Preliminary PMHS Injury Risk Curves & Potential Injury Criteria in Rear Impact

Yun-Seok Kang, Ph.D.
The Ohio State University

Kevin Moorhouse, Ph.D.
NHTSA

Rear Impact Research Objectives

NHTSA
NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION

- **Evaluate biofidelity of available RIDs (BioRID, RID3D, HyIII)**
  - Choose biofidelity test condition
  - Develop experimental seat for rear impact sled testing
  - Conduct sled tests
    - PMHS (Post-Mortem Human Subjects)
    - Dummies (BioRID II, RID3D, Hybrid III)
  - Assess biofidelity and repeatability of dummies
- **Investigate the mechanism of injury**
  - Develop and validate 3-D cervical spine kinematic instrumentation
  - Identify injurious kinematics
- **Relate injury to measured PMHS variables**
  - Assess potential injury criteria for rear impact dummies

Rear Impact Research Objectives

- **Evaluate biofidelity of available RIDs (BioRID, RID3D, HyIII)**
  - Choose biofidelity test condition
  - Develop experimental seat for rear impact sled testing
  - Conduct sled tests
    - PMHS (Post-Mortem Human Subjects)
    - Dummies (BioRID II, RID3D, Hybrid III)
  - Assess biofidelity and repeatability of dummies
- **Investigate the mechanism of injury**
  - Develop and validate 3-D cervical spine kinematic instrumentation
  - Identify injurious kinematics
- **Relate injury to measured PMHS variables**
  - Assess potential injury criteria for rear impact dummies

Rear Impact Research Objectives

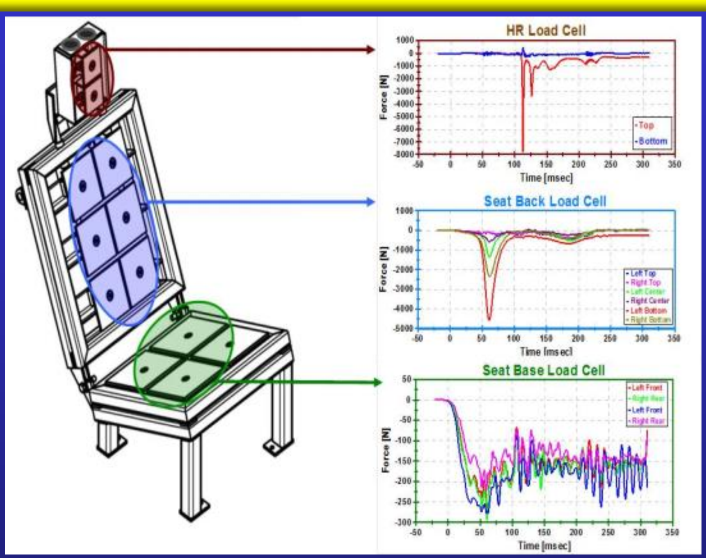
- **Evaluate biofidelity of available RIDs (BioRID, RID3D, HyIII)**
  - Choose biofidelity test condition
  - Develop experimental seat for rear impact sled testing
  - Conduct sled tests
    - PMHS (Post-Mortem Human Subjects)
    - Dummies (BioRID II, RID3D, Hybrid III)
  - Assess biofidelity and repeatability of dummies
- **Investigate the mechanism of injury**
  - Develop and validate 3-D cervical spine kinematic instrumentation
  - Identify injurious kinematics
- **Relate injury to measured PMHS variables**
  - Assess potential injury criteria for rear impact dummies

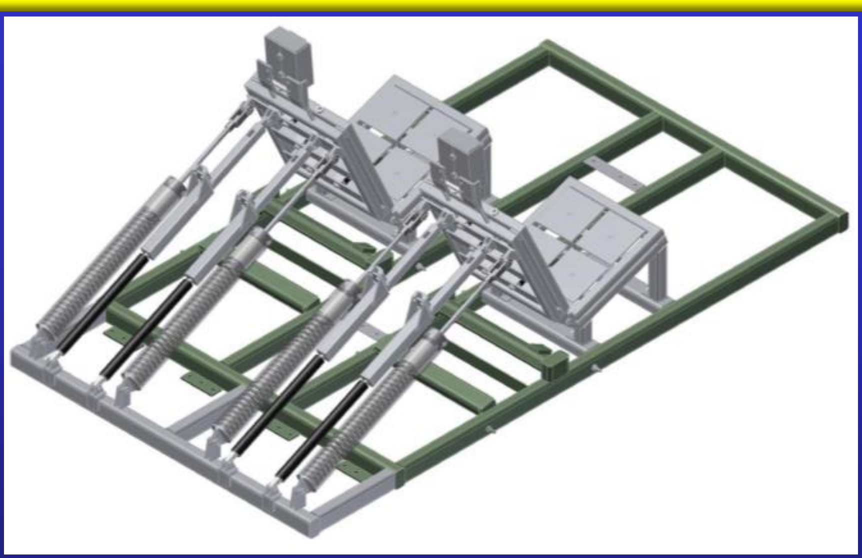
Rear Impact Research Objectives

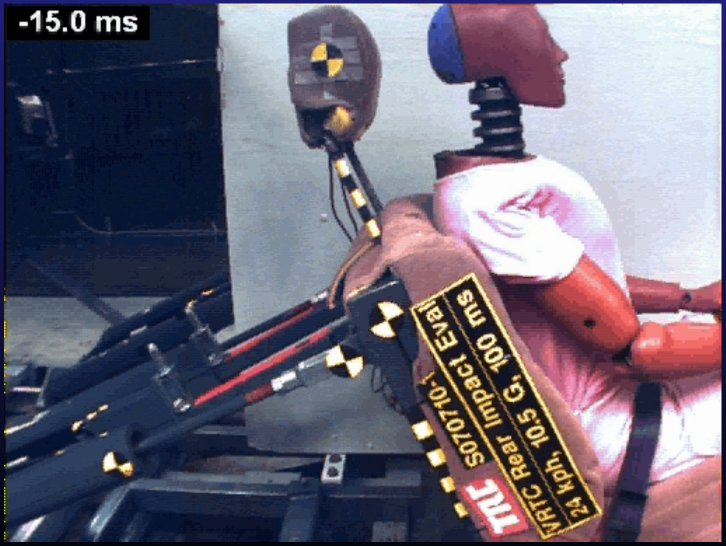
NHTSA
NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION

- **Evaluate biofidelity of available RIDs (BioRID, RID3D, HyIII)**
  - Choose biofidelity test condition
  - Develop experimental seat for rear impact sled testing
  - Conduct sled tests
    - PMHS (Post-Mortem Human Subjects)
    - Dummies (BioRID II, RID3D, Hybrid III)
  - Assess biofidelity and repeatability of dummies
- **Investigate the mechanism of injury**
  - Develop and validate 3-D cervical spine kinematic instrumentation
  - Identify injurious kinematics
- **Relate injury to measured PMHS variables**
  - Assess potential injury criteria for rear impact dummies

Experimental Seat







Test Matrix
Experimental Seat

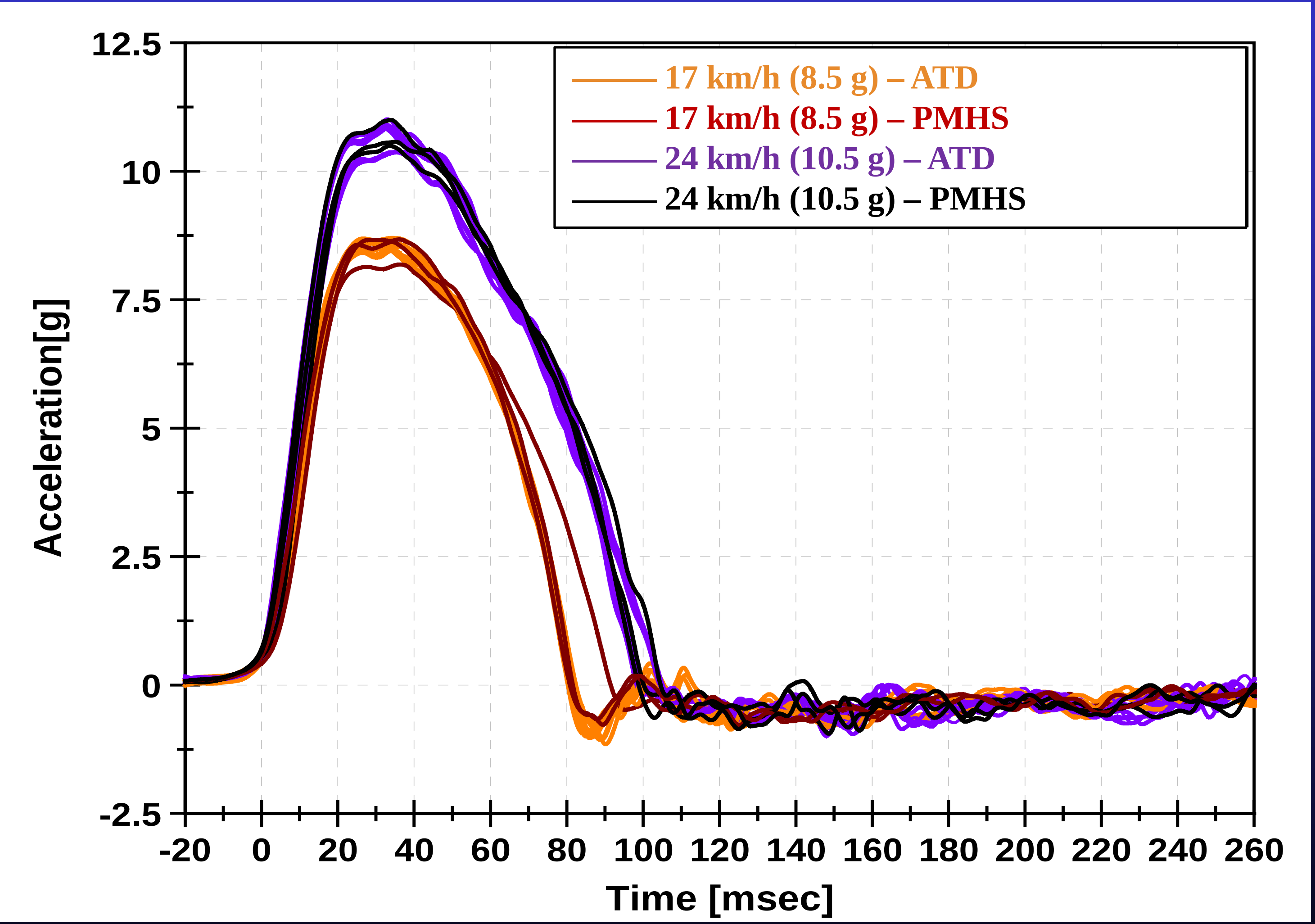
Three repeats at each speed

Dummies			
Test Number	Test Speed	Driver Side Dummy	Passenger Side Dummy
1	L	Hybrid III 50th	BioRID II
2	L	Hybrid III 50th	BioRID II
3	L	RID3D	BioRID II
4	L	RID3D	BioRID II
5	L	RID3D	Hybrid III 50th
6	M	RID3D	Hybrid III 50th
7	M	RID3D	Hybrid III 50th
8	M	RID3D	BioRID II
9	M	RID3D	BioRID II
10	M	Hybrid III 50th	BioRID II

7 PMHS at each speed

PMHS		
Test Number	Test Speed	Driver Side Dummy
1	M	PMHS 01
2	L (4)	PMHS 02
3	L/M	PMHS 03
4	L/M	PMHS 04
5	L/M	PMHS 05
6	L/M	PMHS 06
7	L/M	PMHS 07
8	L/M	PMHS 08

Sled Pulses
Experimental Seat



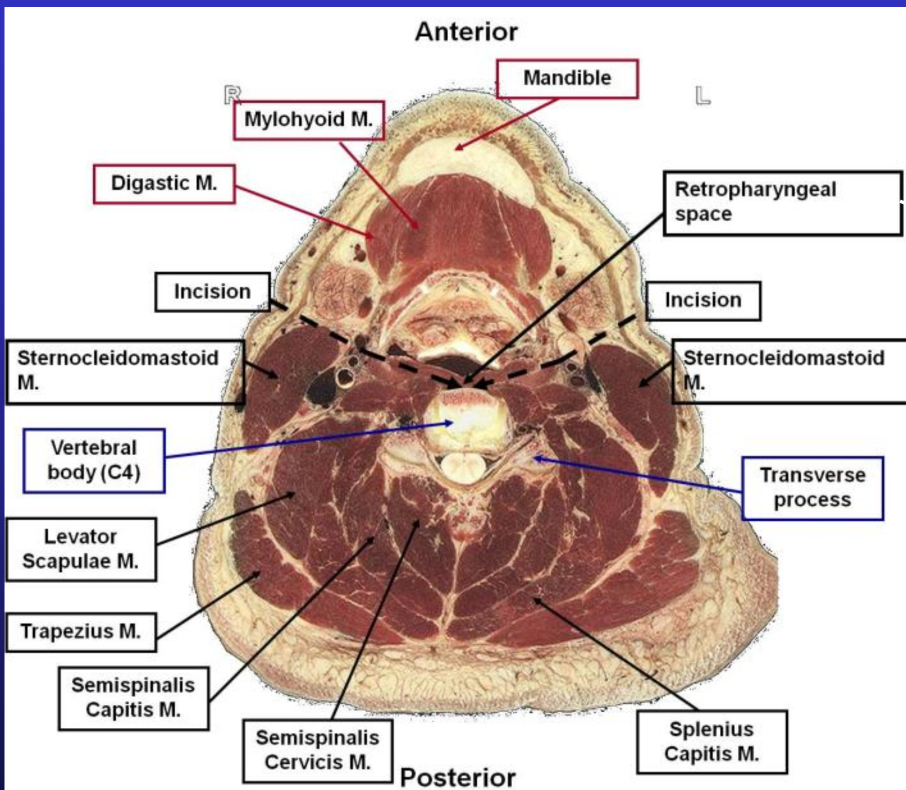
17 km/h; 8.5 g Sled Test
Experimental Seat

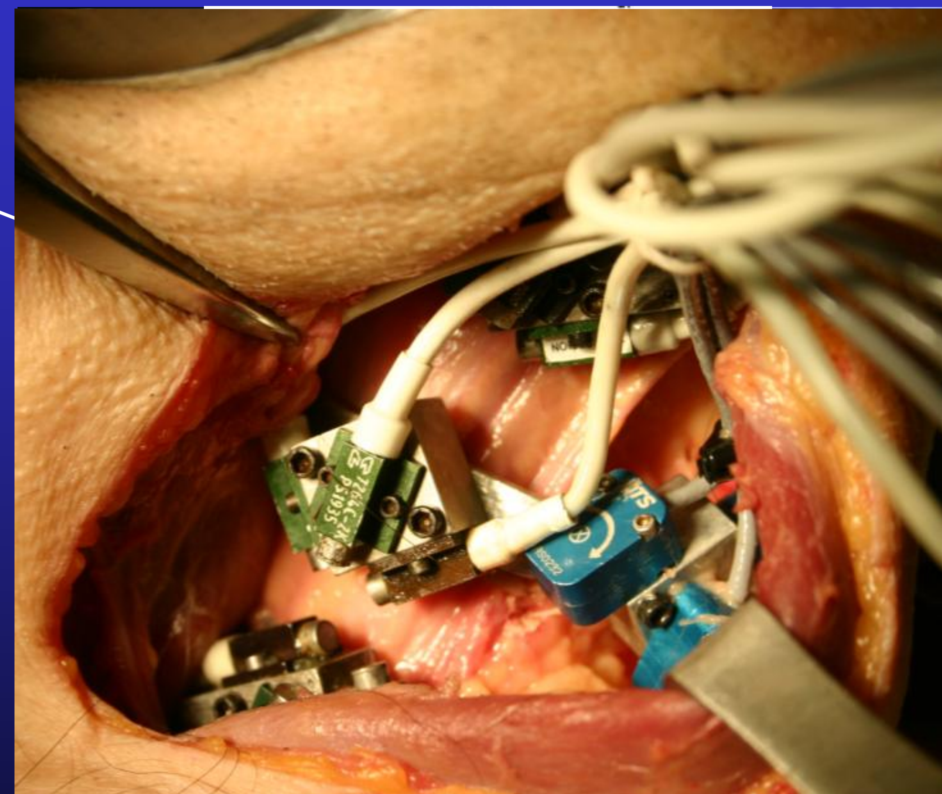
24 km/h; 10.5 g Sled Test
Experimental Seat

Rear Impact Research Objectives

- **Evaluate biofidelity of available RIDs (BioRID, RID3D, HyIII)**
  - Choose biofidelity test condition
  - Develop experimental seat for rear impact sled testing
  - Conduct sled tests
    - PMHS (Post-Mortem Human Subjects)
    - Dummies (BioRID II, RID3D, Hybrid III)
  - Assess biofidelity and repeatability of dummies
- **Investigate the mechanism of injury**
  - Develop and validate 3-D cervical spine kinematic instrumentation
  - Identify injurious kinematics
- **Relate injury to measured PMHS variables**
  - Assess potential injury criteria for rear impact dummies

PMHS Instrumentation
Cervical Spine



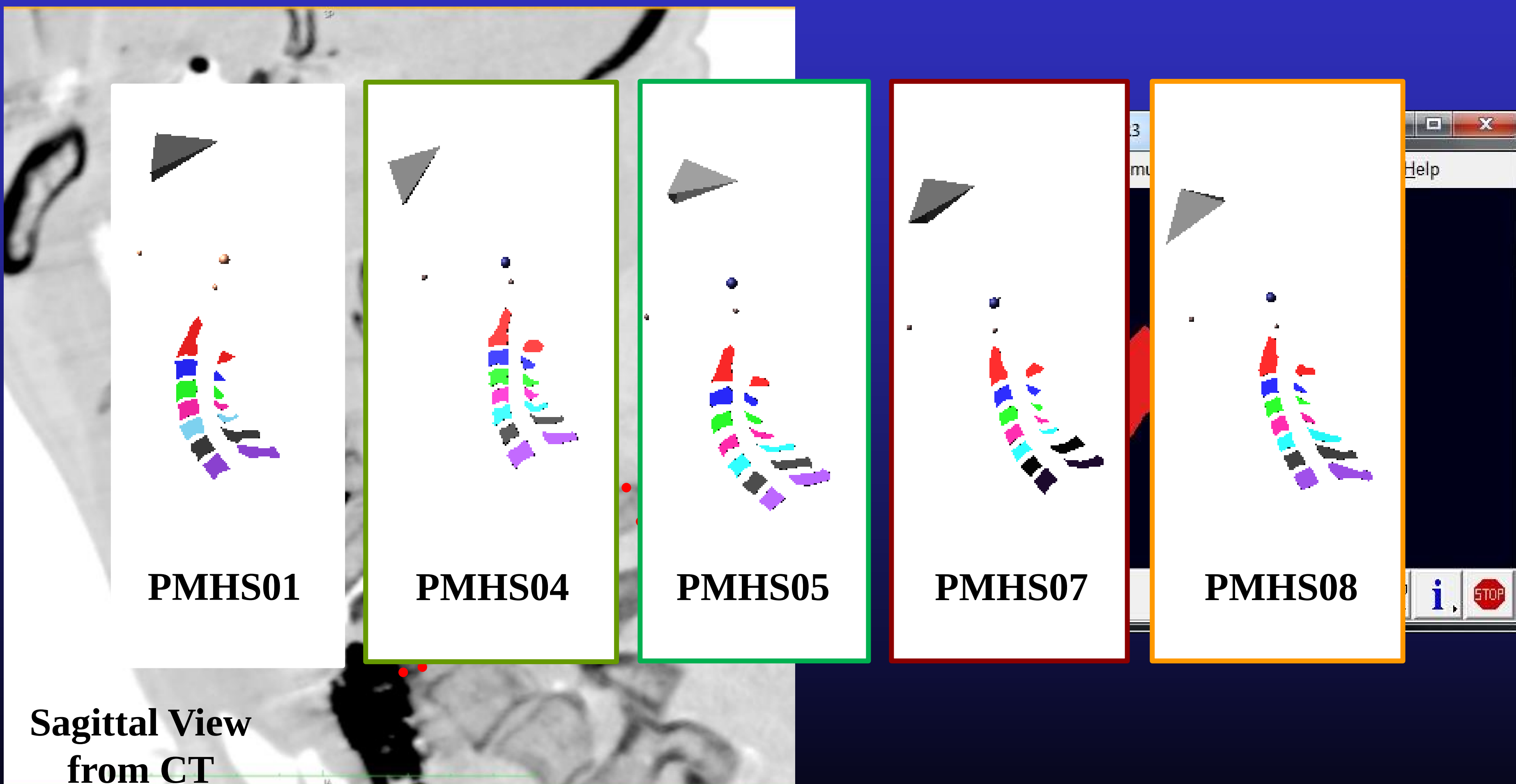


Cervical instrumentation

- Enter the Retropharyngeal space from the lateral aspect of neck
- Instrument the anterior vertebral bodies (C2 – T1)
    - No muscle disruption

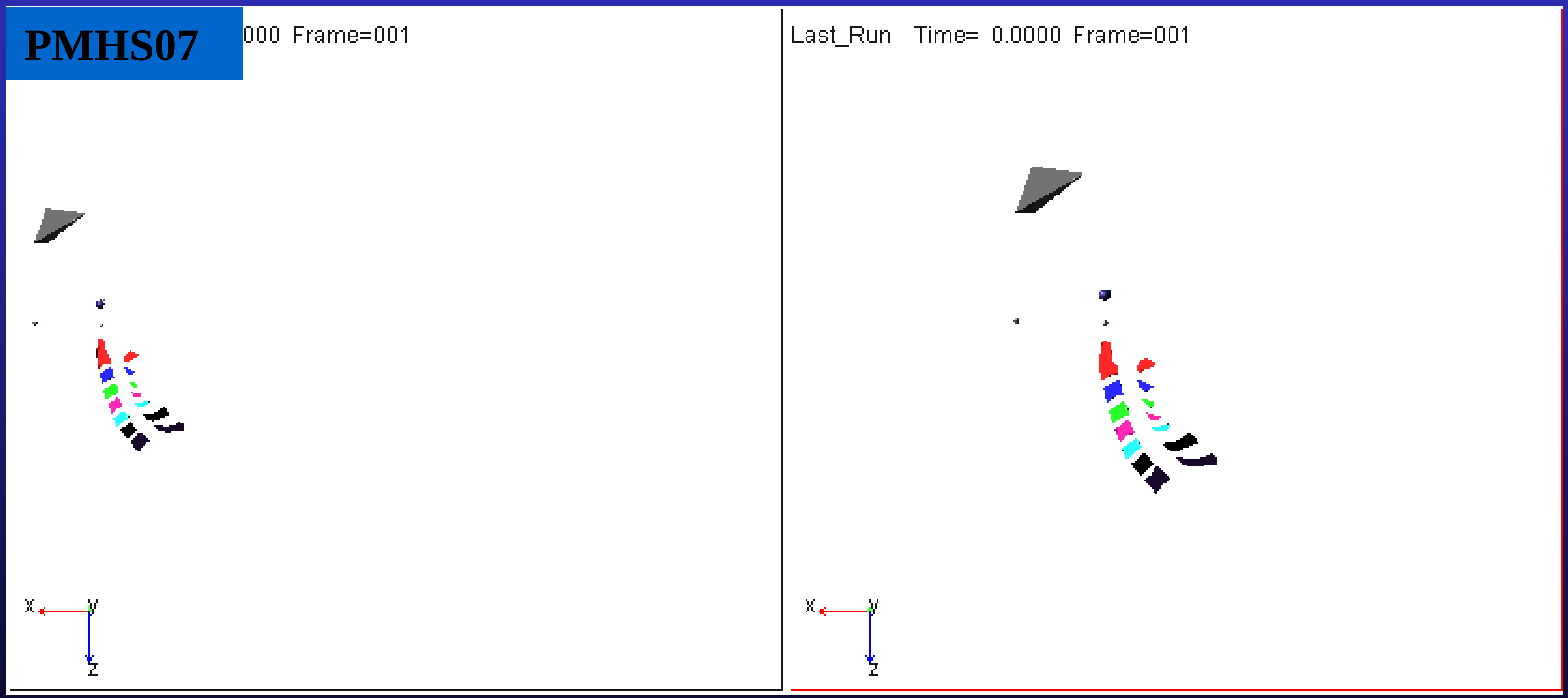
Cervical Kinematics (detailed geometry)

- **Detailed cervical model**



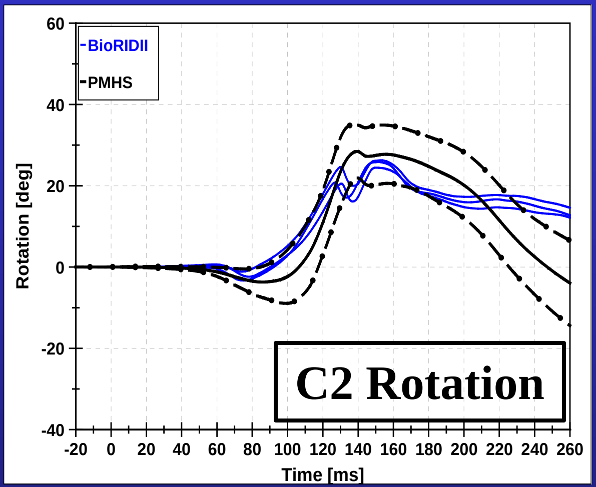
Cervical Kinematics (detailed geometry)

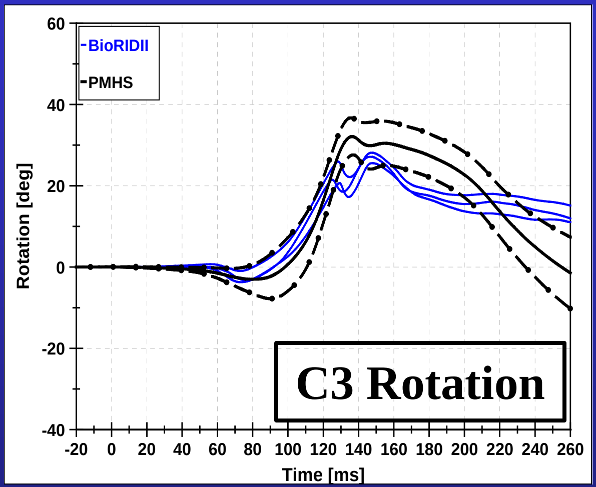
- **Detailed cervical model**
  - able to calculate strain and strain rate between vertebrae

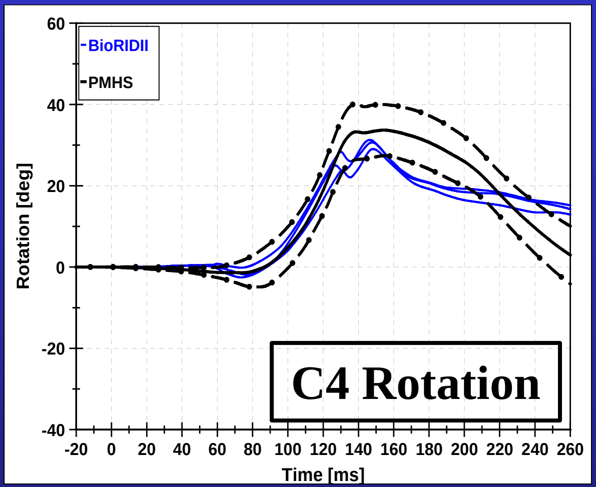


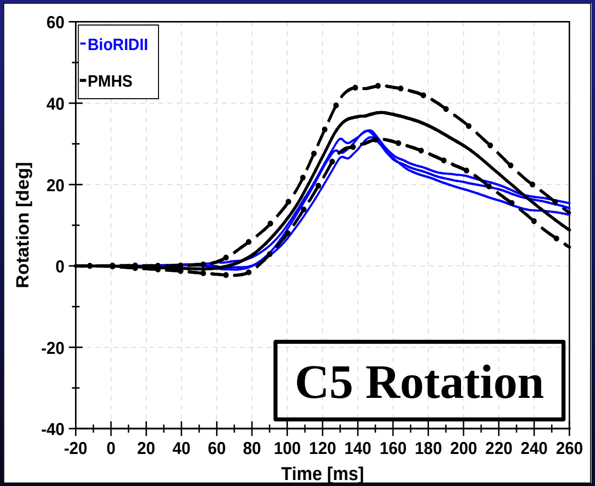
correlation between strain/strain rate and injuries at each level

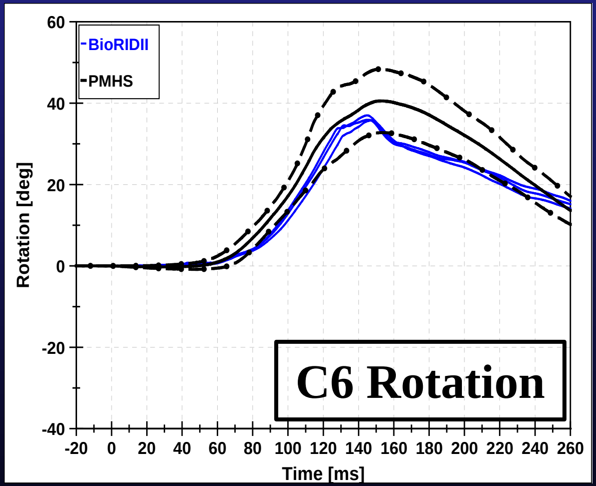
Cervical Kinematics 17 km/h

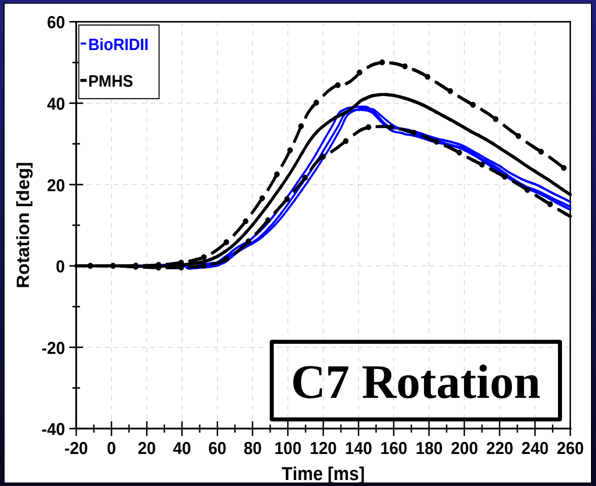




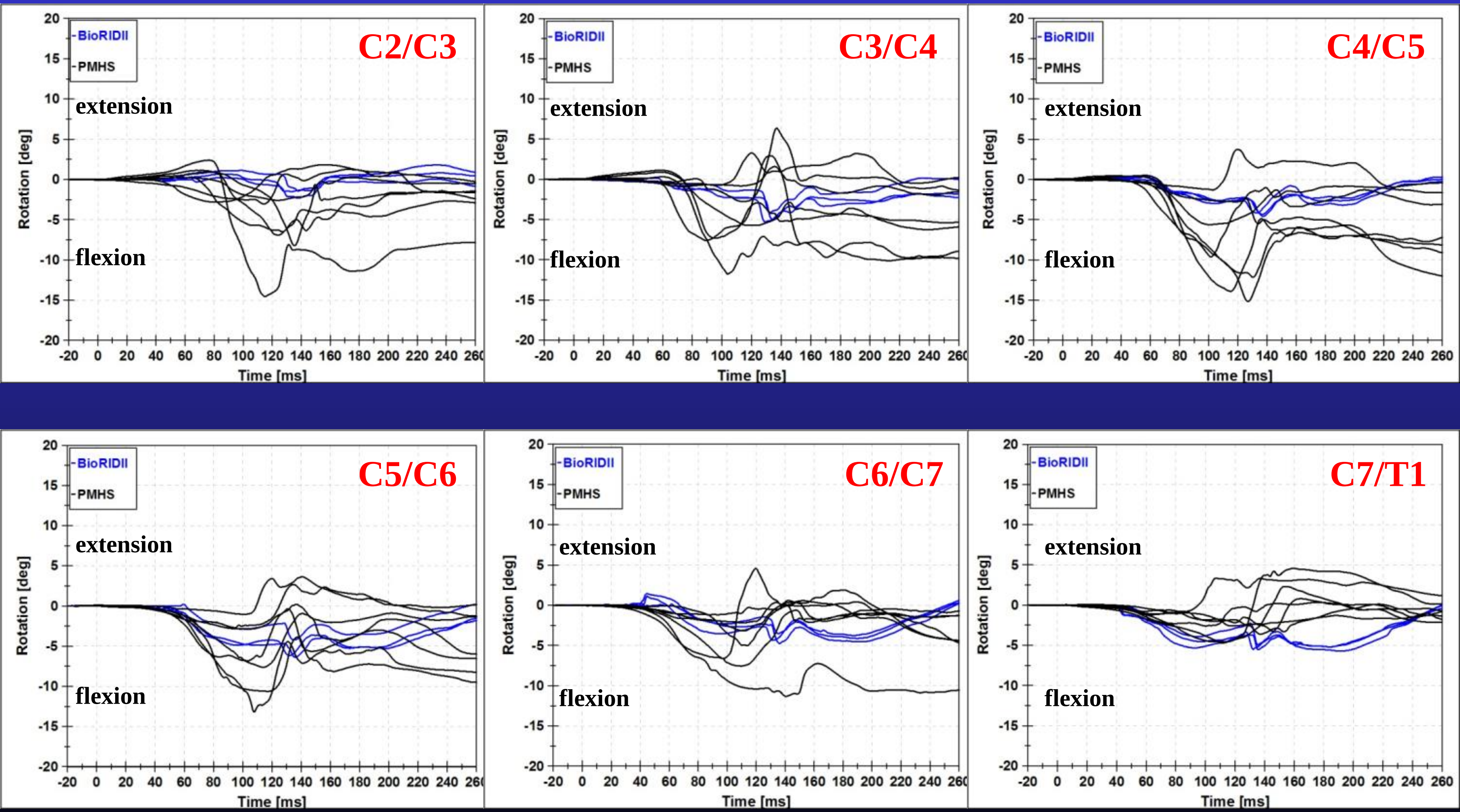




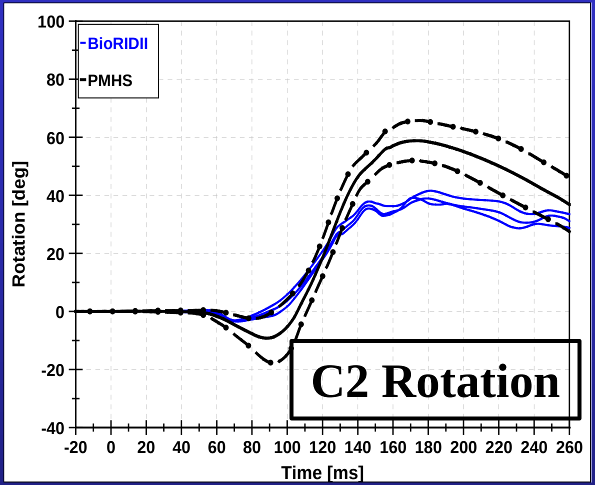


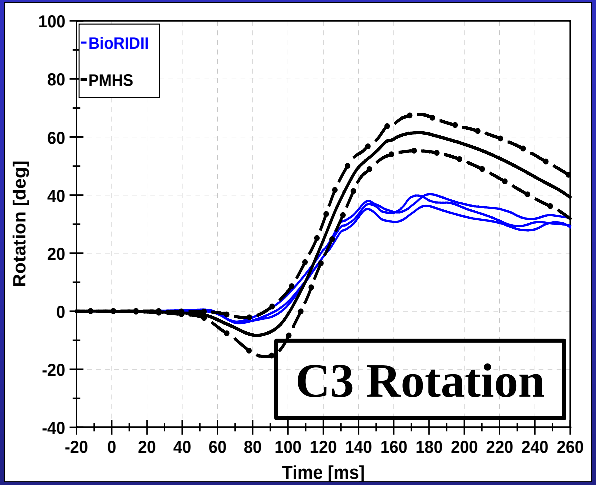


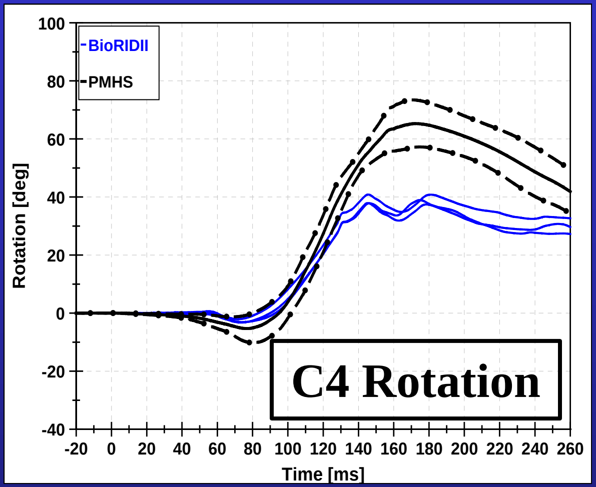
Intervertebral Rotation 17 km/h

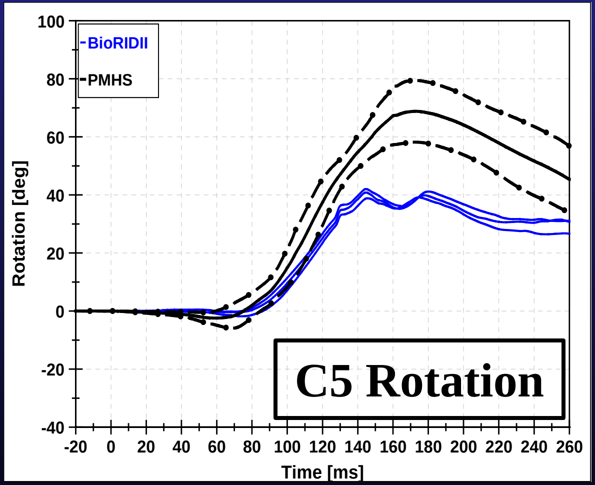


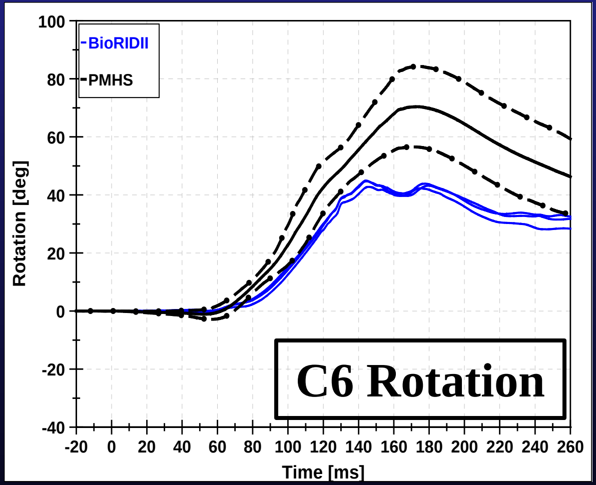
Cervical Kinematics 24 km/h

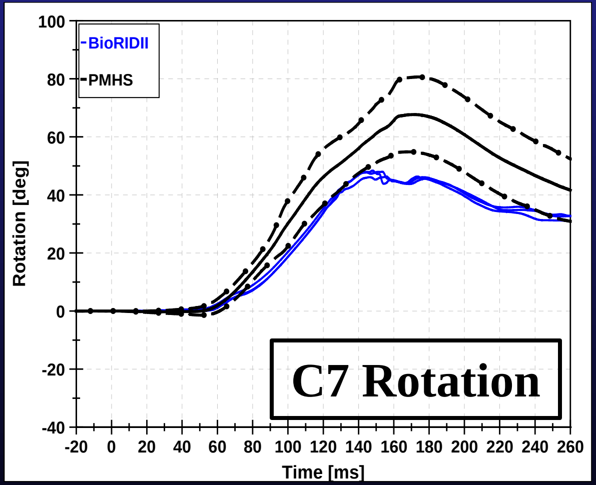




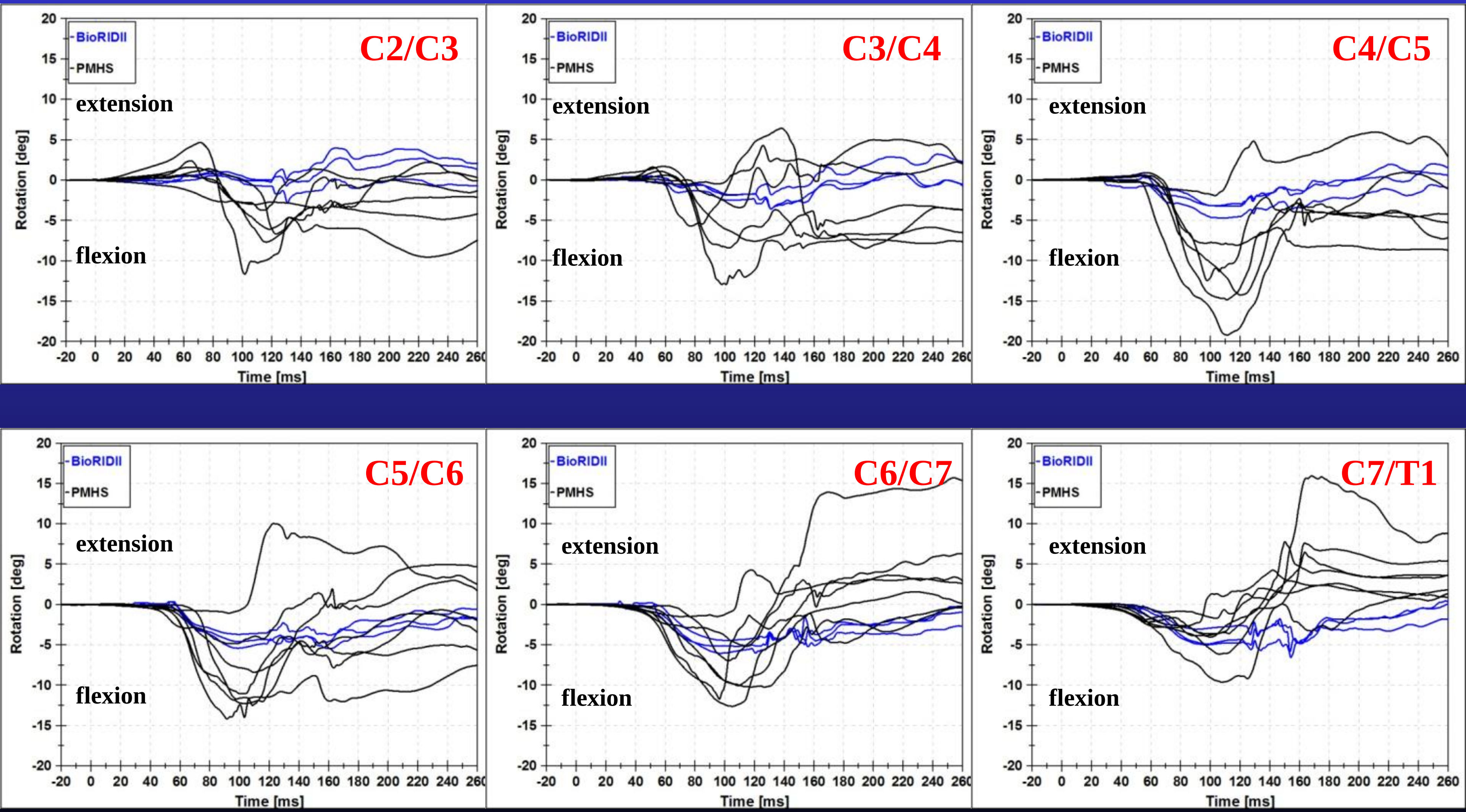






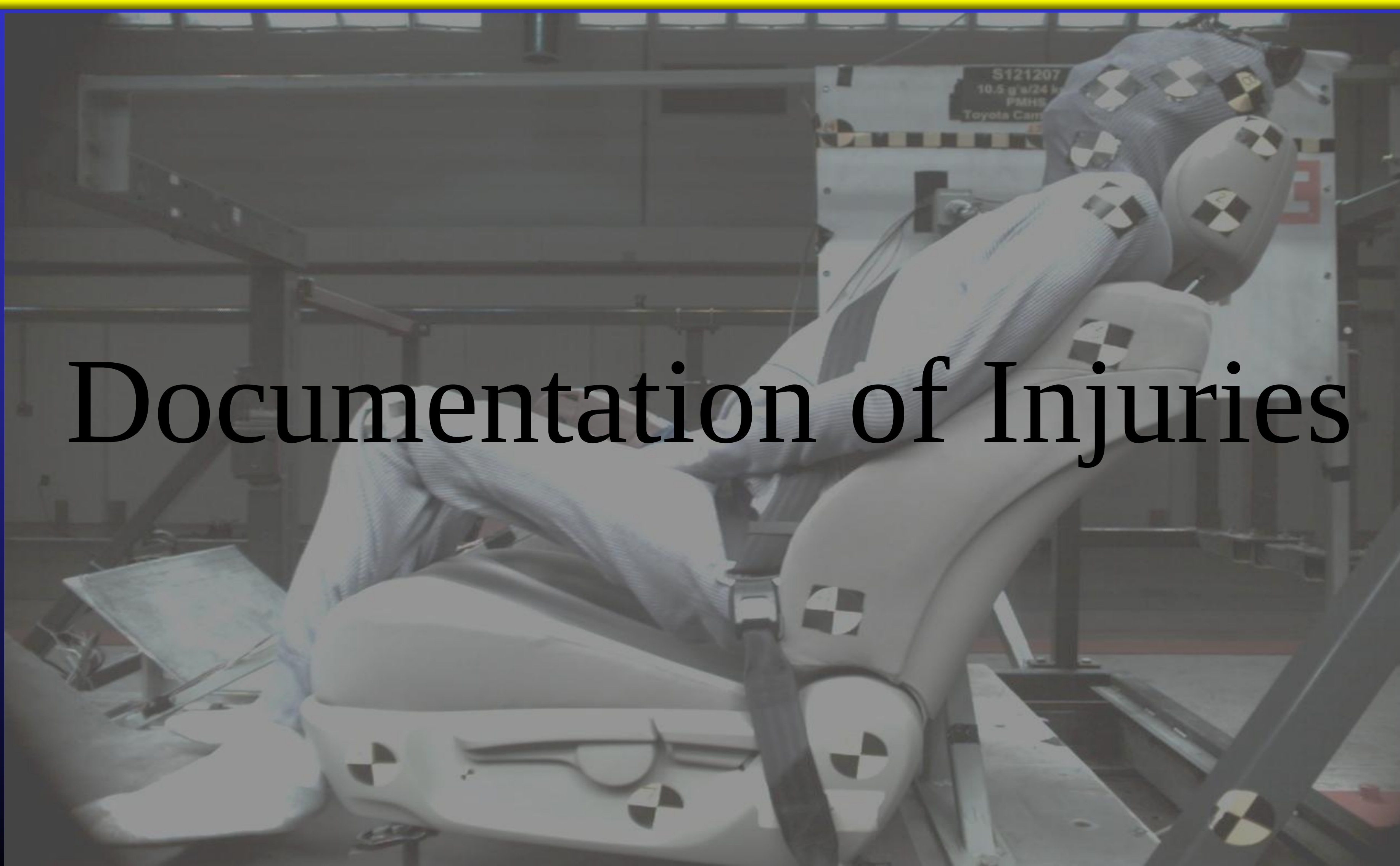


Intervertebral Rotation 24 km/h



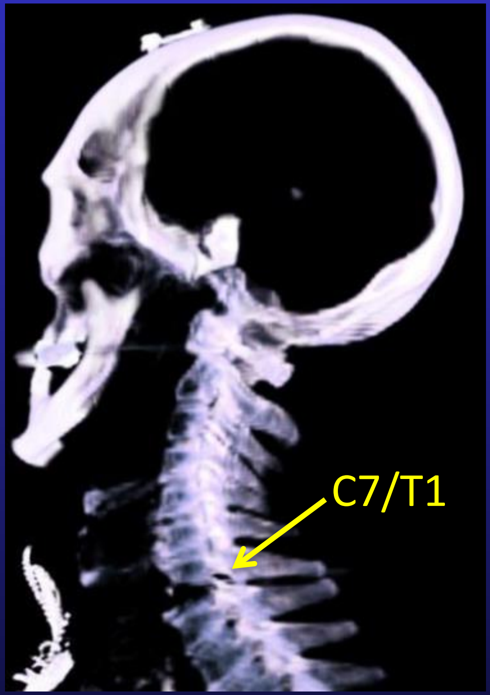
NHTSA
NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION

Documentation of Injuries

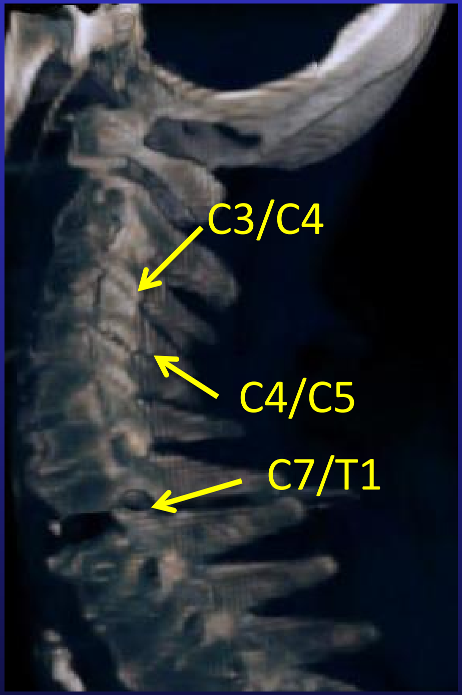


Injury Examples (Post-test CT)

<CT sagittal view>



<Disc rupture w fracture>



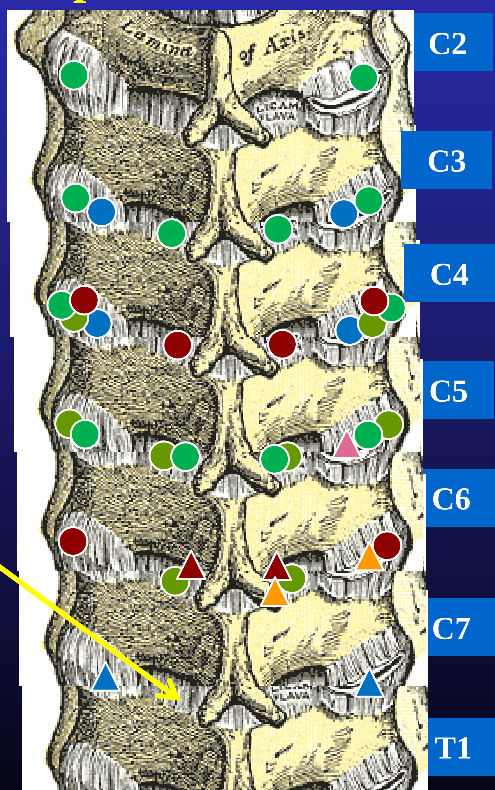
<Facet joint>

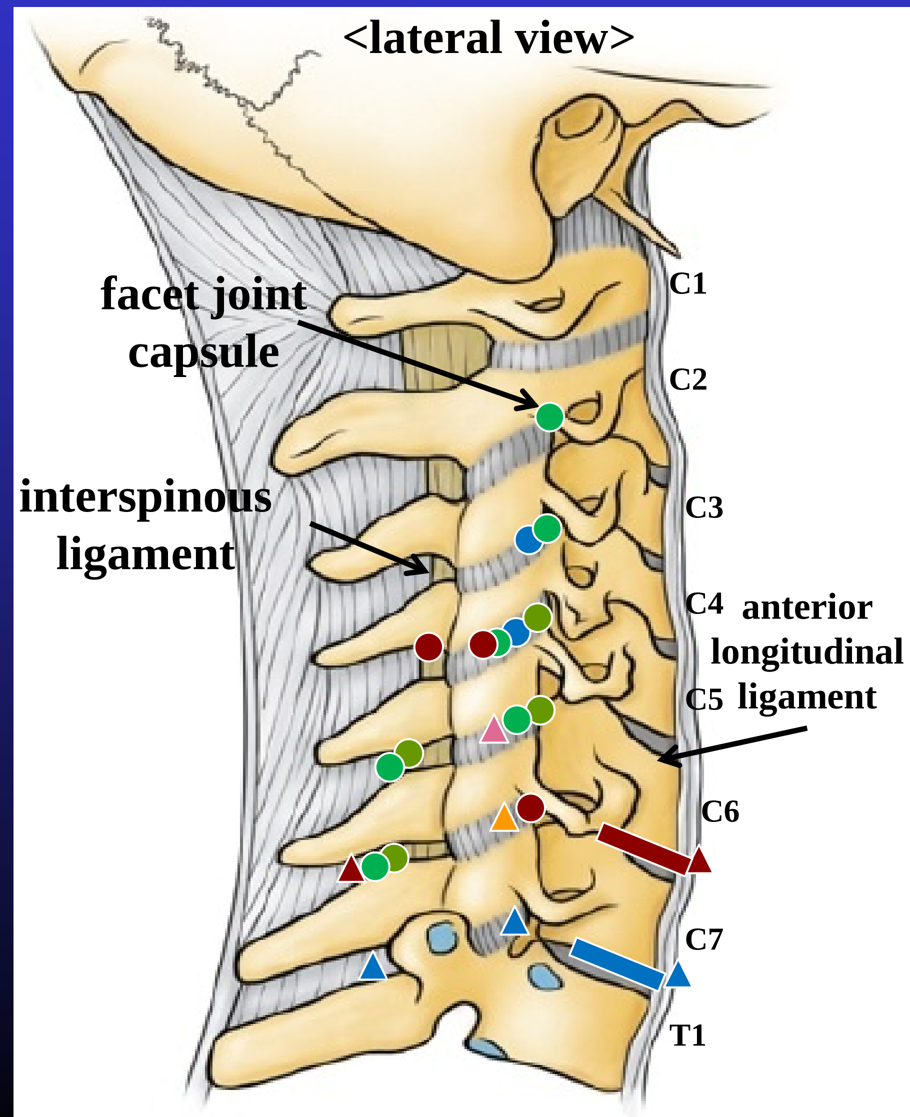
Documentation of Injuries

- ▬ : disc rupture
- ● : subluxation (represents WAD)
- ▲ : laceration (tear)

PMHS03
PMHS04
PMHS05
PMHS06
PMHS07
PMHS08

<posterior view>





Documentation of Injuries

Injury Documentation

	PMHS03	PMHS04	PMHS05	PMHS06	PMHS07	PMHS08
C2/C3	No injury	No injury	Subluxation	No injury	No injury	No injury
C3/C4	Subluxation	No injury	Subluxation	No injury	No injury	No injury
C4/C5	Subluxation	Subluxation	Subluxation	No injury	Subluxation	No injury
C5/C6	No injury	Subluxation	Subluxation	Subluxation	No injury	No injury
C6/C7	No injury	Subluxation	Subluxation	No injury	Subluxation/ligament tear/disc injury	Subluxation

Injury Criteria Analysis

PMHS Injury Analysis

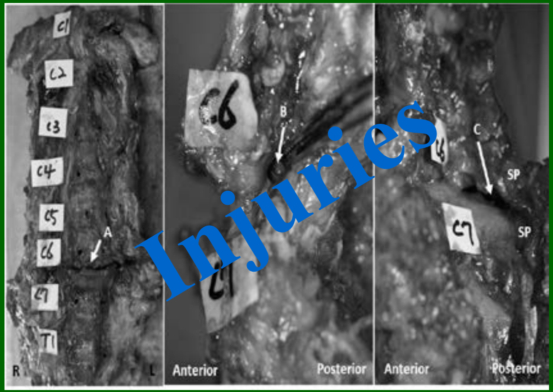
PMHS

Step 1

Intervertebral kinematics

Linear/angular acceleration, velocity, and displacement

Correlation?



PMHS Injury Analysis

PMHS

Step 1

Intervertebral kinematics

Linear/angular acceleration, velocity, and displacement

Correlation?

Injuries

Normalization?

PMHS Injury Analysis

PMHS

Step 1

Intervertebral kinematics

Linear/angular acceleration, velocity, and displacement

Correlation?

Normalization?

Step 2

Best injury predictors

Correlation?

Kinetics/kinematics

Current/potential injury criteria

PMHS Injury Analysis

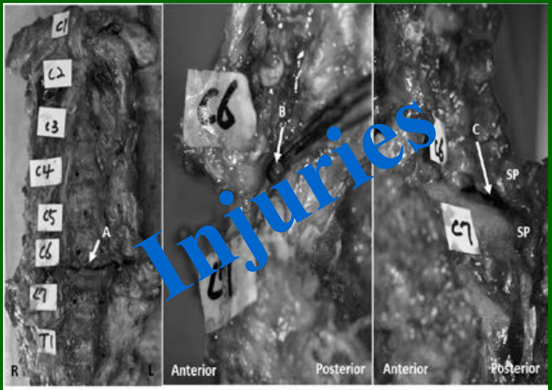
PMHS

Step 1

Intervertebral kinematics

Linear/angular acceleration, velocity, and displacement

Correlation?



Normalization?

Step 2

Best injury predictors

Correlation?

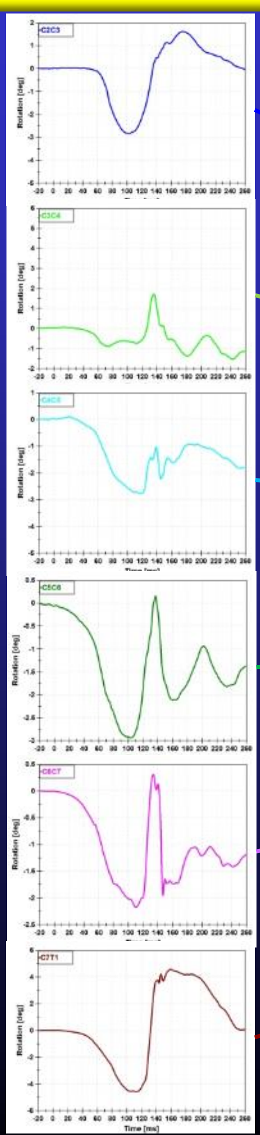
Kinetics/kinematics

Current/potential injury criteria

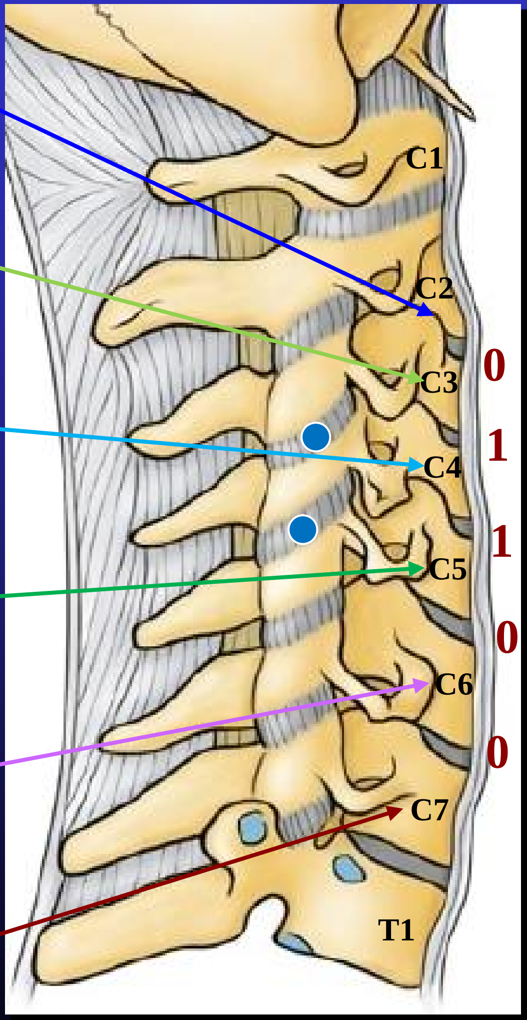
PMHS Injury Analysis

Injury Risk Curves – Intervertebral Kinematics

Intervertebral kinematics

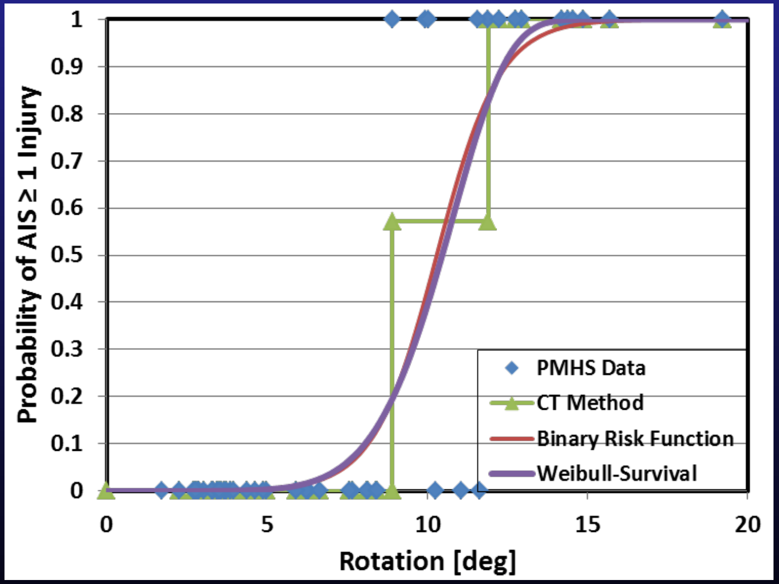


Injuries @ intervertebral levels



- C2/C3 – C6/C7: 5 levels
- 5 data points per test
  - PMHS02-non injurious 4 multiple tests
- n =50

Injury Risk Curves



PMHS Injury Analysis

Injury Risk Curves – Intervertebral Kinematics

Intervertebral kinematics		Pseudo R^2	Nagelkerke R^2	Log-Likelihood	P-value	Goodman-Kruskal Gamma
Acceleration x	(+)	0.05	0.08	-30.377	0.067	0.49
	(-)	0.17	0.25	-26.744	0.001	0.72
	Max	0.09	0.14	-29.142	0.016	0.59
Acceleration z	(+)	0.17	0.26	-26.584	0.001	0.62
	(-)	0.10	0.15	-28.963	0.013	0.59
	Max	0.12	0.19	-28.179	0.005	0.58
Velocity x	(+)	0.04	0.07	-30.612	0.089	0.34
	(-)	0.20	0.29	-25.785	0.000	0.54
	Max	0.20	0.29	-25.797	0.000	0.54
Velocity z	(+)	0.01	0.01	-31.855	0.527	-0.05
	(-)	0.12	0.18	-28.31	0.006	0.47
	Max	0.04	0.06	-30.908	0.130	0.14
Angular velocity y	**(+)**	**0.30**	**0.43**	**-20.696**	**0.000**	**0.83**
	(-)	0.05	0.08	-33.195	0.074	0.42
	Max	0.17	0.26	-28.837	0.001	0.7
Displacement x	Max	0.11	0.17	-29.930	0.008	0.41
Displacement z	Max	0.29	0.41	-23.760	0.000	0.69
Rotation y	**Max**	**0.72**	**0.83**	**-8.236**	**0.000**	**0.96**

(+) : positive peak, (-): negative peak, Max: maximum peak

Peudo $R^2 > 0.2$, Nagelkerke $R^2 > 0.4$, P-value < 0.05 , Goodman-Kruskal Gamma > 0.6

Best correlation and prediction

PMHS Injury Analysis

Injury Risk Curves – Intervertebral Kinematics

Intervertebral kinematics		Pseudo R^2	Nagelkerke R^2	Log-Likelihood	P-value	Goodman-Kruskal Gamma
Acceleration x	(+)	0.05	0.08	-30.377	0.067	0.49
	(-)	0.17	0.25	-26.744	0.001	0.72
	Max	0.09	0.14	-29.142	0.016	0.59
Acceleration z	(+)	0.17	0.26	-26.584	0.001	0.62
	(-)	0.10	0.15	-28.963	0.013	0.59
	Max	0.12	0.19	-28.179	0.005	0.58
Velocity x	(+)	0.04	0.07	-30.612	0.089	0.34
	(-)	0.20	0.29	-25.785	0.000	0.54
	Max	0.20	0.29	-25.797	0.000	0.54
Velocity z	(+)	0.01	0.01	-31.855	0.527	-0.05
	(-)	0.12	0.18	-28.31	0.006	0.47
	Max	0.04	0.06	-30.908	0.130	0.14
Angular velocity y	**(+)**	**0.30**	**0.43**	**-20.696**	**0.000**	**0.83**
	(-)	0.05	0.08	-33.195	0.074	0.42
	Max	0.17	0.26	-28.837	0.001	0.7
Displacement x	Max	0.11	0.17	-29.930	0.008	0.41
Displacement z	Max	0.29	0.41	-23.760	0.000	0.69
Rotation y	**Max**	**0.72**	**0.83**	**-8.236**	**0.000**	**0.96**
Facet JT Slide	**Max**	**0.38**	**0.52**	**-18.528**	**0.000**	**0.77**
Facet JT Slide Rate	Max	0.13	0.20	-30.388	0.003	0.49
Facet JT Axial	Max	0.06	0.10	-32.711	0.041	0.28
Facet JT Axial Rate	Max	0.05	0.09	-32.953	0.055	0.38

(+) : positive peak, (-): negative peak, Max: maximum peak

Peudo R^2 > 0.2, Nagelkerke R^2 > 0.4, P-value < 0.05 , Goodman-Kruskal Gamma > 0.6

Best correlation and prediction

PMHS Injury Analysis

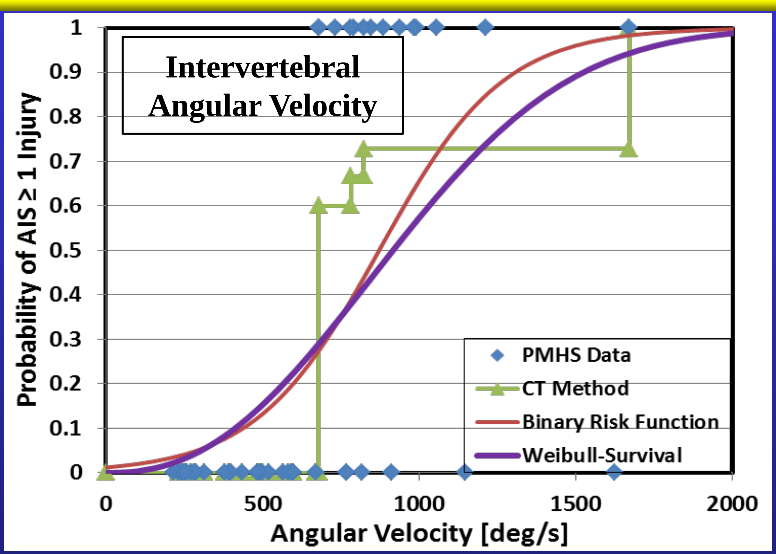
Injury Risk Curves – Intervertebral Kinematics

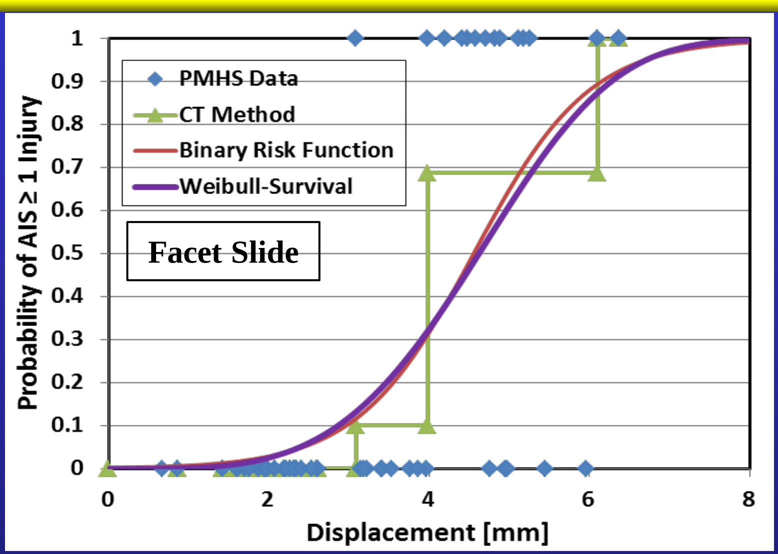
Intervertebral kinematics		Pseudo R^2	Nagelkerke R^2	Log-Likelihood	P-value	Goodman-Kruskal Gamma
Rotation y	**Max**	**0.72**	**0.83**	**-8.236**	**0.000**	**0.96**
Angular velocity y	**(+)**	**0.30**	**0.43**	**-20.696**	**0.000**	**0.83**
Facet JT Slide	**Max**	**0.38**	**0.52**	**-18.5276**	**0.000**	**0.77**
(+) : positive peak, (-): negative peak, Max: maximum peak						

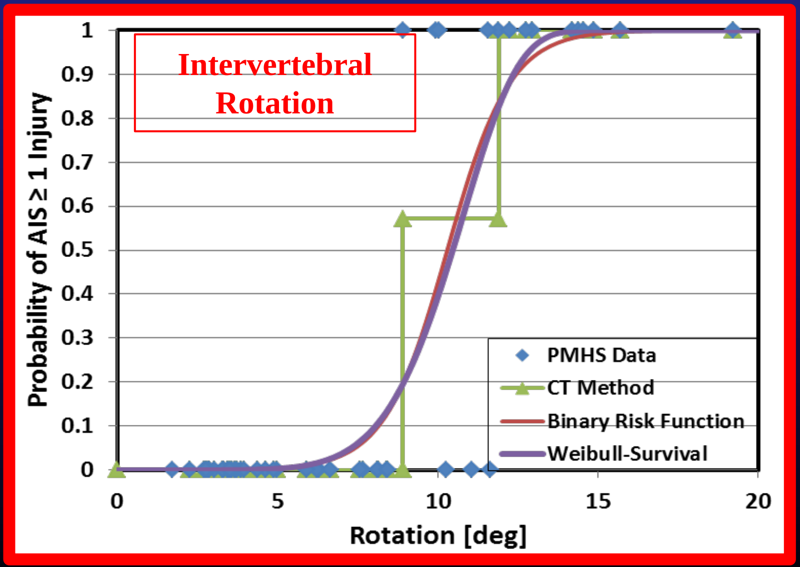
Peudo R^2 > 0.2, Nagelkerke R^2 > 0.4, P-value < 0.05 , Goodman-Kruskal Gamma > 0.6

Best correlation and prediction

PMHS Injury Analysis
Injury Risk Curves – Intervertebral Kinematics







- Each intervertebral level may have different threshold
  - Normalization using physiological range of motion
  - IV-NIC [Panjabi et al., 1999]

PMHS Injury Analysis

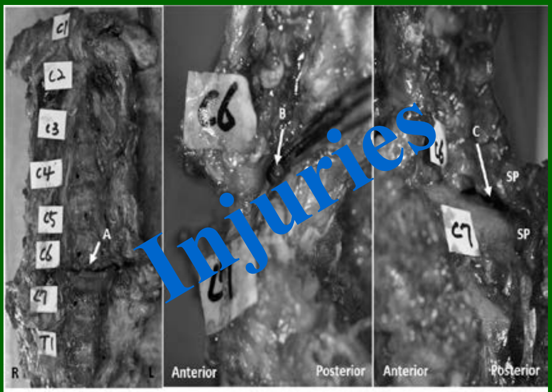
PMHS

Step 1

Intervertebral kinematics

Linear/angular acceleration, velocity, and displacement

Correlation?



Normalization?

Step 2

Best injury predictors

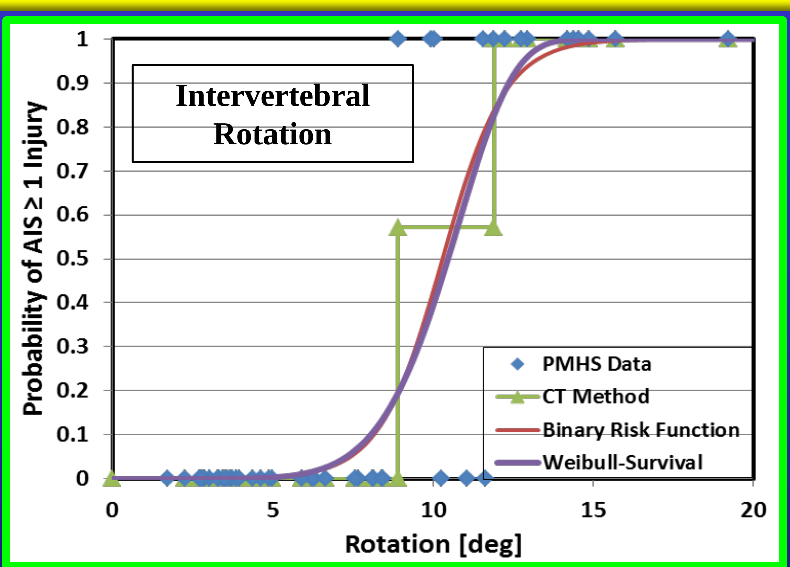
Correlation?

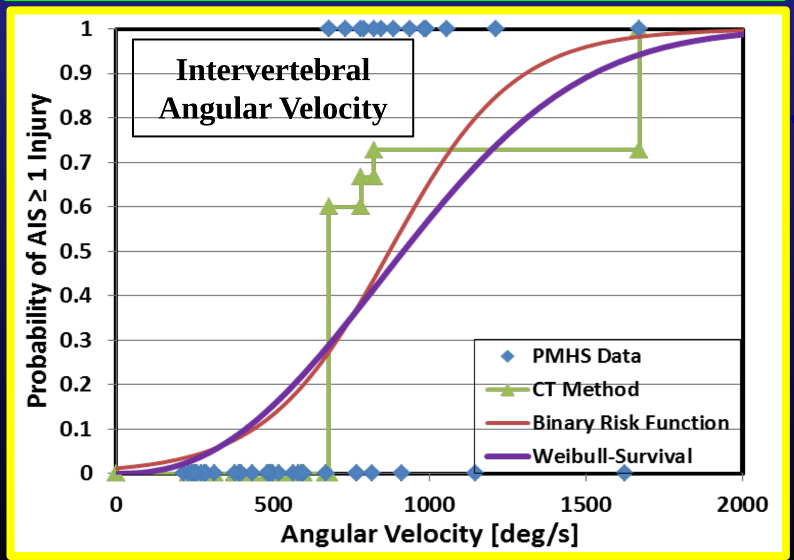
Kinetics/kinematics

Current/potential injury criteria

PMHS Injury Analysis

Injury Risk Curves – Intervertebral Kinematics





IV-NICrot

$$IV-NIC_i = \frac{\Theta_{trauma,i}}{\Theta_{\text{physiological},i}}$$

IV-NICrot Rate

$$\frac{d}{dt}(IV-NIC_i) = \frac{\dot{\Theta}_{trauma,i}}{\Theta_{\text{physiological},i}}$$

IV-NICrot Product

1) IV-NICrot Product (max-max)
   = Max(IV-NICrot) × Max(IV-NICrot Rate)
2) IV-NICrot Product (max)
   = Max(IV-NICrot × IV-NICrot Rate)

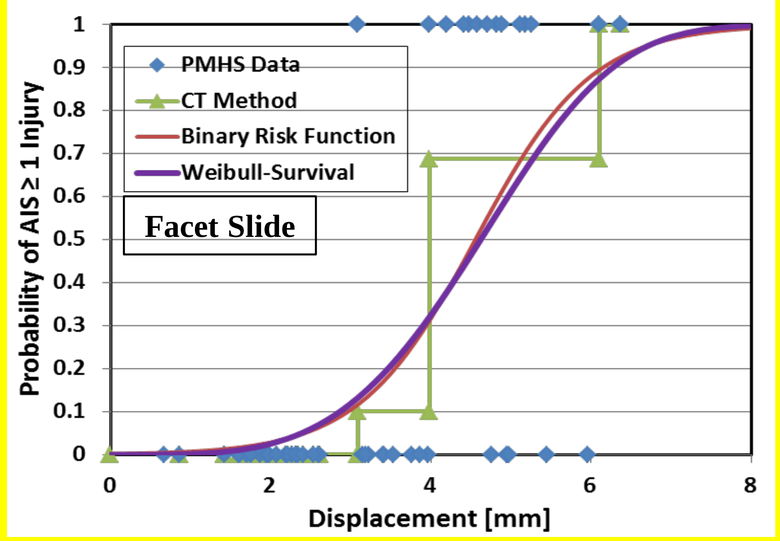
PMHS Injury Analysis

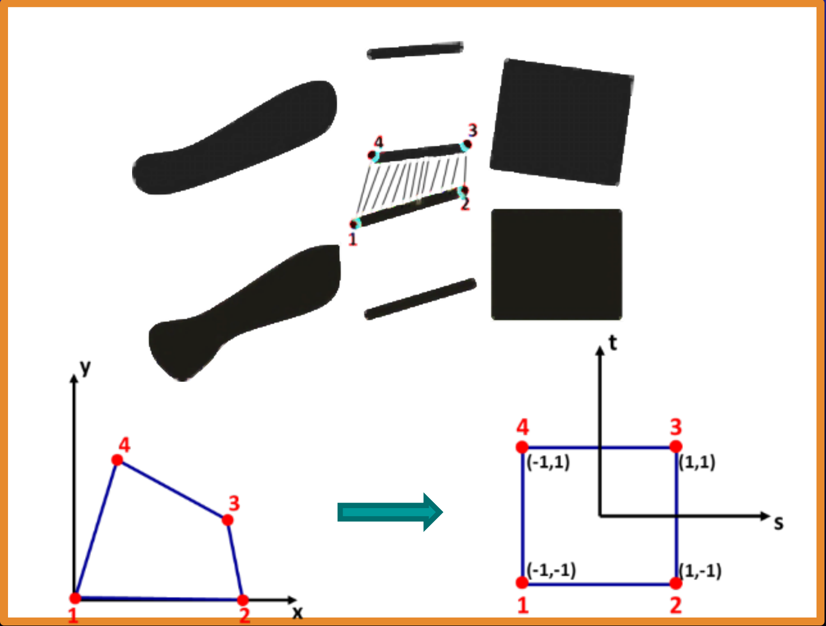
Injury Risk Curves – Intervertebral Kinematics

$$IV - NIC_{Slide,i} = \frac{Disp_{trauma,i}}{Disp_{physiological,i}}$$

$$IV - NIC_{Axial,i} = \frac{Disp_{trauma,i}}{Disp_{physiological,i}}$$

Pearson et al., 2004





2D strain at facet joints

$$E_x = \frac{\partial u}{\partial x} + 0.5 \cdot \left[\left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial x} \right)^2 \right]$$

$$E_x = \frac{\partial v}{\partial y} + 0.5 \cdot \left[\left(\frac{\partial u}{\partial y} \right)^2 + \left(\frac{\partial v}{\partial y} \right)^2 \right]$$

$$R_{xy} = 0.5 \cdot \left[\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} + \left(\frac{\partial u}{\partial x} \right)\left(\frac{\partial u}{\partial y} \right) + \left(\frac{\partial v}{\partial x} \right)\left(\frac{\partial v}{\partial y} \right) \right]$$

Ono et al., 2009

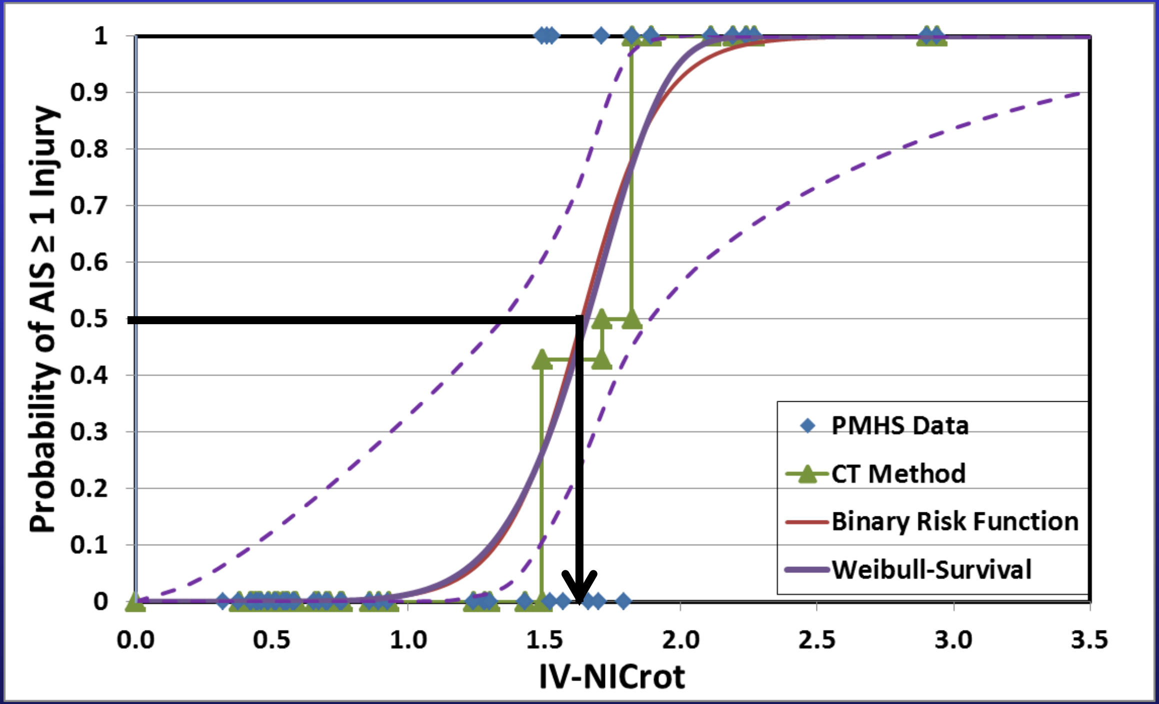
PMHS Injury Analysis

Injury Risk Curves – IV-NIC Parameters

Intervertebral kinematics		Pseudo R^2	Nagelkerke R^2	Log-Likelihood	P-value	Goodman-Kruskal Gamma
IV-NICs (slide)	Max	0.19	0.30	-23.912	0.001	0.58
IV-NICs rate	Max	0.10	0.17	-26.555	0.013	0.44
IV-NICs product	Max	0.16	0.25	-24.824	0.002	0.57
IV-NICa (axial)	Max	0.01	0.02	-29.212	0.350	0.17
IV-NICa rate	Max	0.004	0.007	-29.526	0.621	0.15
IV-NICa product	Max	0.005	0.009	-29.493	0.578	0.23
IV-NICrot (rotation)	**Max**	**0.74**	**0.84**	**-8**	**0.000**	**0.95**
IV-NICrot rate	Max	0.10	0.15	-26.723	0.016	0.59
IV-NICrot product (max-max)	**Max**	**0.40**	**0.55**	**-17.677**	**0.000**	**0.83**
IV-NICrot product (max)	**(-)**	**0.55**	**0.69**	**-13.40**	**0.000**	**0.89**
2D Max Shear Strain	Max	0.06	0.09	-29.953	0.056	0.27
2D Max Principal Strain	Max	0.05	0.09	-30.073	0.065	0.23
2D Shear Strain Rate	(+)	0.07	0.11	-29.651	0.039	0.37
2D Principal Starin Rate	(+)	0.07	0.11	-29.673	0.040	0.39

(+) : positive peak, (-): negative peak, Max: maximum peak

PMHS Injury Analysis
Injury Risk Curves – IV-NIC Parameters



IV-NIC = 1.66

- **Each intervertebral level was normalized by physiological range of motions**
  - **IV-NICrot : best correlation to injuries**
    - **IV-NICrot products: also show correlation**

PMHS Injury Analysis

PMHS

Step 1

Intervertebral kinematics

Linear/angular acceleration, velocity, and displacement

Correlation?

Normalization?

Step 2

Best injury predictors

Correlation?

Kinetics/kinematics

Current/potential injury criteria

PMHS Injury Analysis

IV-NIC vs. Current/Potential Injury Criteria

- **Correlation between IV-NIC values and existing injury criteria**

$$NIC = 0.2 \times a_{rel} + v_{rel}^{2}$$

$$N_{km} = \frac{F_x}{F_{\text{int}}} + \frac{M_y}{M_{\text{int}}}$$

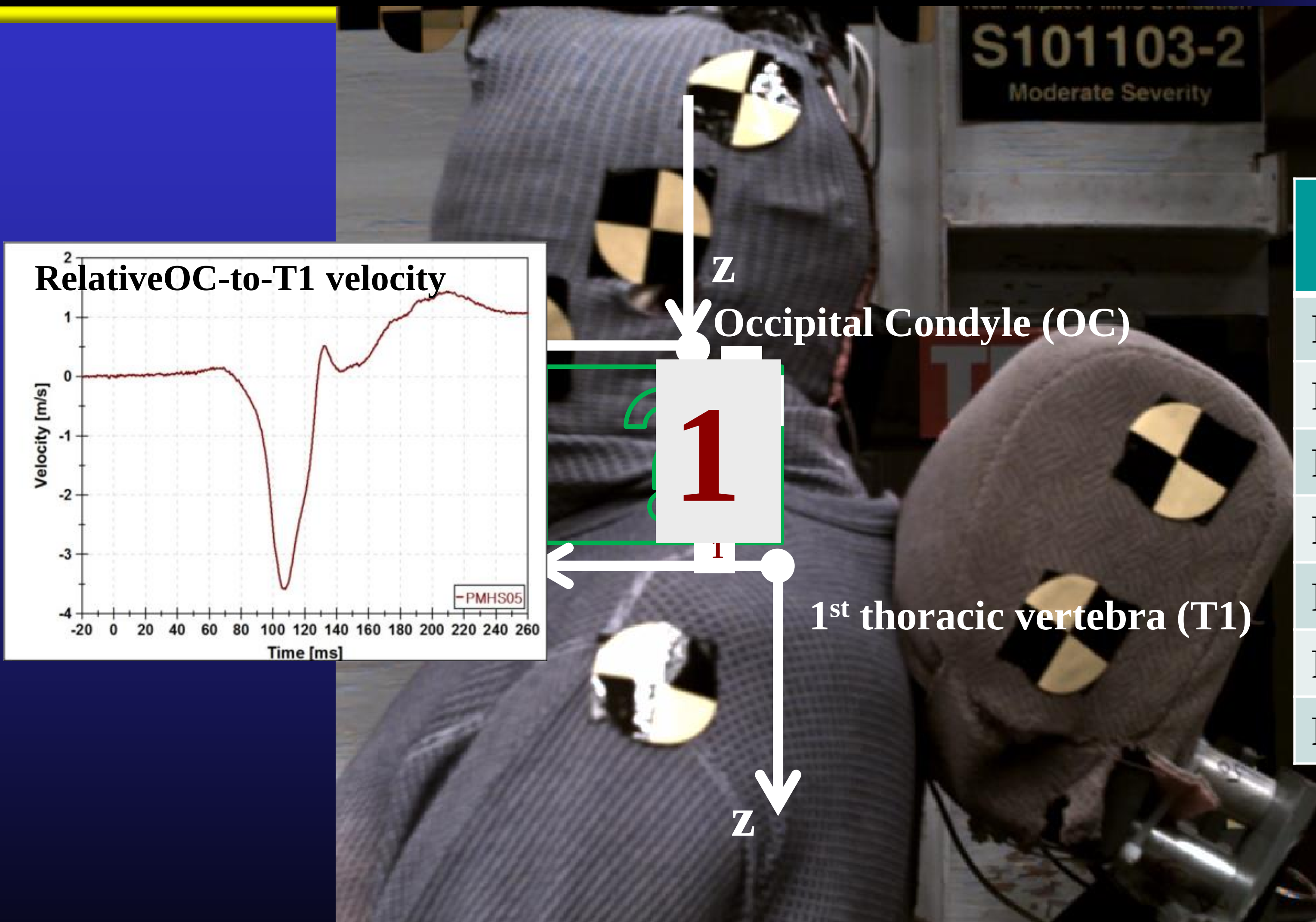
$$LNL-index(t) = \left| \frac{\sqrt{My_{lower}(t)^2 + Mx_{lower}(t)^2}}{C_{moment}} \right| + \left| \frac{\sqrt{Fx_{lower}(t)^2 + Fy_{lower}(t)^2}}{C_{shear}} \right| + \left| \frac{Fz_{lower}(t)}{C_{tension}} \right|$$

NDC, Nij
Head-to-T1 Rotation
Upper/Lower Fx, Fz, My
Any physical parameters

Potential PMHS IARVs

PMHS Injury Analysis

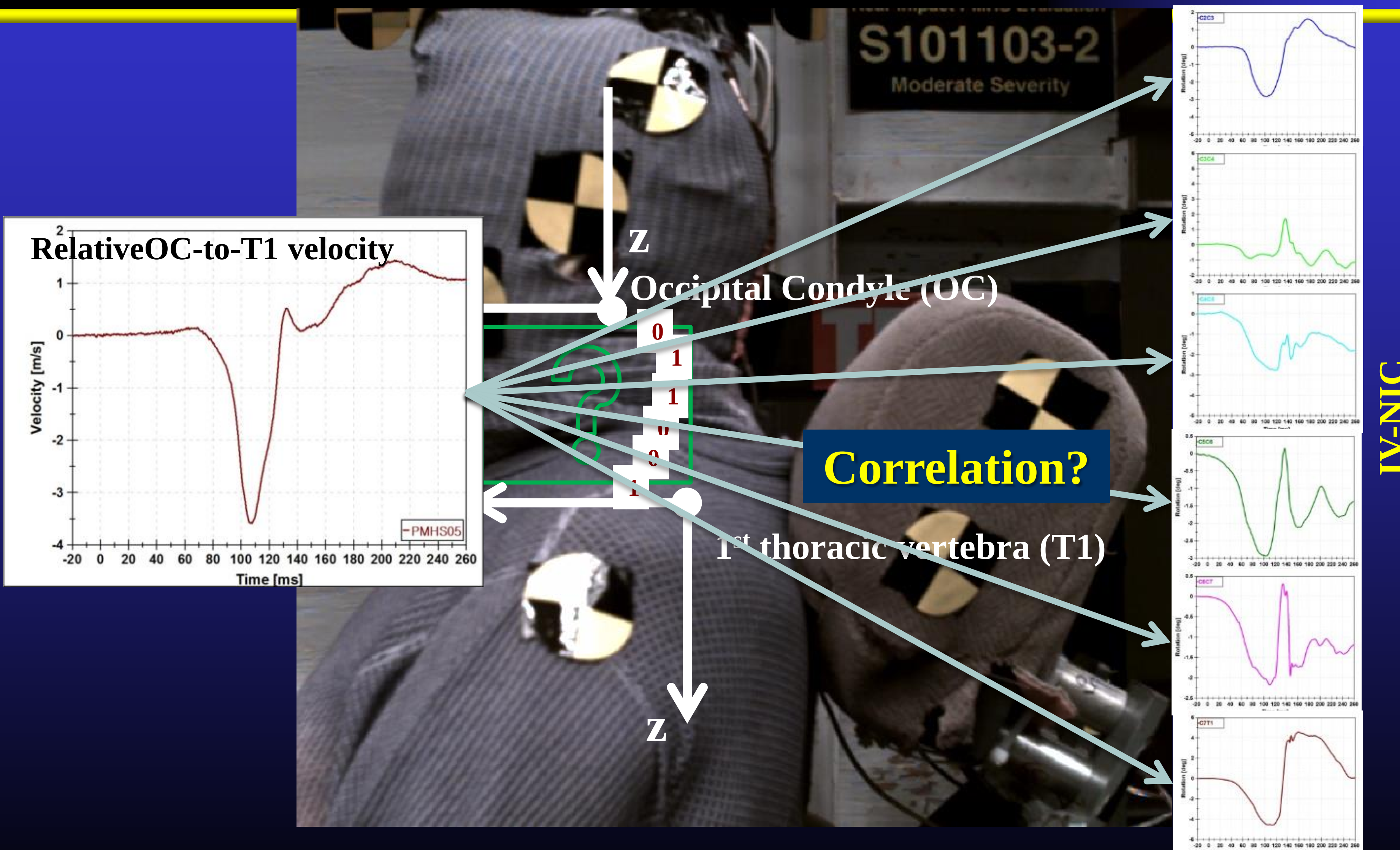
IV-NIC vs. Current/Potential Injury Criteria



PMHS#	Injury Code
PMHS02	0
PMHS03	1
PMHS04	1
PMHS05	1
PMHS06	1
PMHS07	1
PMHS08	1

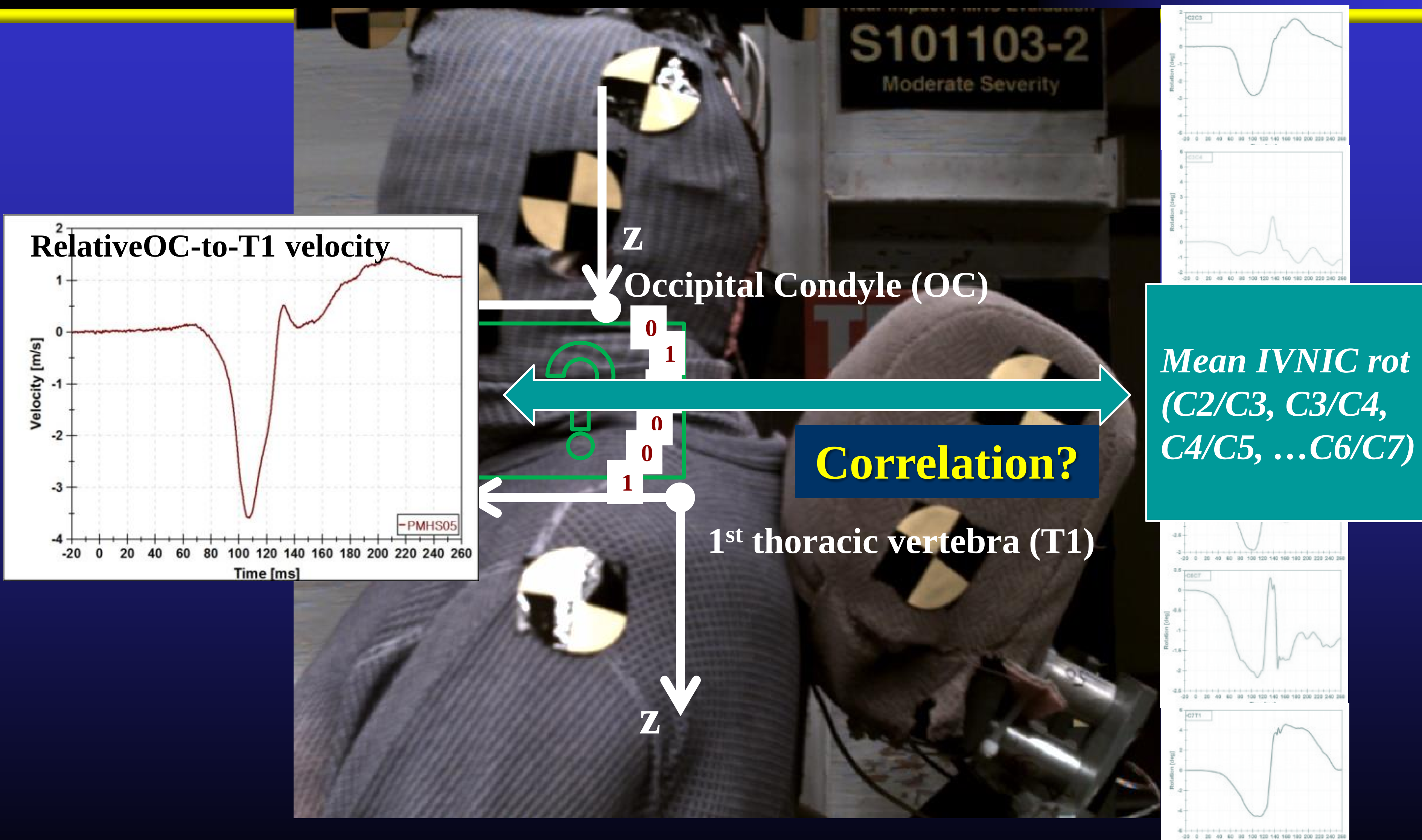
PMHS Injury Analysis

IV-NIC vs. Current/Potential Injury Criteria



PMHS Injury Analysis
IV-NIC vs. Current/Potential Injury Criteria

NHTSA
NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION



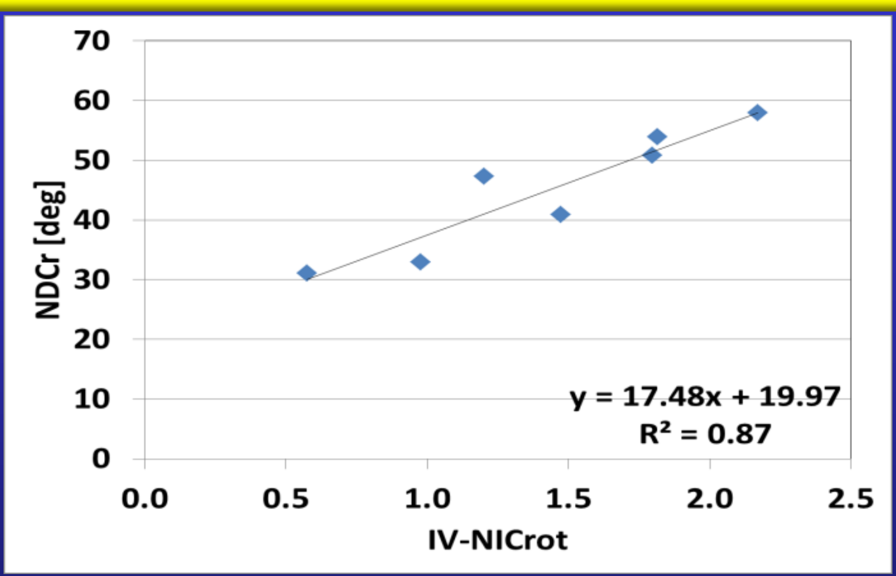
PMHS Injury Analysis

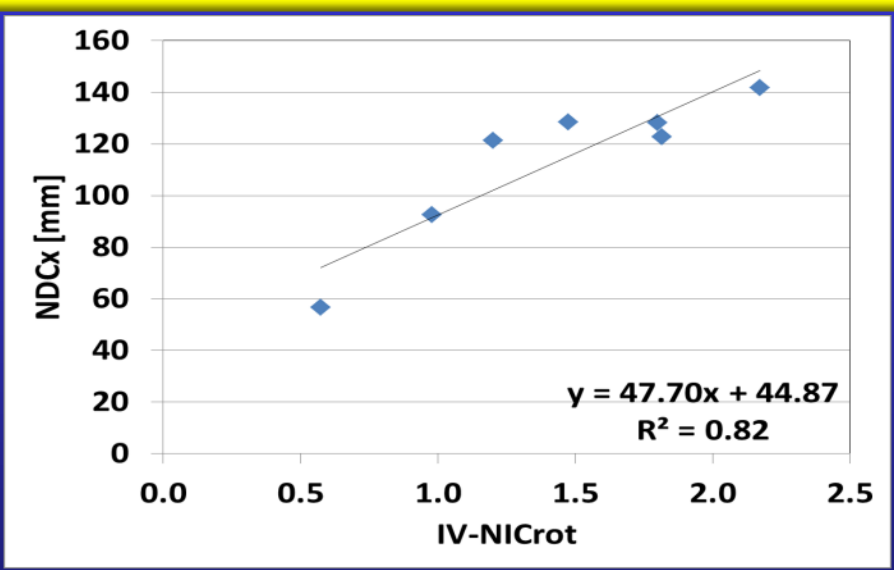
IV-NIC vs. Current/Potential Injury Criteria

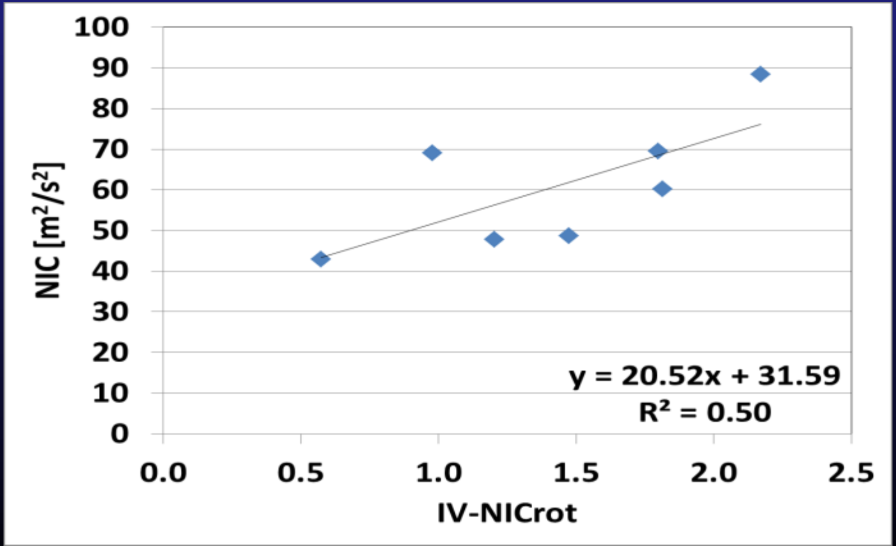
		IV-NICrot	
		R^2 - value	P - value
	NIC	0.50	0.077
Nij	**Nte**	0.22	0.129
Nij	**Ntf**	0.67	0
Nij	**Nce**	0.05	0.724
Nij	**Ncf**	0.31	0.03
Nkm	**Nae**	0.28	0.049
Nkm	**Naf**	0.57	0
Nkm	**Npe**	0.15	0.291
Nkm	**Npf**	0.45	0.001
	LNL	0.30	0.036
NDC	**NDCx**	**0.82**	**0.005**
NDC	**NDCx rate**	0.59	0.044
NDC	**NDCx product (max-max)**	**0.87**	**0.002**
NDC	**NDCx product (max)**	0.34	0.167
NDC	**NDCz**	0.00	0.935
NDC	**NDCz rate**	0.20	0.319
NDC	**NDCz product (max-max)**	0.03	0.700
NDC	**NDCz product (max)**	0.13	0.428
NDC	**NDCr**	**0.86**	**0.002**
NDC	**NDCr rate**	0.66	0.026
NDC	**NDCr product (max-max)**	**0.92**	**0.001**
NDC	**NDCr product (max)**	0.74	0.013

PMHS Injury Analysis

IV-NIC vs. Current/Potential Injury Criteria







- 50 % chance of AIS 1+ injuries for PMHS
  - IV-NICrot : 1.66
  - NDCr : 49.0 deg (flexion)
  - NDCx: 124.1 mm
  - NIC: 65.6 m^2/s^2

Summary

- **Best PMHS injury predictor**
  - IV-NICrot
    - IV-NICrot product also showed correlation
    - Rotation measures were found to be more correlated than displacements/strains
      - For these biofidelity test conditions in the experimental seat
      - Measurement precision??

Summary

- **Best PMHS injury predictor**
  - IV-NICrot
    - IV-NICrot product also showed correlation
    - Rotation measures were found to be more correlated than displacements/strains
      - For these biofidelity test conditions in the experimental seat
      - Measurement precision??
  - Potential "global" PMHS injury criteria
    - NDCr, NDCx
      - Products also
      - NIC also showed correlation

Limitations

- **Experimental Seat**
  - Designed for Biofidelity (not injury criteria development)
    - Repeatability, durability, measure occupant loading, allow SB rotation
    - Not designed to represent a real seat

Limitations

- **Experimental Seat**
  - Designed for Biofidelity (not injury criteria development)
    - Repeatability, durability, measure occupant loading, allow SB rotation
    - Not designed to represent a real seat
  - Rigid HR with load cells affects UN/LN loads
  - UN/LN loads not accurate after HR contact
    - Uniaxial LCs combined with ramping motion
    - Neck interaction with HR

Limitations

- **Experimental Seat**
  - Designed for Biofidelity (not injury criteria development)
    - Repeatability, durability, measure occupant loading, allow SB rotation
    - Not designed to represent a real seat
  - Rigid HR with load cells affects UN/LN loads
  - UN/LN loads not accurate after HR contact
    - Uniaxial LCs combined with ramping motion
    - Neck interaction with HR
  - SB Rotation is more uniform than production SB
    - Large ramping (particularly in moderate-speed test)
      - Neck interaction with HR
      - Lowers effective HR height for PMHS interaction
        - Wrap-around causes large extension in some cases
        - However: peak IV-NIC was still in flexion prior to this

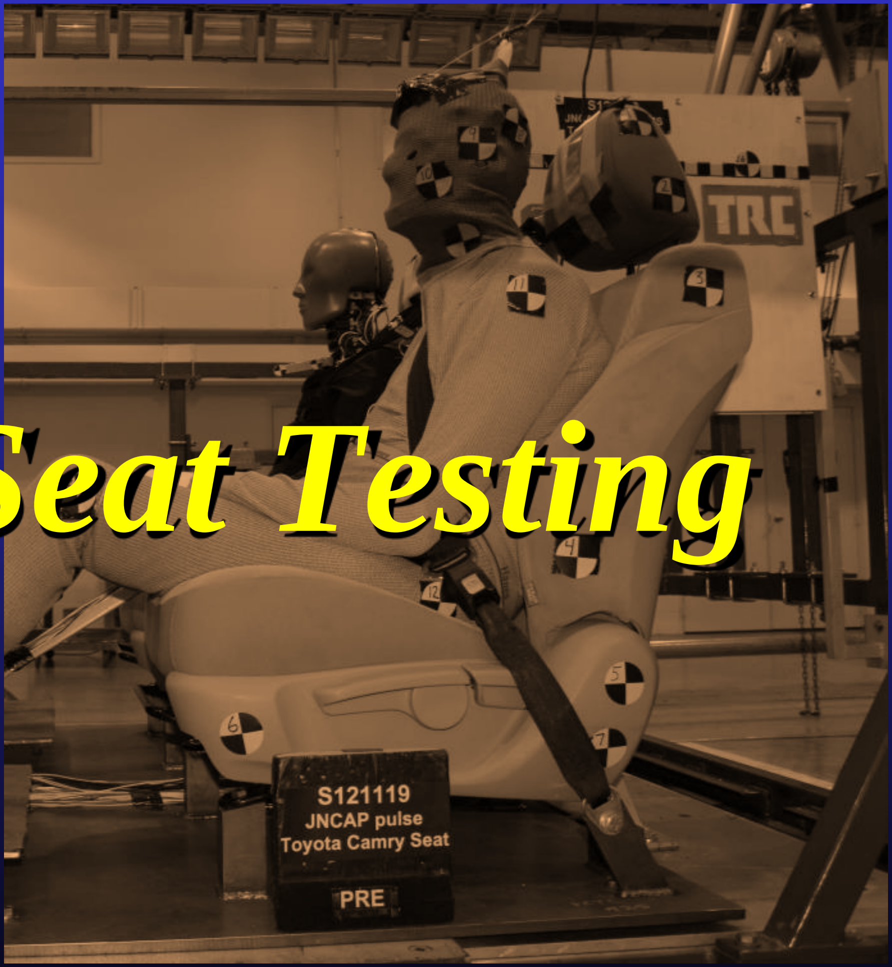
Limitations

- **Intervertebral displacements → double integration**
  - Measurement precision might affect correlations for 2-D strains, strain rates and IV-NIC axial/shear

Limitations

- **Intervertebral displacements → double integration**
  - Measurement precision might affect correlations for 2-D strains, strain rates and IV-NIC axial/shear
- **PMHS subjected to both low-speed and mod-speed test**
  - Low-speed test does not compromise structural integrity or kinematics of the neck
    - Validated in a separate study
  - Peak value obtained from either test was used in analysis
    - Doubly censored data (common for injury criteria analysis)

Production Seat Testing



Production Seat Testing

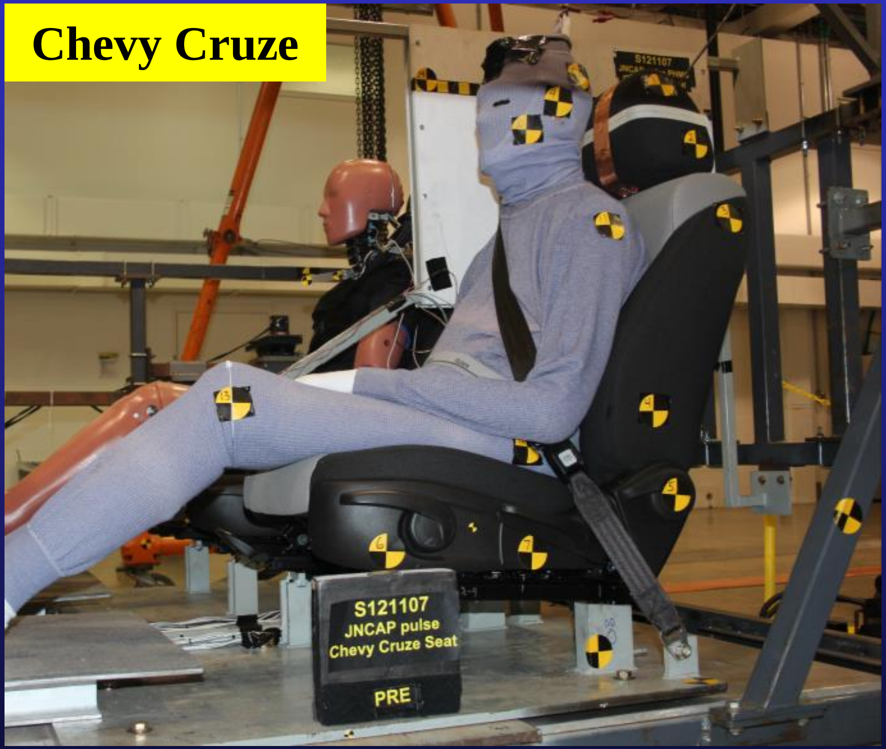
- **Test PMHS and BioRIDII (multiple paired tests)**
  - Verify experimental seat measures highly correlated to injury
    - Use only production seat results if possible
  - Test Matrix (7 PMHS)
    - 2 seats (2010 Toyota Camry, 2010 Chevy Cruze)
    - 3 pulses (FMVSS 202a, JNCAP, 24 km/h)
  - Measure HR loads → strain gages on posts
  - Multiple BioRIDII data points for correlation

Test Matrix
Production Seats

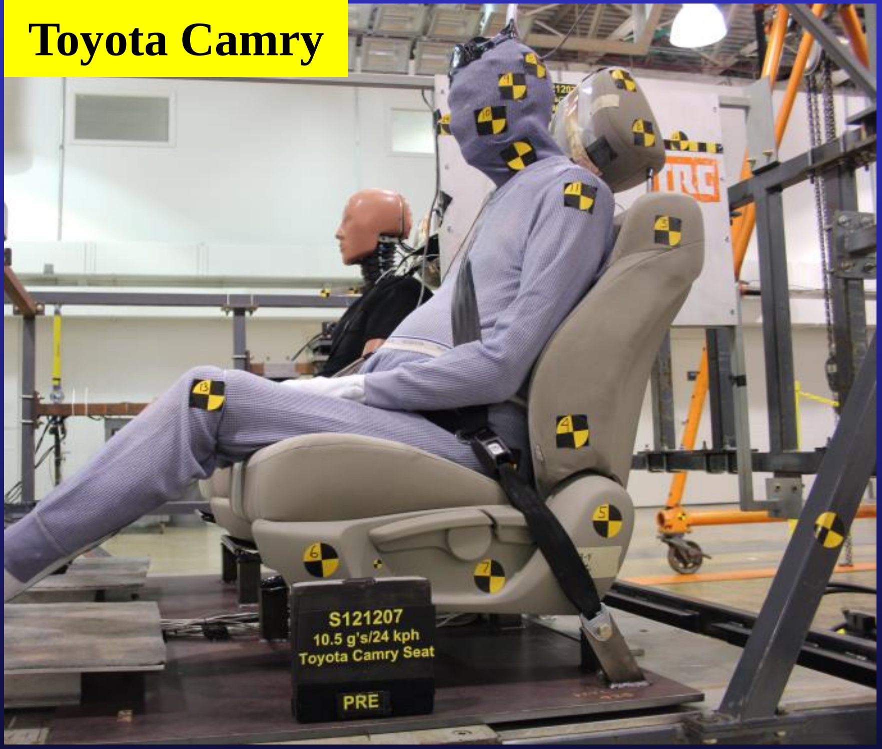
	Seat Type	Input Pulse
PMHS09	Chevy Cruze	FMVSS202a
PMHS10	Chevy Cruze	JNCAP
PMHS11	Toyota Camry	JNCAP
PMHS12	Toyota Camry	24 km/h
PMHS13	Toyota Camry	JNCAP
PMHS14	Chevy Cruze	24 km/h
PMHS15	Toyota Camry	24 km/h

Production Seats

Chevy Cruze

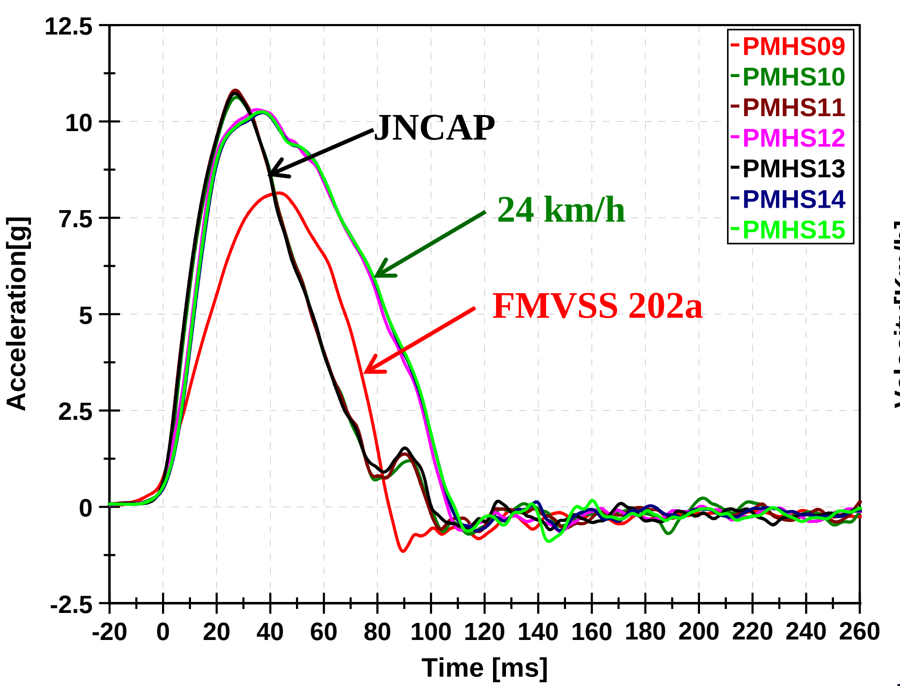


Toyota Camry

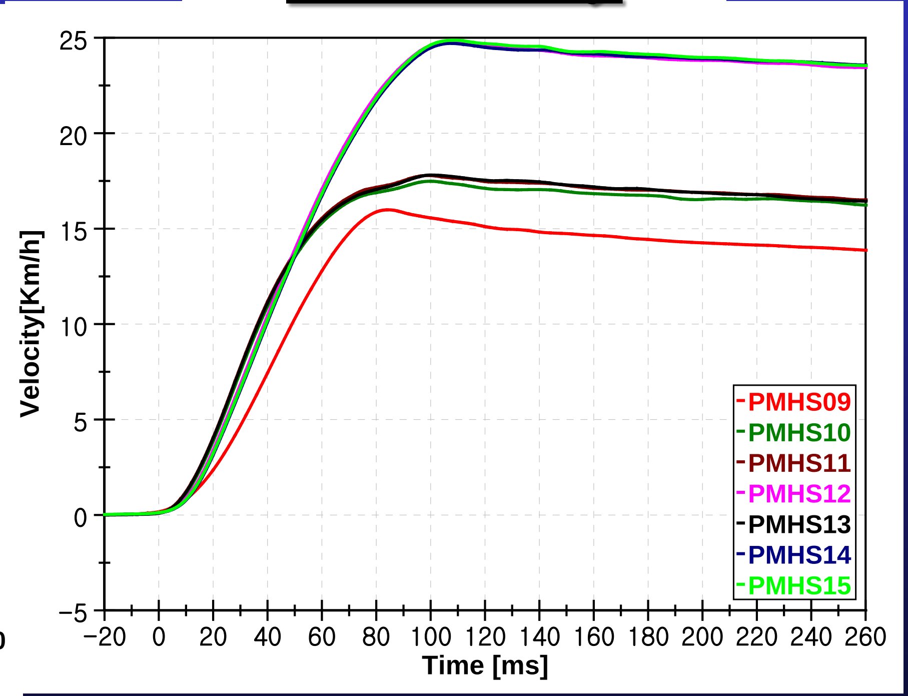


Sled Pulses
Production Seats

Sled Acceleration



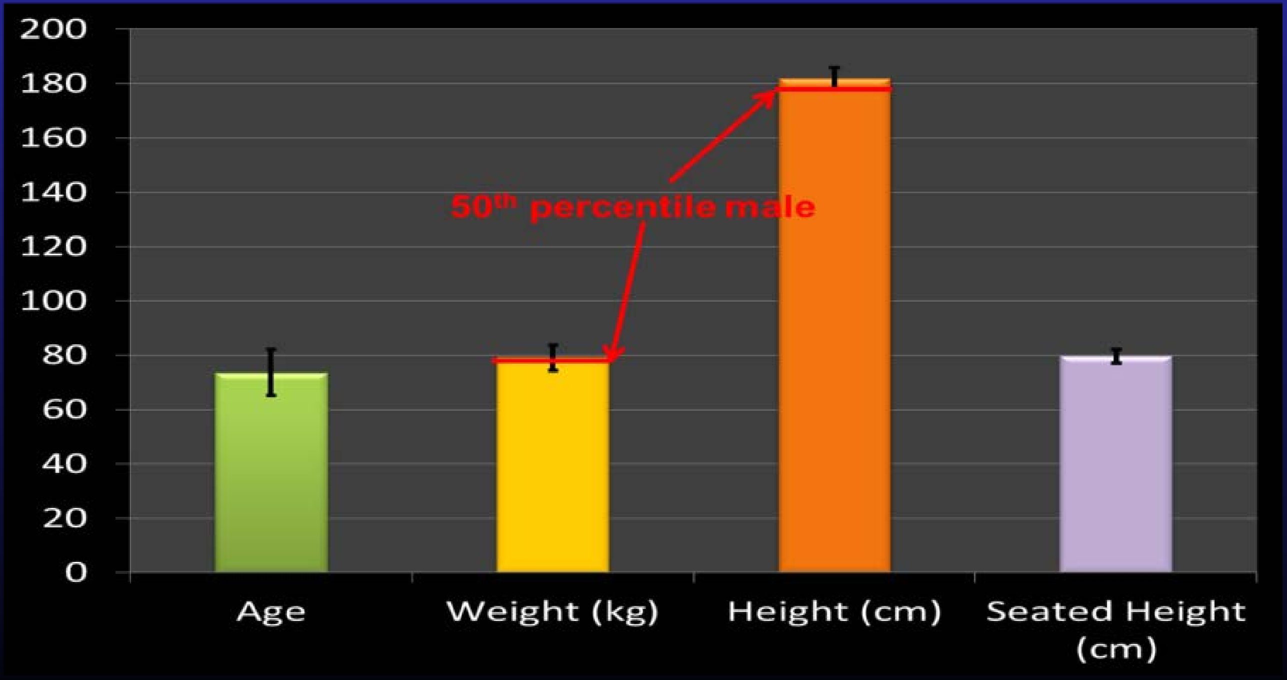
Sled Velocity



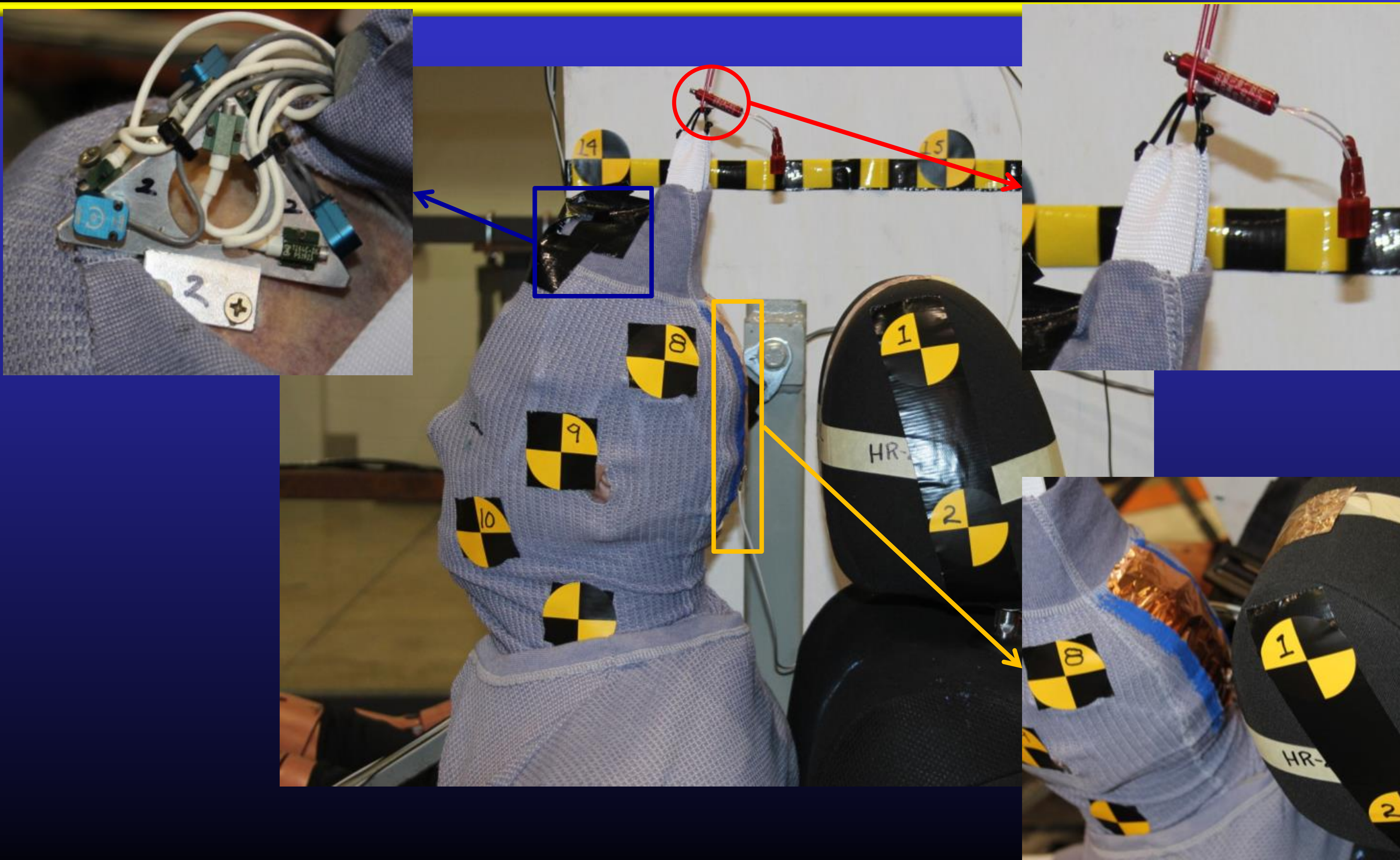
Subject Selection

Production Seats (same as experimental seat)

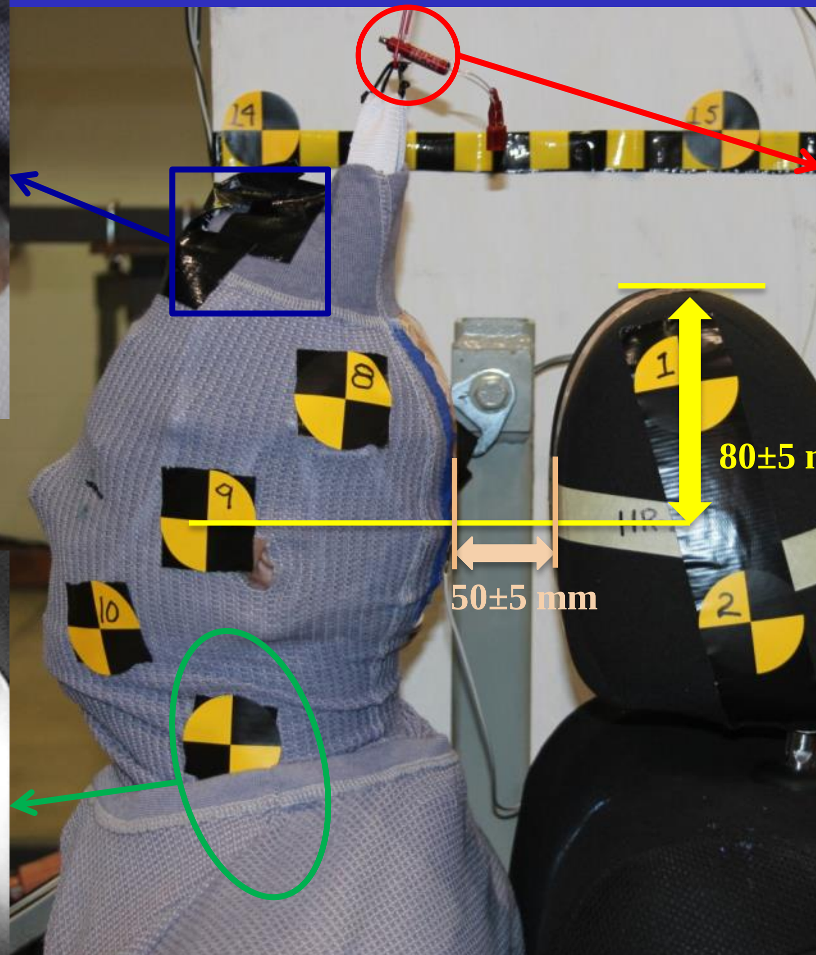
- **Pre CT, DXA scan and fluoroscopy (C-arm)**
  - Excluded severely degenerative disc, osteophytes and previous spinal surgery
- **Seven male subjects (74 ± 8 yo)**

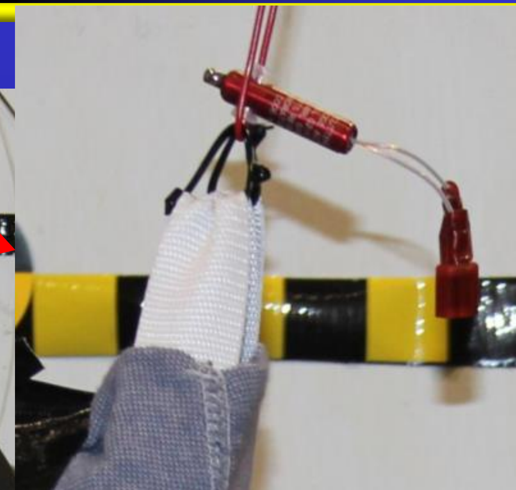


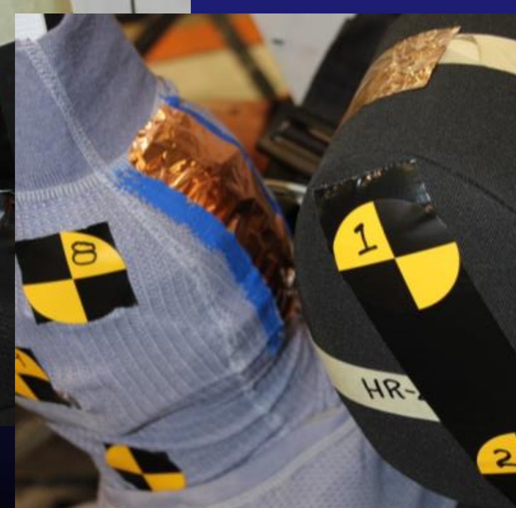
PMHS Instrumentation & Sled Set up



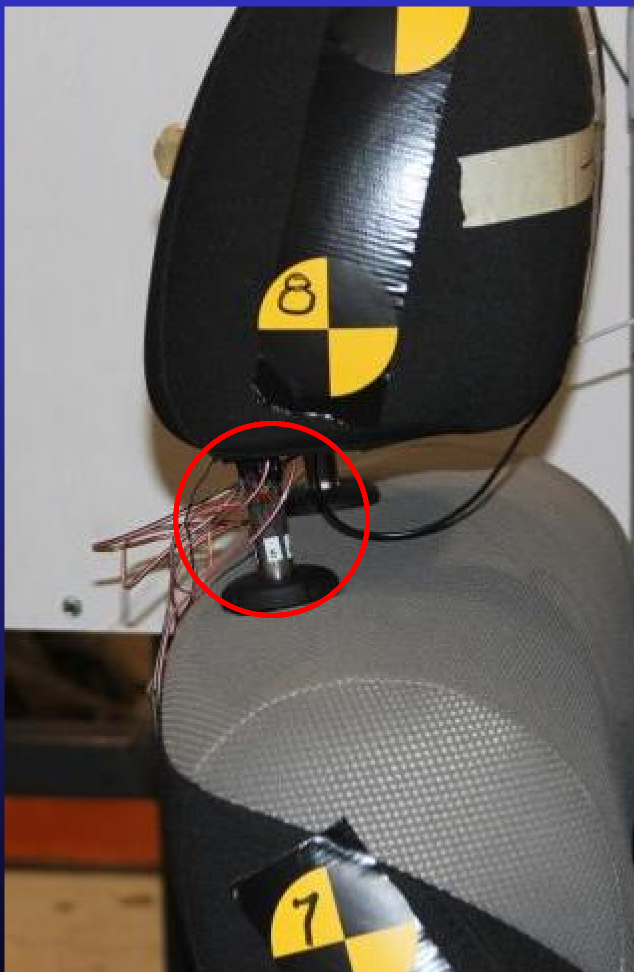
PMHS Instrumentation & Sled Set up



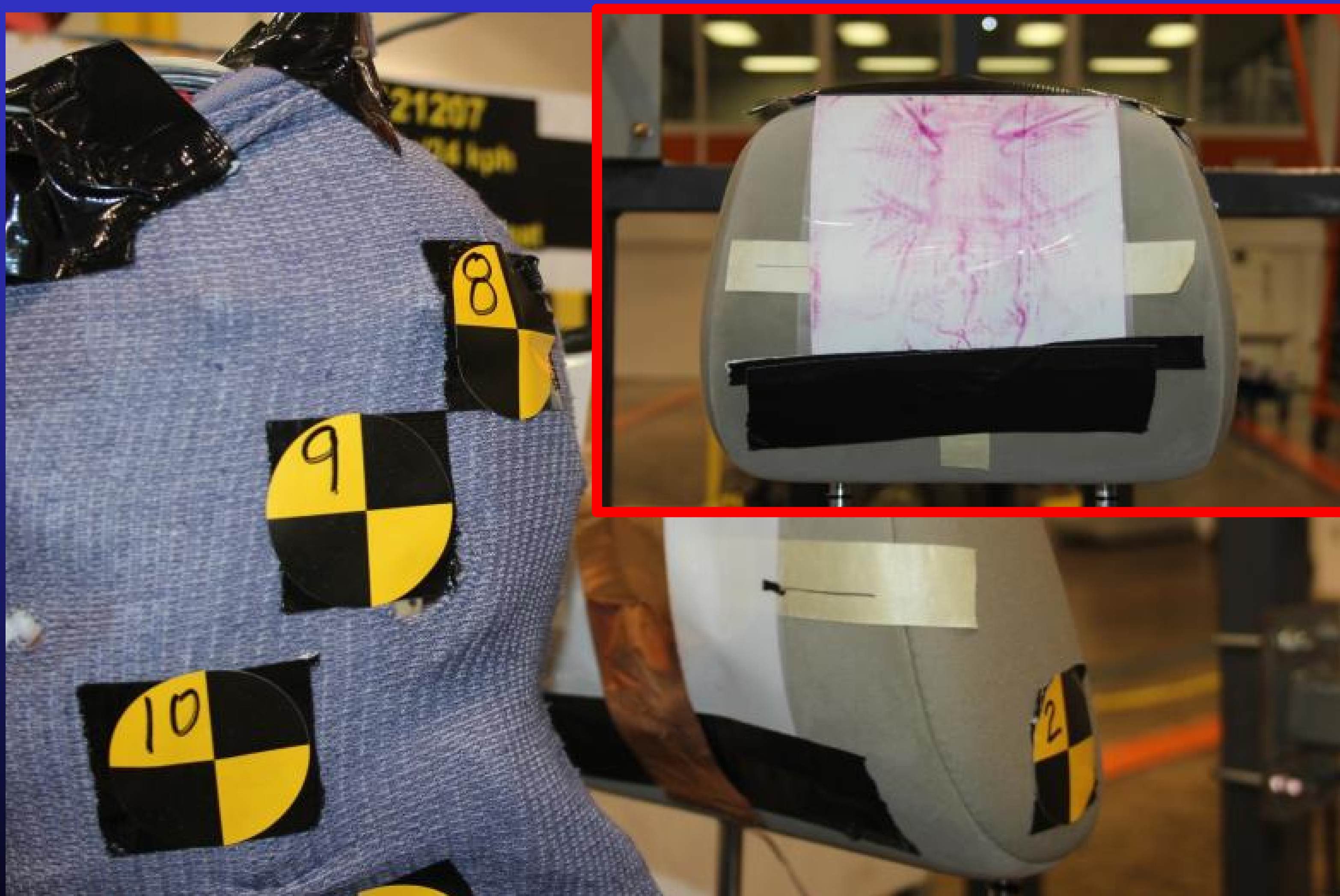




Head Restraint Forces
Production Seat



Head Restraint Forces
Production Seat



PMHS Test Series

High Speed Video

Chevy Cruze
FMVSS 202a
PMHS9

Chevy Cruze
JNCAP
PMHS10

Toyota Camry
JNCAP
PMHS11

Toyota Camry
24 km/h
PMHS12

PMHS Test Series

High Speed Video

Toyota Camry JNCAP

PMHS13

Chevy Cruze 24 km/h

PMHS14

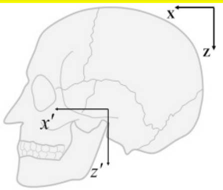
Toyota Camry 24 km/h

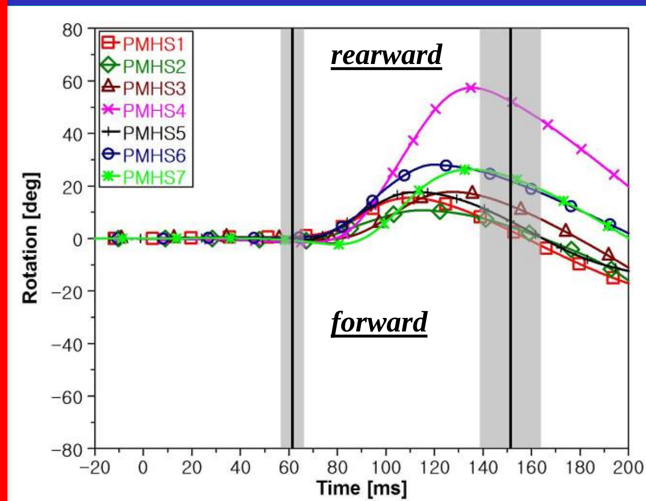
PMHS15

Head and T1 Kinematics

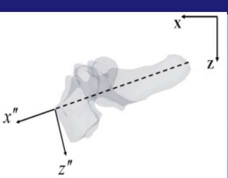
Rotation Y

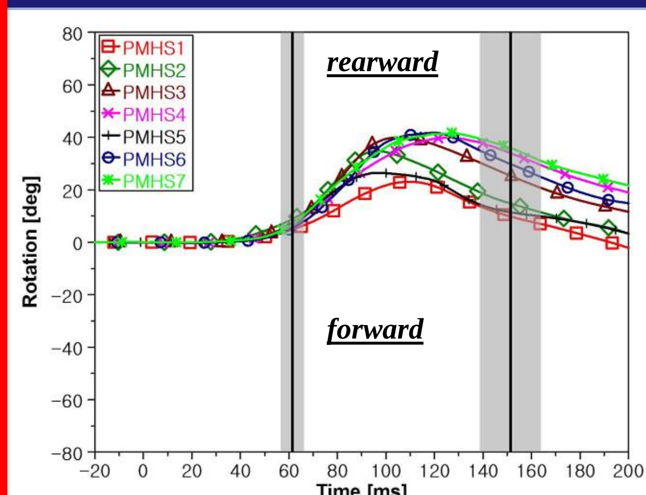
HEAD





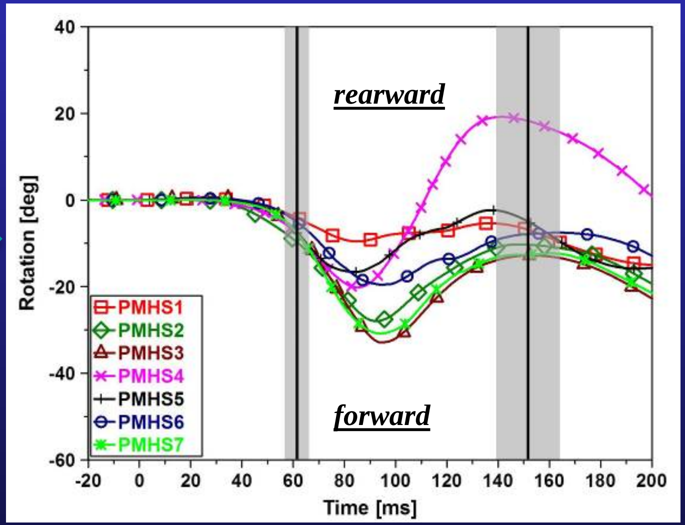
T1



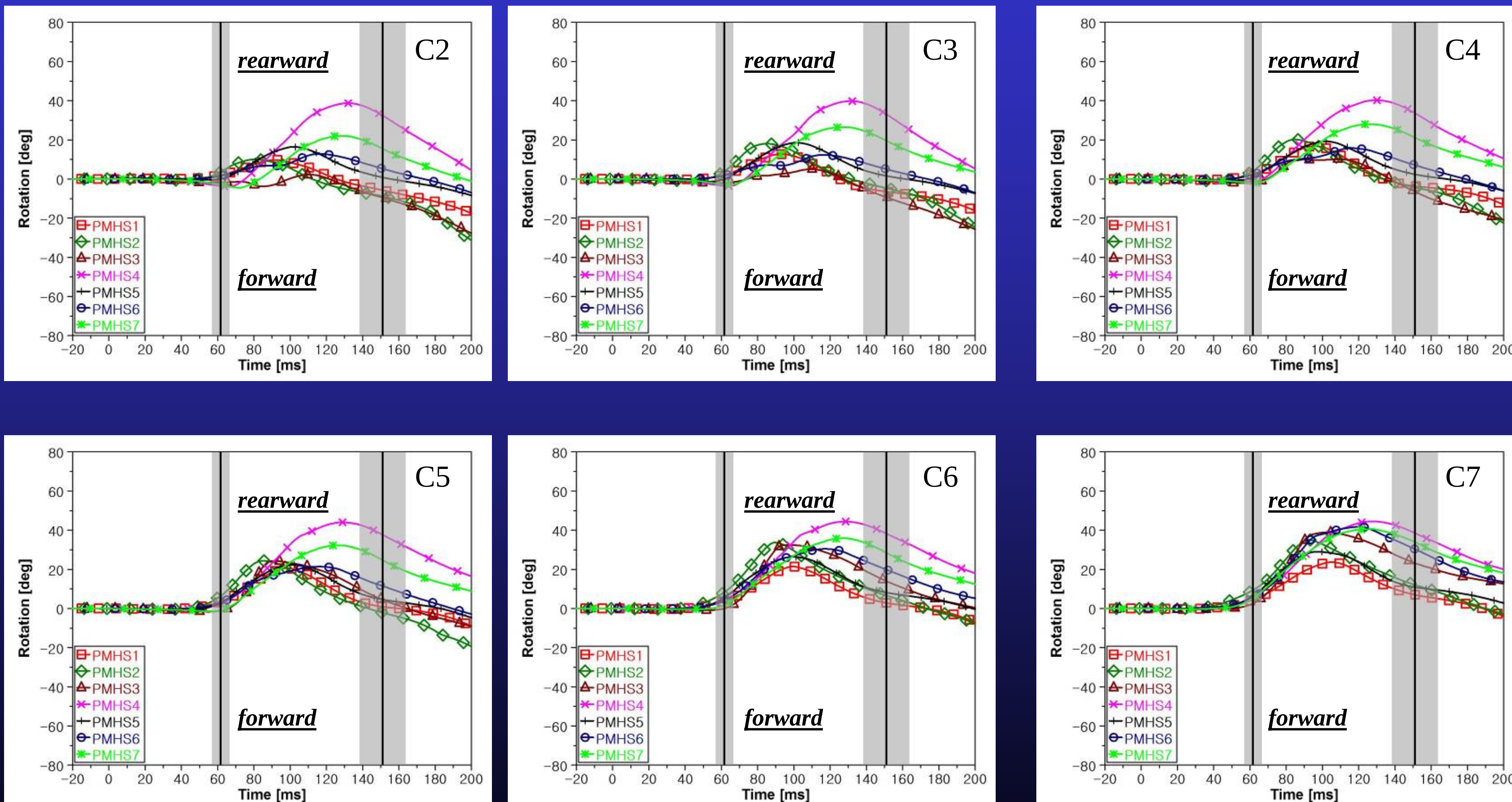


Relative kinematics

Head – T1

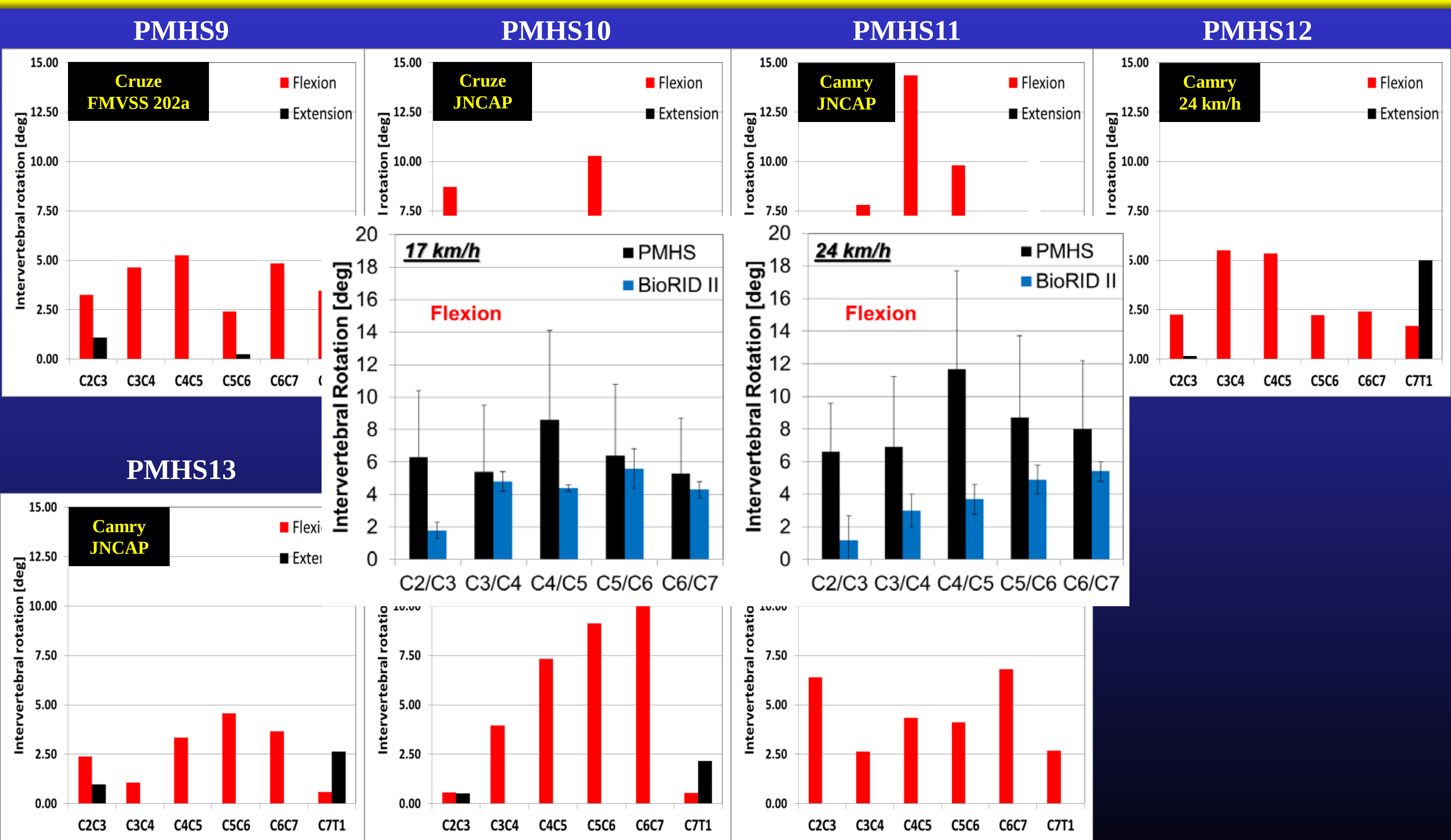


Cervical Spine Kinematics

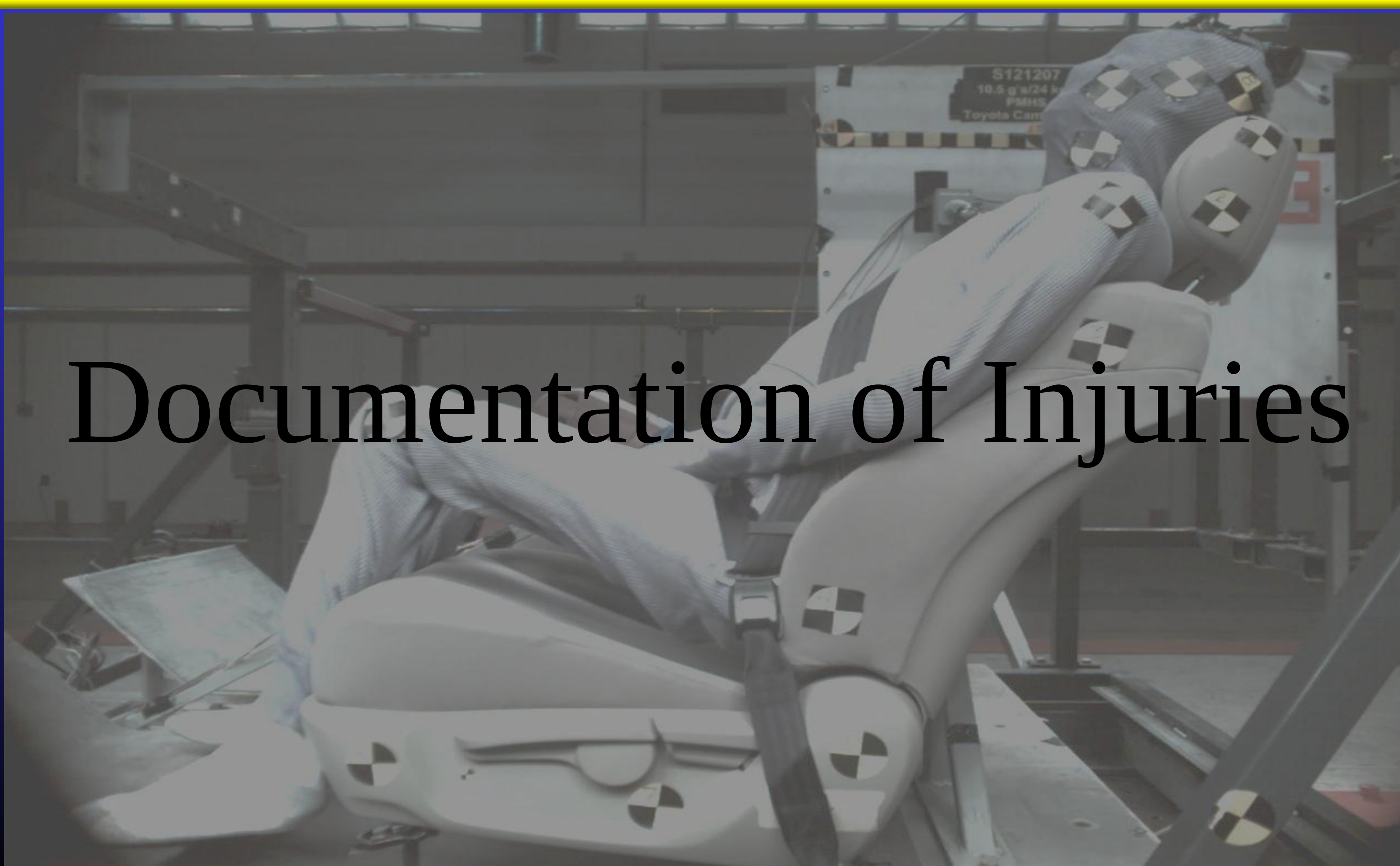


Intervertebral Rotation

Flexion vs. Extension



Documentation of Injuries



Documentation of Injuries
Experimental Seat

Injury Documentation						
	PMHS03	PMHS04	PMHS05	PMHS06	PMHS07	PMHS08
C2/C3			Subluxation			
C3/C4	Subluxation		Subluxation			
C4/C5	Subluxation	Subluxation	Subluxation		Subluxation	
C5/C6		Subluxation	Subluxation	Subluxation		
C6/C7		Subluxation	Subluxation		Subluxation/ligament tear/disc injury	Subluxation

Documentation of Injuries
Production Seat

Injury Documentation							
updated	PMHS09	PMHS10	PMHS11	PMHS12	PMHS13	PMHS14	PMHS15
	FMVSS202	JNCAP	JNCAP	24 km/h	JNCAP	24km/h	24 km/h
C2/C3							Subluxation
C3/C4				Subluxation			
C4/C5	Subluxation		Subluxation	Subluxation			
C5/C6		Subluxation	Subluxation			Subluxation	
C6/C7		Subluxation			Subluxation	Subluxation	Subluxation

Injury Criteria Analysis

PMHS Injury Analysis

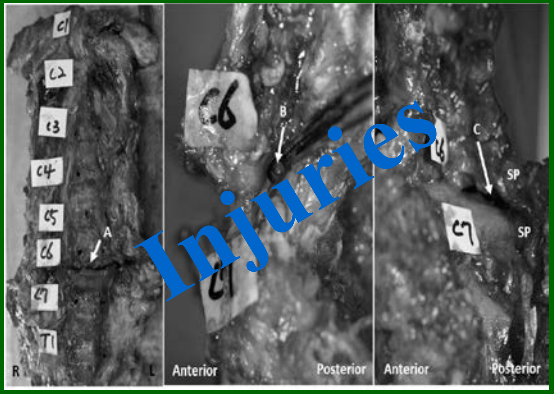
PMHS

Step 1

Intervertebral kinematics

Linear/angular acceleration, velocity, and displacement

Correlation?



Normalization?

Step 2

Best injury predictors

Correlation?

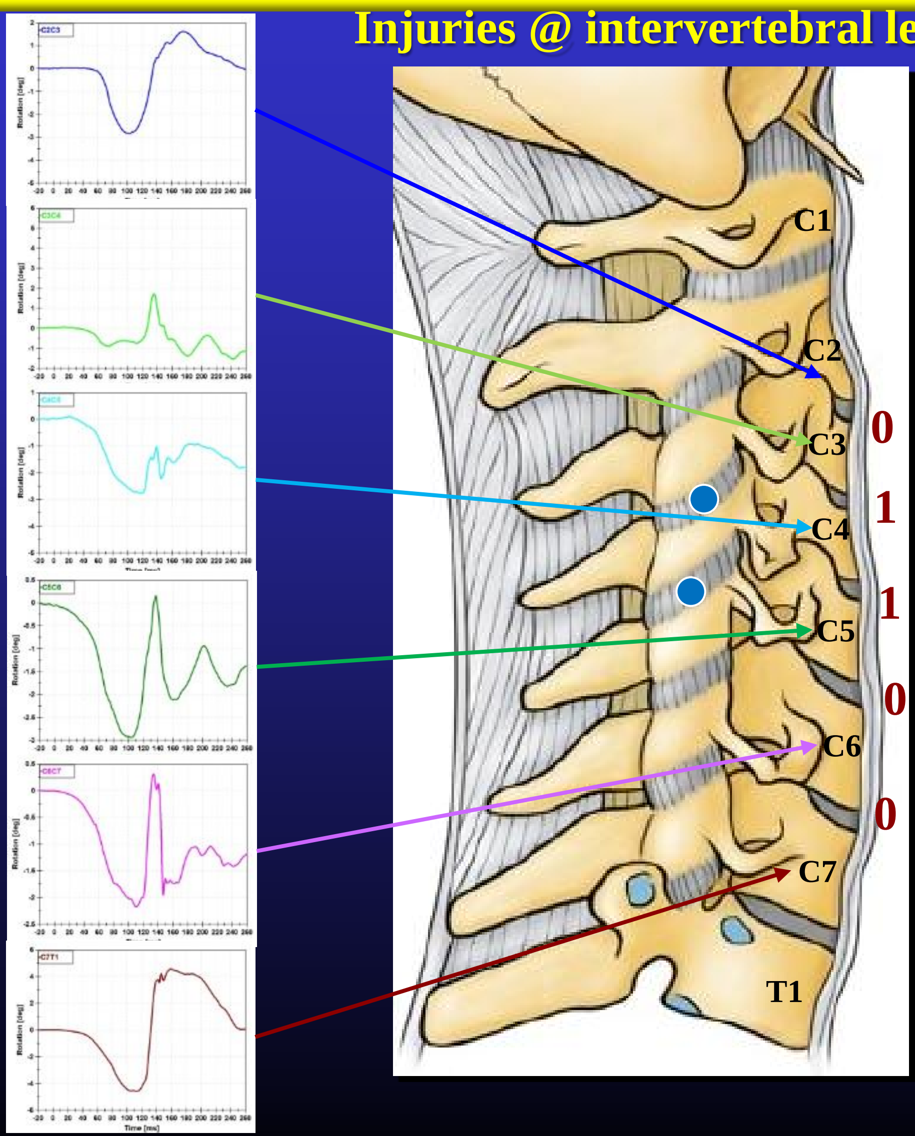
Kinetics/kinematics

Current/potential injury criteria

PMHS Injury Analysis
Injury Risk Curves – Intervertebral Kinematics

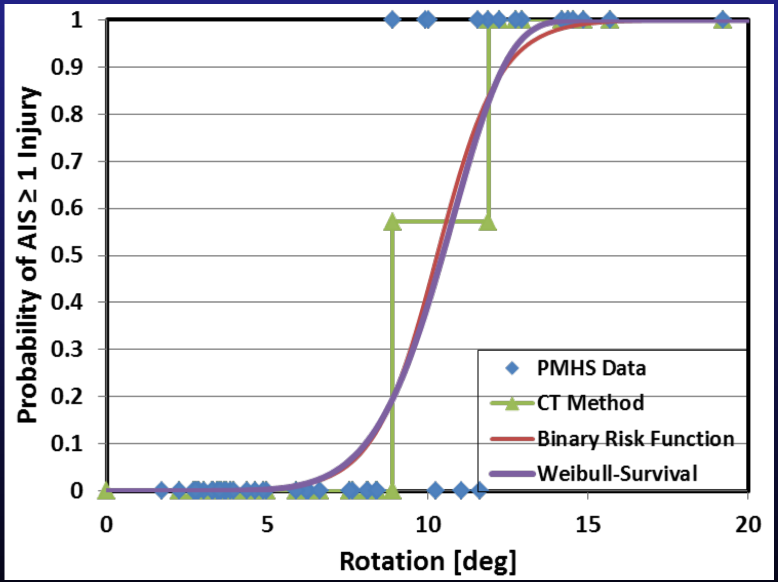
Intervertebral kinematics

Injuries @ intervertebral levels



- C2/C3 – C6/C7: 5 levels
- 5 data points per test
- n =~35

Injury Risk Curves



PMHS Injury Analysis

Injury Risk Curves – Intervertebral Kinematics Production Seats Only

Intervertebral kinematics		Log-Likelihood P-value	Goodman-Kruskal Gamma	AUROC
Acceleration x	(+)	0.026	0.54	0.77
	(-)	0.531	0.17	0.58
	Max	0.038	0.54	0.77
Acceleration z	(+)	0.016	0.46	0.73
	(-)	0.003	0.60	0.80
	Max	0.001	0.62	0.81
Velocity x	(+)	0.477	0.23	0.61
	(-)	0.132	0.33	0.66
	Max	0.104	0.35	0.67
Velocity z	(+)	0.531	0.21	0.59
	(-)	0.447	0.10	0.54
	Max	0.395	0.19	0.59
Angular velocity y	(+)	0.323	0.14	0.56
	(-)	0.003	0.53	0.77
	Max	0.002	0.56	0.78
Rotation y	(-)	**0.000**	**0.76**	**0.88**
Facet JT Slide	(+)	0.058	0.40	0.70
Facet JT Slide Rate	Max	0.083	0.36	0.70
Facet JT Axial	Max	0.005	0.59	0.70
Facet JT Axial Rate	(-)	0.001	0.66	0.83
(+) : positive peak, (-): negative peak, Max: maximum peak				

P-value < 0.005 , Goodman-Kruskal Gamma > 0.7 (yellow)

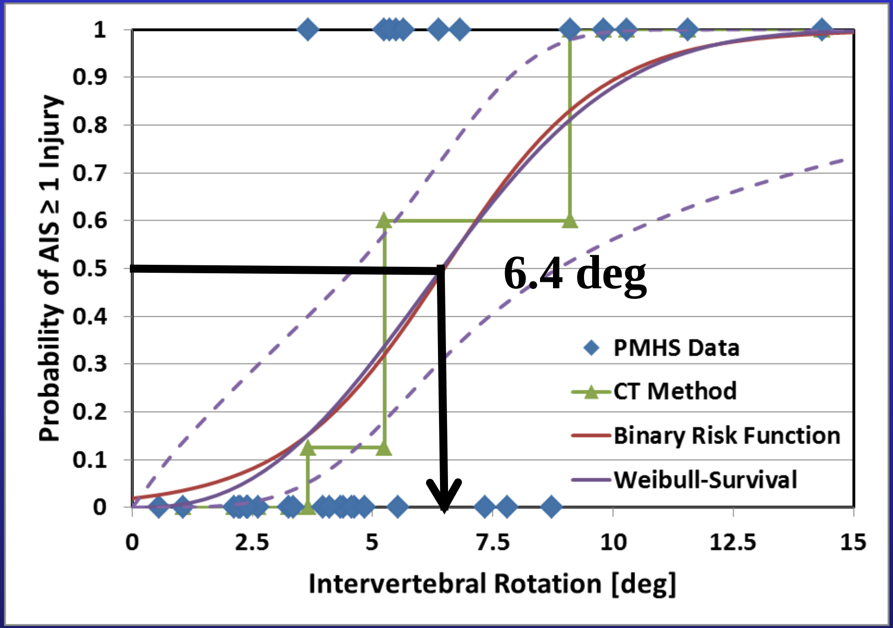
Best correlation and prediction (green)

AUROC

- 0.9-1.0 : excellent
- 0.8-0.9 : good
- 0.7-0.8 : fair
- 0.6-0.7 : poor
- 0.5-0.6 : fail

PMHS Injury Analysis

Injury Risk Curves – Intervertebral Kinematics
Production Seats Only



Intervertebral Rotation	Log-Likelihood P-value	Goodman-Kruskal Gamma	AUROC
Intervertebral Rotation y	0.000	0.76	0.88

PMHS Injury Analysis

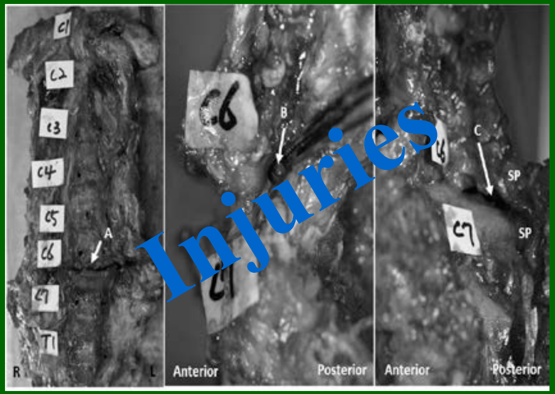
PMHS

Step 1

Intervertebral kinematics

Linear/angular acceleration, velocity, and displacement

Correlation?



$$IV-NIC_i = \frac{\Theta_{trauma,i}}{\Theta_{physiological,i}}$$

Step 2

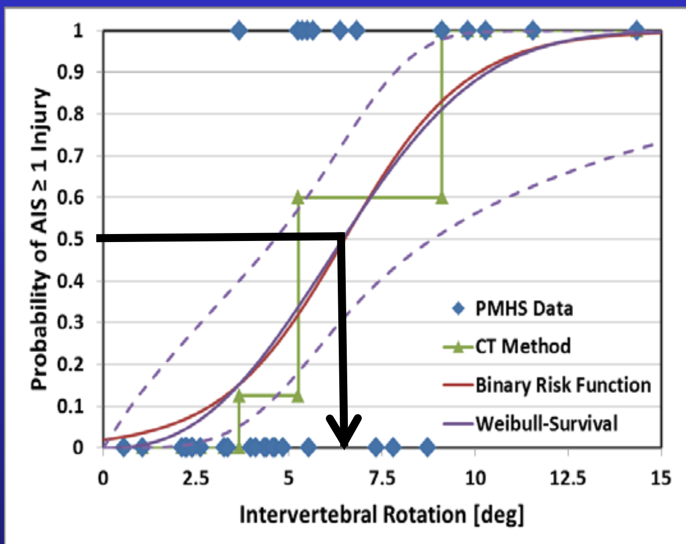
Best injury predictors

Correlation?

Kinetics/kinematics

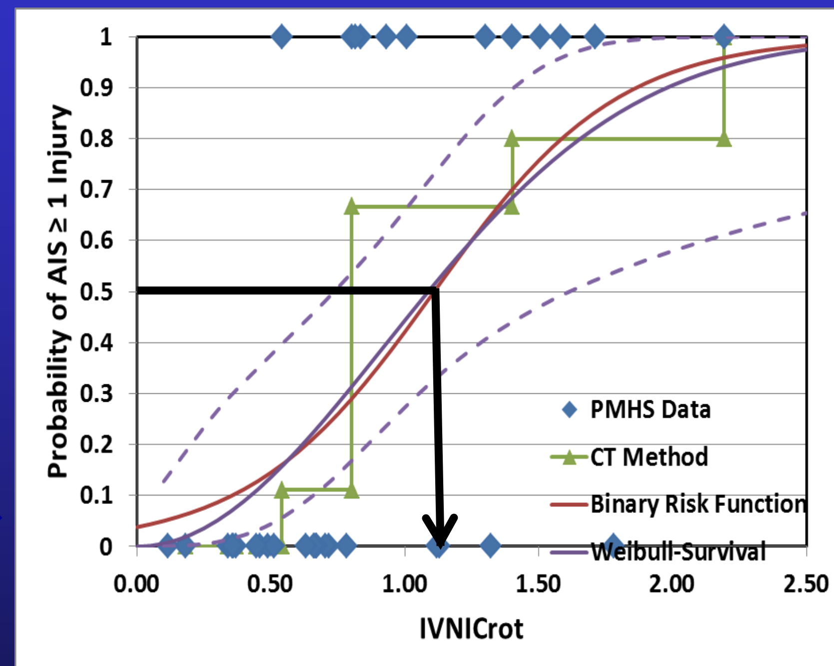
Current/potential injury criteria

PMHS Injury Analysis
Injury Risk Curves – IV-NICrot
Production Seats Only



6.4 deg rotation

$$IV - NIC_i = \frac{\Theta_{trauma,i}}{\Theta_{\text{physiological},i}}$$



IV-NIC = 1.1

Normalized Intervertebral Rotation	Log-Likelihood P-value	Goodman-Kruskal Gamma	AUROC
IVNICrot	0.001	0.71	0.86

PMHS Injury Analysis

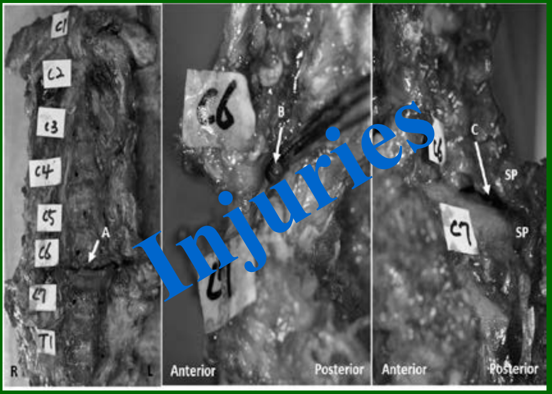
PMHS

Step 1

Intervertebral kinematics

Linear/angular acceleration, velocity, and displacement

Correlation?



Normalization?

Step 2

Best injury predictors

Correlation?

Kinetics/kinematics

Current/potential injury criteria

PMHS Injury Analysis
IV-NIC vs. Current/Potential Injury Criteria

- **Correlation between IV-NIC rotation and existing injury criteria**

$$IV - NICrot$$

Correlation?

$$NIC = 0.2 \times a_{rel} + v_{rel}^{2}$$

$$N_{km} = \frac{F_x}{F_{int}} + \frac{M_y}{M_{int}}$$

$$LNL - index(t) = \left| \frac{\sqrt{My_{lower}(t)^2 + Mx_{lower}(t)^2}}{C_{moment}} \right| + \left| \frac{\sqrt{Fx_{lower}(t)^2 + Fy_{lower}(t)^2}}{C_{shear}} \right| + \left| \frac{Fz_{lower}(t)}{C_{tension}} \right|$$

NDC, Nij
Head-to-T1 Rotation
Upper/Lower Fx, Fz, My
Other physical parameters

Yes

Potential PMHS/BioRID Injury Criteria

PMHS Injury Analysis
IV-NIC vs. Kinematic Criteria

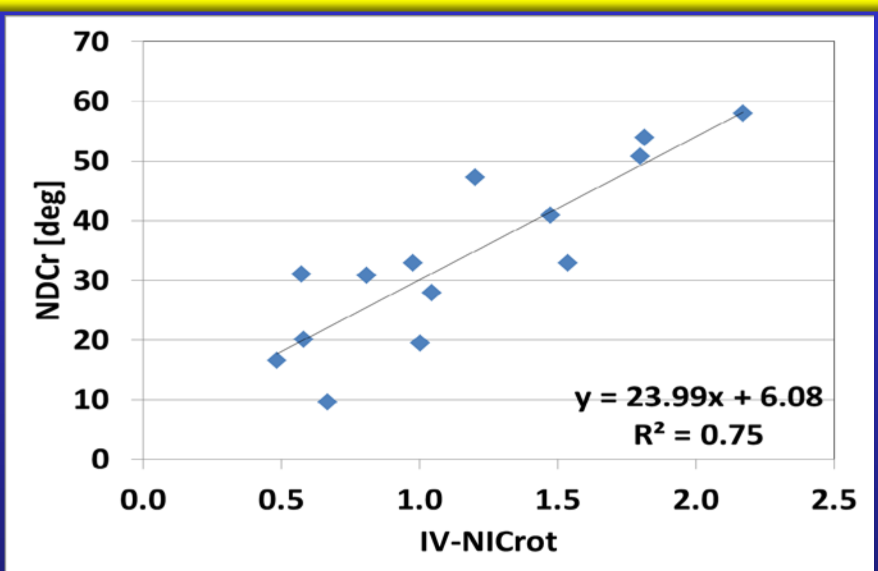
Experimental Seat

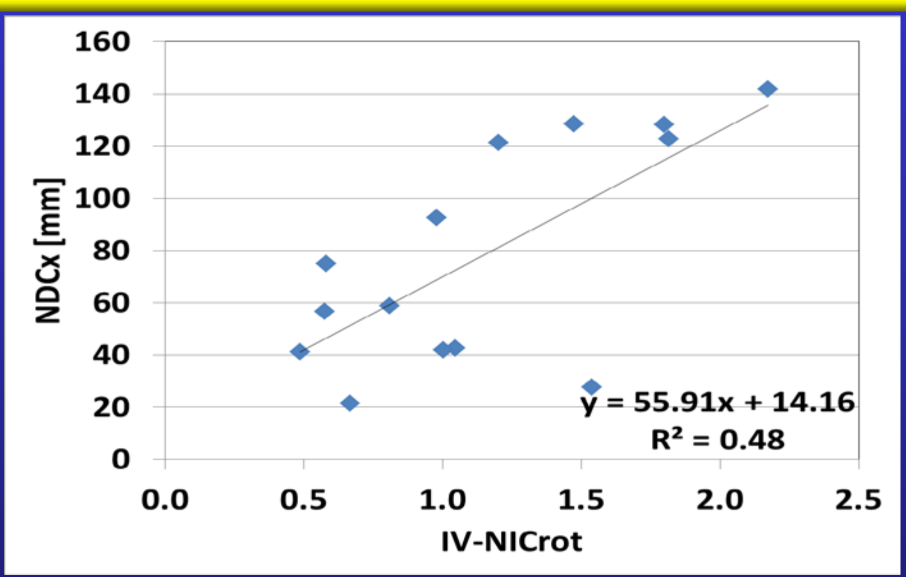
	IV-NICrot
	R^2 - value
NDCrot	0.86
NDCx	0.82
NIC	0.50

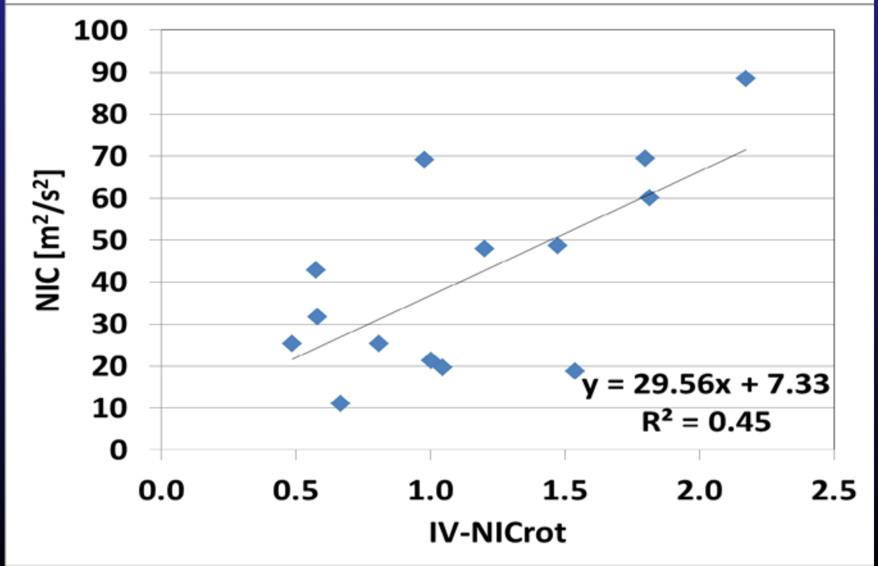
Combined Exp/Prod Seats

	IV-NICrot
	R^2 - value
NDCrot	0.75
NDCx	0.48
NIC	0.45

PMHS Injury Analysis
IV-NIC vs. Kinematic Criteria







- **50 % chance of AIS 1+ injuries**
  - **IV-NICrot : 1.1**
  - **NDCrot : 32.5 deg (flexion)**
  - **NDCx: 75.1 mm**
  - **NIC: 39.6 m^2/s^2**

Summary

- **Best PMHS injury predictor**
  - IV-NICrot
    - 50% chance of AIS 1+ injury = 1.1

- **Most promising BioRID injury criteria**
  - IV Rotation, NDCrot
    - 50% chance of AIS 1+ injury:
      - IV Rotation = 6.4 deg (flex) PMHS
        NDCrot = 32.5 deg (flex) PMHS

USA & Japan Collaboration

NHTSA NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION

- **Best injury predictor**
  - USA → IV-NICrot
  - Japan → IV-NICrot (well correlated with Strain & Strain Rate)
- **Potential "global" injury criteria**
  - USA: IV-NICrot → NDCrot, NDCx, NIC
  - Japan: IV-NICrot → NIC, UNFx, UNMy, LNFx, LNMy
- **Common ground:**
  - NIC
  - USA: Investigated UNFx, UNMy, LNFx, LNMy, Nkm
    - Inverse Dynamics not reliable after HR contact – see next slide
      - Use direct correlation of BioRID measures??
  - Japan: Investigated NDCrot, NDCx (well correlated to WAD2+)

Head Restraint Forces
Production Seats

- **Inherent issues with HR Contact Force Estimation**
  - Force of head contact is perpendicular to HR (x-direction)
    - No axial loading on the HR
    - Predicted HR force is very sensitive to HR contact height
    - Assumptions inherent to inverse dynamics analysis

Head Restraint Forces
Production Seats

- **Analysis of BioRID HR contact force versus Fx skull cap load**

Head Restraint Forces
Production Seats

- **Analysis of BioRID HR contact force versus Fx skull cap load**
  - Match for only 2 out of 7 tests
    - Large Fz skull cap (as much as 50% of Fx)
  - Algorithm to compensate strain gages for axial HR loads
    - 5 out of 7 tests matched

Head Restraint Forces
Production Seats

- **Analysis of BioRID HR contact force versus Fx skull cap load**
  - Match for only 2 out of 7 tests
    - Large Fz skull cap (as much as 50% of Fx)
  - Algorithm to compensate strain gages for axial HR loads
    - 5 out of 7 tests matched
- **PMHS → no way to estimate axial contribution**
  - Assume same Fz/Fx ratio as BioRID for given test condition
  - Apply compensation algorithm
  - Recalculate upper/lower neck loads
  - Still no good correlations

USA & Japan Collaboration

- **BioRID Injury Criteria**
  - USA:
    - Approach: Experimental
      - Direct link to PMHS injury
      - Incorporates BioRID response through paired testing
  - Japan:
    - Approach: Head/neck model, Volunteer testing, accident reconstruction
      - Allows for calculation of Strains/Forces/Moments
      - Measures from model applied directly to BioRID
  - Merge two methods to agree on appropriate criteria

Future Work and outlying questions

- **Conduct paired BioRID/Hybrid III sled tests**
  - 2) Extension tests → NDCrot criterion developed in production seats is flexion only
    - Use modified Chevy Cruze seat to create large backsets
    - All three pulses
    - 12 deg Hybrid III extension = ?? deg BioRID

Future Work and outlying questions

- **Certify and upgrade BioRID dummies**
  - Incorporate design changes that improved reproducibility
  - Ensure these dummies represent the future regulatory tool

- **1) Re-run 5 injury criteria sled tests (using both BioRIDs)**
  - Conduct all 5 tests in one week
  - Refine injury criteria numbers
    - Improve direct correlations and intervertebral kinematics?
  - Two dummies to check reproducibility
  - Seats: Chevy Cruze and Toyota Camry (same as PMHS tests)

Future Work and outlying questions

- **Conduct paired BioRID/Hybrid III sled tests**
  - 3) Small-scale fleet assessment
    - Compare 202a criteria with HyIII to proposed BioRID criteria
    - All three pulses
    - Variety of seats (including active or re-active HR)
      - Chevy Cruze
      - Toyota Camry
      - Toyota Matrix
      - Ford F150
      - Honda Odyssey re-active HR seat (mechanically-induced)

Questions??