.04
E 50	Malta[3]	01.05.04
E 51	Republic of Korea	
E 52	Malaysia	04.04.06
E 53	Thailand	
E 56	Montenegro	03.06.06
E 58	Tunisia	

Agreement Concerning the Adoption of Uniform Conditions of Approval and Reciprocal Recognition of Approval for Motor Vehicle Equipment and Parts, done at Geneva on 20 March 1958.

PERFORMANCE REQUIREMENTS

WHAT HAS TO BE TESTED?

§ 6.6 All projections from or irregularities in the outer surface of the shell greater than 2 mm shall be tested for shear assessment

The outer surface of the helmet shall be tested for friction assessment

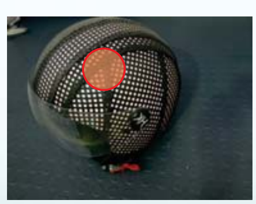
§ 6.7.2 All external projections more than 2 mm above the outer surface of the shell shall have a radius of a minimum of 2 mm.

<u>The latter specific requirements shall not apply if a projection satisfies the requirements</u>

§ 7.4.1.3: esclusions
The rim of the shell and the upper and lower edge of the visor situated within an area bounded by a sector of 120° divided symmetrically by the vertical longitudinal plane of symmetry of the helmet do not constitute a projection for the purpose of this test.

SHEAR ASSESSMENT

The helmet shall be tested in any condition in which it may be placed on the market, that is both with and without accessories if they are supplied as original equipment.



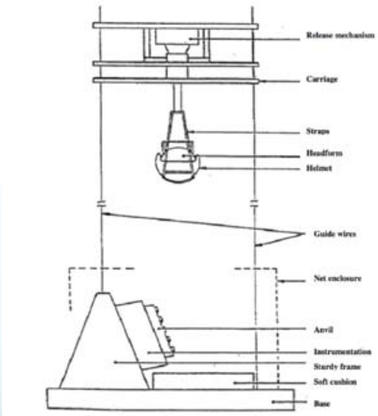
FRICTION ASSESSMENT

HOW TO TEST?

TEST FOR PROJECTIONS AND SURFACE FRICTION: METHOD A

The rotation-inducing forces caused by projections on the helmet and friction against the outer surface of the helmet which occur when a helmeted headform is dropped vertically on to an inclined anvil are measured in the longitudinal axis of the anvil.

The peak force and its integral with respect to time over the duration of the positive impulse are used as performance criteria.

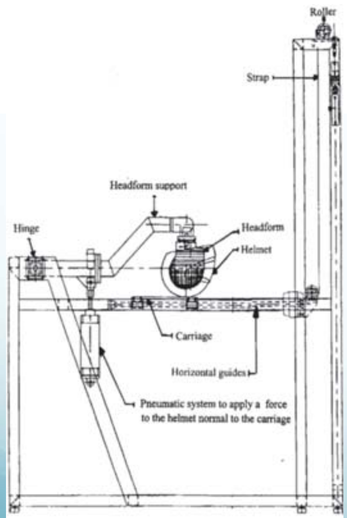


METHOD A: SHEAR ASSESSMENT

TEST FOR PROJECTIONS AND SURFACE FRICTION: METHOD B

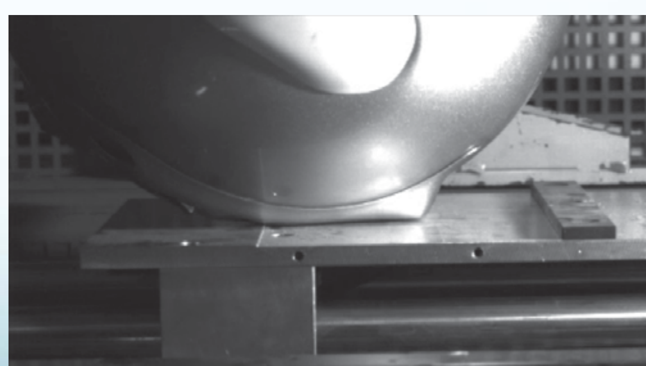
The rotation-inducing forces caused by projections on the helmets and friction against the outer surface of the helmets are assessed firstly by a shear impact on the projections using a shear edge against which the projections shall shear away, be detached, or permit the shear edge to slide past the projections.

The friction is assessed by the displacement of a carriage abrading the outer surface of the helmet. The shear impact and abrading carriage displacement are generated by a drop weight device.



METHOD B: SHEAR ASSESSMENT

FRICTION ASSESSMENT



1985: BSI 6658
Impact speed: 10 m/s

A BRIEF HISTORY

1995-99: COST327
ECE GRSP working group

2000: Reg. ECE22/05

Table 7. Injury related to peak tangential force on a motorcycle helmet

Peak tangential force	AIS	Probability of injury
1000 N	1	-
2000 N	2	-
3500 N (Reg 22-05)	3	<50%
4000 N	3	50%
7000 N	4	-

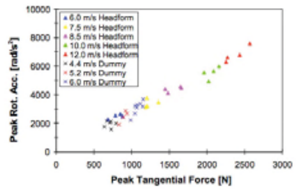


Figure 8.13. Peak rotational acceleration versus peak tangential force for dummy and headform impacts onto the oblique abrasive anvil.

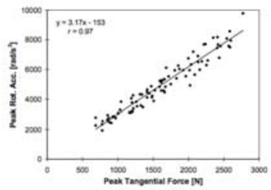
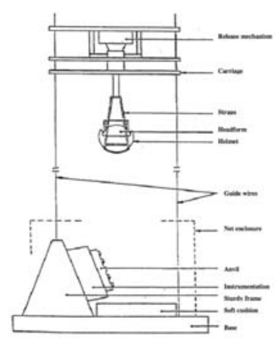


Figure 8.4. Peak rotational acceleration versus peak tangential force for impacts onto the oblique abrasive anvil.

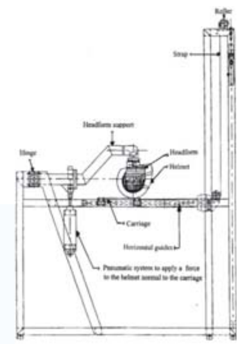
COST

European Co-operation in the Field of Scientific and Technical Research

Method A



Method B



METHOD A
Pro:
- Numerical/Quantitative performance criteria

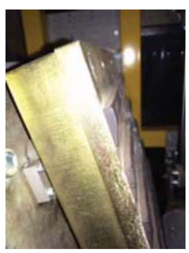
Cons:
- cost: plate load cell (KISTLER9293)/ 3 triaxial load cell + high structure
- Calibration cost
- Time to set up the tests in order to grant repeatibility

METHOD B
Pro:
- Easy to use
- Low price

Cons:
- Maintenance to grant the speed accuracy

TEST FOR PROJECTIONS AND SURFACE FRICTION

Method A



TEST FOR PROJECTIONS
Helmet impact speed: 8.5 m/s
Bar anvil cross section : h= 6 mm (centres@40mm)
Impact angle:15°
Headform: size J (4,7 kg)

Pass criteria:
the peak longitudinal force measured on the anvil shall not exceed 2,500 N, nor shall its integral with respect to time over the duration of the impact exceed 12.5 Ns

TEST FOR SURFACE FRICTION
Speed: 8.5 m/s
Grade 80 abrasive paper (L>225 mm)
Impact angle:15°
Headform: size J (4,7 kg)

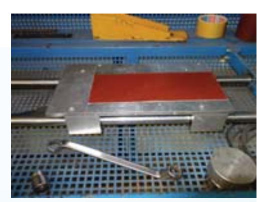
Pass criteria: the peak longitudinal force measured on the anvil shall not exceed 3,500 N, nor shall its integral with respect to time over the duration of the impact exceed 25 Ns

.

Method B

TEST FOR PROJECTIONS
Bar anvil cross section : 25x6 mm
Application force: 400 N
Carriage mass: 5 kg
Drop weight mass: 15 kg
Height of drop: 500 mm

Headform: proper size
Pass criteria:
For shear assessment the tested projection shall shear away, be detached or alternatively shall not prevent the assessment bar from sliding past the projection. In all cases the bar on the horizontal carriage shall travel past the projection.



Application force: 400 N
Carriage mass: 5 kg
Drop weight mass: 15 kg
Height of drop: 500 mm

Headform: proper size

Pass criteria: the abrasive carriage shall not be brought to rest by the helmet.

Thanks for your kind attention!

Motocross Helmets and Concussion Risk Reducing Technologies Do They Work?

Terry Smith, Scott Kebschull

Dynamic Research Inc.
Torrance, California
USA

IRCOBI-NOCSAE-PDB-Snell Workshop
Lyon, France September 9, 2015

Dynamic Research Inc.

BACKGROUND TO THE PROBLEM

Dynamic Research Inc.

METHODOLOGY – IMPACT TESTING

- P50 Hybrid III headform and neck with NAP
- Free fall carriage mounted onto a monorail drop tower
- 45 degree high mu impact surface
- Drop heights of 1.0m, 1.5m, 2.0m, 2.9m
- Four impact locations per helmet sample
- 10 kHz sample rate per channel
- anti-aliasing, SAE J211 Class 1000 Filters

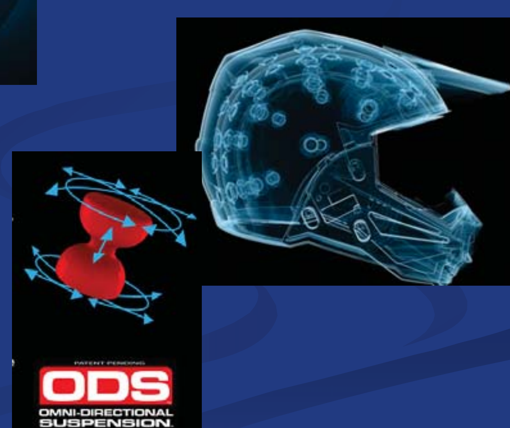
Dynamic Research Inc.

METHODOLOGY – IMPACT TESTING

- Three samples each of different motocross helmet models
  - 6-D ATR1 with ODS Technology
  - Bell Moto-9 with Bell Flex Technology
  - 2 Motocross helmets with MIPS technology
  - 2 Motocross helmets without MIPS technology (n=1)

Dynamic Research Inc.

METHODOLOGY – IMPACT TESTING



METHODOLOGY – DATA REDUCTION

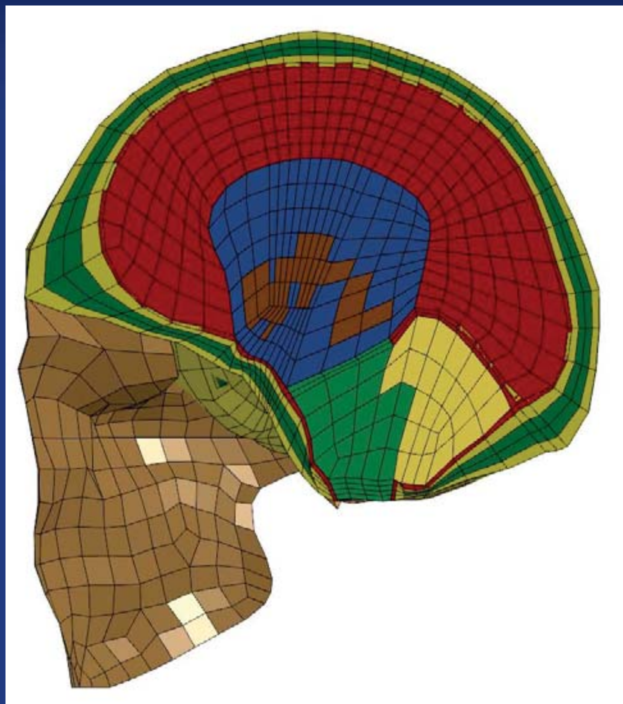
- Peak Linear and Angular Acceleration
- Head Injury Criteria (HIC)
- GAMBIT
- Head Impact Power (HIP)
- LS DYNA FE with UCD Brain Model
  - Maximum Principal Strain

METHODOLOGY – MODELLING

- Skull and brain model developed by University College Dublin (Horgan and Gilchrist, 2003)
- Consists of 18,448 solid elements and 7,877 shell elements
- 13 different anatomical components
- Validated using data from Nahum et al. (1977)
- Output from Hybrid III testing used as an input to drive the skull (modeled as a rigid shell)

Dynamic Research Inc.

METHODOLOGY – MODELLING



Dynamic Research Inc.

RESULTS

Mean Peak Linear Resultant Acceleration (g)

6-D	Bell Flex	Mx1 MIPS	Mx1 No MIPS	Mx2 MIPS	Mx2 No MIPS
75.5 (6.5)	96.8 (7.8)	101.2 (5.9)	103.5 (16.8)	94.2 (10.3)	103.8 (20.8)

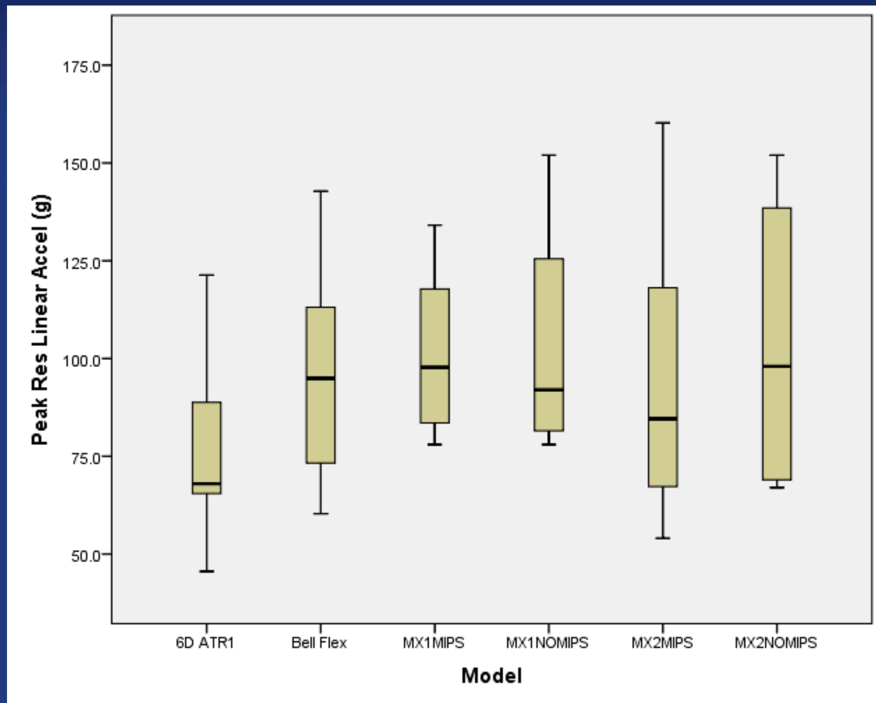
Mean Peak Angular Resultant Acceleration (krad/s^2)*

6-D	Bell Flex	Mx1 MIPS	Mx1 No MIPS	Mx2 MIPS	Mx2 No MIPS
3.82 (0.41)	3.95 (0.29)	4.27 (0.70)	6.41 (1.58)	4.61 (0.69)	7.70 (1.90)

* Significant across helmet model (alpha = .05)

Dynamic Research Inc.

RESULTS



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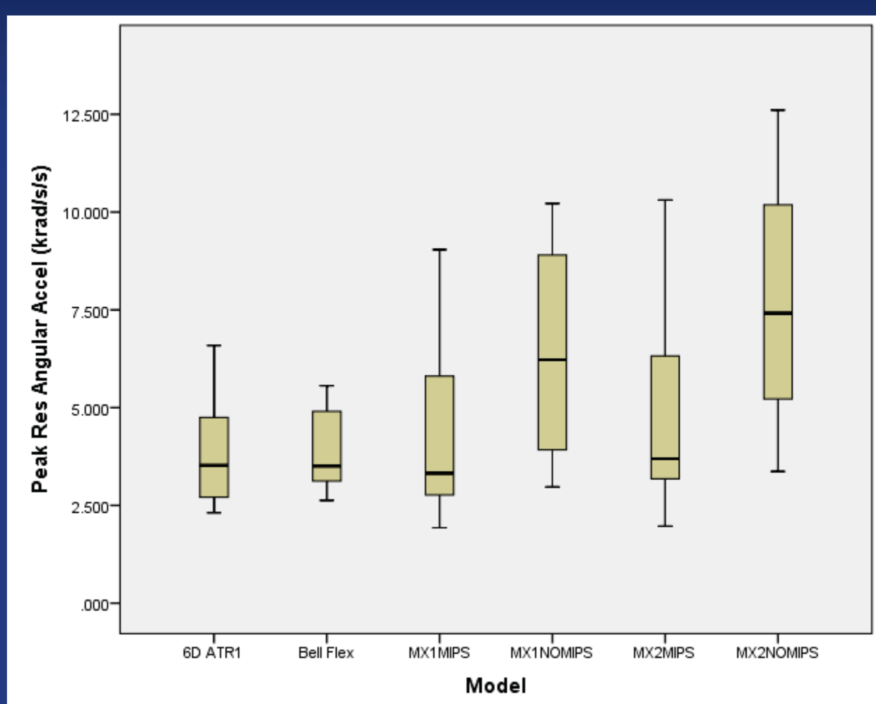
RESULTS



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RESULTS

Mean Difference Peak Angular Resultant Acceleration (krad/s^2)*

	6-D	Bell Flex	Mx1 MIPS	Mx1 No MIPS	Mx2 MIPS	Mx2 No MIPS
6-D		-0.13	-0.45	-2.59*	-0.79	-3.88*
Bell Flex	0.13		-0.32	-2.46	-0.66	-3.75*
Mx1 MIPS	0.45	0.32		-2.14	-0.34	-3.43*
Mx1 No MIPS	2.59*	2.46	2.14		1.80	-1.29
Mx2 MIPS	0.79	0.66	0.34	-1.80		-3.09*
Mx2 No MIPS	3.88*	3.75*	3.43*	1.20	3.09*	

* Significant across helmet model (alpha = .05)

Dynamic Research Inc.

RESULTS

Mean Head Injury Criteria (HIC)

6-D	Bell Flex	Mx1 MIPS	Mx1 No MIPS	Mx2 MIPS	Mx2 No MIPS
237 (40)	369 (57)	395 (53)	429 (150)	356 (73)	472 (192)

Mean GAMBIT

6-D	Bell Flex	Mx1 MIPS	Mx1 No MIPS	Mx2 MIPS	Mx2 No MIPS
0.33 (0.03)	0.40 (0.03)	0.43 (0.03)	0.46 (0.08)	0.41 (0.04)	0.48 (0.08)

RESULTS

Mean Head Impact Power (HIP)

6-D	Bell Flex	Mx1 MIPS	Mx1 No MIPS	Mx2 MIPS	Mx2 No MIPS
13.43 (1.89)	17.10 (2.27)	19.53 (2.34)	20.26 (7.14)	17.51 (3.34)	21.99 (7.57)

RESULTS

Mean Maximum Principal Strain (200cm)

6-D	Bell Flex	Mx1 MIPS	Mx1 No MIPS	Mx2 MIPS	Mx2 No MIPS
.156 (.016)	.158 (.018)	.122 (.003)	.227	.107 (.023)	.435

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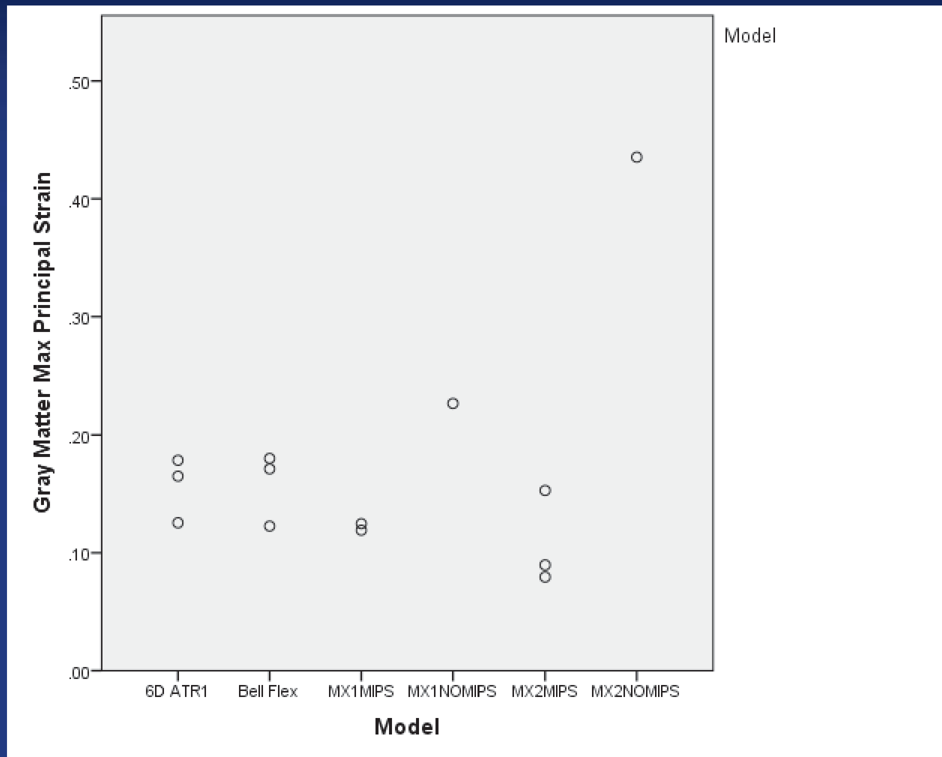
Results



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SUMMARY AND CONCLUSIONS

- No significant difference in linear acceleration between motocross helmets with technology and motocross helmets without technology
- Significant differences in angular acceleration between motocross helmets with technology and motocross helmets without technology were observed. Motocross helmets with concussion reducing technology were found to have significantly lower peak angular accelerations

SUMMARY AND CONCLUSIONS

- When measured across a range of drop heights, there does not appear to be a significant difference between the different concussion reducing technologies (6-D, MIPS, Bell Flex)
- The free fall headform/incline anvil test methodology is sensitive enough to identify differences between very similar helmets (i.e. with and without technology added).

SUMMARY AND CONCLUSIONS

Thank You

Proposal for a new test method measuring the head kinematics in angled helmeted impacts

This document is a quick summary of the work within CEN TC158 – WG11.
Covering the work since 2013.

Peter Halldin (Convener)

European Committee for Standardization
Comité Européen de Normalisation
Europäisches Komitee für Normung

Presenting the work within CEN/TC 158 - WG11 (Head forms and test methods)

Peter Halldin

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MIPS AB, Stockholm, Sweden

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KTH Technology and Health

CEN TC158 - WG11 - New test method proposal – April 2015

CEN/TC 158 - WG11 Rotational test methods (Focusing on bike, equestrian and ski helmets)

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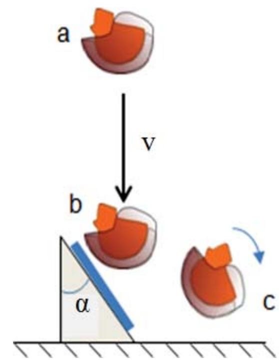


Organization within CEN/TC 158 – Head Protection

European Committee for Standardization
Comité Européen de Normalisation
Europäisches Komitee für Normung

Head protection - Structure

Secretariat
BSI

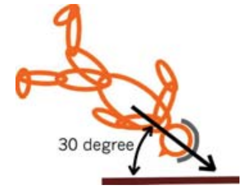
Chairperson
Dr J.Forrest

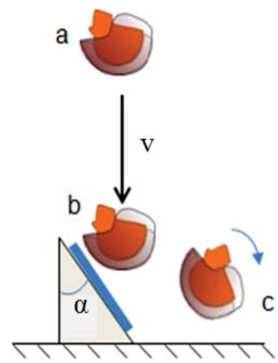
Secretary
Ms M.Di Carlo

SC/WG	Title
CEN/TC 158/WG 11	Headforms and test methods
CEN/TC 158/WG 10	Protective helmets for canoeing
CEN/TC 158/WG 12	Helmets for snow activities other than skiing
CEN/TC 158/WG 14	Helmets for field sports
CEN/TC 158/WG 13	Helmets for mountaineers
CEN/TC 158/WG 7	Head protectors for ice-hockey
CEN/TC 158/WG 3	Firefighters helmets
CEN/TC 158/WG 1	Industrial safety helmets
CEN/TC 158/WG 4	Helmets for cyclists
CEN/TC 158/WG 6	Airborne sports helmets
CEN/TC 158/WG 5	Helmets for horse riders

Objectives

- Within WG11 continue the work aimed to 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
    - 6-7m/s, 45degrees, hard impact surface
  - The test must be *simple, robust and cost effective*.





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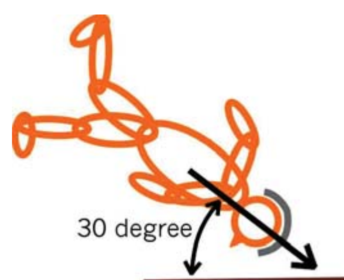
The fundaments for a new test method

T1: Test method specification
- T1.1 Impact method
- T1.2 With or without neck
- T1.3 Instrumentation in the head form.
- T1.4 Head form
- T1.5 Fixation of the helmet

T2: Test parameter specification
- T2.1 Impact velocity
- T2.2 Impact angle
- T2.3 Impact site
- T2.4 Impact surface
- T2.5 Conditioning

T3: Pass fail criteria
- T3.1 Mild / severe brain injury
- T3.2 Global 6DOF / FE model



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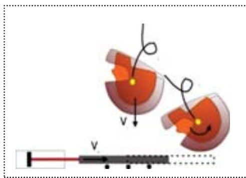
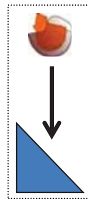
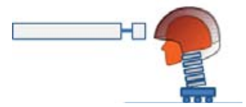
Possible test methods

Moving ground	Vertical drop against angled anvil	Linear impactor
		
		
• Complicated • Neck?	• Can use existing drop tower • Neck?	• This test method requires a neck. • Tangential loading?

Neck / no neck

Reference	Method	Test method	Difference/Correlation of rotational components
COST 327	Experimental study	HIII dummy v.s. HII head form	17%
Beusenberger et al 2001	Simulation of helmeted football impacts	MADYMO (1997)	Bad
Verschueren 2006	Reconstruction of Bike accidents	MADYMO HBM (2005)	Good to bad
Forero 2009	Reconstruction of Equestrian accidents	MADYMO HBM (2005)	Good to bad
Ghajari et al. 2012	FE simmulation of MC accident	Human FE model (THUMS)	20%
Halldin (ongoing)	FE simulation of MC and Bike helmet impacts	Human FE model (THUMS and HIII)	Good to bad

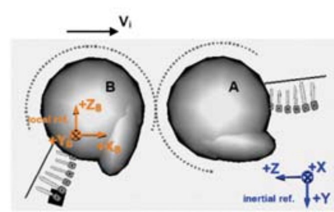
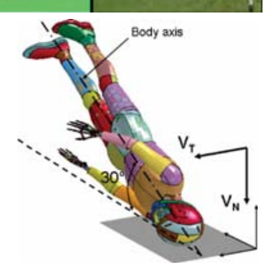
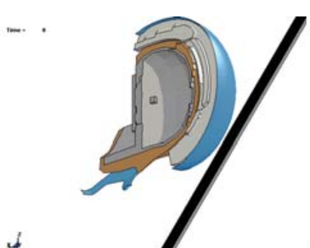
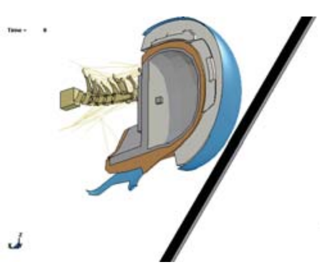
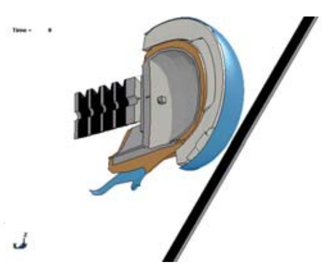


Figure 5: Basic model set-up



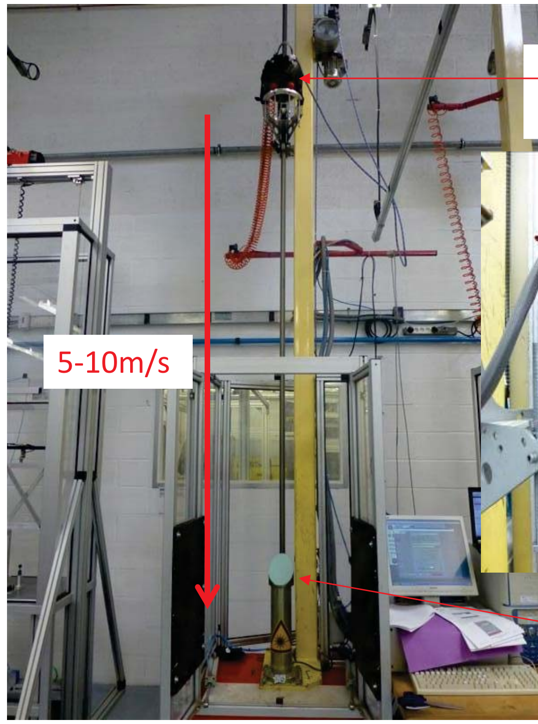






Proposal for the new oblique test method

Built around existing test rigs from AD Engineering or Cadex



5-10m/s

Hybrid III head form and helmet

30-60° anvil with abrasive paper

Standard helmet drop test machine adapted for rotational impact

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A typical test

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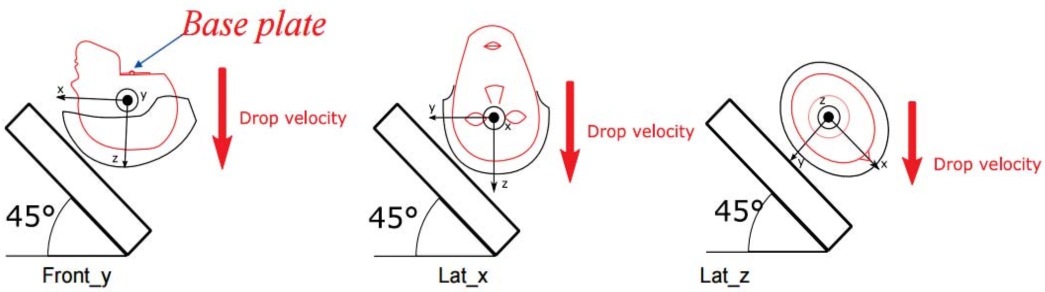
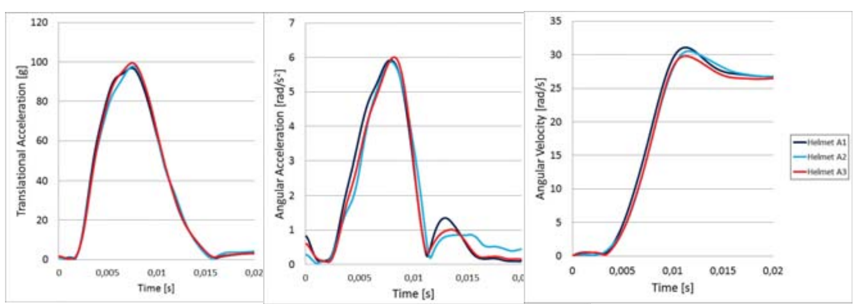
At least three impact points/directions – 6.5m/s, 45 degree impact

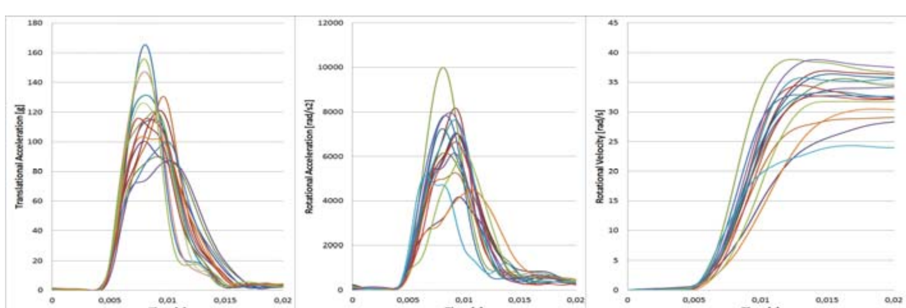


Example of test with the new oblique test method

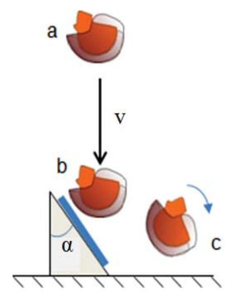
Three identical helmets



Benchmark of 17 bike helmets

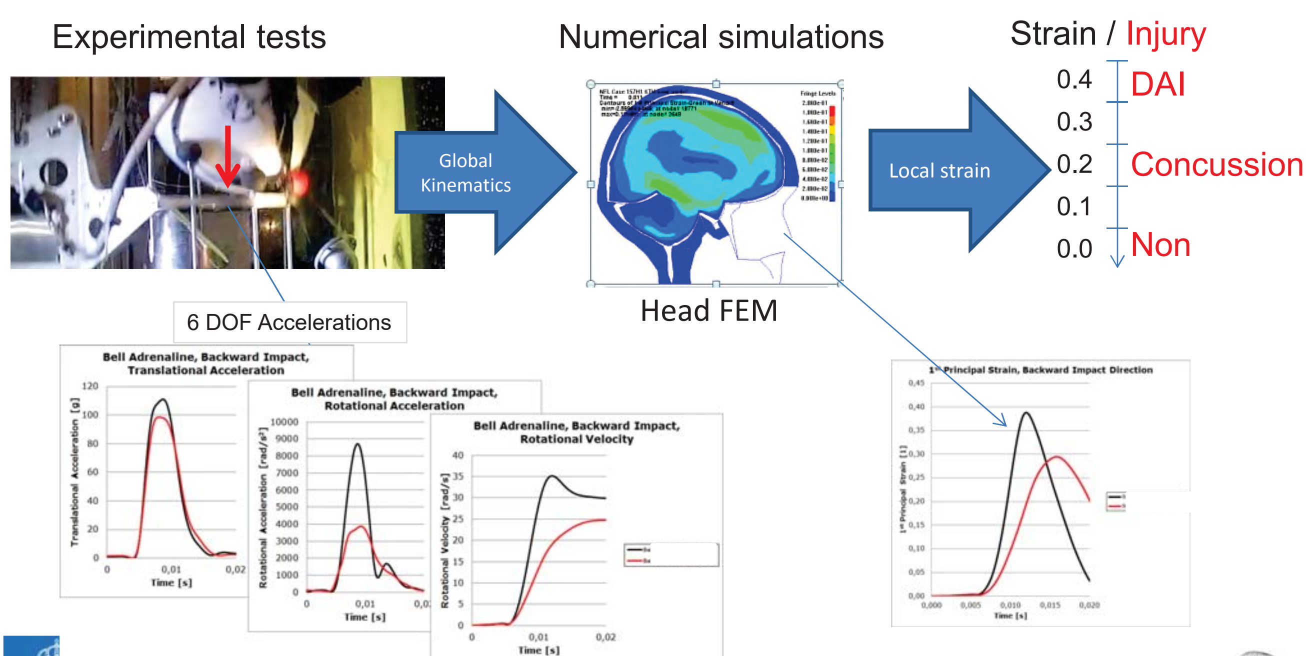


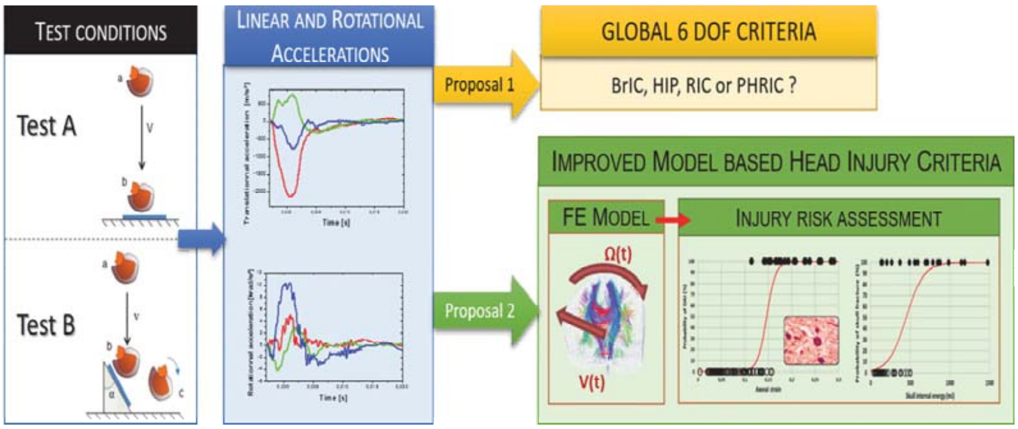
Proposal by WG11 per October2014



- Free falling head against angled plate (30-60 degree) using existing test drop tower from CADEX or AD Engineering. (The main reason for this test method is low cost and simplicity)
- No neck (The main reason is that the existing HIII neck has been shown to be less humanlike than no neck, for the first 10ms of an helmeted impact to a hard surCEN are open for a discussion regarding the neck/no neck question with other test organizations in order to work for a global harmonizationface.)
- HIII head (The reason for this head form is the human like mass and inertial properties. Missing! two head sizes, 56cm and 62cm.)
- Head instrumentation: 9-acc-array (until ARS are proven to work for a typical helmet impact situation)

Pass/fail criteria





Next step

- Test *point* or test *area* on helmet
  - The sensitivity of changes in impact points and impact directions needs to be understood
- Calibration tests
  - Instrumentation
  - Rubber skin
- Pass/Fail criteria
  - derived from 6 DOF accelerations that are combined in a criteria (HIP, BRIC,,) or
  - Injury Risk Assessment Tool based on a validated FE model.

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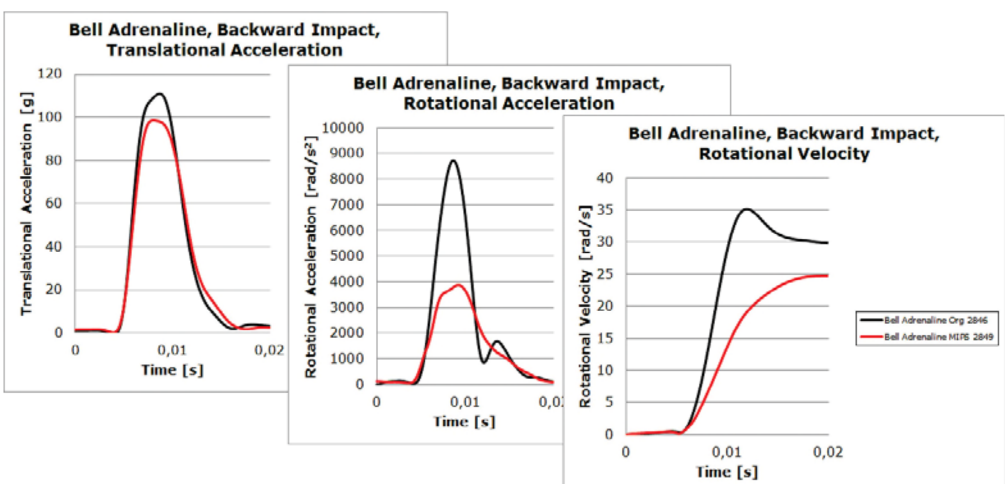
CEN TC158 - WG11 - New test method proposal – April 2015

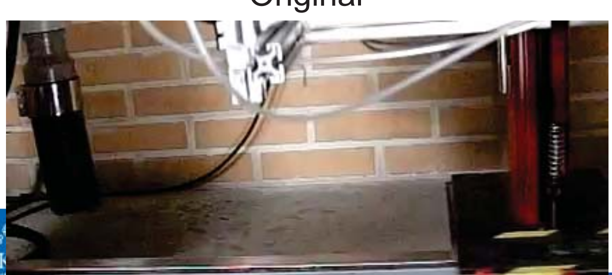
Any questions could be sent to:

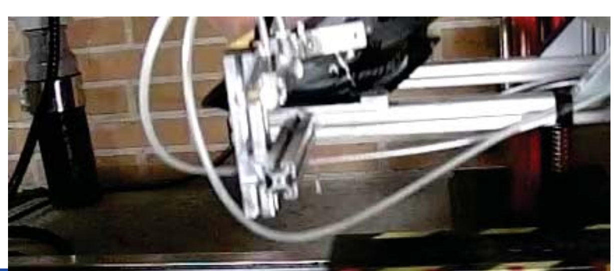
- Peterh@kth.se
- Peter.halldin@mipshelmet.com

Results from a typical test



Original





HIII head sizes v.s. EN 960 head form

EN 960 headform size	Headcircumference [mm]	Dummy model	Head circumference [mm]
A	500	HIII 3 Year Old	508
B	510		
C	520	HIII 6 Year Old	520.7
D	530		
E	540	HIII 5% Female	538.5
F	550		
G	560		
J	570		
K	580	Hybrid III 95% Large Male	584
L	590		
M	600	HIII 50t% Male	597
N	610		
O	620		
P	630		
Q	640		

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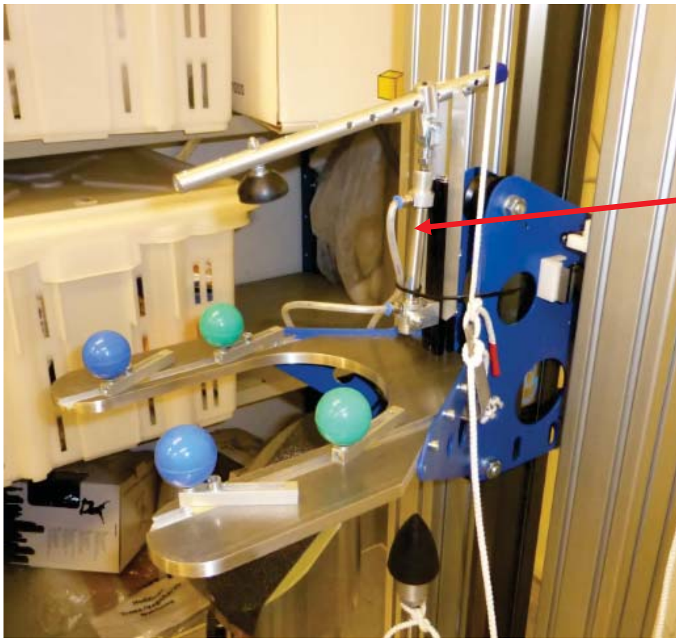
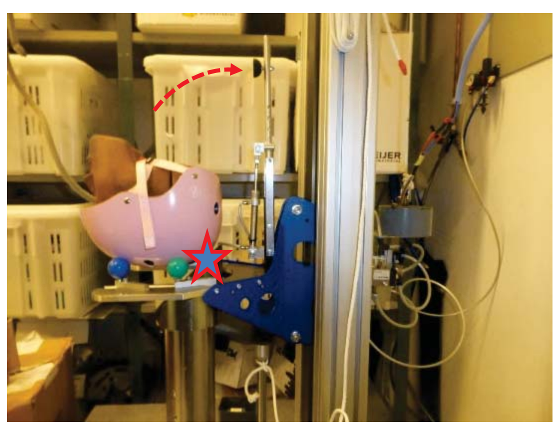
Fixation of assemly by one pneumatic cylinder



Pneumatic cylinder aimed to clam the helmet during the vertical drop.

Fixation of assemly by one pneumatic cylinder

Fixation arm releases 5cm befor helmet impacts the anvil



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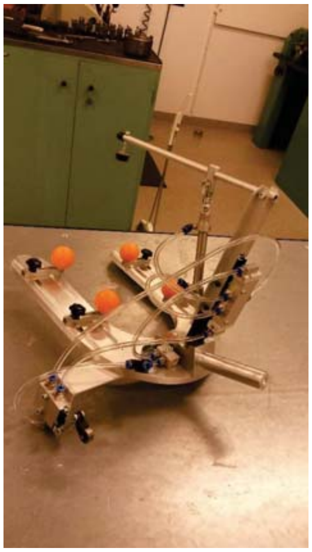
Fixation for a CADEX machine



Summary

- Upgrades to existing test equipment are:
  – Angled impact anvil
  – Five sizes of HIII head form with 3-2-2-2 accelerometer array
  – Software/hardware updates to handle the 9-channel output from accelerometers
  – New helmet basket/carrier

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FE simulations of angled impacts the helmeted HIII Head alone compared to the HIII head attached to the HIII neck and a human neck model.

Objectives

- How is the head kinematics effected by the neck in direct impact conditions.

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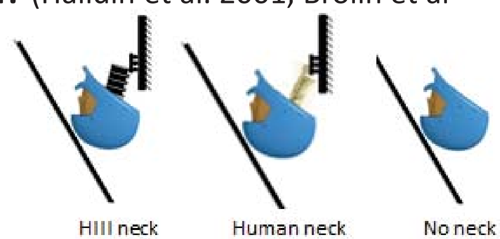
Configuration details

- Boundary condition neck: “Guided” neck bottom plate (T1) locked in Global X, Y, RotX, RotY and RotZ.
- Weight “T1-plate” =10kg-(mass of current neck)
- Coefficient of friction between:
  - Helmet/plate: 0.4
  - Helmet/head: 0.3
- Compare the results from the HIII neck with no neck and also a human neck model. (Halldin et al. 2001, Brolin et al 2005, Hedenstierna 2008).
- Impact speed: 7m/s
- Angle of Anvil : 45degree

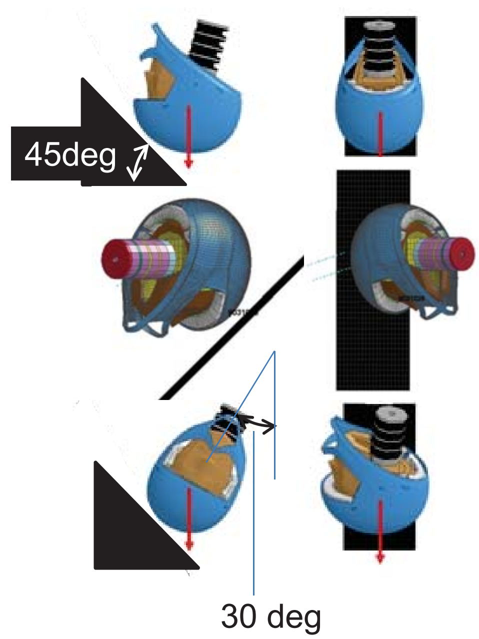


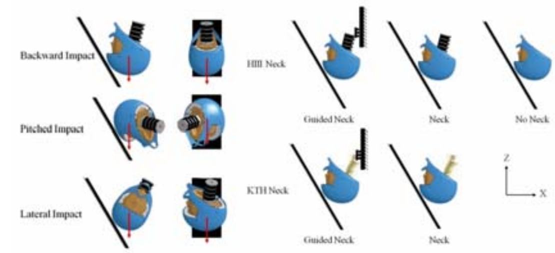
Simulation set up

Impact Ry

Impact Rz

Impact Rx





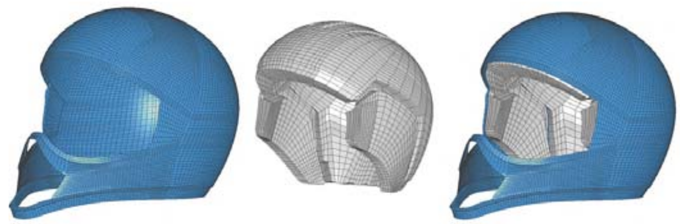
al.

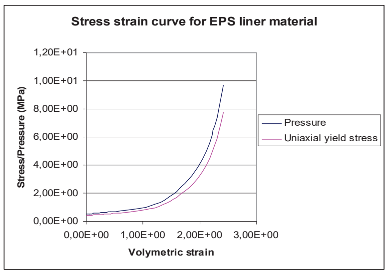
local X-axis 45 degree.

Bottom plate of HIII head is horizontal. Then rotate head 30 degree around local X-axis.

FE model of helmet

- The helmet shell was modeled by 13470 shell elements with a thickness of 1,5mm
- The shell was modeled as a glass fibre reinforce shell (*MAT_COMPOSITE_ FAILURE_SHELL_MODEL
- The liner consists of three different parts and was modeled as EPS liner with densities 35, 50 and 70 kg/m^3 (*MAT_ BILKHU/DUBOIS_FOAM in LSDYNA). A total of 14582 elements were used.

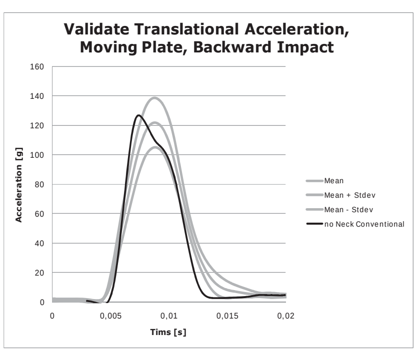


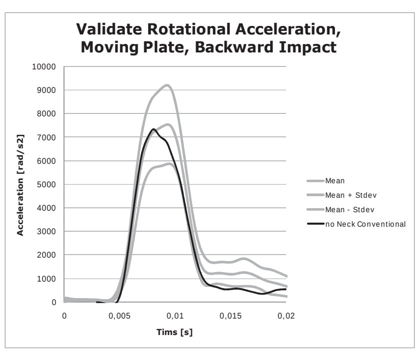


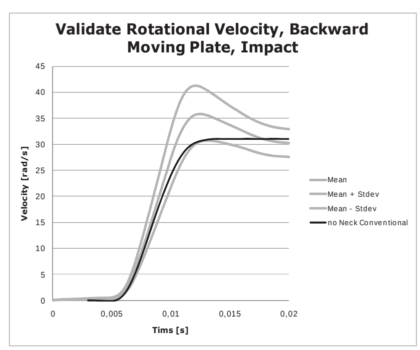
*MAT_COMPOSITE_FAILURE_SHELL_MODEL						
Density (Kg/M^3)	**Ea (Pa)**	**Eb (Pa)**	**Ec (Pa)**	**Poisions ratio, ba**	**Poisions ratio, ca**	**Poisions ratio, cb**
1054.0	6.8900E+10	6.8900E+10	4.0300E+9	0.30	0.24	0.24
Gab (Pa)	**Gbc (Pa)**	**Gca (Pa)**	**Bulk modulud of failed material**			
27.0E+9	1.55E+9	1.55E+9	6.72E+9			
Longitudinal compressive strength	**Longitudinal tensile strength**	**Transverse compressive strength**	**Transverse tensile strength**	**Shear strength**		
1.8000E+8	3.3100E+9	1.8000E+8	3.3100E+9	1.1550E+7		

Peter Halldin, peterh@kth.se

Comparison of FE model of MC helmet to benchmark study of 12 different MC helmets







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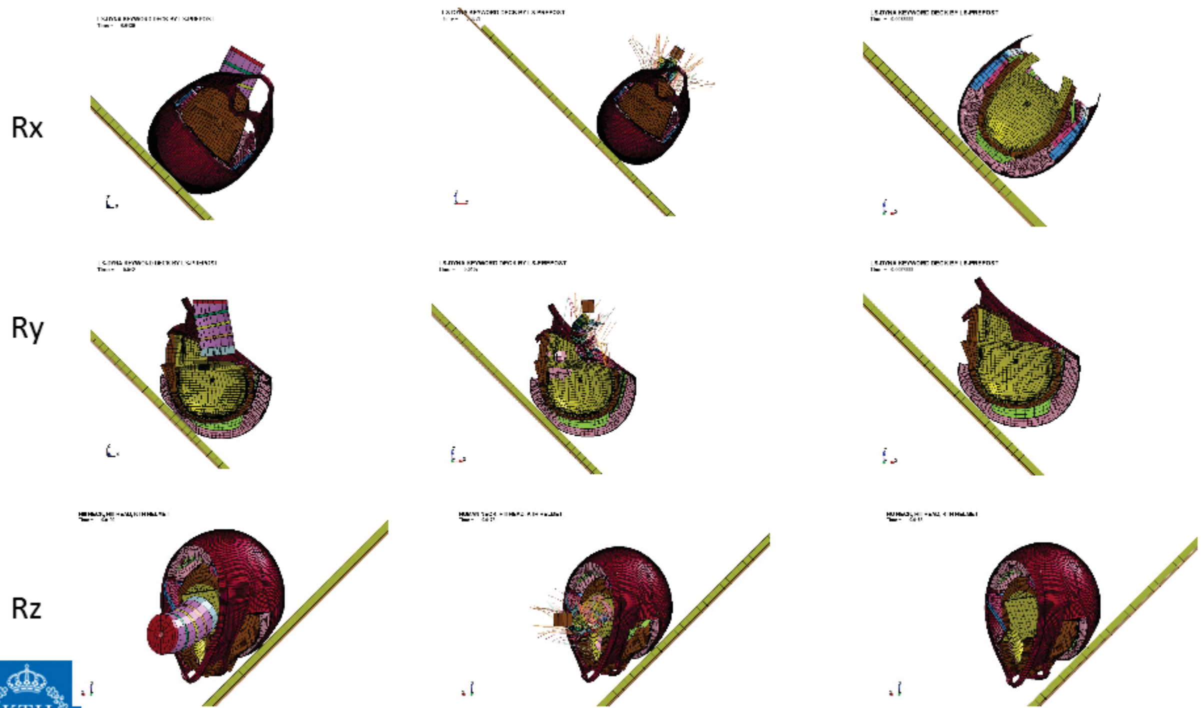
Examples from simulations



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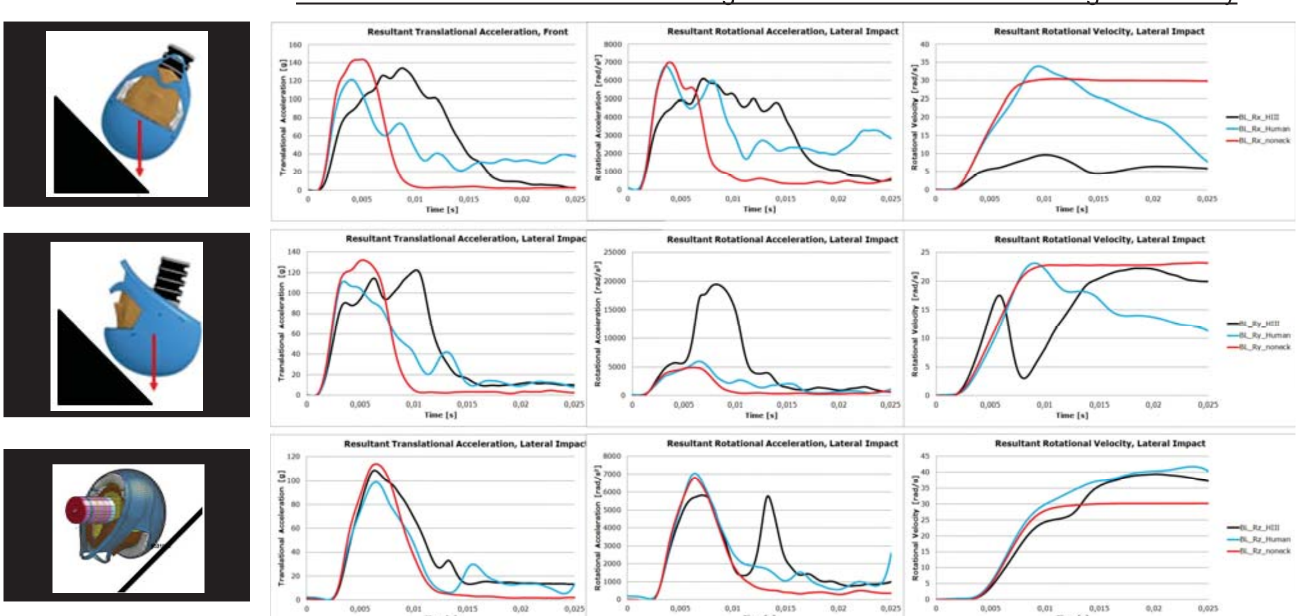
Results from simulations

Translational acceleration Angular acceleration Angular velocity



HIII neck Human neck No neck

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Conclusion

- The results differs significanlt between the different neck configurations for the Lateral (Rx and the Frontal (Ry).
- It is believed that the HIII neck could be used for Pitched Rz impact.
- Frontal and Ry impacts must be unvestigated further.

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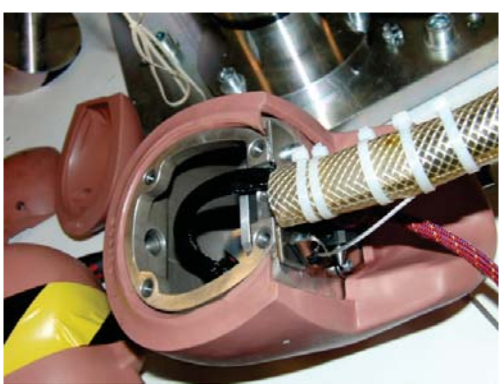
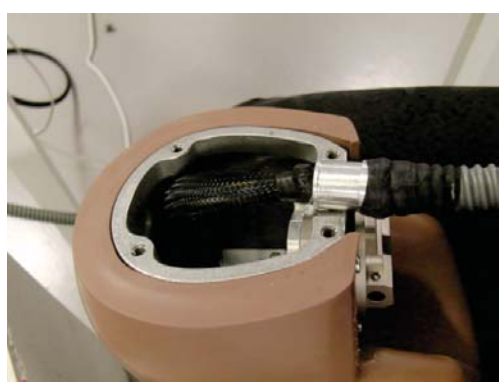
Attachment of cable to head





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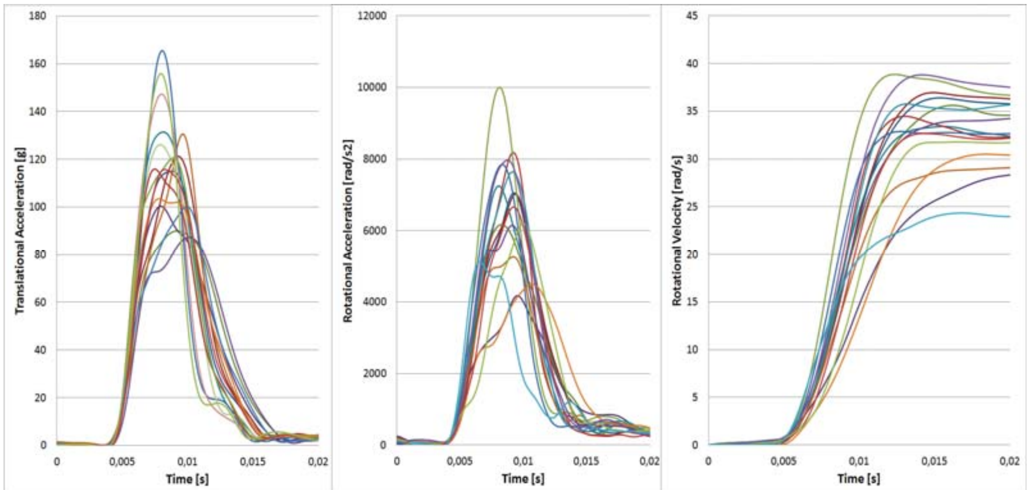
Example from Benchmark test of 17 Bike helmets from Swedish market



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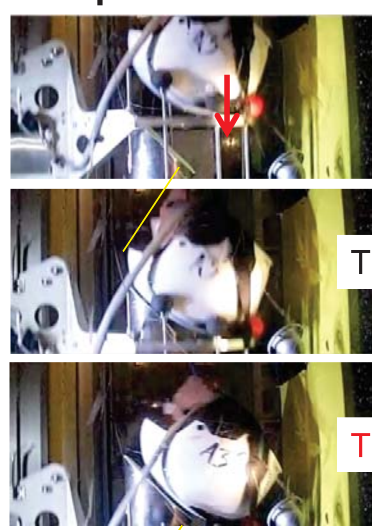
Example of test with the new oblique test method

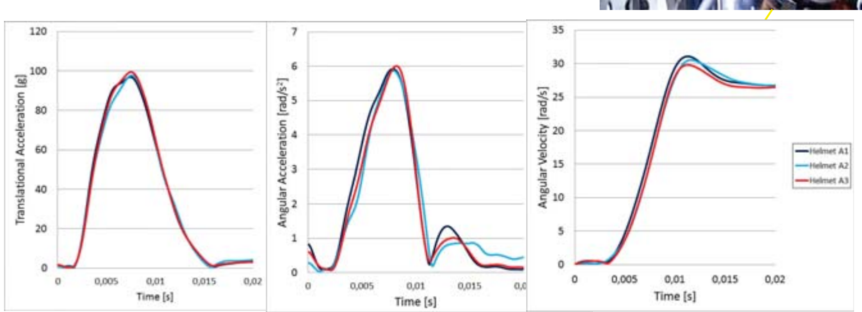
- 50% HIII head form
- Impact velocity: 6.5m/s
- Impact angle: 45 degrees
- Impact surface: Steel covered with grinding paper



T=0.000

T=0.010s

Results from three identical ski helmets



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