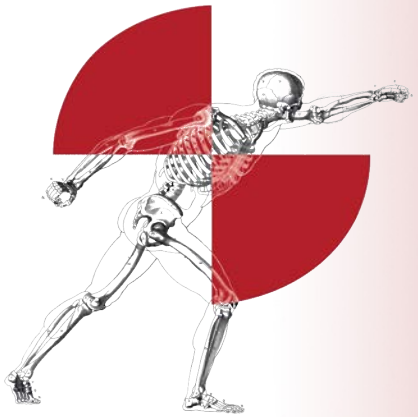
Occupant Safety in Highly Automated Vehicles

John H Bolte IV, PhD

Injury Biomechanics Research Center, The Ohio State University

Automotive Safety Council
March 19, 2022



INJURY BIOMECHANICS RESEARCH CENTER

THE OHIO STATE UNIVERSITY

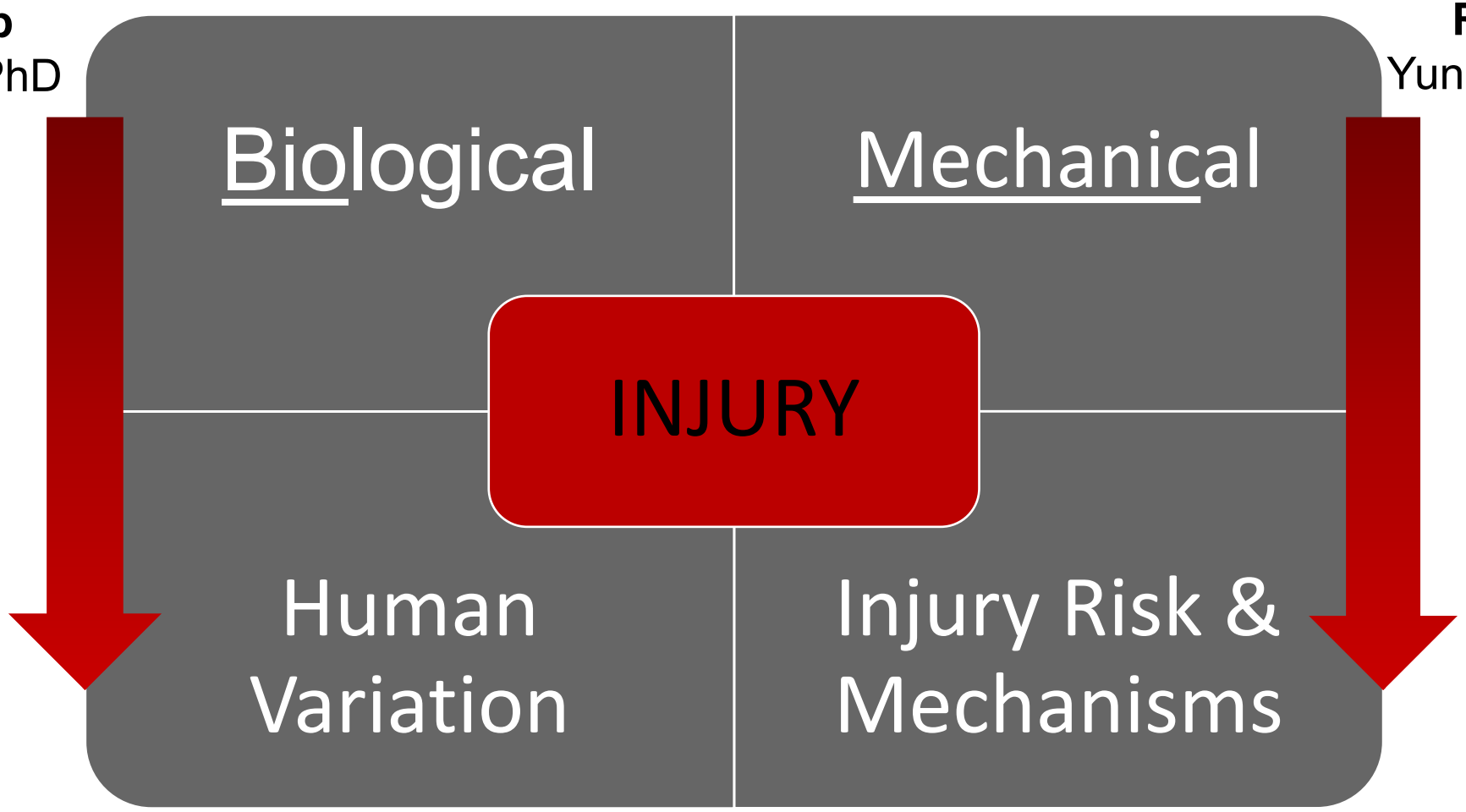
Our approach is ***interdisciplinary…***

Injury Biomechanics Research Center

John Bolte IV, PhD

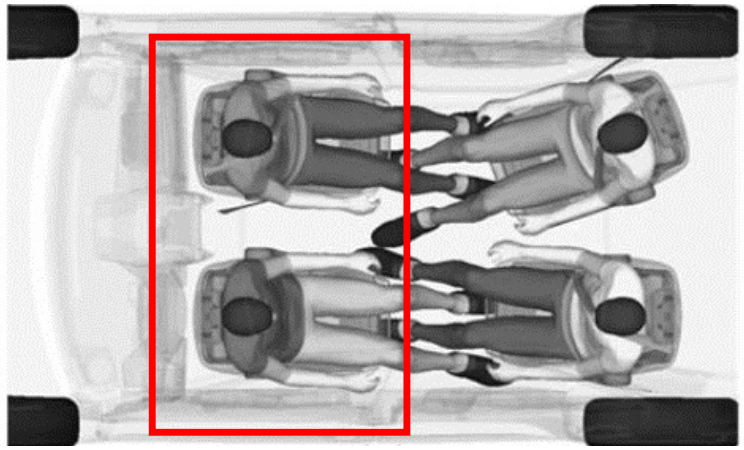
Skeletal Biology Research Lab
Mandy Agnew, PhD

Injury Biomechanics Research Lab
Yun-Seok Kang, PhD



Introduction

- 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; Ostling and Larsson, 2019]
  - Studies using computational models and ATDs [Kitagawa et al., 2017; Jin et al., 2018; Zeller and Manneck, 2019]
    - FE models: validated in low-speeds (< 17 km/h)
    - ATDs: not validated for rear impacts

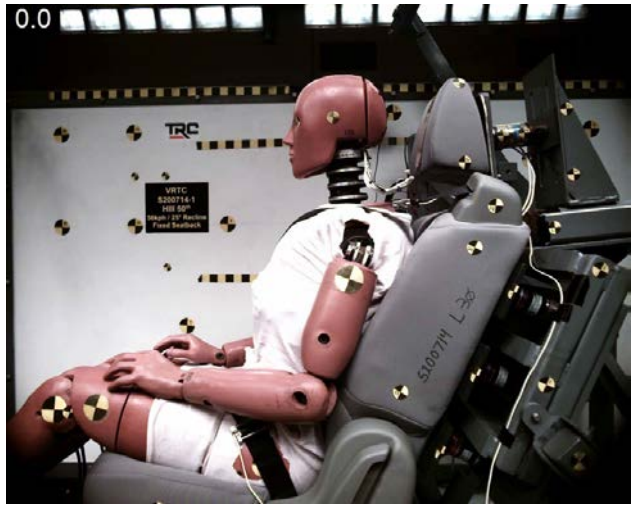


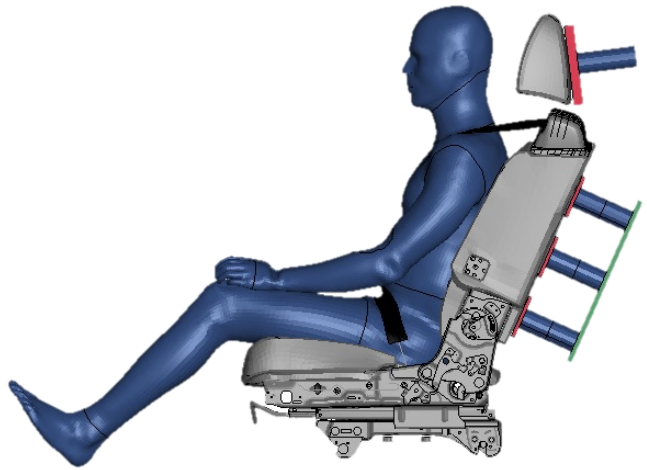
Kitagawa et al., 2017

Zellmer and Manneck, 2019

Objective

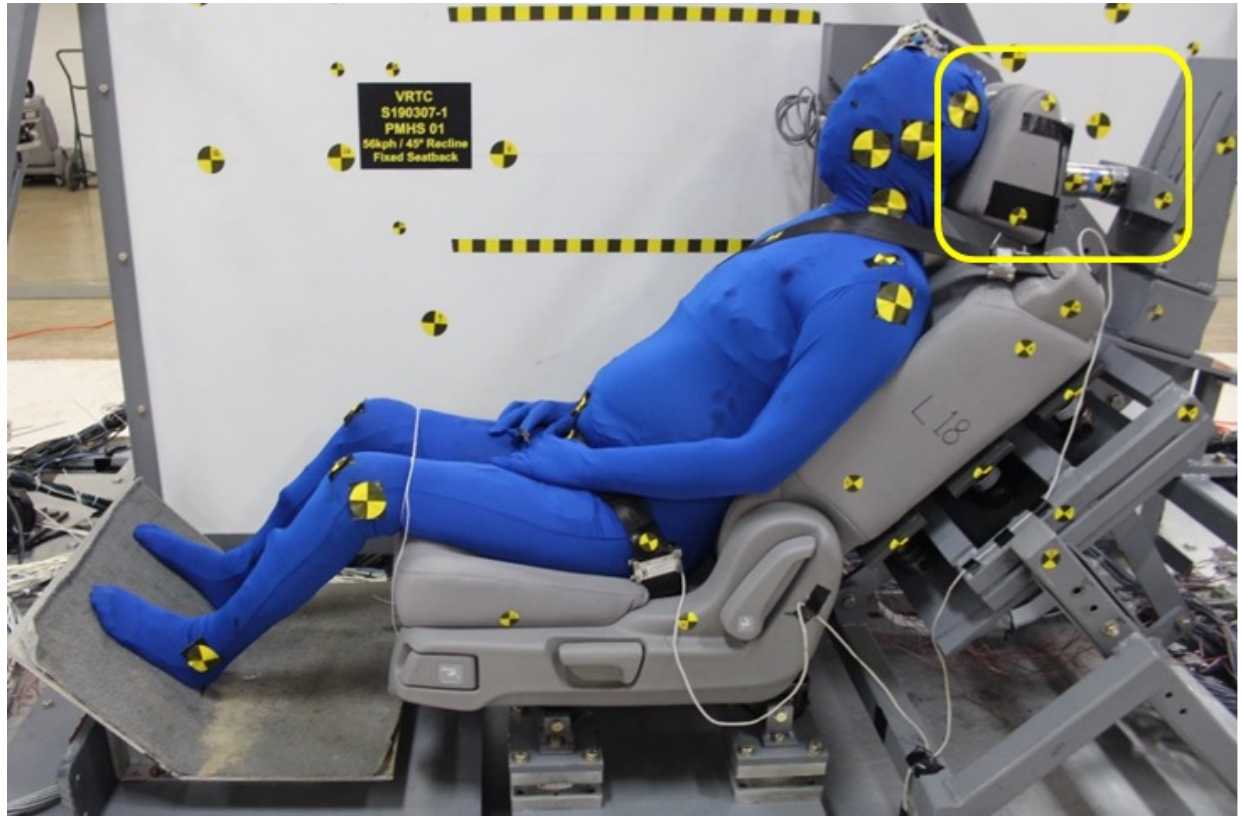
- To investigate responses and injuries from PMHS in multiple scenarios in a rear-facing seating configuration during frontal crashes
  - Effect of Seat Back Recline (25 deg vs. 45 deg)
  - Effect of Belt Restraint/Seat Type (Integrated vs. Fixed D-ring)
  - Effect of Speed (24 km/h vs. 56 km/h)



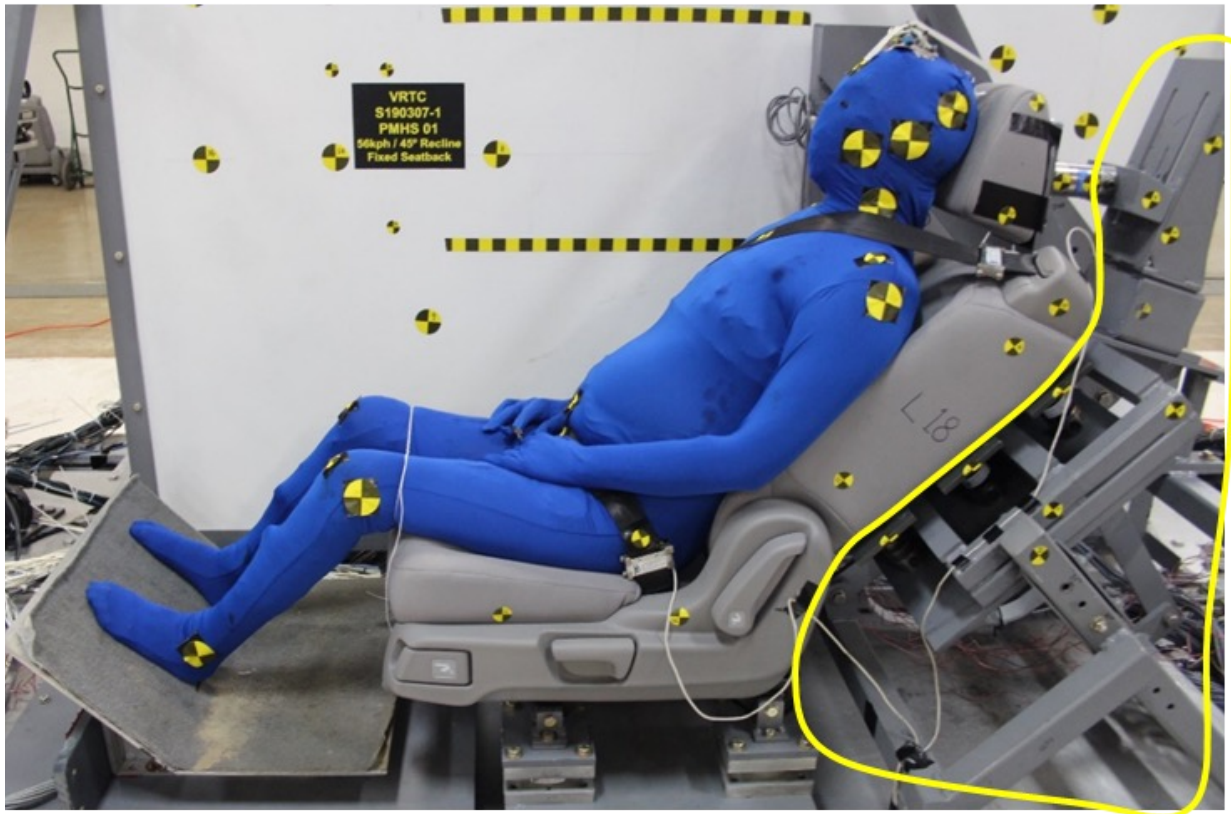


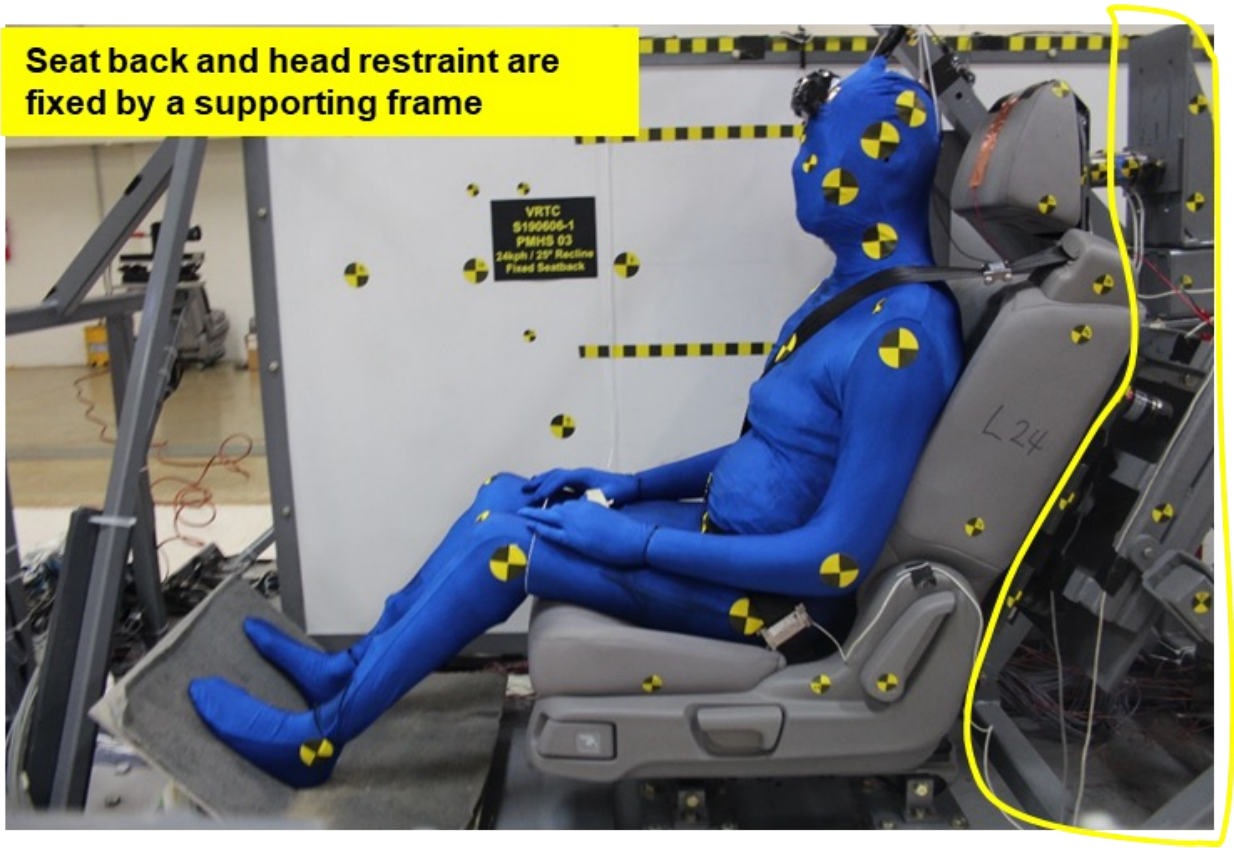
Content Warning

Sled Buck Description



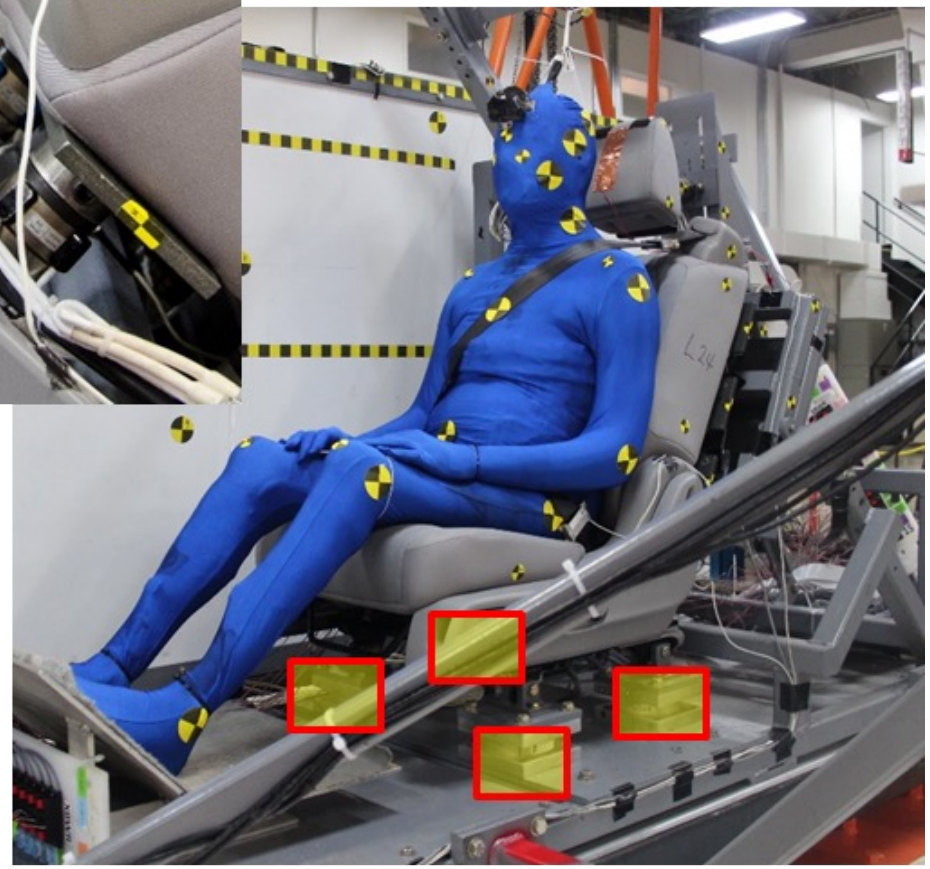
Sled Buck Description



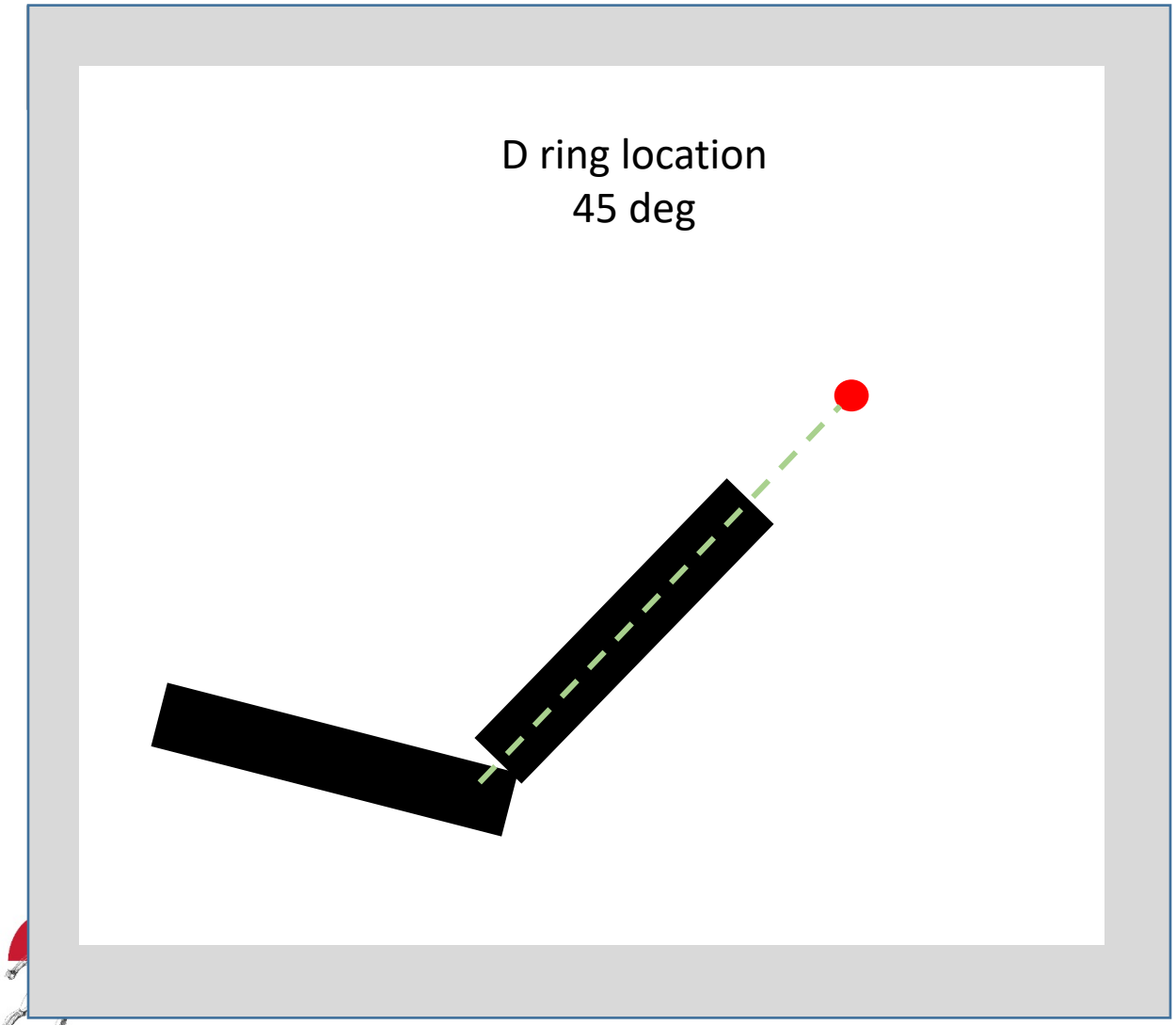


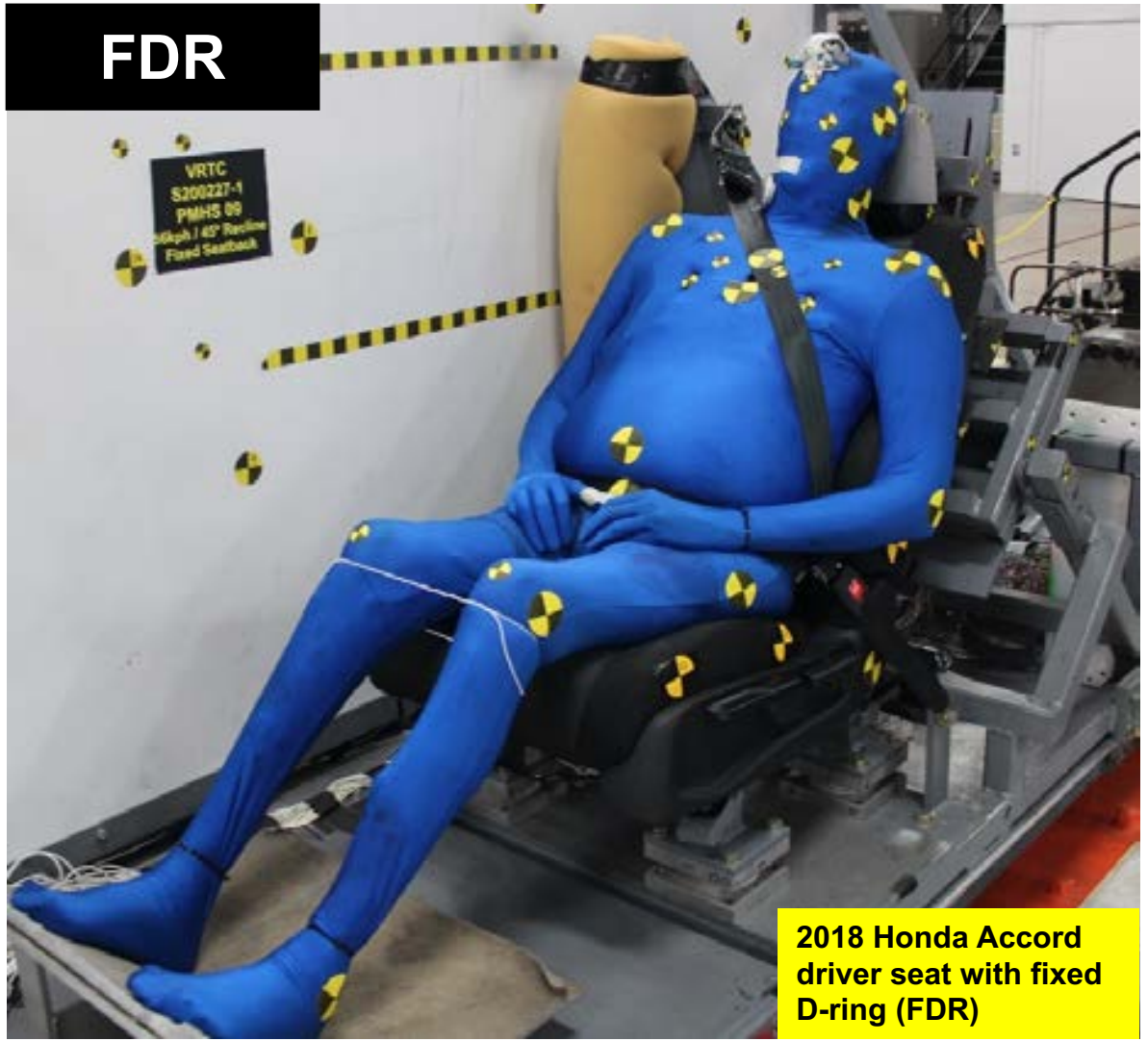
Sled Buck Description

Load cells at head restraint (1), seat back (6), and seat anchors (4) to measure reaction loads



Sled Buck Description





2018 Honda Accord driver seat with fixed D-ring (FDR)

PMHS Characteristics – 56 km/h

N=14	Speed	Seat	Recline	Age	Height (cm)	Weight (kg)	Seated Height (cm)	Head Mass (kg)	Chest Depth (cm)	Cause of Death
PMHS01	56	ABTS	45	57	167.0	62.6	90.0	3.8	20.6	Chronic Obstructive Pulmonary Disease
PMHS02	56	ABTS	25	64	171.0	62.6	92.4	3.6	17.6	Alcohol Abuse
PMHS03	56	ABTS	25	54	174.0	93.9	97.0	5.0	20.6	Choking and asphyxiation
PMHS04	56	ABTS	45	59	178.0	96.2	96.5	4.4	23.2	Chronic Obstructive Pulmonary Disease
PMHS05	56	ABTS	45	62	176.0	77.1	95.7	3.5	21.2	Pancreatic CA
PMHS06	56	ABTS	25	61	176.5	72.6	94.0	3.9	20.2	Ischemic stroke, heart failure
PMHS09	56	FDR	45	71	187.5	89.4	96.5	4.3	17.1	Chronic Obstructive Pulmonary Disease
PMHS10	56	FDR	25	62	177.8	100.7	94.5	4.4	20.1	Cardiac Arrest
PMHS11	56	FDR	25	65	181.0	92.1	96.5	4.3	21.7	Stroke
PMHS12	56	FDR	25	58	177.8	71.7	94.2	3.9	21.1	Lung CA with mets
PMHS13	56	FDR	45	53	176.3	76.2	95.7	3.7	19.7	Melanoma with mets
PMHS14	56	FDR	45	63	172.3	85.3	93.0	3.8	23.4	Heart failure
PMHS21	56	FDR	25	62	172.7	68.5	89.7	3.8	20.2	Lung CA with mets
PMHS22	56	FDR	45	61	176.6	71.7	94.1	3.6	19.3	Metastatic squamous cell carcinoma
Mean (SD)	N/A	N/A	N/A	61 (5)	176.0 (4.8)	80.0 (12.7)	94.3 (2.3)	4.0 (0.4)	20.4 (1.8)	N/A
50th Male	N/A	N/A	N/A	45	175	78.2	90.7	4.5	22.9	N/A

PMHS Characteristics – **56 km/h**

N=14	Speed	Seat	Recline	Age	Height (cm)	Weight (kg)	Seated Height (cm)	Head Mass	Chest Depth	Cause of Death
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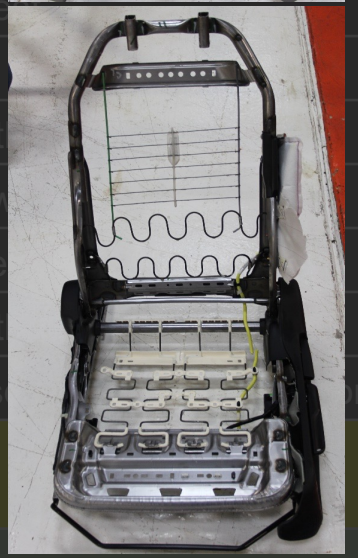
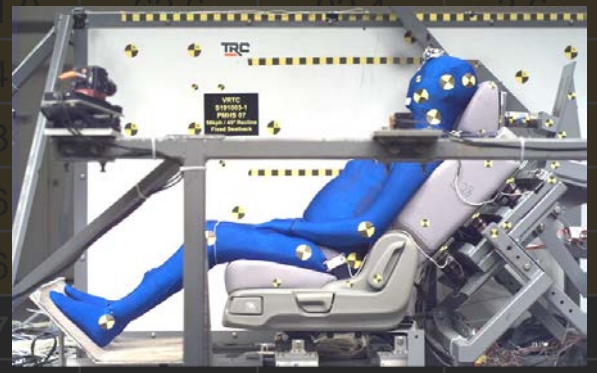
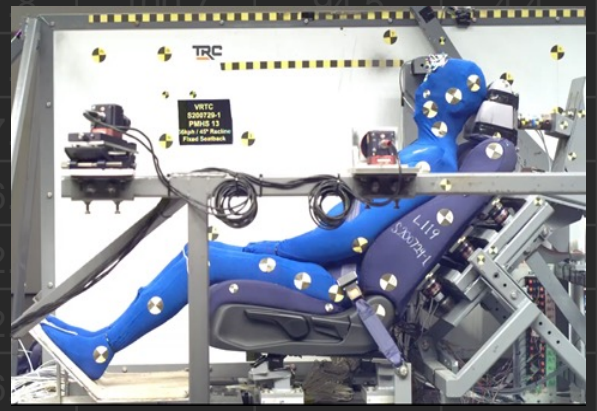
PMHS02	56	ABTS	25				92.4			hol Abus
PMHS03	56	ABTS	25				97.0			king and
PMHS04	56	ABTS	45				96.5			onic Obs Disease
PMHS05	56	ABTS	45				95.7			creatic C
PMHS06	56	ABTS	25				94.0			emic str
PMHS09	56	FDR	45				96.5			onic Obs Disease
PMHS10	56	FDR	25				94.5			diac Arre
PMHS11	56	FDR	25				96.5			ke
PMHS12	56	FDR	25				94.2			g CA wit
PMHS13	56	FDR	45				95.7			anoma w
PMHS14	56	FDR	45				93.0			rt failure
PMHS21	56	FDR	25				89.7			g CA wit
PMHS22	56	FDR	45				94.1			astatic s oma
Mean (SD)	N/A	N/A	N/A				94.3 (2.3)			
50th Male	N/A	N/A	N/A	45	175	78.2	90.7	4.5	22.9	N/A

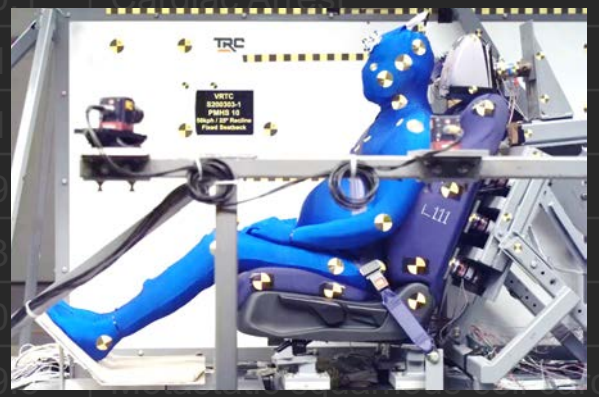


PMHS Characteristics – **56 km/h**

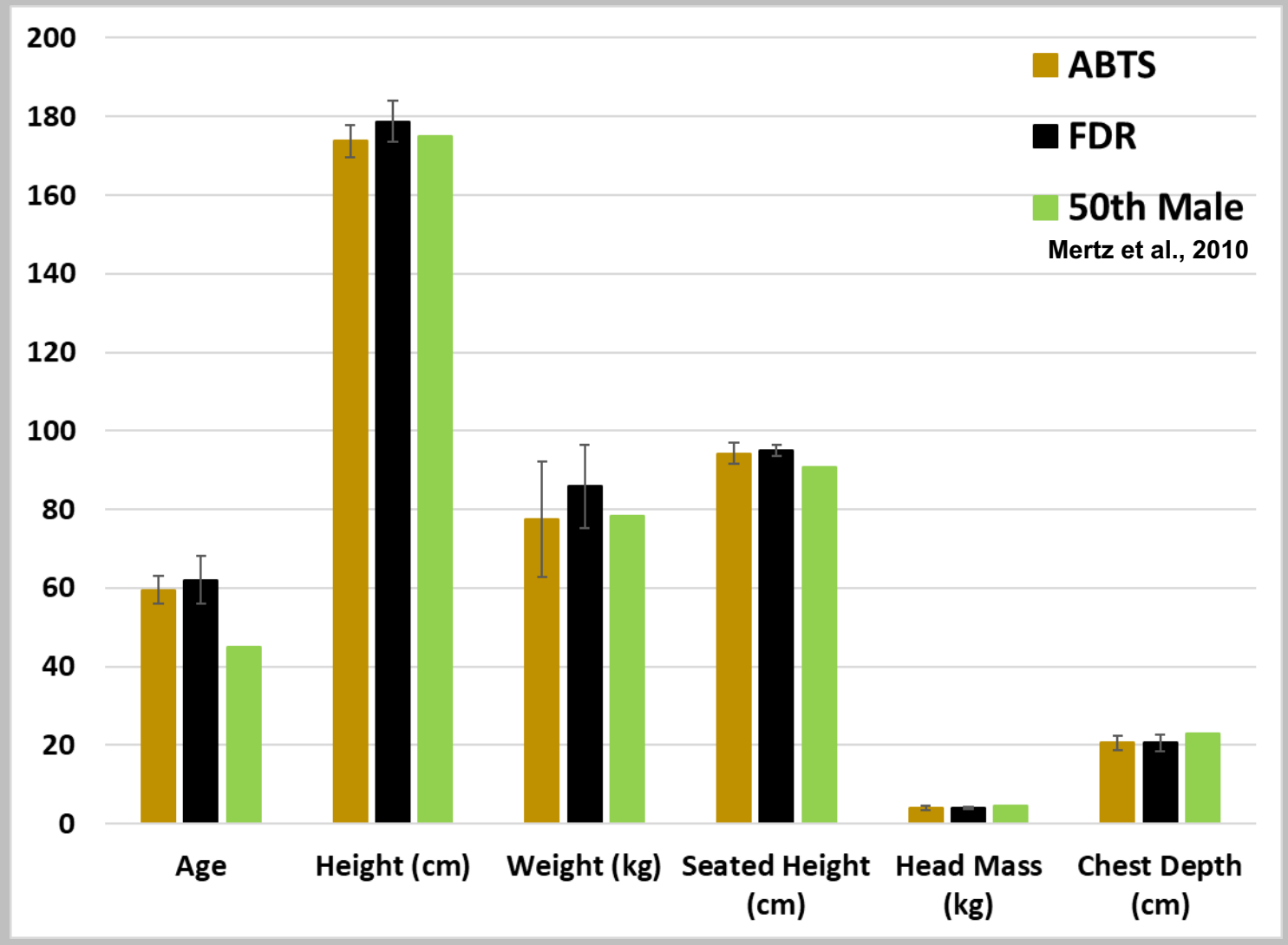
N=14	Speed	Seat	Recline	Age	Height (cm)	Weight (kg)	Seated Height (cm)	Head Mass (kg)	Chest Depth (cm)	Cause of Death
PMHS01	56	ABTS	45	57	167.0	62.6	90.0	3.8	20.6	Chronic Obstructive Pulmonary Disease
PMHS02	56	ABTS	25	64	171				17	
PMHS03	56	ABTS	25	54	174				20	
PMHS04	56	ABTS	45	59	178				23	ry Disease
PMHS05	56	ABTS	45	62	176				21	
PMHS06	56	ABTS	25	61	176				20	
PMHS09	56	FDR	45	71	187				17	ry Disease
PMHS10	56	FDR	25	62	177.8	100.7	94.5	4.4	20.1	Cardiac Arrest
PMHS11	56	FDR	25	65	181				21	
PMHS12	56	FDR	25	58	177				21	
PMHS13	56	FDR	45	53	176				19	
PMHS14	56	FDR	45	63	172				23	
PMHS21	56	FDR	25	62	172				20	
PMHS22	56	FDR	45	61	176				19	cinoma
Mean (SD)	N/A	N/A	N/A	61 (5)	176.0 (4.8)	80.0 (12.7)	94.3 (2.3)	4.0 (0.4)	20.4 (1.8)	N/A
50th Male	N/A	N/A	N/A	45	175	78.2	90.7	4.5	22.9	N/A







PMHS Characteristics – **56 km/h**



PMHS Characteristics – 24 km/h

N=8	Speed	Seat	Recline	Age	Height (cm)	Weight (kg)	Seated Height (cm)	Head Mass (kg)	Chest Depth (cm)	Cause of Death
PMHS07	24	ABTS	25	68	174.3	71.7	91.6	3.9	20.4	Coronary artery disease
PMHS08	24	ABTS	45	71	178.0	72.1	95.0	3.6	21.6	Throat & lung CA
PMHS19	24	ABTS	45	60	184.7	87.1	97.4	4.6	20.4	Glioblastoma
PMHS20	24	ABTS	25	67	167.2	68.0	92.2	3.3	20.5	Bladder CA
PMHS15	24	FDR	45	83	173.0	81.6	93.0	3.9	20.7	Respiratory failure
PMHS16	24	FDR	25	58	169.1	63.5	94.7	4.3	22.2	Lung CA
PMHS17	24	FDR	25	57	169.1	55.3	93.8	3.6	18.9	Lung CA
PMHS18	24	FDR	45	54	173.0	59.0	91.3	3.6	19.1	Lung CA
Mean (SD)	N/A	N/A	N/A	65 (10)	173.6 (5.7)	69.8 (10.8)	93.6 (2.0)	3.9 (0.4)	20.5 (1.1)	N/A
50th Male	N/A	N/A	N/A	45	175	78.2	90.7	4.5	22.9	N/A

PMHS Characteristics – 24 km/h

N=8	Speed	Seat	Recline	Age	Height (cm)	Weight (kg)	Seated Height (cm)	Head Mass (kg)	Chest Depth (cm)	Cause of Death
PMHS07	24	ABTS	25	68	174.3	71.7	91.6	3.9	20.4	Coronary artery disease
PMHS08	24	ABTS	45	71	178.0	72.1	95.0	3.6	21.6	Throat & lung CA
PMHS19	24	ABTS	45	60	184.7	87.1	97.4	4.6	20.4	Glioblastoma
PMHS20	24	ABTS	25	67	167.2	68.0	92.2	3.3	20.5	Bladder CA
PMHS15	24	FDR	45	83	173.0	81.6	93.0	3.9	20.7	Respiratory failure
PMHS16	24	FDR	25	58	169.1	63.5	94.7	4.3	22.2	Lung CA
PMHS17	24	FDR	25	57	169.1	55.3	93.8	3.6	18.9	Lung CA
PMHS18	24	FDR	45	54	173.0	59.0	91.3	3.6	19.1	Lung CA
Mean (SD)	N/A	N/A	N/A	65 (10)	173.6 (5.7)	69.8 (10.8)	93.6 (2.0)	3.9 (0.4)	20.5 (1.1)	N/A
50th Male	N/A	N/A	N/A	45	175	78.2	90.7	4.5	22.9	N/A

Total: 22 PMHS tests (2 speeds, 2 reclines, 2 seat/restraint systems)

56 km/h: 14 PMHS tests & 24 km/h: 8 PMHS tests

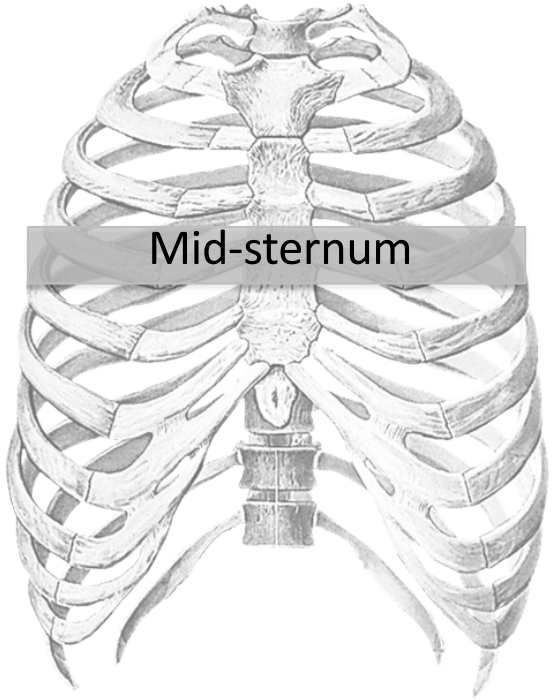
PMHS Instrumentation

6aω

Chestband

Strain Gauges

Head	
Chest	
C2/C4/C6	
T1	
T4	
T8	
T12	
S1	
Pelvis	
Femur	
Tibia	
L Humerus	



PMHS Instrumentation

6aω

Chestband

Strain Gauges

Head	
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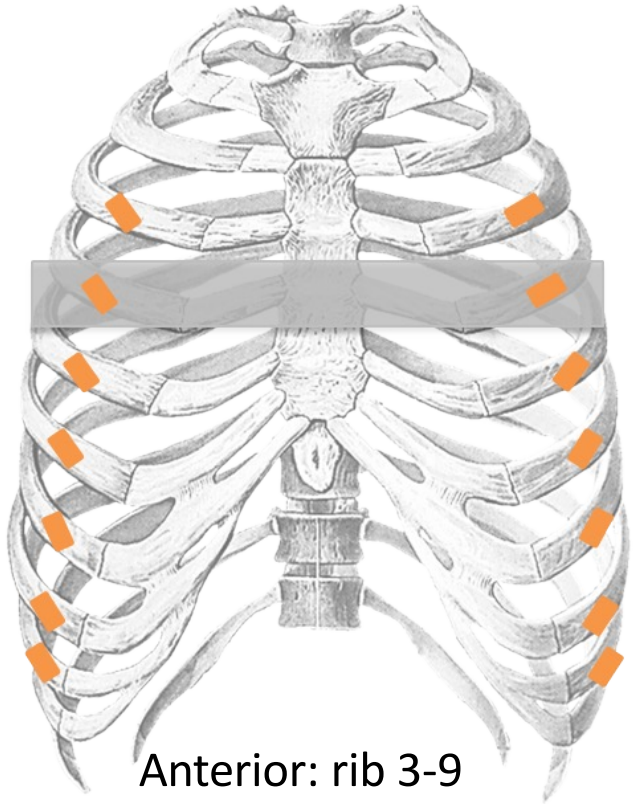
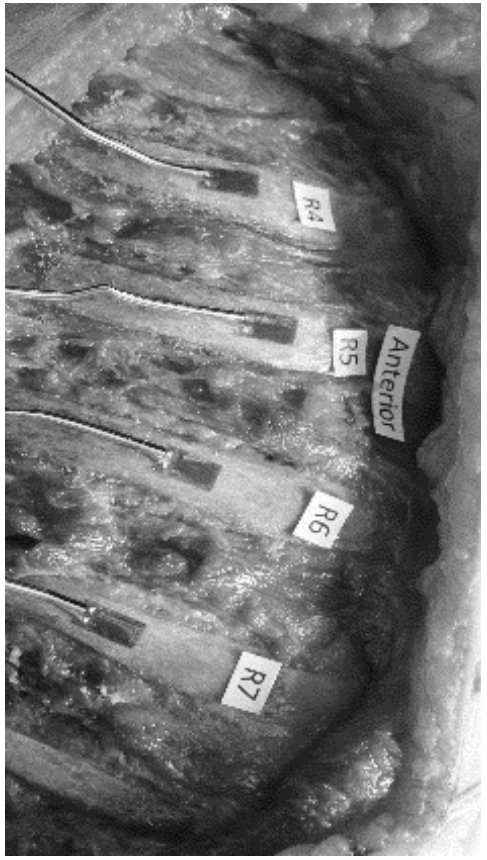
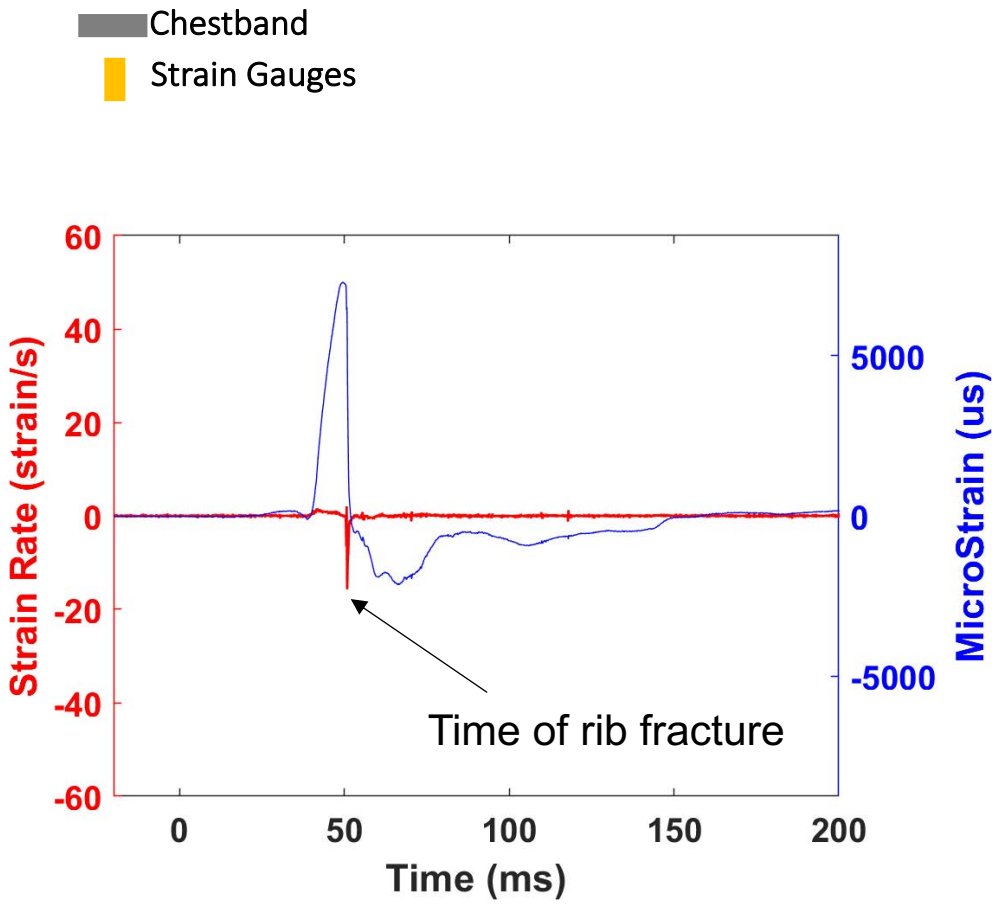


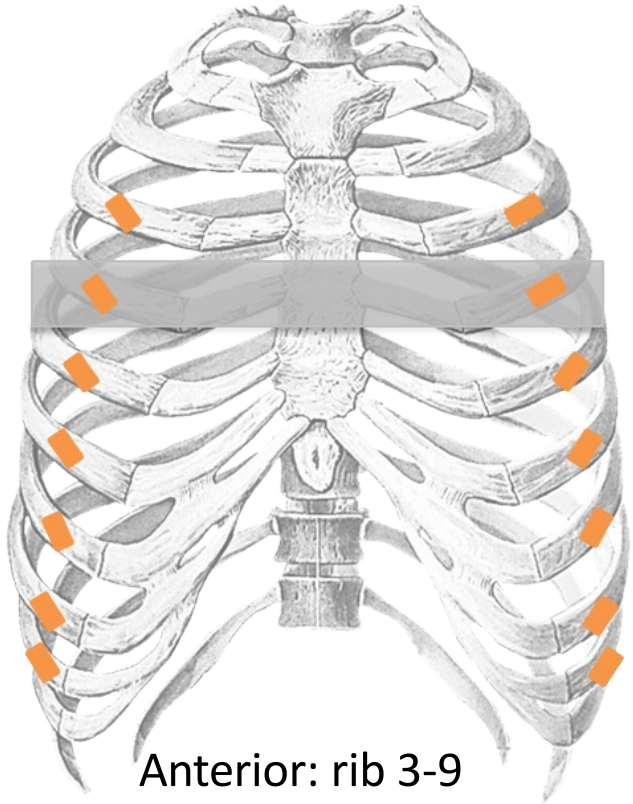
Anterior: rib 3-9

Posterior: rib 3-10

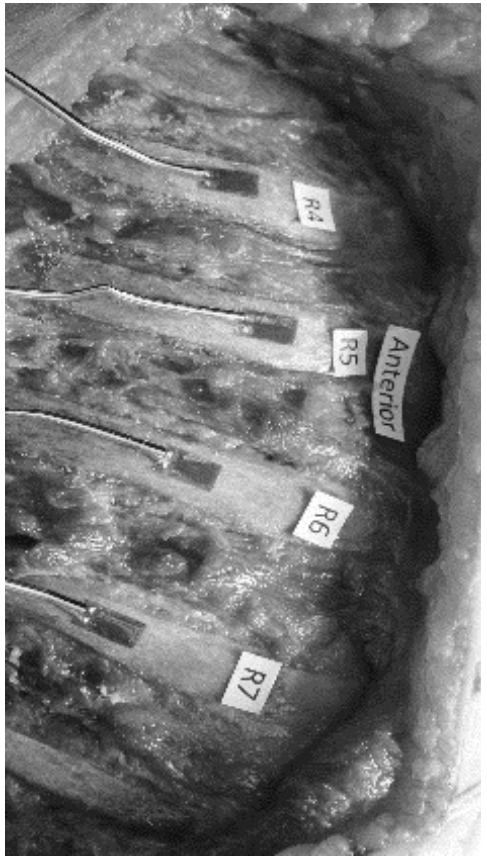


PMHS Instrumentation – Rib Strain Gage





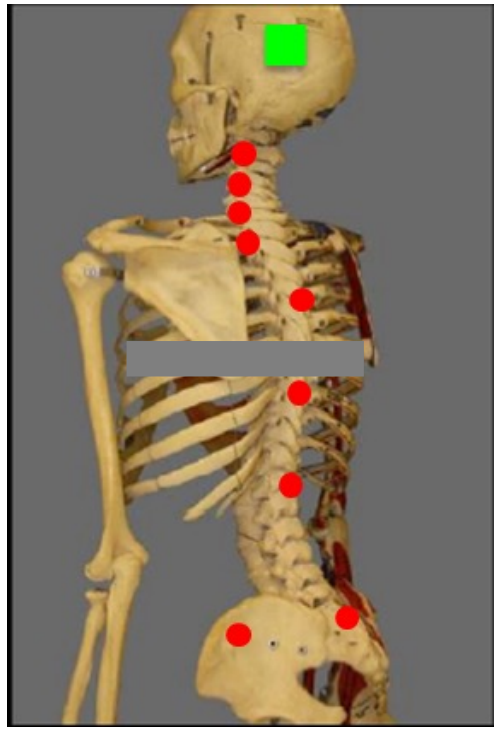
Anterior: rib 3-9
Posterior: rib 3-10

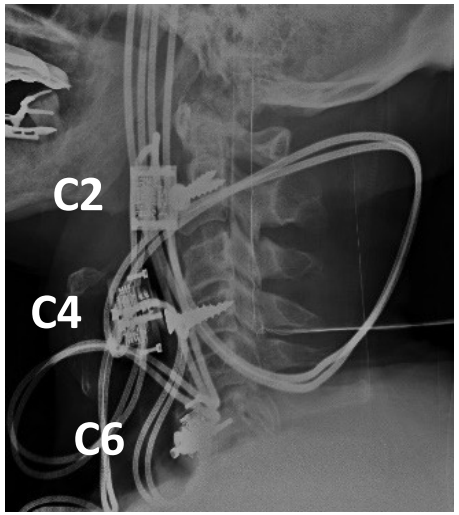


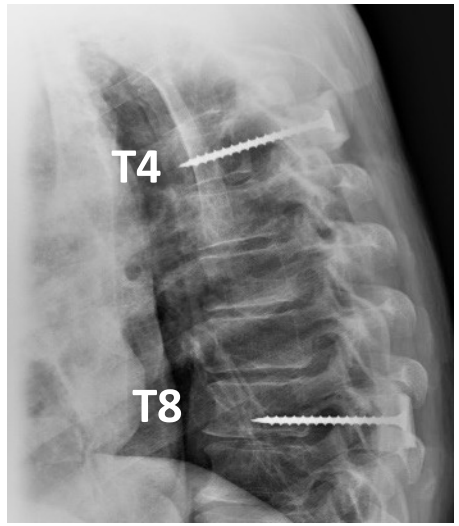
PMHS Instrumentation

6aω
Chestband
Strain Gauges
3aω

Head	
Chest	
C2/C4/C6	
T1	
T4	
T8	
T12	
S1	
Pelvis	
Femur	
Tibia	
L Humerus	





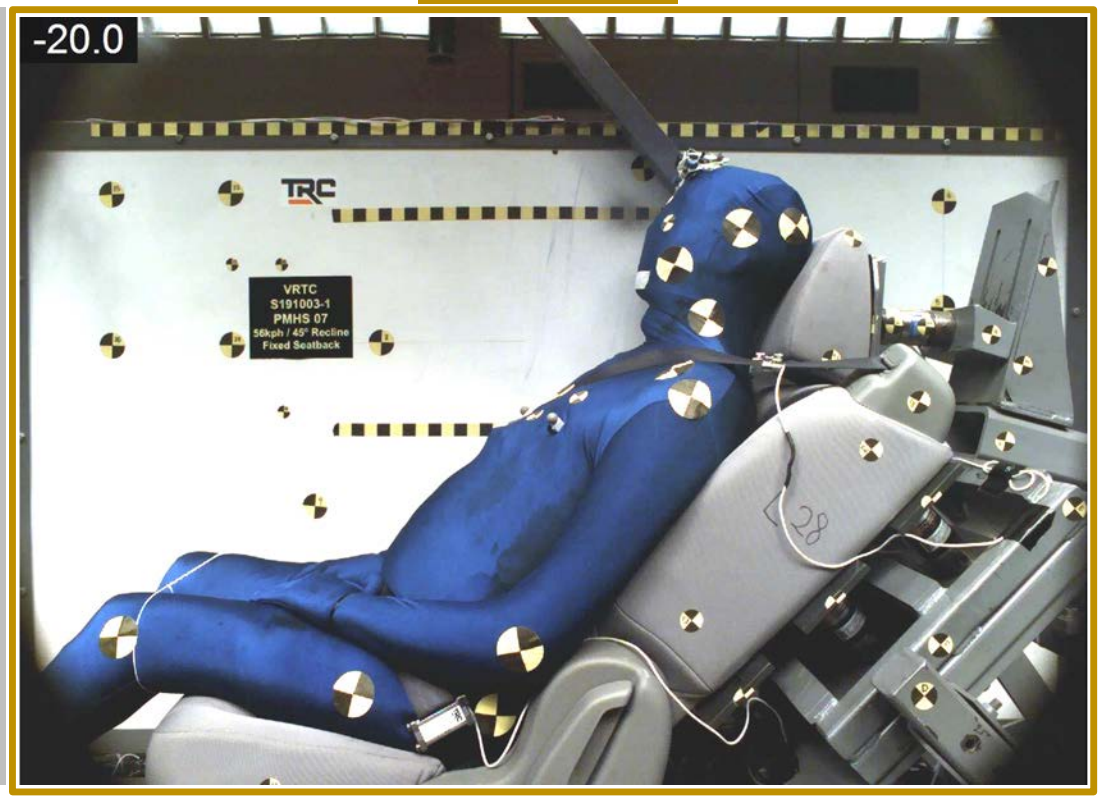


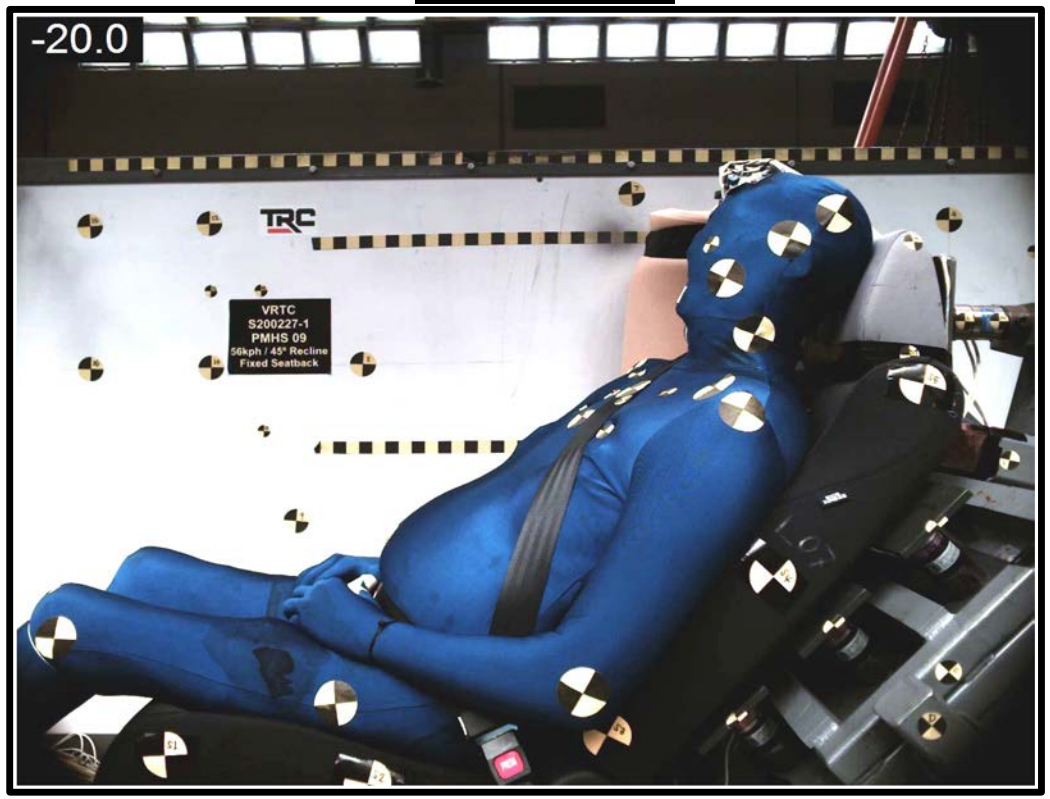
High Speed Videos – 56 km/h

ABTS

FDR

45 deg



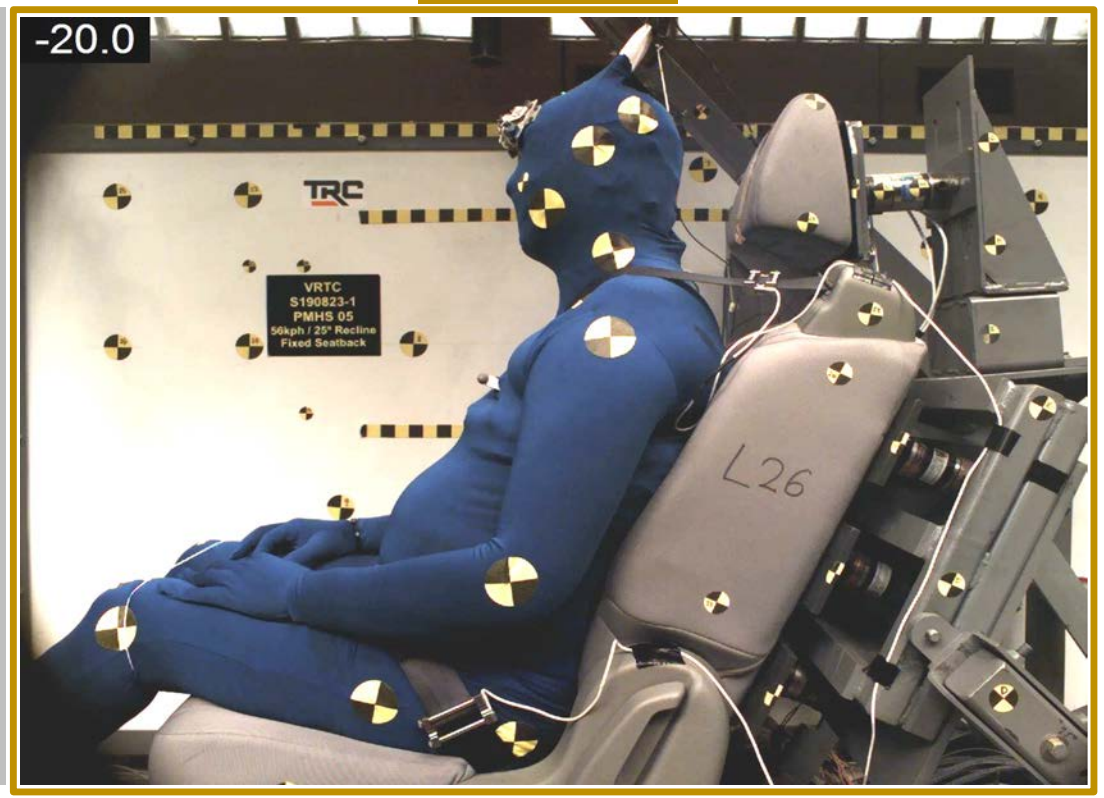


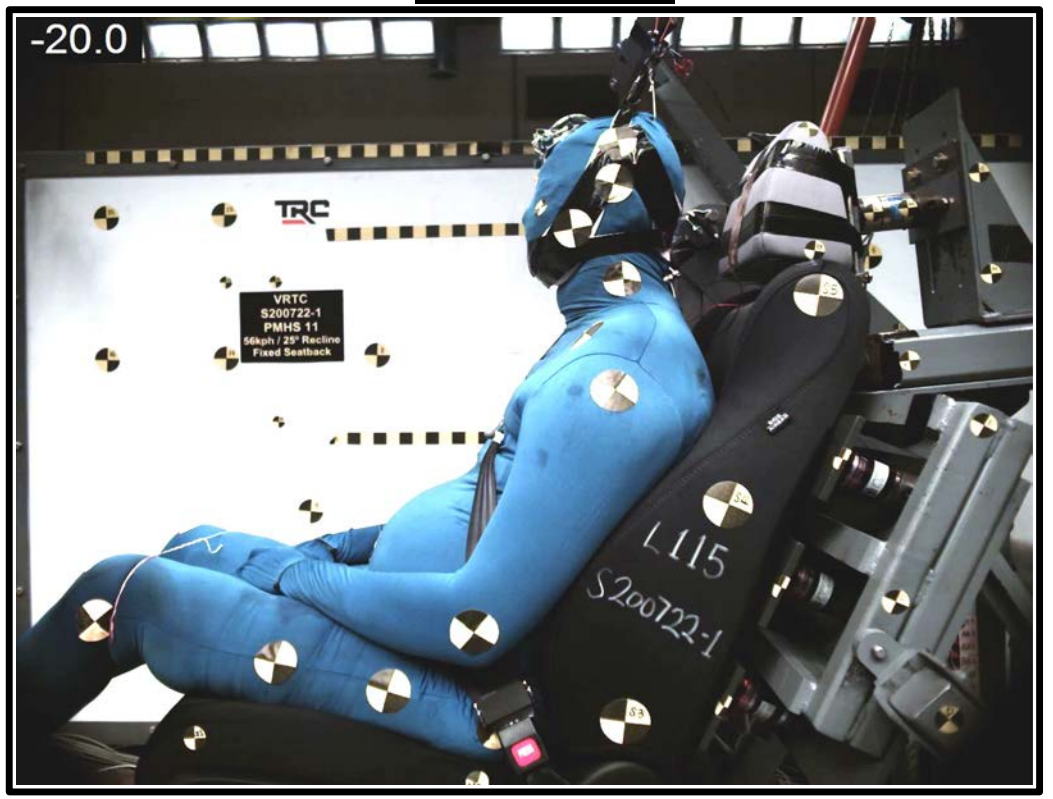
High Speed Videos – 56 km/h

ABTS

FDR

25 deg





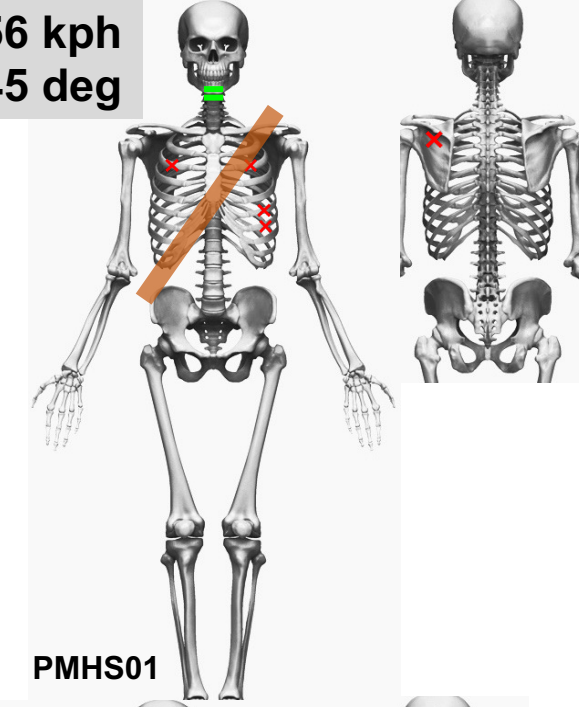
PMHS Injury – 56 km/h

ABTS

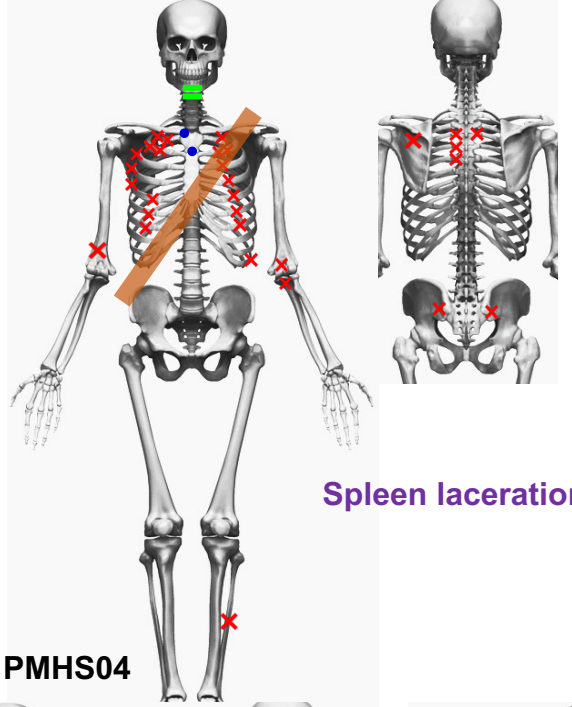
FDR

56 kph
45 deg

laxity
Fracture
Joint damage

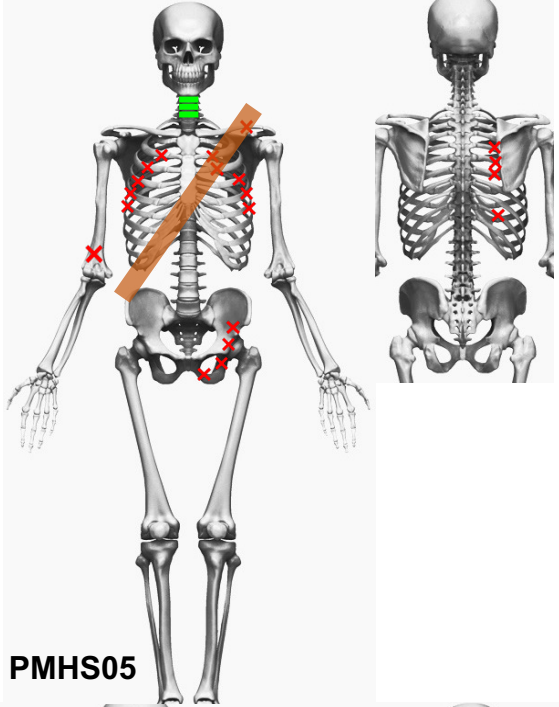


PMHS01

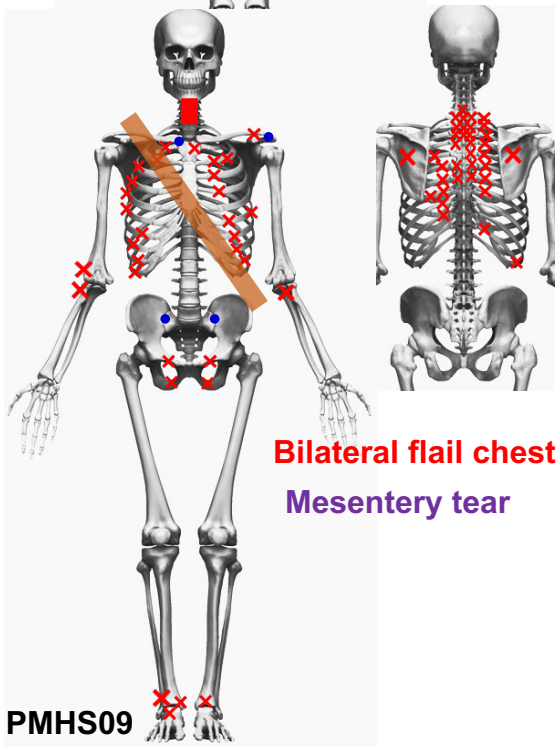


Spleen laceration

PMHS04

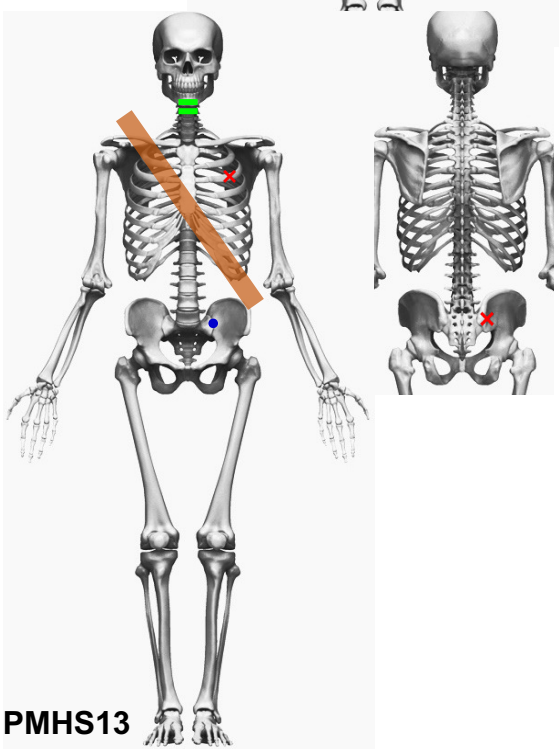


PMHS05

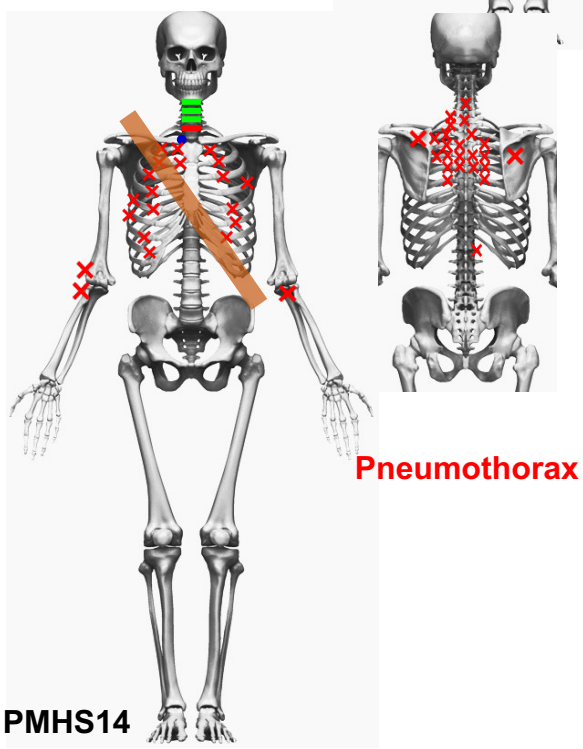


Bilateral flail chest
Mesentery tear

PMHS09

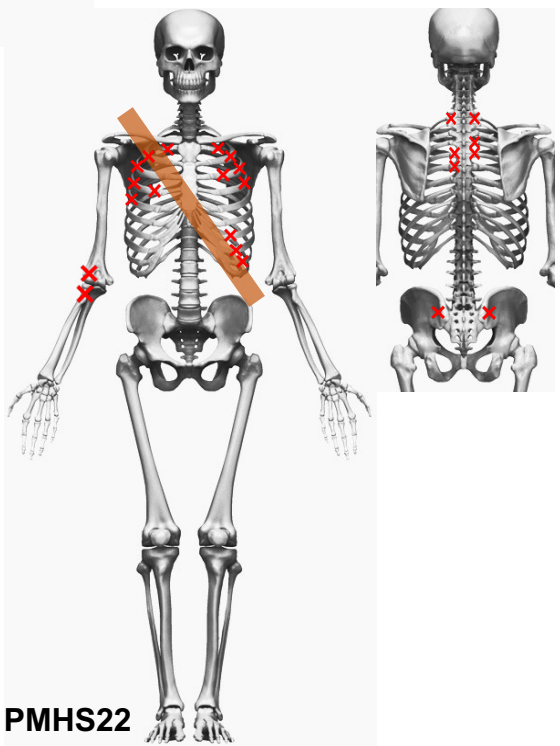


PMHS13



Pneumothorax

PMHS14



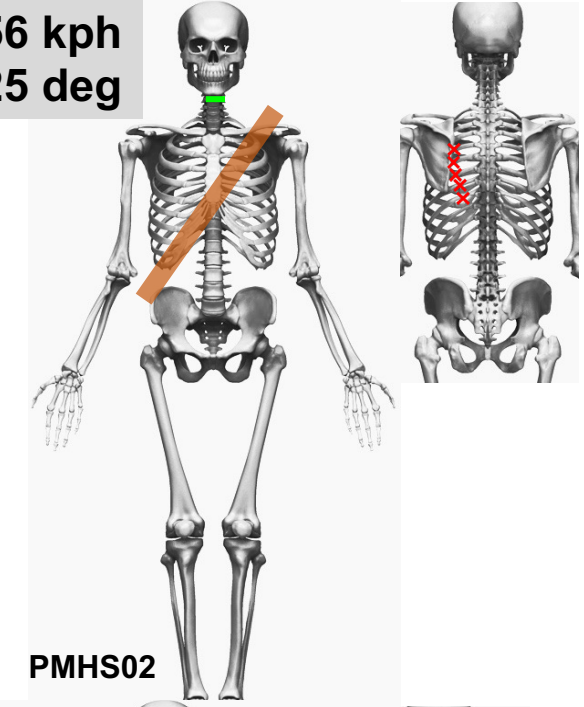
PMHS22

ABTS

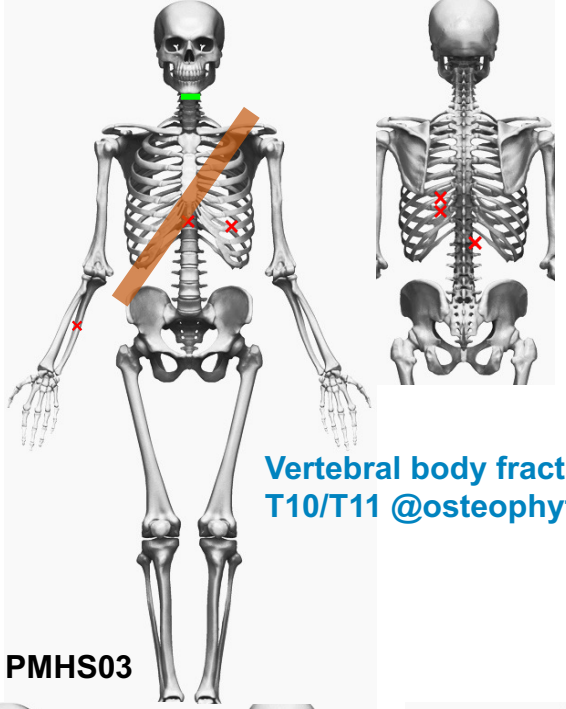
FDR

56 kph
25 deg

laxity
Fracture
Joint damage

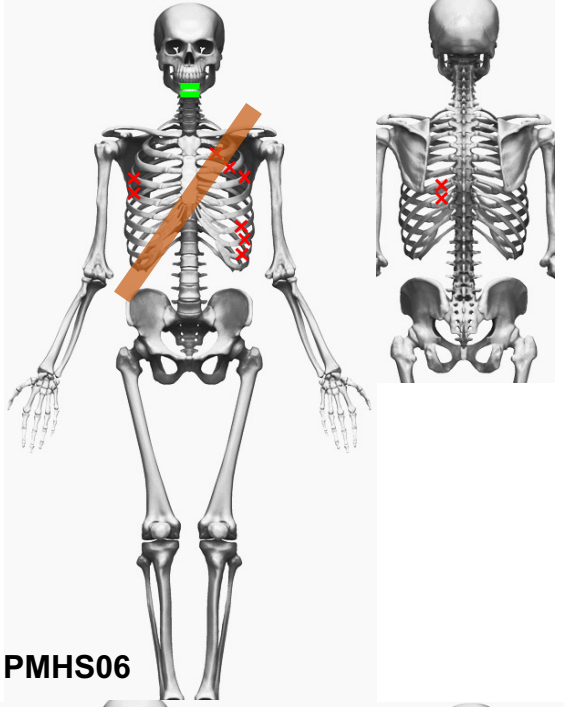


PMHS02

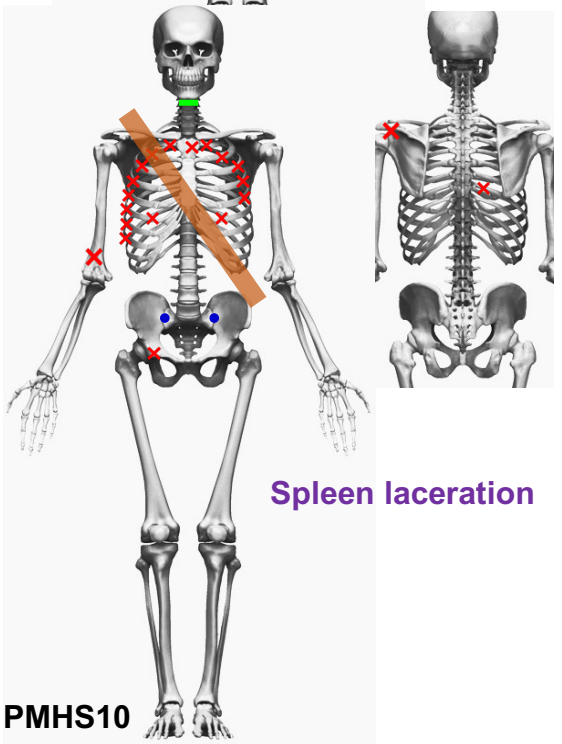


Vertebral body fracture at
T10/T11 @osteophyte

PMHS03

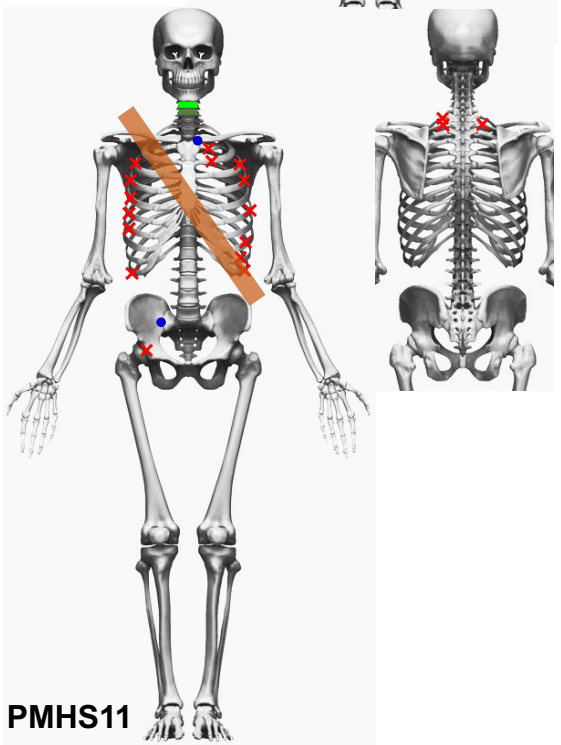


PMHS06

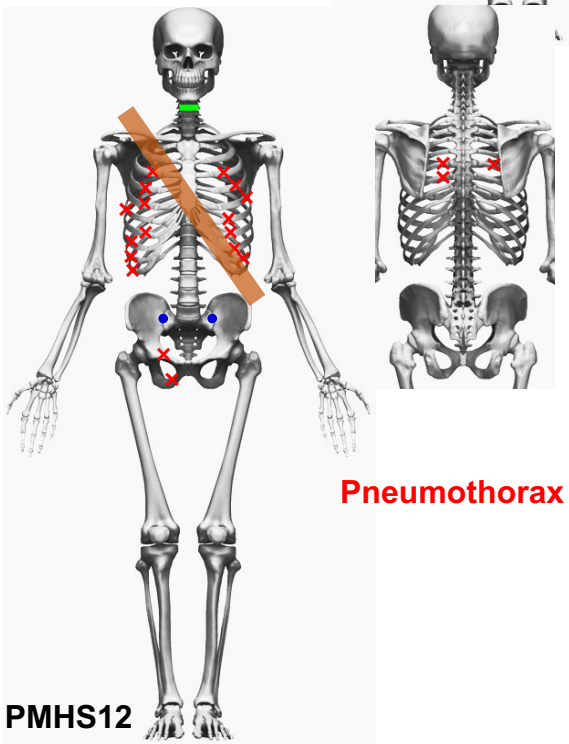


Spleen laceration

PMHS10

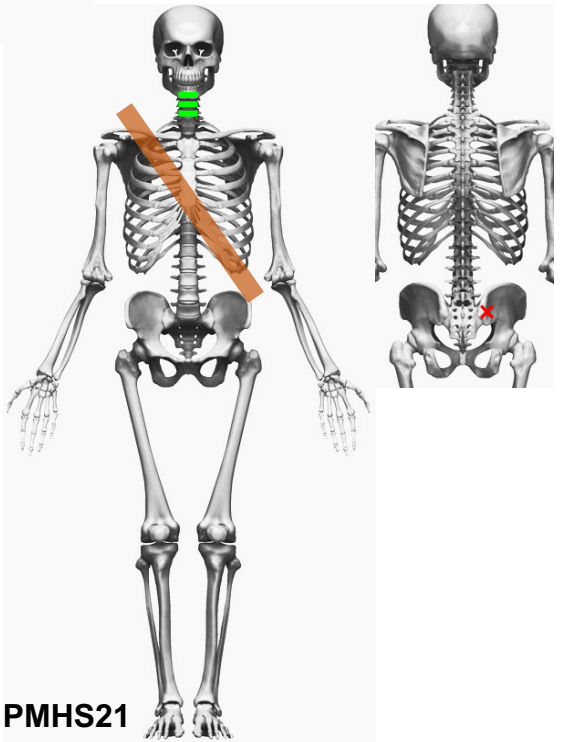


PMHS11



Pneumothorax

PMHS12



PMHS21

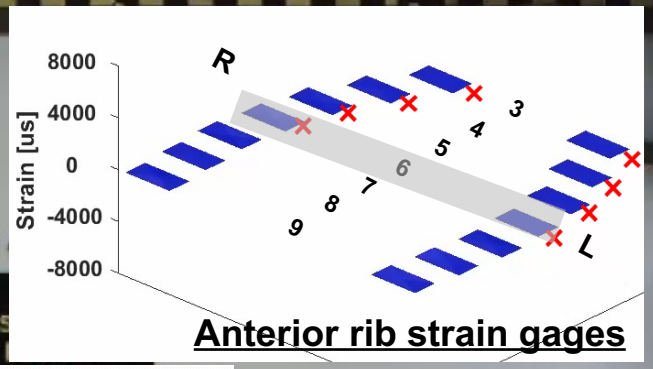
No major injuries

-No rib fractures

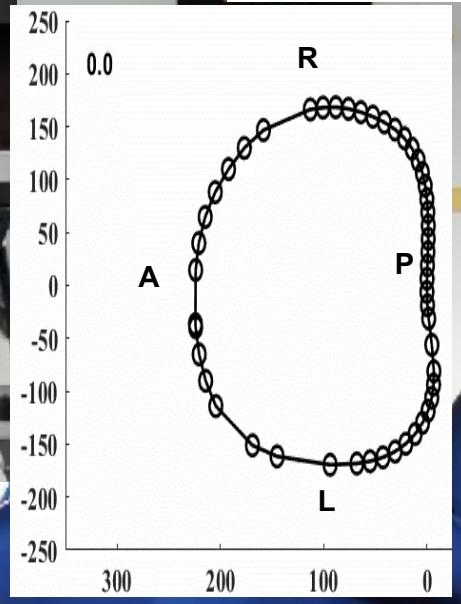
-No pelvis fractures

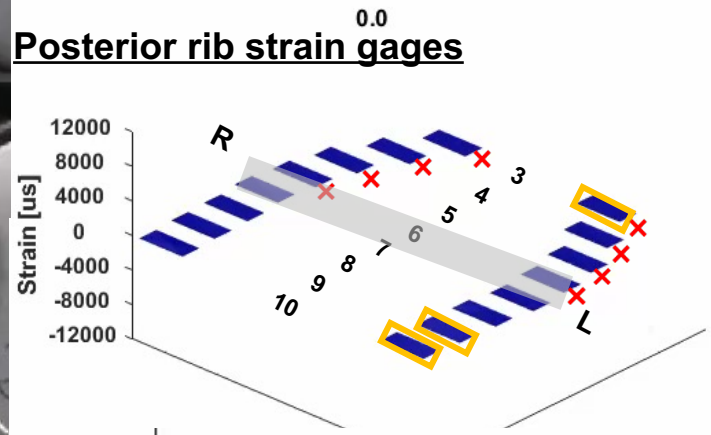
PMHS Injury – 24 km/h

ABTS 45deg at 56 km/h

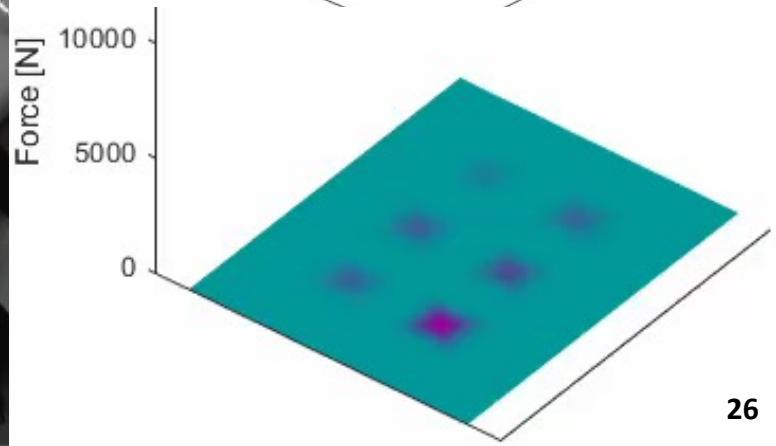


Anterior rib strain gages





Posterior rib strain gages

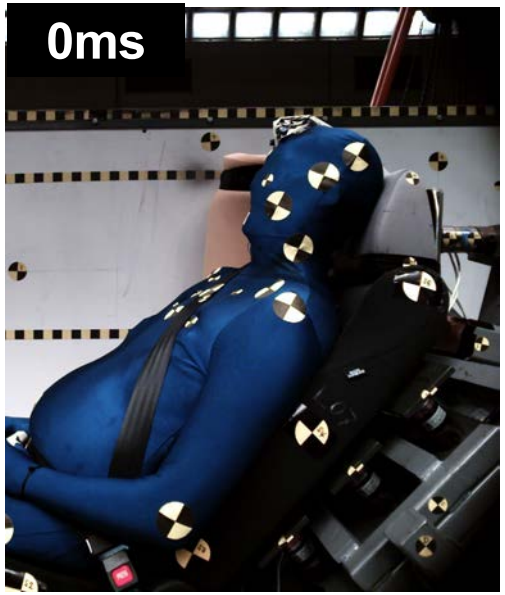


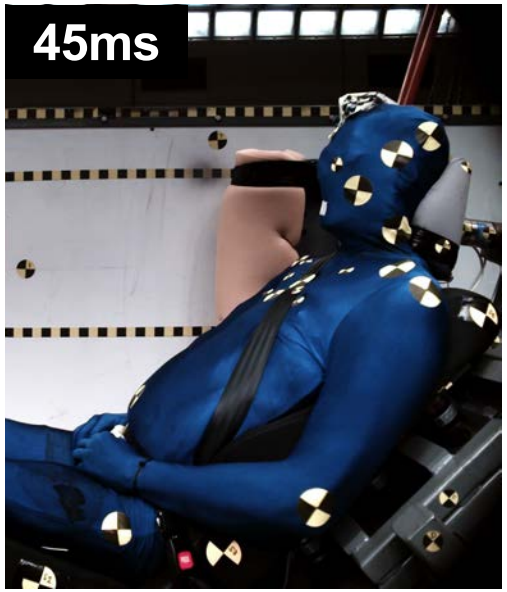
Fracture

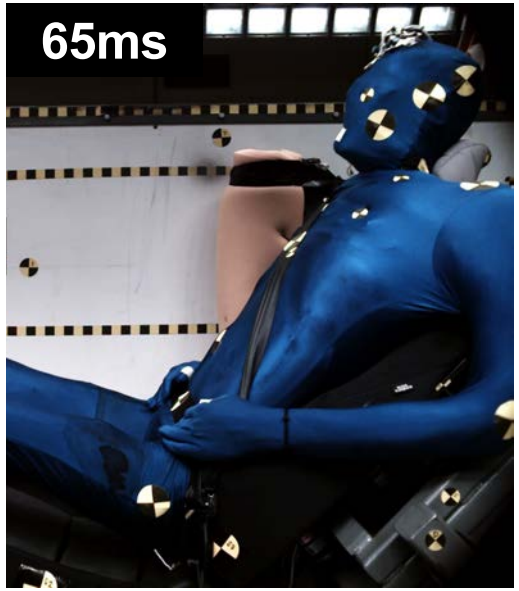
Broken gage

Rib Fracture Timing

FDR 45deg

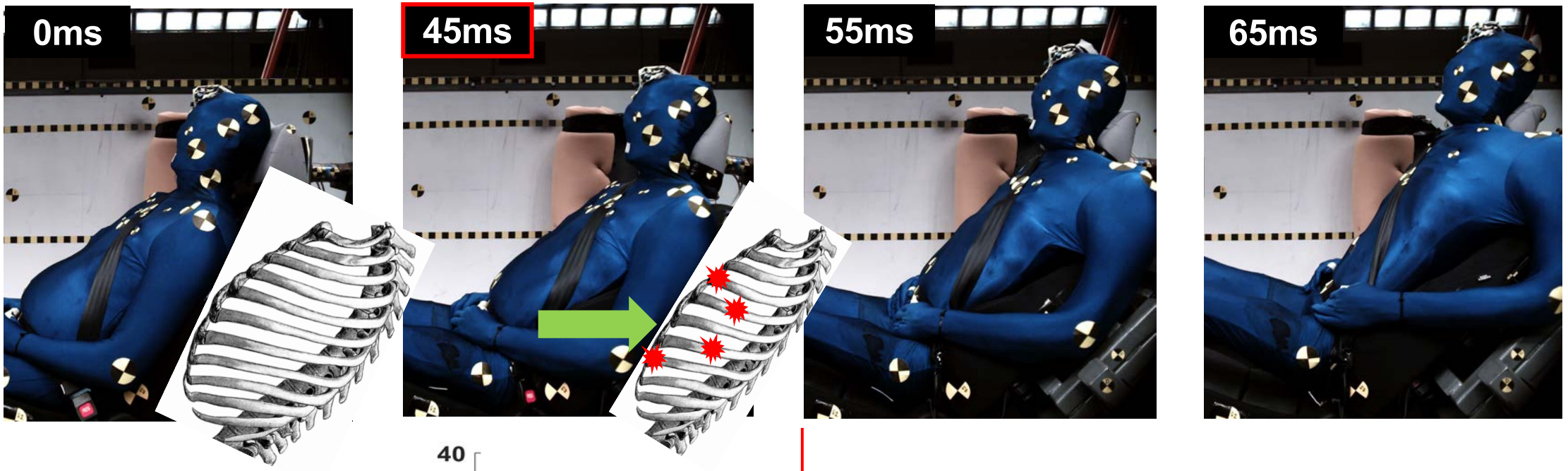


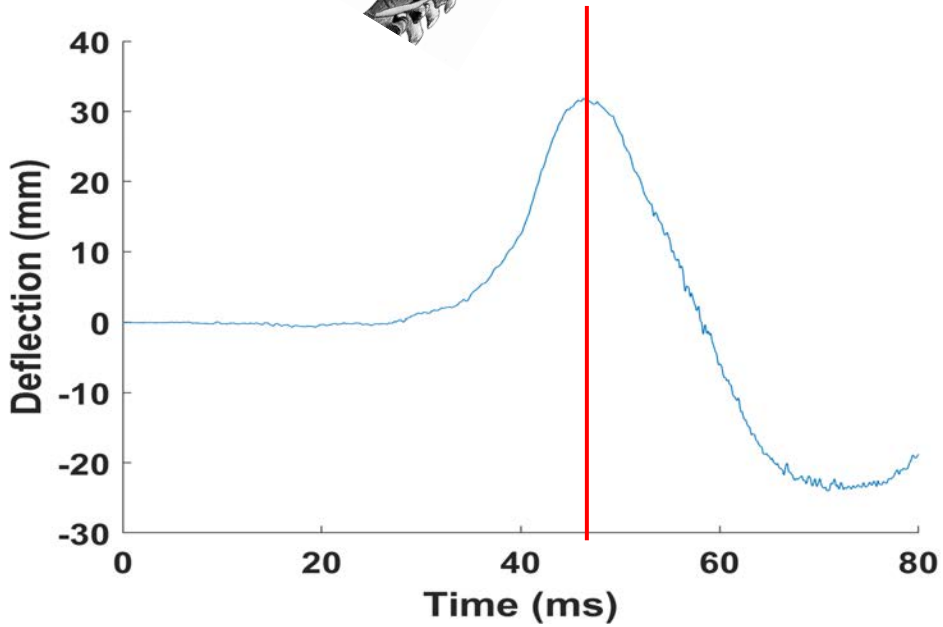




Rib Fracture Timing

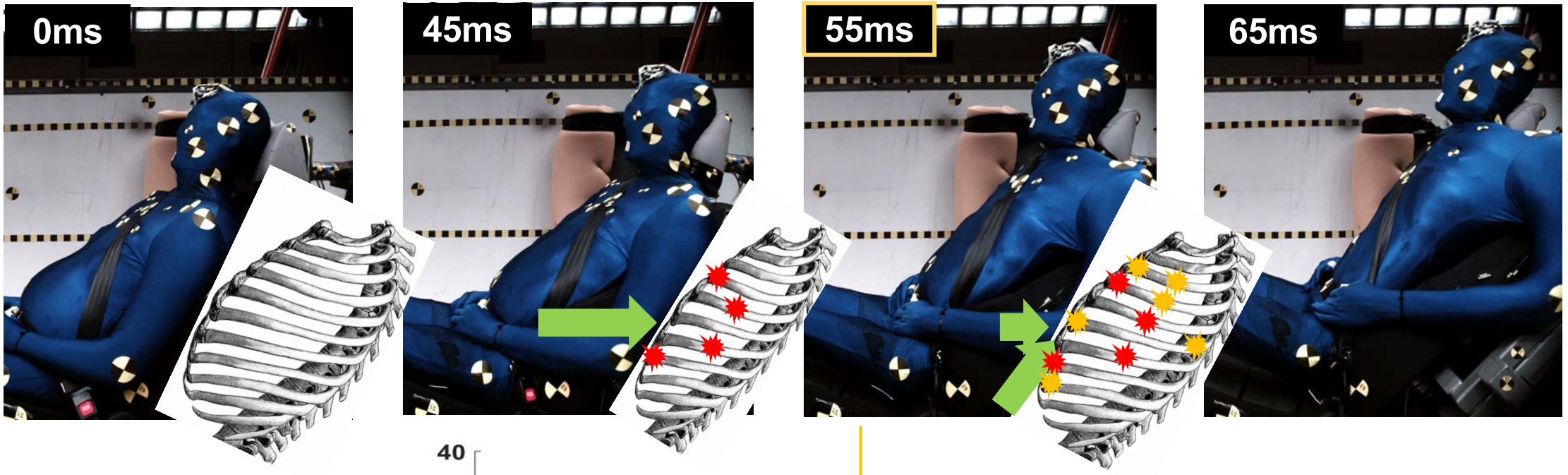
FDR 45deg

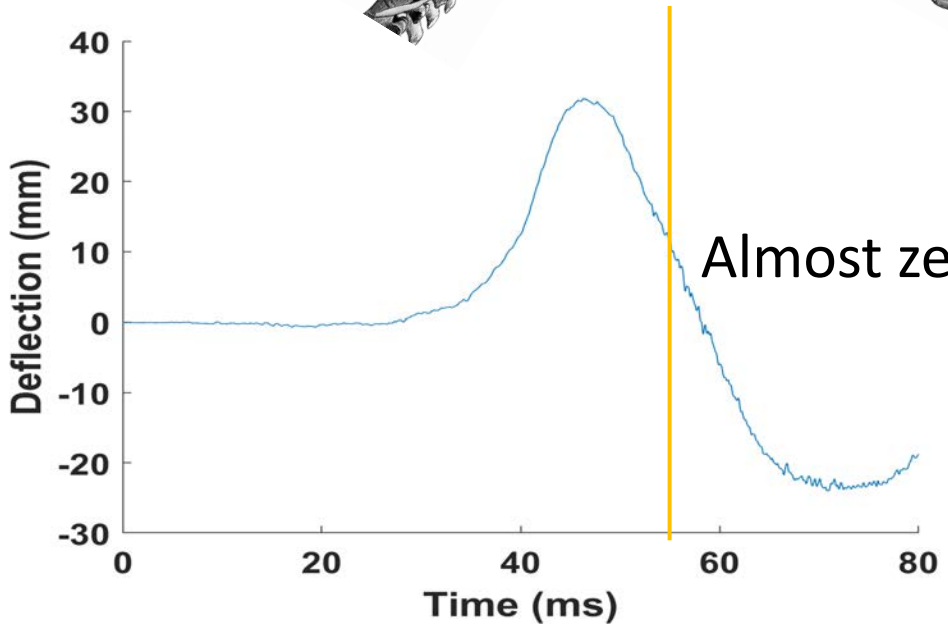




Rib Fracture Timing

FDR 45deg

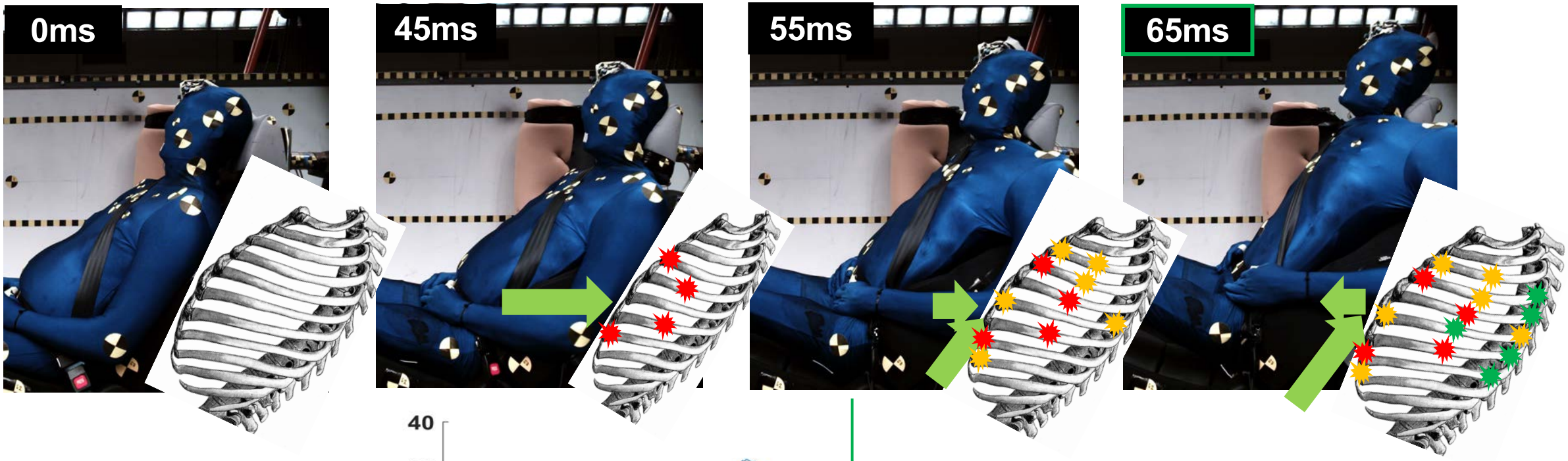


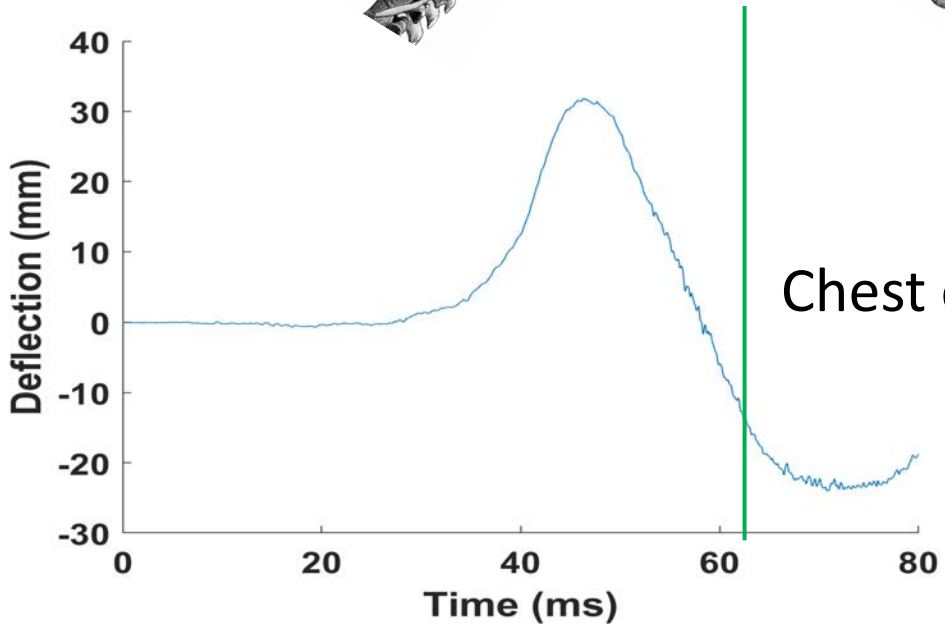


Almost zero chest deflection

Rib Fracture Timing

FDR 45deg





Chest expansion

Summary

- Injury
  - More injuries were observed in the FDR seats during 56 km/h
  - No major injuries in 24 km/h even with the rigidized seatback
- Rib fracture
  - Difference in fracture distribution between ABTS and FDR
    - More rib fractures in 45deg
    - Anterior & lateral fractures occurred due to chest inertial loads
  - Rib fractures after maximum chest deflection
    - Thorax experiences complex combined loading
      - Compression due to A-P inertial loading
      - Shear due to ramping up motion
- Pelvis fracture
  - Off-axis rotations from both iliac wings represent pelvis outward deformation
    - Maybe an indicator of the pubic ramus fractures

Thoracic Response & Injury Analysis of Small, Elderly Female PMHS in Simulated Near-Side Crashes

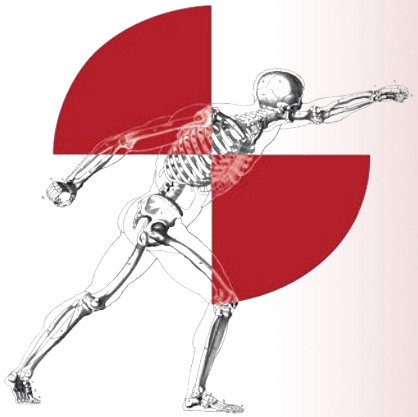
J. Bolte IV[1], B. Shurtz[2], B. Pipkorn[2], H. Rhule[3], K. Moorhouse[3], A. Agnew[1], Y-S. Kang[1]

[1]Injury Biomechanics Research Center, OSU

[2]Autoliv; [3]Vehicle Research and Test Center, NHTSA

49th NHTSA Workshop on Human Subjects for Biomechanical Research

27 October, 2021



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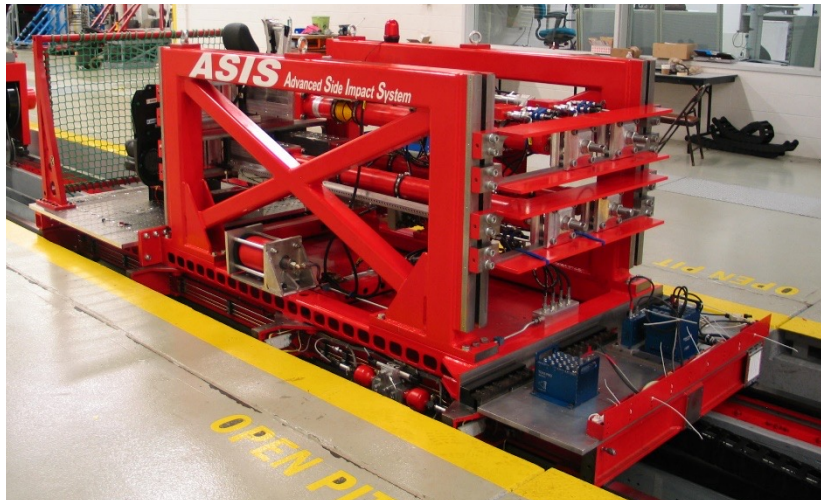
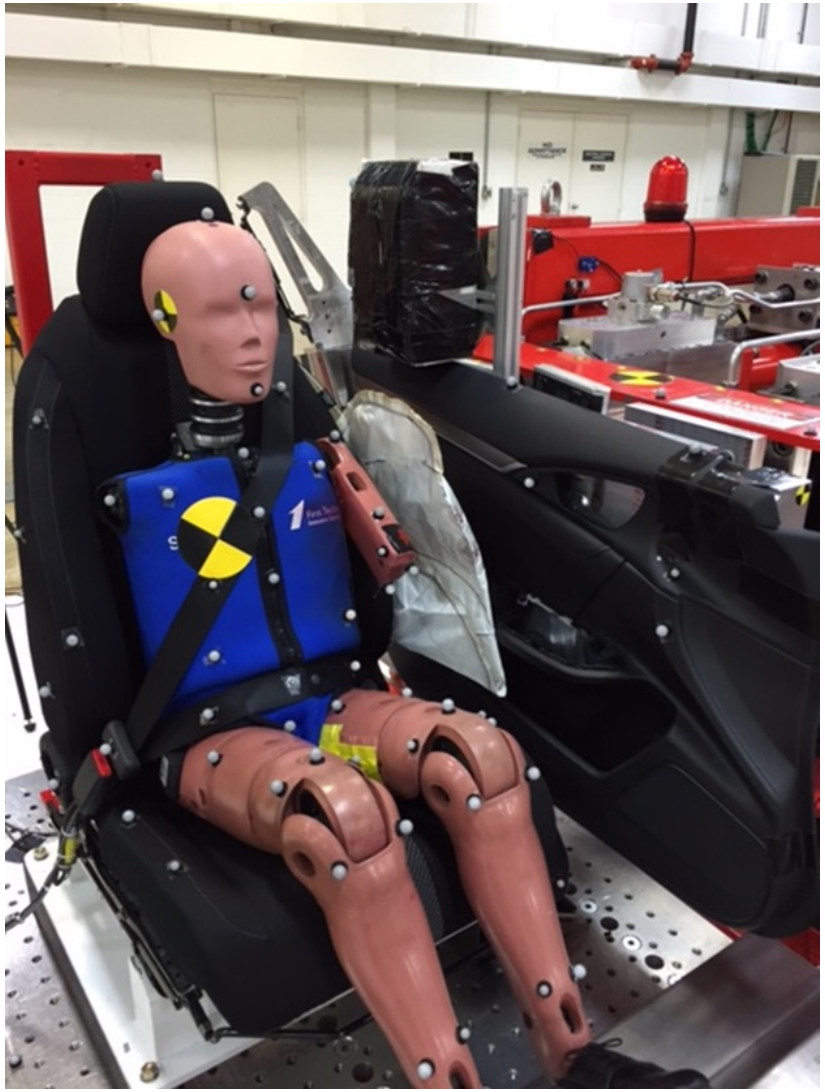
Methods

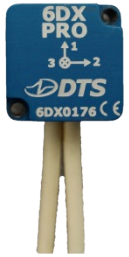

ASIS
Advanced Side Impact System
OPEN PIT




TRC
OSU
S170321-1
ESI1702

Instrumentation

- Strain Gages
  - Sternum
  - Impacted Side:
    - Lateral Clavicle
    - Anterior ribs 2-10
    - Posterior ribs 4-9
  - Non-Impacted Side:
    - Anterior ribs 3-10
    - Posterior ribs 4-7
- Chestbands
  - Axilla
  - Xiphoid process
- 6DX Pro
  - Manubrium

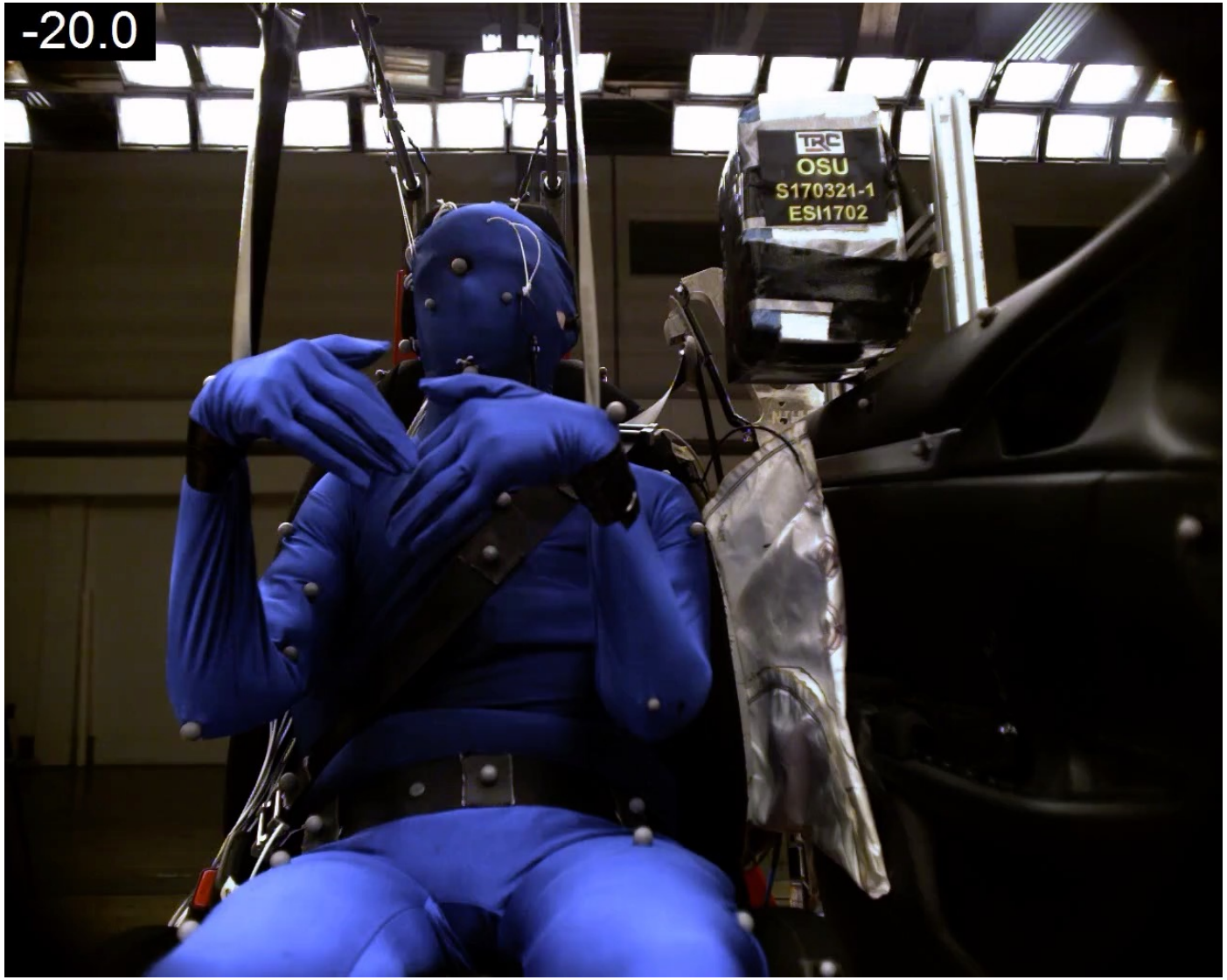


Phase I – Initial Positions

ESI 01	ESI 02	ESI 03	ESI 04	ESI 05
				
Seated Ht.				
81 cm	71 cm	81 cm	80 cm	82 cm

*All photos are approx. lined up with the silver line on the door frame lining

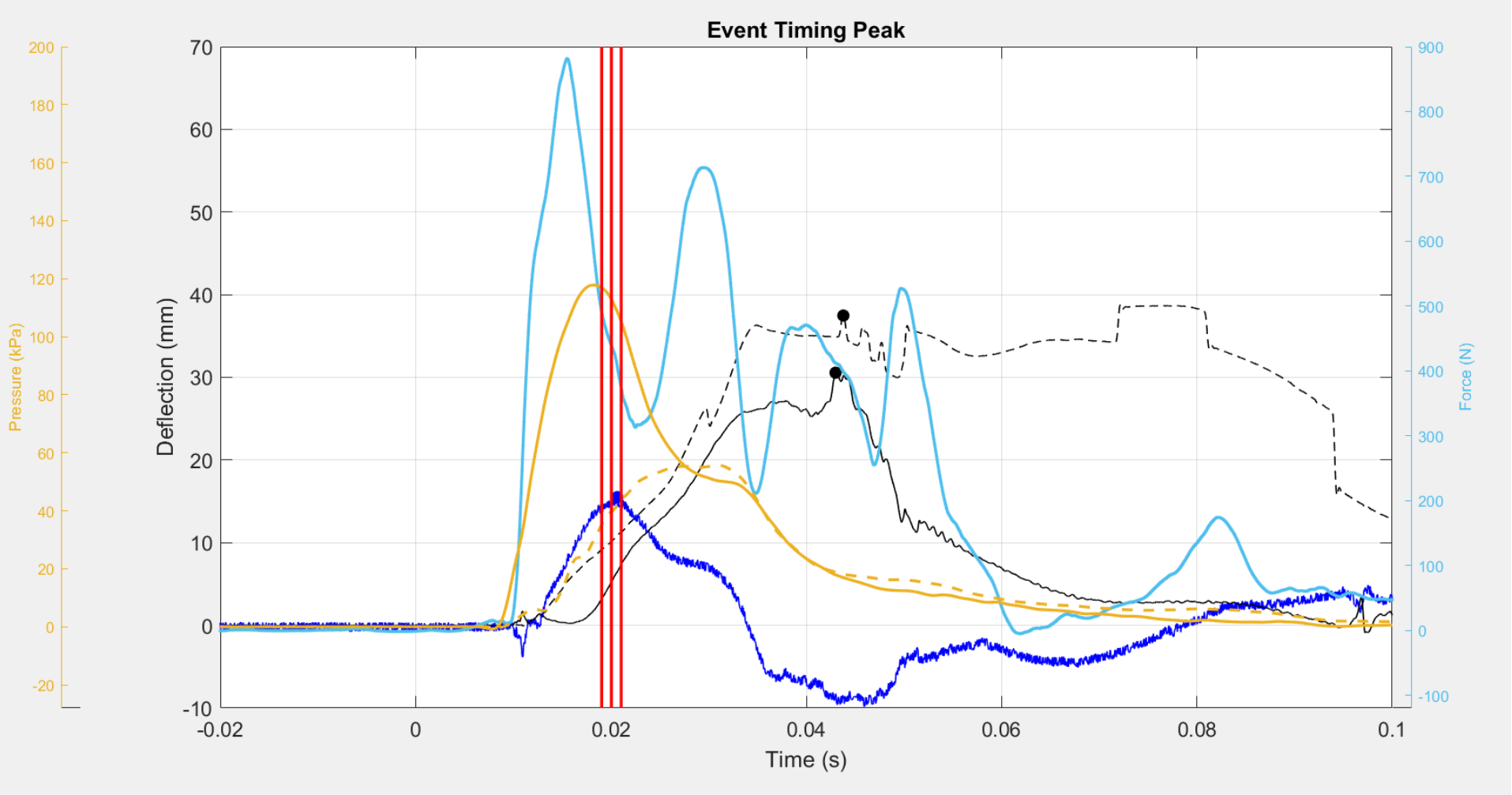
Phase I – Exemplar Video



Phase I – Injury Summary

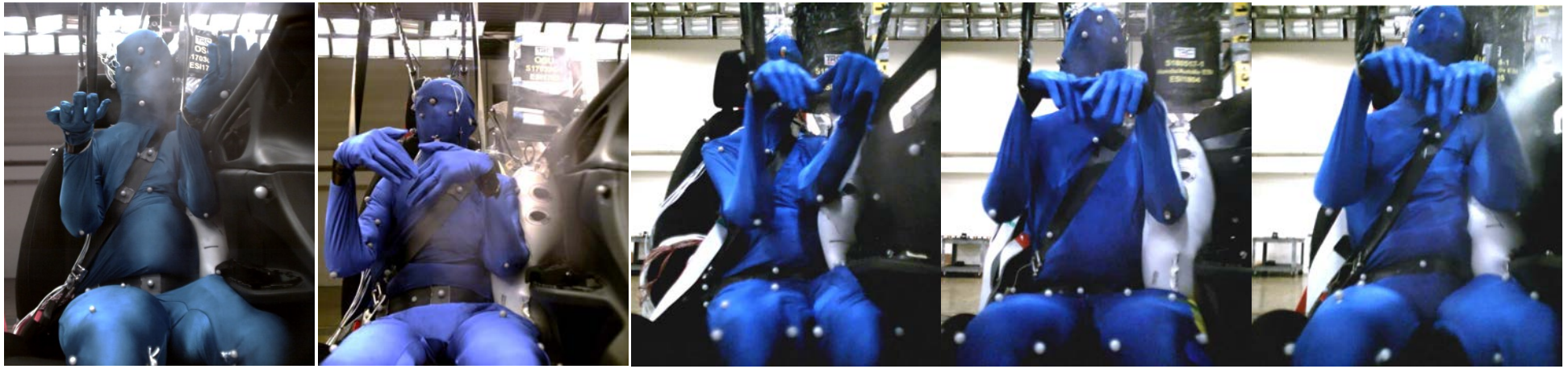
	TARGET (female)	ESI 01	ESI 02	ESI 03	ESI 04	ESI 05
Age (yrs)	60+	61	83	81	67	69
Height (cm)	136-167	167	155	160	155	165
Weight (kg)	42-56	56	44	51.7	54.9	54.9
aBMD (t-score)	-2.5 < x < -1	-2.4	-1.6	-1.4	-1.5	-2.2
Test Injuries	-	**5 rib fx**	**15 rib fx** L clavicle fx spleen lac	**5 rib fx**	**20 rib fx** sternum fx	**5 rib fx** L clavicle fx
MAIS	-	3	3	3	3	3

Event Timing - ESI 02



Chest Deflection & Compression

AIS=3 timing

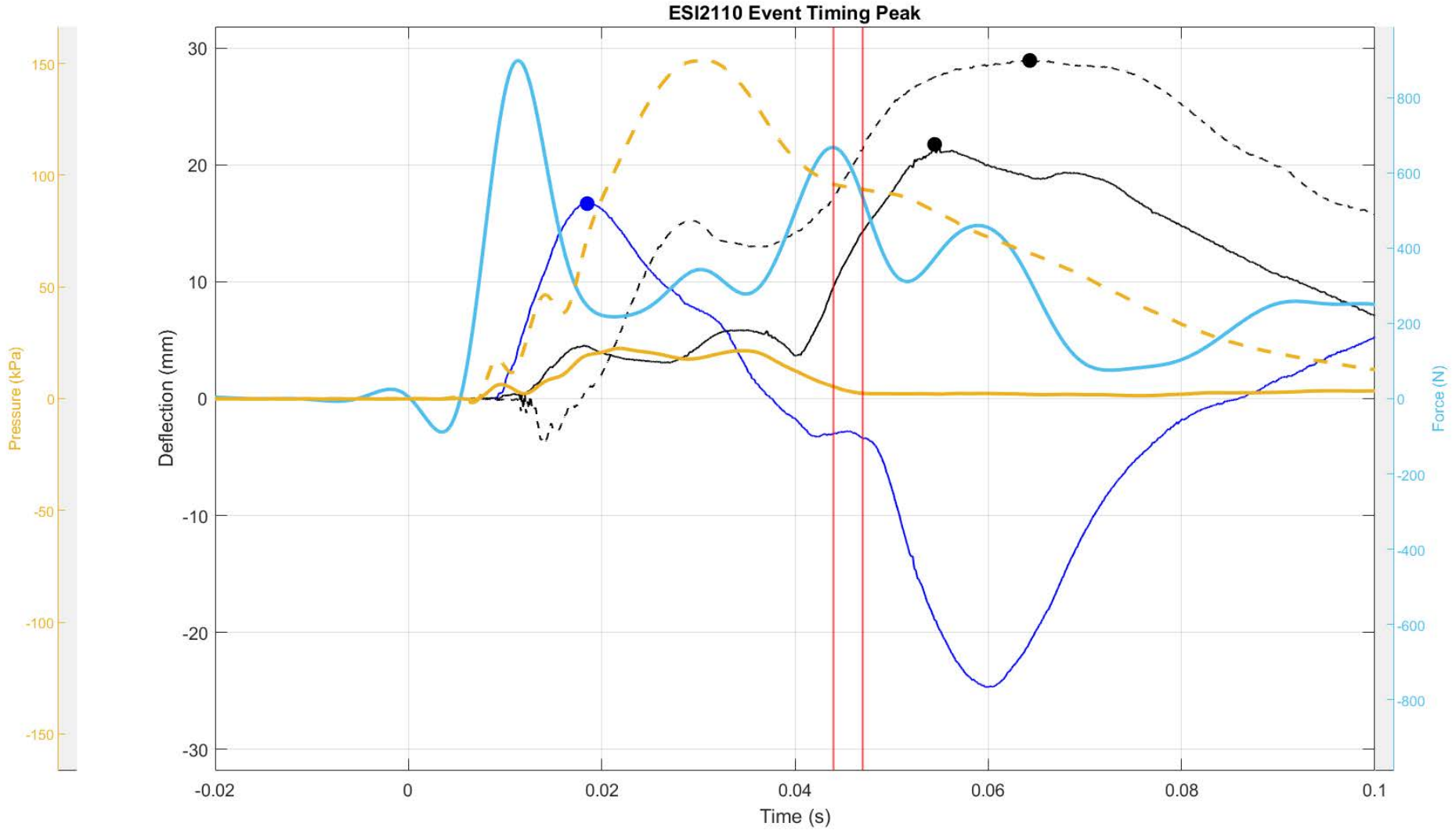


	ESI 01		ESI 02		ESI 03		ESI 04		ESI 05	
	Peak	AIS=3	Peak	AIS=3	Peak	AIS=3	Peak	AIS=3	Peak	AIS=3
Axillary Half Defl (mm)	23	19	31	7	12	1	21	4	24	18
Axillary Half Comp (%)	**8.3**	**6.8**	**11.7**	**2.7**	**4.4**	**0.0**	**7.6**	**1.4**	**8.7**	**6.5**
Axillary AP Defl (mm)	16	-20	15	14	16	16	15	12	14	-11

Phase II Sled – PMHS Summary

	Phase I	ESI 07	ESI 08	ESI 09	ESI 10	ESI 11	Phase II
Age (yrs)	74.2 (±9.7)	62	67	94	83	80	77.2 (±12.8)
Height (cm)	161.5 (±5.6)	147	159	152	163	158	155.8 (±6.3)
Weight (kg)	52.1 (±4.4)	56	51	55	50	40	50.4 (±6.3)
aBMD (t)	-1.6 (±0.4)	-1.0	-2.1	-2.2	-1.4	-1.7	-1.7 (±0.5)
Test Injuries	-	**3 rib fx**	**14 rib fx**	**5 rib fx** L clavicle fx	**19 rib fx** Pneumothorax L clavicle fx		
MAIS	-	**2**	3	3	4	**0**	

ESI 10 – Injuries & Timing



ESI Test Summary

ESI Test	MAIS	Rib Fx(s)	Time of AIS 3 (msec)	Axillary Compression @ AIS 3
ESI 01	3	5	39	7%
ESI 02	3	15	21	3%
ESI 03	3	5	23	0% (1 mm)
ESI 04	3	20	24	1%
ESI 05	3	5	30	7%
ESI 07	2	3	51	8%
ESI 08	3	14	39	1%
ESI 09	3	5	46	9%
ESI 10	4	19	46	3%
ESI 11	0	0		Peak - 3%
			Avg -	**4.5%**

Acknowledgements

Anatomical Donors of… The Ohio State University

NHTSA

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Alena Hagedorn, Rakshit Ramachandra, Colton Thomas, Hyun Jung Kwon

Co-PIs: Yun Kang & John Bolte
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Alex Bendig, Vikram Pradhan, Gretchen Baker, Amanda Agnew, Akshara Sreedhar, Molly Tillis, Myeongkwan Kang, Angela Tesny, Zac Haverfield, Tim DeWitt, Angela Harden, Randee Hunter

Occupant Safety in Highly Automated Vehicles

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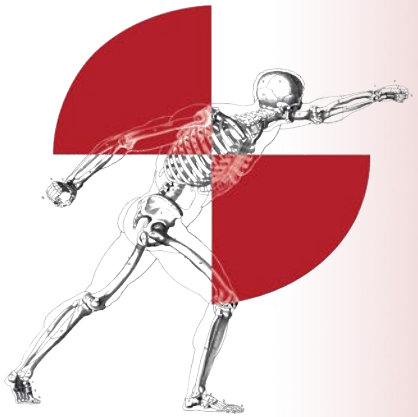

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