



GTR 9 Informal Working Group
March 19, 2012
London



Preliminary PMHS Injury Risk Curves & Potential IARVs in Rear Impact

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NHTSA

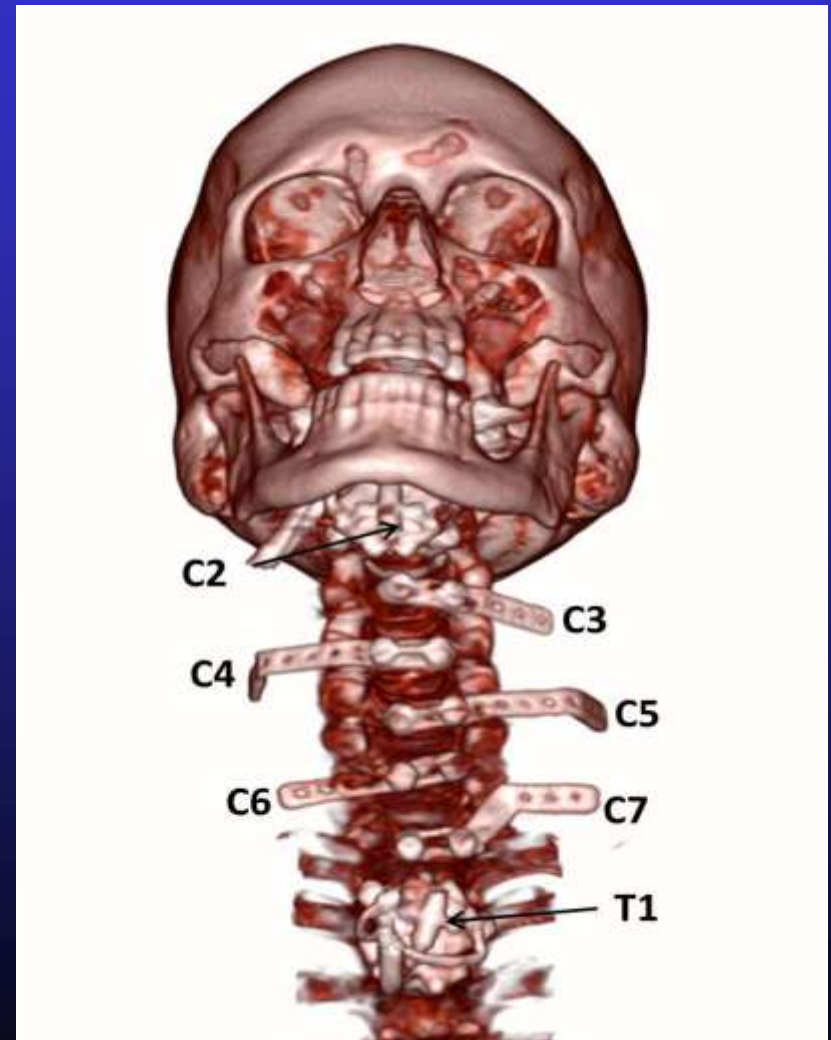
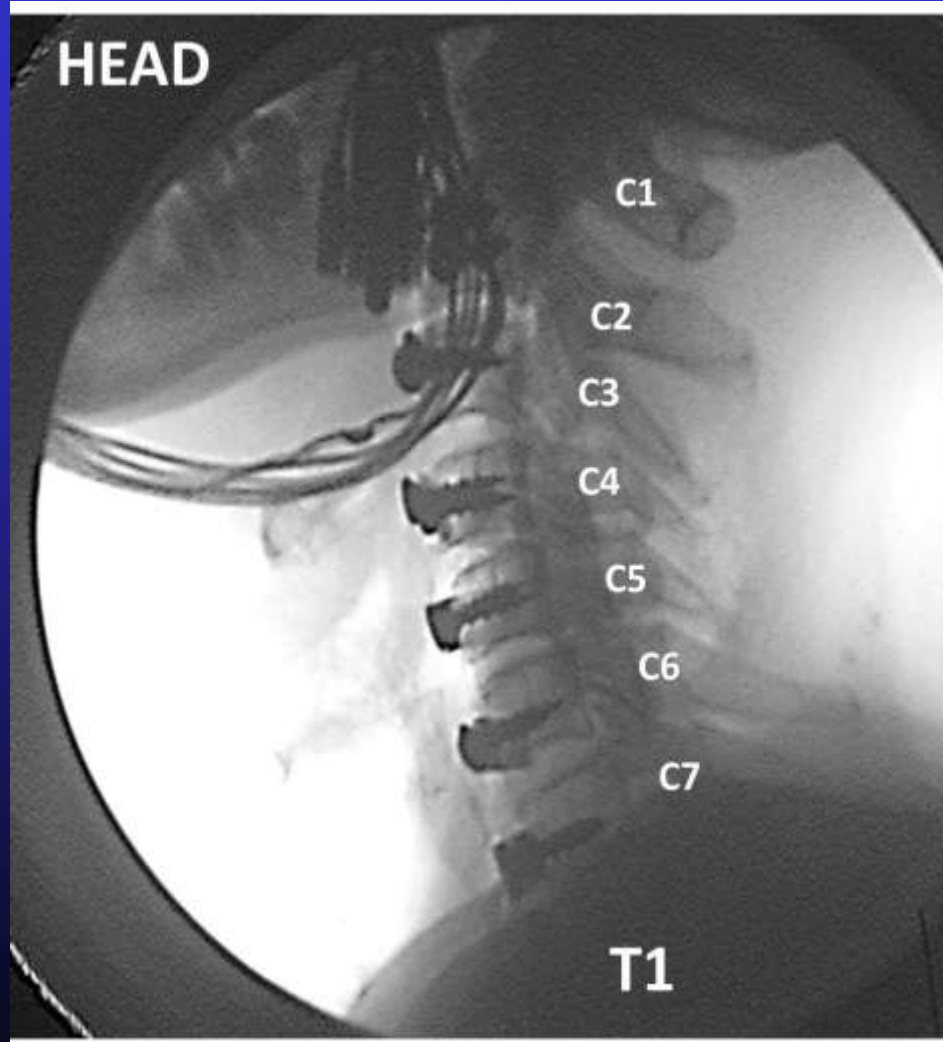


Rear Impact Research Objectives

- **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
- **Choose appropriate injury criterion**
 - Assess efficacy of various ICs

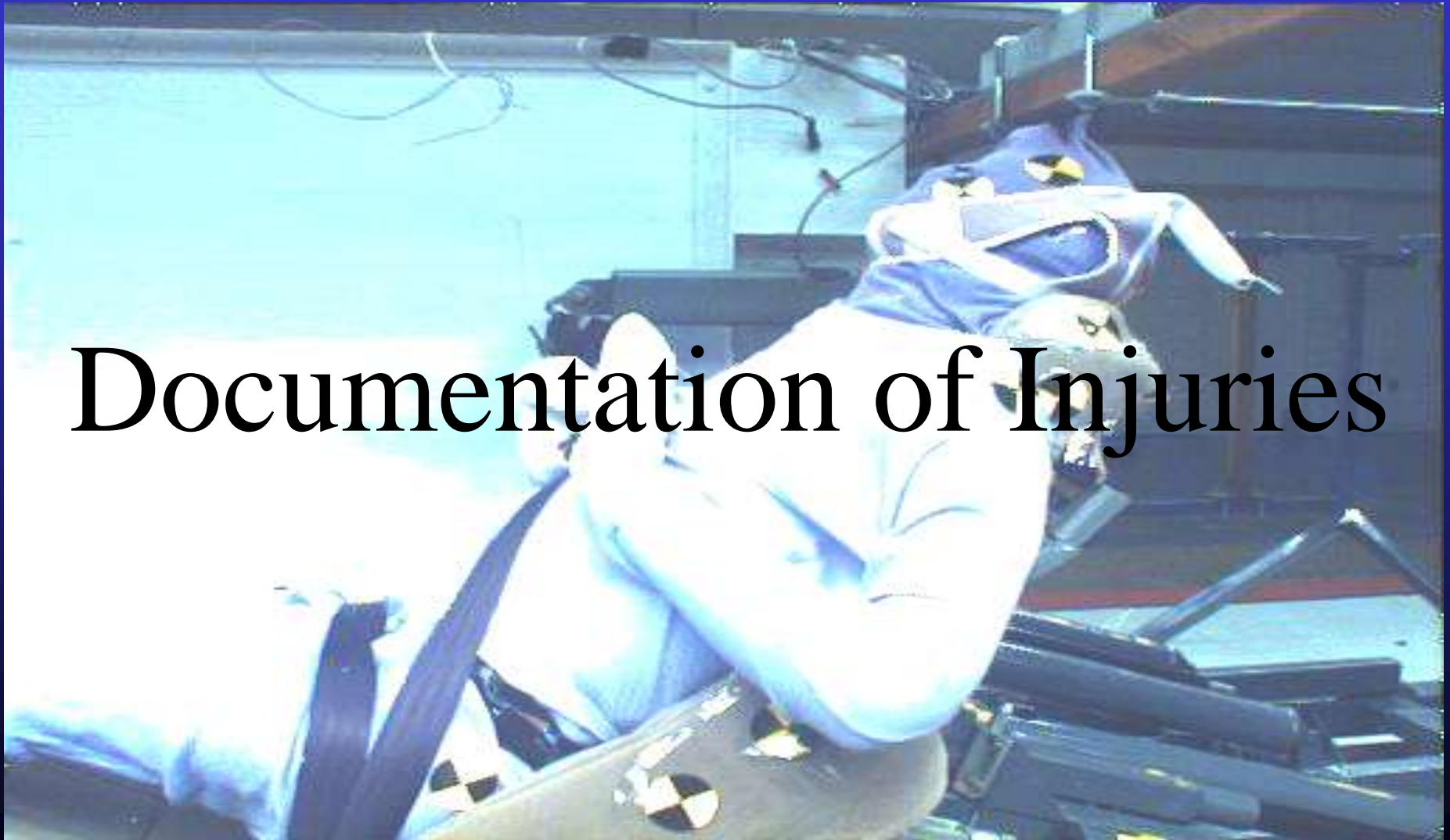


Rear Impact Injury Mechanism





Documentation of Injuries

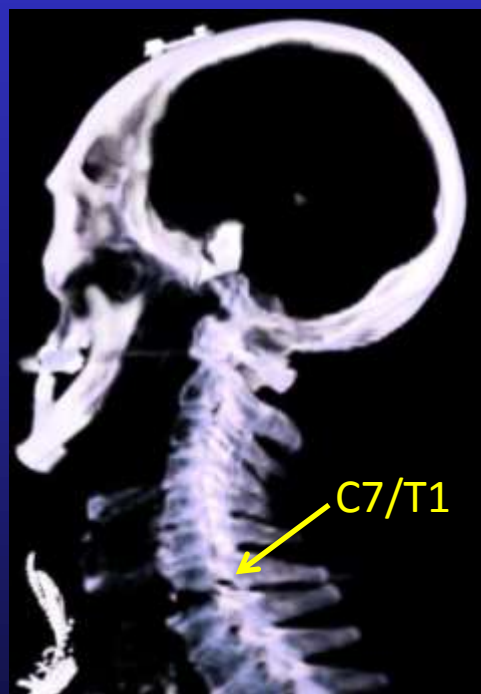




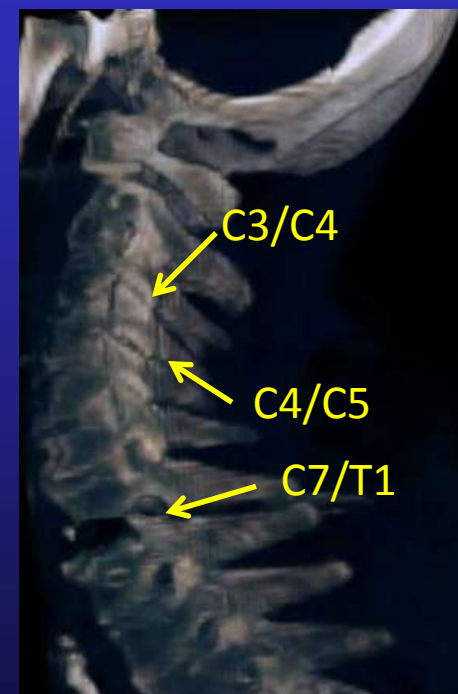
Injury Examples (Post-test CT)



<CT sagittal
view>



<Disc rupture w
fracture>



<Facet
joint>

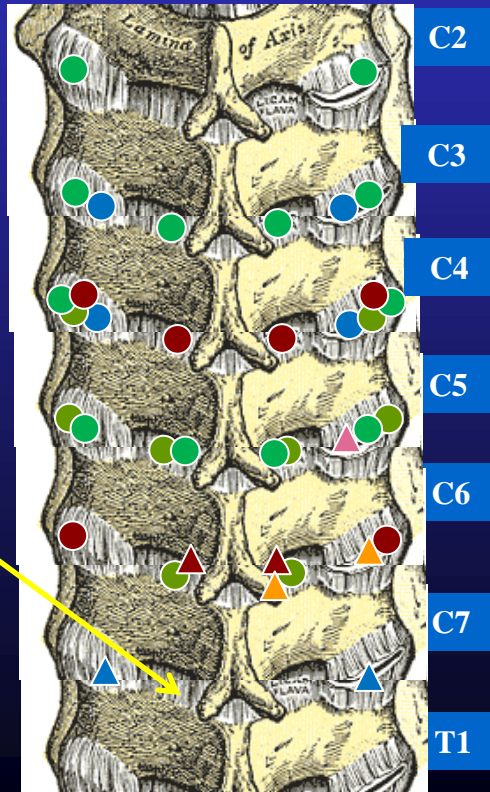


Documentation of Injuries

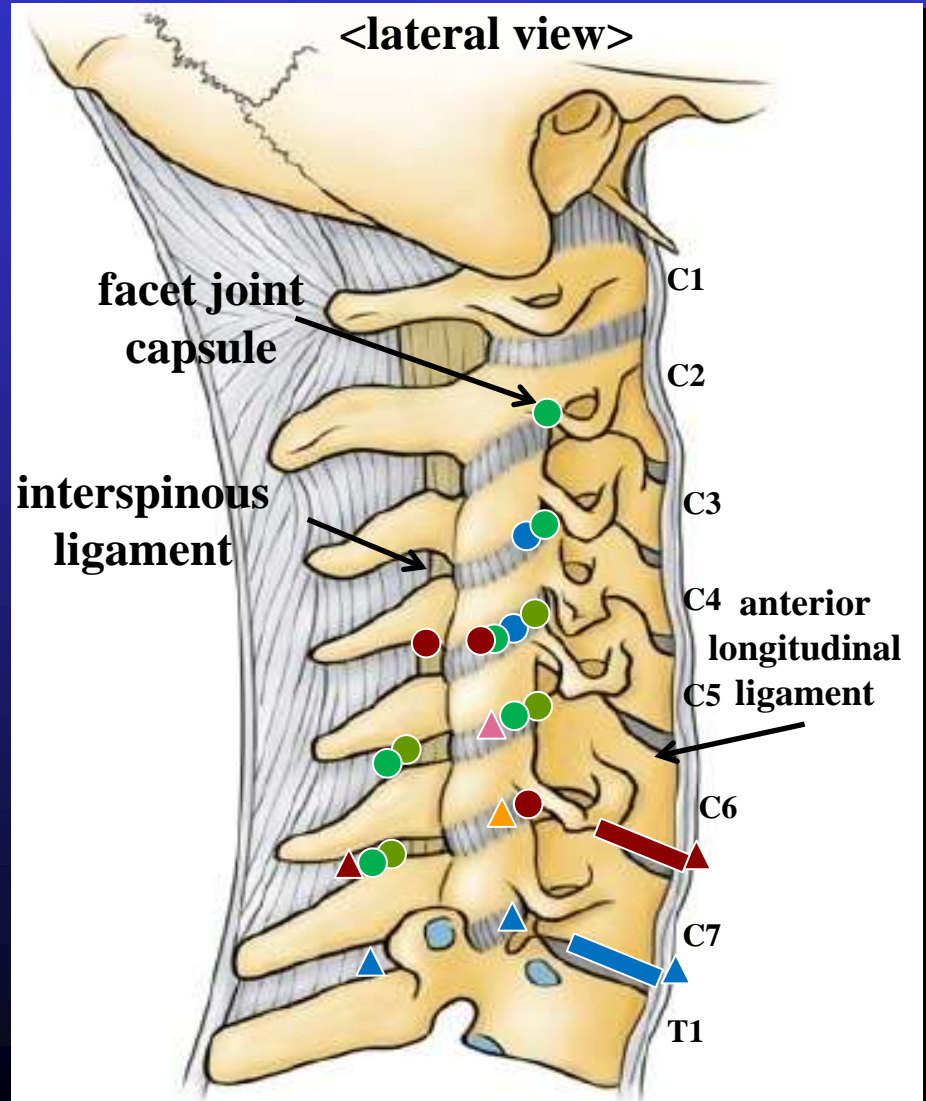
- : disc rupture
- : subluxation (likely represents WAD)
- ▲ : laceration (tear)

PMHS03
PMHS04
PMHS05
PMHS06
PMHS07
PMHS08

<posterior view>



ligamentum flavum



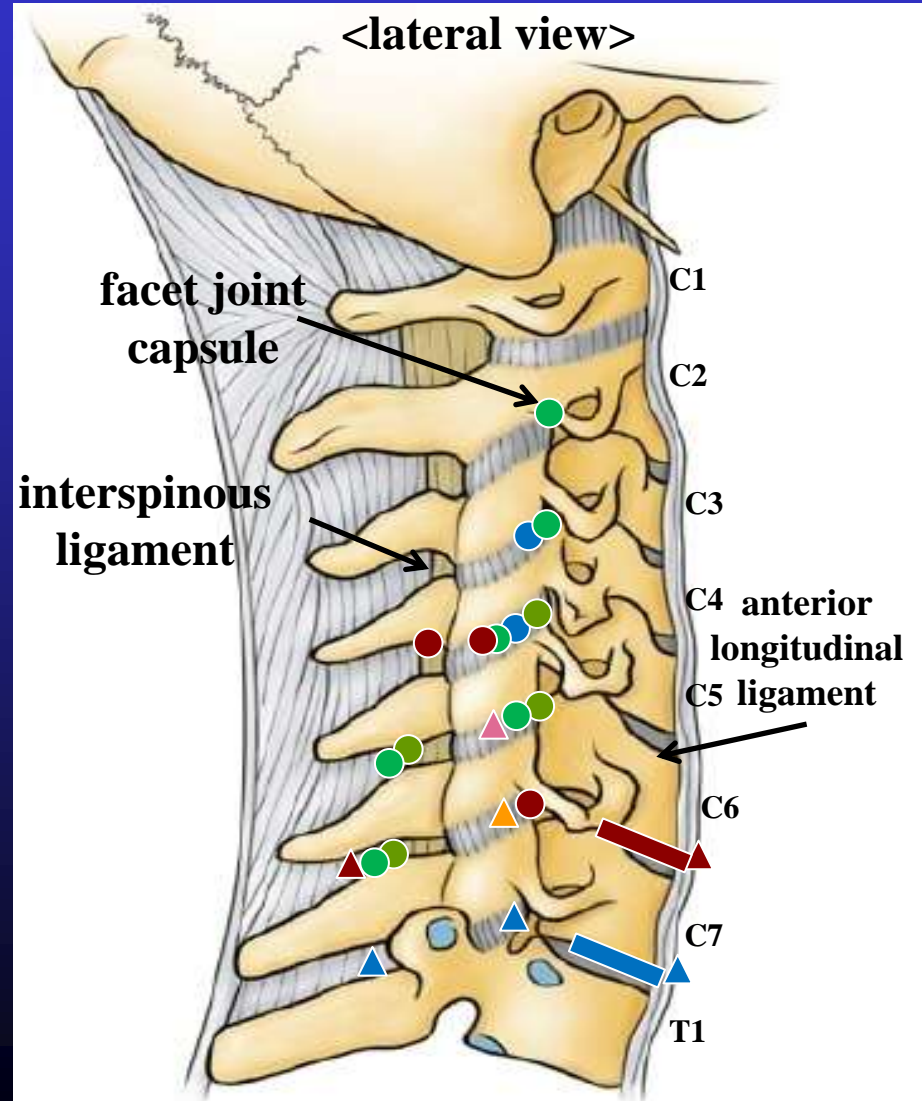
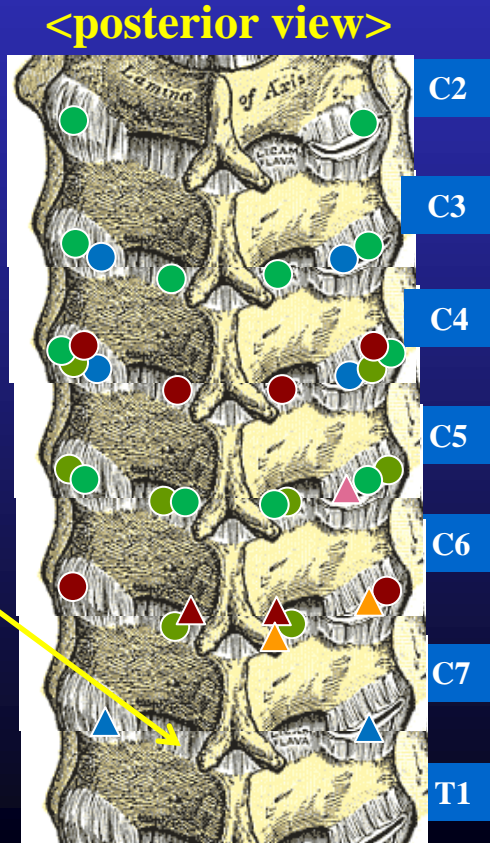


Documentation of Injuries

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

PMHS03
PMHS04
PMHS05
PMHS06
PMHS07
PMHS08

ligamentum flavum





Documentation of Injuries

PMHS	#1	#2	#3	#4	#5	#6	#7	#8
C2/C3	No injury	No injury	No injury	No injury	Subluxation bilateral@ FJ (AIS3)	No injury	No injury	No injury
C3/C4	No injury	No injury	Subluxation bilateral@ FJ (AIS3)	No injury	Subluxation bilateral@ FJ (AIS3) and ligamentum flavum (AIS1)	No injury	No injury	No injury
C4/C5	No injury	No injury	Subluxation bilateral@ FJ (AIS3)	Subluxation bilateral@ FJ (AIS3)	Subluxation bilateral@ FJ (AIS3)	No injury	Subluxation bilateral@ FJ (AIS3) and ligamentum flavum/interspinous lig(AIS1)	No injury
C5/C6	No injury	No injury	No injury	Subluxation bilateral@ FJ (AIS3) and ligamentum flavum/interspinous lig(AIS1)	Subluxation bilateral@ FJ (AIS3) and ligamentum flavum/interspinous lig(AIS1)	Facet joint capsule tear on right side/ degeneration disc-mild subluxation (AIS1)	No injury	No injury
C6/C7	No injury	No injury	No injury	Subluxation bilateral@ ligamentum flavum (AIS1) & interspinous lig (AIS1)	Subluxation @ Interspinous lig (AIS1)	No injury	Anterior longitudinal lig tear (posterior intact), Severe Subluxation @ FJ on both sides, ligamentum flavum tear, Disc injury w ruptured (AIS3), Interspinous lig tear (AIS1)	Seperation of degenerative disc, ligamentum flavum tear @ right side close to spinous process, facet joint capsule tear on the right side (AIS1)
C7/T1	No injury	No injury	Anterior longitudinal lig. tear (posterior intact), FJ capsule tear on both sides, ligamentum flavum tear on left side, Disc rupture w fracture (AIS3), Interspinous lig. tear (AIS1)	Seperation of degenerative disc	No injury	No injury	No injury	No injury



Injury Criteria Analysis





PMHS Injury Analysis

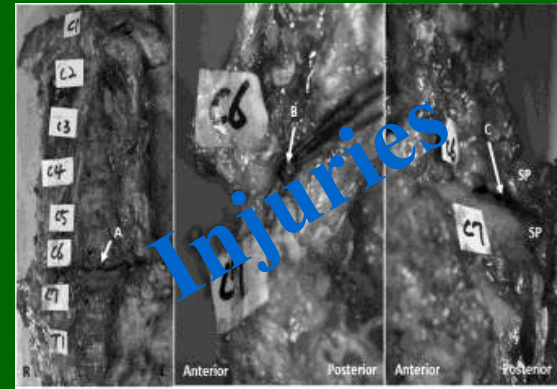
PMHS

Step 1

Intervertebral kinematics

Linear/angular acceleration,
velocity, and displacement

Correlation?



Normalization?

Step 2

Best injury
predictors

Correlation?

Kinetics/kinematics

Current/potential injury
criteria



BioRID II IARV Analysis

Step 3

PMHS

Best injury predictors



Best injury predictors



Injury risk curves


linear regression

linear regression


Risk curves

BioRIDII

Current/potential injury criteria



Intervertebral kinematics



Injury risk curves

Scaling technique for IARV(s)



PMHS Injury Analysis

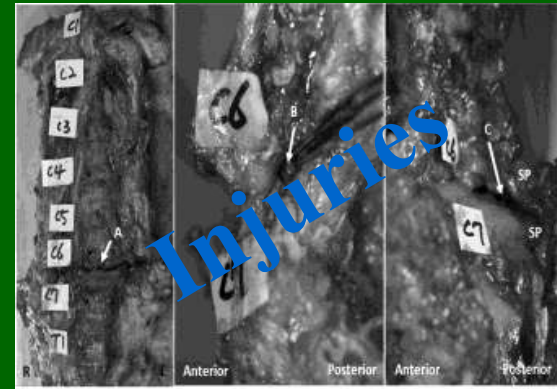
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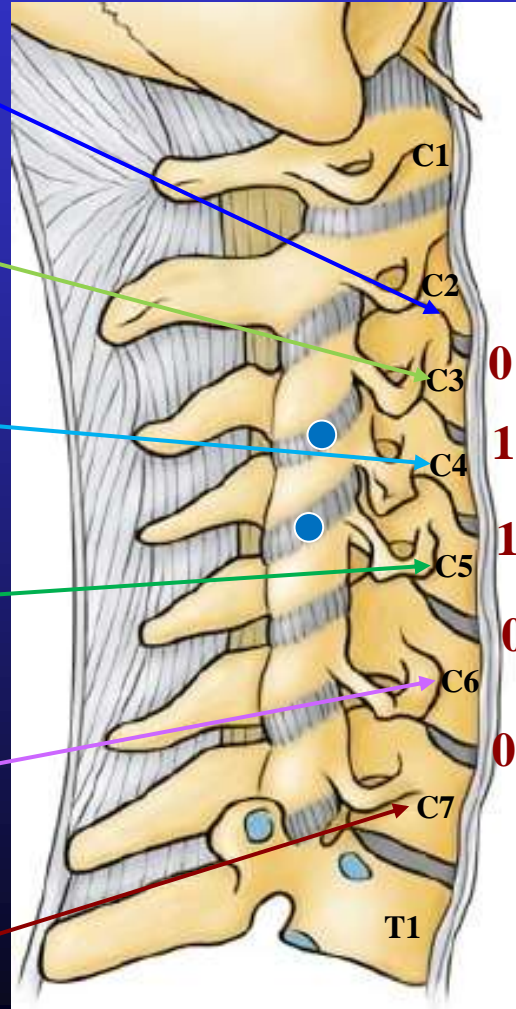
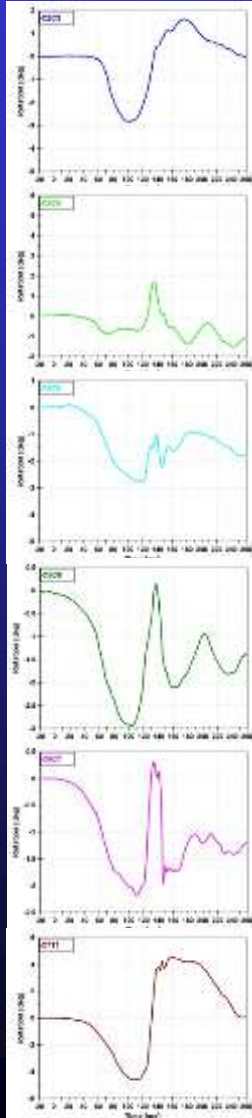


Injury Analysis

Injury Risk Curves – Intervertebral Kinematics

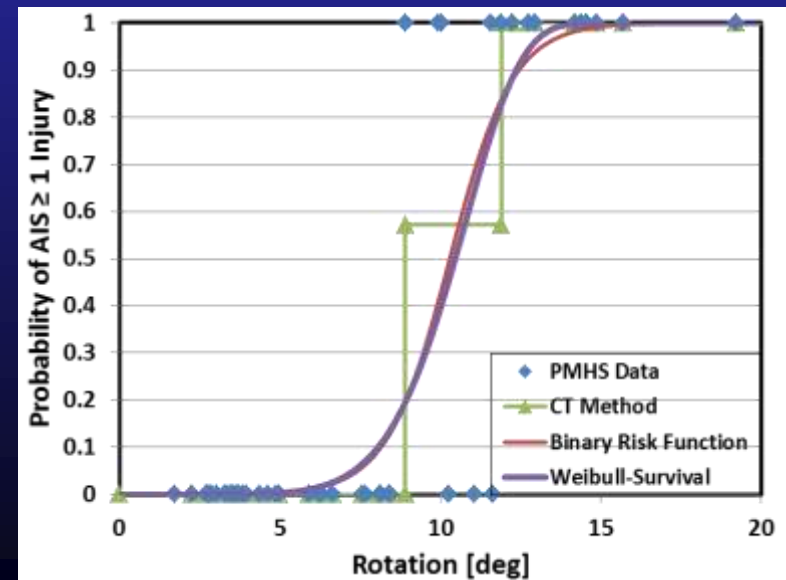
Intervertebral kinematics

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





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

Yellow background: Pseudo R² > 0.2, Nagelkerke R² > 0.4, P-value < 0.05, Goodman-Kruskal Gamma > 0.6

Green background: Best correlation and prediction



Injury Analysis

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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 R² > 0.2, Nagelkerke R² > 0.4, P-value < 0.05 , Goodman-Kruskal Gamma > 0.6

Best correlation and prediction



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

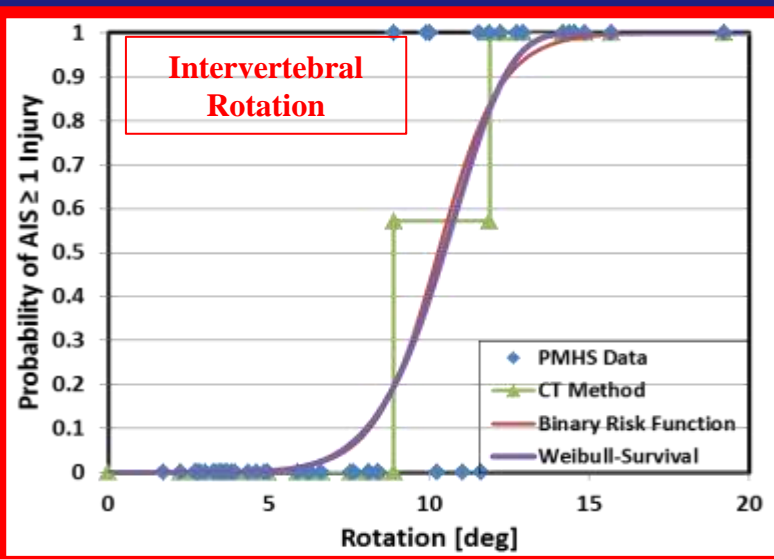
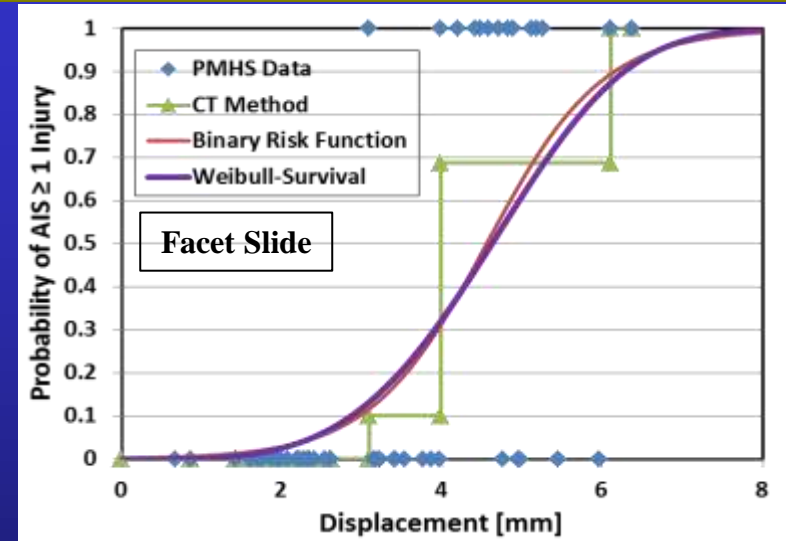
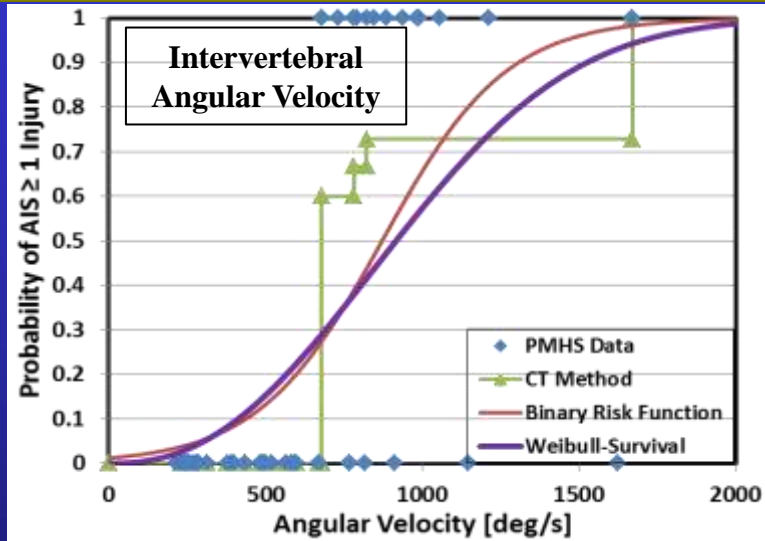
Peudo R² > 0.2, Nagelkerke R² > 0.4, P-value < 0.05, Goodman-Kruskal Gamma > 0.6

Best correlation and prediction



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

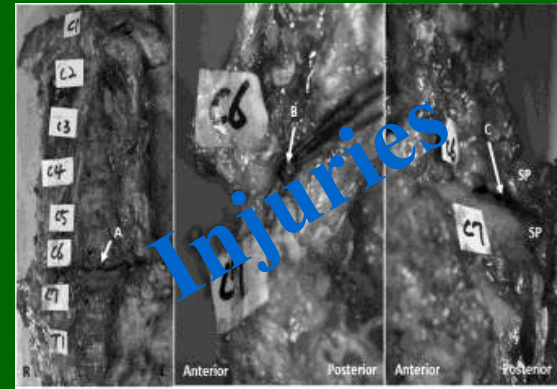
PMHS

Step 1

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Correlation?



Normalization?

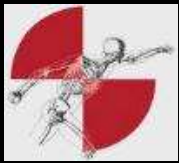
Step 2

Best injury
predictors

Correlation?

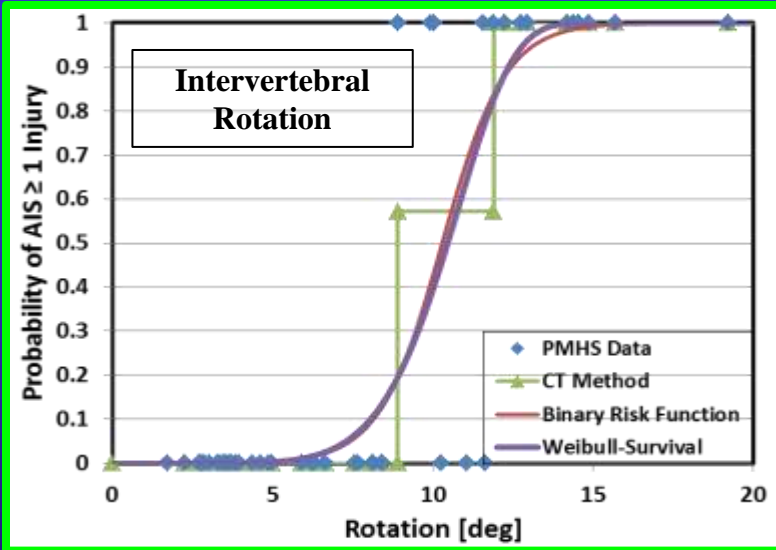
Kinetics/kinematics

Current/potential injury
criteria



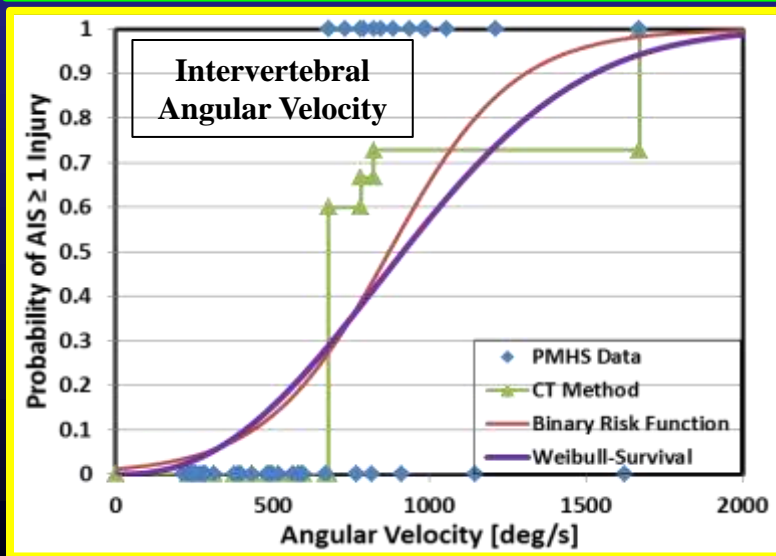
Injury Analysis

Injury Risk Curves – Intervertebral Kinematics



IV-NICrot

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



IV-NICrot Rate

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

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)



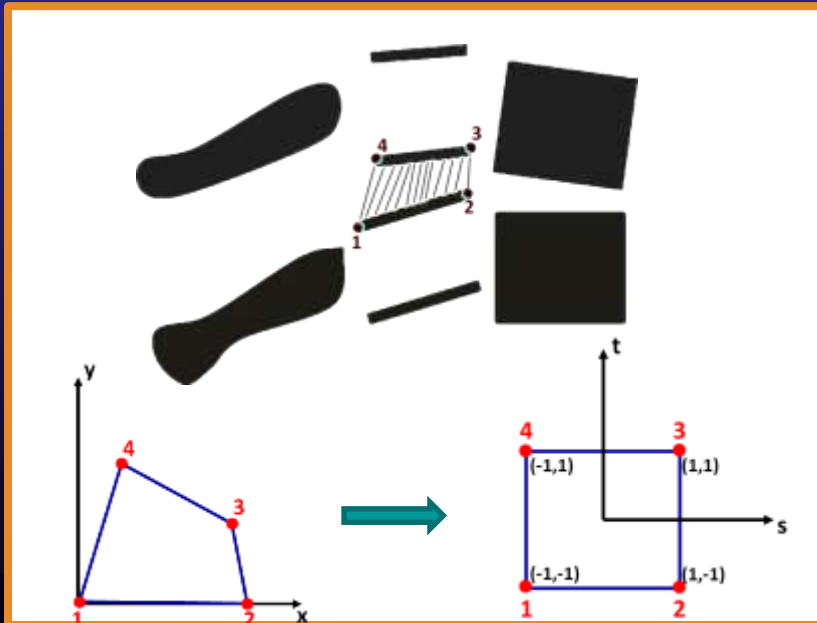
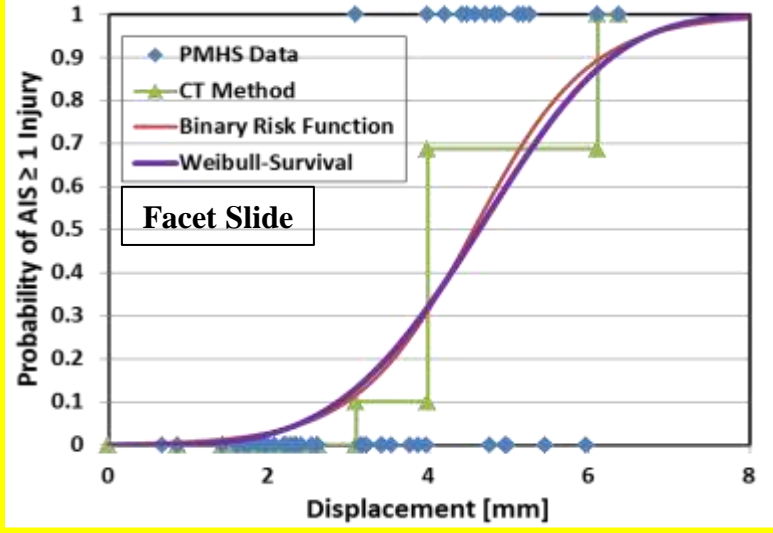
Injury Analysis

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



Qualitative Correlation - IV-NICrot and Injuries



IV-NICrot (Rotation)												
	PMHS03		PMHS04		PMHS05		PMHS06		PMHS07		PMHS08	
	Low	Moderate	Low	Moderate	Low	Moderate	Low	Moderate	Low	Moderate	Low	Moderate
C2/C3	-0.85	-0.79	-1.06**	-0.87	-1.84	-1.52	-0.40	-0.49	-0.90	-0.99	-0.34	-0.45
	+0.26	+0.67	+0.17	+0.26	0.46	0.86	0.23	+0.41	+0.21	+0.30	+0.04	+0.19
C3/C4	-1.18	-1.07	-0.27	-0.41	-1.59	-1.54	-0.09	-0.07	-0.87	-1.00	-0.68	-0.90
	+0.48	+1.05	+1.02**	+0.51	+0.05	+0.18	+0.54	+0.94	+0.15	+0.10	+0.19	+0.28
C4/C5	-1.47	-1.87	-1.17	-1.40	-1.37	-1.16	-0.13	-0.19	-1.48	-1.44	-0.54	-0.79
	+0.01	+0.01	+0.00	+0.00	+0.00	+0.05	+0.39	+0.62	+0.05	+0.09	+0.05	+0.10
C5/C6	-0.56	-0.40	-0.96	-1.00	-1.08	-1.19	-0.09	-0.09	-0.85	-0.91	-0.69	-0.69
	+0.27	+0.30	+0.00	+0.01	+0.01	+0.00	+0.36	+1.00	+0.00	0.00	+0.00	+0.50
C6/C7	-0.33	-0.54	-1.15	-1.33	-0.84	-1.20	-0.16	-0.16	-0.72	-0.73	-0.79	-1.05
	+0.05	+0.68	+0.00	+0.00	+0.44	+0.20	+0.05	+0.47	+0.06	+1.69	+0.00	+0.35
C7/T1	-0.61	-0.73	-0.80	-0.68	-0.69	-0.56	-0.48	-0.32	-0.73	-0.76	-0.89	-1.16
	+0.19	+3.79	+0.00	+1.93	+0.81	+0.90	+0.10	+0.96	+0.84	+1.86	0.05	1.54



Qualitative Correlation - IV-NICrot and Injuries



Injury Documentation

	PMHS03	PMHS04	PMHS05	PMHS06	PMHS07	PMHS08
C2/C3	No injury	No injury	Subluxation bilateral@ FJ (AIS3)	No injury	No injury	No injury
C3/C4	Subluxation bilateral@ FJ (AIS3)	No injury	Subluxation bilateral@ FJ (AIS3) and ligamentum flavum	No injury	No injury	No injury
C4/C5	Subluxation bilateral@ FJ (AIS3)	Subluxation bilateral@ FJ (AIS3)	Subluxation bilateral@ FJ (AIS3)	No injury	Subluxation bilateral@ FJ (AIS3) and ligamentum flavum/interspinous lig.	No injury
C5/C6	No injury	Subluxation bilateral@ FJ (AIS3) and ligamentum flavum/interspinous lig.	Subluxation bilateral@ FJ (AIS3) and ligamentum flavum/interspinous lig.	Facet joint capsule tear on right side/ degeneration disc-mild subluxation	No injury	No injury
C6/C7	No injury	Subluxation bilateral@ ligamentum flavum & interspinous lig.	Subluxation @ Interspinous lig	No injury	Anterior longitudinal lig. tear (posterior intact), Severe Subluxation @ FJ on both sides, ligamentum flavum tear, Disc injury w ruptured (AIS3), Interspinous lig. tear (AIS1)	Seperation of degenerative disc, ligamentum flavum tear @ right side close to spinous process, facet joint capsule tear on the right side
C7/T1	Anterior longitudinal lig. tear (posterior intact), FJ capsule tear on both sides, ligamentum flavum tear on left side, Disc injury w ruptured (AIS3), Interspinous lig. tear (AIS1)	Seperation of degenerative disc	No injury	No injury	No injury	No injury



Qualitative Correlation - IV-NICrot and Injuries



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C2/C3	-0.85	-0.79	-1.06**	-0.87	-1.84	-1.52	-0.40	-0.49	-0.90	-0.99	-0.34	-0.45
	+0.26	+0.67	+0.17	+0.26	0.46	0.86	0.23	+0.41	+0.21	+0.30	+0.04	+0.19
C3/C4	-1.18	-1.07	-0.27	-0.41	-1.59	-1.54	-0.09	-0.07	-0.87	-1.00	-0.68	-0.90
	+0.48	+1.05	+1.02**	+0.51	+0.05	+0.18	+0.54	+0.94	+0.15	+0.10	+0.19	+0.28
C4/C5	-1.47	-1.87	-1.17	-1.40	-1.37	-1.16	-0.13	-0.19	-1.48	-1.44	-0.54	-0.79
	+0.01	+0.01	+0.00	+0.00	+0.00	+0.05	+0.39	+0.62	+0.05	+0.09	+0.05	+0.10
C5/C6	-0.56	-0.40	-0.96	-1.00	-1.08	-1.19	-0.09	-0.09	-0.85	-0.91	-0.69	-0.69
	+0.27	+0.30	+0.00	+0.01	+0.01	+0.00	+0.36	+1.00	+0.00	0.00	+0.00	+0.50
C6/C7	-0.33	-0.54	-1.15	-1.33	-0.84	-1.20	-0.16	-0.16	-0.72	-0.73	-0.79	-1.05
	+0.05	+0.68	+0.00	+0.00	+0.44	+0.20	+0.05	+0.47	+0.06	+1.69	+0.00	+0.35
C7/T1	-0.61	-0.73	-0.80	-0.68	-0.69	-0.56	-0.48	-0.32	-0.73	-0.76	-0.89	-1.16
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C4/C5	Subluxation bilateral@ FJ (AIS3)	Subluxation bilateral@ FJ (AIS3)	Subluxation bilateral@ FJ (AIS3)	No injury	Subluxation bilateral@ FJ (AIS3) and ligamentum flavum/interspinous lig.	No injury
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Injury Analysis

Injury Risk Curves – IV-NIC parameters

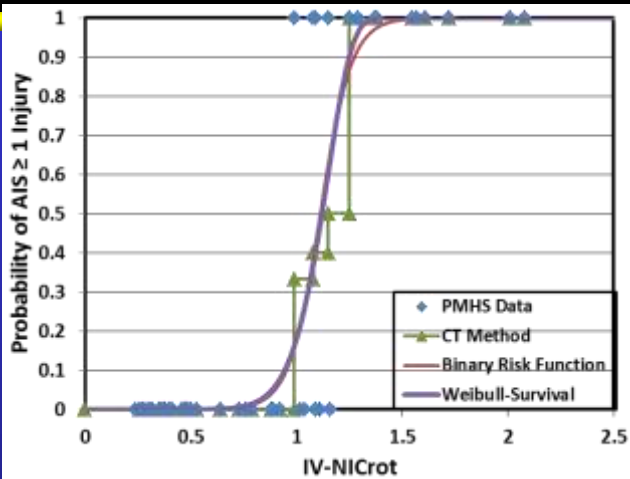
Intervertebral kinematics		Pseudo R ²	Nagelkerke R ²	Log-Likelihood	P-value	Goodman-Kruskal Gamma
IV-NICs (slide)	Max	0.19	0.30	-23.912	0.001	0.58
IV-NICs rate	Max	0.10	0.17	-26.555	0.013	0.44
IV-NICs product	Max	0.16	0.25	-24.824	0.002	0.57
IV-NICa (axial)	Max	0.01	0.02	-29.212	0.350	0.17
IV-NICa rate	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 Strain Rate	(+)	0.07	0.11	-29.673	0.040	0.39

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

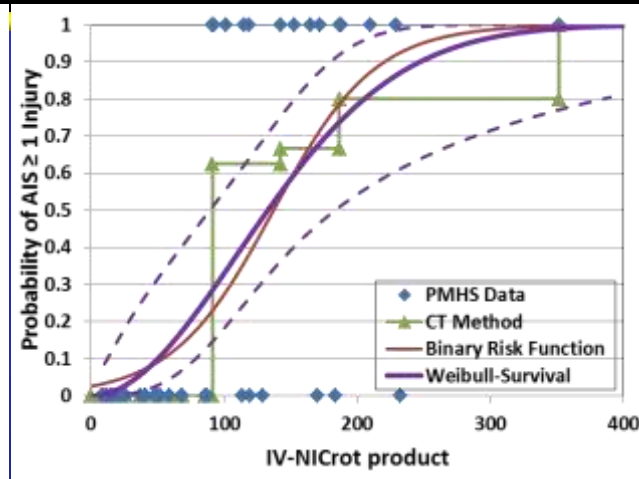


Injury Analysis

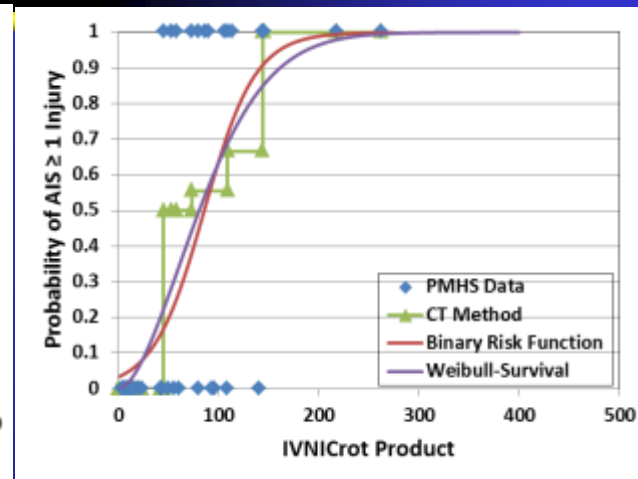
Injury Risk Curves – IV-NIC parameters



<IV-NICrot>



<IV-NICrot product (max-max)>
=Max(IV-NICrot) × Max(IV-NICrot Rate)



<IV-NICrot product (max)>
Max(IV-NICrot × IV-NICrot Rate)

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

- 50 % chance of AIS 1+ injuries
 - IV-NICrot : 1.12
 - IV-NICrot product (max-max): 132.58
 - IV-NICrot product (max): 72.00



PMHS Injury Analysis

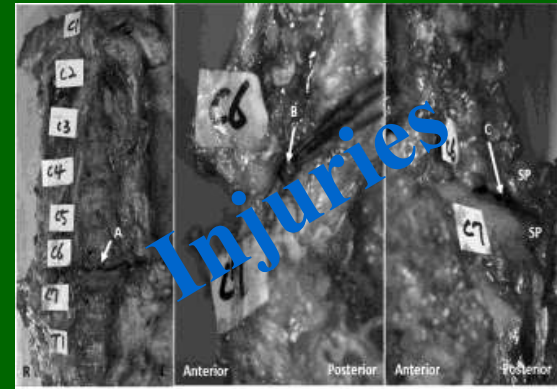
PMHS

Step 1

Intervertebral kinematics

Linear/angular acceleration,
velocity, and displacement

Correlation?



Injuries

Normalization?

Step 2

Best injury
predictors

Correlation?

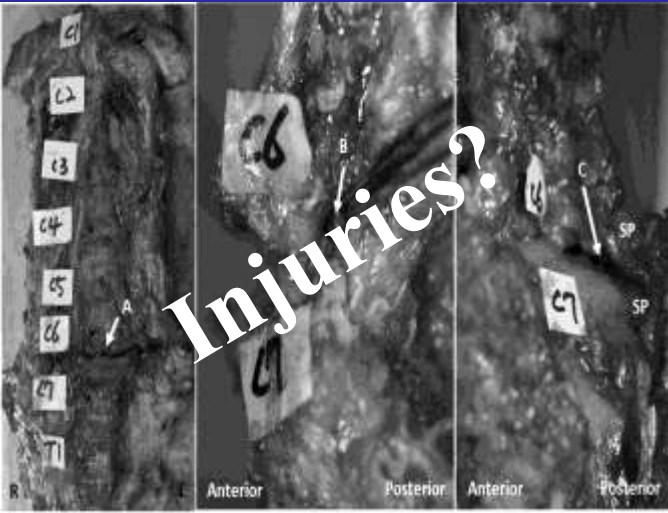
Kinetics/kinematics

Current/potential injury
criteria



Current/Potential Injury Criteria

- Correlation between IV-NIC values and existing injury criteria



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

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

NDC, Nij

Head-to-T1 Rotation

Upper/Lower Fx, Fz, My

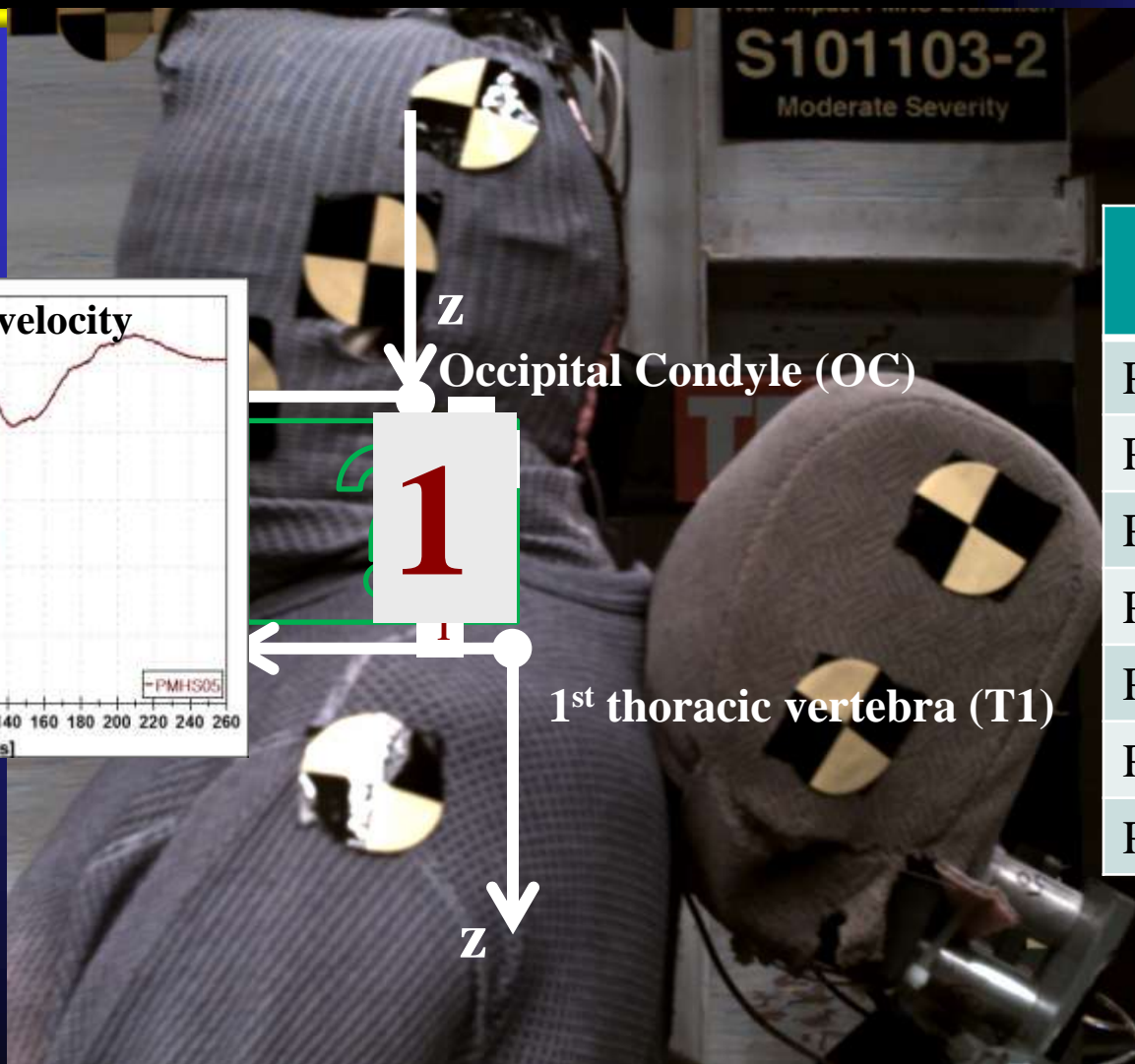
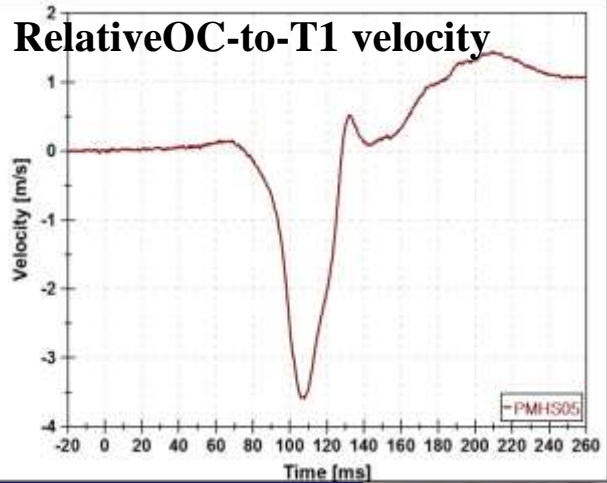
Any physical parameters

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

Potential PMHS IARVs



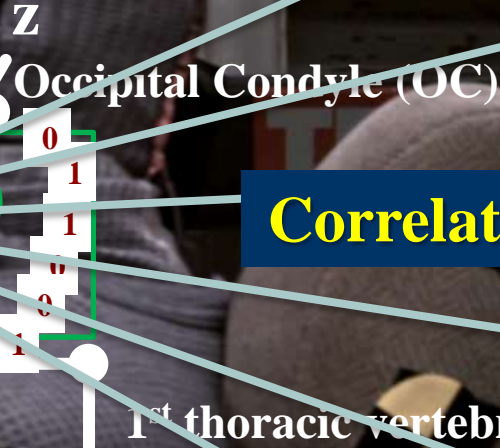
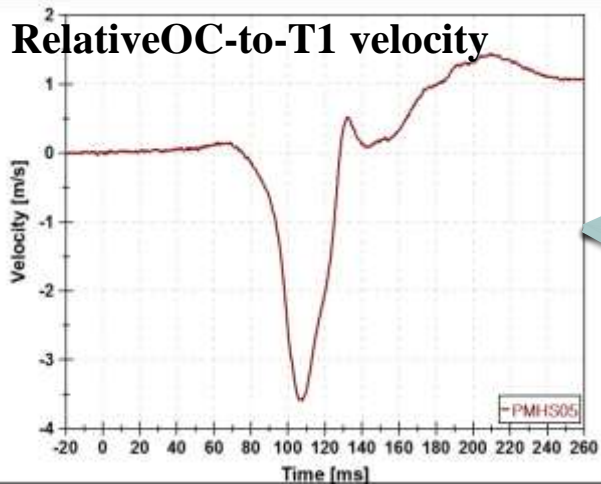
Current Injury Criteria & Potential Injury Predictors (Statistical Method)



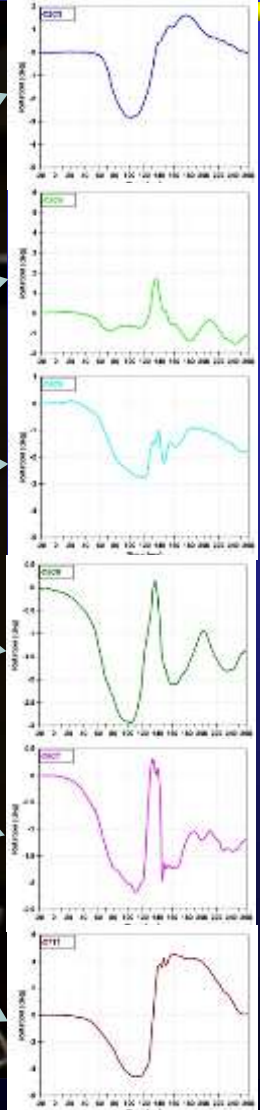
PMHS#	Injury Code
PMHS02	0
PMHS03	1
PMHS04	1
PMHS05	1
PMHS06	1
PMHS07	1
PMHS08	1



Current Injury Criteria & Potential Injury Predictors (Statistical Method)



Correlation?



IV-NIC and IV-NIC product



Injury Analysis

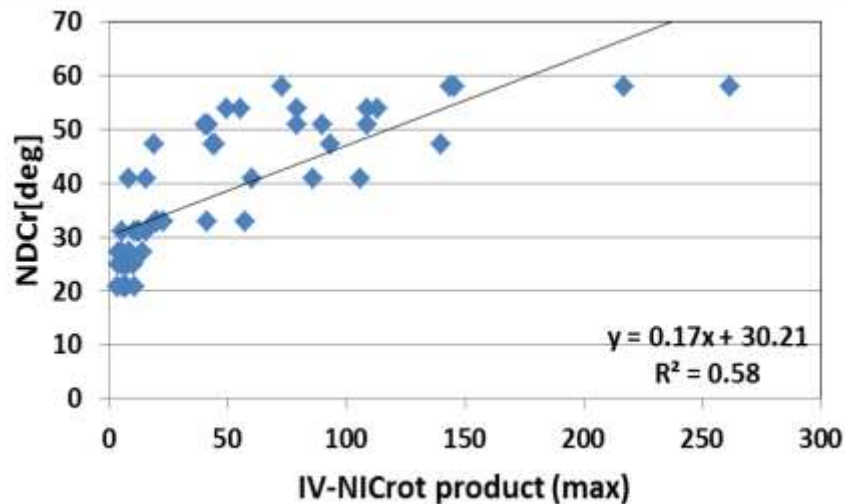
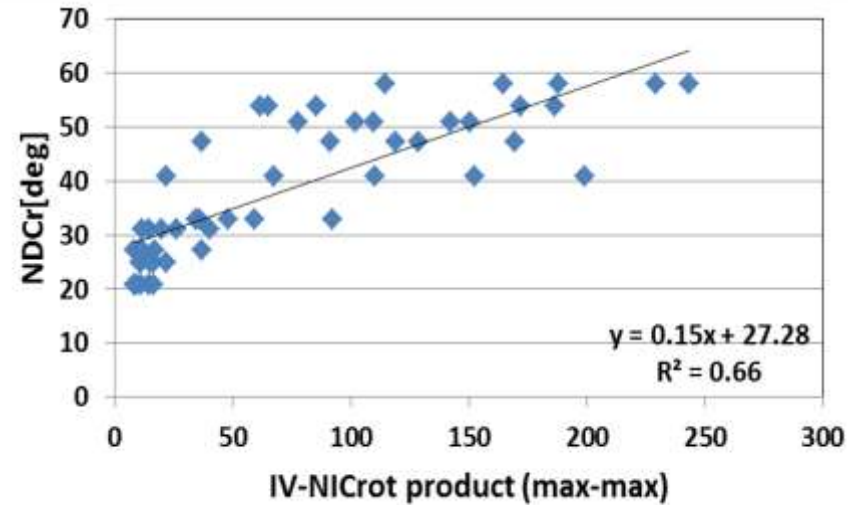
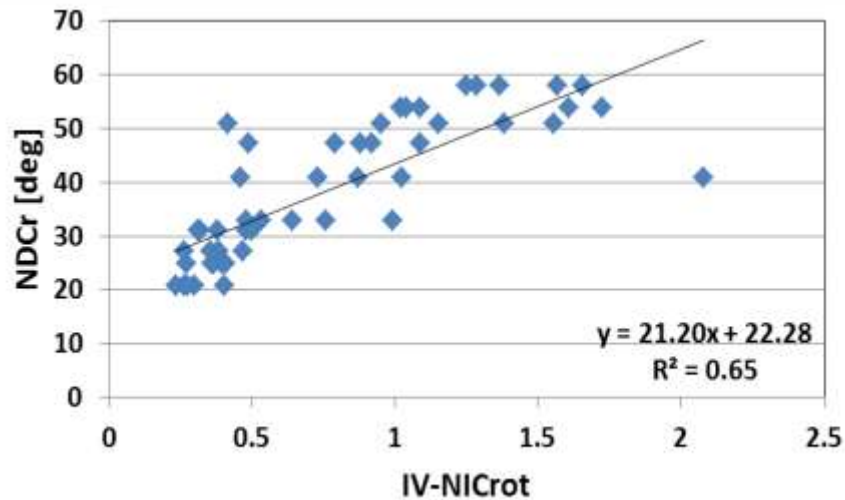
IV-NIC vs. Current/Potential Injury Criteria

	IV-NICrot		IV-NICrot product (max-max)		IV-NICrot product (max)		
	R - value	P - value	R - value	P - value	R - value	P - value	
Nij	NIC	0.685	0	0.700	0	0.722	0
	Nte	0.217	0.129	0.360	0.01	0.271	0.057
	Ntf	0.671	0	0.692	0	0.735	0
	Nce	0.051	0.724	0.102	0.482	0.077	0.593
	Ncf	0.308	0.03	0.344	0.015	0.433	0.002
Nkm	Nae	0.28	0.049	0.418	0.002	0.344	0.014
	Naf	0.568	0	0.531	0	0.594	0
	Npe	0.152	0.291	0.032	0.826	0.138	0.338
	Npf	0.454	0.001	0.492	0	0.479	0
	LNL	0.297	0.036	0.423	0.002	0.357	0.011
NDC	NDCx	0.717	0	0.727	0	0.614	0
	NDCx rate	0.798	0	0.785	0	0.791	0
	NDCx product (max-max)	0.808	0	0.808	0	0.756	0
	NDCx product (max)	0.616	0	0.670	0	0.672	0
	NDCz	0.694	0	0.751	0	0.668	0
	NDCz rate	0.604	0	0.722	0	0.706	0
	NDCz product (max-max)	0.588	0	0.703	0	0.666	0
	NDCz product (max)	0.503	0	0.585	0	0.499	0
	NDCr	0.805	0	0.811	0	0.764	0
	NDCr rate	0.818	0	0.810	0	0.751	0
	NDCr product (max-max)	0.818	0	0.818	0	0.78	0
	NDCr product (max)	0.754	0	0.744	0	0.738	0



Injury Analysis

IV-NIC vs. Current/Potential Injury Criteria



- 50 % chance of AIS 1+ injuries for PMHS
 - IV-NICrot : 1.12
 - NDCr : 46.04 deg
 - IV-NICrot product (max-max): 132.58
 - NDCr: 47.17 deg
 - IV-NICrot product (max): 72.00
 - NDCr: 42.45 deg



Injury Analysis

IV-NIC vs. Current/Potential Injury Criteria

		IV-NICrot		IV-NICrot product (max-max)		IV-NICrot product (max)		
		R - value	P - value	R - value	P - value	R - value	P - value	
NIC		0.685	0	0.700	0	0.722	0	
Nij	Nte	0.217	?		0.01	0.271	0.057	
	Ntf	0.671			0	0.735	0	
	Nce	0.051			0.482	0.077	0.593	
	Ncf	0.308			0.015	0.433	0.002	
Nkm	Nae	0.28			0.002	0.344	0.014	
	Naf	0.568			0	0.594	0	
	Npe	0.152			0.826	0.138	0.338	
	Npf	0.454			0	0.479	0	
	LNL	0.297			0.002	0.357	0.011	
NDCx		0.717		0	0.727	0	0.614	0
NDCx rate		0.798		0	0.785	0	0.791	0
NDCx product (max-max)		0.808		0	0.808	0	0.756	0
NDCx product (max)		0.616	0	0.670	0	0.672	0	
NDCz		0.694	0	0.751	0	0.668	0	
NDC	NDCz rate	0.604	0	0.722	0	0.706	0	
	NDCz product (max-max)	0.588	0	0.703	0	0.666	0	
	NDCz product (max)	0.503	0	0.585	0	0.499	0	
	NDCr	0.805	0	0.811	0	0.764	0	
	NDCr rate	0.818	0	0.810	0	0.751	0	
	NDCr product (max-max)	0.818	0	0.818	0	0.78	0	
	NDCr product (max)	0.754	0	0.744	0	0.738	0	

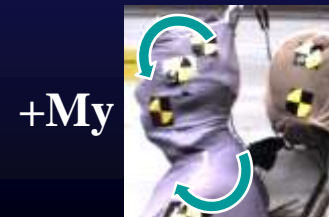
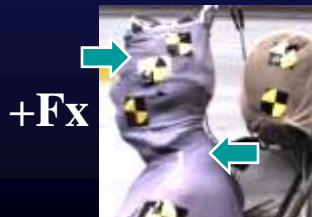


Injury Analysis

IV-NICrot vs. Upper/Lower Neck Loads

<Entire time histories>

			IV-NICrot	
			R - value	P - value
Upper Neck	Fx	+	0.183	0.204
		-	0.04	0.784
	Fz	+	0.573	0
		-	0.421	0.002
	My	+	0.695	0
		-	0.193	0.179
Lower Neck	Fx	+	0.16	0.268
		-	0.293	0.039
	Fz	+	0.582	0
		-	0.024	0.871
	My	+	0.533	0
		-	0.49	0





Injury Analysis

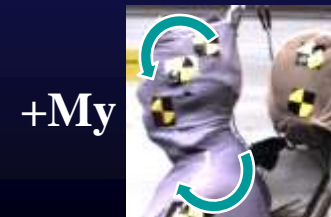
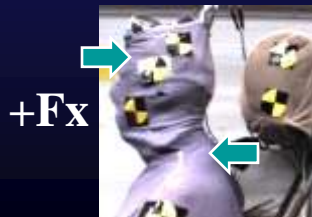
IV-NICrot vs. Upper/Lower Neck Loads

<Entire time histories>

			IV-NICrot	
			R - value	P - value
Upper Neck	F_x	+	0.183	0.204
		-	0.04	0.784
	F_z	+	0.573	0
		-	0.421	0.002
	M_y	+	0.695	0
		-	0.193	0.179
Lower Neck	F_x	+	0.16	0.268
		-	0.293	0.039
	F_z	+	0.582	0
		-	0.024	0.871
	M_y	+	0.533	0
		-	0.49	0

<Before head restraint contact>

			IV-NICrot	
			R - value	P - value
Upper Neck	F_x	+	0.756	0
		-	0.35	0.013
	F_z	+	0.592	0
		-	0.698	0
	M_y	+	0.726	0
		-	0.626	0
Lower Neck	F_x	+	0.217	0.13
		-	0.718	0
	F_z	+	0.778	0
		-	0.636	0
	M_y	+	0.704	0
		-	0.595	0





Injury Analysis

IV-NICrot vs. Loads based injury criteria



<Entire time histories>

	IV-NICu	
	R - value	P - value
Nte	0.217	0.129
Ntf	0.671	0
Nce	0.051	0.724
Ncf	0.308	0.03
Nae	0.28	0.049
Naf	0.568	0
Npe	0.152	0.291
Npf	0.454	0.001
LNL	0.297	0.036

<Before head restraint contact>

	IV-NICu	
	R - value	P - value
Nte	0.711	0
Ntf	0.686	0
Nce	0.684	0
Ncf	0.3	0.034
Nae	0.144	0.319
Naf	0.8	0
Npe	0.647	0
Npf	0.492	0
LNL	0.722	0



Injury Assessment Reference Values

Biofidelic Rear Impact Dummy - BioRIDII



BioRIDII





BioRID II IARV Analysis

Step 3

PMHS

Best injury predictors

Best injury predictors

Injury risk curves

BioRIDII

Current/potential injury criteria

Intervertebral kinematics

Injury risk curves

linear regression

linear regression

Risk curves

Scaling technique for IARV(s)



IARV analysis



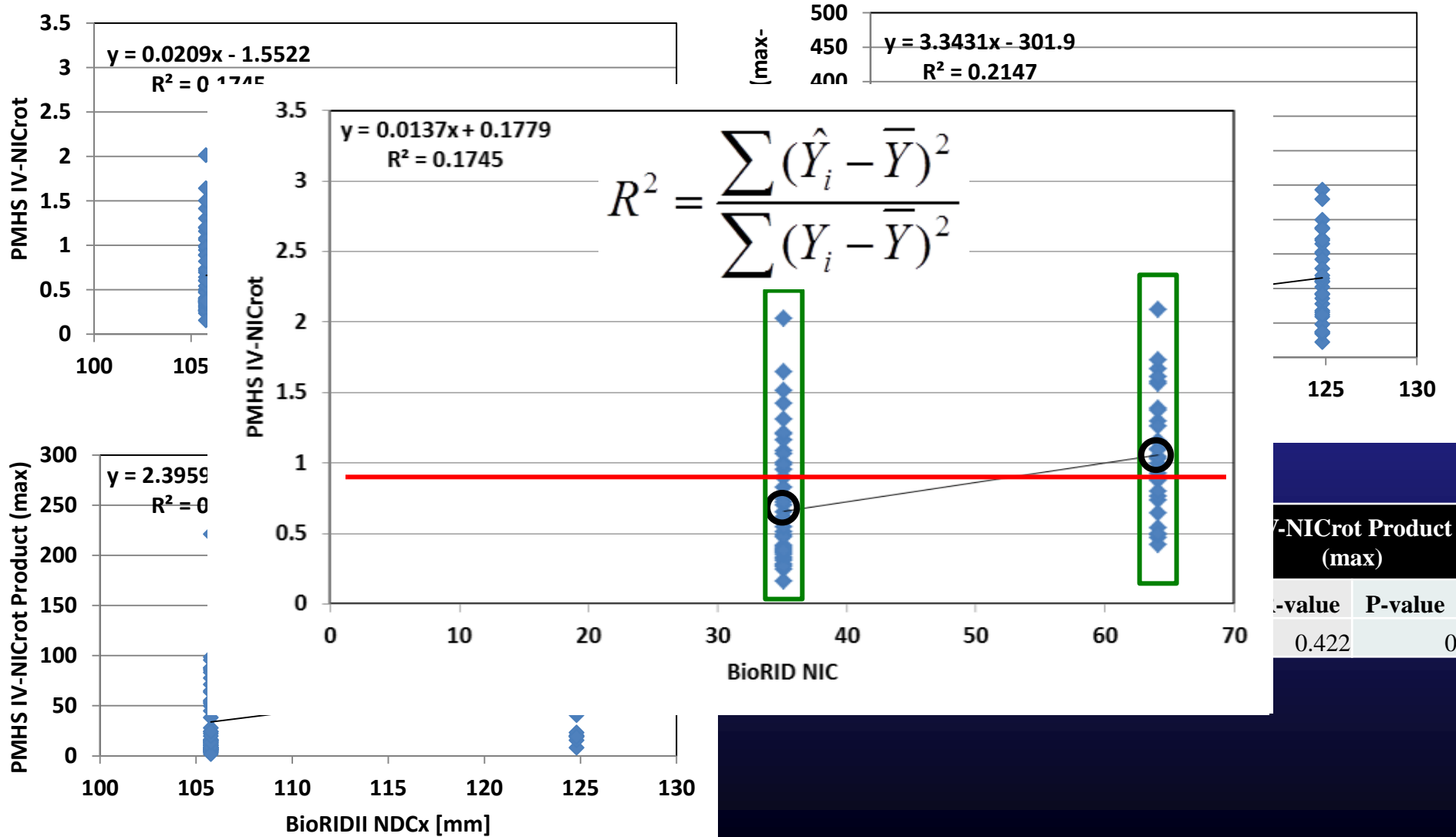
Correlation - IV-NIC parameters (PMHS) and Current Injury Criteria (BioRIDII)

	IV-NICrot		IV-NICrot Product (max-max)		IV-NICrot Product (max)	
	R-value	P-value	R-value	P-value	R-value	P-value
NIC	0.418	0	0.463	0	0.422	0
NDCx	0.418	0	0.463	0	0.422	0
NDCxRate	0.418	0	0.463	0	0.422	0
NDCxProd	0.418	0	0.463	0	0.422	0
NDCz	0.418	0	0.463	0	0.422	0
NDCzRate	0.418	0	0.463	0	0.422	0
NDCzProd	0.418	0	0.463	0	0.422	0
NDCr	-0.418	0	-0.463	0	-0.422	0
NDCrRate	-0.418	0	-0.463	0	-0.422	0
NDCrProd	-0.418	0	-0.463	0	-0.422	0
Nte	0.418	0	0.463	0	0.422	0
Ntf	0.418	0	0.463	0	0.422	0
Nce	0.418	0	0.463	0	0.422	0
Ncf	-0.418	0	-0.463	0	-0.422	0
Nfa	-0.418	0	-0.463	0	-0.422	0
Nea	-0.418	0	-0.463	0	-0.422	0
Nfp	-0.418	0	-0.456	0	-0.422	0
Nep	0.418	0	0.463	0	0.422	0
LNL	0.418	0	0.463	0	0.422	0



IARV analysis

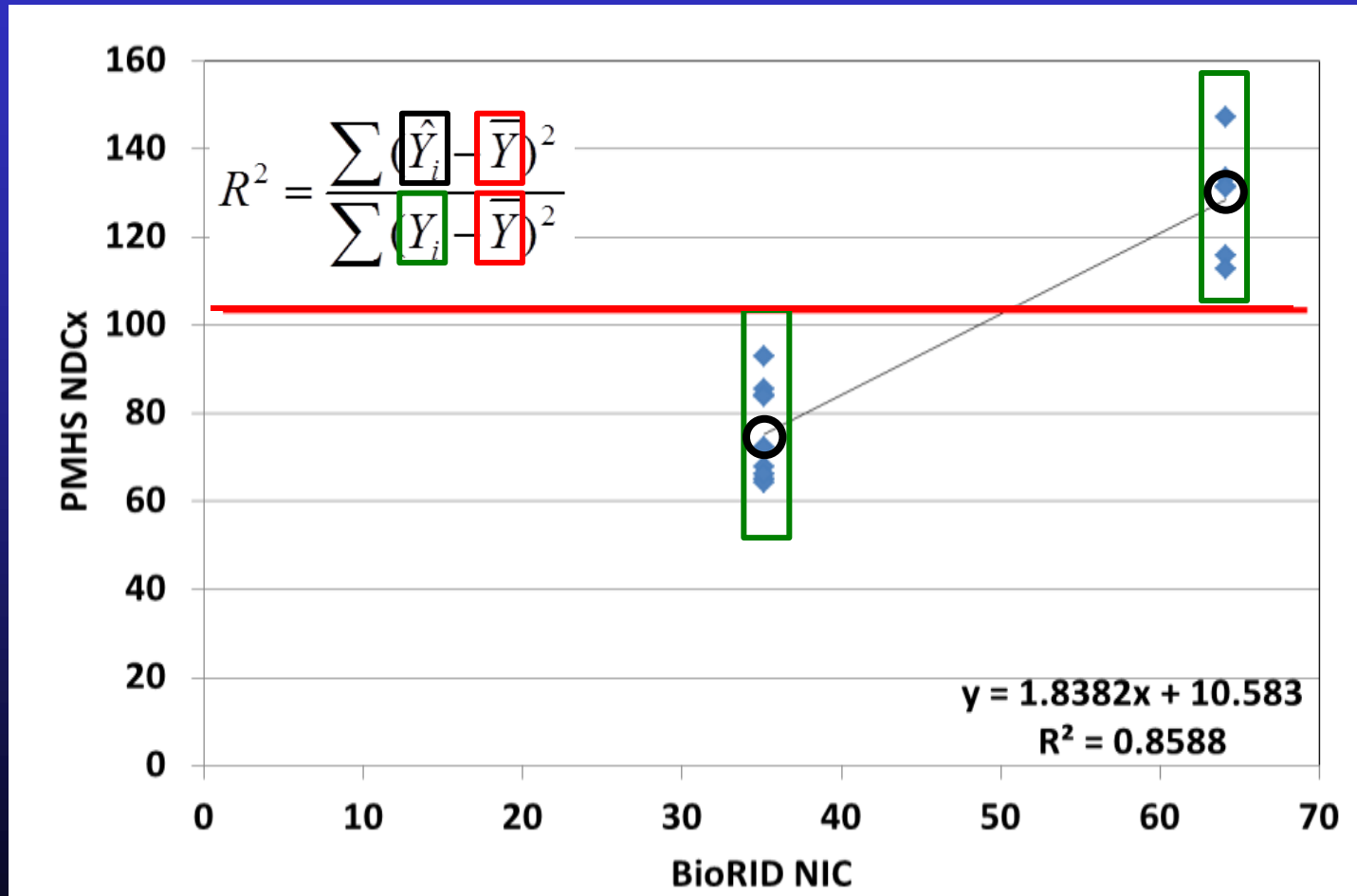
Correlation - IV-NIC parameters (PMHS) and Current Injury Criteria (BioRIDII)





IARV analysis

Correlation – Current Injury Criteria (PMHS) and Current Injury Criteria (BioRIDII)





BioRID II IARV Analysis

Step 3

PMHS

Best injury predictors

Best injury predictors

Injury risk curves

linear regression

linear regression

Risk curves

BioRIDII

Current/potential injury criteria

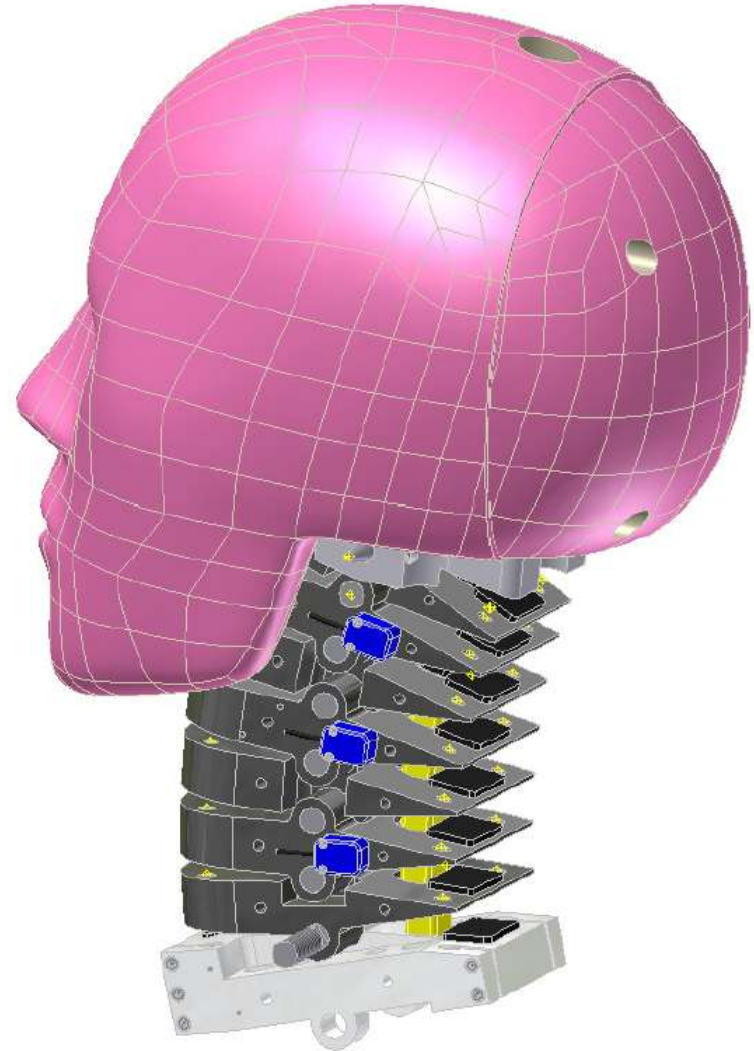
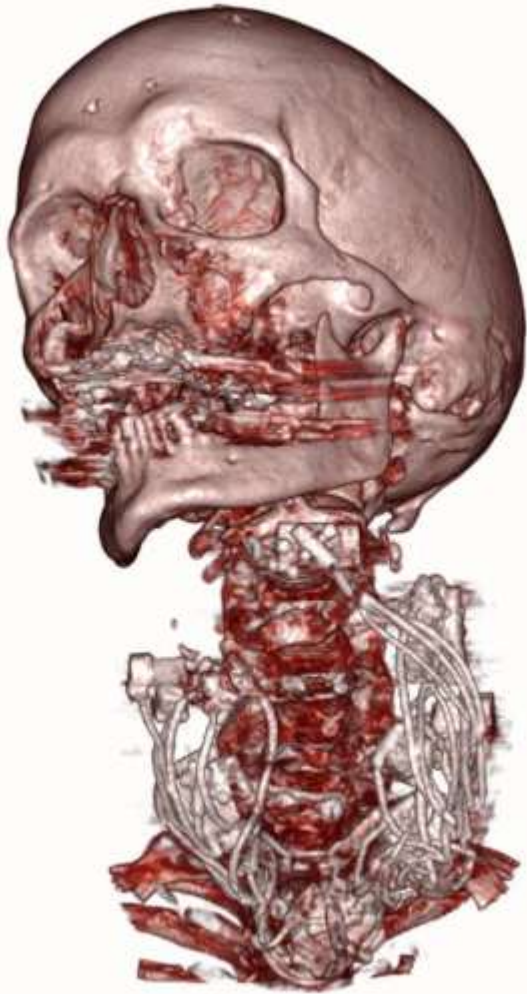
Intervertebral kinematics

Injury risk curves

Scaling technique for IARV(s)



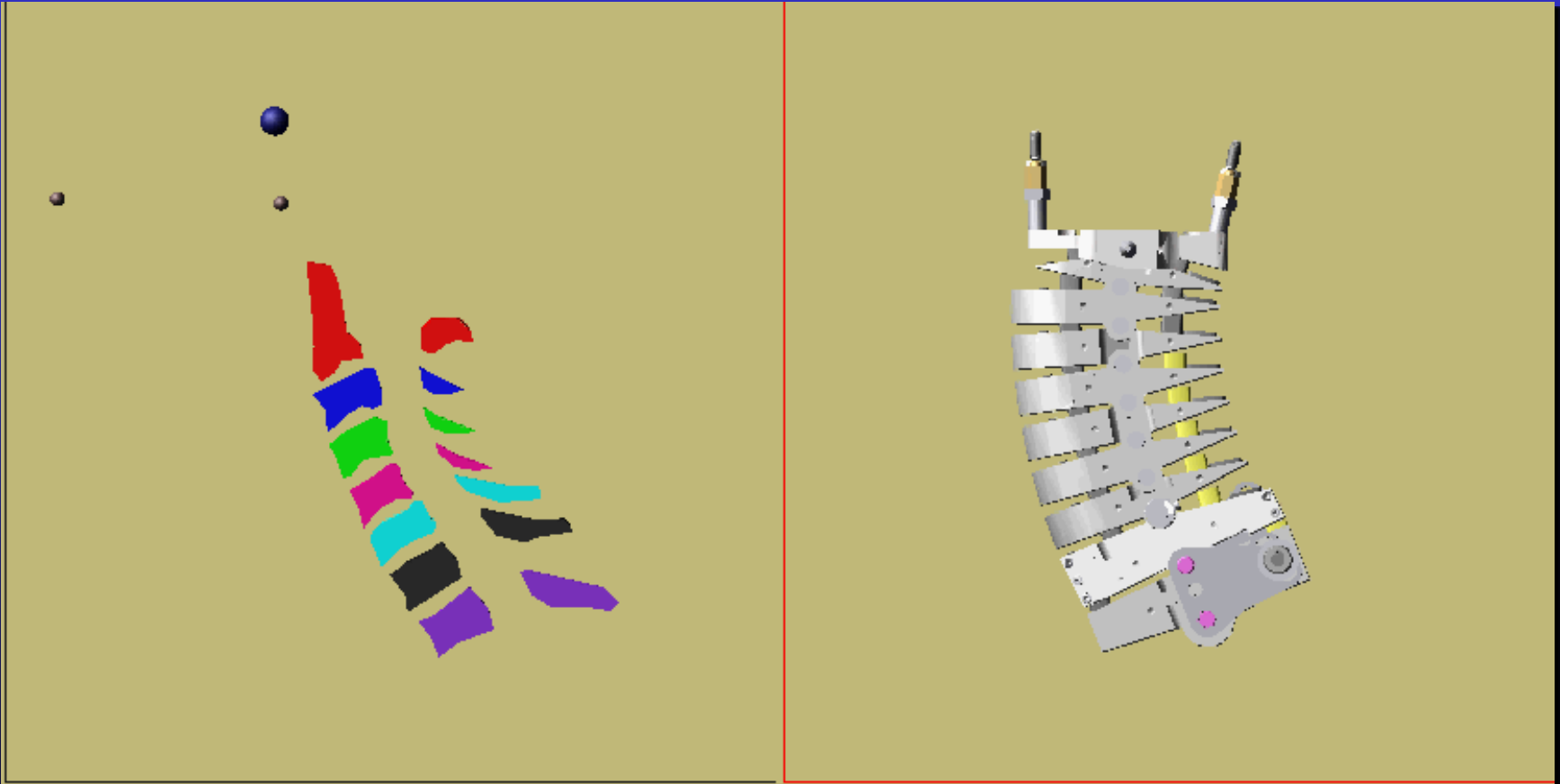
BioRIDII - Cervical Kinematics





IARV analysis

PMHS vs. BioRIDII - Cervical kinematics (low speed)

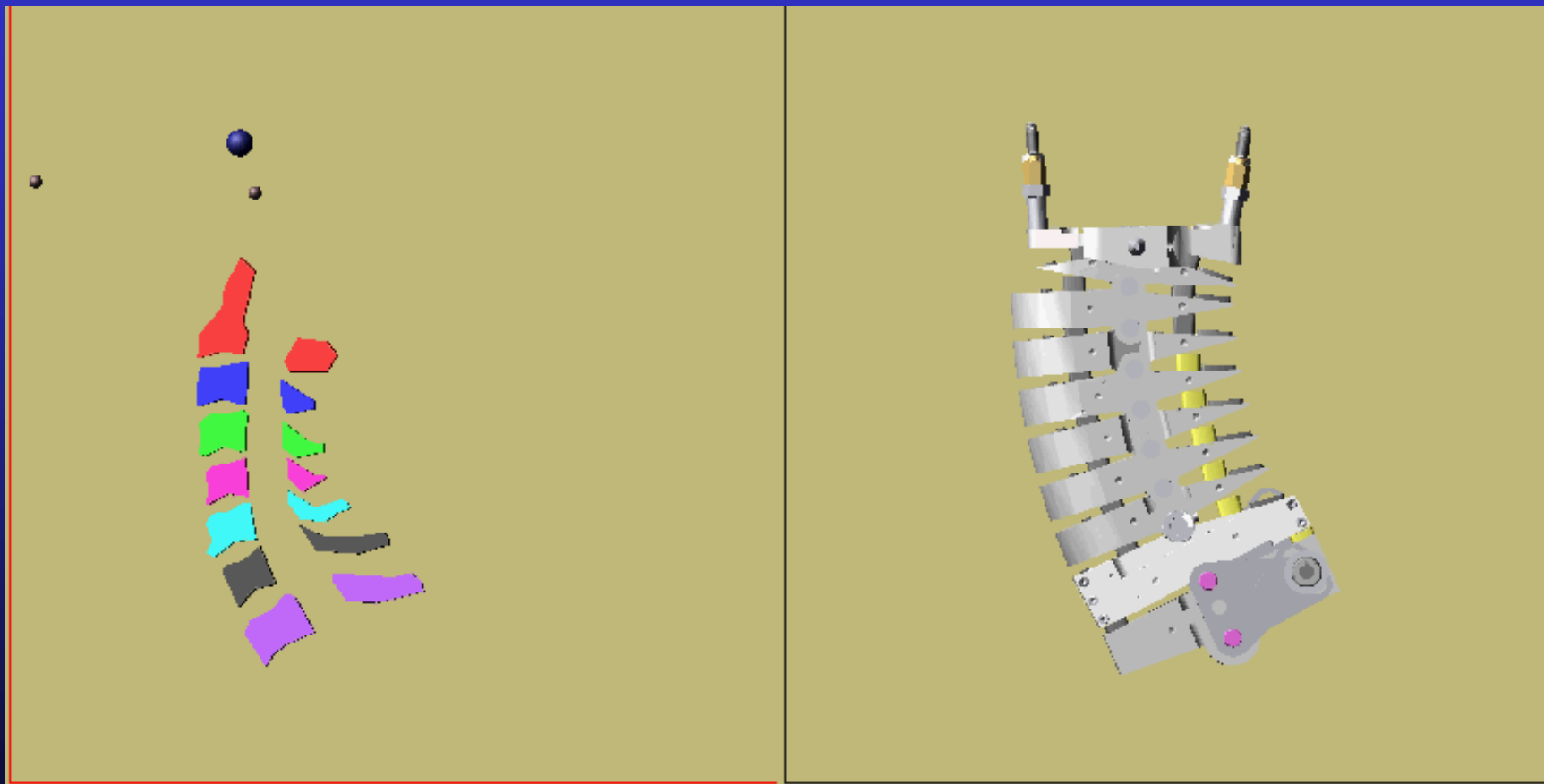




IARV analysis



PMHS vs. BioRIDII - Cervical kinematics (moderate speed)

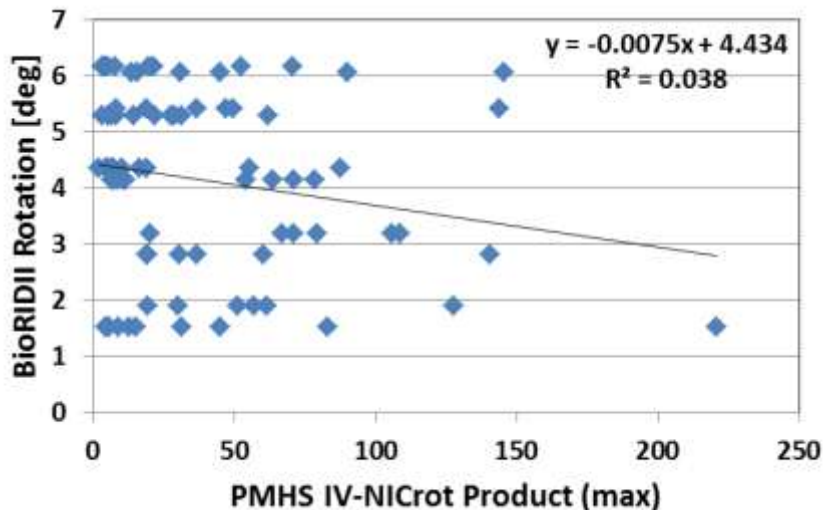
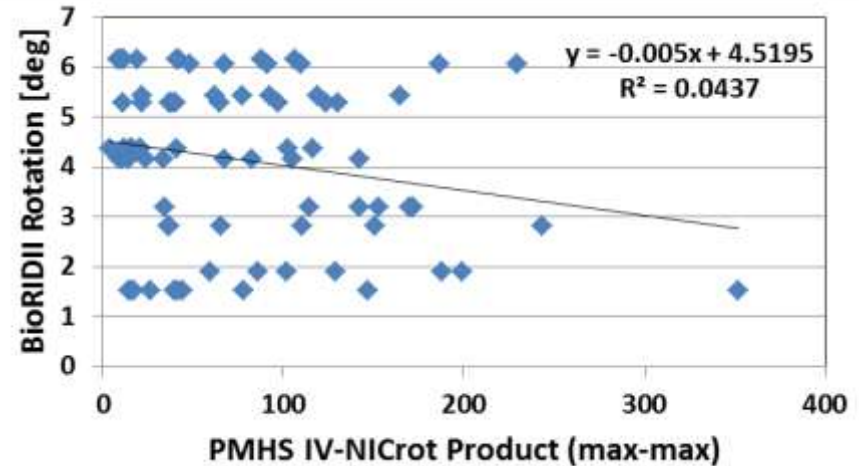
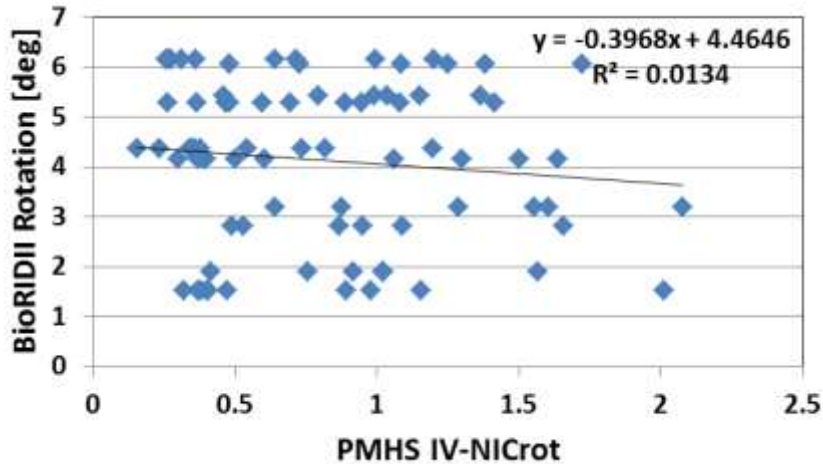




IARV analysis



Correlation - IV-NIC parameters (PMHS) and Intervertebral kinematics (BioRIDII)



	IV-NICrot		IV-NICrot Product (max-max)		IV-NICrot Product (max)	
	R-value	P-value	R-value	P-value	R-value	P-value
BioRIDII						
Angular Acceleration (F)	0.19	0.092	0.171	0.13	0.172	0.127
Angular Acceleration (E)	0.019	0.867	0.043	0.702	0	0.998
Angular Velocity (F)	-0.056	0.62	0.028	0.806	-0.097	0.39
Angular Velocity (E)	0.082	0.47	0.14	0.216	0.096	0.399
Rotation (F)	-0.116	0.307	-0.209	0.063	-0.195	0.083
Rotation (E)	0.096	0.396	0.231	0.039	0.173	0.124



BioRID II IARV Analysis

Step 3

PMHS

Best injury predictors

Best injury predictors

Injury risk curves

linear regression

linear regression

Risk curves

BioRIDII

Current/potential injury criteria

Intervertebral kinematics

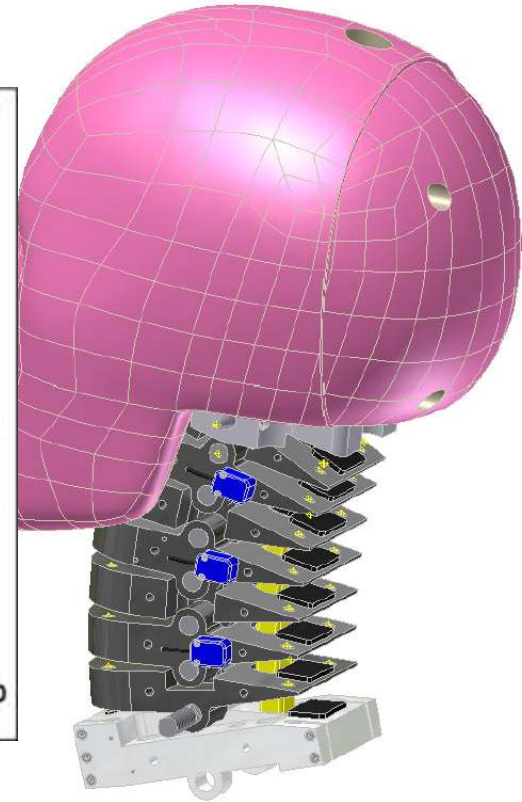
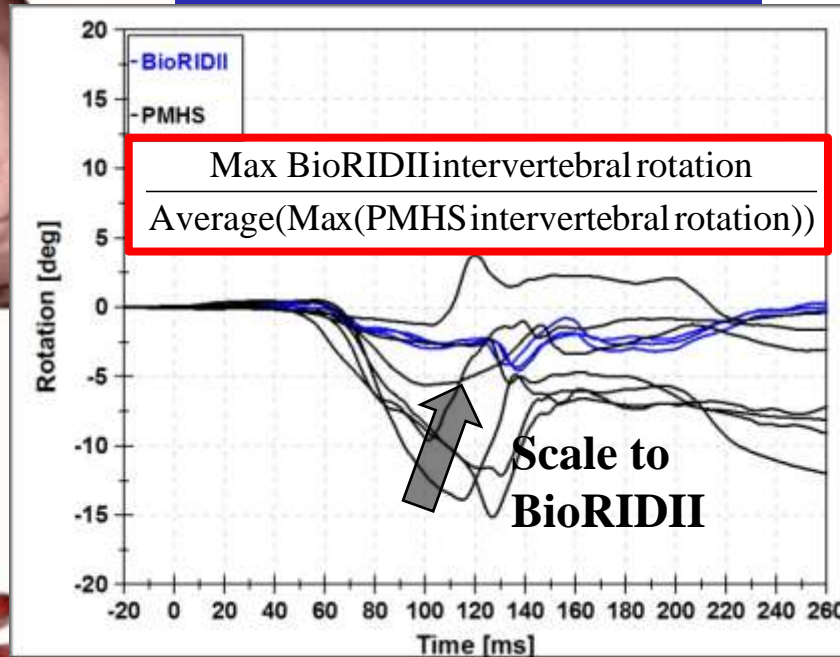
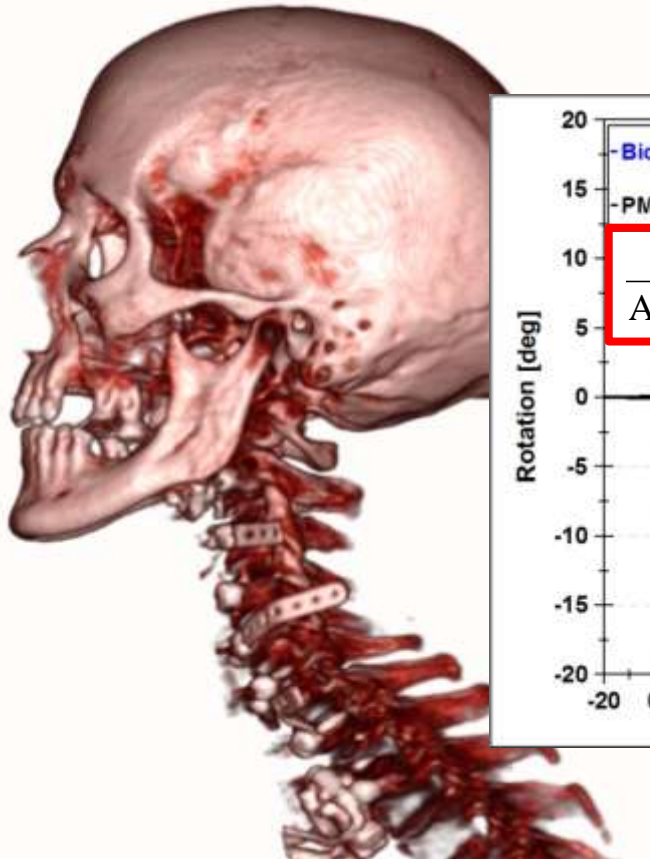
Injury risk curves

Scaling technique for IARV(s)



IARV Analysis

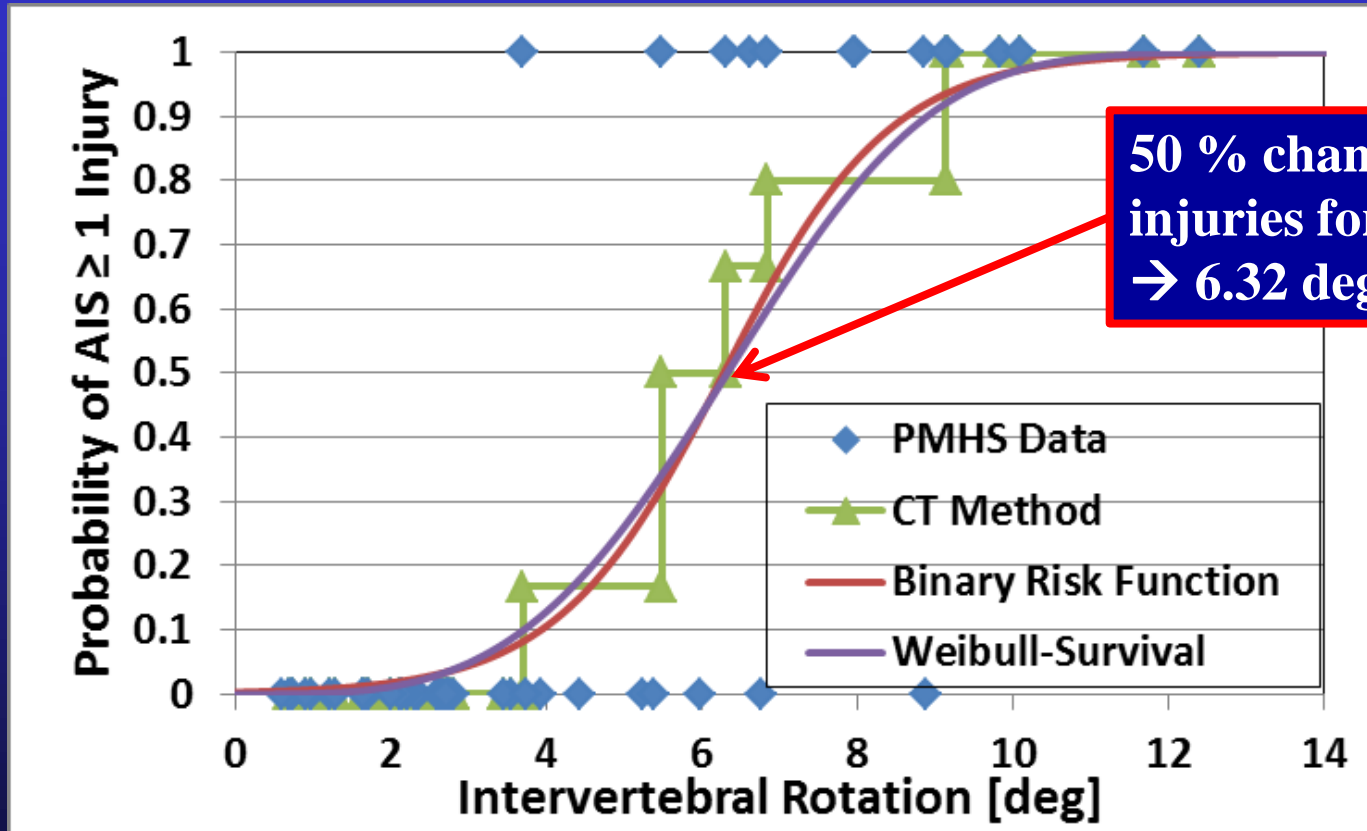
Scaling method





IARV Analysis

Scaling method – BioRIDII Injury Risk Curve



50 % chance of AIS 1+ injuries for BioRIDII → 6.32 deg

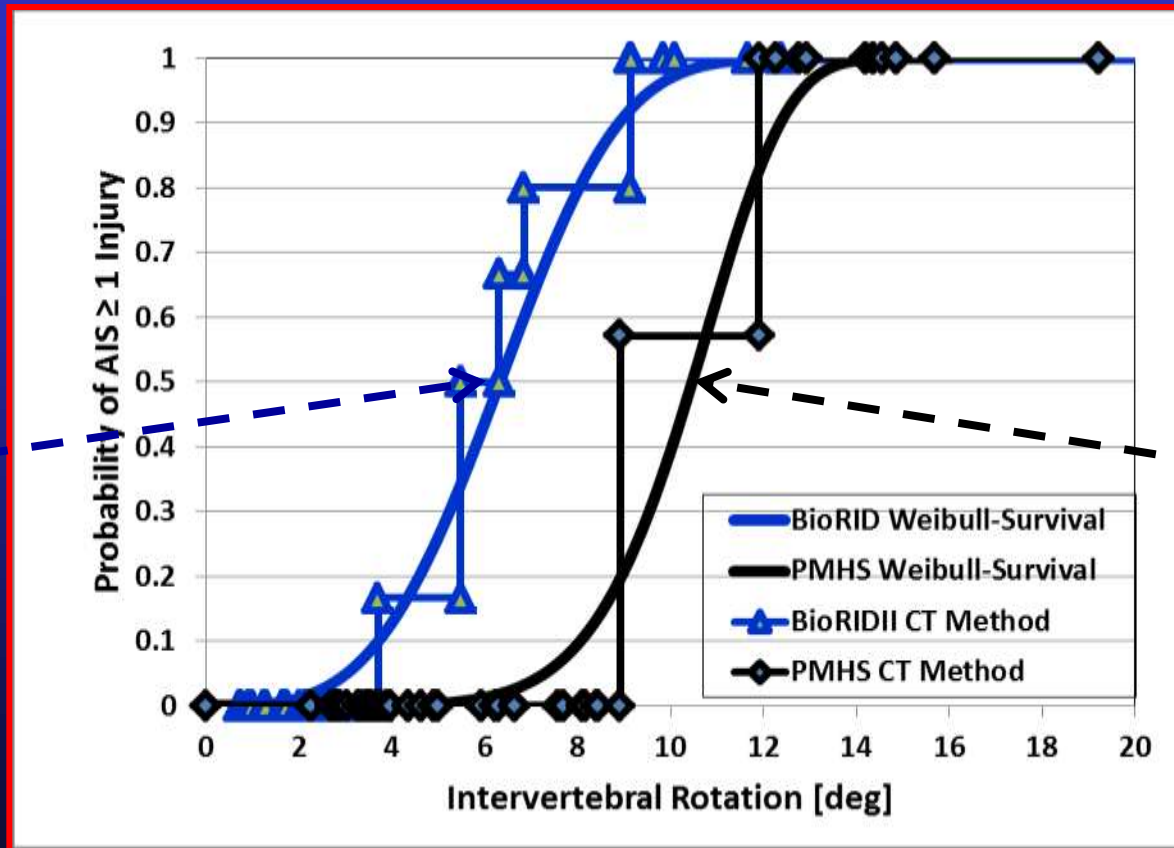
Intervertebral kinematics		Pseudo R ²	Nagelkerke R ²	Log-Likelihood	P-value	Goodman-Kruskal Gamma
Intervertebral rotation	Max	0.61	0.74	-11.687	0.000	0.93



IARV Analysis

Scaling method – BioRIDII Injury Risk Curve

BioRIDII/PMHS Injury Risk Curve for Intervertebral Rotation



BioRIDII

6.32 deg

PMHS

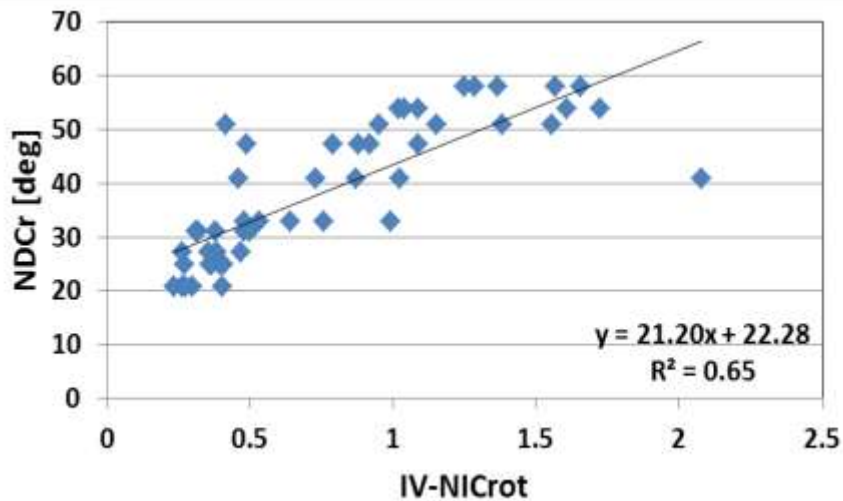
10.46 deg



IARV Analysis

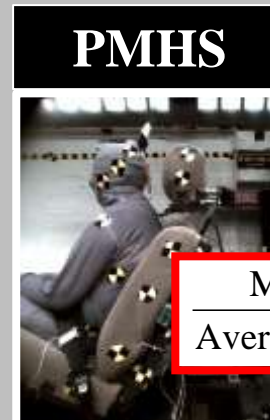
Scaling method – BioRIDII Injury Threshold

PMHS Regression model



50 % chance of AIS 1+ injuries
for BioRIDII
NDCr : 11.78 deg (flexion)

50 % chance of AIS 1+ injuries for
PMHS
IV-NICrot : 1.12 → NDCr : 46.04 deg



Scaling

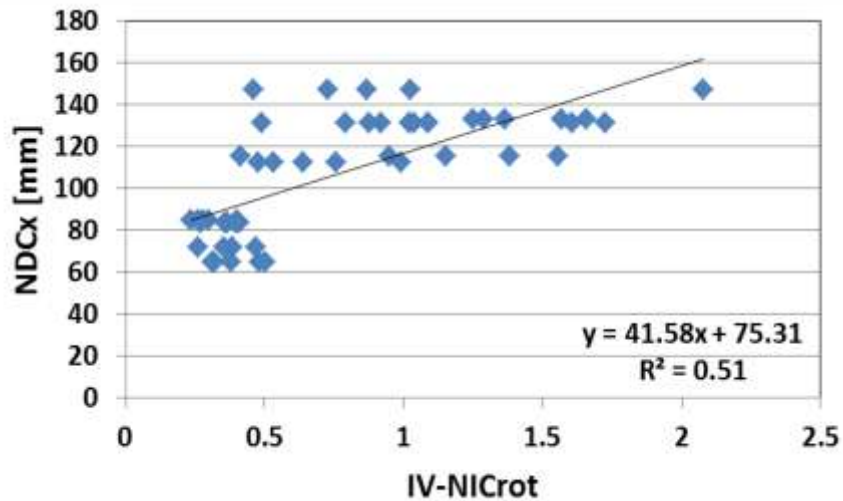
$$\frac{\text{Max BioRIDII- NDCr}}{\text{Average(Max PMHS- NDCr)}}$$



IARV Analysis

Scaling method – BioRIDII Injury Threshold

PMHS Regression model



50 % chance of AIS 1+ injuries
for BioRIDII

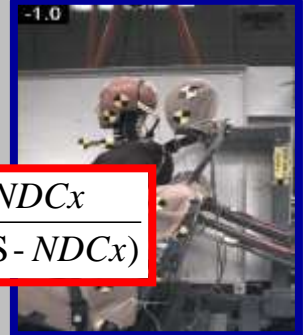
NDCx : 144.66 mm

50 % chance of AIS 1+ injuries for
PMHS
IV-NICrot : 1.12 \rightarrow NDCx : 121.88 mm

PMHS



BioRIDII



Scaling

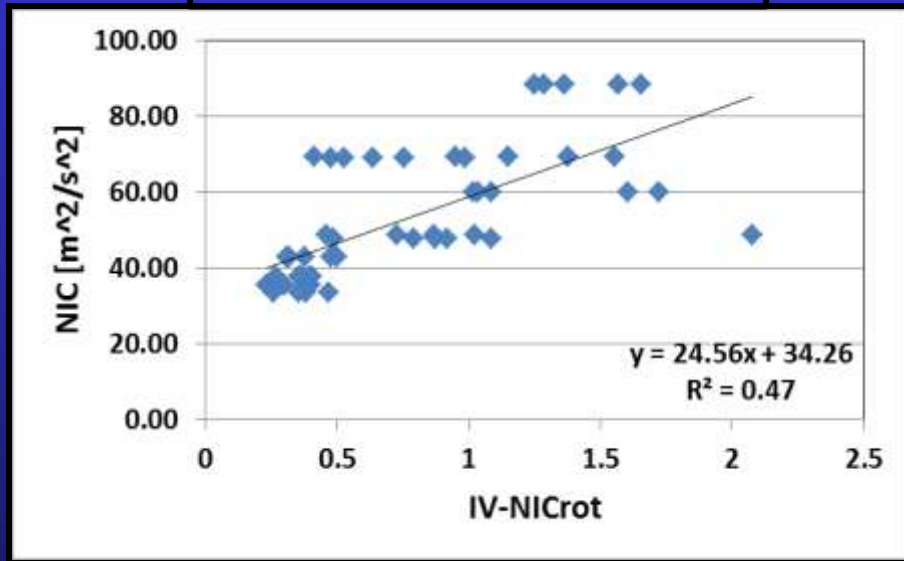
Max BioRIDII - NDCx
Average(Max PMHS - NDCx)



IARV Analysis

Scaling method – BioRIDII Injury Threshold

PMHS Regression model

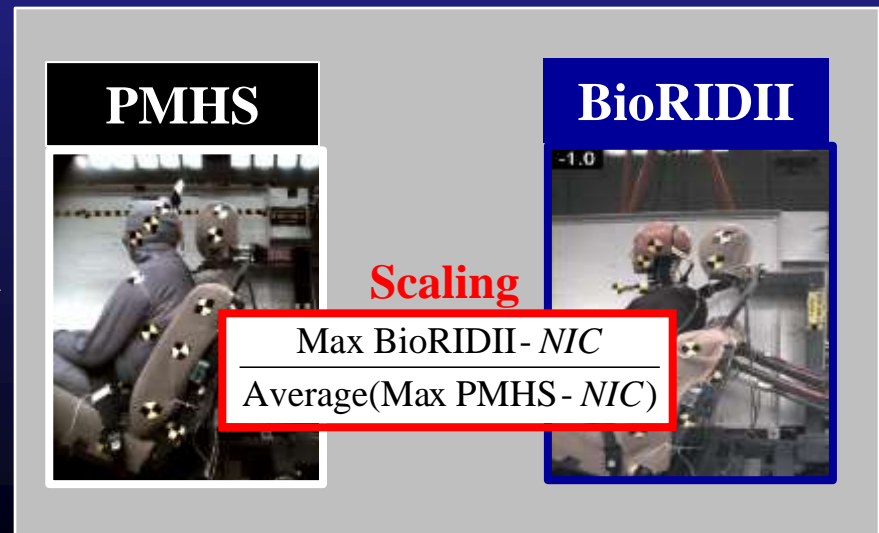


50 % chance of AIS 1+ injuries for BioRIDII

NIC : 61.27 m²/s²



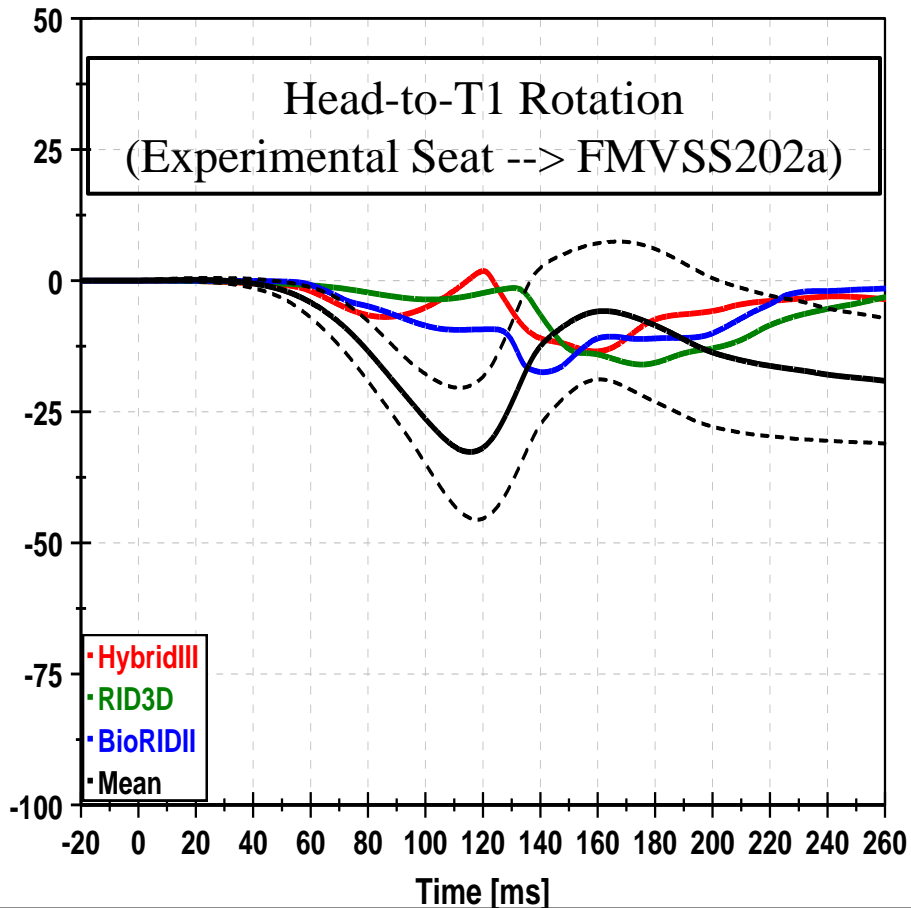
50 % chance of AIS 1+ injuries for PMHS
IV-NICrot : 1.12 → NIC: 61.77 m²/s²





IARV Analysis

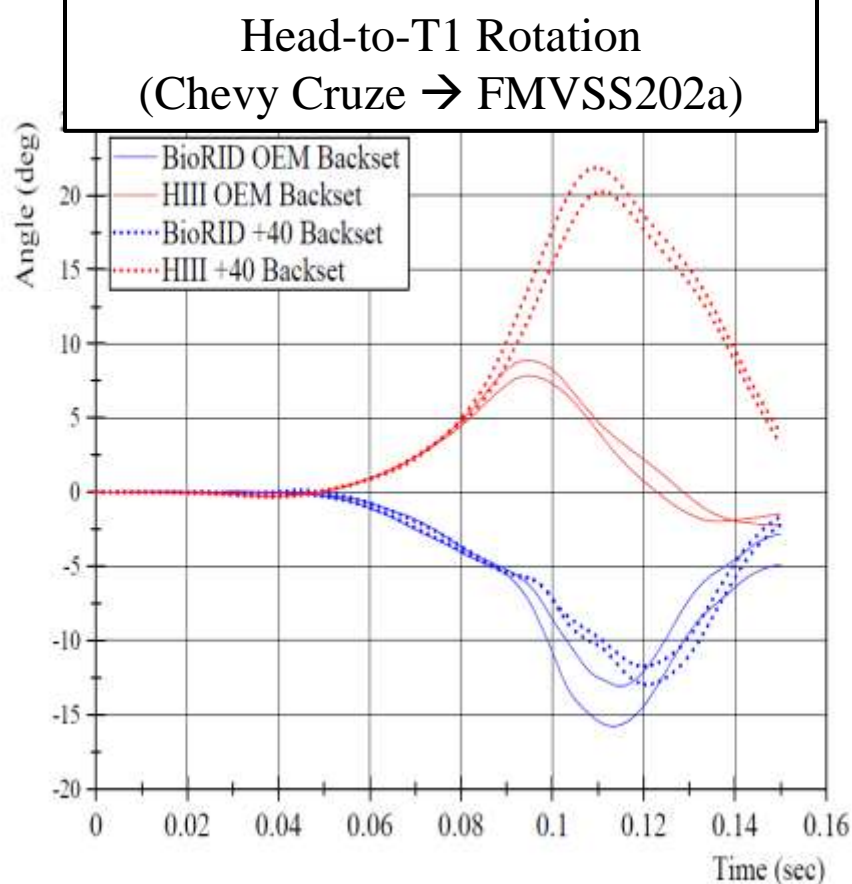
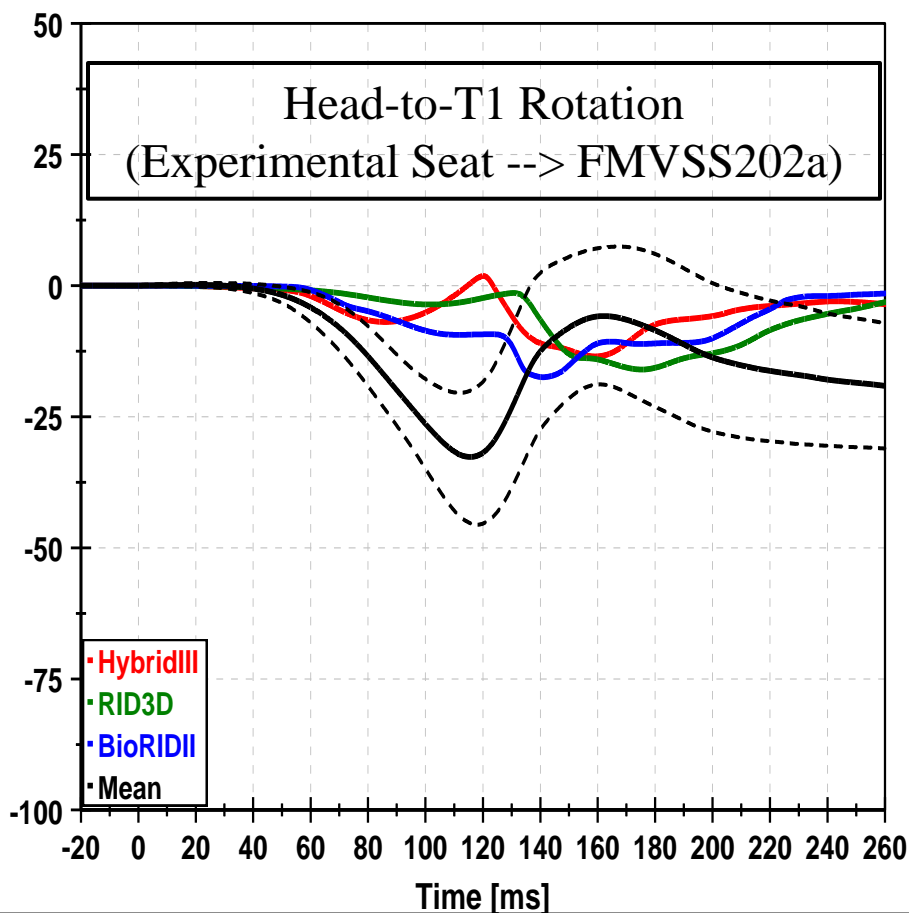
NDCr IARV in flexion??? FMVSS202a criteria is extension





IARV Analysis

NDCr IARV in flexion??? FMVSS202a criteria is extension





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??



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 - For these biofidelity test conditions in the experimental seat
 - Measurement precision??
 - Potential “global” PMHS injury criteria
 - NDCr, NDCx
 - Rates and Products also
 - NDCz and NIC also showed correlation
 - UN/LN Fx & My may have potential



Summary



- BioRIDII IARV(s)
 - PMHS to BioRIDII Correlation study (no success)
 - PMHS IV-NICrot vs. BioRIDII global measures
 - Only two data points
 - PMHS IV-NICrot vs. BioRIDII intervertebral kinematics
 - Poor correlation



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 - PMHS IV-NICrot vs. BioRIDII intervertebral kinematics
 - Poor correlation
 - PMHS to BioRIDII Scaling
 - 50% chance of AIS1+ injuries for BioRIDII
 - Intervertebral rotation : 6.3 deg
 - NDCr : 11.8 deg
 - NDCx: 145 mm
 - NIC: 61.3 m²/s²



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



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 - 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)



Limitations

- **Two Biofidelity test conditions (low-speed, mod-speed)**
 - Yields only two BioRIDII data points
 - Can't do traditional correlation study between BioRIDII measures and PMHS injury predictors
 - Need more paired test conditions



USA & Japan Collaboration



- **Best injury predictor**
 - USA → IV-NICrot
 - Japan → Strain & Strain Rate
 - Common ground:
 - Good correlation between the two



USA & Japan Collaboration



- **Potential “global” injury criteria**
 - USA: IV-NICrot → NDCr, NDCx, NIC
 - Japan: IV-NICrot → NIC, UNFx, UNMy, LNFx, LNMy
 - Common ground:
 - NIC
 - USA: UNFx, UNMy, LNFx, LNMy correlation prior to HR contact
 - Japan: NDCr?? NDCx??



USA & Japan Collaboration



- BioRIDII IARV(s)

- USA: PMHS to BioRIDII scaling

- Preliminary values:

- Intervertebral rotation : 6.3 deg

- NDCr : 11.8 deg

- NDCx: 145 mm

- More testing to strengthen/verify

- Japan: Model IARV(s) applied directly to BioRIDII



Future Work

- **Strengthen and verify results using realistic seats**
 - Test PMHS and BioRIDII (paired tests)
 - Production seats (or more realistic experimental seat)
 - Measure HR loads → pressure mat? load cells?
 - Potential Test Matrix
 - 8 PMHS
 - 2 production seats x 2 pulses x 2 SB angles
 - Feedback or suggestions?
 - Multiple BioRIDII data points for correlation



Thanks for your attention

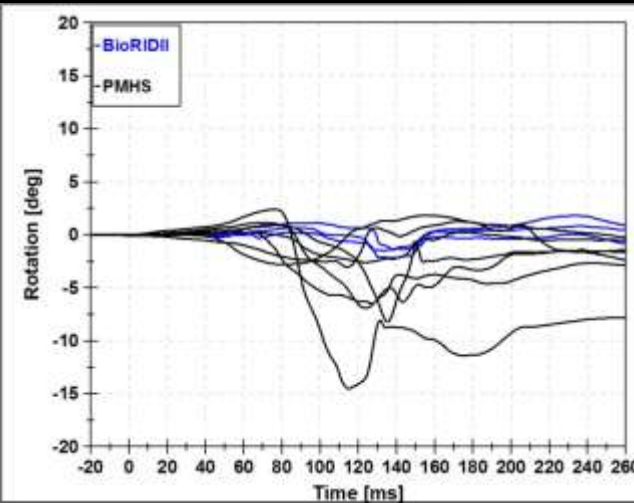


Questions?

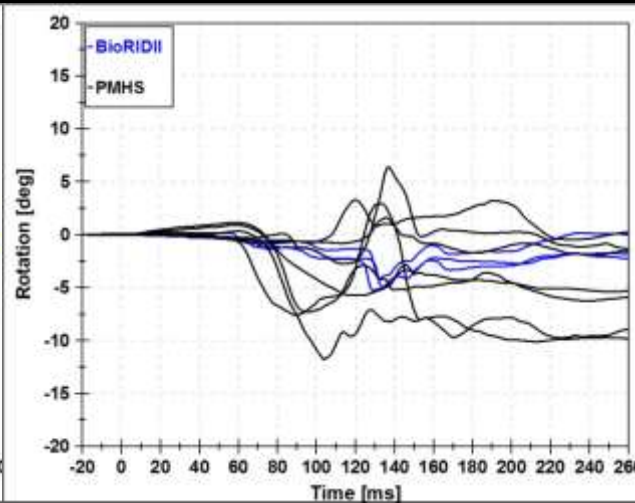




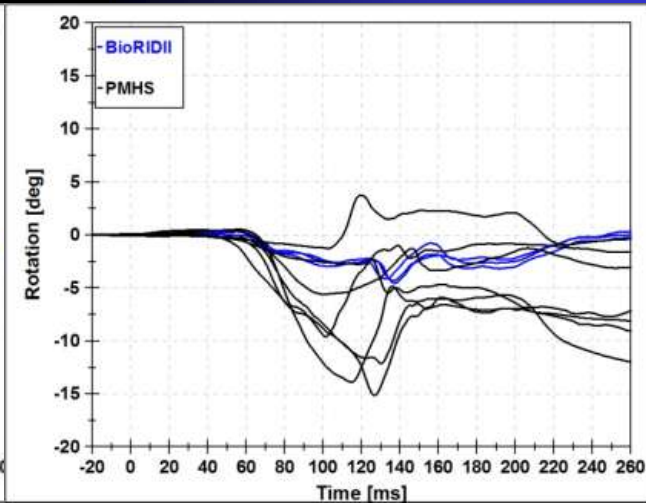
Low Speed – Neck Intervertebral Kinematics



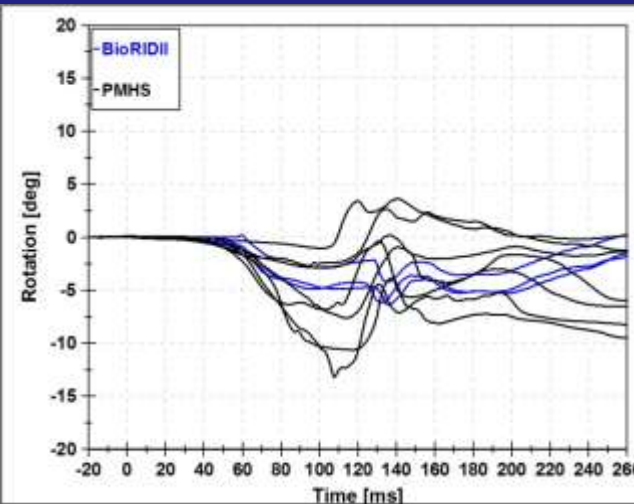
C2/C3



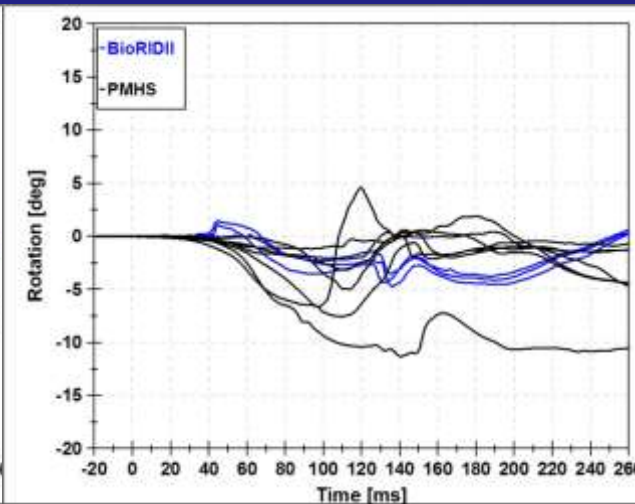
C3/C4



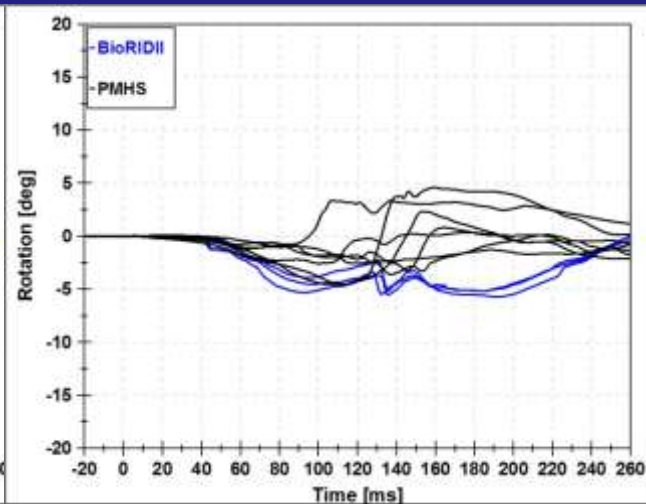
C4/C5



C5/C6



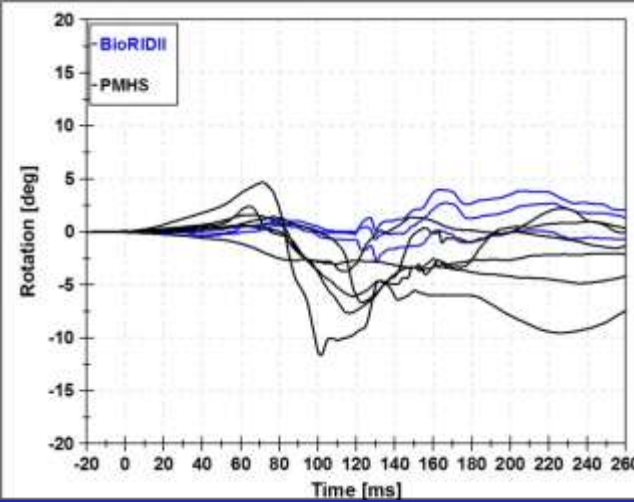
C6/C7



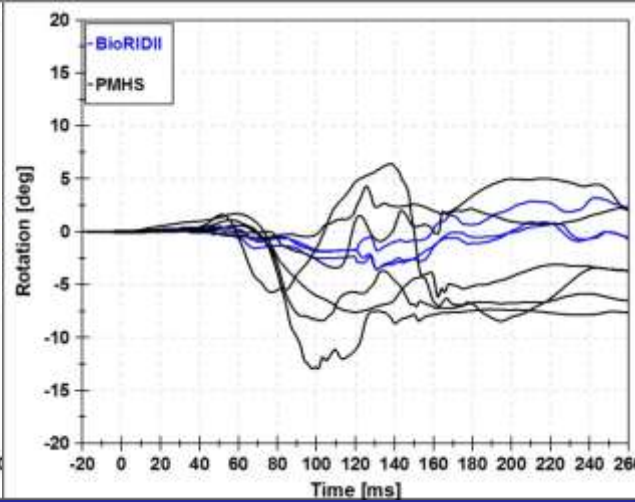
C7/T1



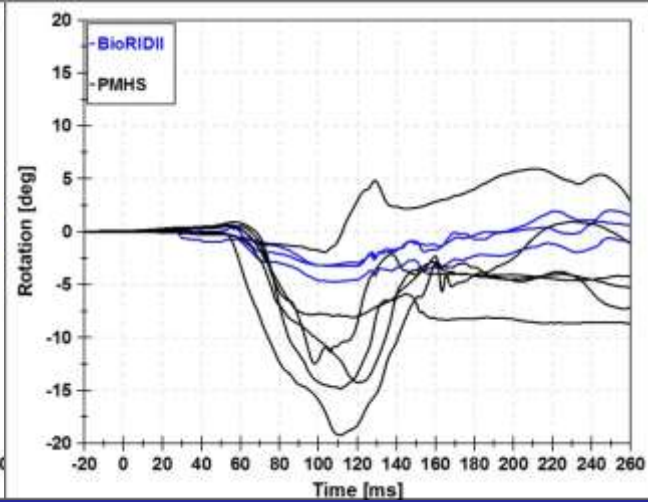
Moderate Speed – Neck Intervertebral Kinematics



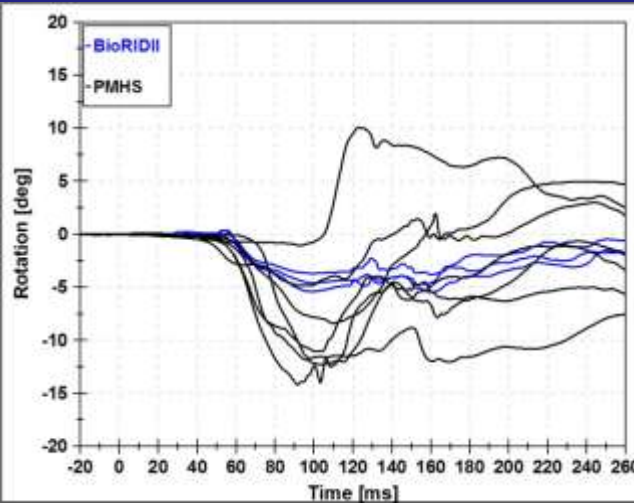
C2/C3



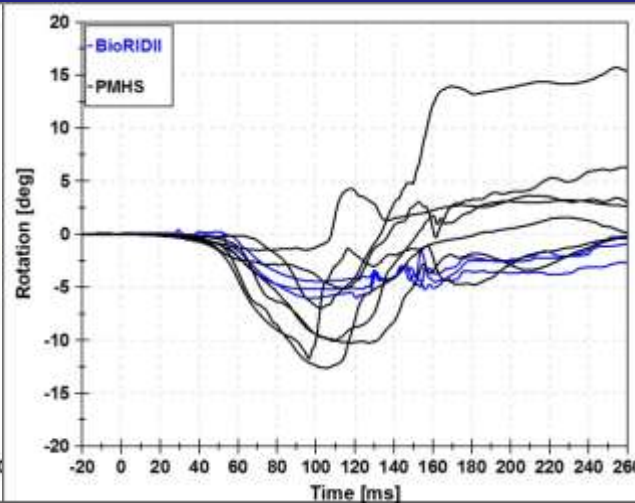
C3/C4



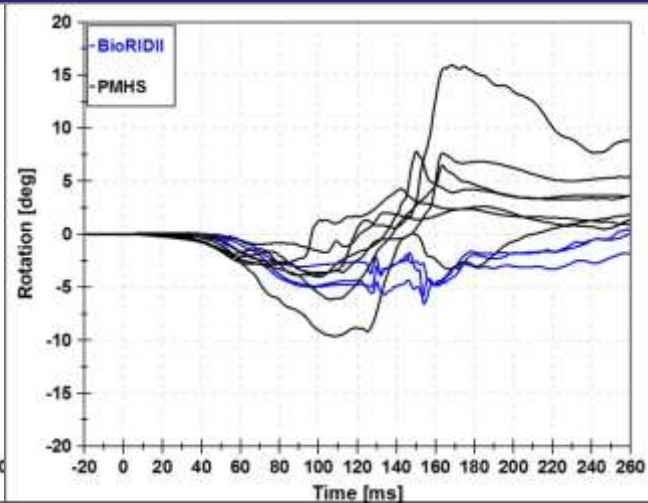
C4/C5



C5/C6



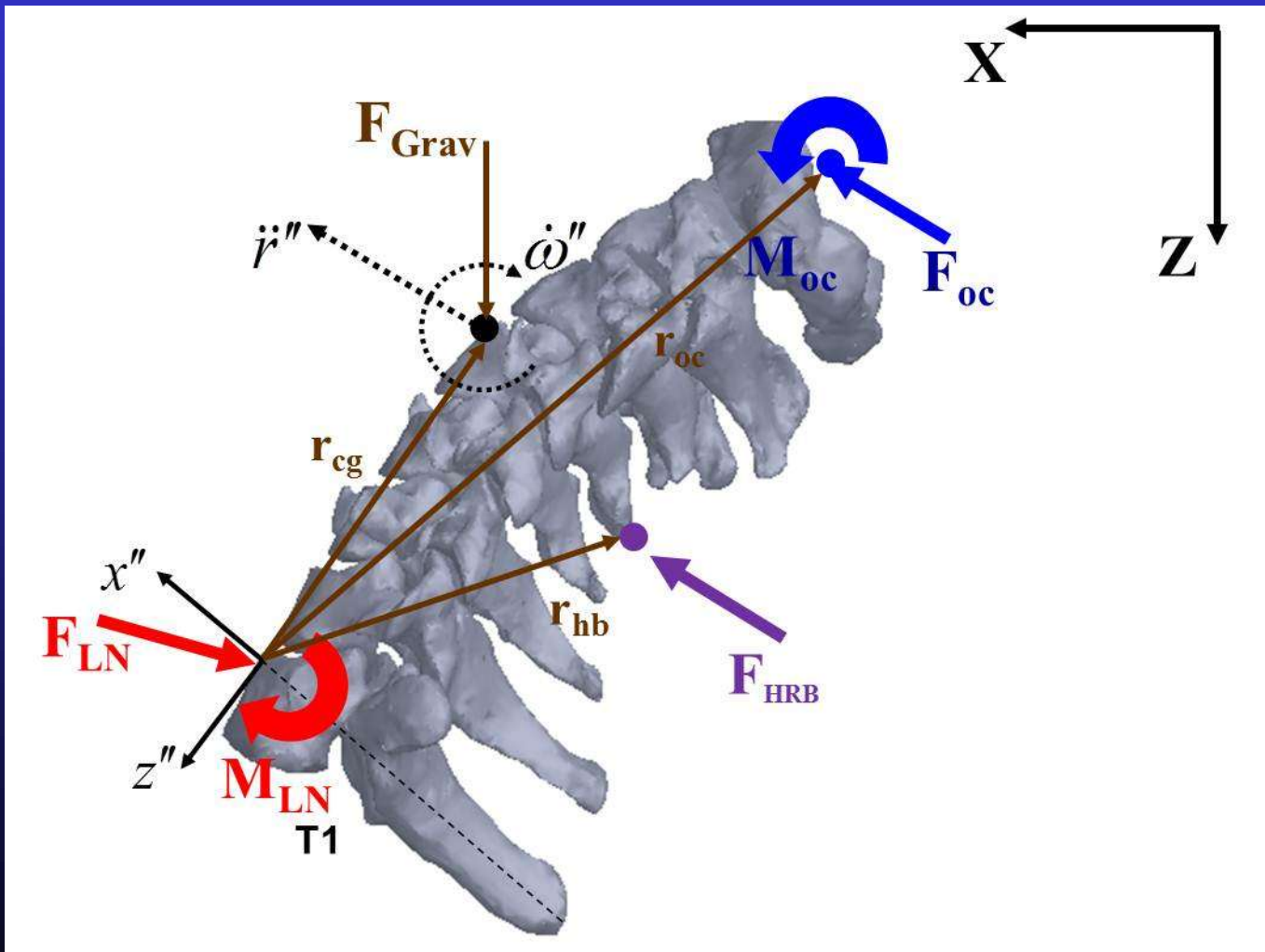
C6/C7



C7/T1



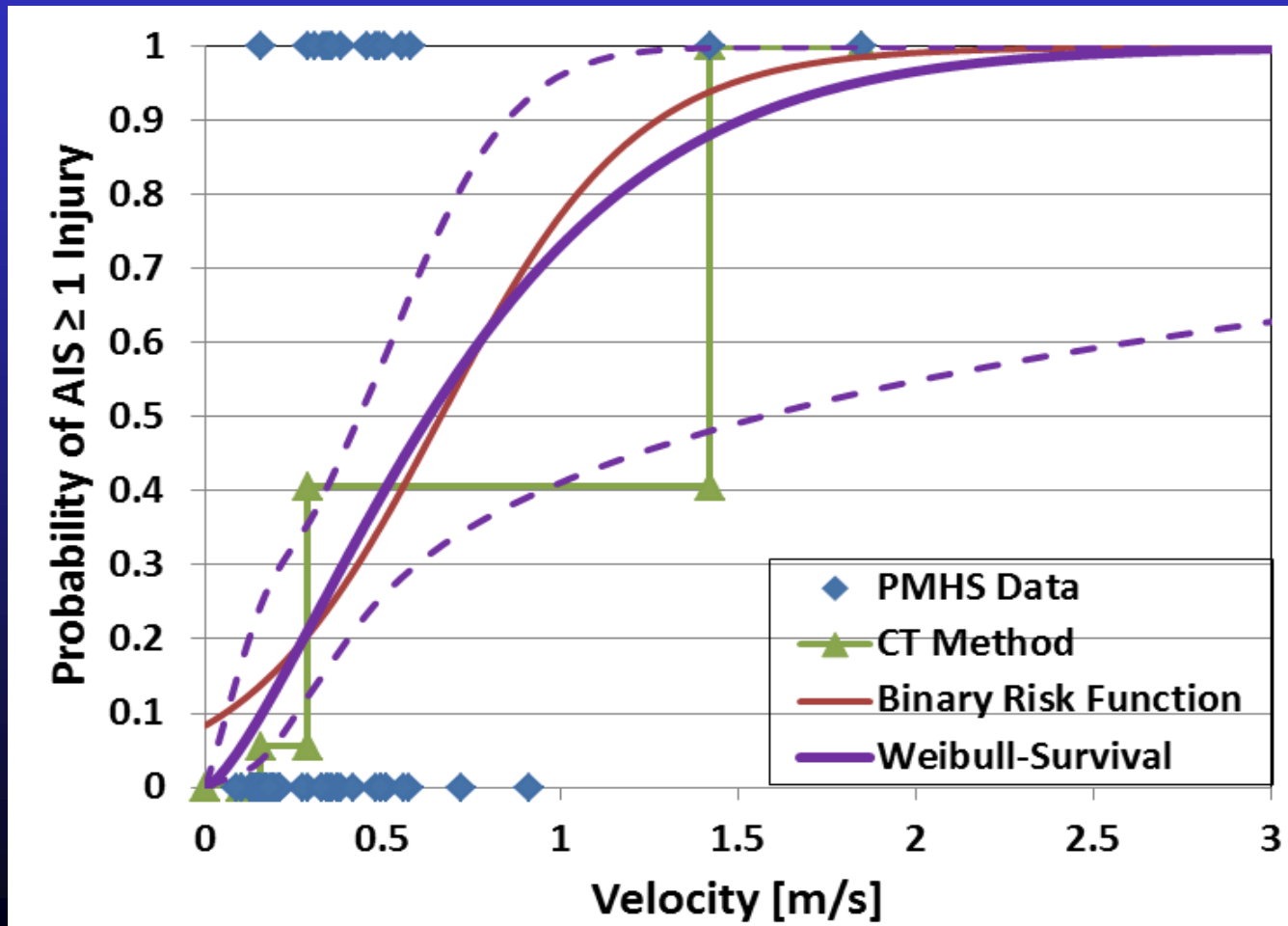
FBD for Lower Neck Loads





Additional Injury Risk Curves

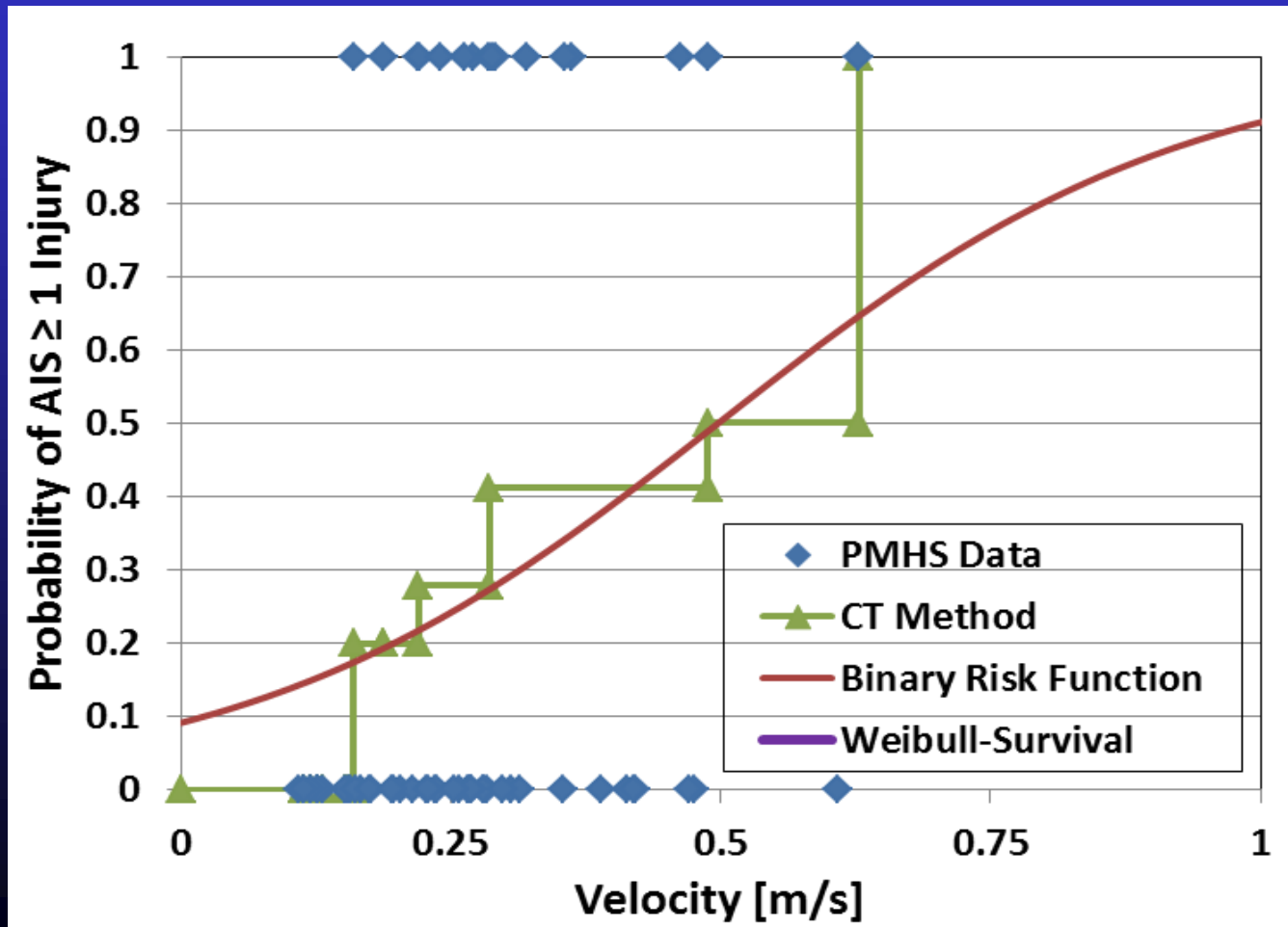
- Intervertebral facet sliding rate (maximum peak)





Additional Injury Risk Curves

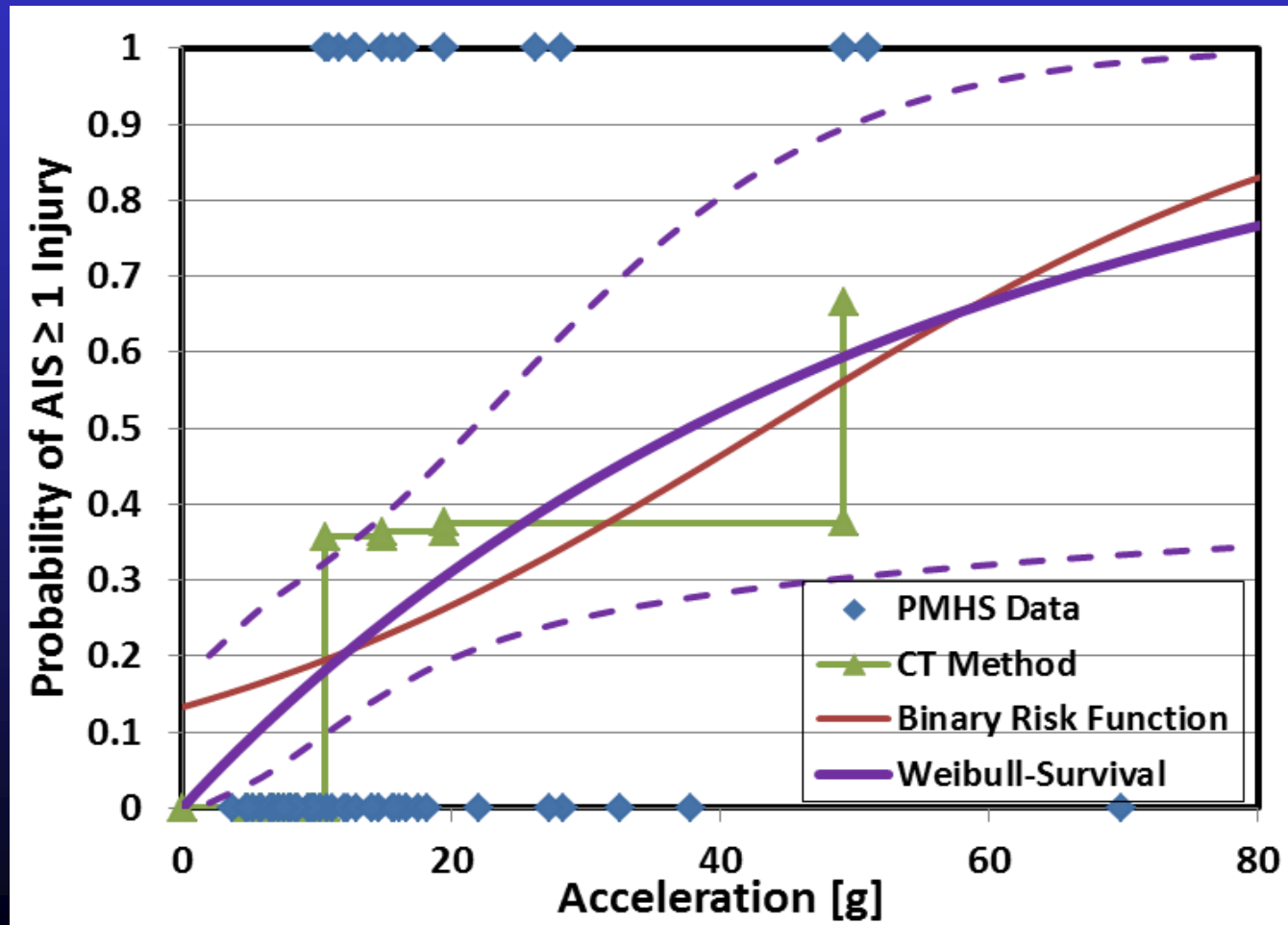
- Intervertebral facet axial rate (maximum peak)





Additional Injury Risk Curves

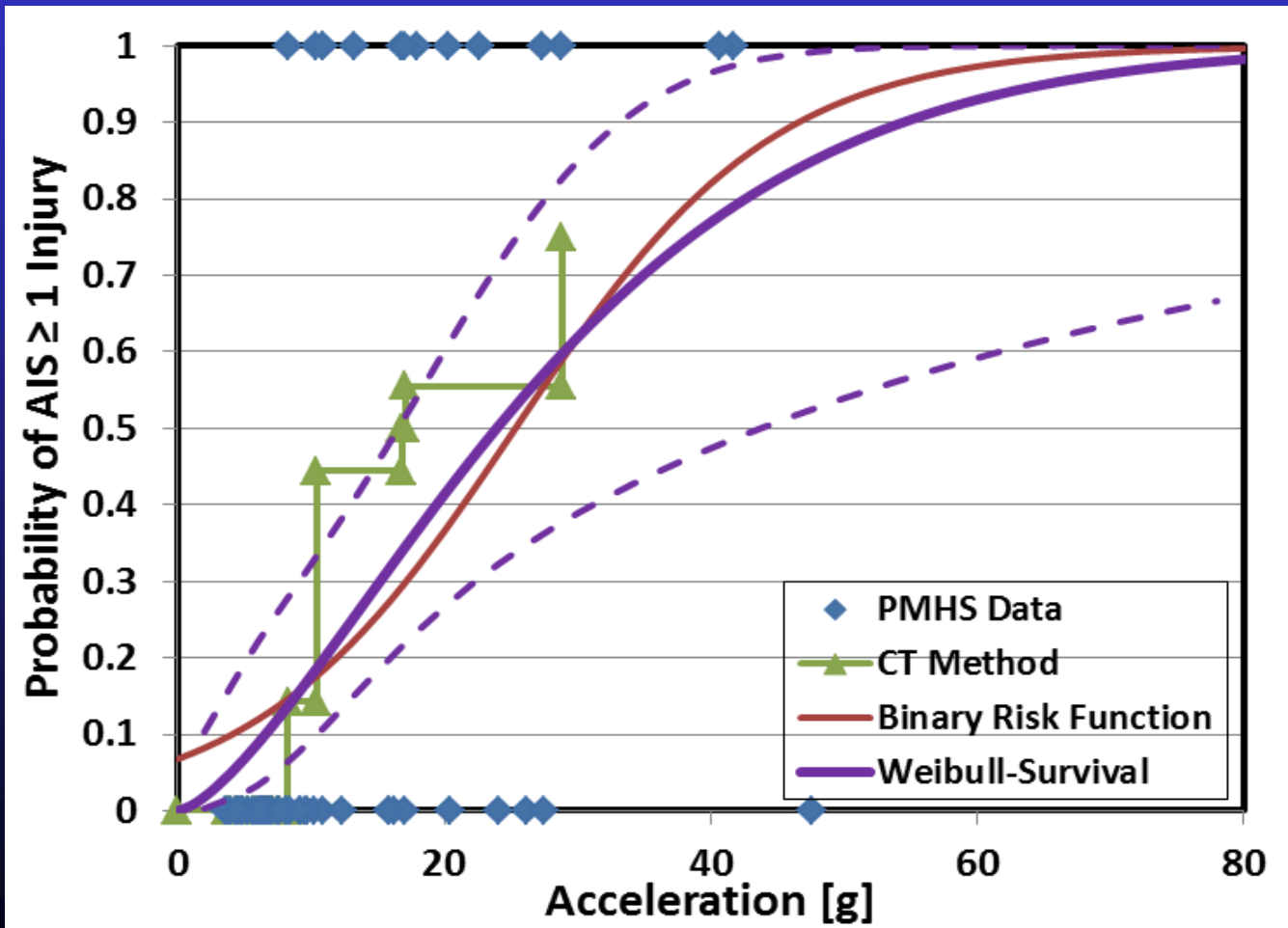
- Intervertebral acceleration (positive peak x)





Additional Injury Risk Curves

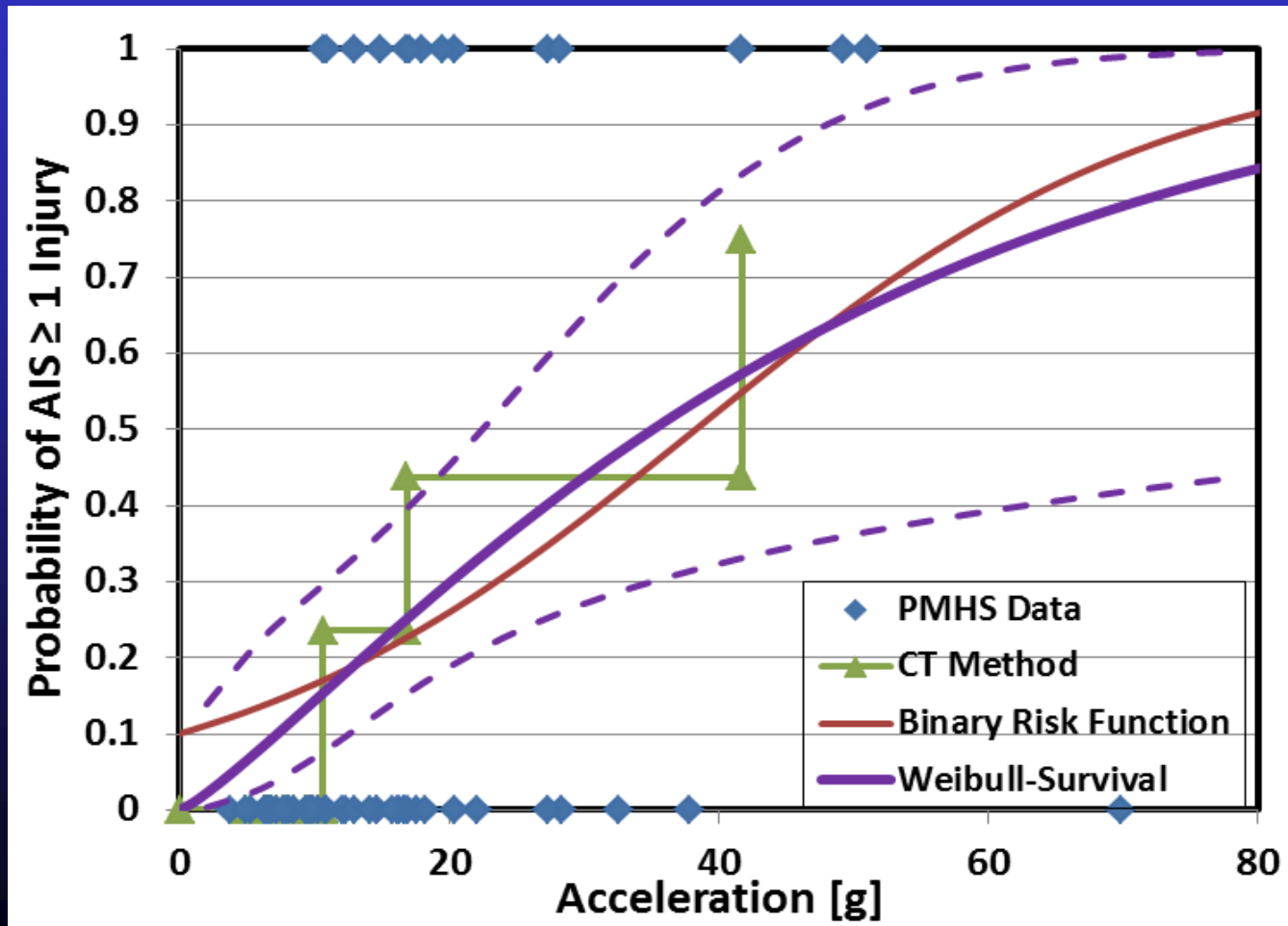
- Intervertebral acceleration (negative peak x)





Additional Injury Risk Curves

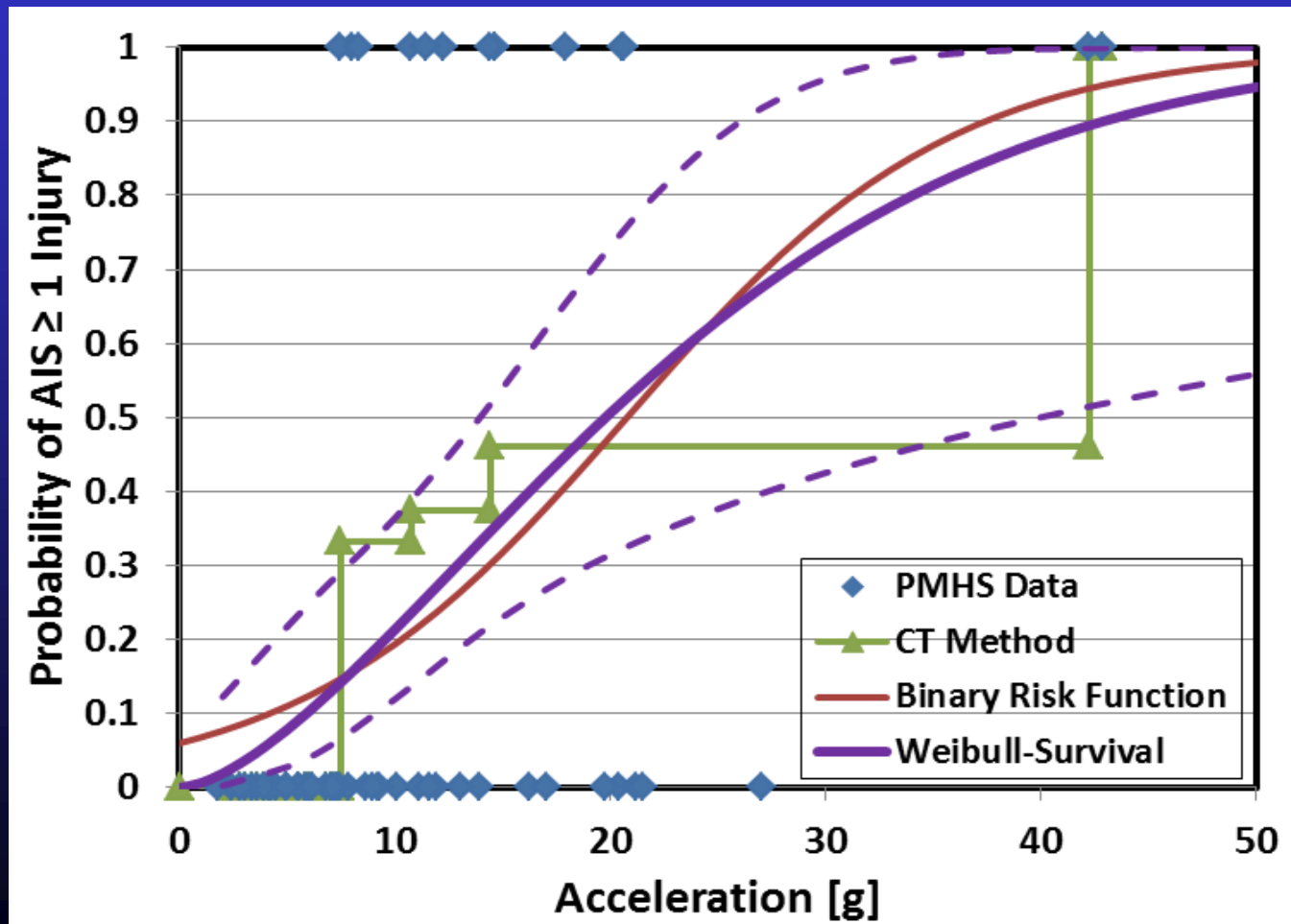
- Intervertebral acceleration (maximum peak x)





Additional Injury Risk Curves

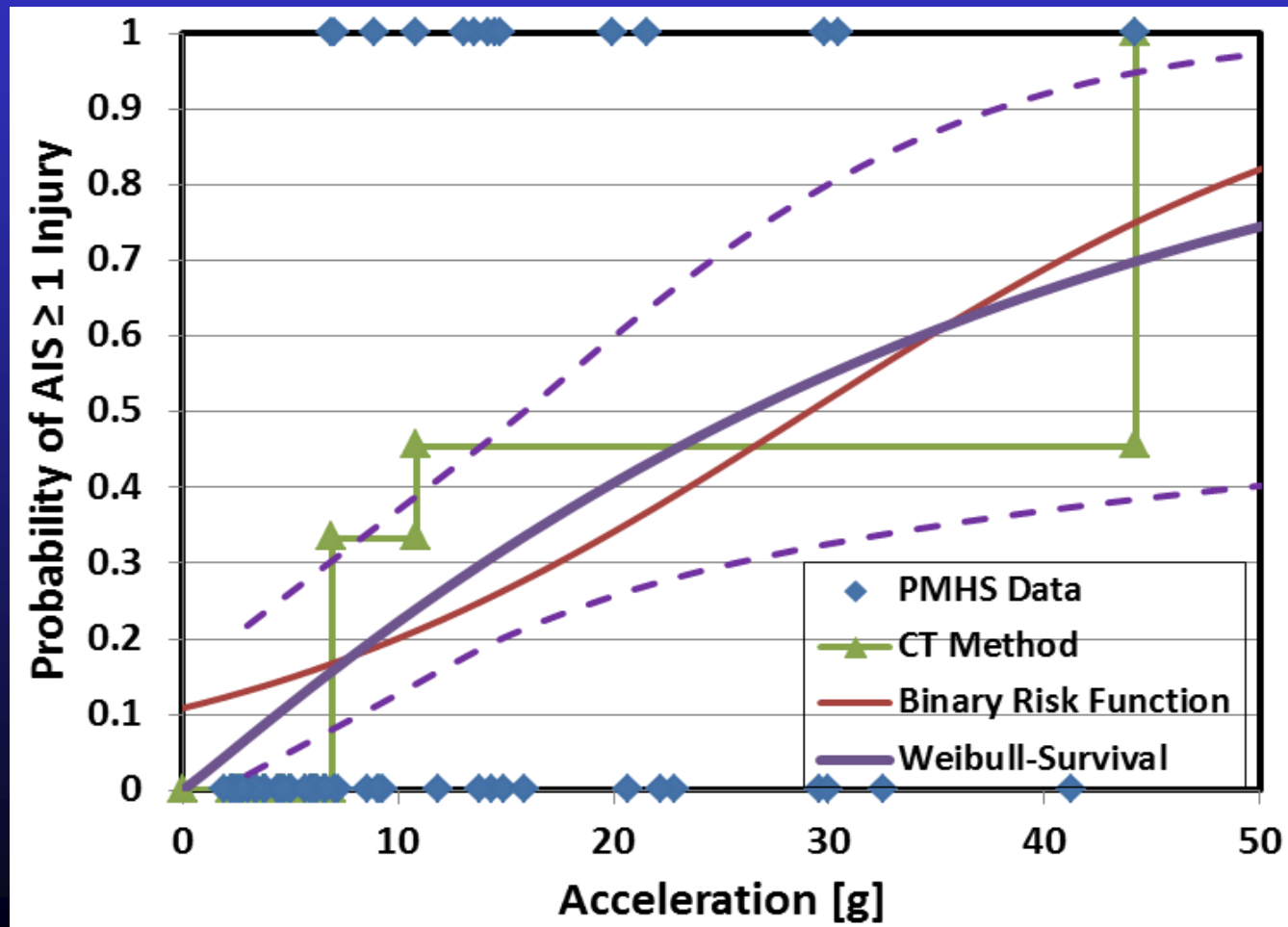
- Intervertebral acceleration (positive peak z)





Additional Injury Risk Curves

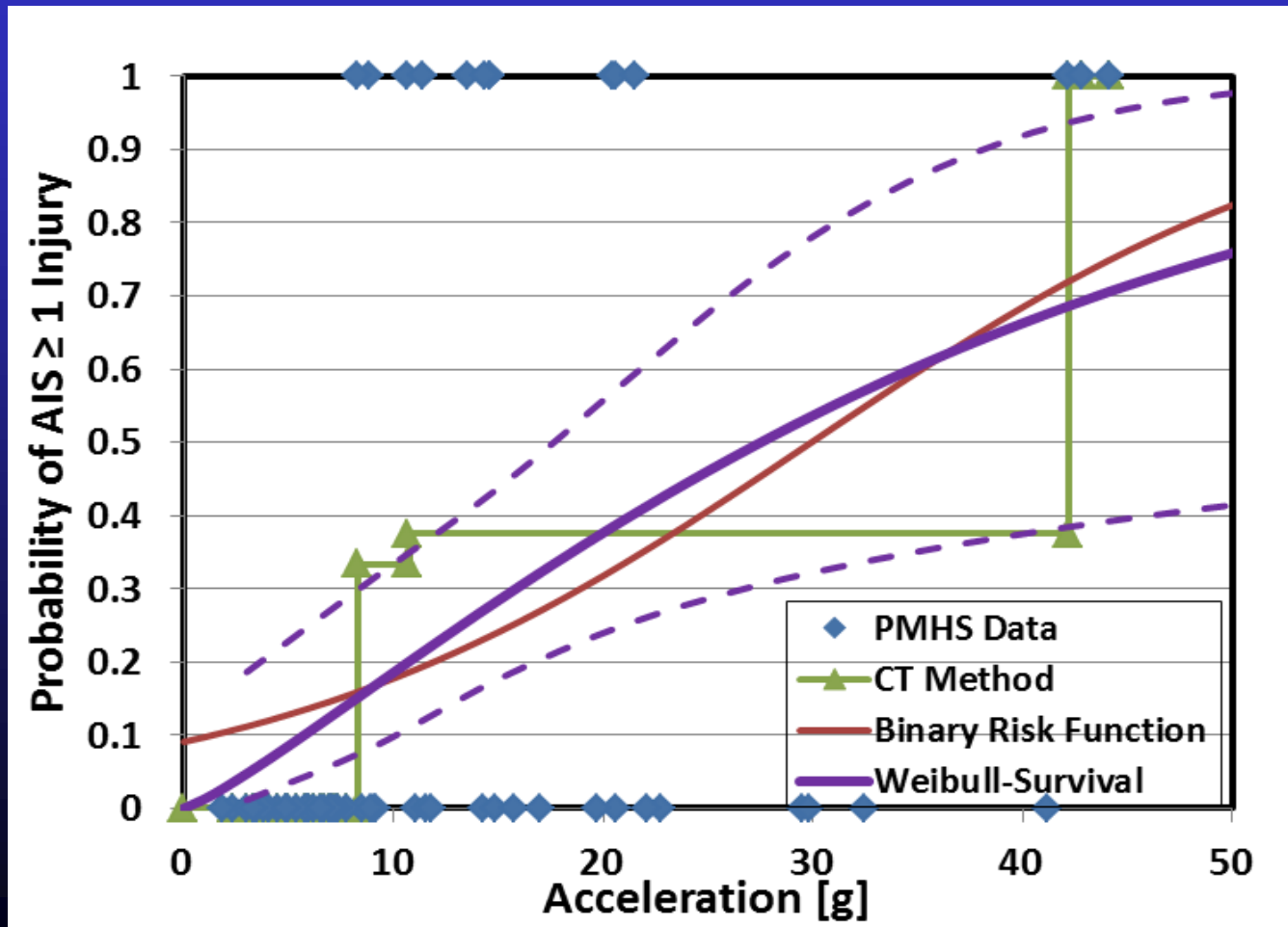
- Intervertebral acceleration (negative peak z)





Additional Injury Risk Curves

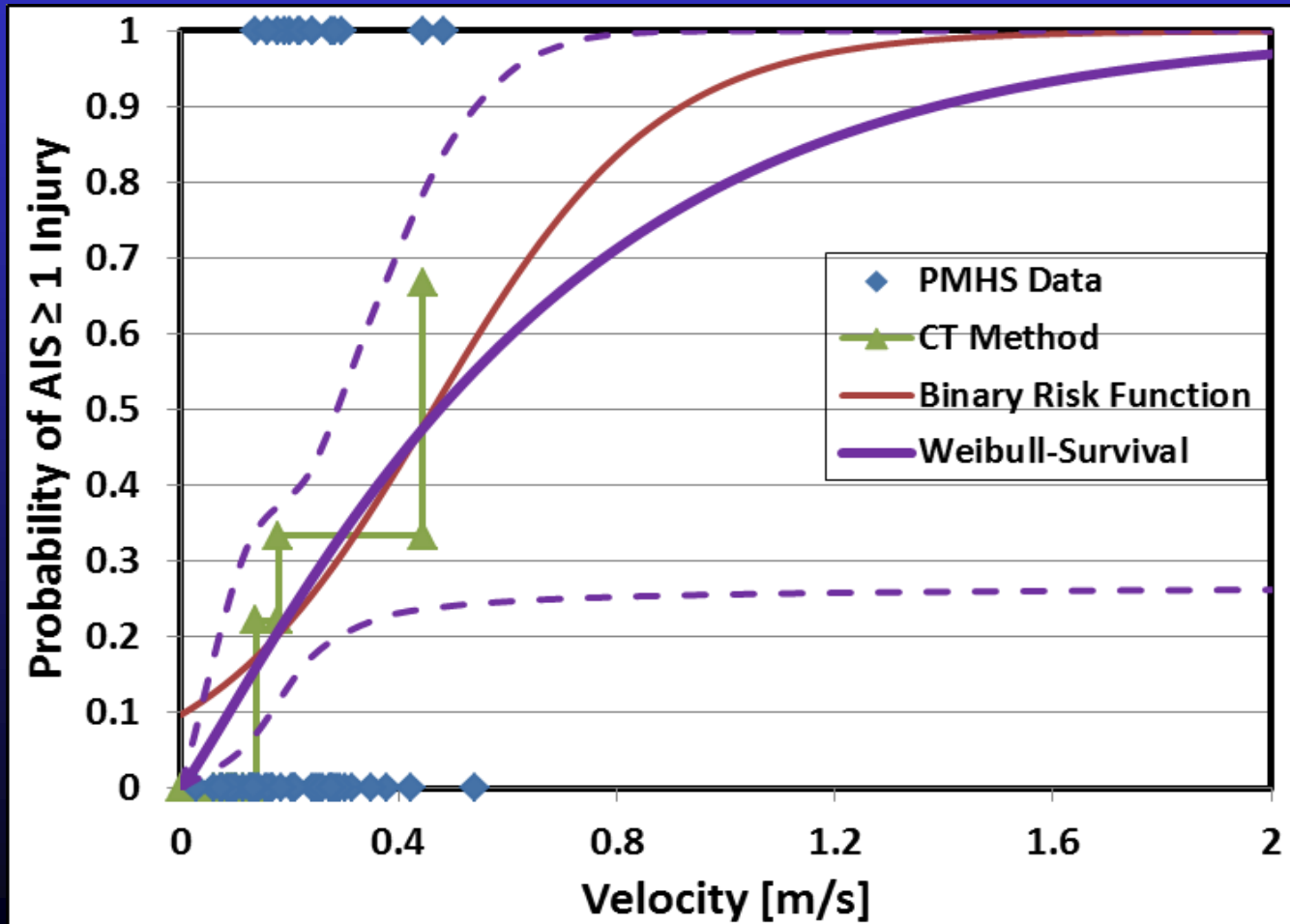
- Intervertebral acceleration (maximum peak z)





Additional Injury Risk Curves

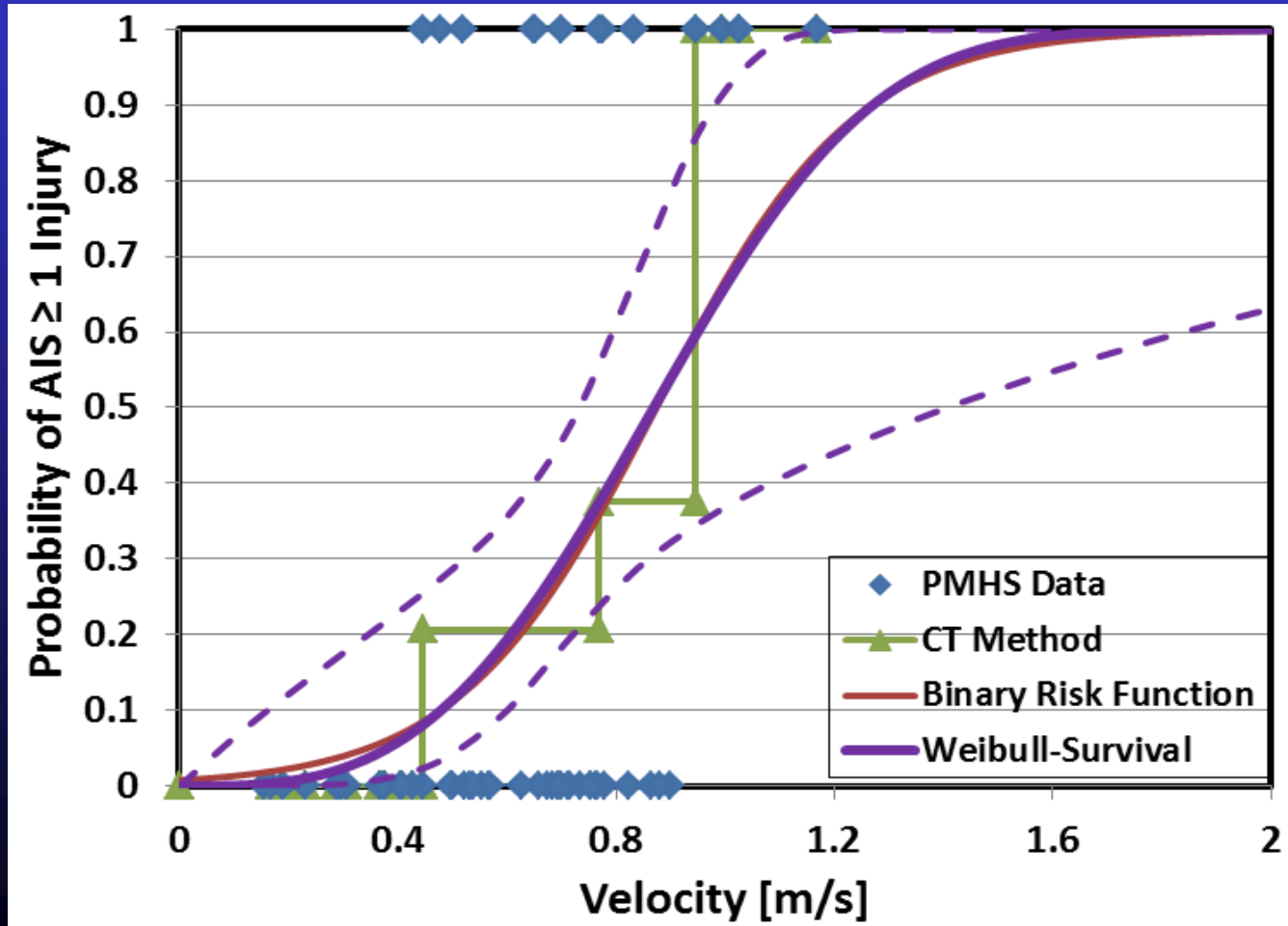
- Intervertebral velocity (positive peak x)





Additional Injury Risk Curves

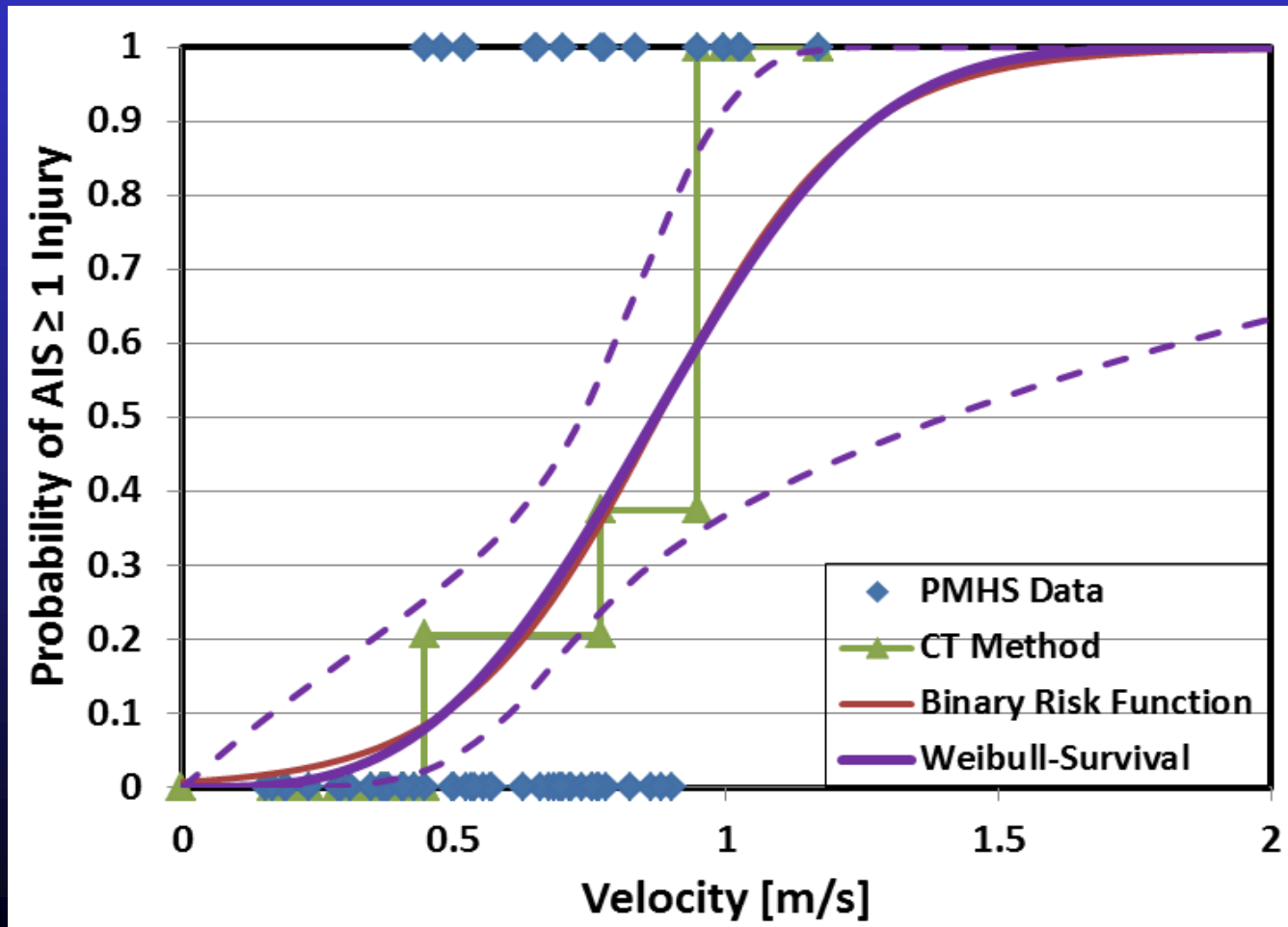
- Intervertebral velocity (negative peak x)





Additional Injury Risk Curves

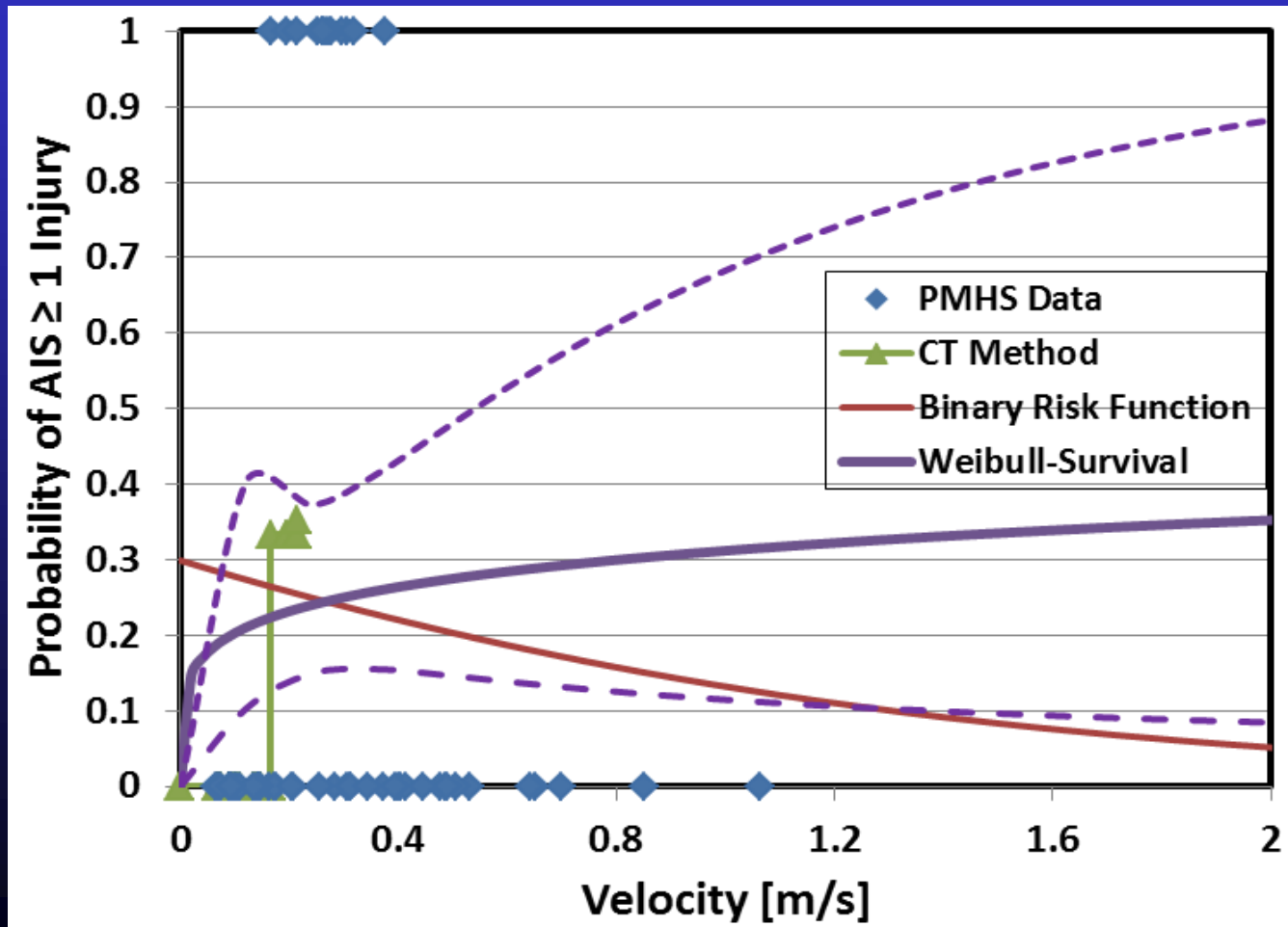
- **Intervertebral velocity (maximum peak x)**





Additional Injury Risk Curves

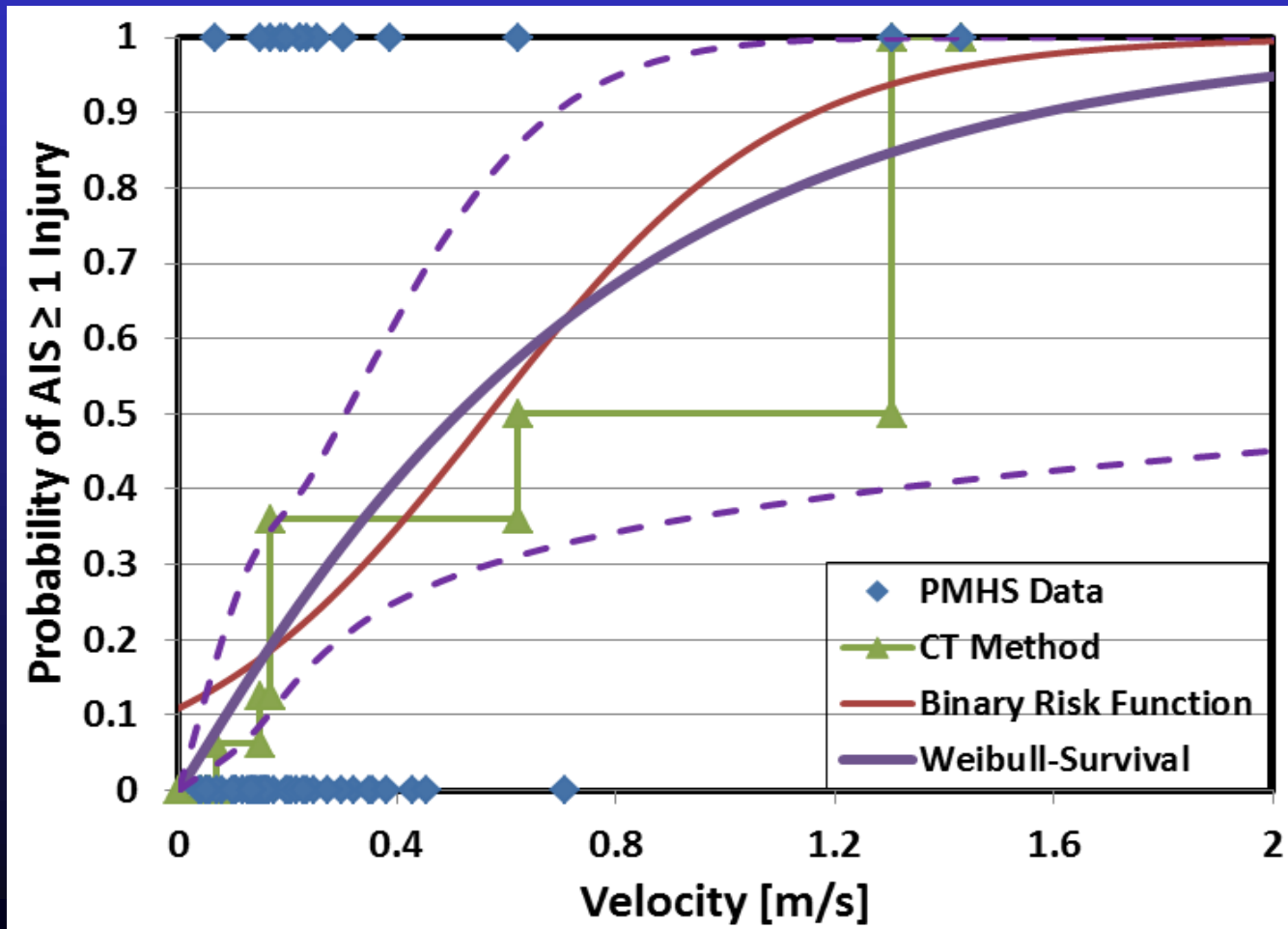
- Intervertebral velocity (positive peak z)





Additional Injury Risk Curves

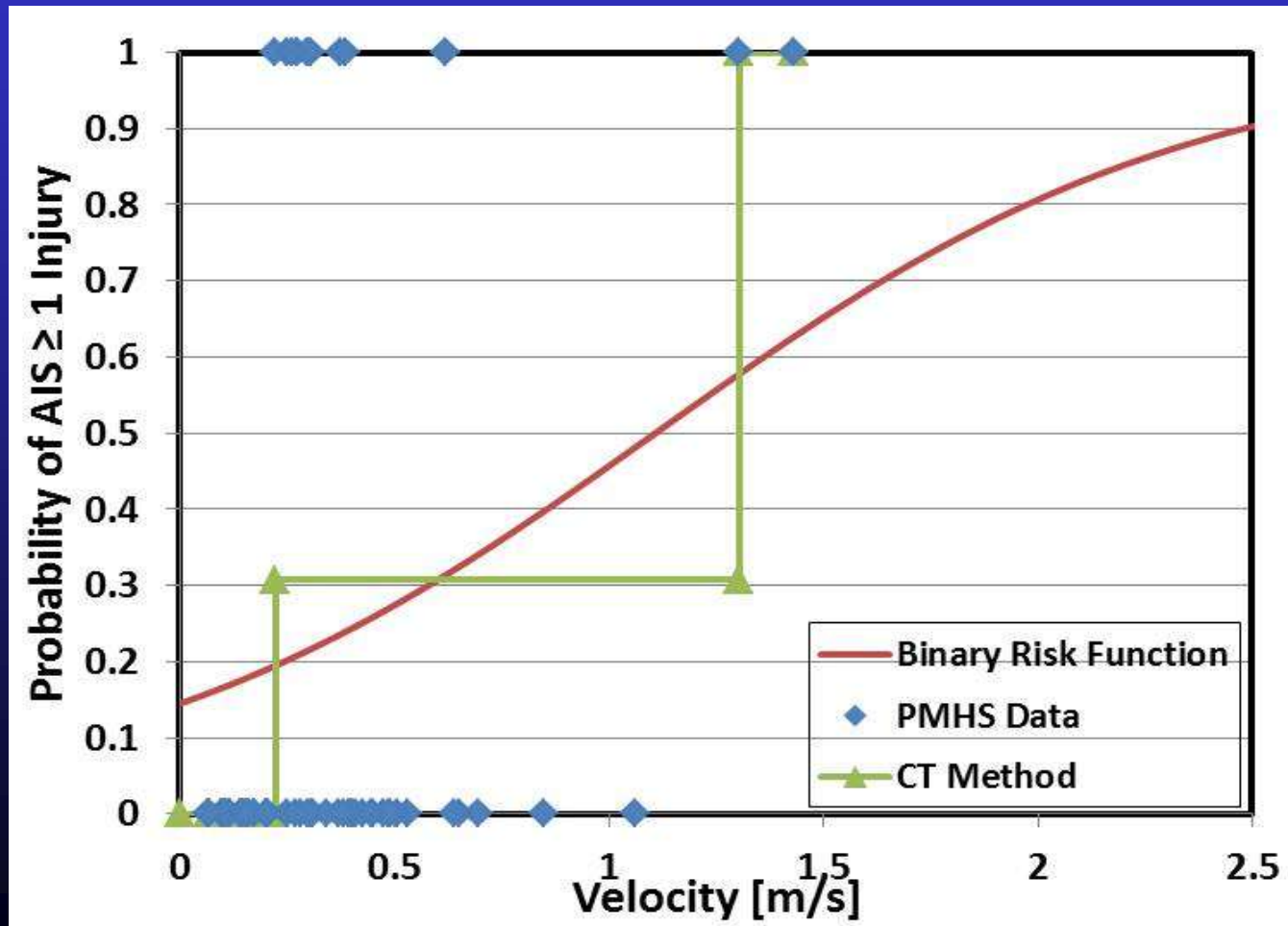
- Intervertebral velocity (negative peak z)





Additional Injury Risk Curves

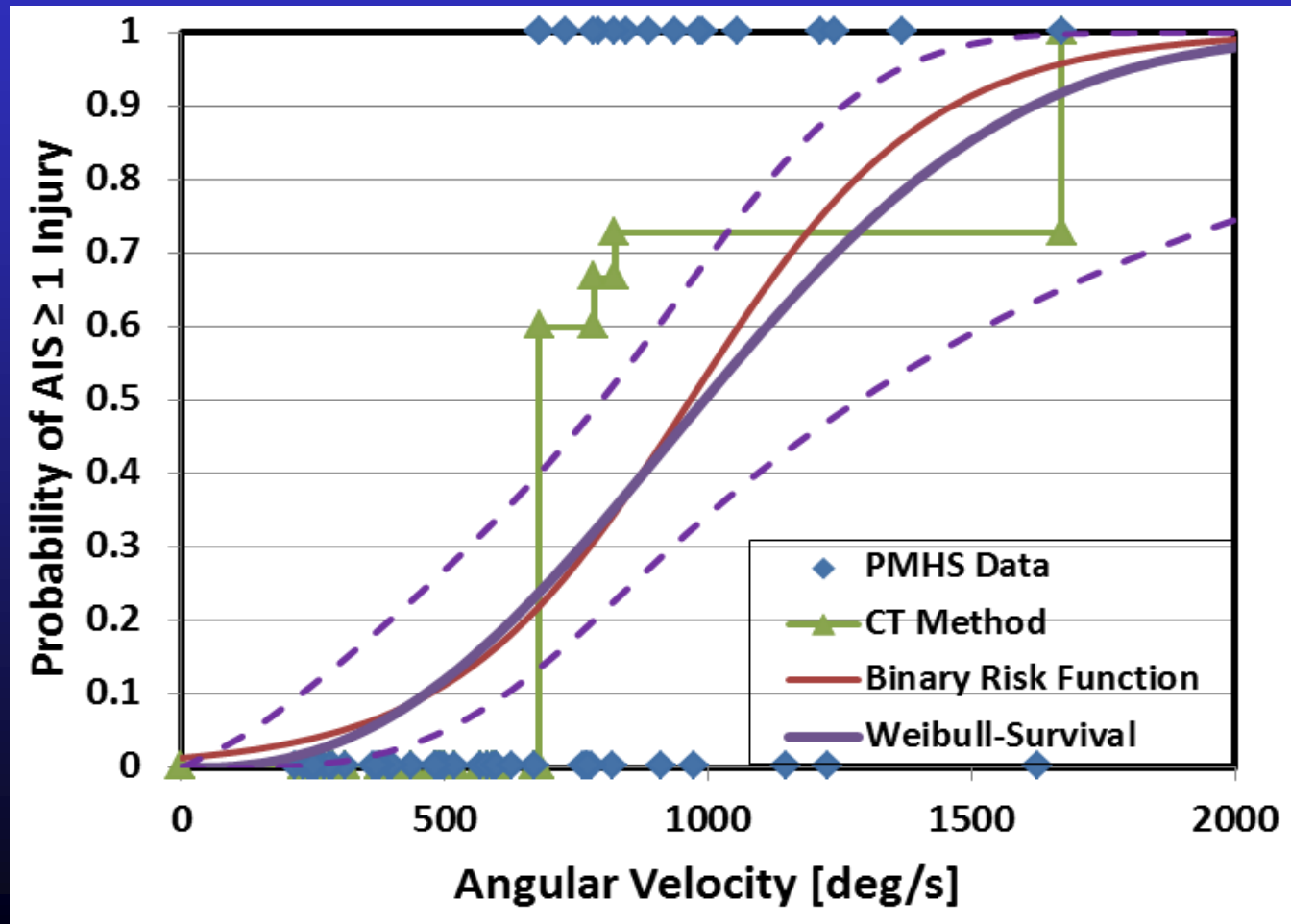
- **Intervertebral velocity (maximum peak z)**





Additional Injury Risk Curves

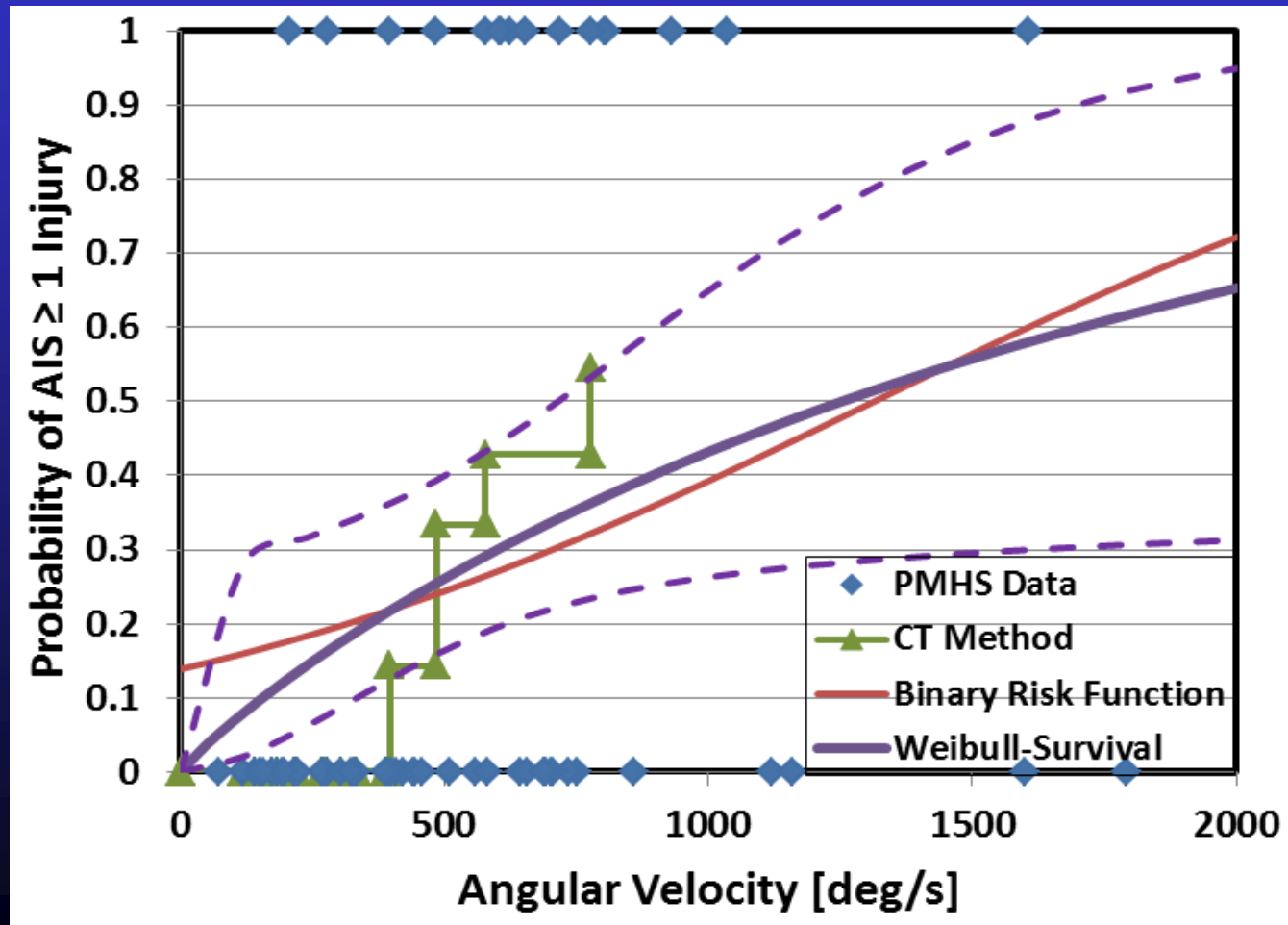
- Intervertebral angular velocity (positive peak $\dot{\gamma}$)





Additional Injury Risk Curves

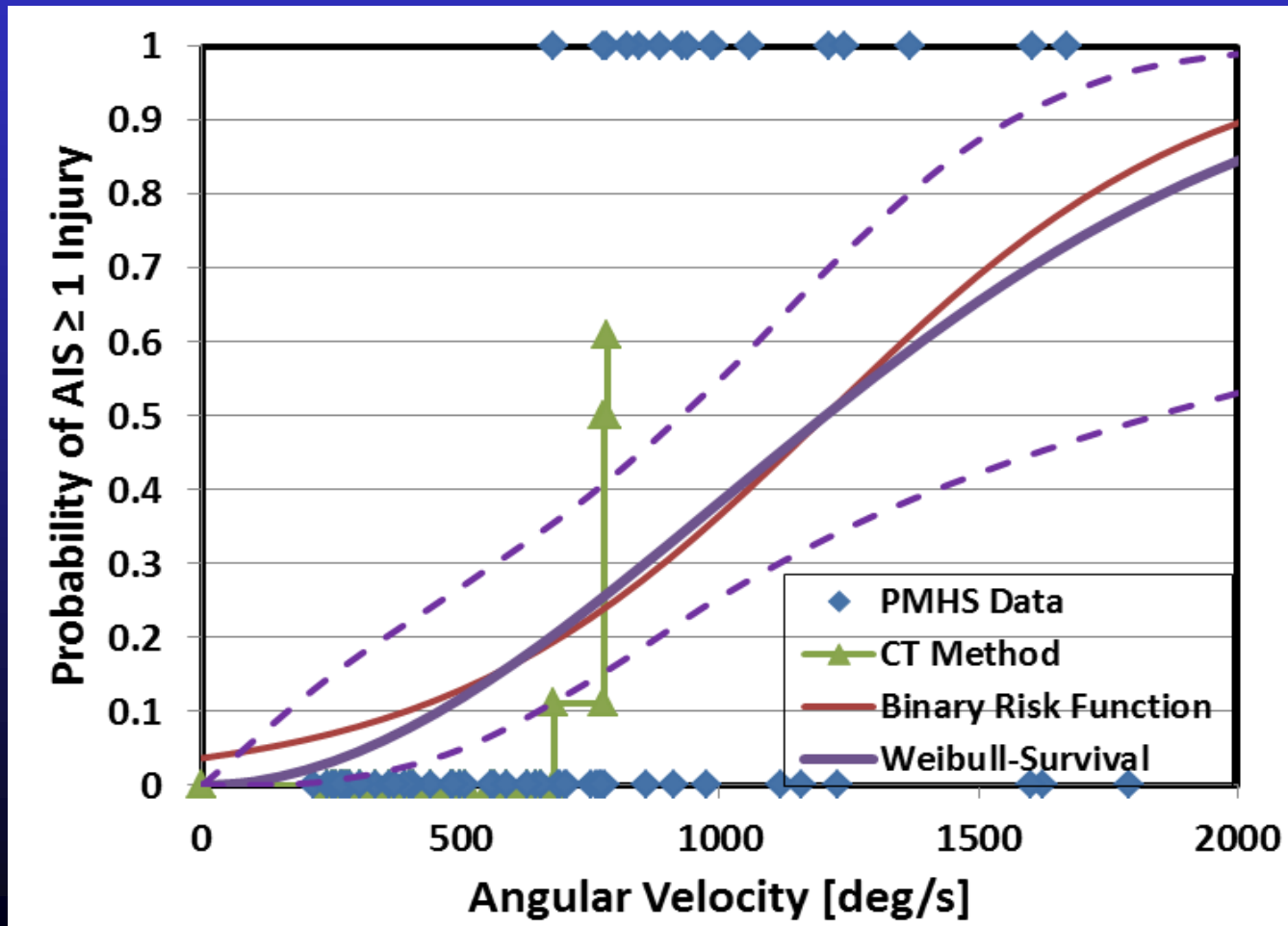
- Intervertebral angular velocity (negative peak $\dot{\gamma}$)





Additional Injury Risk Curves

- Intervertebral angular velocity (maximum peak $\dot{\gamma}$)





Cervical Kinematics (detailed geometry)

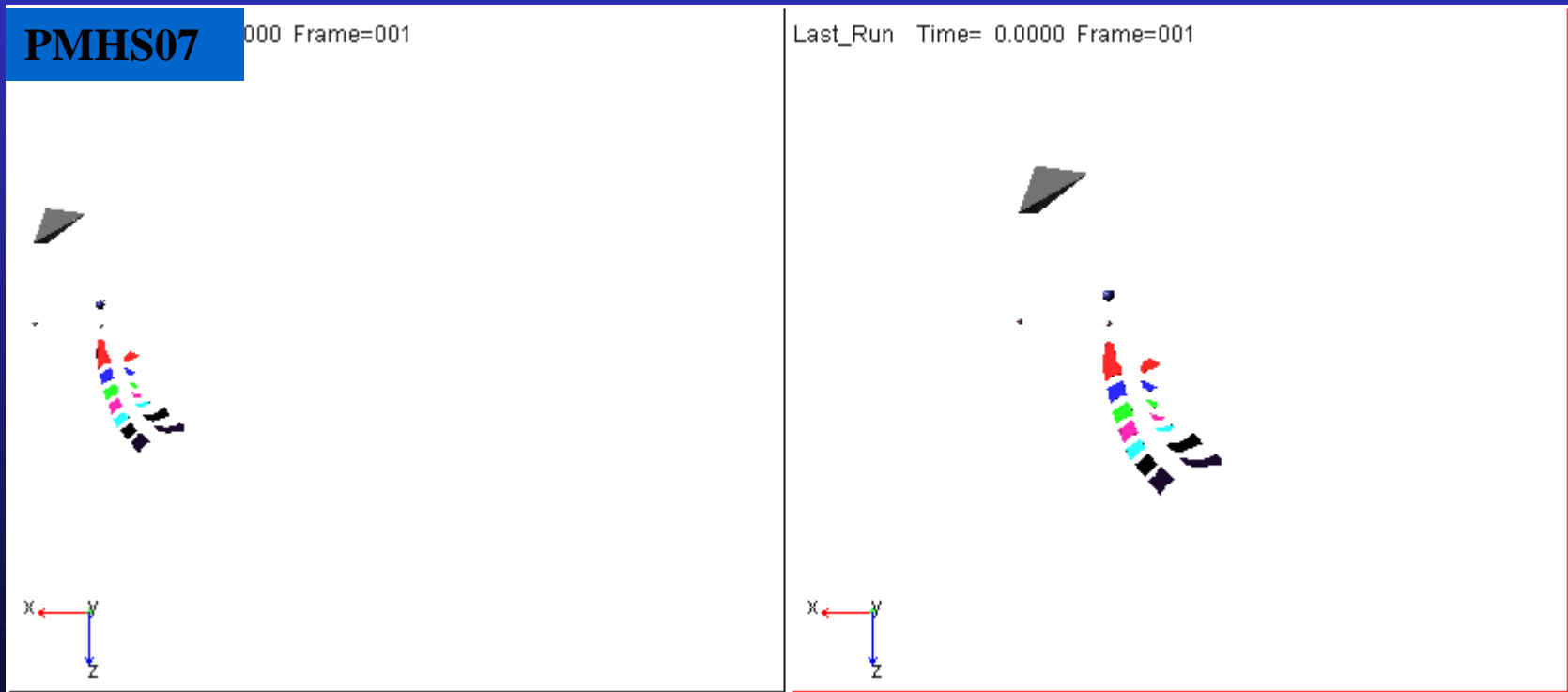
- Detailed cervical model





Cervical Kinematics (detailed geometry)

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

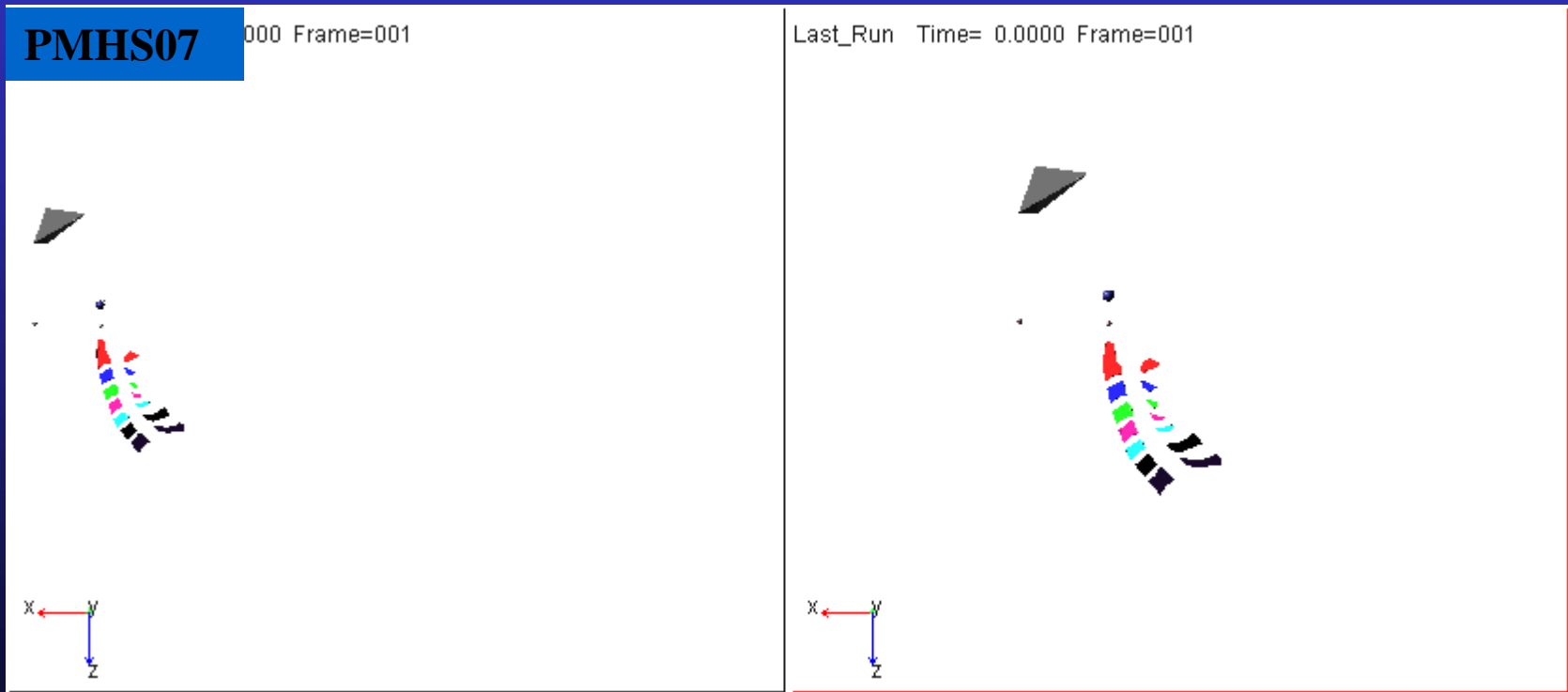


correlation between strain/strain rate and injuries at each level



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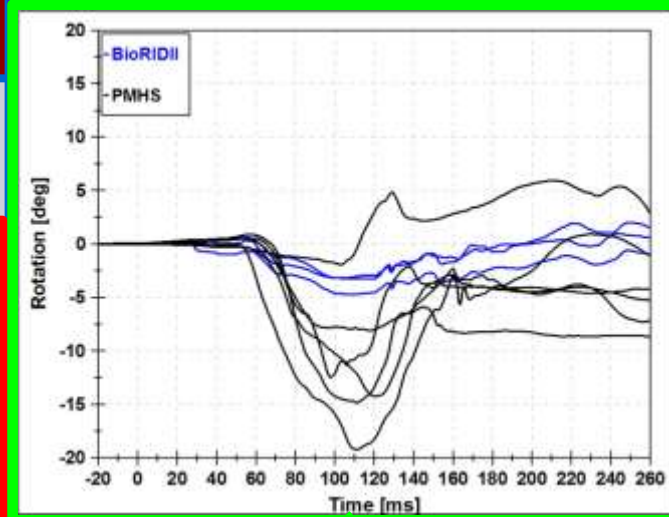
correlation between strain/strain rate and injuries at each level



IV-NIC Calculation

Physiological Relative Rotation (Panjabi, 2005)

	Physiological Flexion(-)/Extension(+)	Max values Flexion/Extension
C2/C3	-5.4(2.3)/+3.6(1.8)	-7.7/+5.4
C3/C4	-5.7(2.7)/+4.2(1.9)	-8.4/+6.1
C4/C5	-7.6(2.7)/+6.7(2.9)	-10.3/+9.6
C5/C6	-7.7(4.5)/+6.5(3.5)	-12.2/+10.0
C6/C7	-8.0(1.6)/+7.1(2.2)	-9.6/+9.3
C7/T1	-3.7(1.6)/+3.1(1.1)	-5.3/+4.2



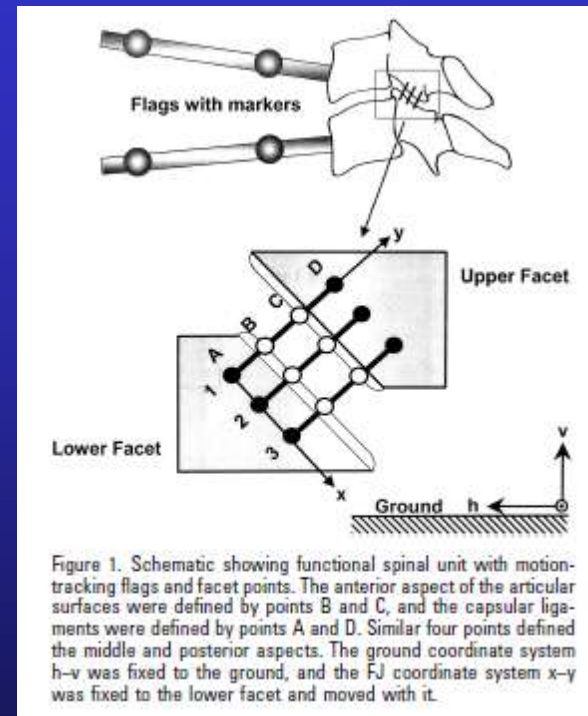
$$IV - NIC = \begin{matrix} \text{⊖} & \text{⊕} \\ \text{trauma} & \text{physiological} \end{matrix}$$



IV-NIC Calculation

Physiological Relative Displacement (Pearson, 2004)

	Physiological Compression (y) (mm)	Physiological Sliding (x) (mm)
C2/C3	-0.40	2.40
C3/C4	-0.20	1.60
C4/C5	-1.00	2.80
C5/C6	-0.60	2.70
C6/C7	-1.80	2.90



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

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