

# PMHS Responses and Injuries in a Homogeneous Rear-Facing Seat Condition at a High-Speed Frontal Impact

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RCCADS Public Workshop



**I N J U R Y   B I O M E C H A N I C S**  
**R E S E A R C H   C E N T E R**



**THE OHIO STATE UNIVERSITY**

# Importance of Study

- Future vehicle interior cabin designs may incorporate non-standard seating configurations for vehicles with Automated Driving Systems (ADS).
  - One potential configuration is a reclined seat that is rear-facing in a frontal collision

[Jorlov et al., 2017; Koppel et al., 2019; Östling and Larsson, 2019]



# Importance of Study

- Future vehicle interior cabin designs may incorporate non-standard seating configurations for vehicles with Automated Driving Systems (ADS).
  - One potential configuration is a reclined seat that is rear-facing in a frontal collision

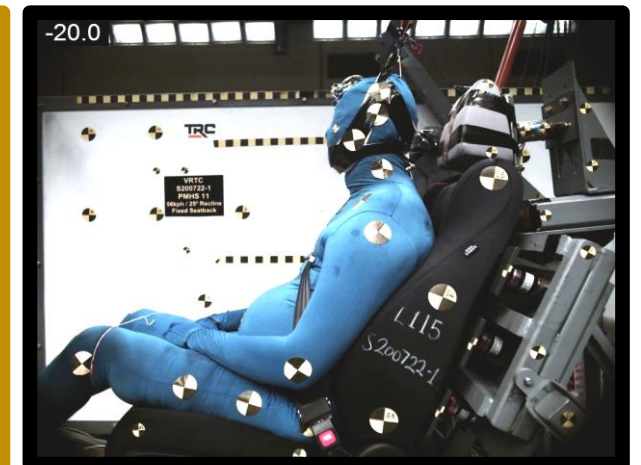
[Jorlov et al., 2017; Koppel et al., 2019; Östling and Larsson, 2019]

- OSU/NHTSA [Kang et al., 2020 & 2021]
  - PMHS responses and injuries at  $\Delta V$  of 56km/h
  - Original equipment manufacture (OEM) seats
  - PMHS injuries
    - Cervical spine laxity
    - Upper extremity injuries
    - Lower extremity injuries
    - Rib fractures
    - Pelvis fractures

ABTS/Odyssey



FDR/accord



# Motivation

- PMHS rib fractures
  - Both 25- and 45-degree recline conditions
  - Both OEM seats
- Seatback properties of the OEM seats
  - Not designed for rear-facing conditions
- Key design parameters
  - Evenly distributed loading

ABTS/Odyssey



FDR/Accord



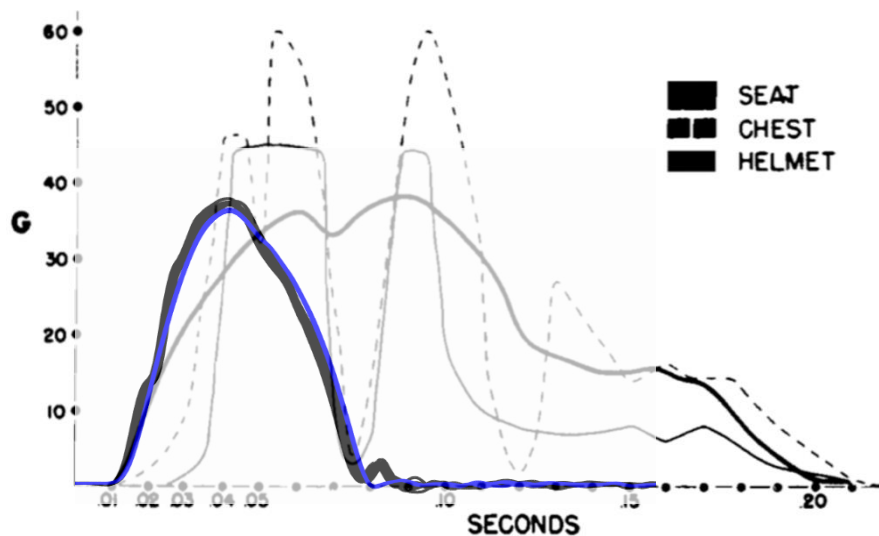
# Motivation

- Colonel John Paul Stapp, M.D., Ph.D
  - Rocket sled/seat
    - Followed safety design principles
      - Fully supported torso and head
      - Continuous seatback
      - No comfort foam



# Motivation

- Colonel John Paul Stapp, M.D., Ph.D.
  - Rocket sled/seat
    - Followed safety design principles
      - Fully supported torso and head
      - Continuous seatback
      - No comfort foam
  - No injuries up to 40g (~ 125kph pulse)



Experiment 113, accelerometer records. Human subject seated facing



# Motivation

- Captain Eli Lackland Beeding Jr. (1928 - 2013)
  - Daisy sled (40g)



After the test, Beeding was moved onto the side of the sled and elevated his feet. Ten minutes later, Beeding emerged from shock (tunnel vision and passed out) and was rushed to the base hospital.

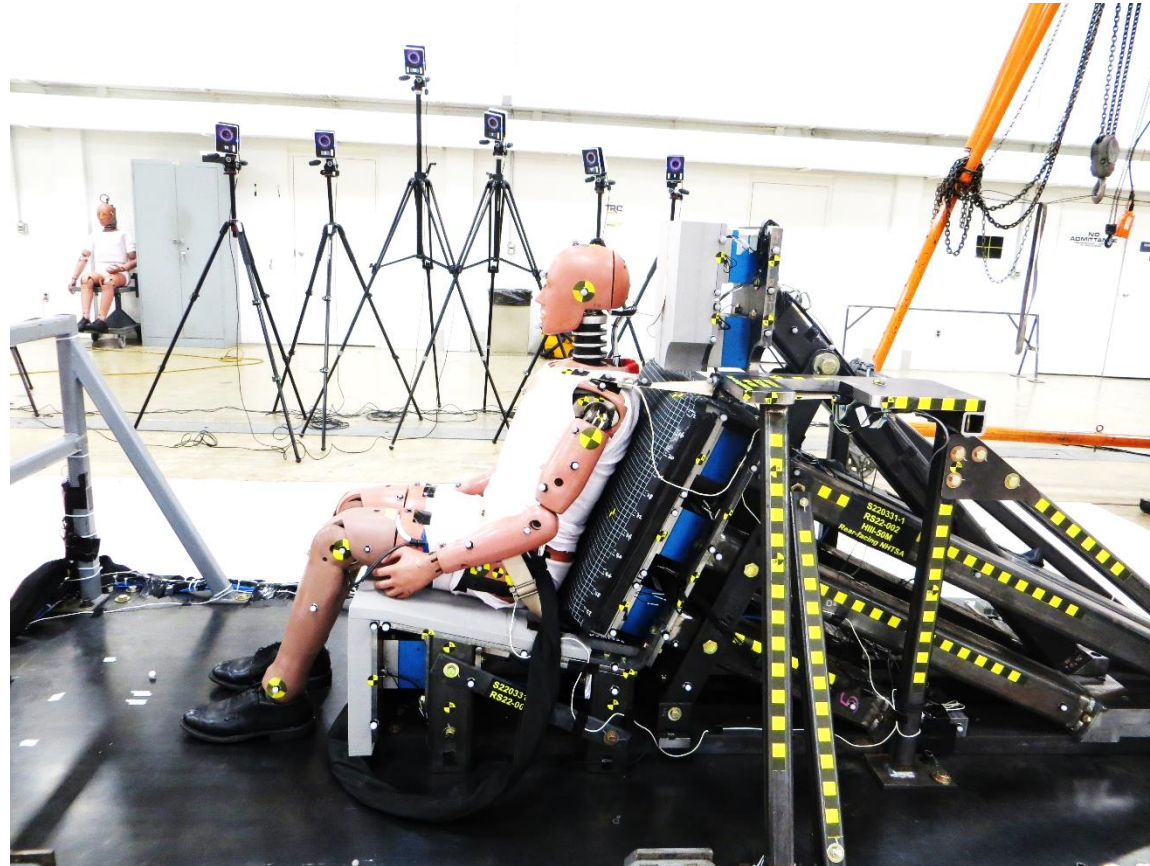
*Doctors determined his back was only badly bruised.*

[https://www.youtube.com/watch?v=JHGJ\\_y4aJlI](https://www.youtube.com/watch?v=JHGJ_y4aJlI)



# Objectives

- Investigate biomechanical responses and injuries of PMHS seated in a homogeneous seat in a rear-facing frontal impact ( $\Delta V$  of 56km/h)
  - Thorax and pelvis

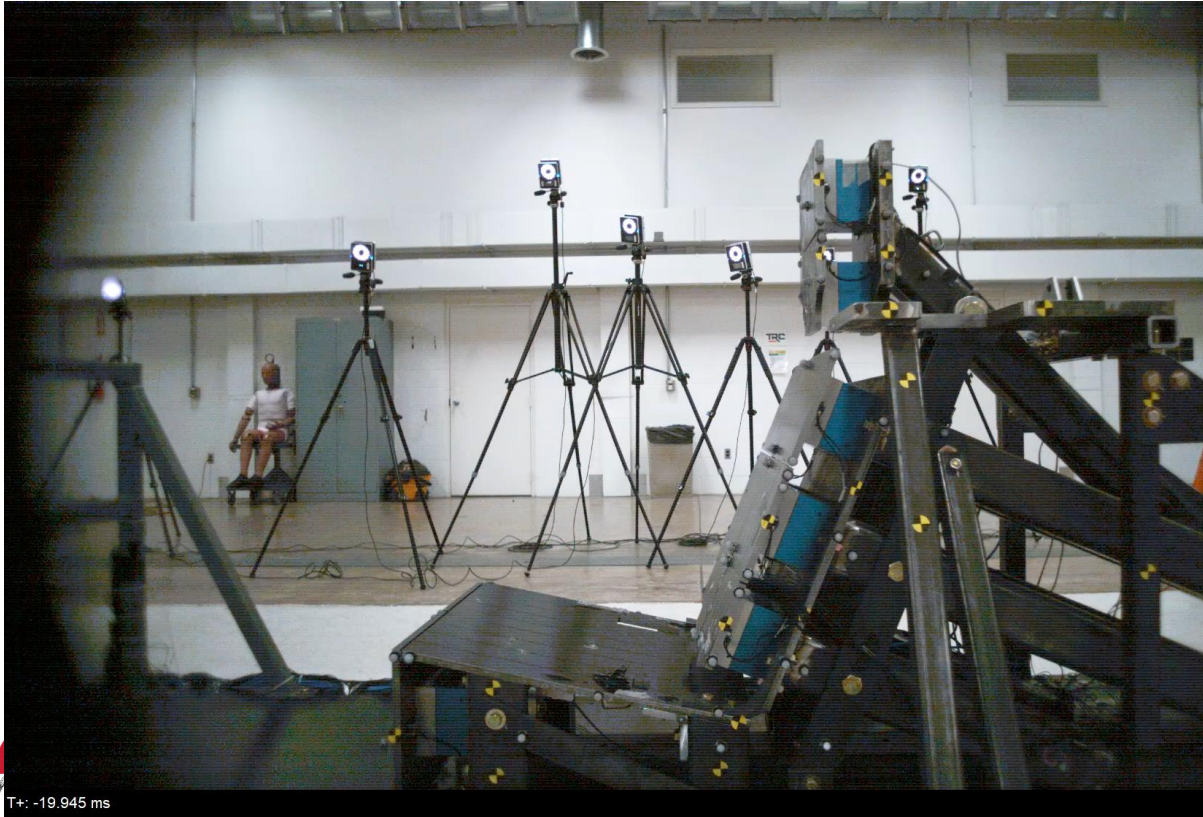




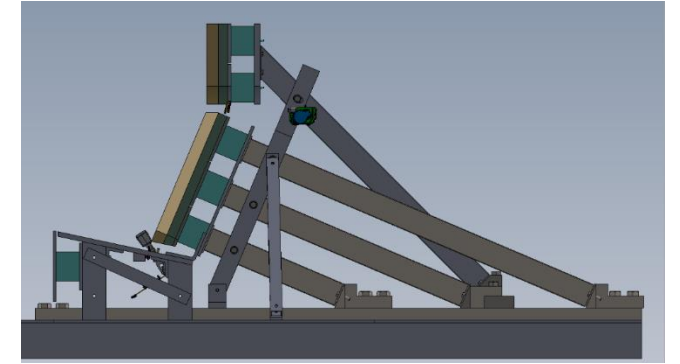
# Seat Design

- Durable, Repeatable, Reproducible
- Rigid
  - deformation < 2mm, no more than 5mm

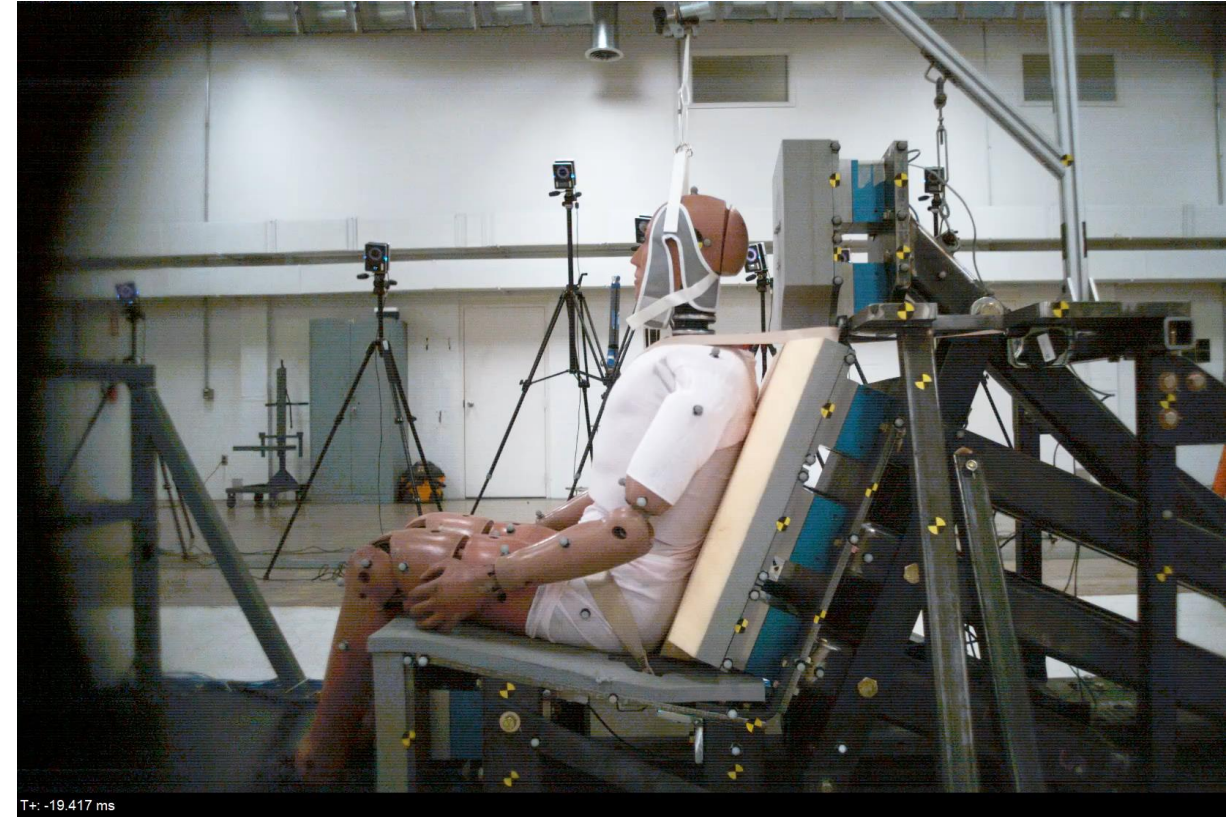
Seat only test



T+: -19.945 ms



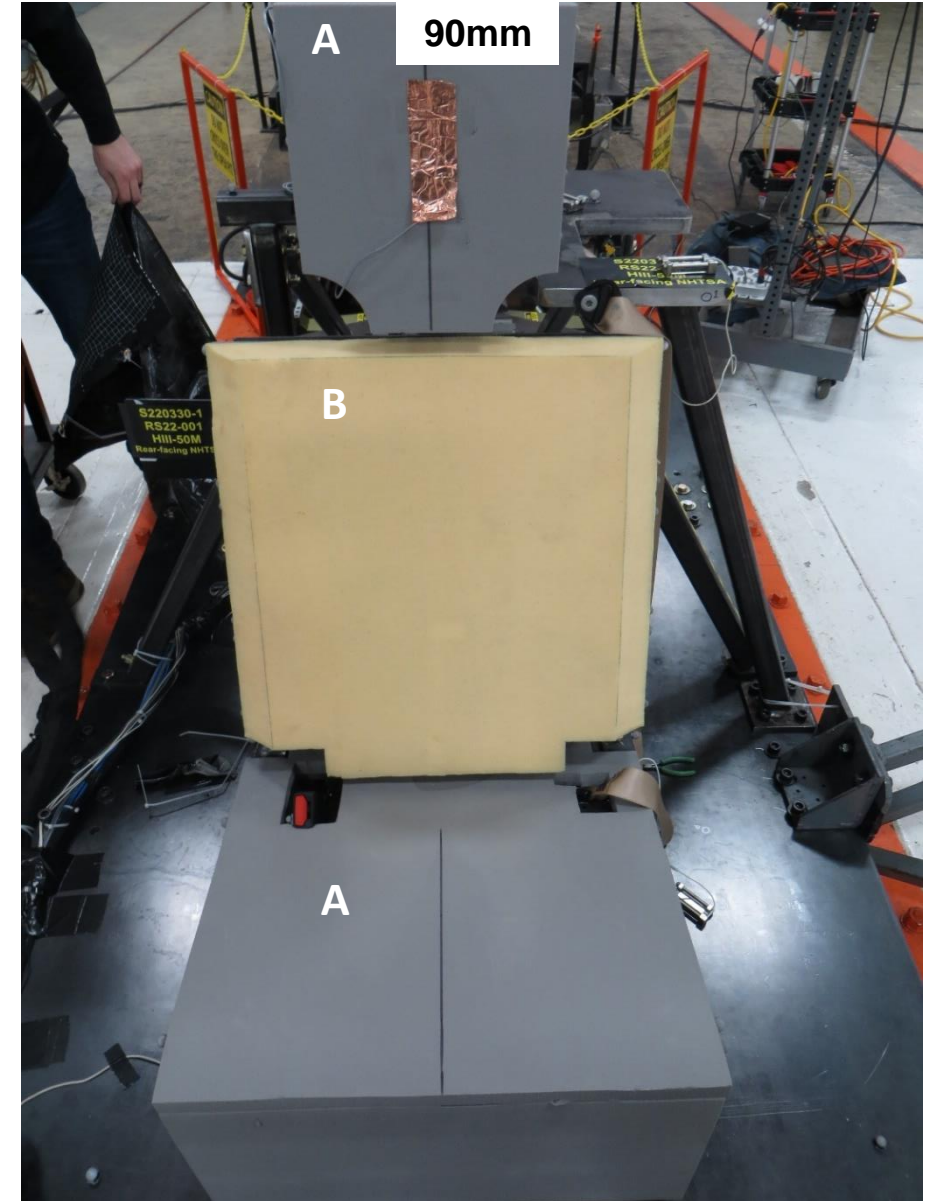
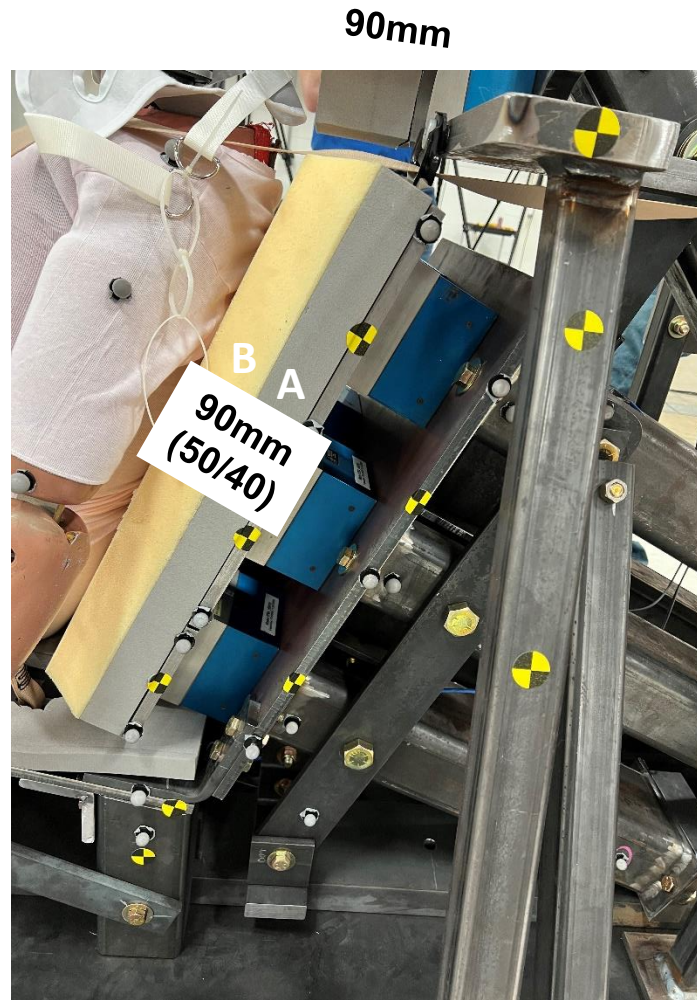
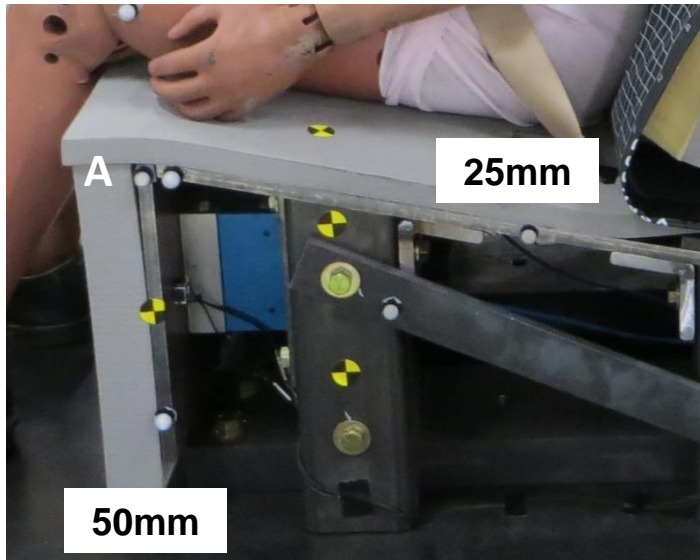
Ballast ATD test



T+: -19.417 ms

# Seat Foam

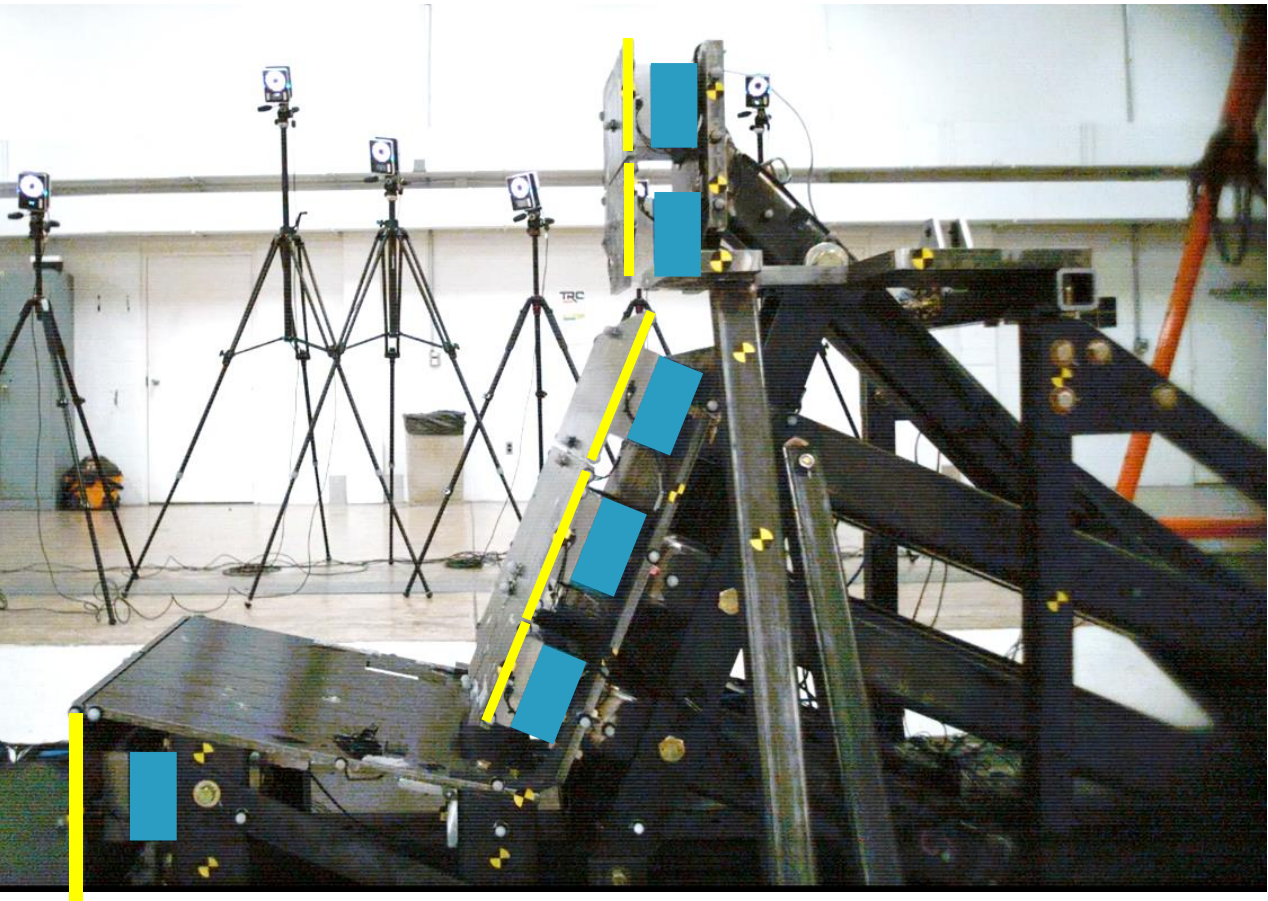
A: safety foam (MP15FR Polyethylene)  
B: comfort foam (Q31 Polyurethane)



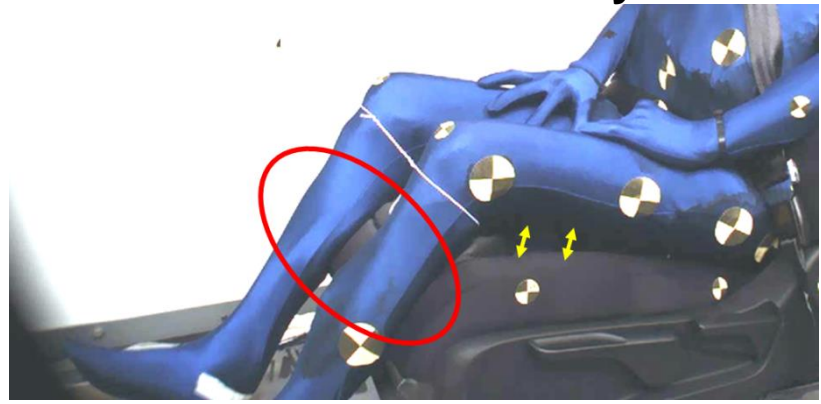
Comfort foam

Energy absorption foam


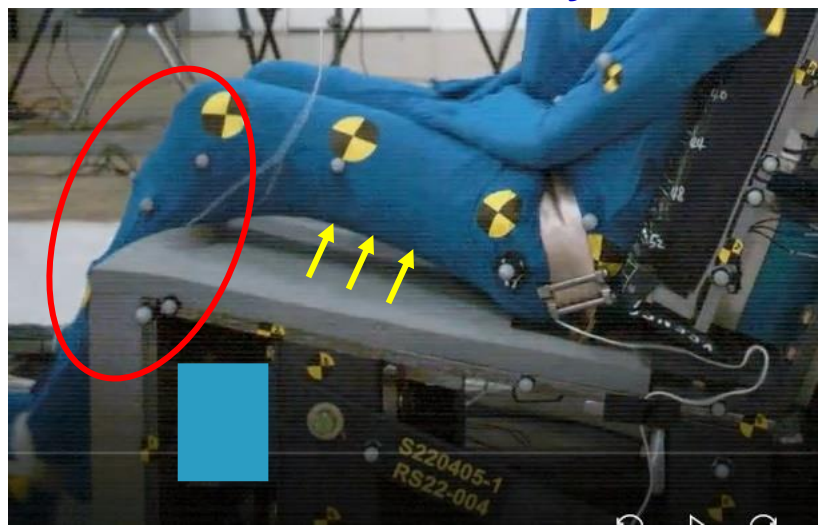
# Seat Instrumentation




OSU/NHTSA study



Current study

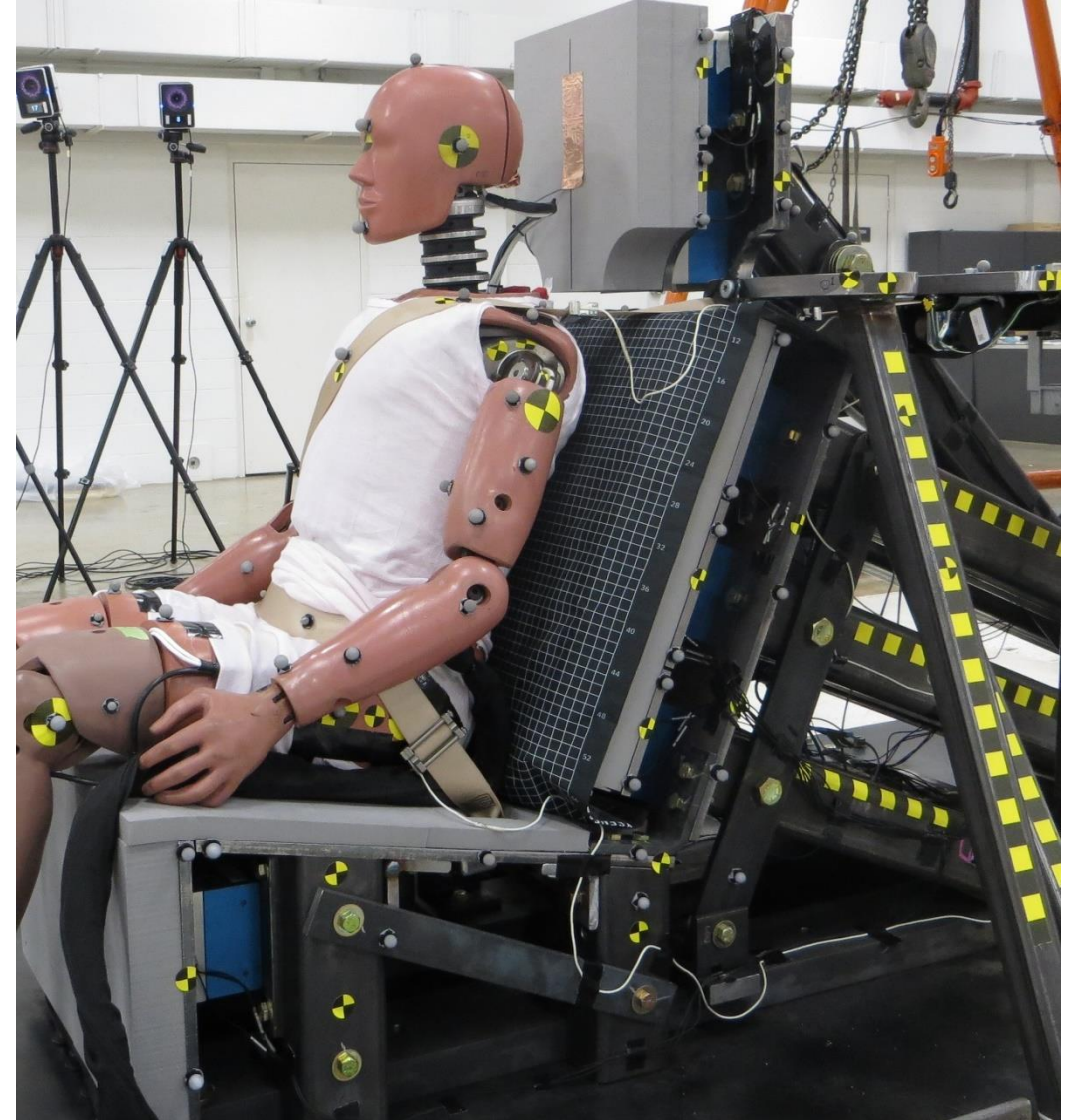


-  3-axis load cell
-  Load cell plate

# Seat Instrumentation

XSENSOR pressure mat:

- HX210:48.64.02-61cmx81cm, 12.7mm resolution – calibration using 64psi)
- Sampling rate: 2481Hz

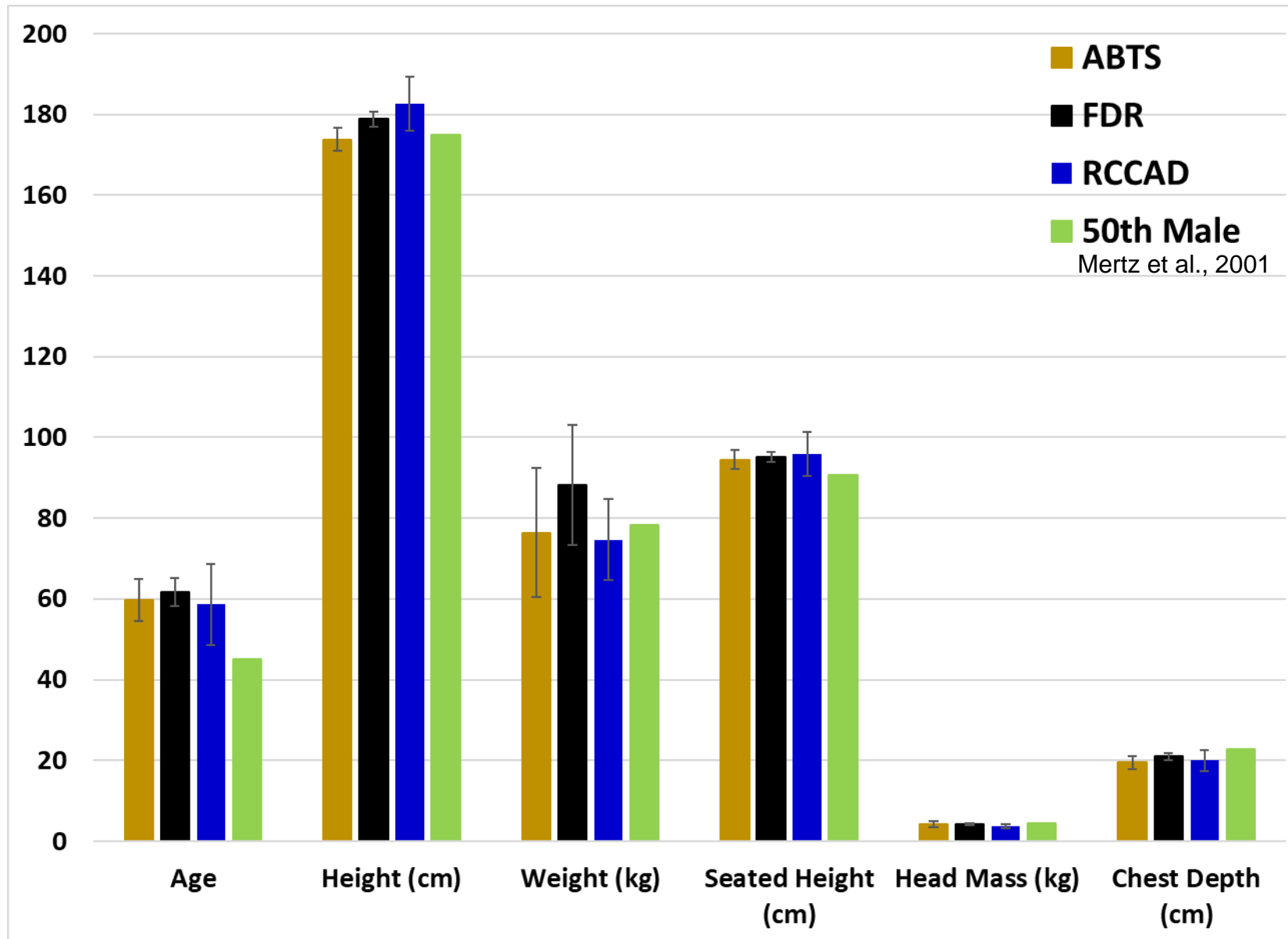


# PMHS Characteristics

PMHS Number	Sex	Age (yrs)	Height (cm)	Weight (kg)	BMI	Lumbar T-score	COD
	M	50-65	176.0	77.6	18.5-24.9	> -1.0	
PMHS1	M	58	187.2	86.2	25	1.8	Lung Cancer
PMHS2	M	69	185.6	68.0	20	-0.2	Resp Failure
PMHS3	M	49	174.9	69.9	23	0.4	Lung Cancer
Mean (SD)	--	59 (10)	182.6 (6.7)	74.7 (9.9)	23 (3)	0.7 (1.0)	--
NHTSA AV Mean (SD)	--	60 (4)	175.8 (3.4)	80.3 (14.9)	25 (3)	0.6 (1.2)	--



# PMHS Characteristics



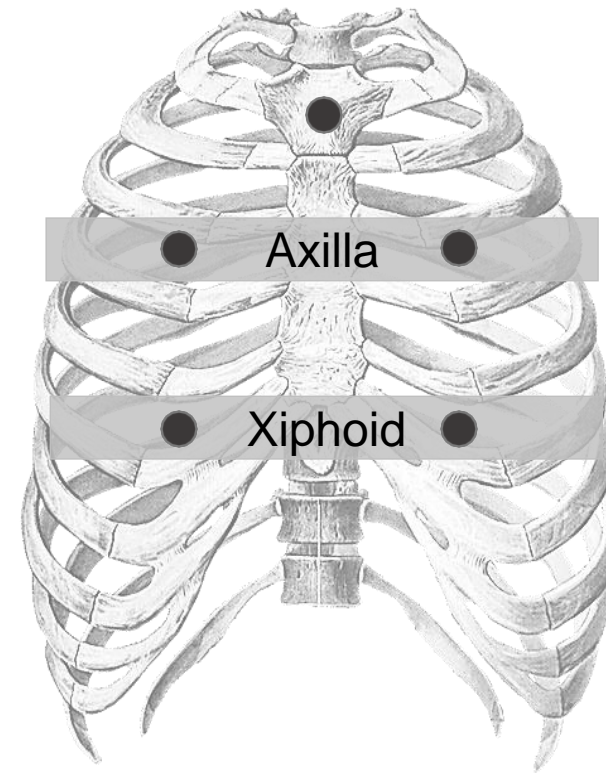
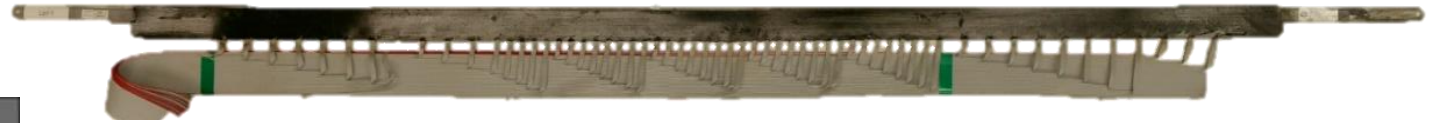
# PMHS Instrumentation

● VICON Marker

■ Chestband

■ Strain Gauges

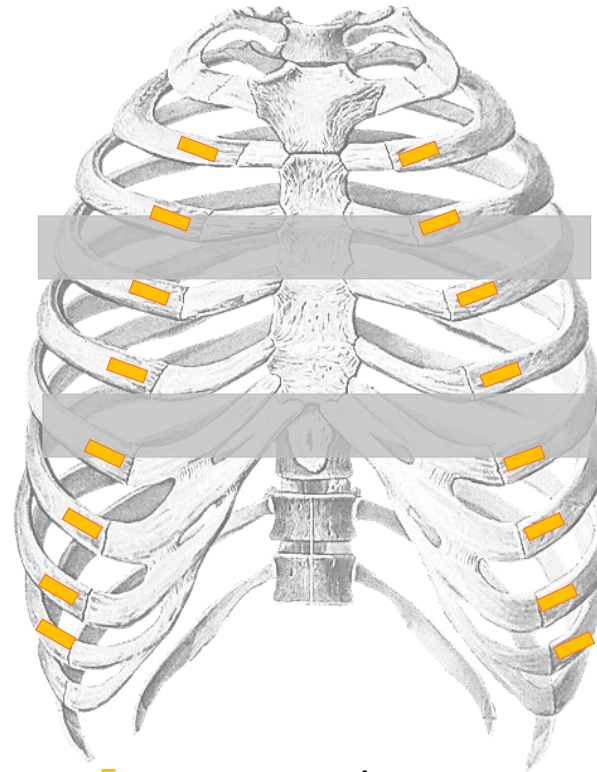
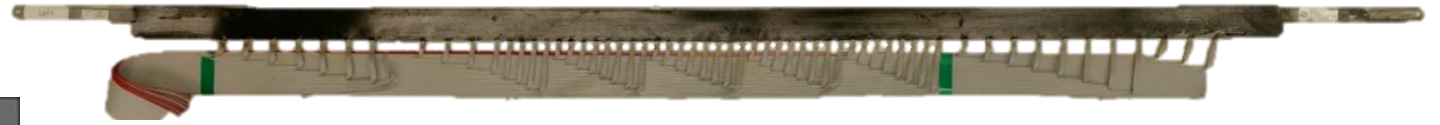
Head	■
Chest	■ ■
T1	●
T4	●
T8	●
T12	●
S1	●
Pelvis	● ■
Femur	● ■
Tibia	● ■
Humerus	■
Clavicle	■



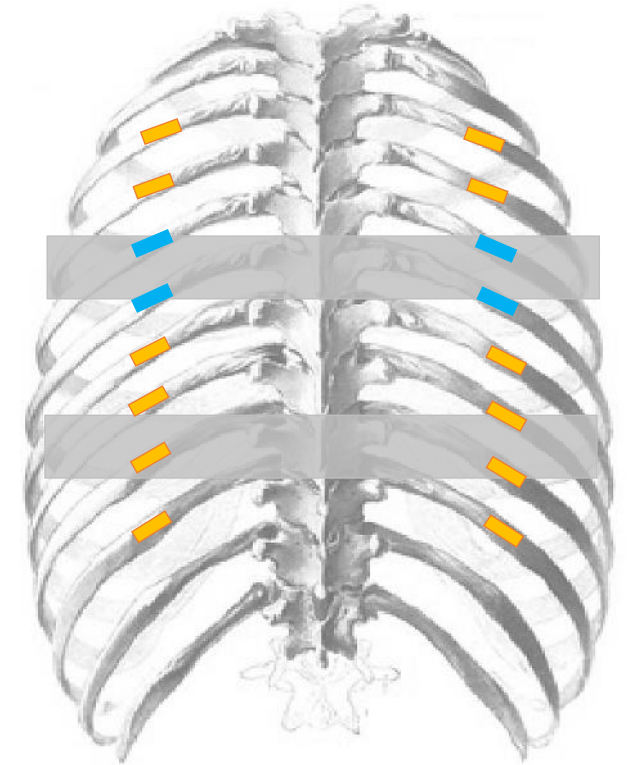
# PMHS Instrumentation

- VICON Marker
- Chestband
- Strain Gauges

Head	■
<b>Chest</b>	■ ■
T1	●
T4	●
T8	●
T12	●
S1	●
Pelvis	● ■
Femur	● ■
Tibia	● ■
Humerus	■
Clavicle	■



■ Anterior: rib 2-9



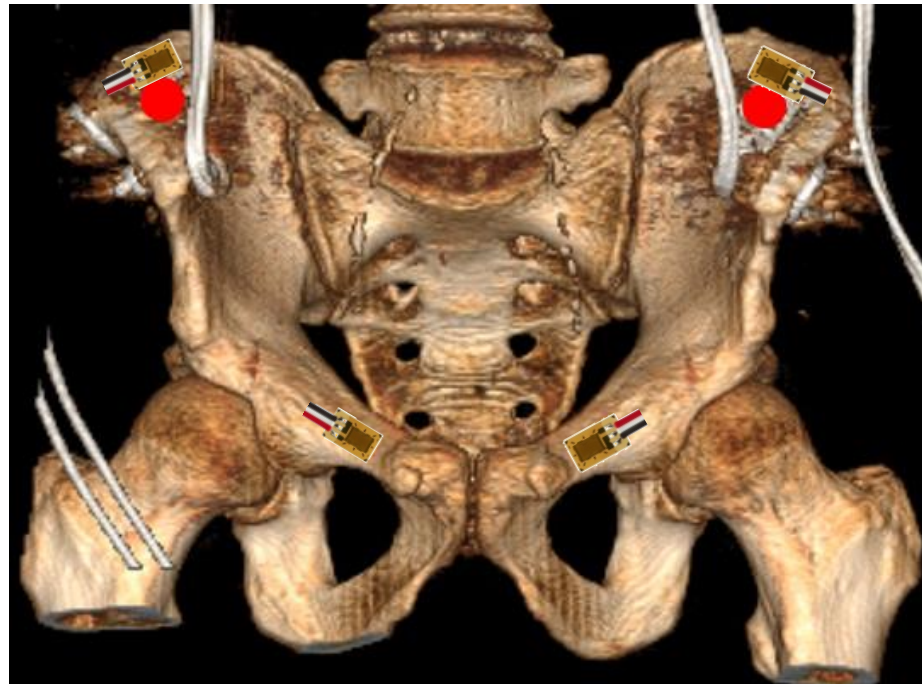
■ Posterior: rib 3-10  
■ strain rosette rib 5-6



# PMHS Instrumentation

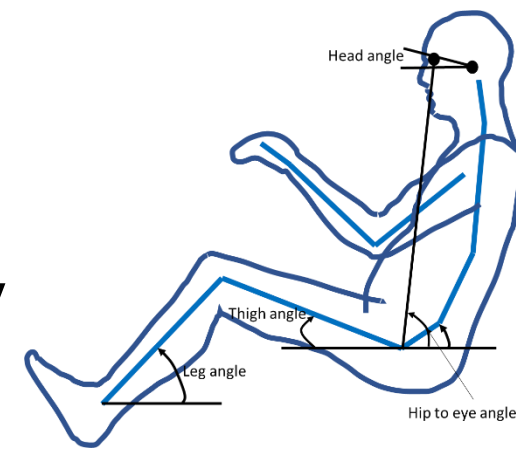
- Chestband
- Strain Gauges
- $3a\omega$

Head	■
Chest	■ ■
T1	●
T4	●
T8	●
T12	●
S1	●
<b>Pelvis</b>	● ■
Femur	● ■
Tibia	● ■
Humerus	■
Clavicle	■



# PMHS Positioning

- Seating procedure same as NHTSA study
  - UMTRI position regression model [Reed et al., 2019]

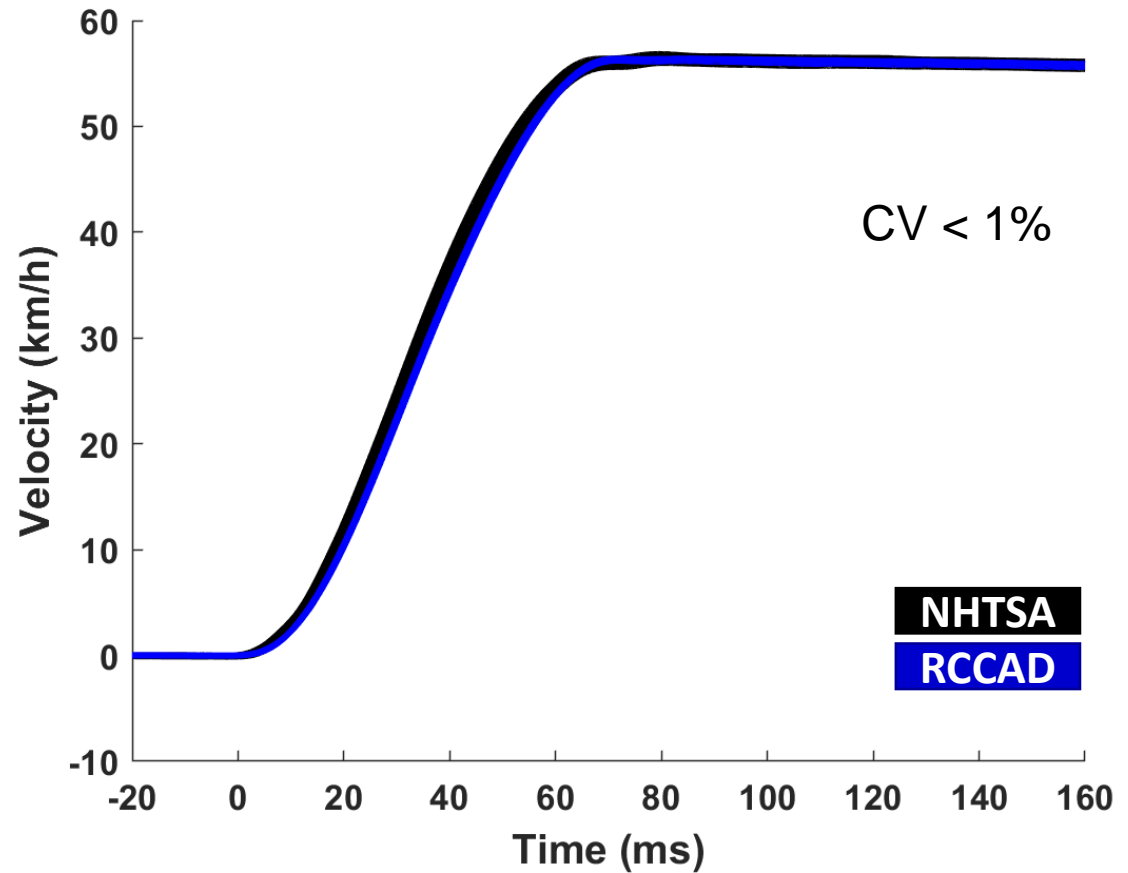
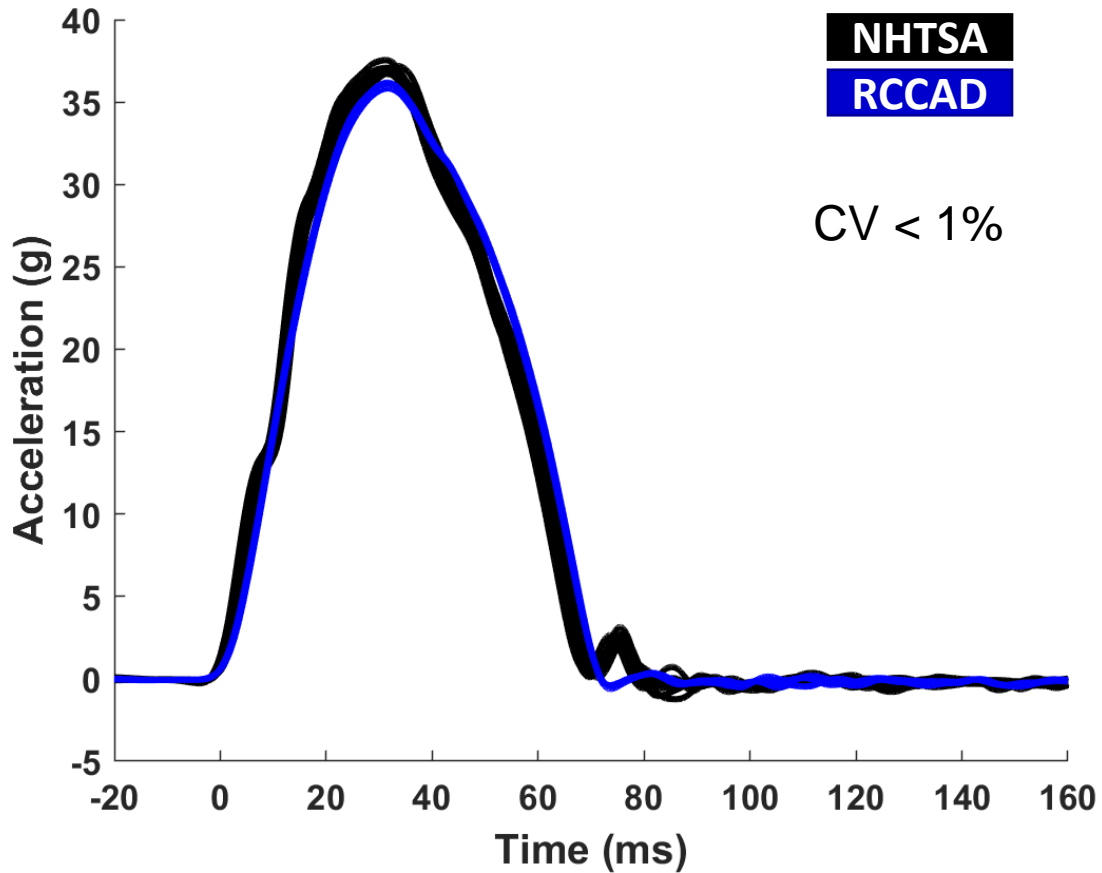


unit: degree, mm

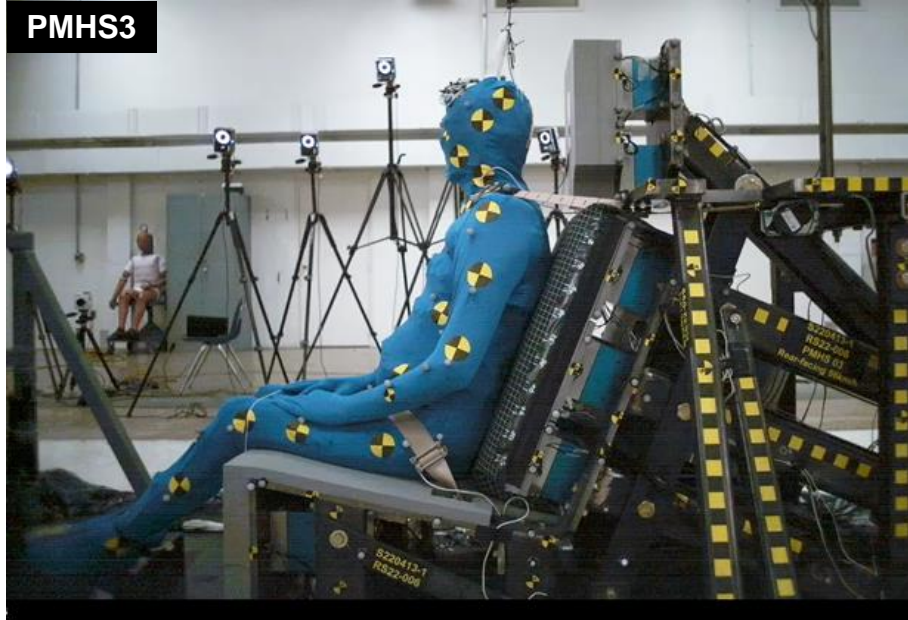
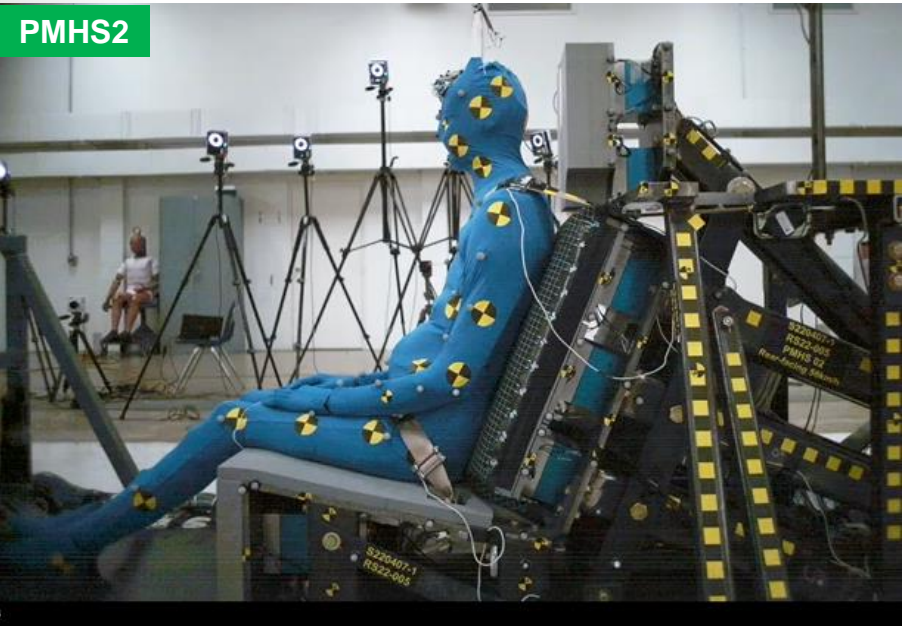
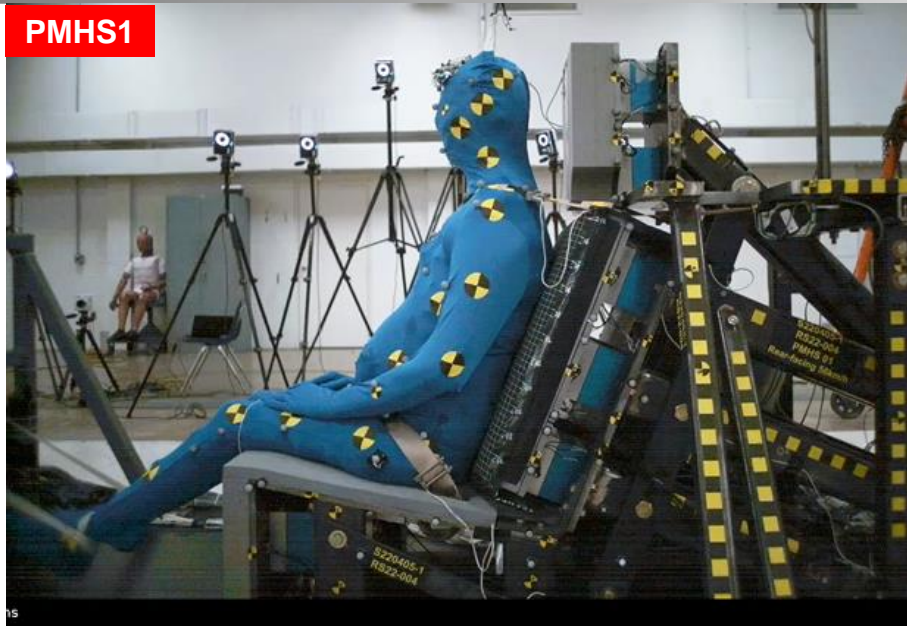
PMHS angle (UMTRI target $\pm$ tolerance)	PMHS1	PMHS2	PMHS3
Head angle	0.4 (0.0 $\pm$ 2.0)	0.3 (0.0 $\pm$ 2.0)	0.7 (0.0 $\pm$ 2.0)
Hip to eye	79.5 (77.7 $\pm$ 5.0)	86.0 (76.7 $\pm$ 5.0)	86.0 (77.4 $\pm$ 5.0)
Backset (head to HR distance)	84.0 (N/A)	83.0 (N/A)	82.7 (N/A)
Pelvis angle (GT to L5S1)	36.0 (31.2 $\pm$ 5.0)	28.7 (24.6 $\pm$ 5.0)	33.9 (28.9 $\pm$ 5.0)
Thigh angle	11.0 (11.5 $\pm$ 2.0)	10.2 (10.5 $\pm$ 2.0)	11.5 (11.2 $\pm$ 2.0)
Leg angle	36.0 (36.0 $\pm$ 2.0)	37.0 (36.7 $\pm$ 2.0)	42.2 (40.9 $\pm$ 2.0)



# Sled Pulse



# High Speed Videos

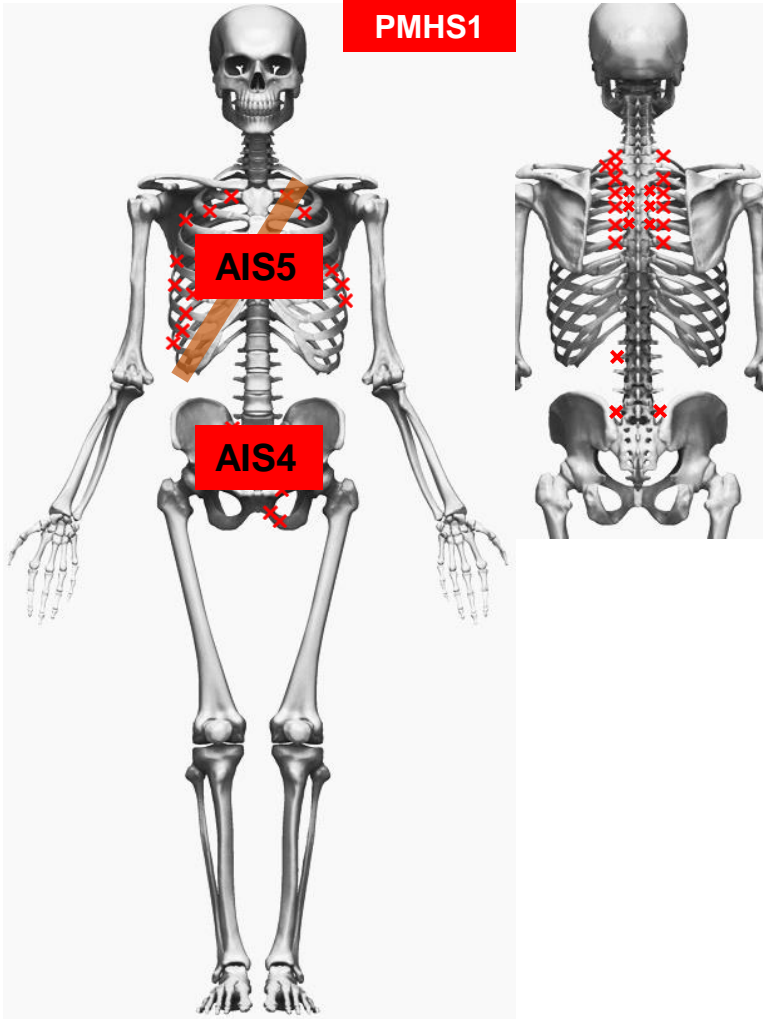


# High Speed Videos



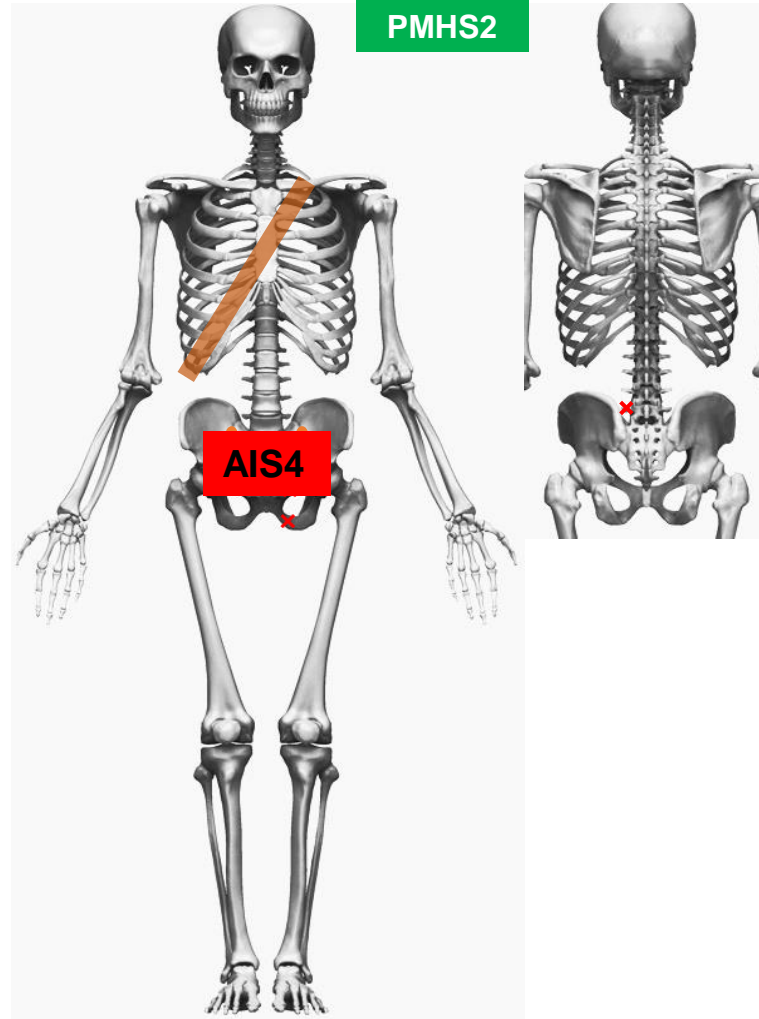
# Injury Summary

PMHS1



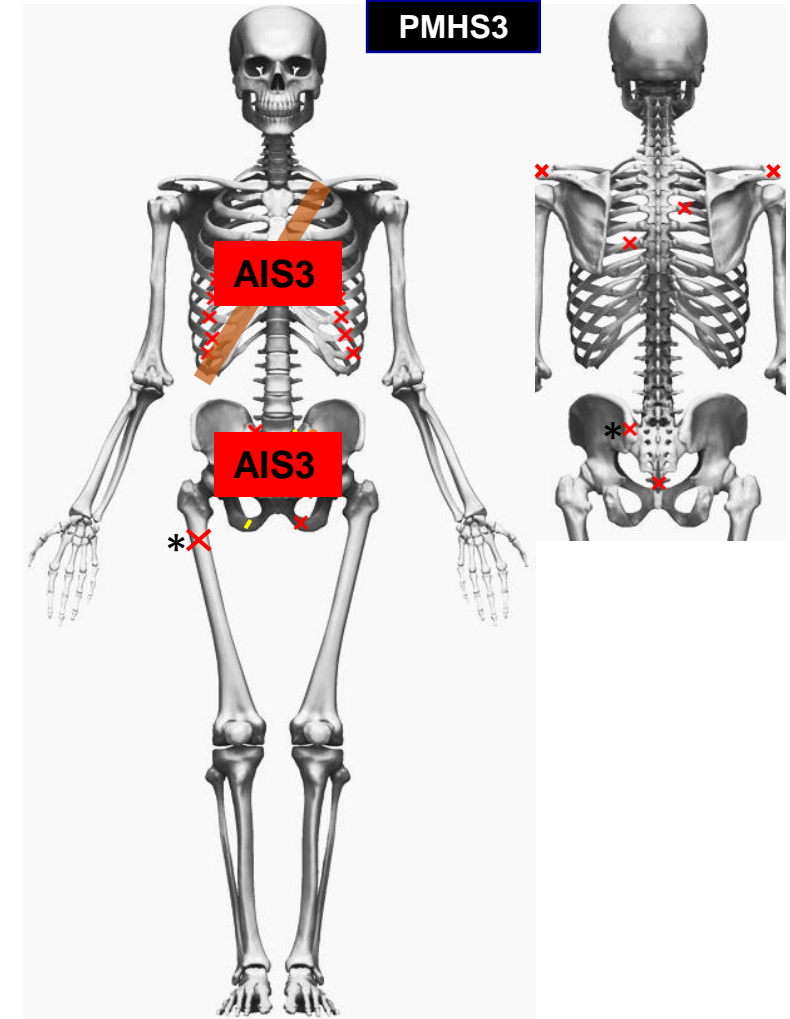
- T2 vertebral body fracture (AIS2)
- Liver contusion (AIS2)
- Mesentery laceration (AIS2)

PMHS2



- L4 superior endplate fracture (AIS2)
- Spleen laceration (AIS2)

PMHS3



- No spine injury
- No abdomen injury
- \* Pre-existing lesion

# Injury Summary

PMHS1

PMHS2

PMHS3

Thorax (AIS3 & 5)

Pelvis (AIS3 & 4)

- T2 vertebral body fracture (AIS2)
- Liver contusion (AIS2)
- Mesentery laceration (AIS2)

- L4 superior endplate fracture (AIS2)
- Spleen laceration (AIS2)

- No spine injury
- No abdomen injury
- \* lesion

# Rib Fractures

PMHS1	PMHS2	PMHS3
30 on 16 ribs	None	13 on 10 ribs





# Rib Fracture Timing

ABTS/25deg

	P	L	A	A	L	P	
R1							L1
R2				N/A			L2
R3				44.10			L3
R4		50.25			46.40		L4
R5		47.15				41.70	L5
R6						40.05	L6
R7				48.05		39.65	L7
R8				43.35		37.20	L8
R9				38.70		38.78	L9
R10						37.30	L10
R11							L11
R12							L12

FDR/25deg

	P	L	A	A	L	P	
R1				N/A			L1
R2				47.85			L2
R3				51.45			L3
R4				49.25			L4
R5				50.20		43.40	L5
R6				49.08		48.10	L6
R7				50.35		43.30	L7
R8				47.15		46.65	L8
R9							L9
R10							L10
R11							L11
R12							L12

PMHS1

\* two fractures

	P	L	A	A	L	P	
R1	N/A		N/A	N/A		N/A	L1
R2			47.30	N/A		N/A*	L2
R3	49.15	48.95				43.30	L3
R4	47.25		47.15			43.20	L4
R5	45.30	45.70		48.20		48.40	L5
R6	48.25*	48.53	48.80		N/A	44.50	L6
R7	48.85		50.30		46.10	46.30	L7
R8			44.65				L8
R9		N/A					L9
R10							L10
R11							L11
R12							L12

43 – 51 ms

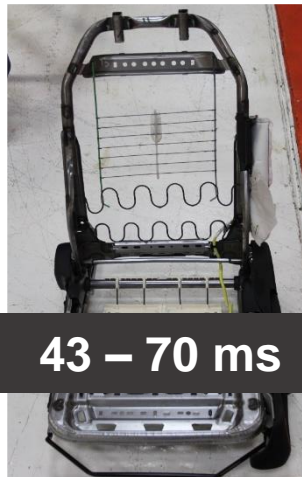
PMHS3

	P	L	A	A	L	P	
R1							L1
R2							L2
R3							L3
R4							L4
R5	52.30	52.35		47.60			L5
R6		46.35		47.20		42.25	L6
R7		42.75		46.9*			L7
R8			48.50	N/A			L8
R9			49.25	42.55			L9
R10							L10
R11							L11
R12							L12

43 – 53 ms



37 – 51 ms

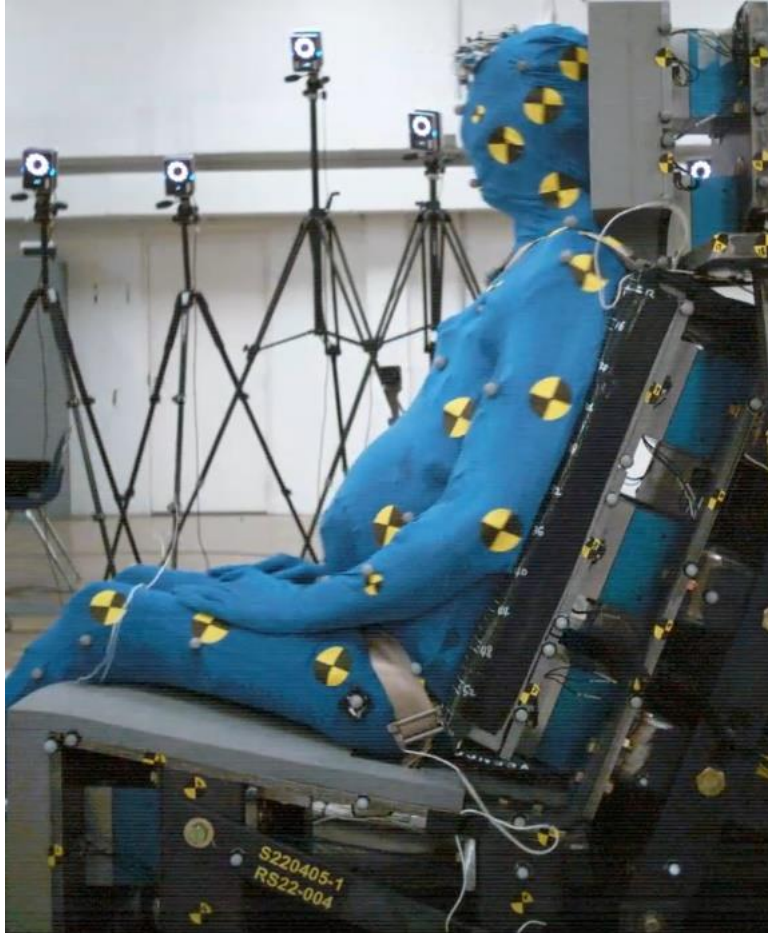


43 – 70 ms



# PMHS Motion

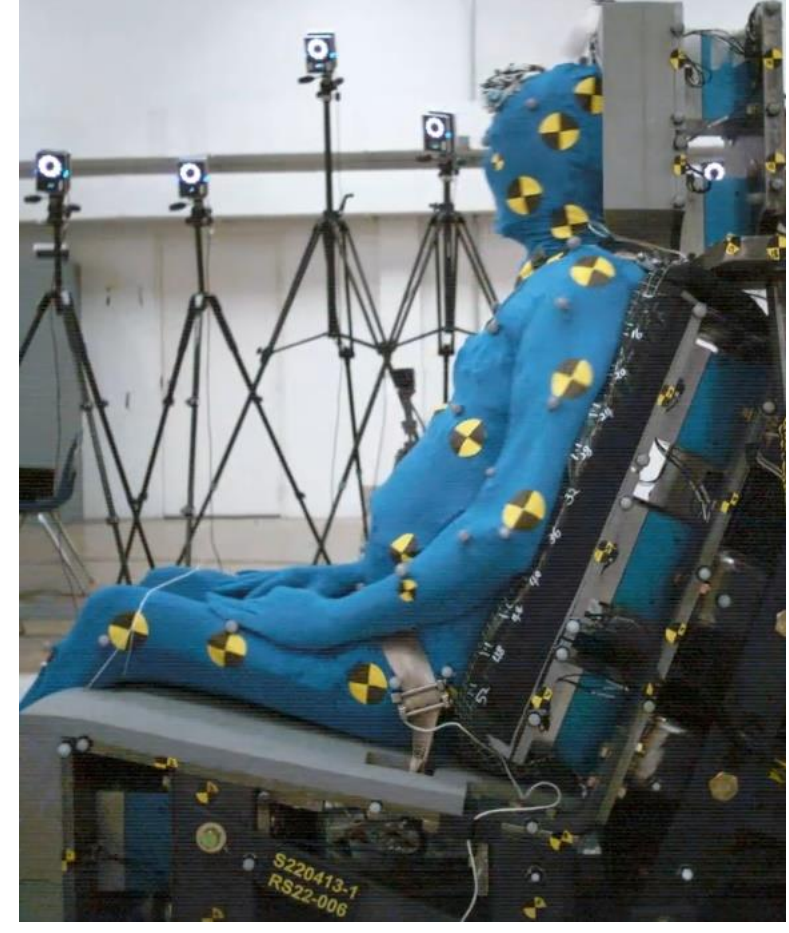
43ms



PMHS1



PMHS2



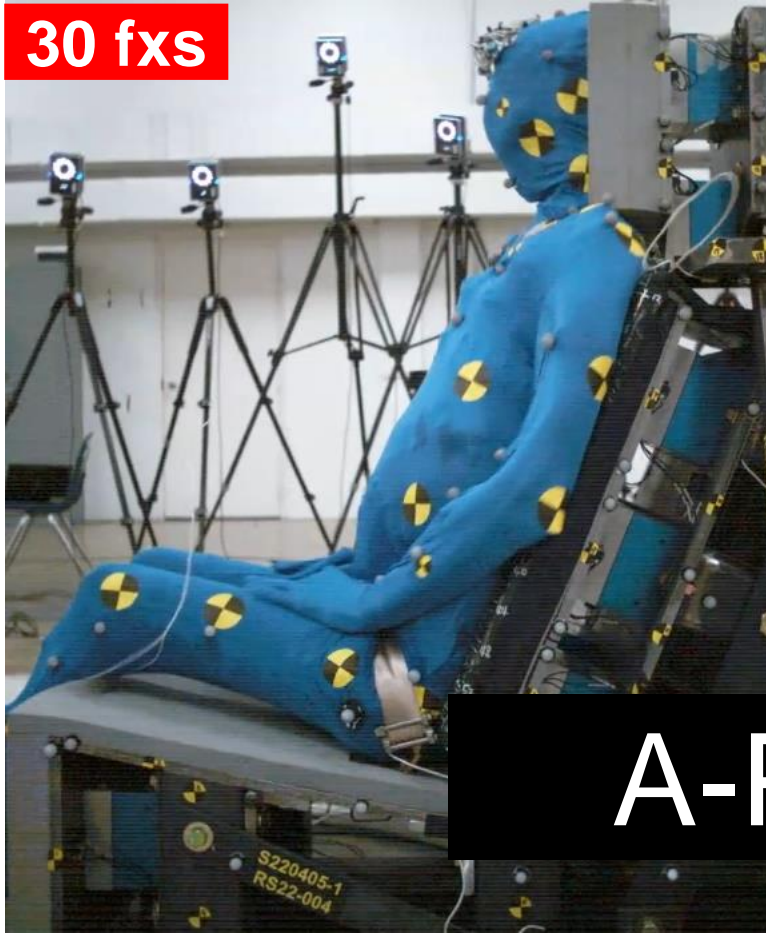
PMHS3



# PMHS Motion

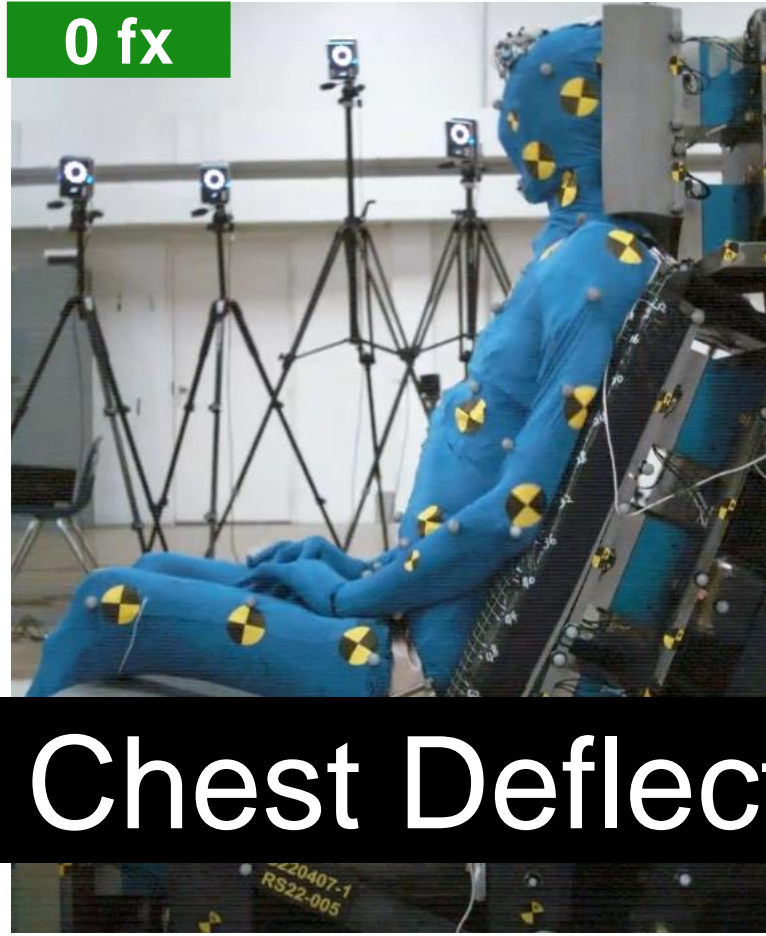
52ms

30 fxs



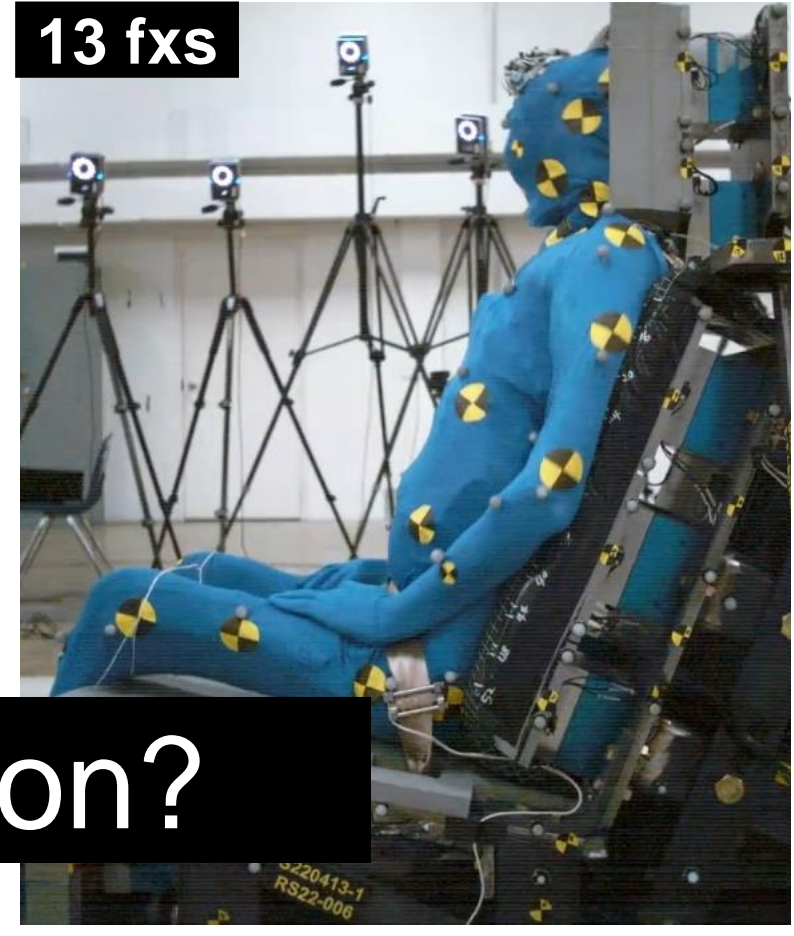
PMHS1

0 fx



PMHS2

13 fxs



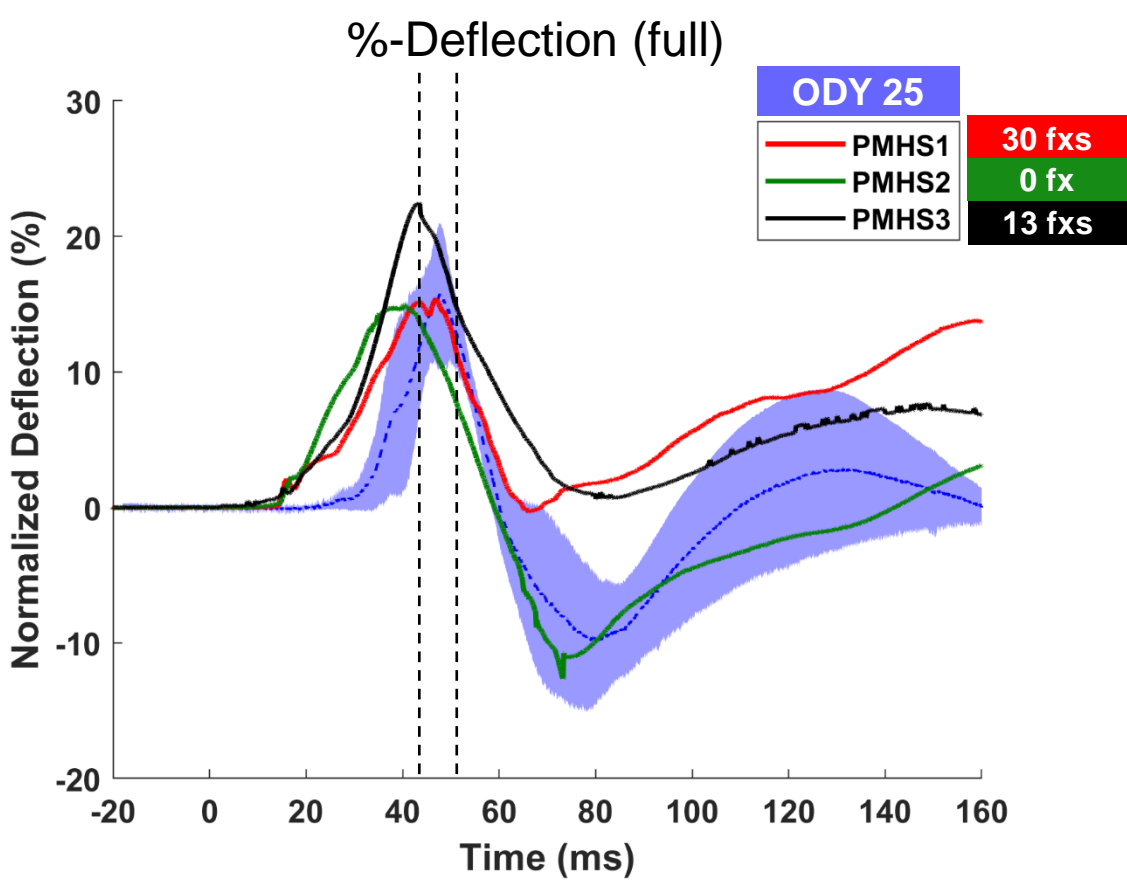
PMHS3

A-P Chest Deflection?



# A-P Chest Deflection

Estimated deflection at Mid-sternum (interpolated deflection between two CBs)



ODY: Odyssey  
Corridors from Kang et al. (2020)

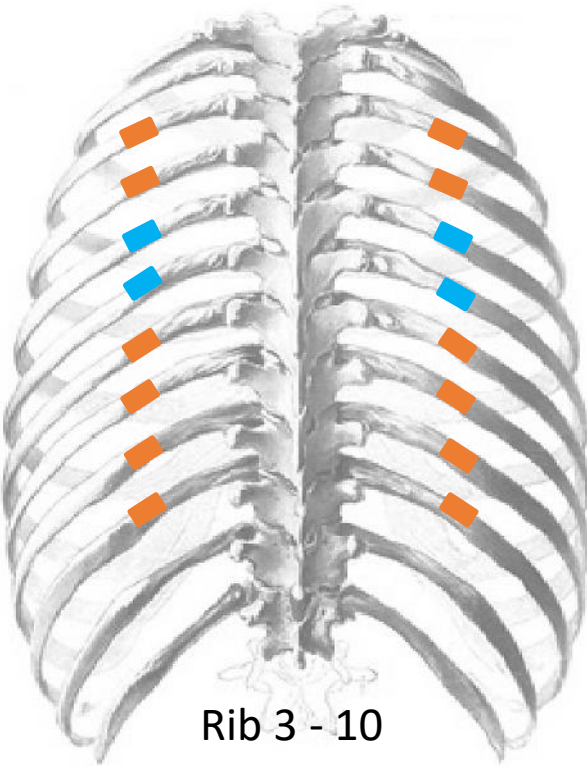
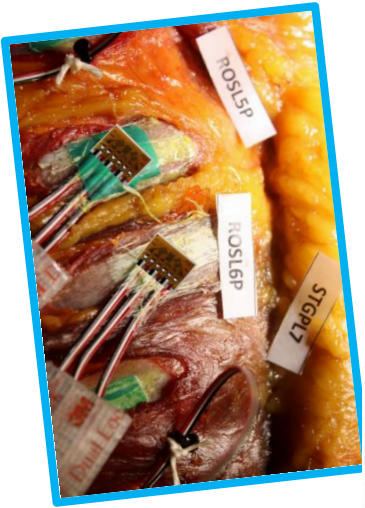
A-P chest deflection may not be an injury predictor



# Strain Rosette

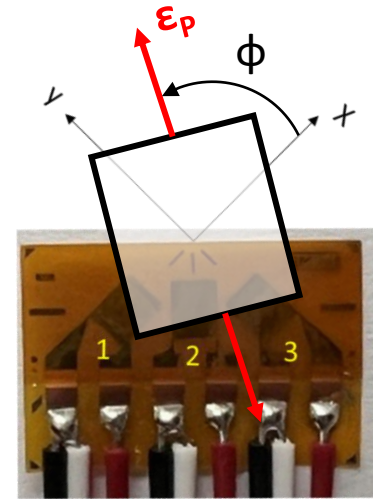
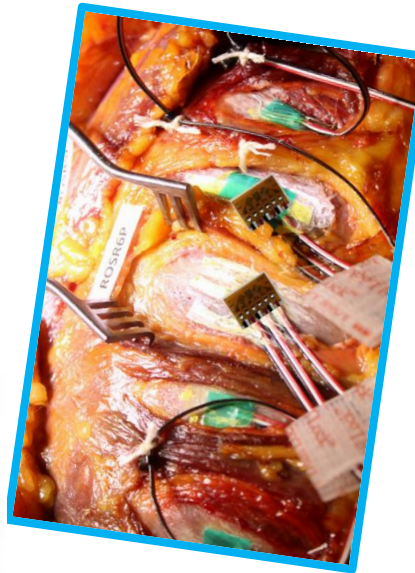
■ : Strain Gage

■ : Strain Rosette



Rib 3 - 10

Posterior

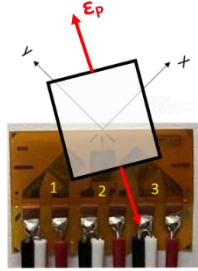
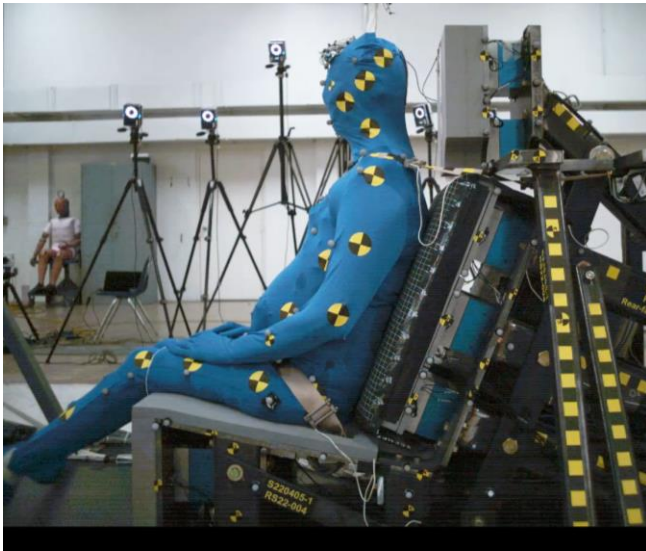


$$\epsilon_{P,Q} = \frac{\epsilon_1 + \epsilon_3}{2} \pm \frac{1}{\sqrt{2}} \sqrt{(\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2}$$

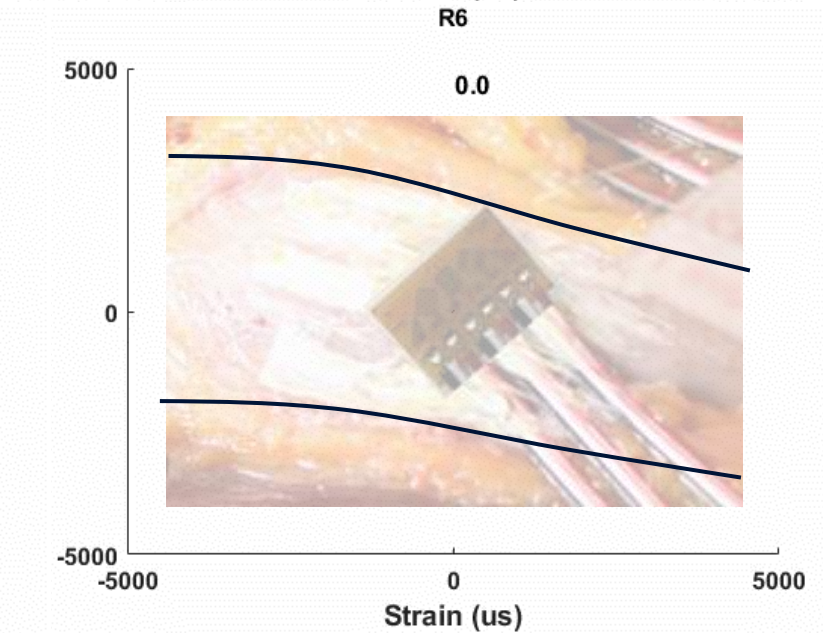
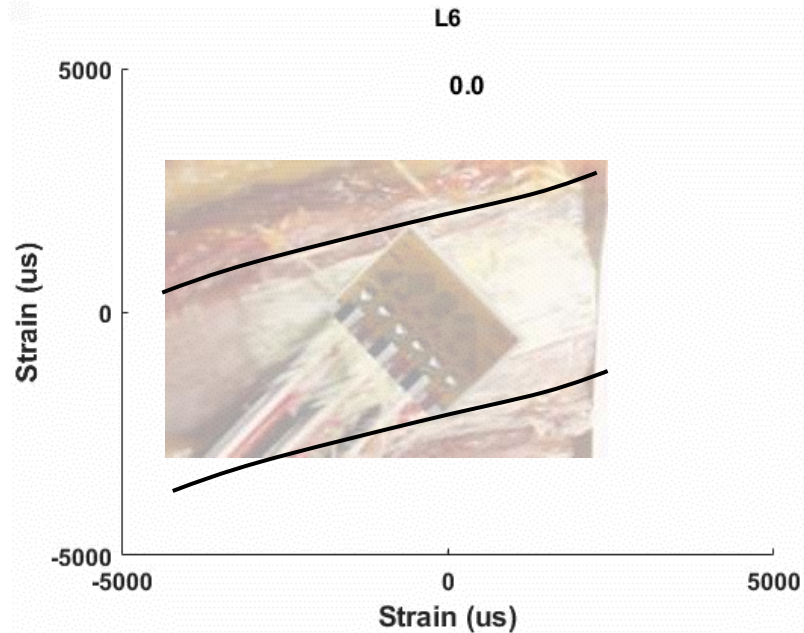
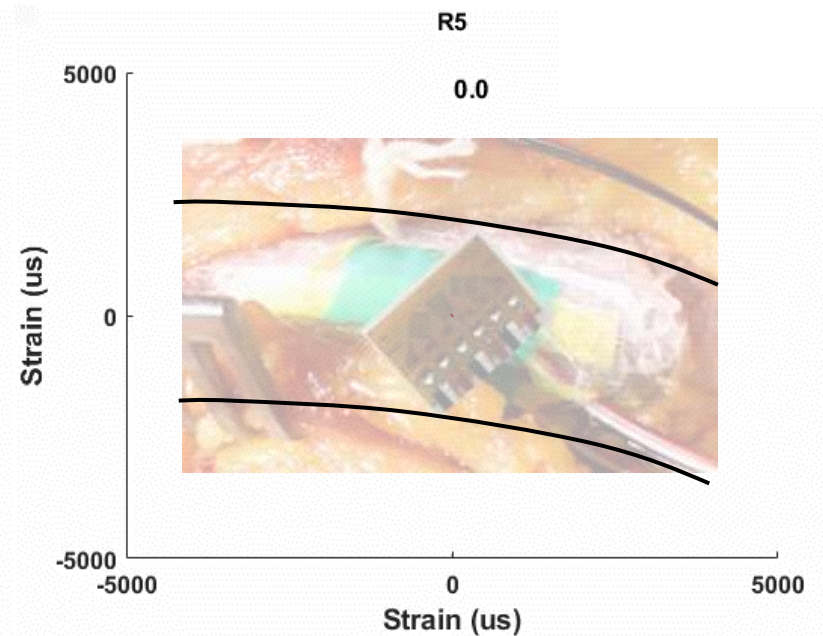
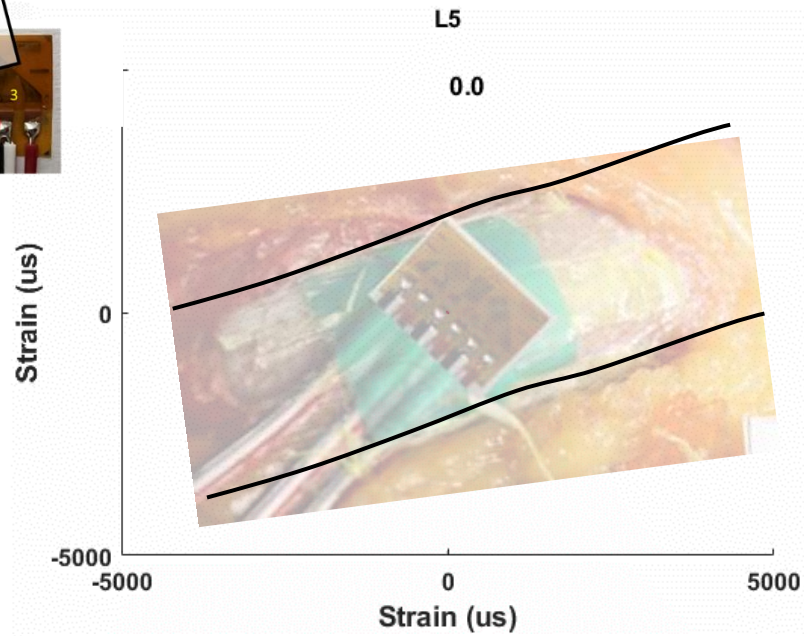
$$\phi_{P,Q} = -\theta = \frac{1}{2} \tan^{-1} \left( \frac{2\epsilon_2 - \epsilon_1 - \epsilon_3}{\epsilon_1 - \epsilon_3} \right)$$



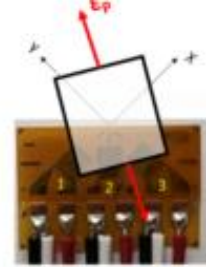
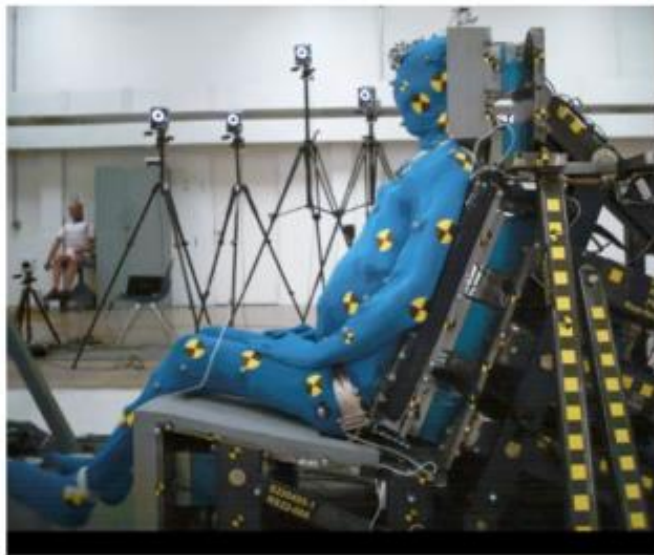
# PMHS1



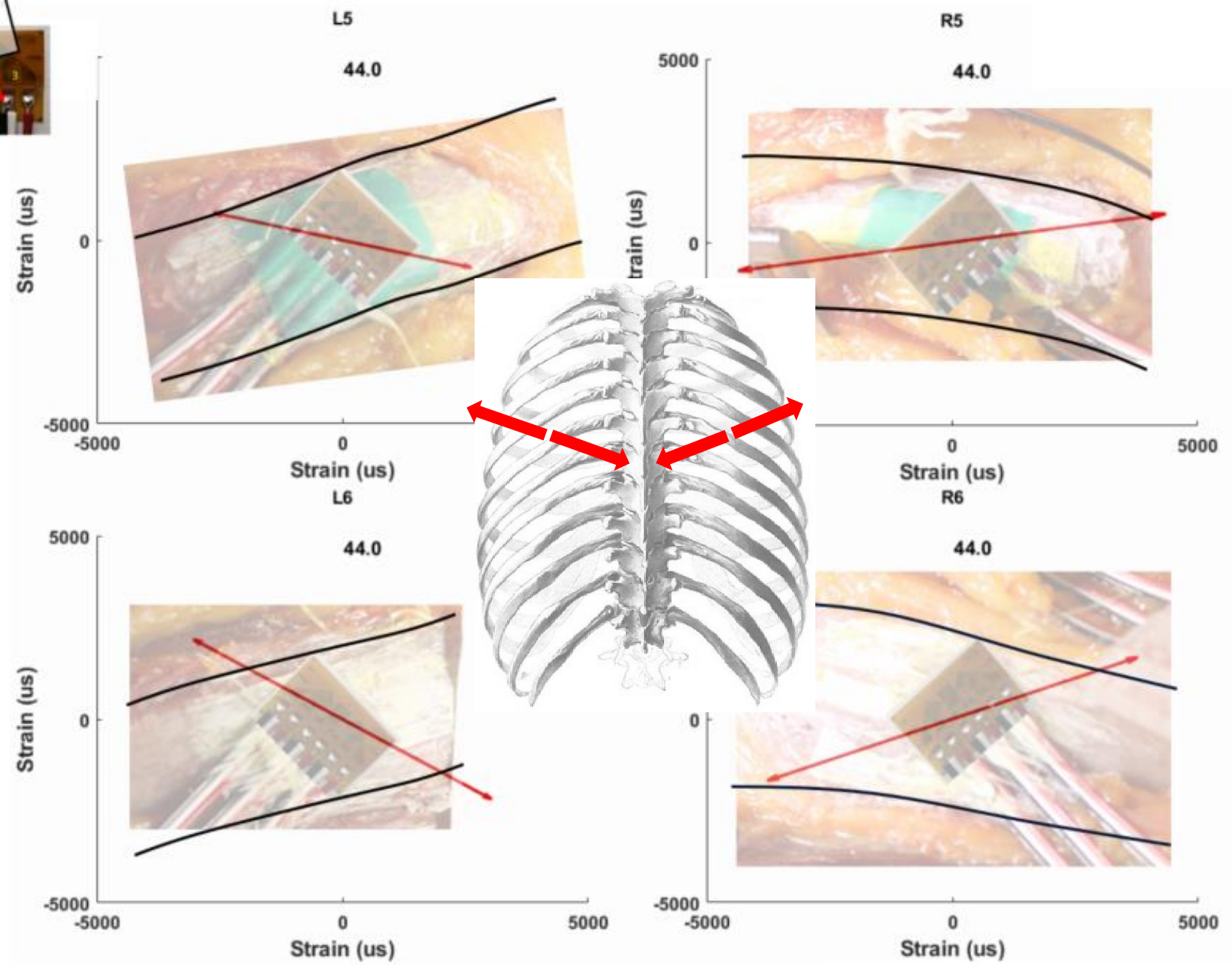
A	L	P		R1	P	L	A
N/A		N/A	L1	R1	N/A		N/A
N/A		N/A*	L2	R2			47.30
		43.30	L3	R3	49.15	48.95	
		43.20	L4	R4	47.25		47.15
48.20		48.40	L5	R5	45.30	45.70	
	N/A	44.50	L6	R6	48.25	48.53	48.80
	46.10	46.30	L7	R7	48.85		50.30
			L8	R8			44.65
			L9	R9		N/A	
			L10	R10			
			L11	R11			
			L12	R12			



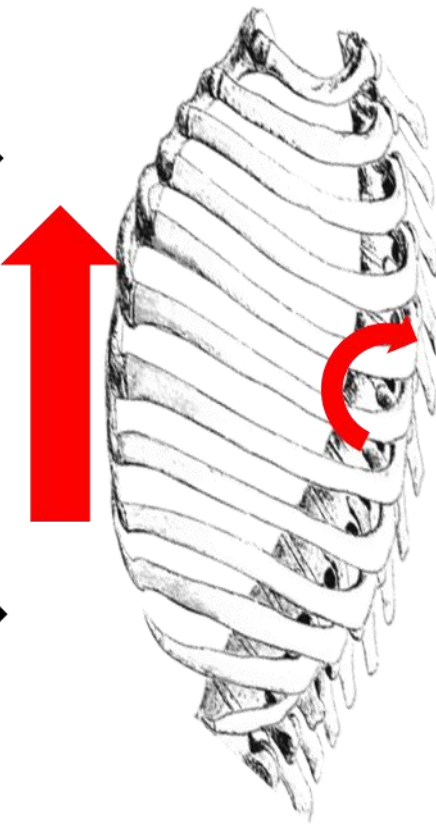
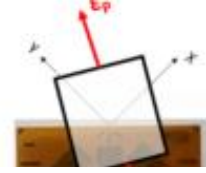
# PMHS1



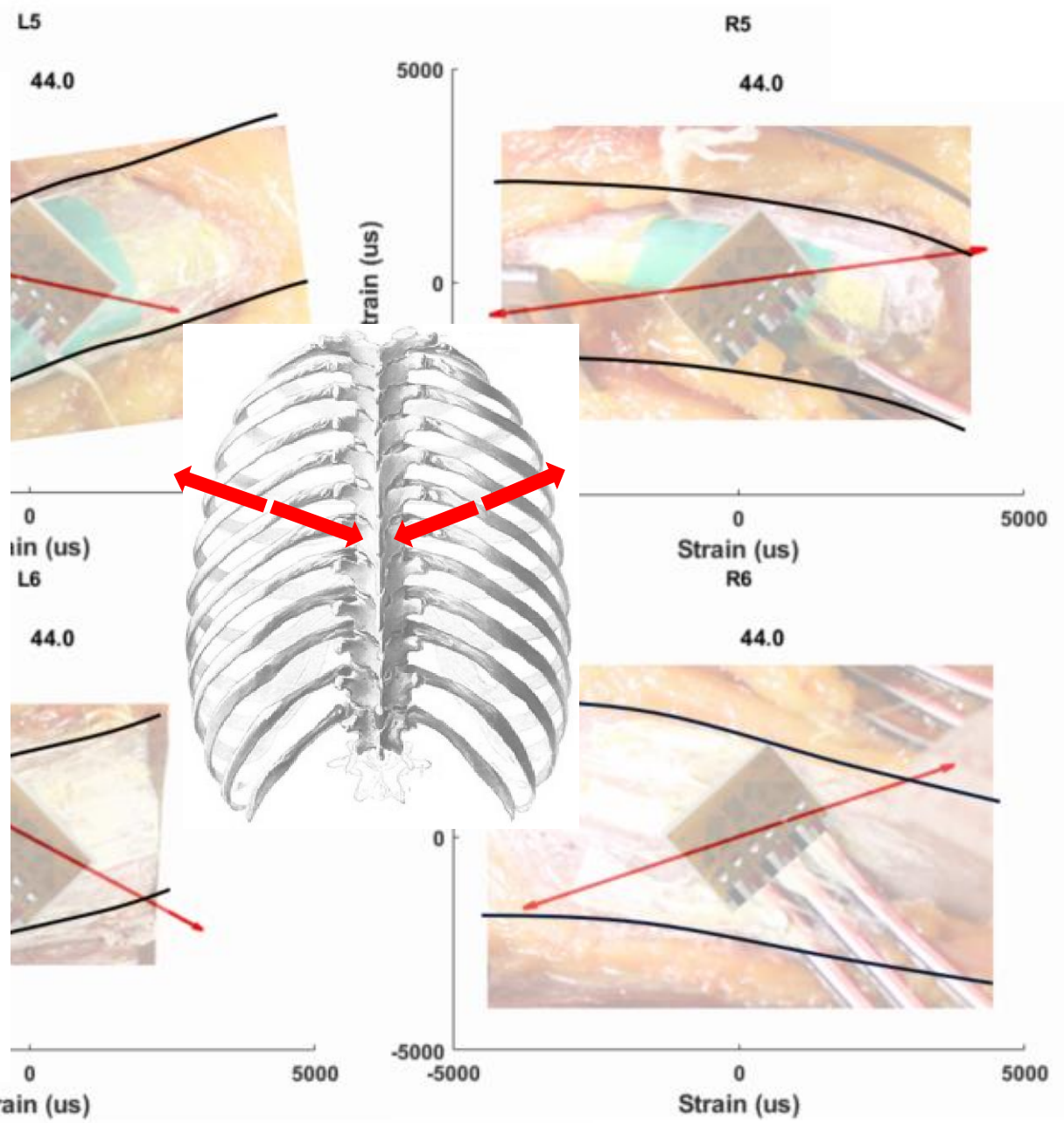
A	L	P		P	L	A
N/A		N/A	L1	R1	N/A	N/A
N/A		N/A*	L2	R2		47.30
		43.30	L3	R3	49.15	48.95
		43.20	L4	R4	47.25	47.15
48.20		48.40	L5	R5	45.30	45.70
	N/A	44.50	L6	R6	48.25	48.53
	46.10	46.30	L7	R7	48.85	50.30
			L8	R8		44.65
			L9	R9		N/A
			L10	R10		
			L11	R11		
			L12	R12		



# PMHS1



A	L	P	L1	R1	P
N/A		N/A	L1	R1	N/A
N/A		N/A*	L2	R2	
		43.30	L3	R3	49.15
		43.20	L4	R4	47.25
48.20		48.40	L5	R5	45.30
	N/A	44.50	L6	R6	48.25
	46.10	46.30	L7	R7	48.85
			L8	R8	
			L9	R9	
			L10	R10	
			L11	R11	
			L12	R12	





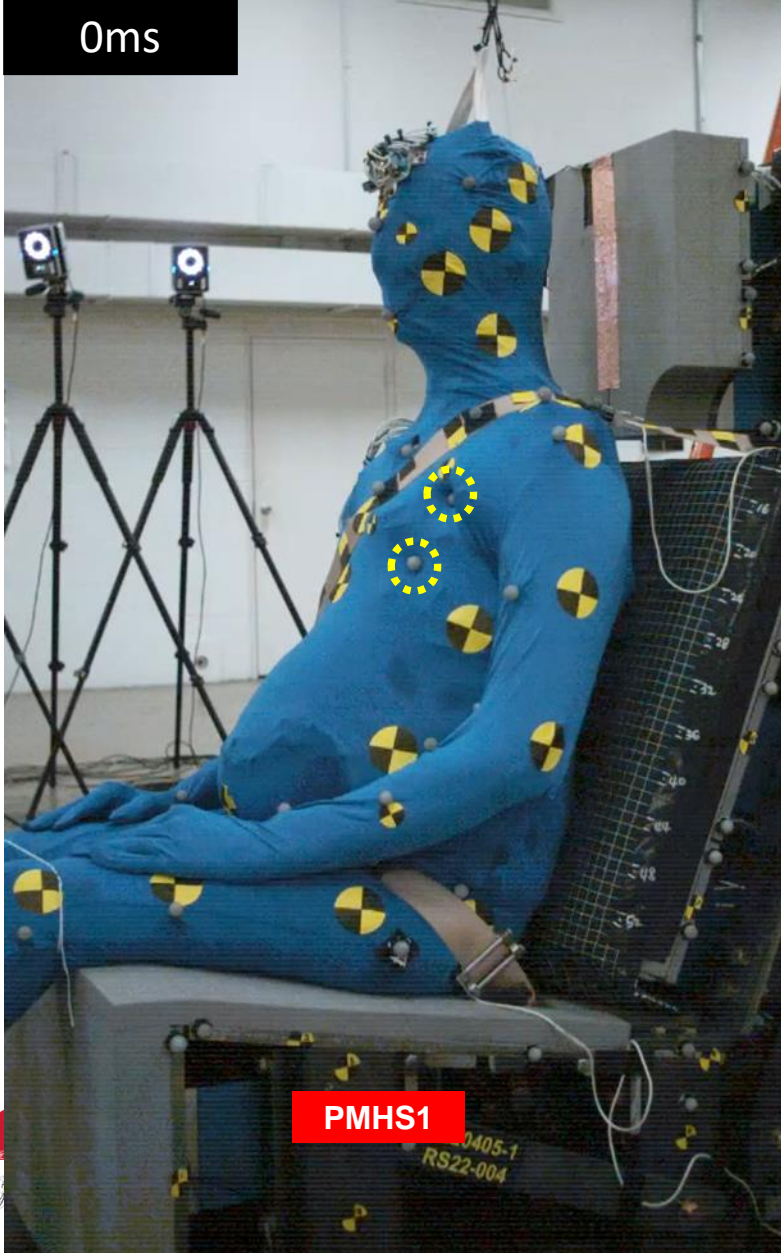
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# Chest Z-deformation



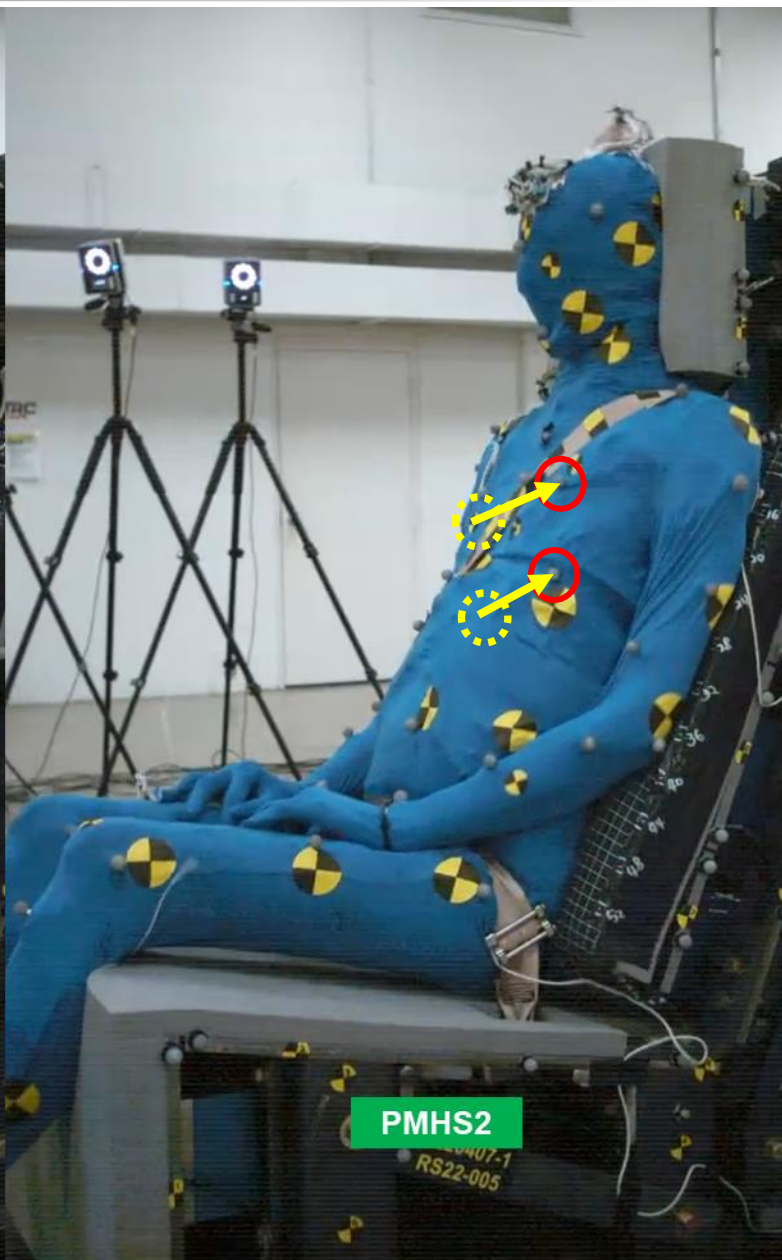
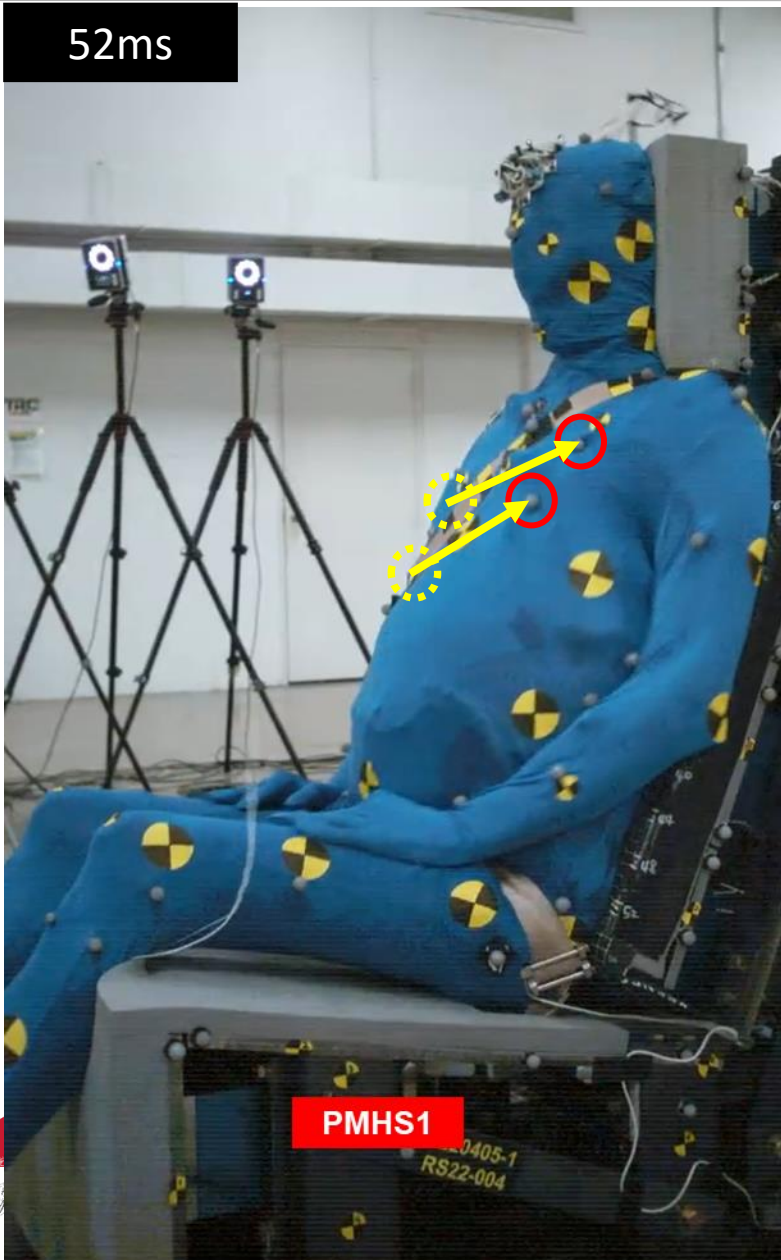
# PMHS Motion (Chest Z-deformation)

0ms

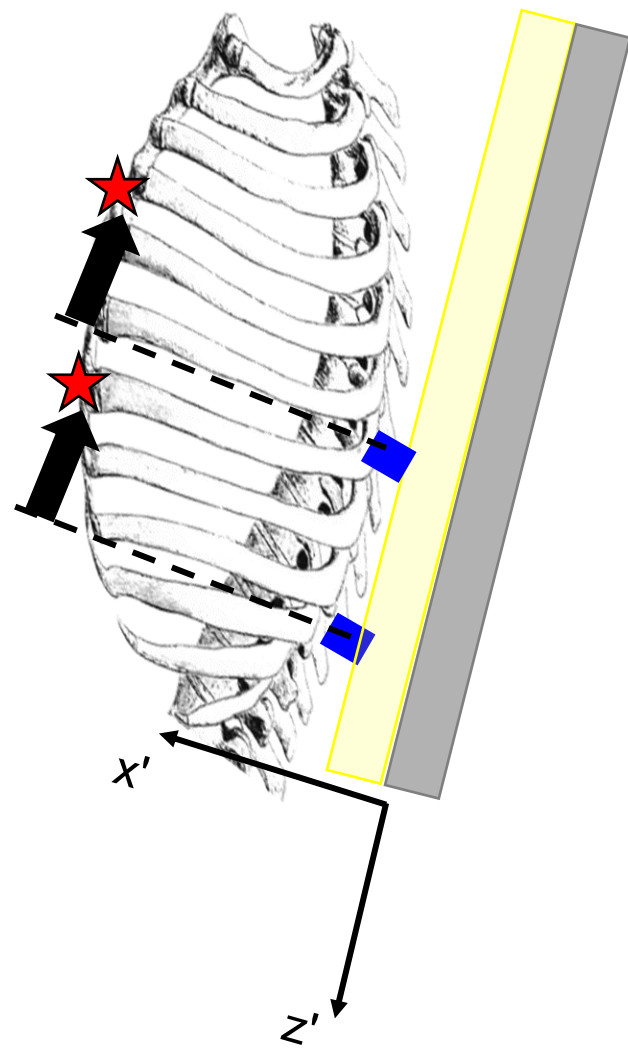
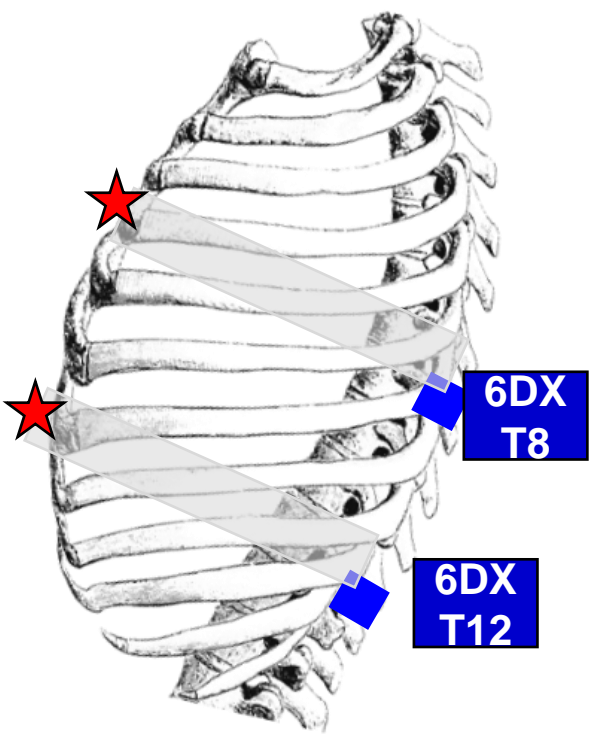


# PMHS Motion (Chest Z-deformation)

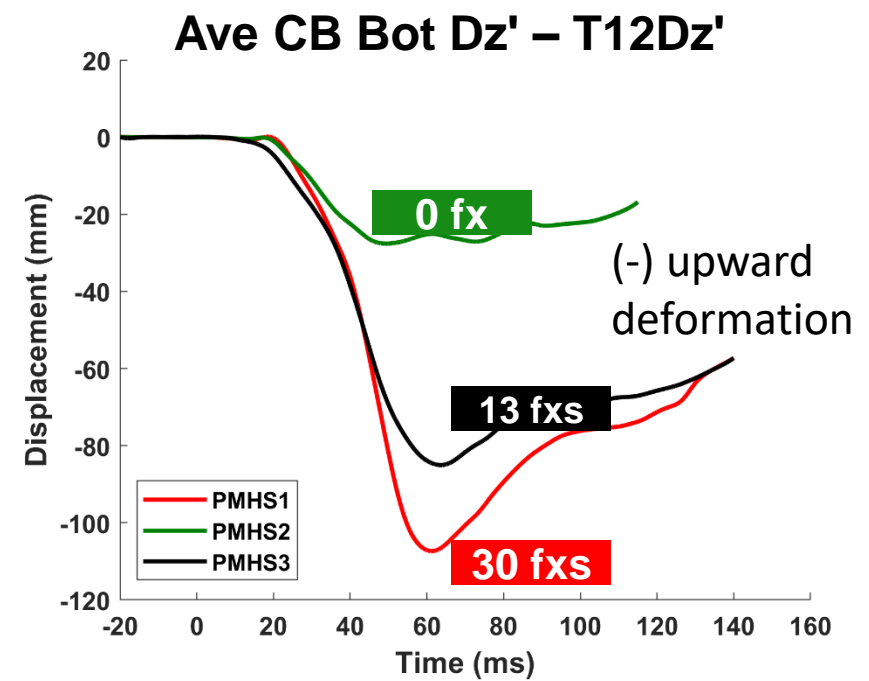
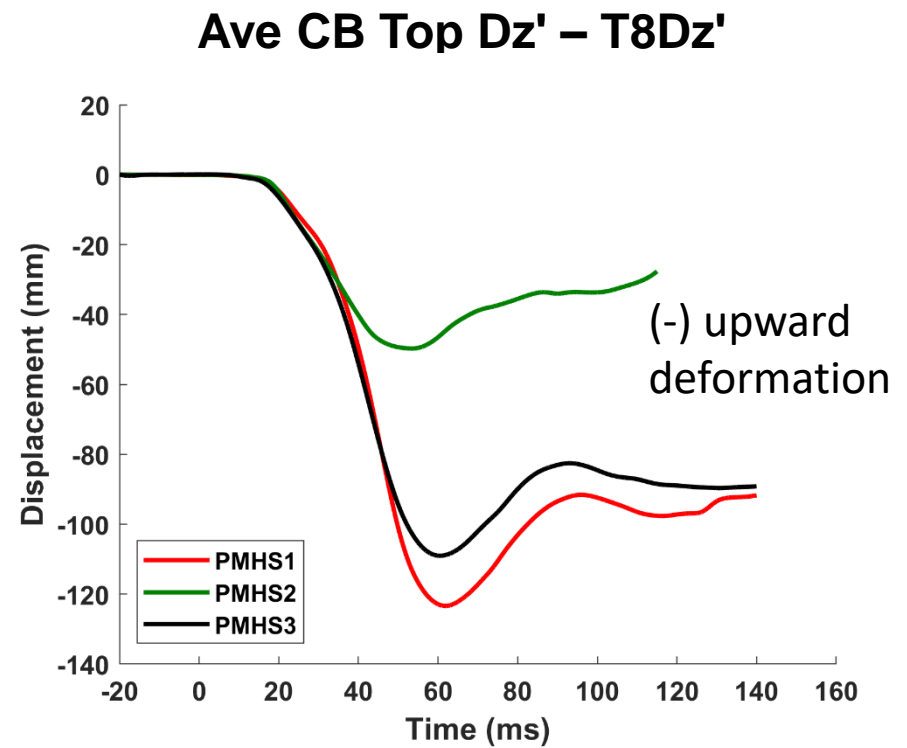
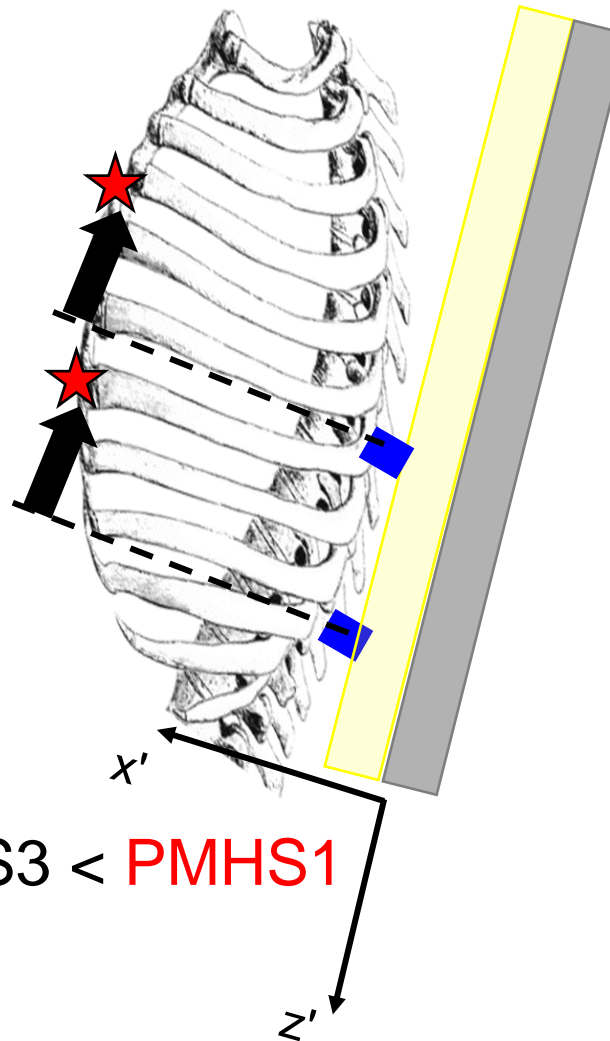
52ms



# Chest Z-deformation



# Chest Z-deformation

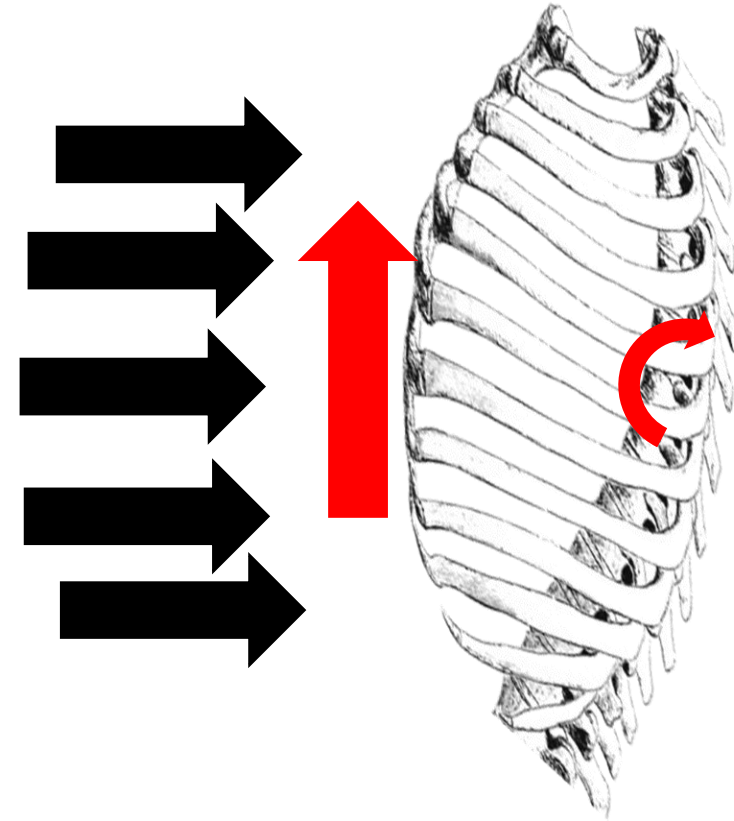
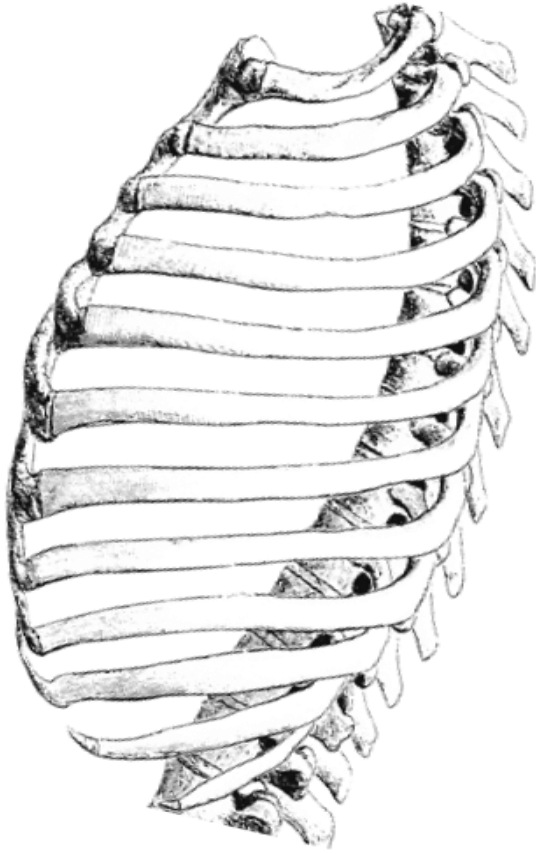


Dz'

PMHS2 (no rib fracture) < PMHS3 < PMHS1



# Potential Injury Mechanism

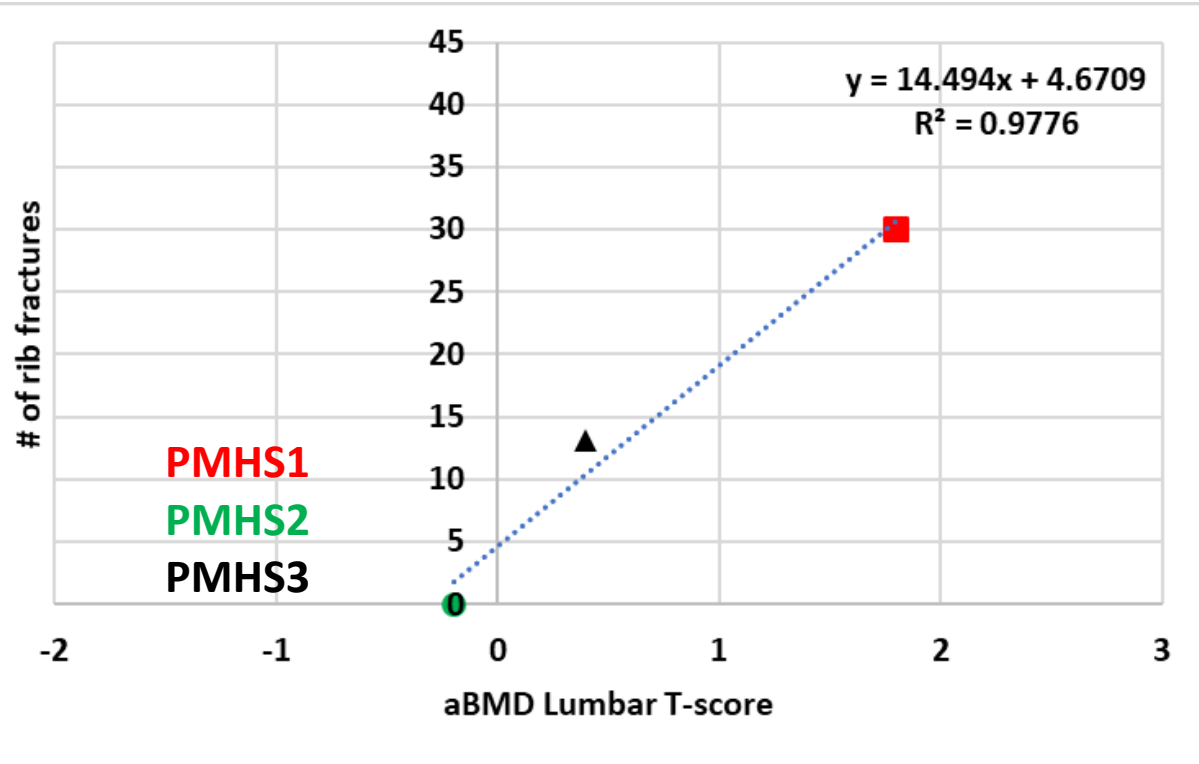




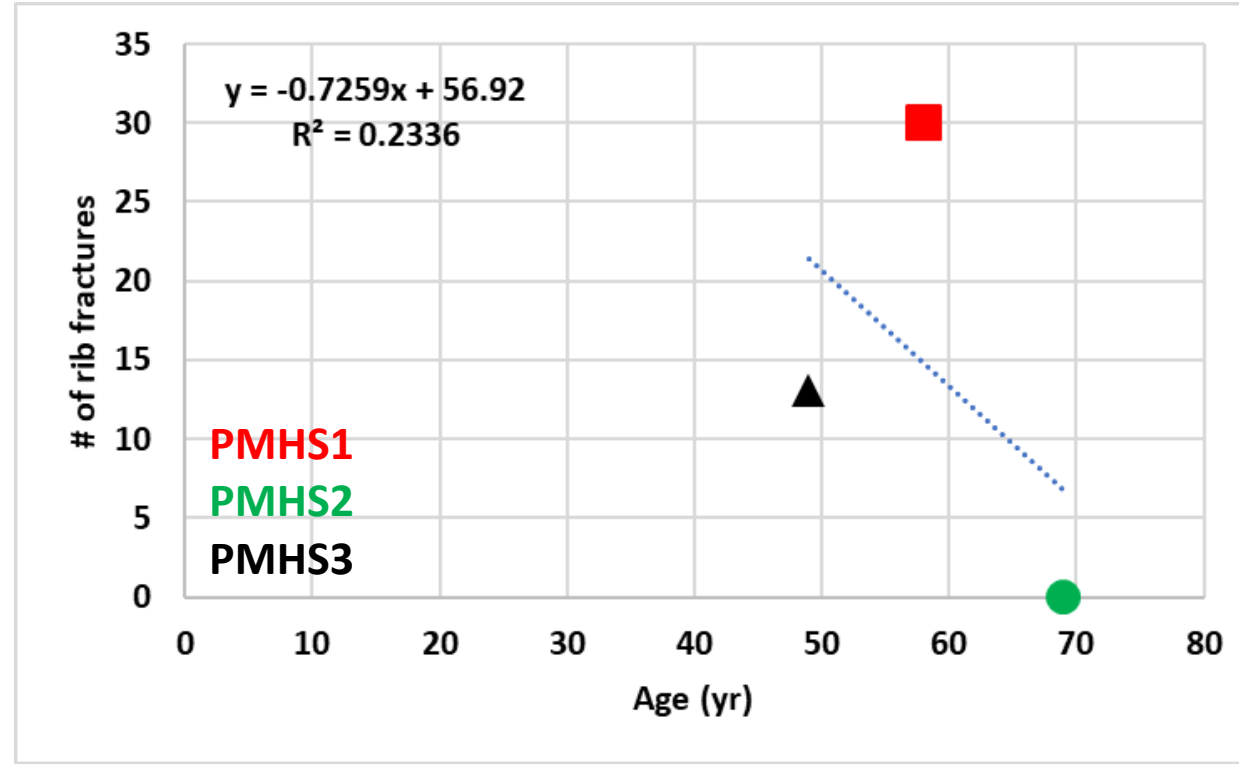
# PMHS Characteristics vs. # of Rib Fractures



# PMHS Characteristics



Aerial BMD (aBMD) – Lumbar Spine T-score

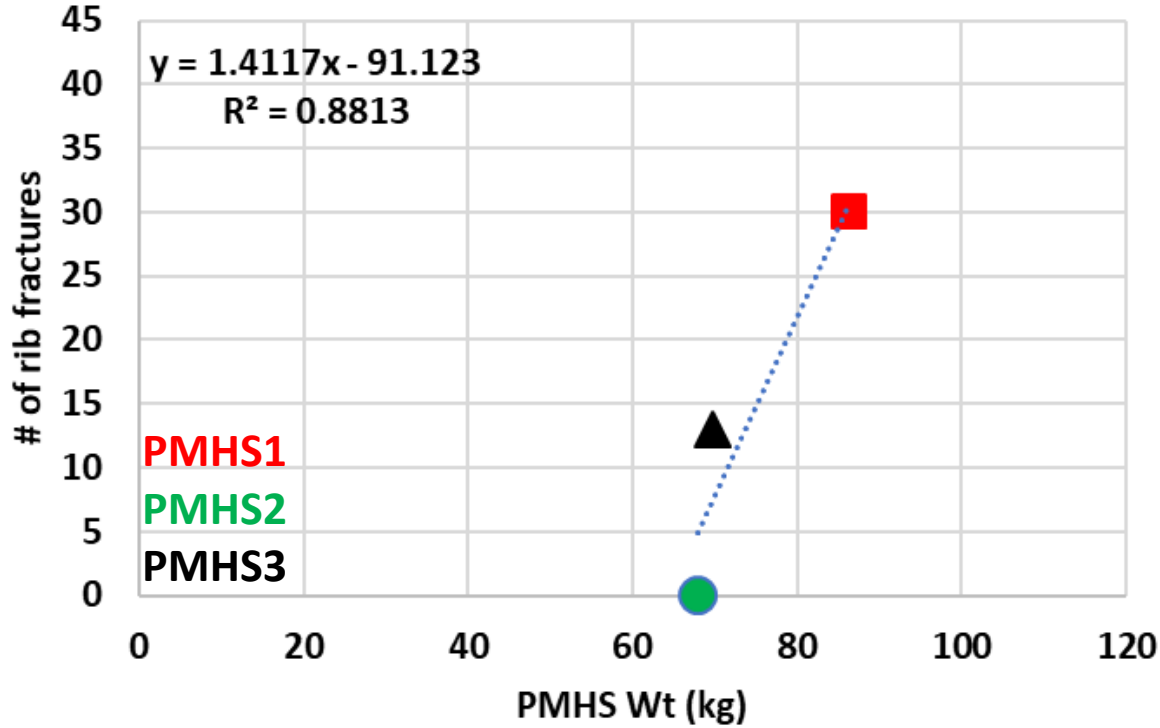


Age

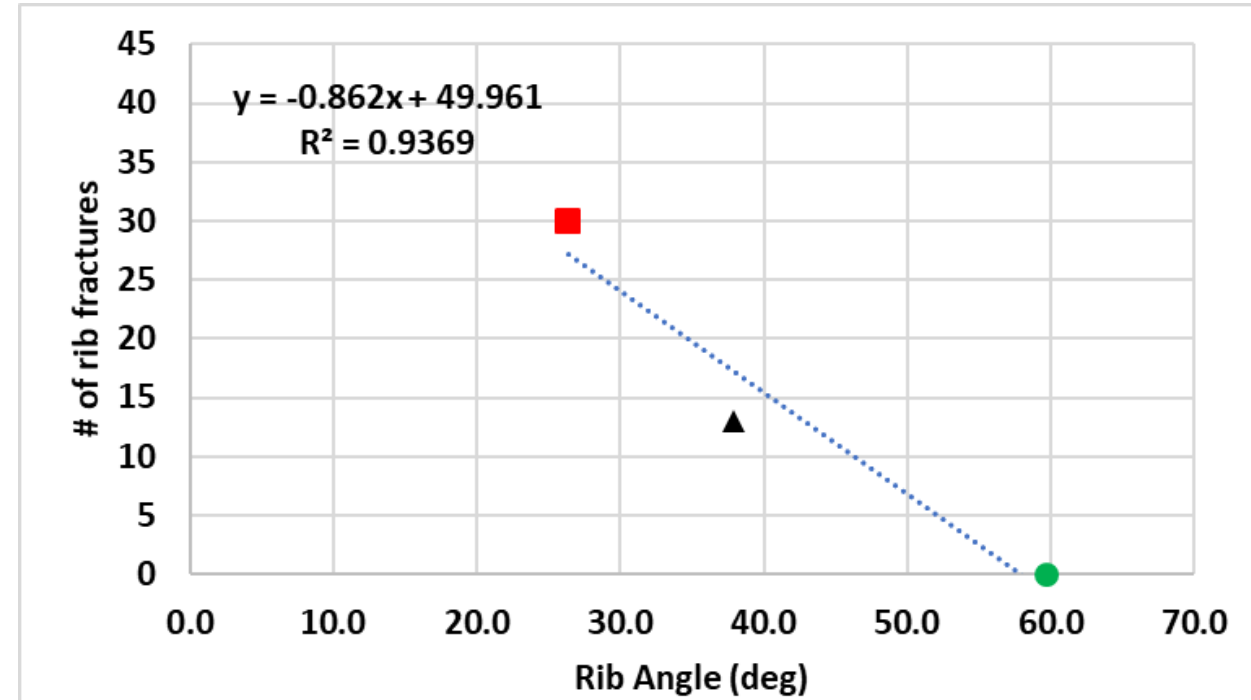




# PMHS Characteristics



Weight



PMHS1

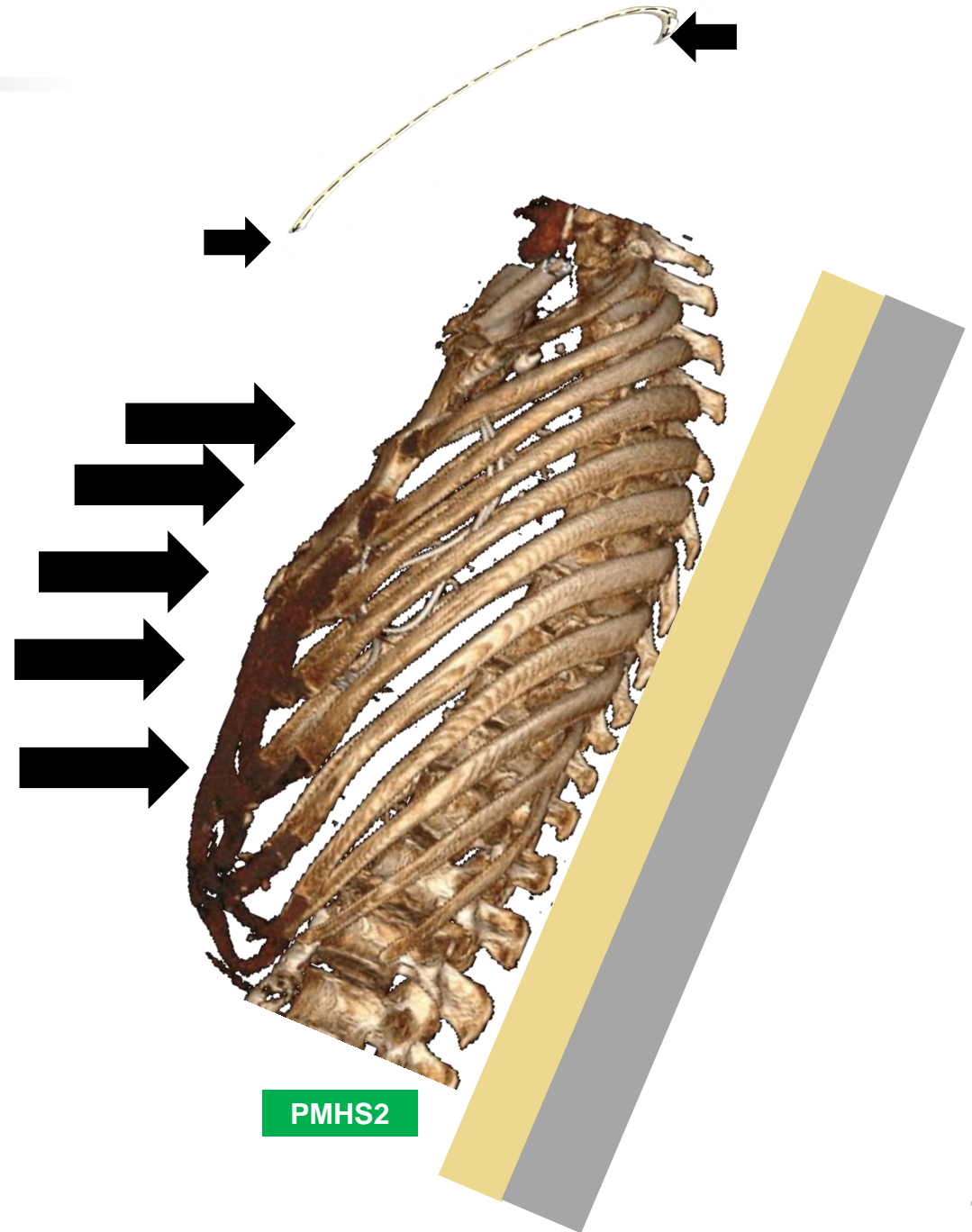
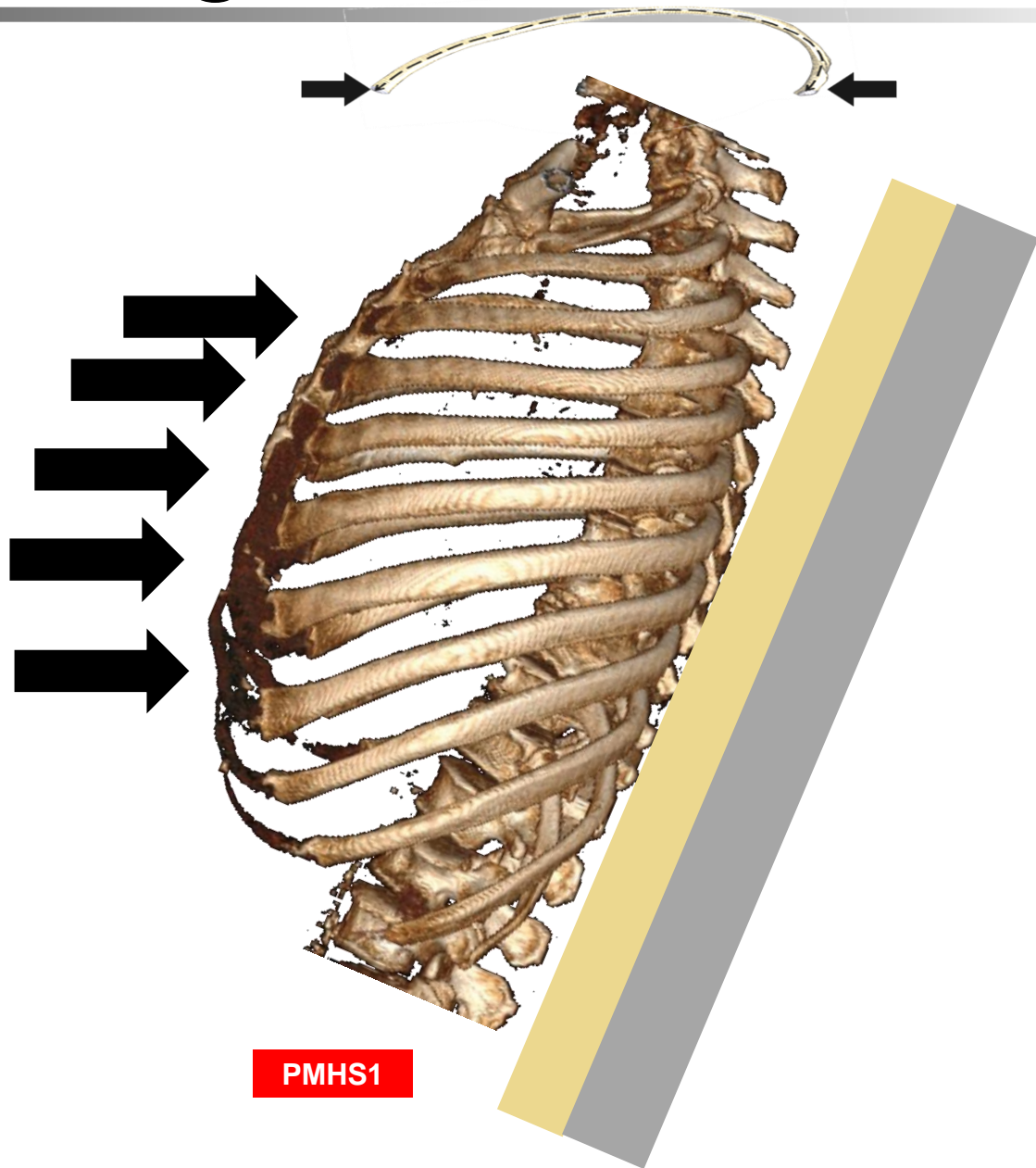
PMHS2

PMHS3

Rib Angle

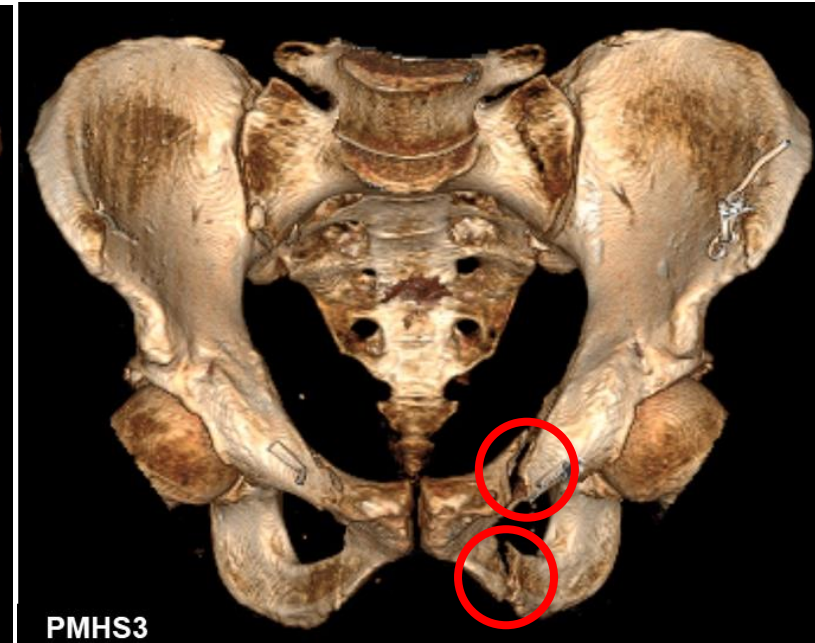
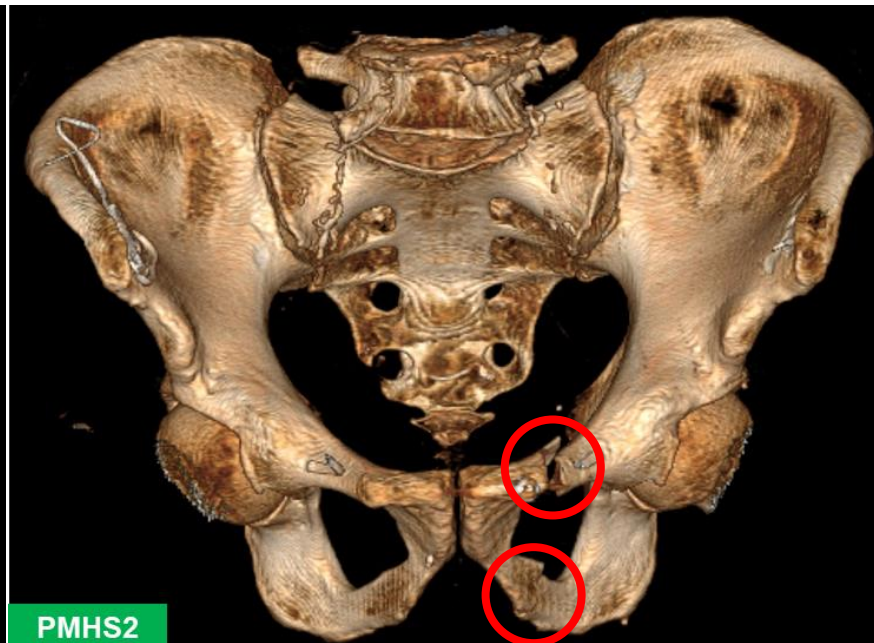
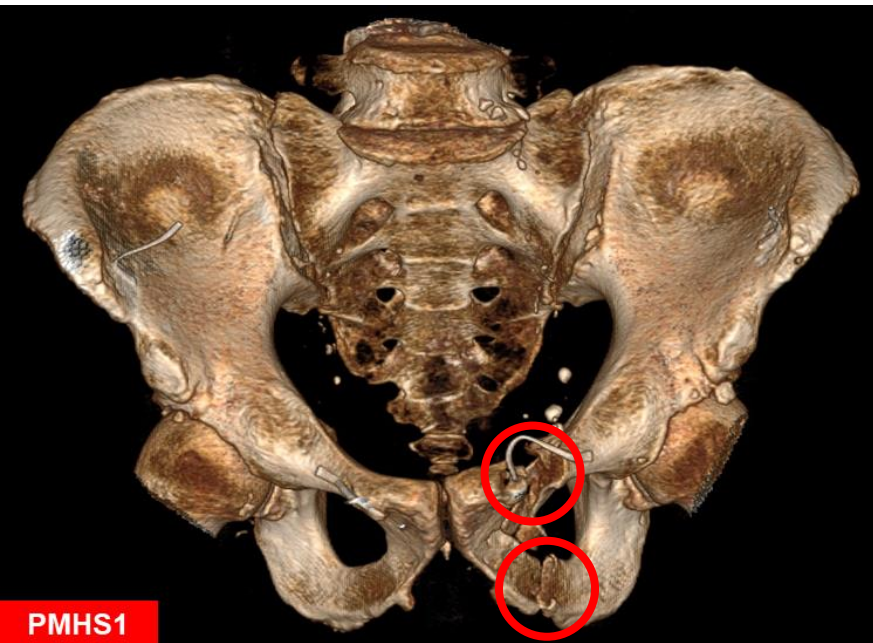


# Rib Angle



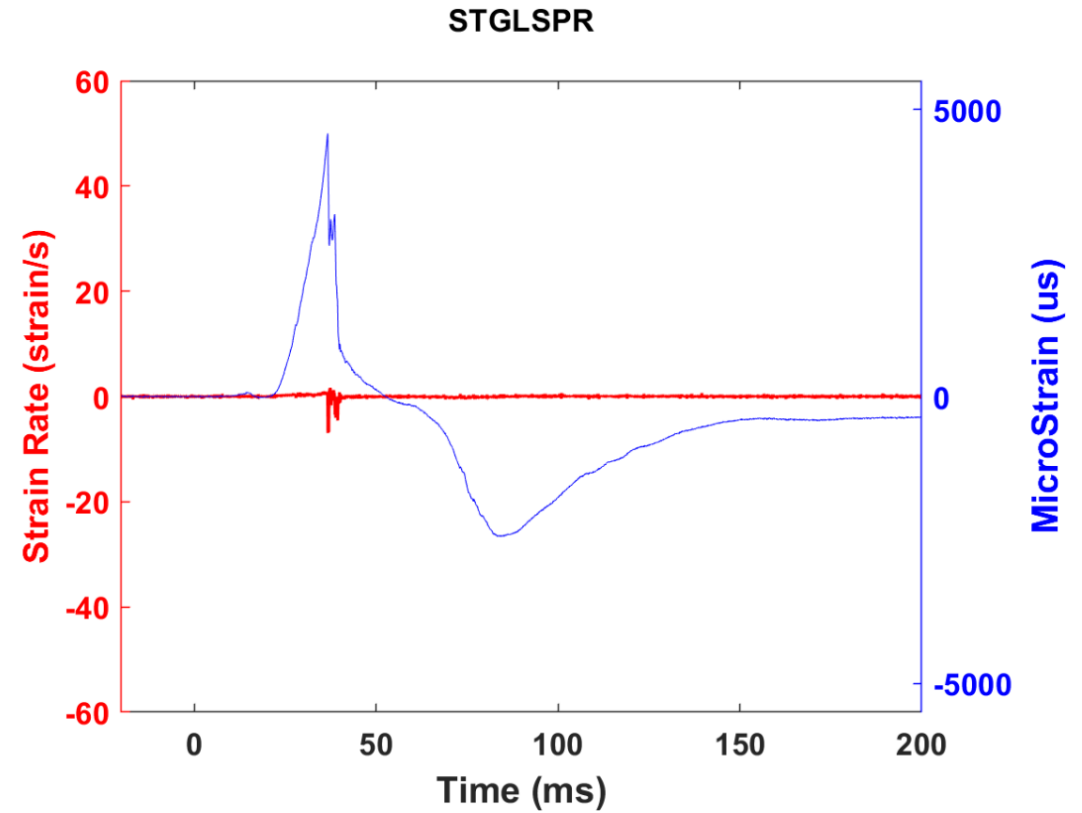
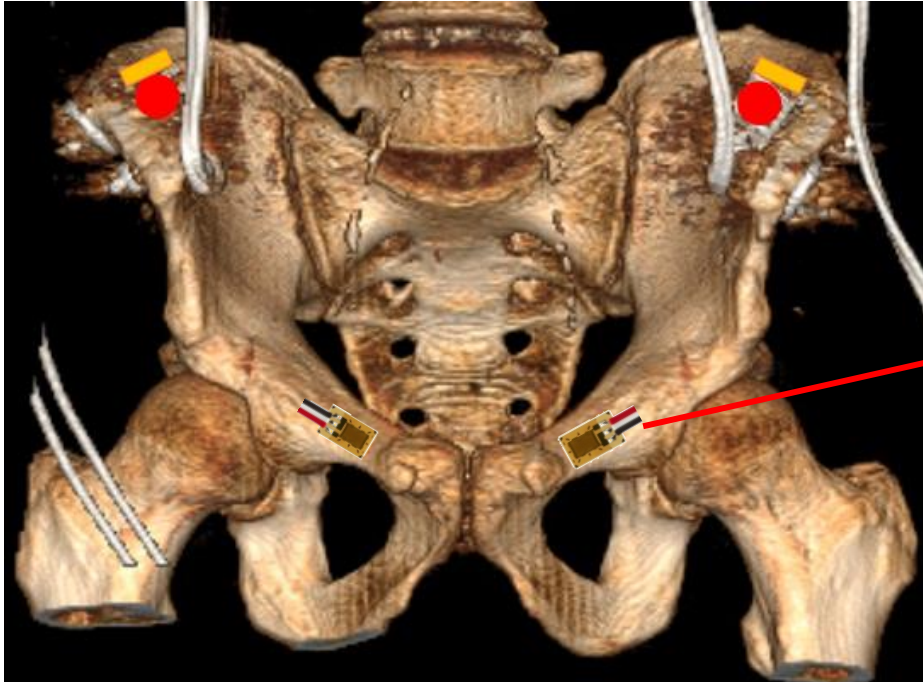
# Pelvis Injury

	PMHS1	PMHS2	PMHS3
MAIS	4	4	3
Description	L & R SI joints open <b>L Sup/Inf pubic ramus fx</b>	L & R SI joints open <b>L Sup/Inf pubic ramus fx</b>	L & R SI joints open <b>L Sup/Inf pubic ramus fx</b> L PSIS (ilium) fx Sacrum fx



# Strain Gage

All three PMHS sustained left sup/inf pubic ramus fxs

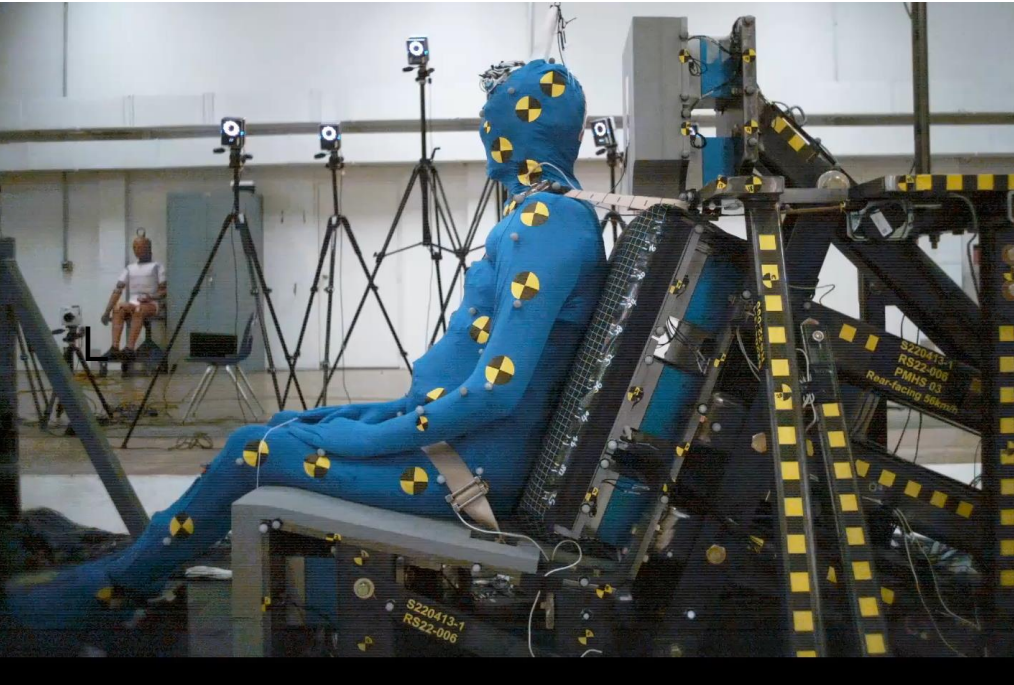


Strain Gage	PMHS1	PMHS2	PMHS3
Fx timing (ms)	38.05	39.60	36.75

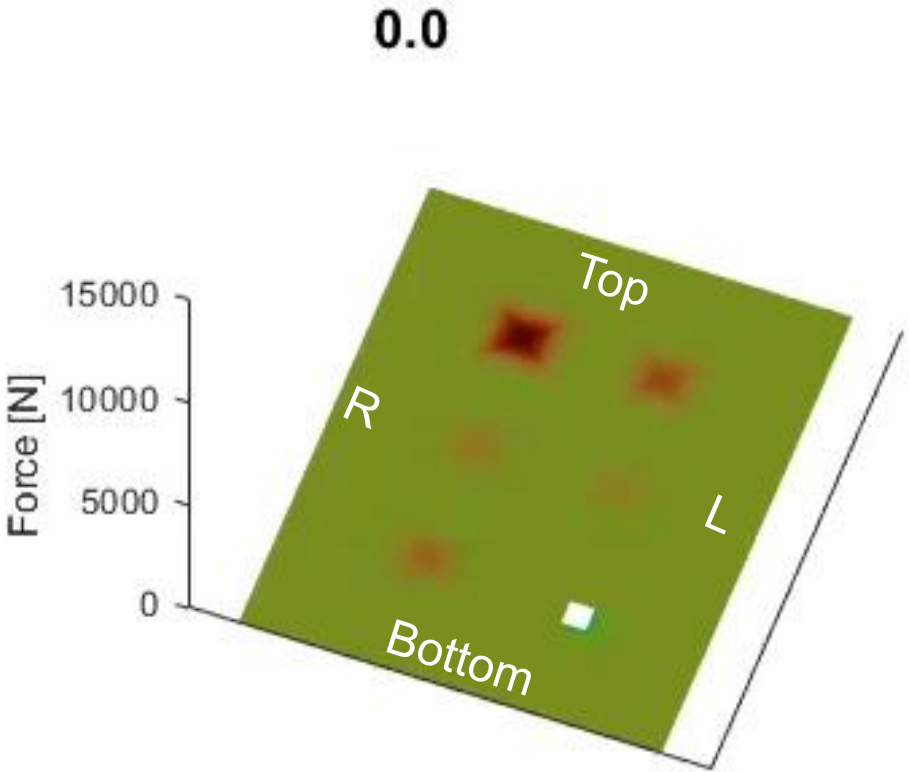
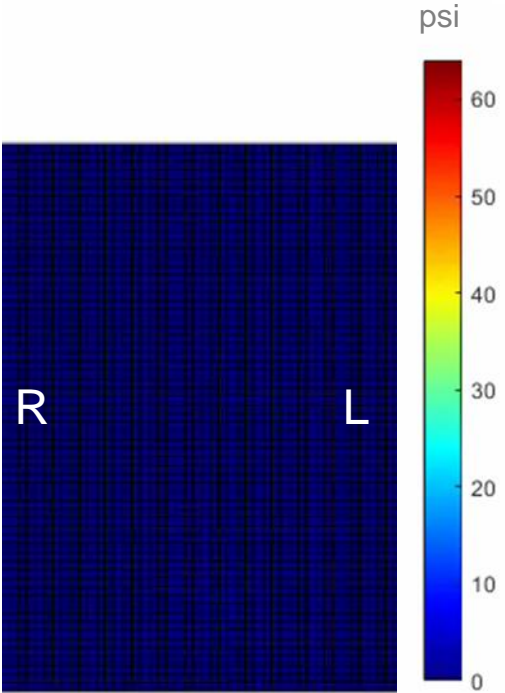
Uncensored data



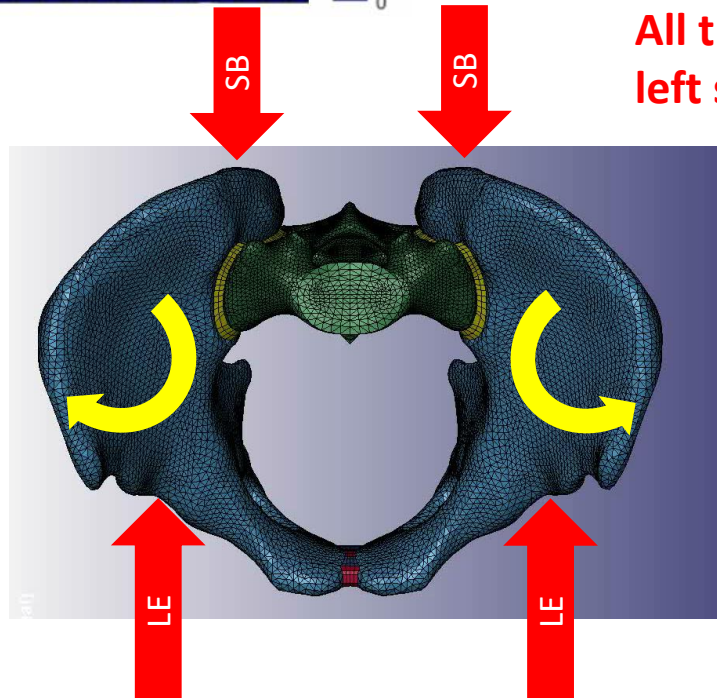
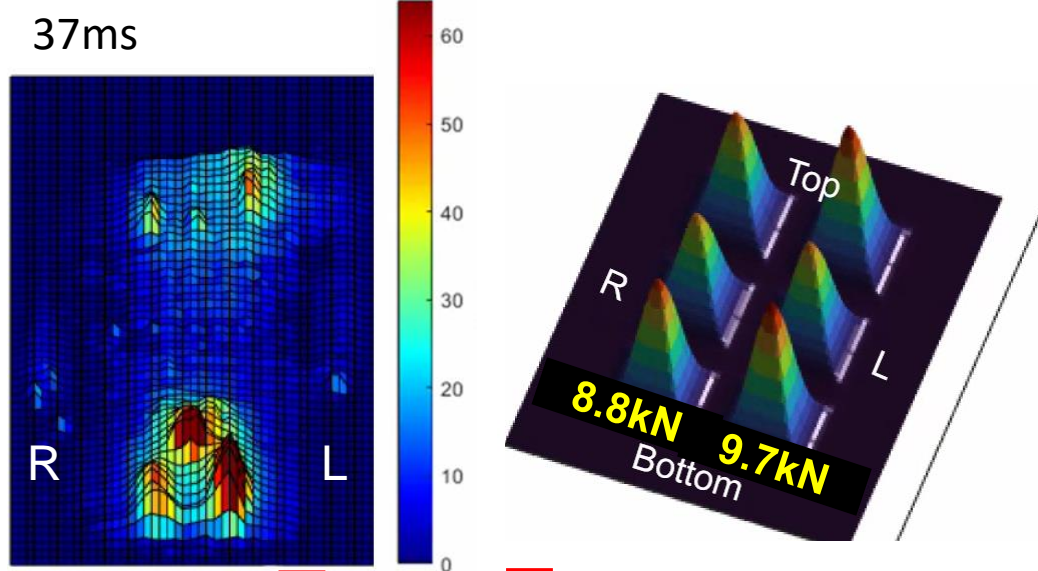
# Seatback Pressure & Load



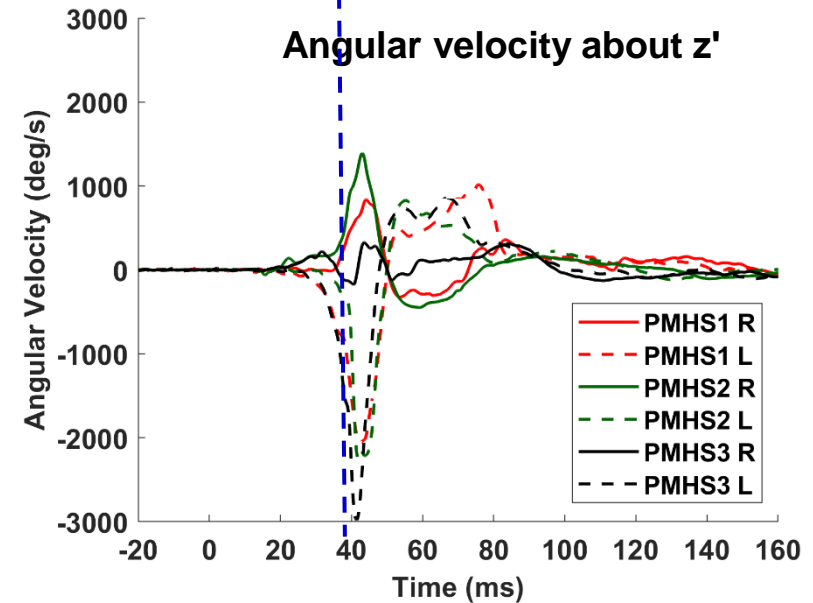
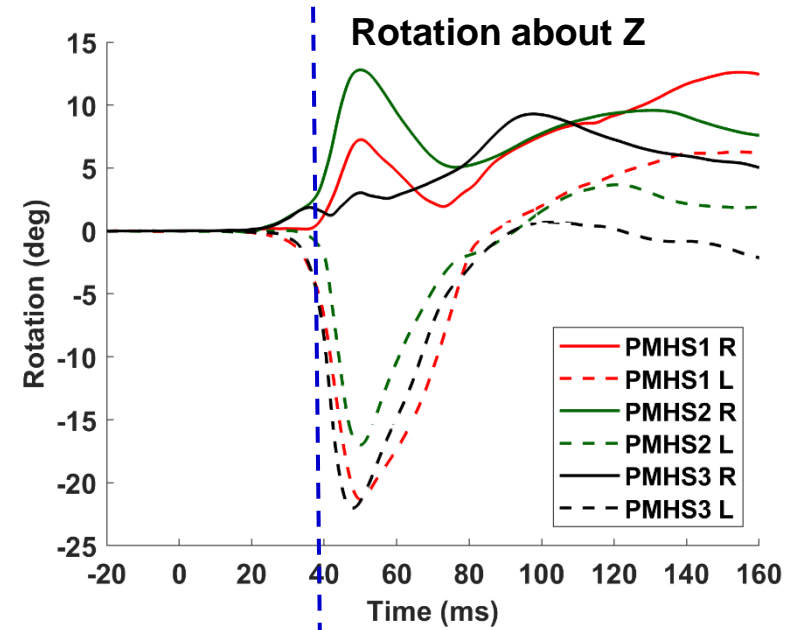
PMHS3



# Pelvis Off-axis Angular Kinematics



All three PMHS sustained left sup/inf pubic ramus fxs



# Summary

- Two PMHS sustained rib fractures
  - A-P % chest deflection may not be a good injury predictor
    - Similar normalized chest deflection between injurious and non-injurious PMHS
  - Principal strain direction determined from strain rosette at fracture showed combined strains
    - Not only strain along the rib but shear
  - Chest Z-deformation may be a potential predictable variable of rib fractures
- All three PMHS sustained left side pubic ramus fractures
  - Load cell and XSENSOR
    - Higher loads/pressures on the left side (non-buckle side)
  - Off-axis angular kinematics
    - Rotation → angular velocity



# Acknowledgements

Anatomical Donors of...



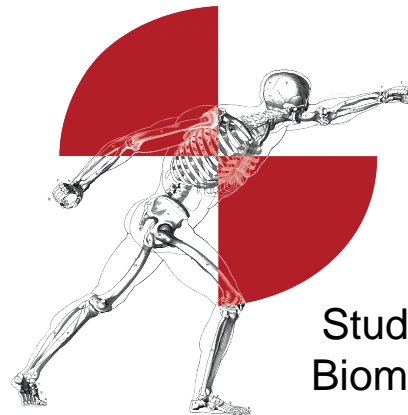
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The opinions expressed within are solely those of the authors and do not represent the views of any sponsors or collaborators



Hyun Jung Kwon, PhD  
Oliver Lindemer  
Steve Christmans  
Jason Jenkins



Students and staff of the Injury  
Biomechanics Research Center



# PMHS Responses and Injuries in a Homogeneous Rear-Facing Seat Condition at a High-Speed Frontal Impact

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*Yun-Seok Kang, Vikram Pradhan, Angela Tesny, Tim DeWitt, Alexander Bendig, Gretchen Baker, Angelo Marcallini, Zachary Haverfield, Amanda M. Agnew, John H. Bolte IV*  
*Injury Biomechanics Research Center, OSU*

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5/25/2023

RCCADS Public Workshop



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**R E S E A R C H   C E N T E R**



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