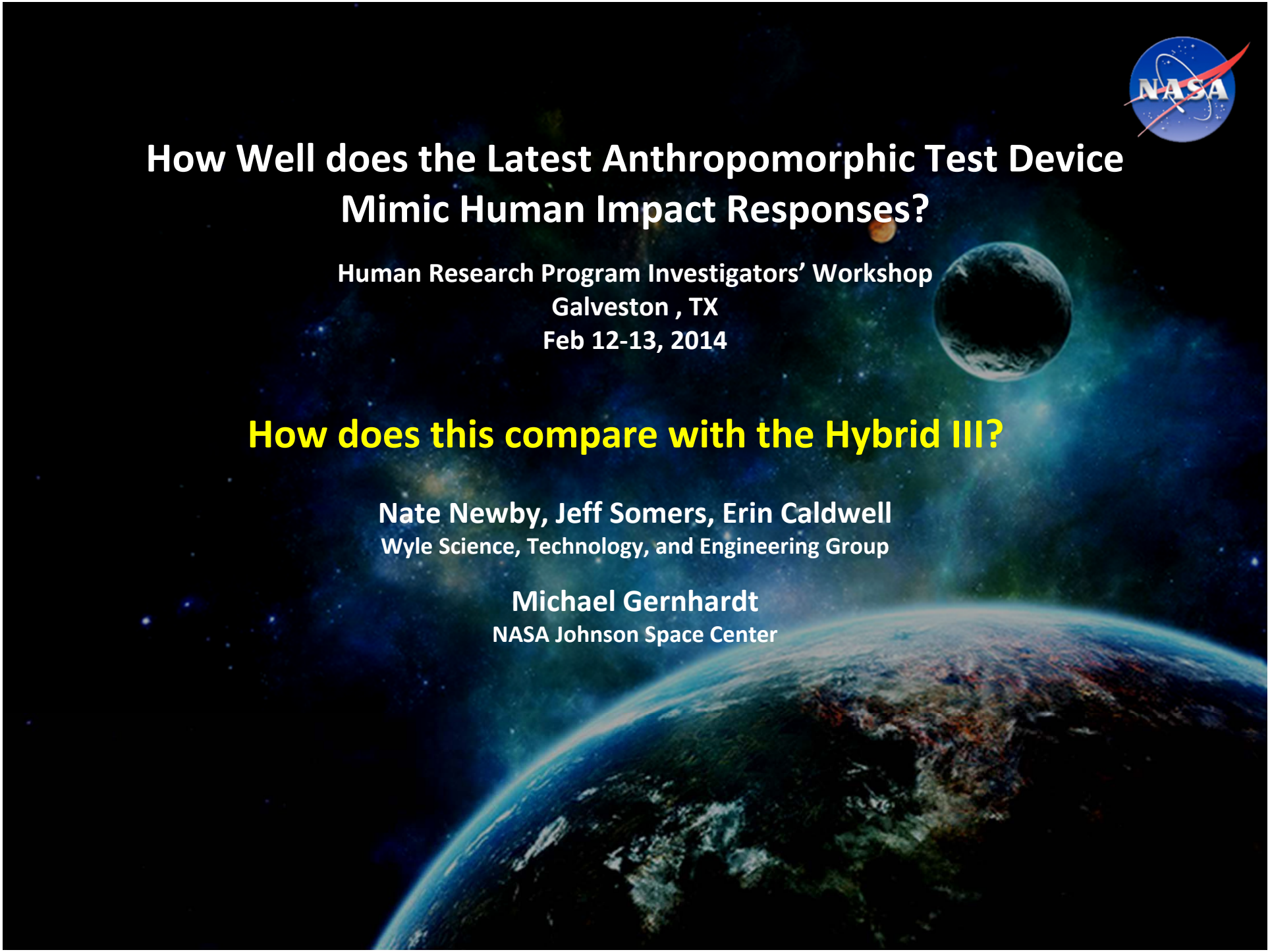


How Well does the Latest Anthropomorphic Test Device Mimic Human Impact Responses?

Human Research Program Investigators' Workshop
Galveston , TX
Feb 12-13, 2014

How does this compare with the Hybrid III?

Nate Newby, Jeff Somers, Erin Caldwell
Wyle Science, Technology, and Engineering Group

Michael Gernhardt
NASA Johnson Space Center

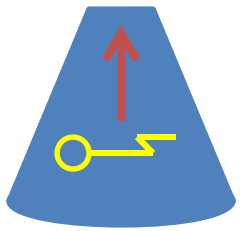
Background: NASA Crew Orientations & Risk Tolerance

- **NASA is developing new vehicles which launch, abort, and land in various orientations**
  - Most are Capsule Based
    - $-G_X$ for launch/abort
    - $-G_X$, $+G_z$ for landing
  - One is a Winged / Lifting Body
    - $-G_X$ for launch/abort
    - $+G_X$, $+G_z$ for landing

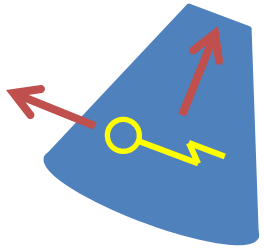
- **NASA is interested in lower risk of injury than analogs**
  1. Probability of Occurrence
     - Automotive – Very Low
     - NASA – every time the vehicle flies
  2. Injury Tolerance
     - Automotive – higher due to low probability of occurrence
     - NASA – low due to certainty of occurrence

Launch / Abort Landing

Capsule

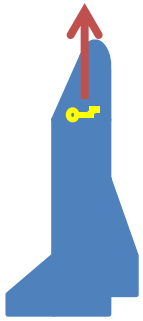


$-G_X$ Acceleration
(Eyeballs In)

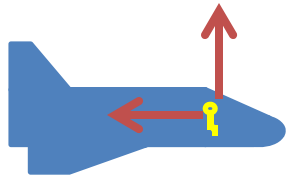


$-G_X$, $+G_z$ Acceleration
(Eyeballs in and Down)

Winged / Lifting Body



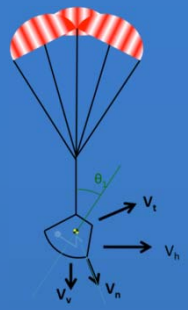
$-G_X$ Acceleration
(Eyeballs In)



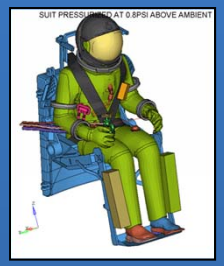
$+G_X$, $+G_z$ Acceleration
(Eyeballs Out and Down)

Why use ATDs at NASA? Potential way to verify Spacecraft Design

Spacecraft Design



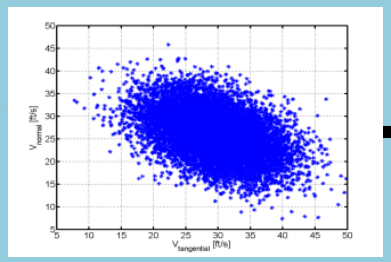
Vehicle Environments



FE Models

Physical Test Articles

Environments Monte Carlo

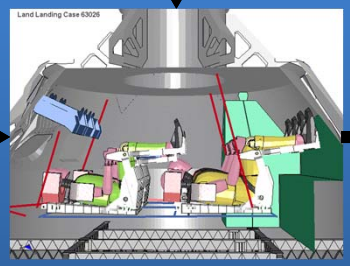


Certified Landing Cases

Vehicle Dynamics Test / Analysis

Occupant Accelerations

ATD FE

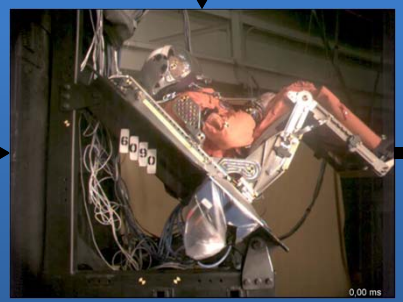


Simulation

Worst Case ATD Responses

Worst Case Occupant Accelerations

ATD

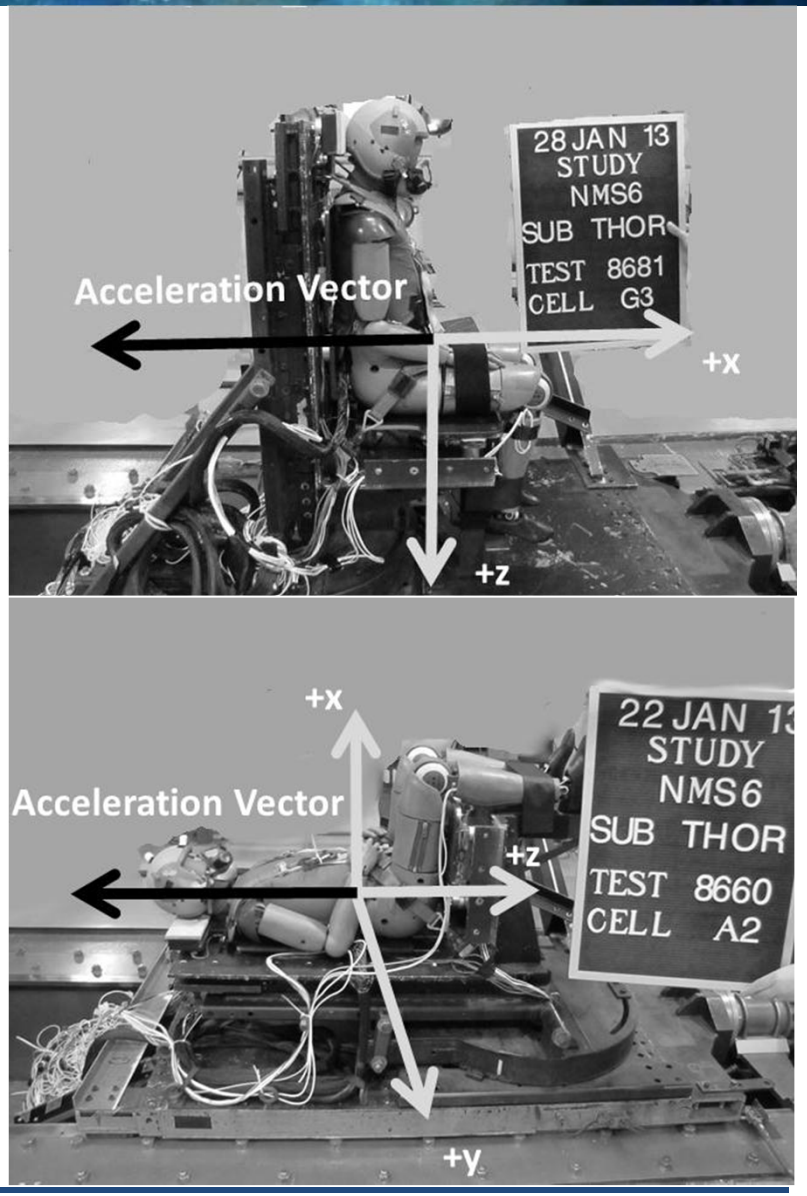


Physical Test

Vehicle Passes?

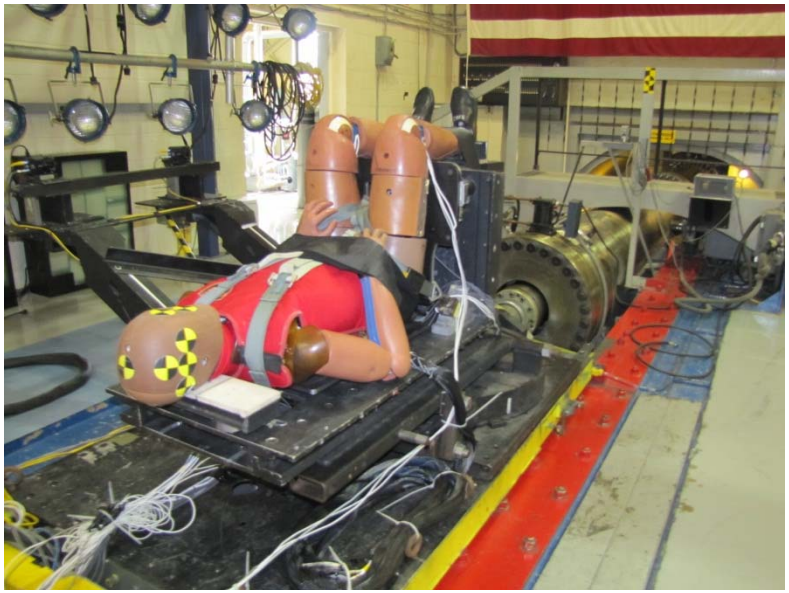
Current Study Objectives

- **THOR was designed for the automotive industry. Typically 35 mph frontal crash.**
- **THOR designed to have a more biofidelic response to impacts than previous ATDs like Hybrid III**
- **Investigate THOR responses in orientations and dynamics similar to those expected during spacecraft operations**
  - -X axis testing (frontal Impact)
    - 8G, 100ms rise time
    - 10G, 70 & 100ms rise time
  - -Z axis testing (spinal Impact)
    - 8G, 100ms rise time
    - 10G, 40, 70, & 100ms rise time
    - 12G, 100ms rise time
- **Compare these responses to historical human responses in identical orientations & accelerations**
- **Characterize the performance of the THOR in cases outside of the automotive certification**
- **Compare performance with Hybrid III responses**



Methods: THOR & Hybrid III Testing

- **Testing was conducted at the Air Force Research Laboratory on the Horizontal Impact Accelerator at Wright Patterson Air Force Base**
- **24” HYGE system with a generic seat fixture**
- **All tests were conducted with a 5-point restraint**
- **A total of 39 tests were conducted in 3 different axes (only a subset reported here)**
- **Test conditions were matched as closely as possible to the original human test conditions**

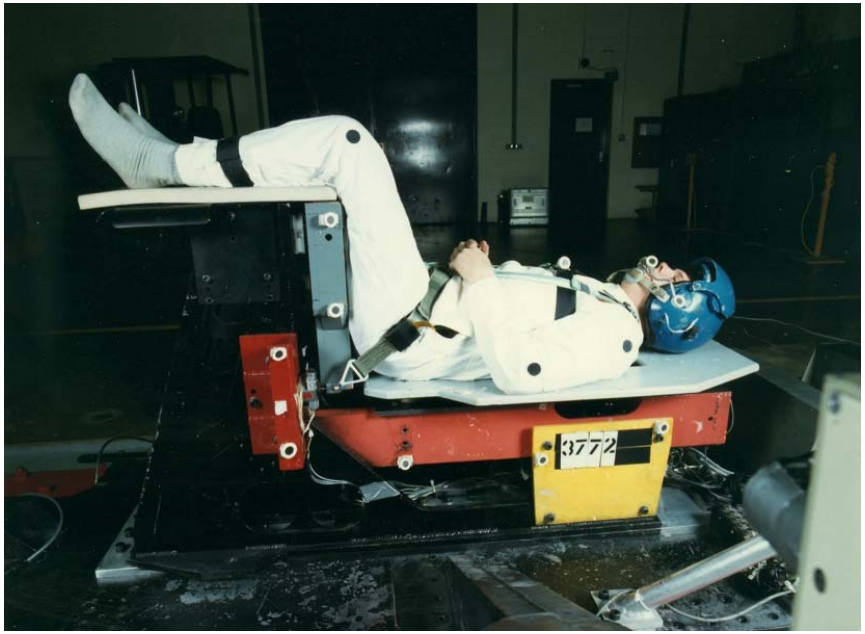


	Human Studies			THOR			Hybrid III		
	Tests	Average Peak G	Average Rise Time (ms)	Test	Peak G	Rise Time (ms)	Test	Peak G	Rise Time (ms)
-x	199503 Cell B	8.02	102.55	8681	8.00	81.0	8663	7.93	81.9
-x	199503 Cell C	9.99	98.65	8682	9.87	88.5			
-x	200301 Cell E & E1	10.00	71.50	8700 8701	9.88 10.00	61.3 60.3	8702	10.03	60.9
-z	198901 Cell G	7.95	108.00	8676	8.00	102.6			
-z	198901 Cell H	9.94	101.53	8673	9.97	99.6	8677	9.89	83.7
-z	198901 Cell I	11.99	99.43	8675	12.22	91.0			
-z	198901 Cell D	10.02	71.31	8665	9.73	63.7	8665	10.2	74.7
-z	198901 Cell C	10.03	37.81	8660	10.01	32.5	8661	9.95	32.7

Methods: Human Data

- **Historic data was obtained from the Air Force Collaborative Biodynamics Network**

  https://biodyn.istdayton.com/CBDN/
- **Three studies were identified from the database (shown below)**
- **Every effort was made to match the input accelerations. Differences in the deceleration phase of some of the pulses were present.**

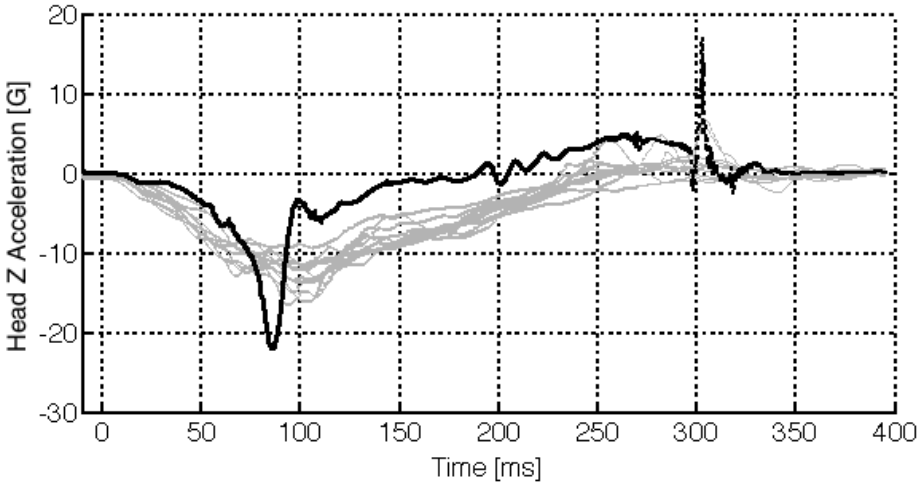


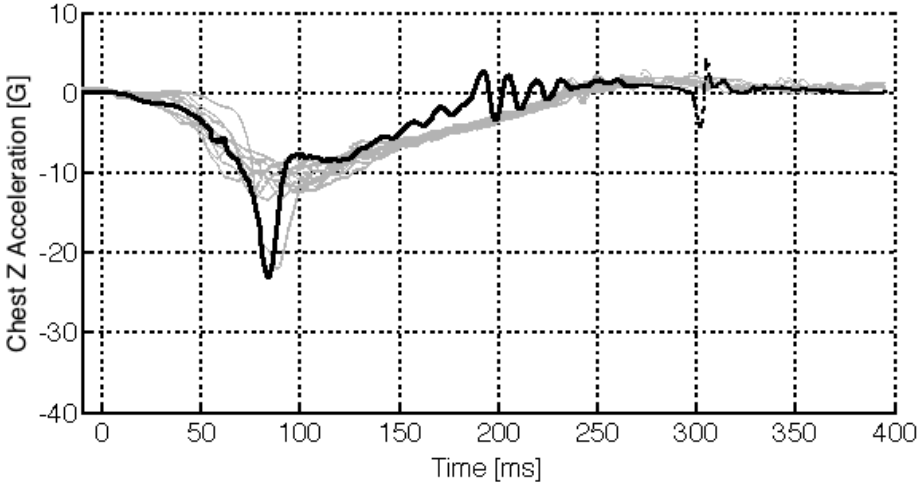
	Study 198901		Study 199503		Study 200301	
	Females	Males	Females	Males	Females	Males
Total Number	2 (8 trials)	11 (50 trials)	12 (25 trials)	15 (30 trials)	7 (14 trials)	13 (26 trials)
Standing Ht. [cm]	163.98-172.7	167.6-190.5	154.9-172.7	157.48-186.7	157.5-175.3	172.7-193.0
Subject Wt. [kg]	46.7-61.7	54.0-102.1	49.9-63.5	46.2-107.9	65.3-86.2	67.6-125.2
Seated Ht. [cm]	86.4-88.4	83.8-95.0	82.6-90.2	83.8-98.0	87.0-95.3	87.6-100.3
Age	24-27	22-39	20-29	25-39	23-46	24-37

Methods: Data

- **Dependent Variables**
  - Head X & Z acceleration
  - Head X & Z displacement
  - Chest X & Z acceleration
  - Shoulder X & Z displacement
  - Seat Pan Z Force (For –Z cases)
- **Acceleration is inertial**
- **Kinematics are sled referenced**
- **Filters**
  - THOR & H-III – CFC1000
  - 1995: 4-pole Butterworth, 60 Hz
  - 1989 & 2003: 8-pole Butterworth, 120Hz
- **Sampling Rate**
  - 1989: 1kHz, 10kHz for all other accelerations
  - 500 Hz kinematics
- **Seats & Restraints**
  - Human studies:

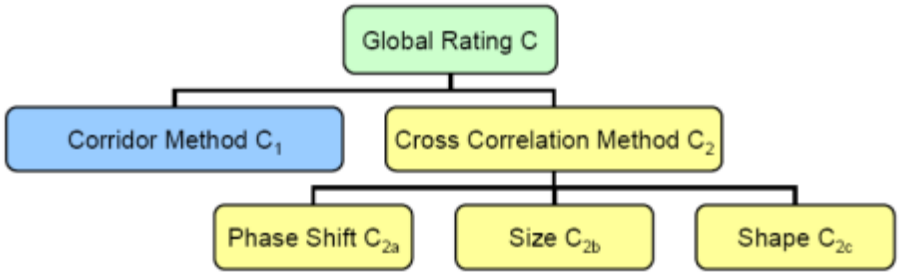
    VIP seat, PCU-15/P, PCU-16/P, & MB-6 restraints
  - THOR & H-III: Generic seat, MB-6 restraint

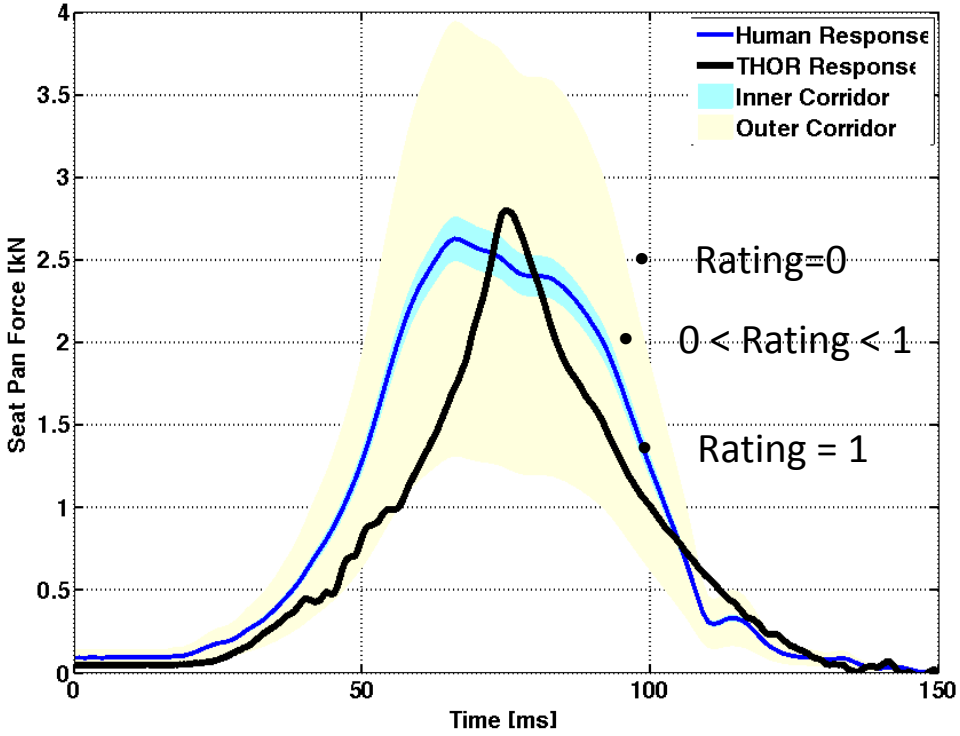




Methods: CORA Analysis

- **CORA score was calculated between THOR and <u>each</u> human response. Also for each Hybrid III and human response.**
- **CORA approach used in ATD testing. Ideal for time series data.**
- **Overall score ranges from 0 (no correlation) to 1 (perfect correlation).**
- **The score consists of a weighted sum of the sub-methods shown to the right**
- **Scoring parameters were used that the software developer recommends for ATD testing.**
- **Corridor Method**
  - Point by point comparison
- **Cross-Correlation Method**
  - Phase-Shift, Size, Shape





Methods: Statistics

- **To determine the effects of each covariate, a beta model was used**
- **The beta distribution has two parameters, α and β**
- **These can be re-parameterized in terms of the mean (μ) and a shape parameter (φ)**
- **The resulting CORA score was analyzed for each dependent variable using a maximum likelihood estimation in Stata.**
- **Statistical significance for covariates was defined as having P < 0.05**
- **For THOR, the following covariates were investigated:**
  - Peak seat acceleration
  - Seat acceleration rise time
  - Duration of impact
  - Subject sitting height
  - Subject Weight
  - Subject Age
  - Subject Sex
- **Hybrid III vs. THOR scatter plots for all dependent measures**

Mean

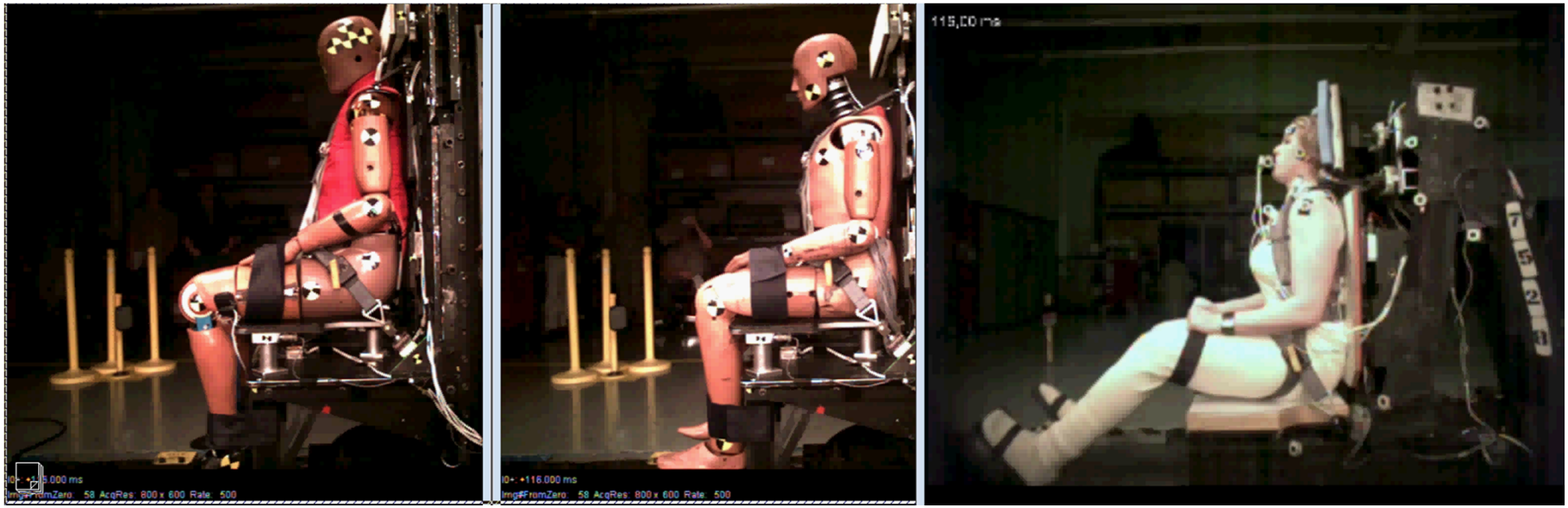
$$\mu = \frac{\alpha}{\alpha + \beta}$$

Shape

$$\varphi = \alpha + \beta$$

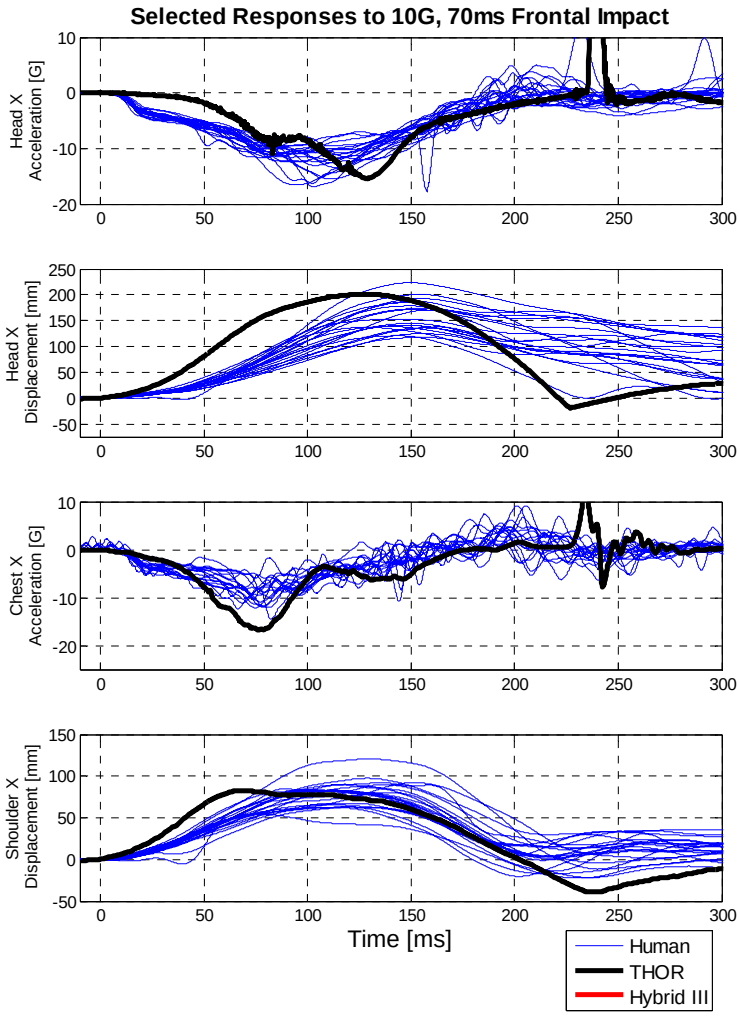
Frontal Comparison

THOR **Hybrid III** **Human**



Results: Frontal Impact

- Head x-acceleration
  - Peak response correlated with the human response at 8 and 10G 100ms, but not 10G 70ms
  - Phase lagged the human response
- Head x-displacement
  - Phase led the human response
  - Several subjects responded with the same peak displacement, but the mean of the group was lower
- Chest x-acceleration
  - Phase was similar to humans
  - Higher peak response, and was well correlated with lighter subjects (Cora = 0.8 for 46 kg vs. Cora = 0.4 for 126kg)
- Shoulder x-displacement
  - Phase was similar to humans
  - Higher peaks than the human response



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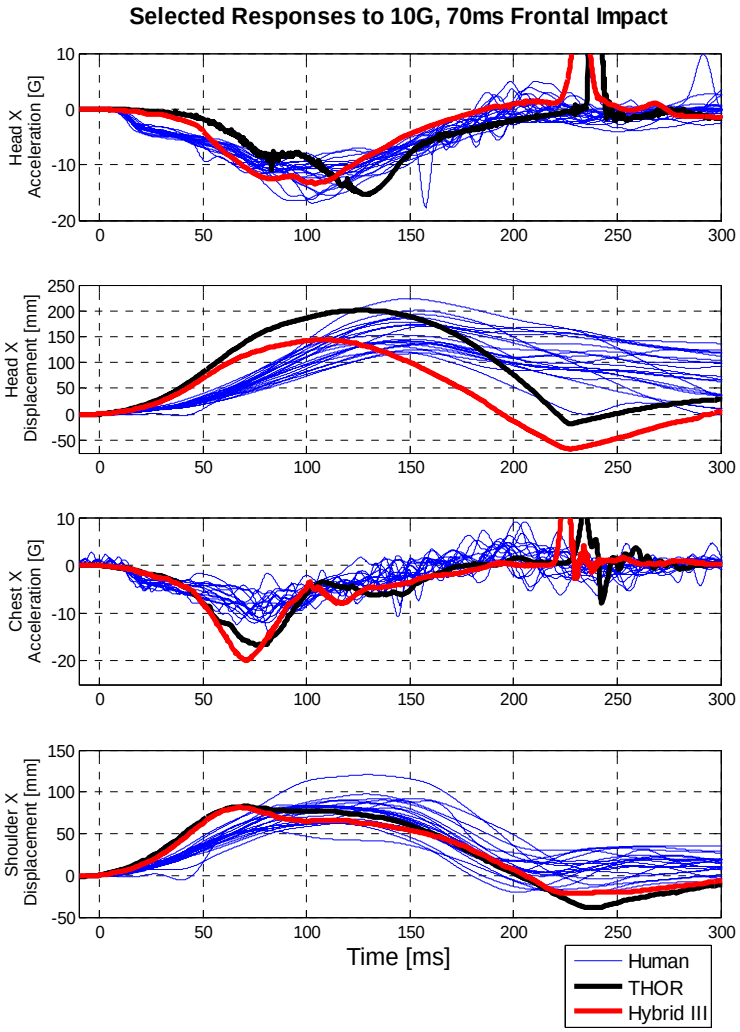
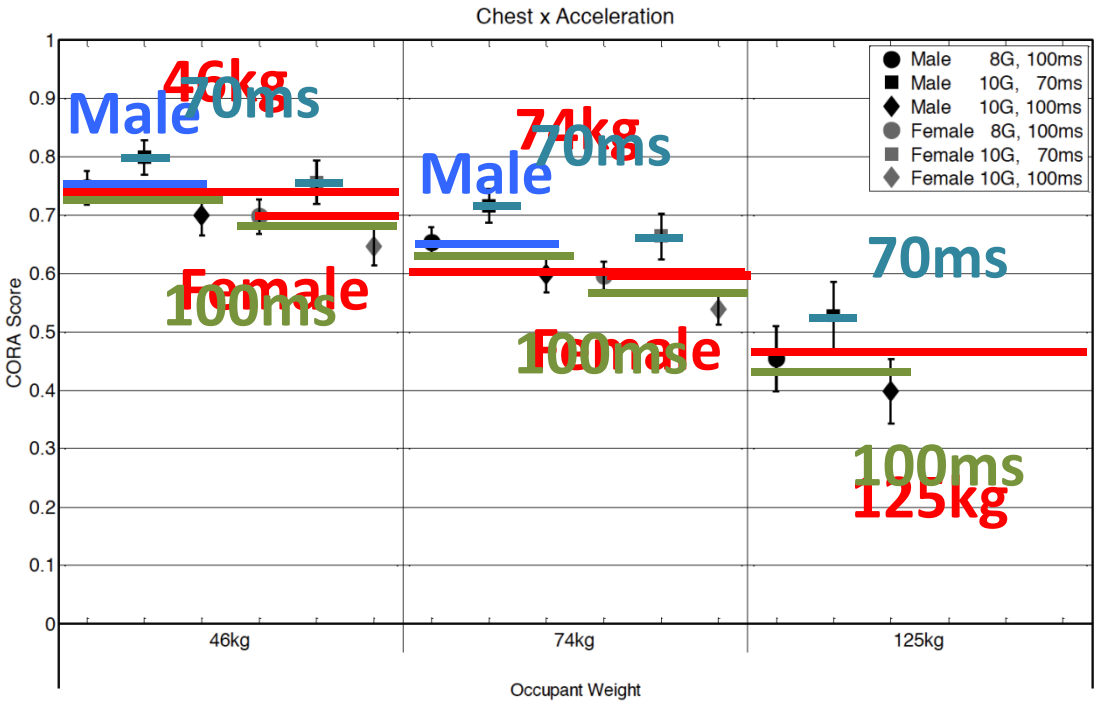


Results: Frontal

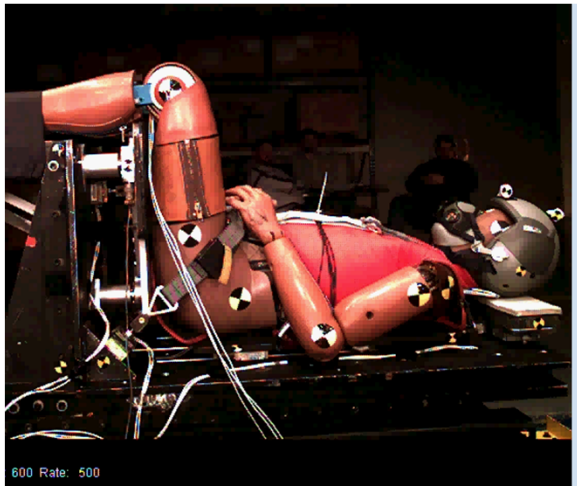
- **No clear correlation between all THOR responses and any one demographic for all the metrics**
- **In general, the THOR responses were better matched to lower peak accelerations, longer pulse durations, and females**



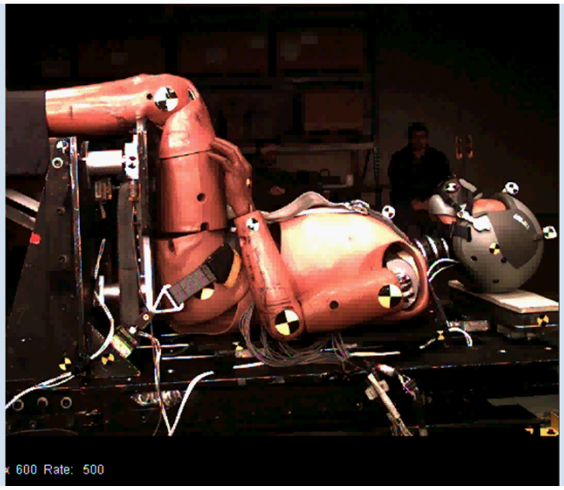
Metric	Overall CORA Score	Peak Acceleration	Pulse Rise Time	Duration of Impact	Subject Sitting Height	Subject Weight	Subject Age	Subject Sex
Sled X Acceleration	0.95 ± 0.004	↓	↑	↓	↑		↓	
Head X Acceleration	0.65 ± 0.01			↑	↓	↑		
Head Z Acceleration	0.28 ± 0.01			↑				↓M
Head X Displacement	0.49 ± 0.01	↓						↓M
Head Z Displacement	0.51 ± 0.01	↓		↑				↓M
Chest X Acceleration	0.64 ± 0.01	↓	↓	↑	↑	↓		↑M
Shoulder X Displacement	0.51 ± 0.01		↓			↑		

Spinal Comparison

THOR



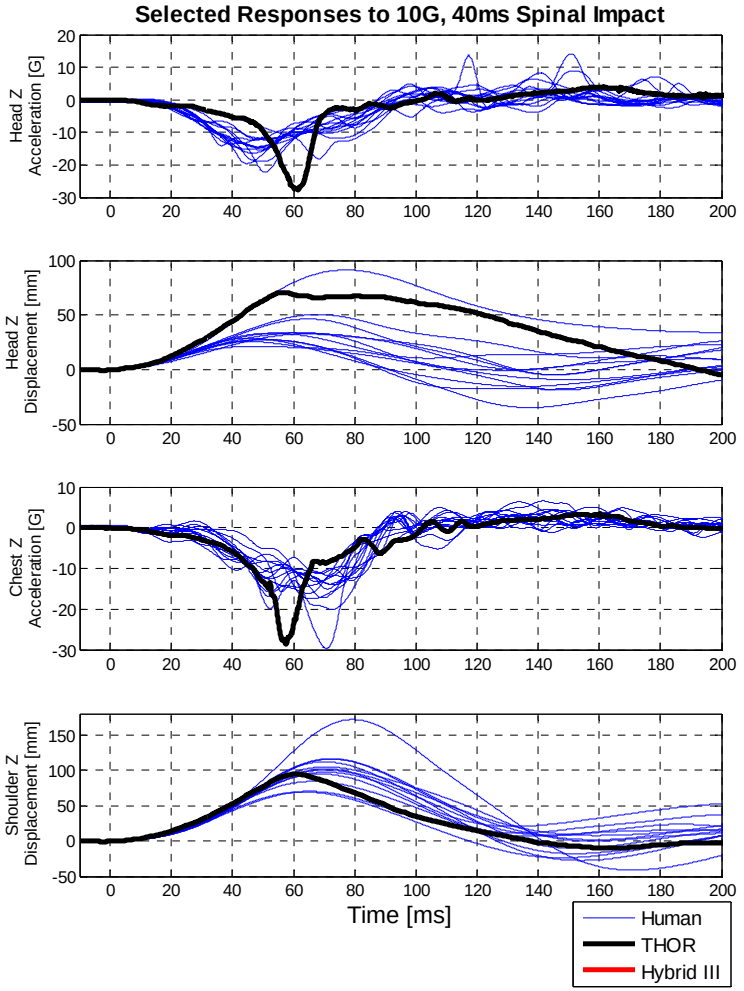
Hybrid III



Human

Results: Spinal Impact

- Head z-acceleration
  - In phase (8G 100ms & 10G 70ms), lag 10G 40 ms, lead (10 & 12G 100ms)
  - Higher peak response
- Head z-displacement
  - Variable human response
  - In phase
  - Higher peak response
- Chest z-acceleration
  - In phase
  - Higher peak response
  - Highly correlated with heavier subjects at lower G pulses (Cora = 0.86 for 125kg at 8G).
- Shoulder z-displacement
  - In phase and comparable peak
- Seat pan force
  - Well correlated & in phase



Results: Spinal Impact

- Head z-acceleration
  - In phase (8G 100ms & 10G 70ms), lag 10G 40 ms, lead (10 & 12G 100ms)
  - Higher peak response
- Head z-displacement
  - Variable human response
  - In phase
  - Higher peak response
- Chest z-acceleration
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  - Higher peak response
  - Highly correlated with heavier subjects at lower G pulses (Cora = 0.86 for 125kg at 8G).
- Shoulder z-displacement
  - In phase and comparable peak
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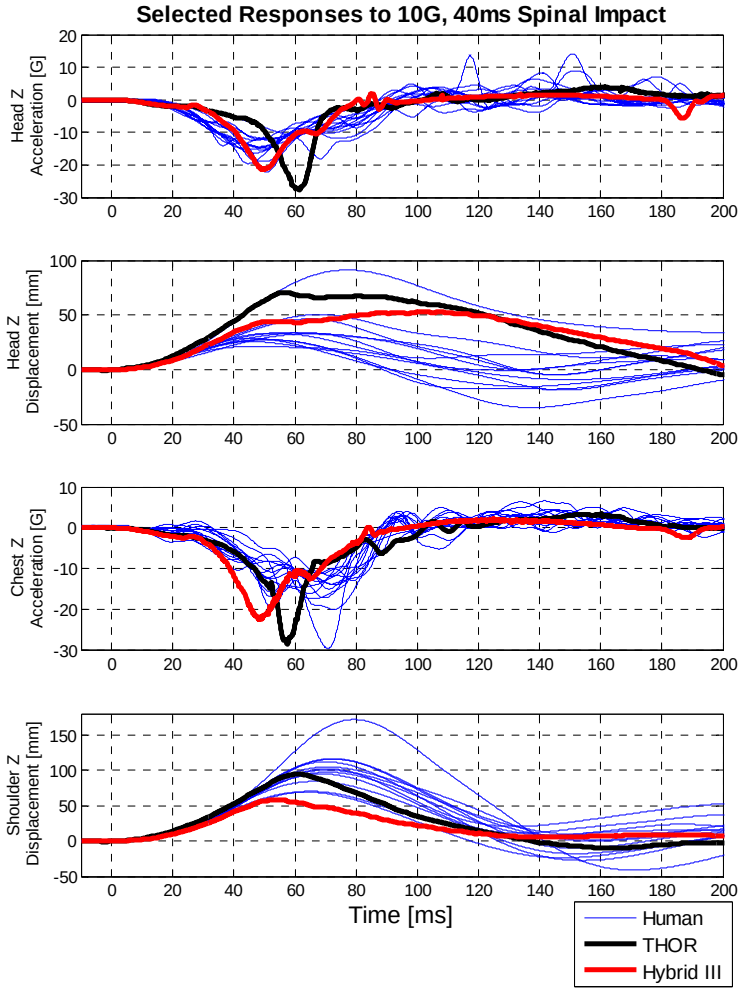
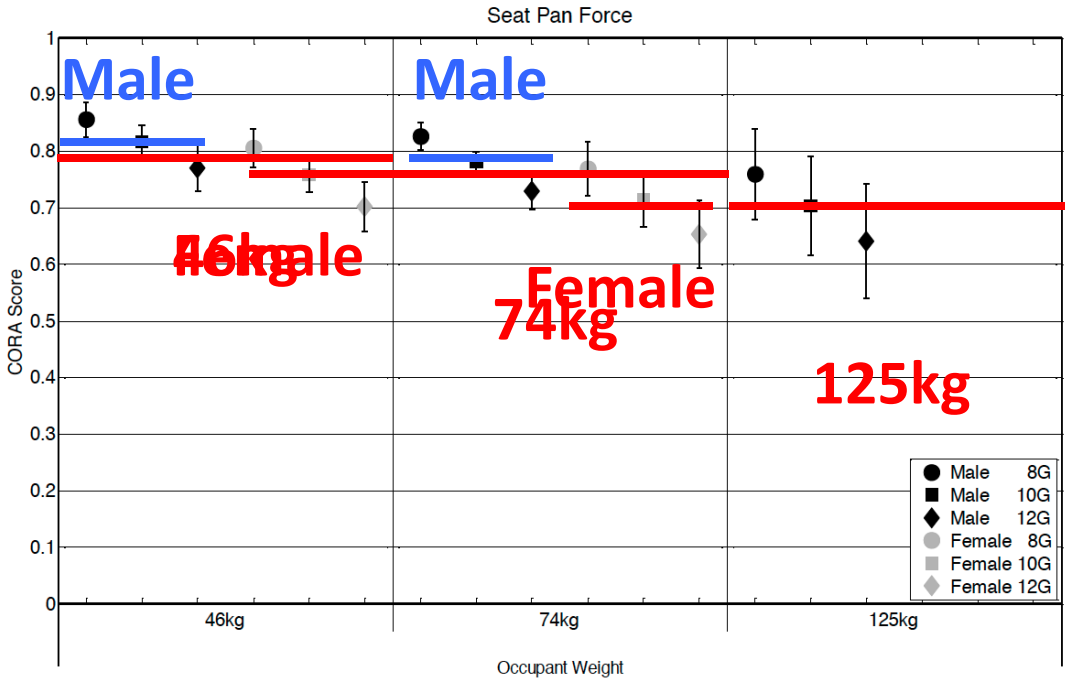


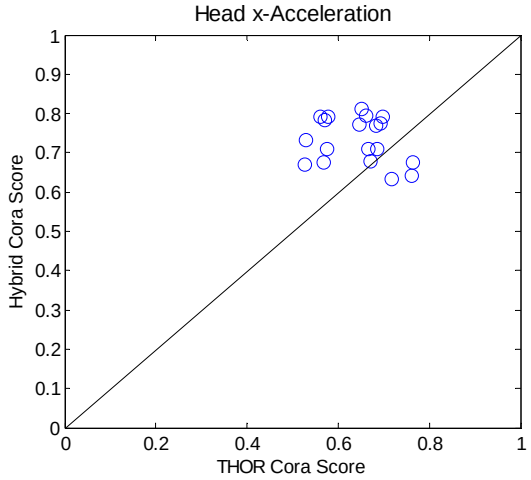
Results: Spinal

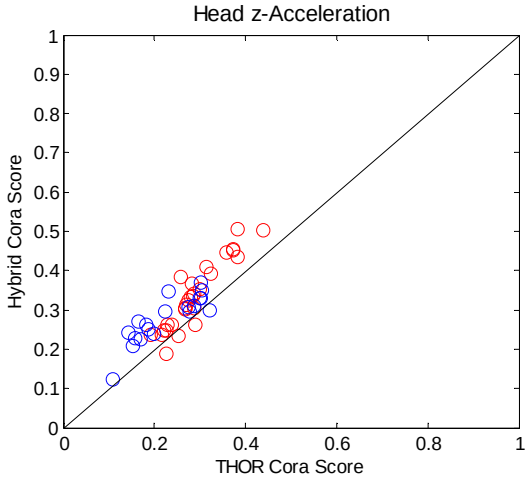
- **No clear correlation between all THOR responses and any one demographic for all the metrics**
- **In general, the THOR responses were better matched to lower peak accelerations and longer rise times**

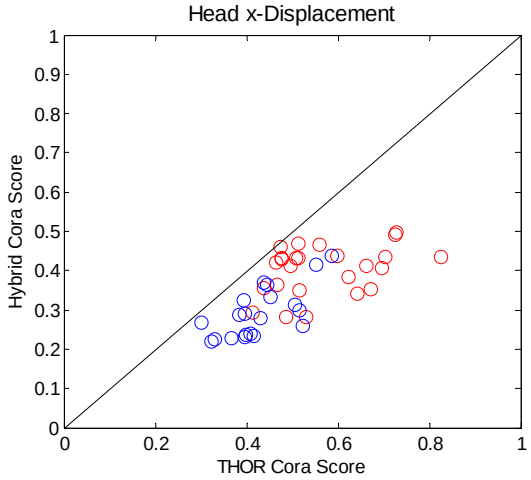


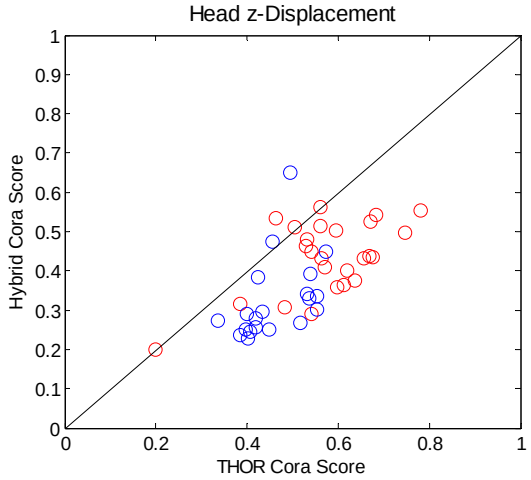
Metric	Overall CORA Score	Peak Acceleration	Pulse Rise Time	Duration of Impact	Subject Sitting Height	Subject Weight	Subject Age	Subject Sex
Sled X Acceleration	0.84 ± 0.01	↓	↑	↓	↑	↓		
Head X Acceleration	0.26 ± 0.02		↓				↓	
Head Z Acceleration	0.49 ± 0.02	↓	↑	↓				
Head X Displacement	0.39 ± 0.02							
Head Z Displacement	0.37 ± 0.02		↑					↓M
Chest Z Acceleration	0.73 ± 0.01	↓				↑		
Shoulder Z Displacement	0.63 ± 0.02	↑	↑		↑			↑M
Seat Pan Force	0.78 ± 0.01	↓				↓		↑M

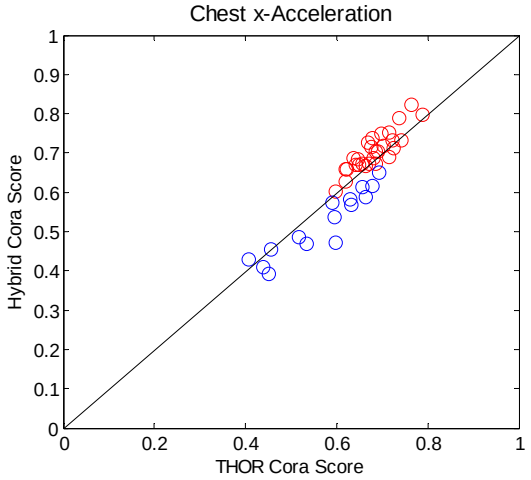
Hybrid III vs. THOR: Frontal Impacts

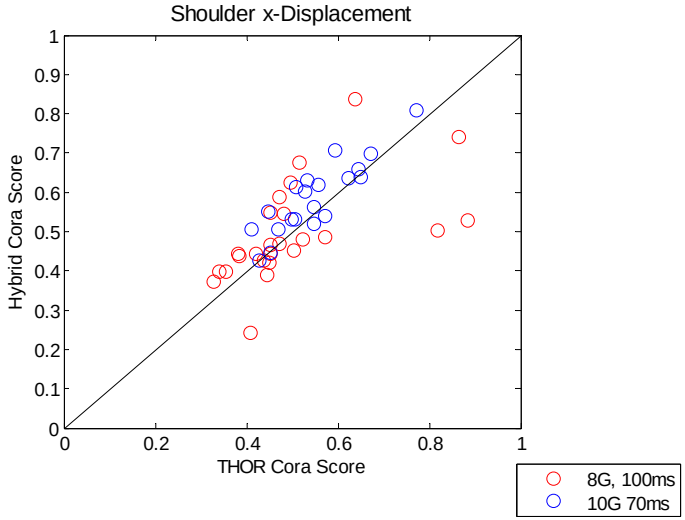




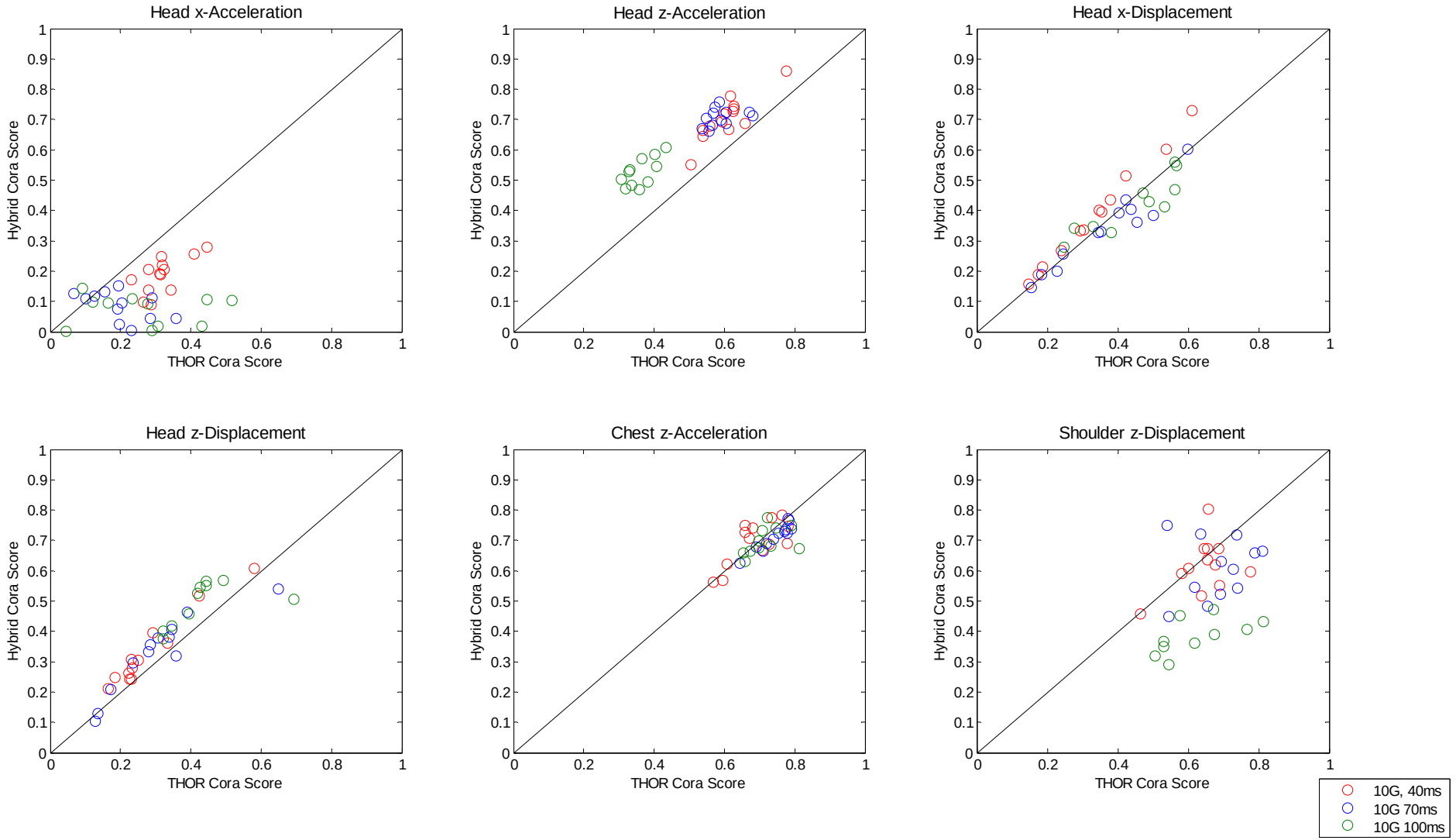








Hybrid III vs. THOR: Spinal Impacts



ATD Comparison by Measure & Condition

Hybrid III

	Pulse Axis	G	Rise Time	Measure	Better ATD
6/11	'-X'	8	100	'chestx'	'Hybrid'
	'-X'	10	70	'headx'	'Hybrid'
	'-X'	8	100	'headz'	'Hybrid'
	'-X'	10	70	'headz'	'Hybrid'
	'-X'	8	100	'shoulderx'	'Hybrid'
	'-X'	10	70	'shoulderx'	'Hybrid'
8/18	'-Z'	10	40	'chestz'	'Hybrid'
	'-Z'	10	40	'headx_disp'	'Hybrid'
	'-Z'	10	40	'headz'	'Hybrid'
	'-Z'	10	70	'headz'	'Hybrid'
	'-Z'	10	100	'headz'	'Hybrid'
	'-Z'	10	40	'headz_disp'	'Hybrid'
	'-Z'	10	70	'headz_disp'	'Hybrid'
	'-Z'	10	100	'headz_disp'	'Hybrid'

Head: 10/19
Chest/Shoulder: 4/10
All conditions: 14/29

THOR

	Pulse Axis	G	Rise Time	Measure	Better ATD
5/11	'-X'	10	70	'chestx'	'THOR'
	'-X'	8	100	'headx_disp'	'THOR'
	'-X'	10	70	'headx_disp'	'THOR'
	'-X'	8	100	'headz_disp'	'THOR'
	'-X'	10	70	'headz_disp'	'THOR'
10/18	'-Z'	10	70	'chestz'	'THOR'
	'-Z'	10	100	'chestz'	'THOR'
	'-Z'	10	40	'headx'	'THOR'
	'-Z'	10	70	'headx'	'THOR'
	'-Z'	10	100	'headx'	'THOR'
	'-Z'	10	70	'headx_disp'	'THOR'
	'-Z'	10	100	'headx_disp'	'THOR'
	'-Z'	10	40	'shoulderz'	'THOR'
	'-Z'	10	70	'shoulderz'	'THOR'
	'-Z'	10	100	'shoulderz'	'THOR'

Head: 9/19
Chest/Shoulder: 6/10
All conditions: 15/29

Discussion

- **The impact pulses were selected to meet 2 requirements**
  - Well matched to expected spacecraft capsule landings
  - Matched to existing historical human data
- **Investigation was not a systematic assessment of THOR responses across a range of conditions**
- **Although the THOR was designed for specific frontal impacts, there have not been many spinal axis tests of the THOR, which is a primary load vector for spacecraft landings**
- **Subject bracing appeared to account for differences observed in the THOR motion during testing**
  - May explain why the chest acceleration and seat pan forces had higher correlations than the head accelerations and displacements
- **Compared with the Hybrid III, the THOR does not appear to have any distinct advantages for these types of impacts**
  - THOR is only available in 50th % male. Hybrid III covers 5-95th % male and female
  - THOR is quite expensive and is not readily available
  - Hybrid III finite element model is well established

Conclusions

- **THOR is not representative of human responses in spinal and frontal impacts in some of the conditions reported here**
- **Chest responses are a better match than head responses**
- **Seat pan forces are well matched, especially for certain subjects**
- **Active bracing coached in the human testing is not replicated by the THOR**
- **THOR matches some human responses quite well**
  - Understanding where the THOR is well matched and where it is not can allow the THOR to be used at NASA to help develop occupant protection standards for spaceflight.
- **The Hybrid III mimics human responses about as well as the THOR**
  - Could also be due to bracing

Acknowledgements

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- **Thanks to Dan Parent for help obtaining a THOR for testing**
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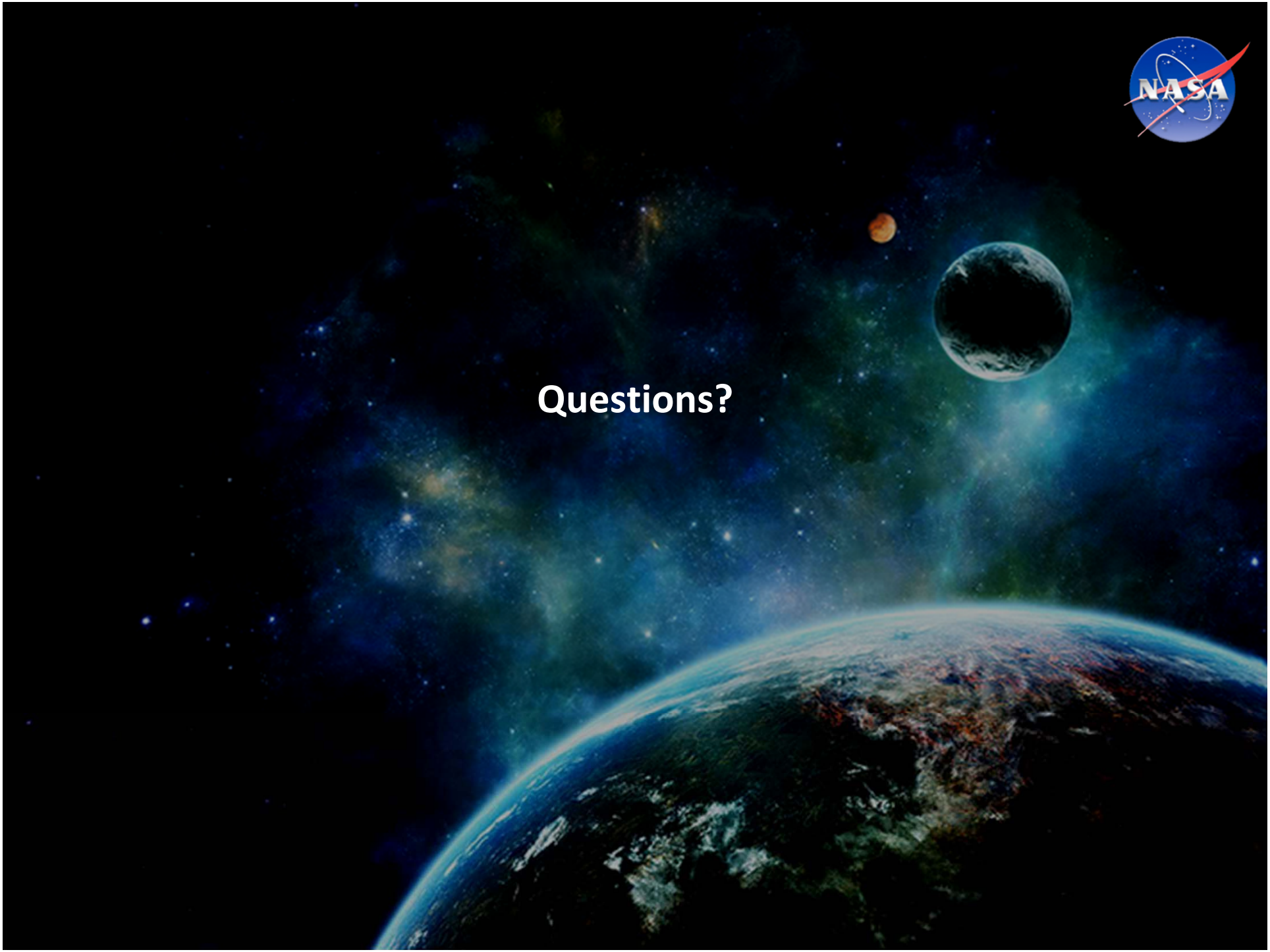
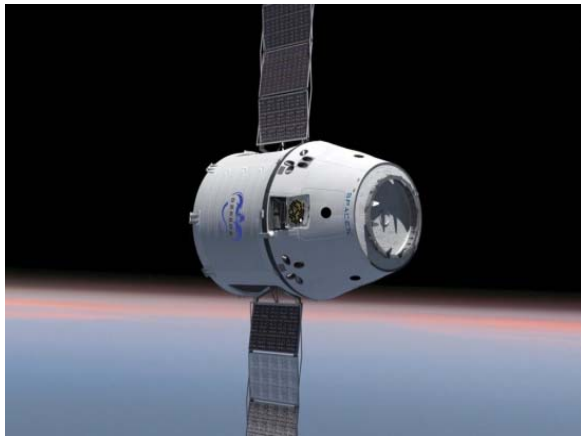

Questions?

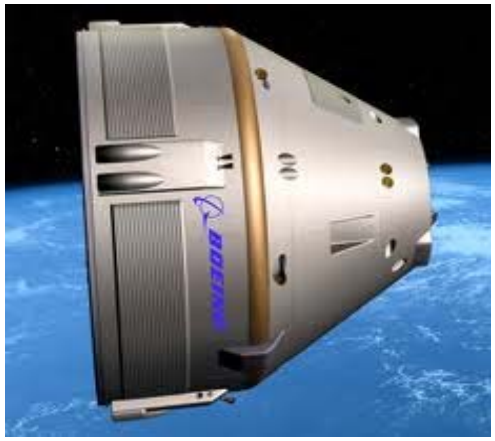
NASA After the Space Shuttle

Soyuz TMA-M
3 Crew

Orion / MPCV
4 crew



SpaceX Dragon
7 Crew



Boeing CCT-100
7 Crew

Sierra Nevada DreamChaser
6 Crew

Blue Origin New Shepard
7 Crew

Limitations

- **Seats/restraints**
  - Seat Pan in THOR tests heavier than human tests
  - Lead to higher seat pan forces in THOR
  - Restraints were not exactly the same for some test conditions
- **Filters**
  - Because the human data were taken from a database, the filters used for those tests could not be changed
  - A comparison was made with different filtering used on the THOR responses with little effect on the resulting CORA scores
- **Seat pulse durations**
  - Although every effort was made to match the acceleration inputs, differences did exist in the pulse duration
- **Transducer location in THOR vs. humans**
  - Different transducer locations were used for the human tests compared to the internal instrumentation of the THOR
  - It is possible that for future tests, additional external sensors could be used to better approximate the sensor locations used in the human dataset
- **Human responses could be scaled to match THOR anthropometrics**

Future Work

- **Scaling human responses**
- **Assess THOR lateral impact response**
  - Additional data were collected in lateral impact conditions and will be compared to available human data
- **Conduct human testing in conjunction with THOR and HIII**
  - Because of NASA's need for low risk on injury, additional human testing in conditions similar to nominal spacecraft landing are planned
- **Validate FEM of THOR**
  - In cooperation with NHTSA and Virginia Tech, NASA is working to validate the THOR FEM in these additional loading conditions for future use with spacecraft design

Overall Test Program

Orientation	Peak G	Rise Time [ms]	Helmet	Number of THOR Tests	Number of Hybrid III Tests
Frontal (-X)	8	100	Yes	1	1
Frontal (-X)	8	100	No	2	0
Frontal (-X)	10	70	No	2	1
Frontal (-X)	10	100	Yes	1	1
Frontal (-X)	20	70	No	2	1
Lateral (+Y)	10	40	No	2	1
Lateral (+Y)	10	70	No	2	2
Lateral (+Y)	10	100	No	2	2
Lateral (+Y)	20	70	No	3	0
Spinal (-Z)	8	100	Yes	1	0
Spinal (-Z)	10	40	No	4	0
Spinal (-Z)	10	40	Yes	1	1
Spinal (-Z)	10	70	No	2	0
Spinal (-Z)	10	70	Yes	1	3
Spinal (-Z)	10	100	No	3	0
Spinal (-Z)	10	100	Yes	1	1
Spinal (-Z)	12	100	Yes	2	0
Spinal (-Z)	20	70	No	2	0

Results: Frontal Impacts

- **Seat Acceleration**
  - Peaks are matched, some difference in duration

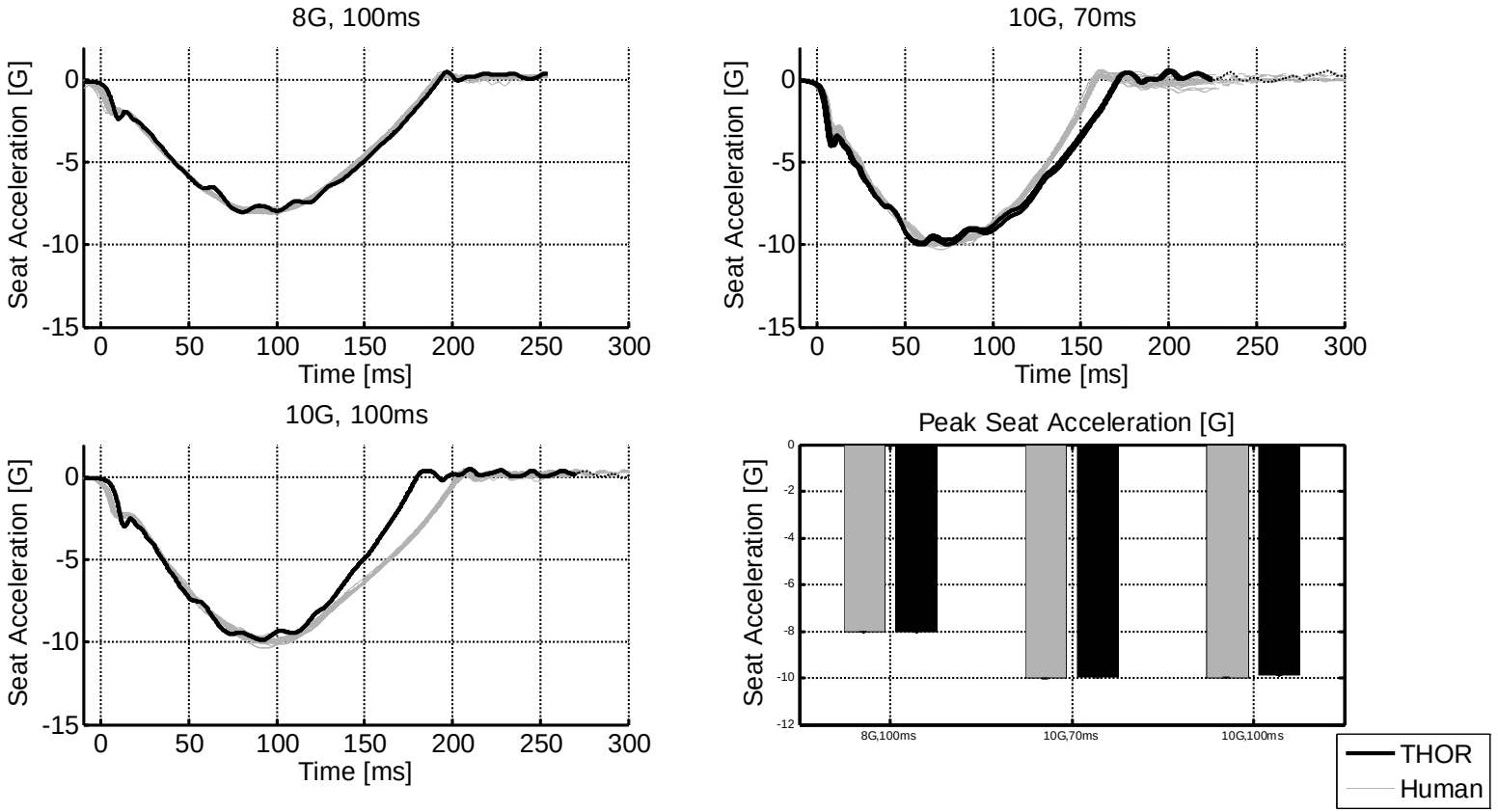


Figure 5. Frontal impact (-x) seat acceleration time histories. Dotted line portions of the THOR trace indicate data that were not included in the time period of CORA analysis.

Results: Frontal Impacts

Head x-axis Acceleration

- THOR response improves with increasing subject weight
- THOR response improves with increasing pulse duration

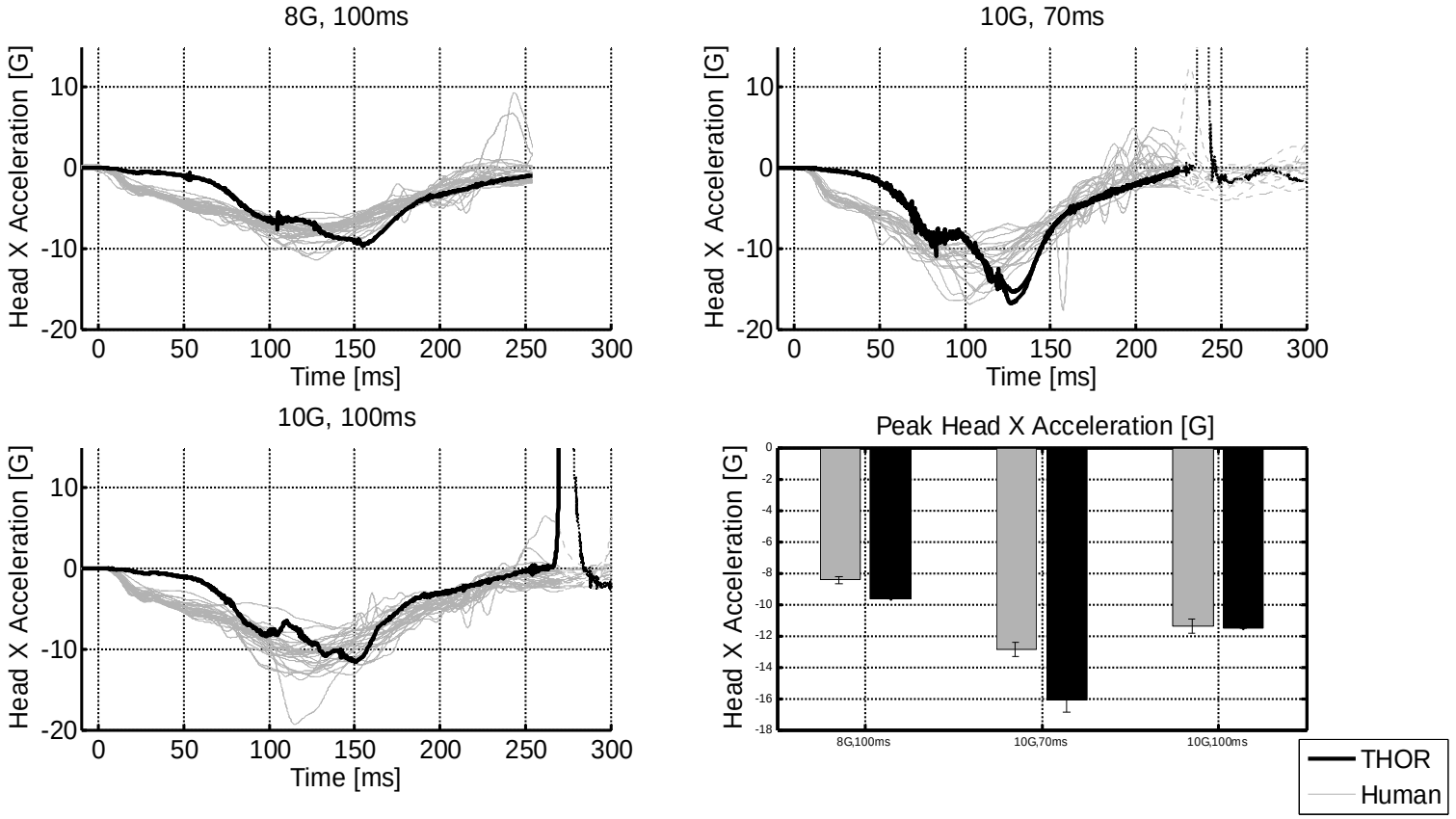


Figure 7. THOR and human head x-axis acceleration responses to frontal impacts. Dotted line portions of the THOR trace indicate data that were not included in the time period of CORA analysis.

Results: Frontal Impacts

Head z-axis Acceleration

- THOR response improves with increasing pulse duration
- THOR response improves for females

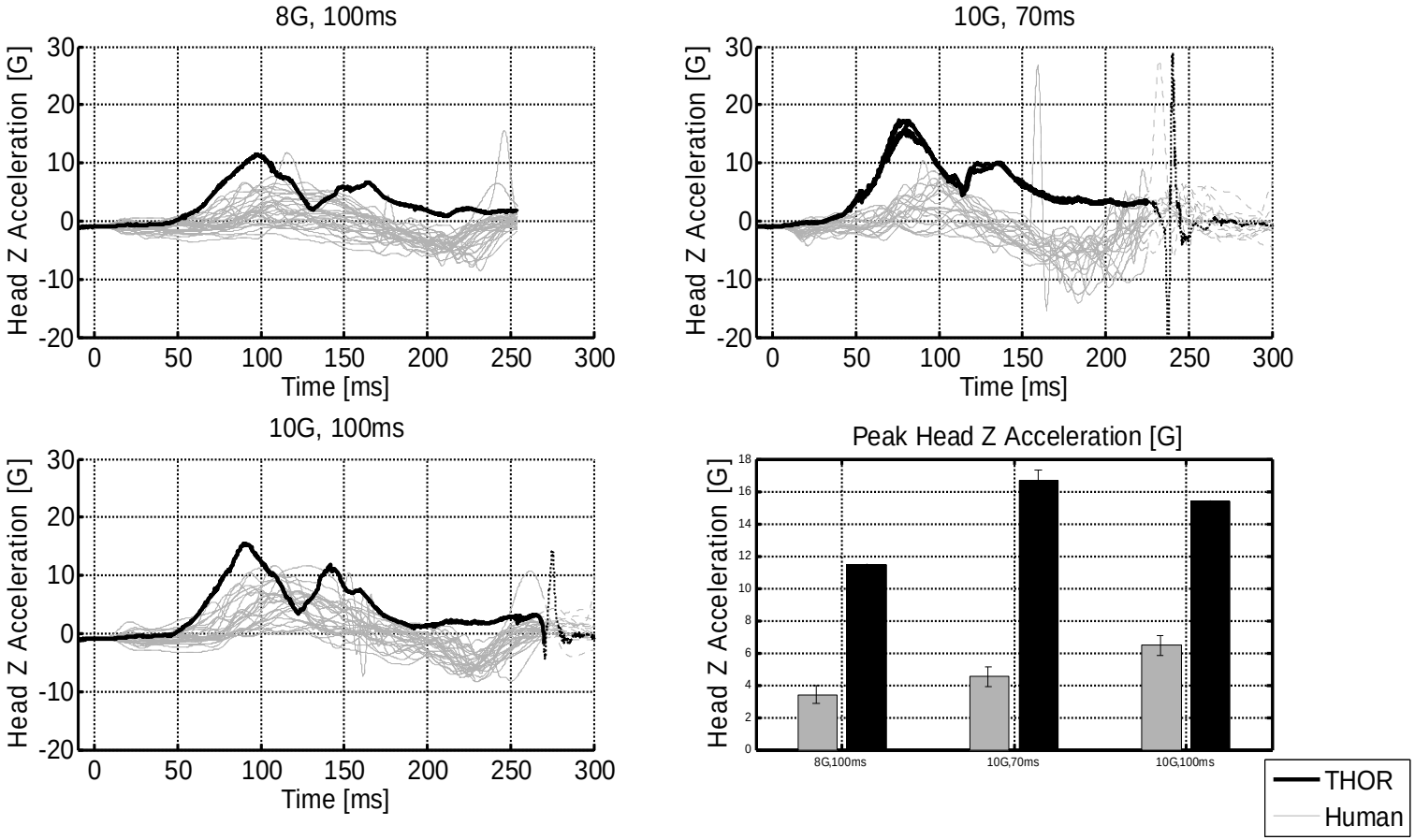


Figure 9. THOR and human head z-axis acceleration responses to frontal impacts. Dotted line portions of the THOR trace indicate data that were not included in the time period of CORA analysis.

Results: Frontal Impacts

Chest x-axis Acceleration

- THOR response improves with decreasing subject weight
- THOR response is significantly better for males
- THOR response improves with decreasing pulse width

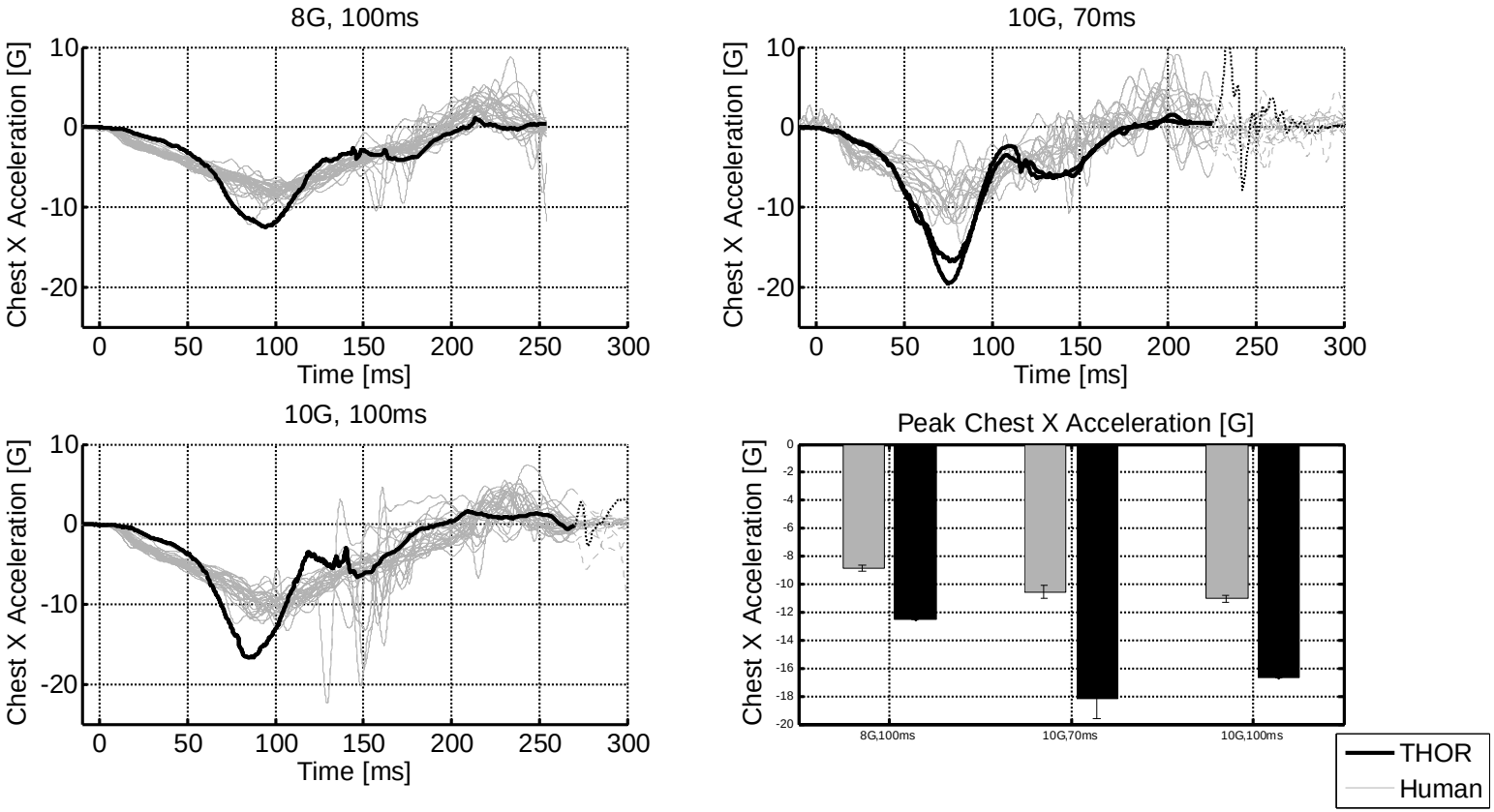


Figure 11. THOR and human chest x-axis acceleration responses to frontal (-x) impacts. Dotted line portions of the THOR trace indicate data that were not included in the time period of CORA analysis.

Results: Frontal Impacts

Shoulder x-axis Displacement

- THOR response improves with increasing subject weight
- THOR response improves with decreasing rise time

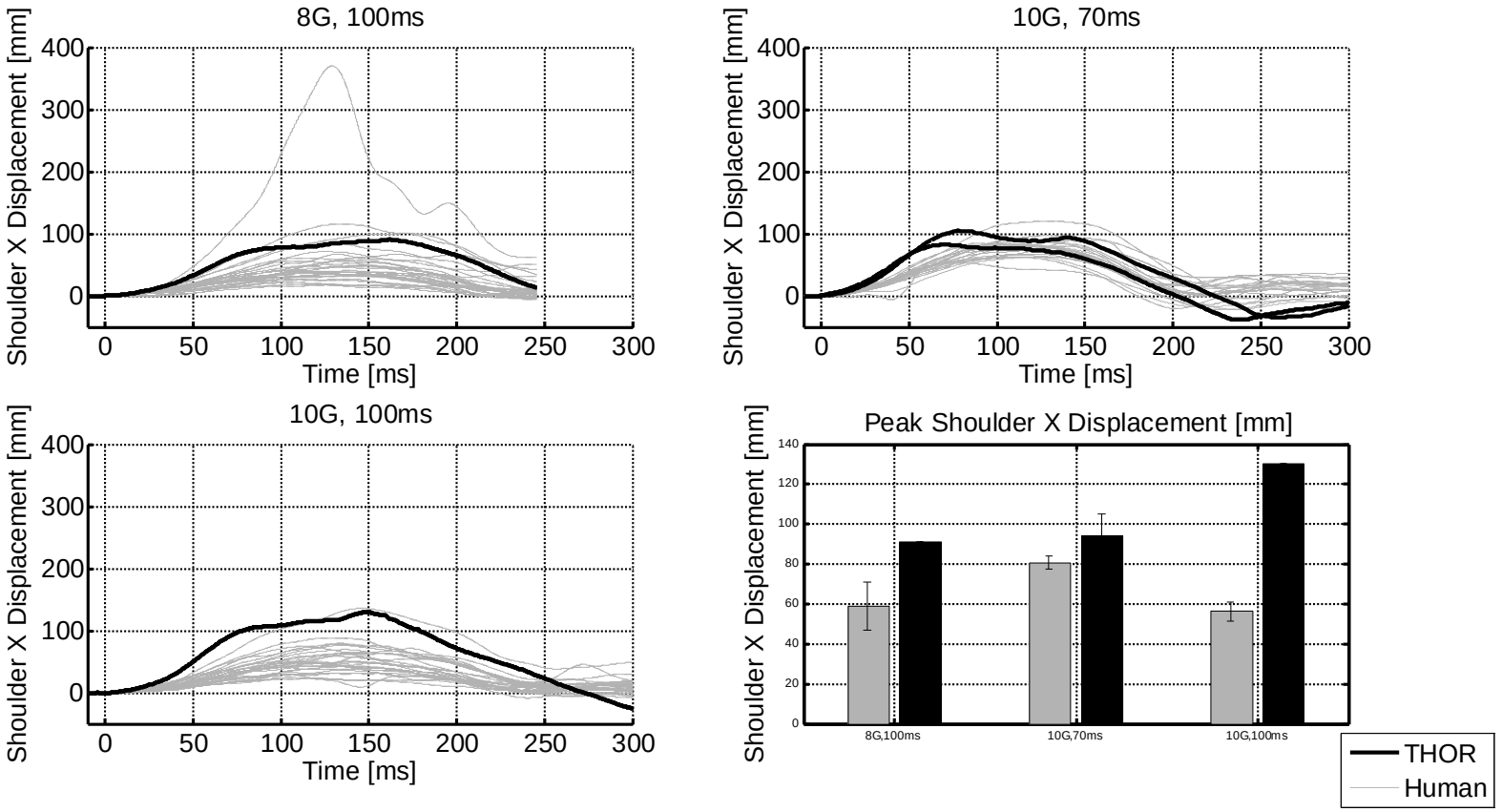


Figure 13. THOR and human shoulder x-axis displacement responses to frontal (-x) impacts. Dotted line portions of the THOR trace indicate data that were not included in the time period of CORA analysis.

Results: Frontal Impacts

Head x-axis Displacement
THOR response improves with increasing

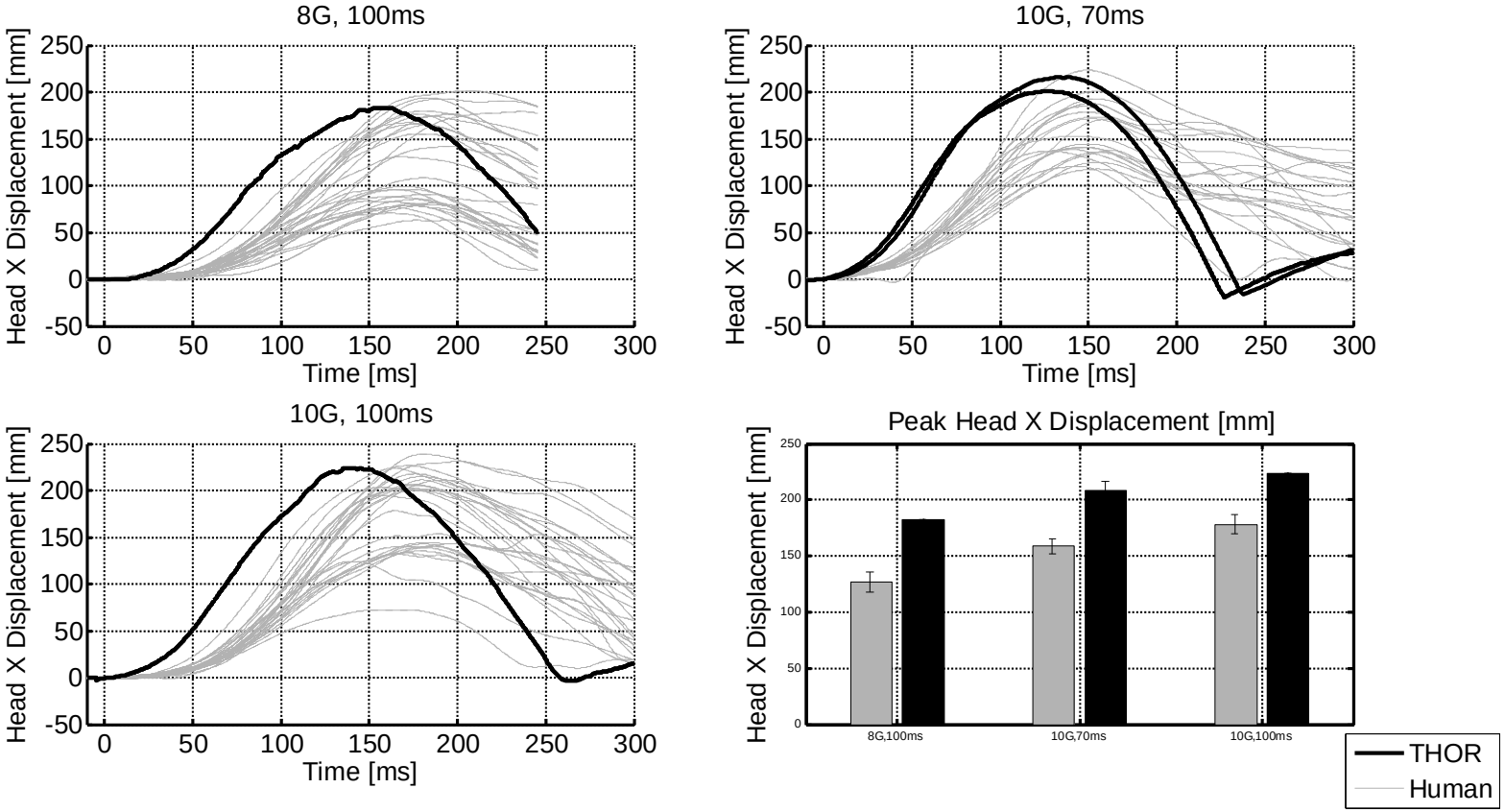


Figure 15. THOR and human head x-axis displacement responses to frontal (-x) impacts. Dotted line portions of the THOR trace indicate data that were not included in the time period of CORA analysis.

Results: Frontal Impacts

Head z-axis Displacement
THOR response improves with increasing

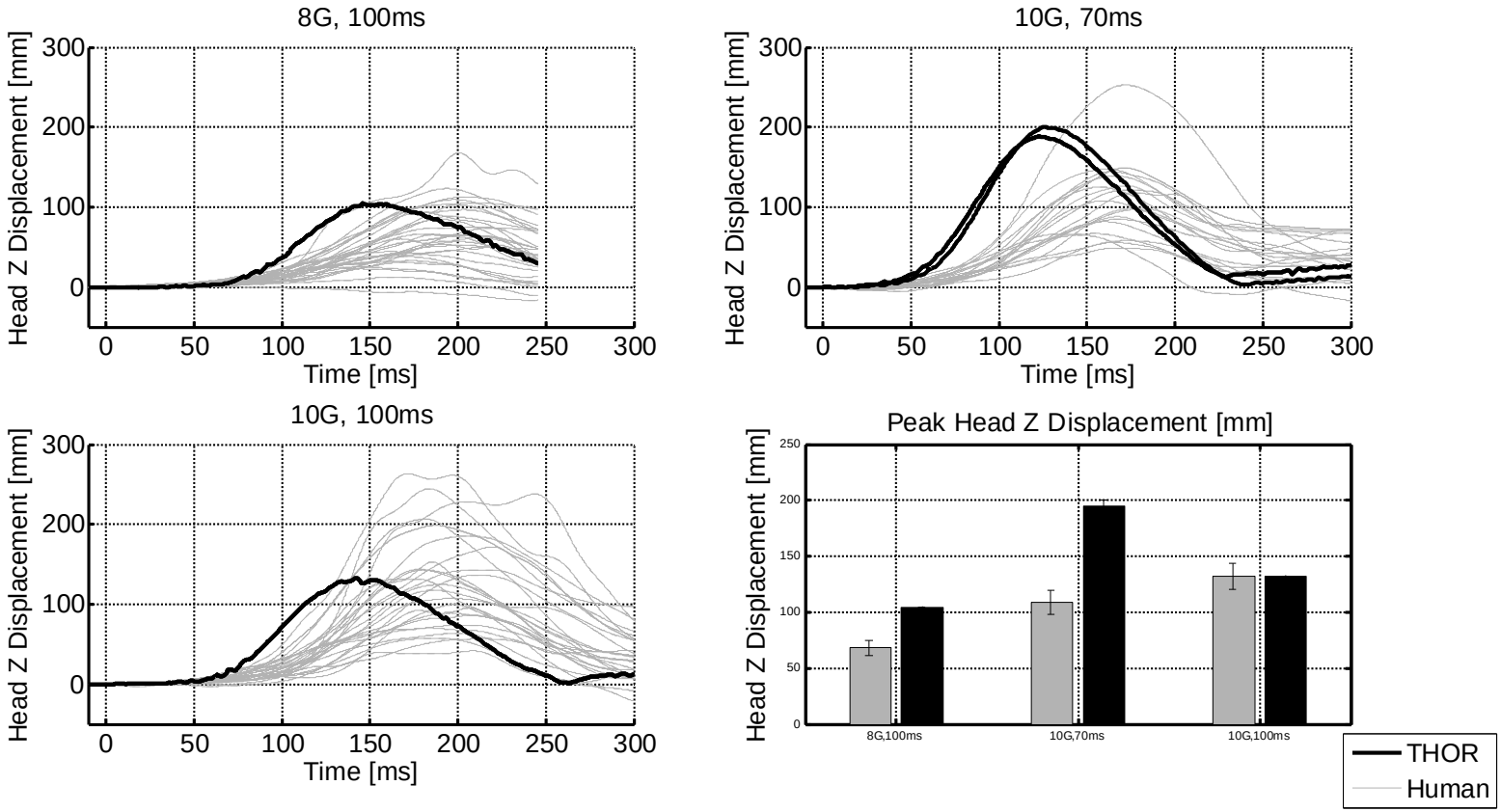


Figure 17. THOR and human head z-axis displacement responses to frontal (-x) impacts. Dotted line portions of the THOR trace indicate data that were not included in the time period of CORA analysis.

Results: Spinal Impacts

- **Seat Acceleration**

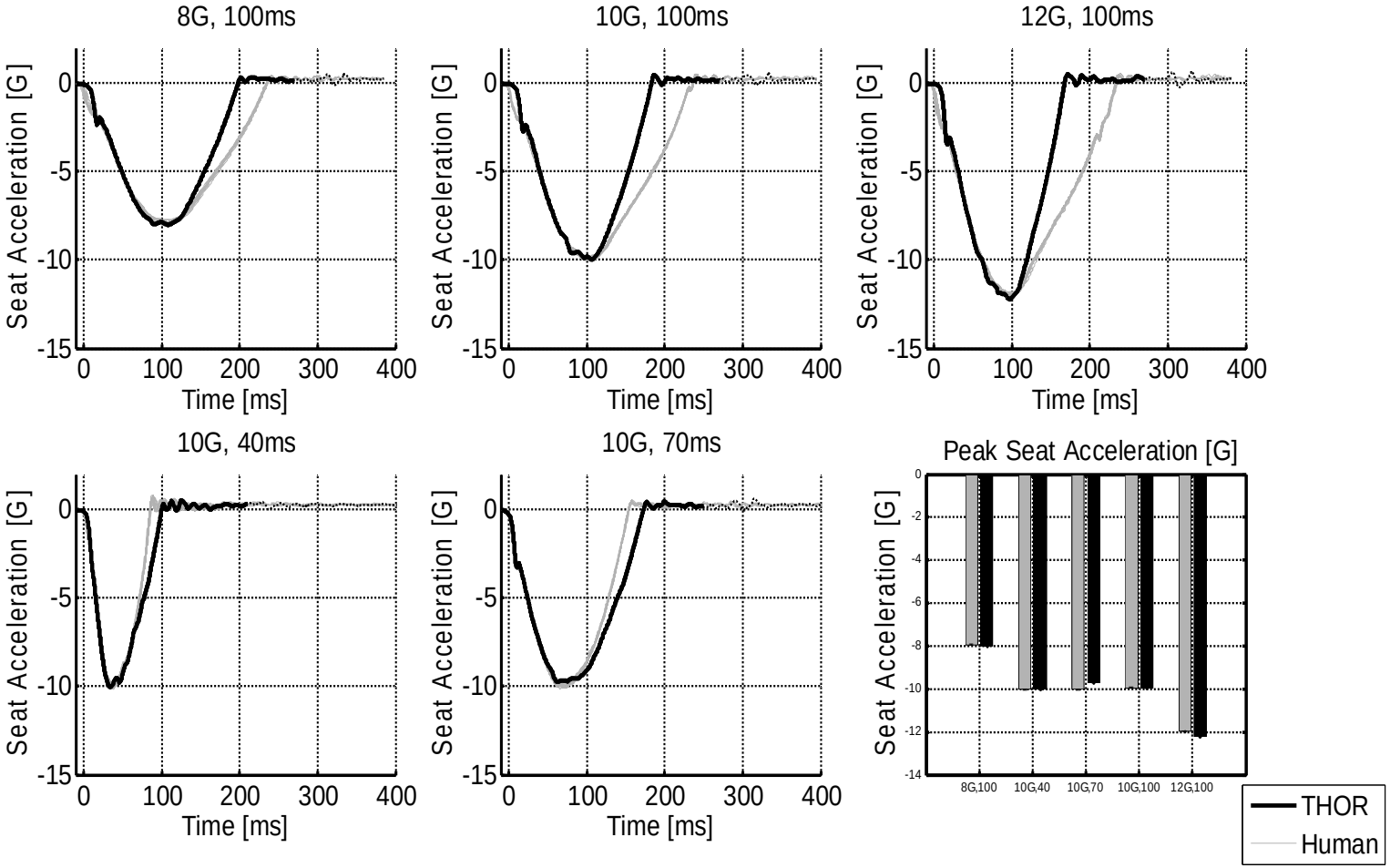


Figure 19. Seat acceleration time histories for THOR and humans for spinal (-z) impacts. Dotted line portions of the THOR trace indicate data that were not included in the time period of CORA analysis.

Results: Spinal Impacts

Head x-axis Acceleration

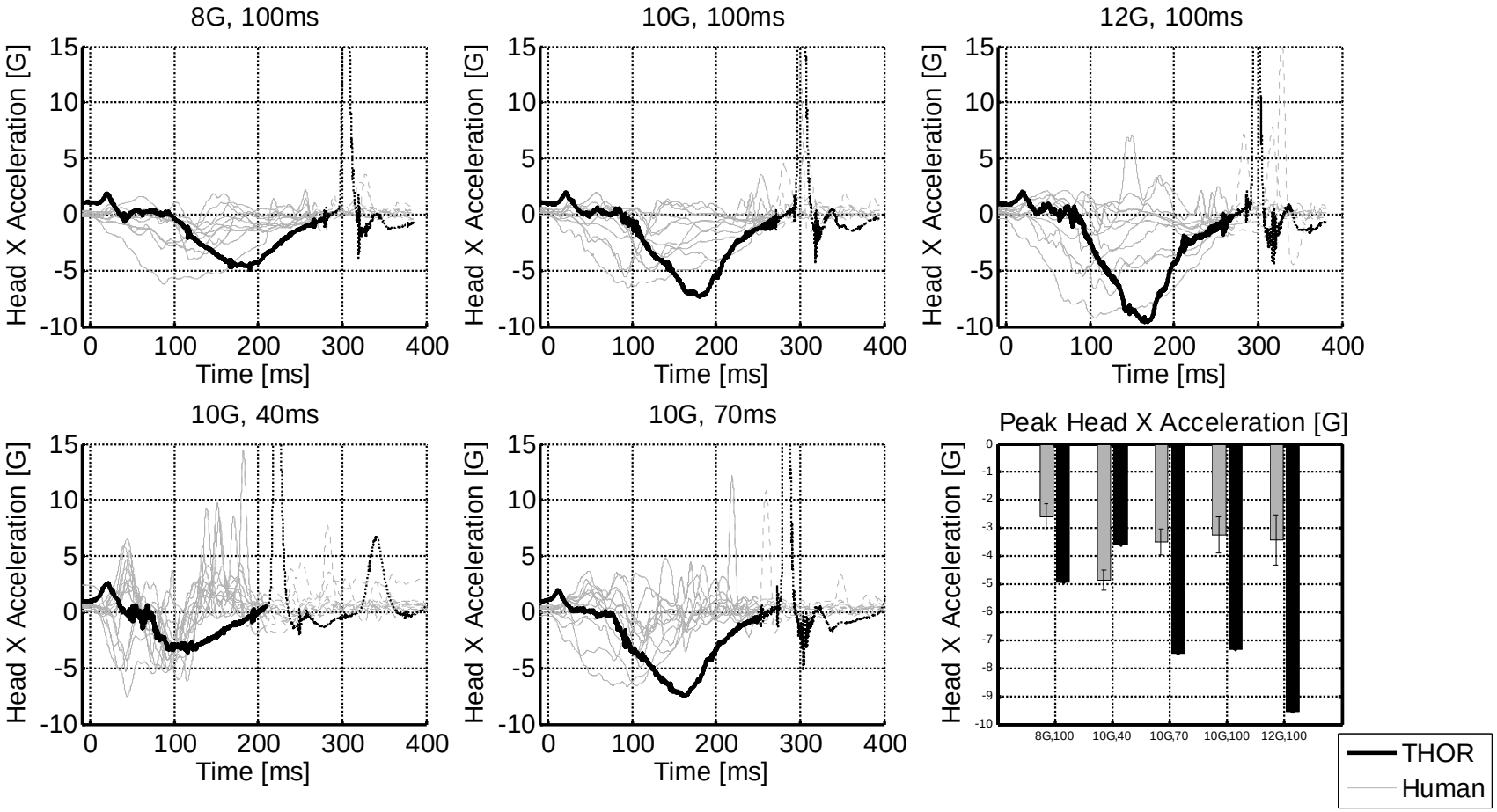


Figure 21. THOR and human head x-axis acceleration responses to spinal (-z) impacts. Dotted line portions of the THOR trace indicate data that were not included in the time period of CORA analysis.

Results: Spinal Impacts

Head z-axis Acceleration

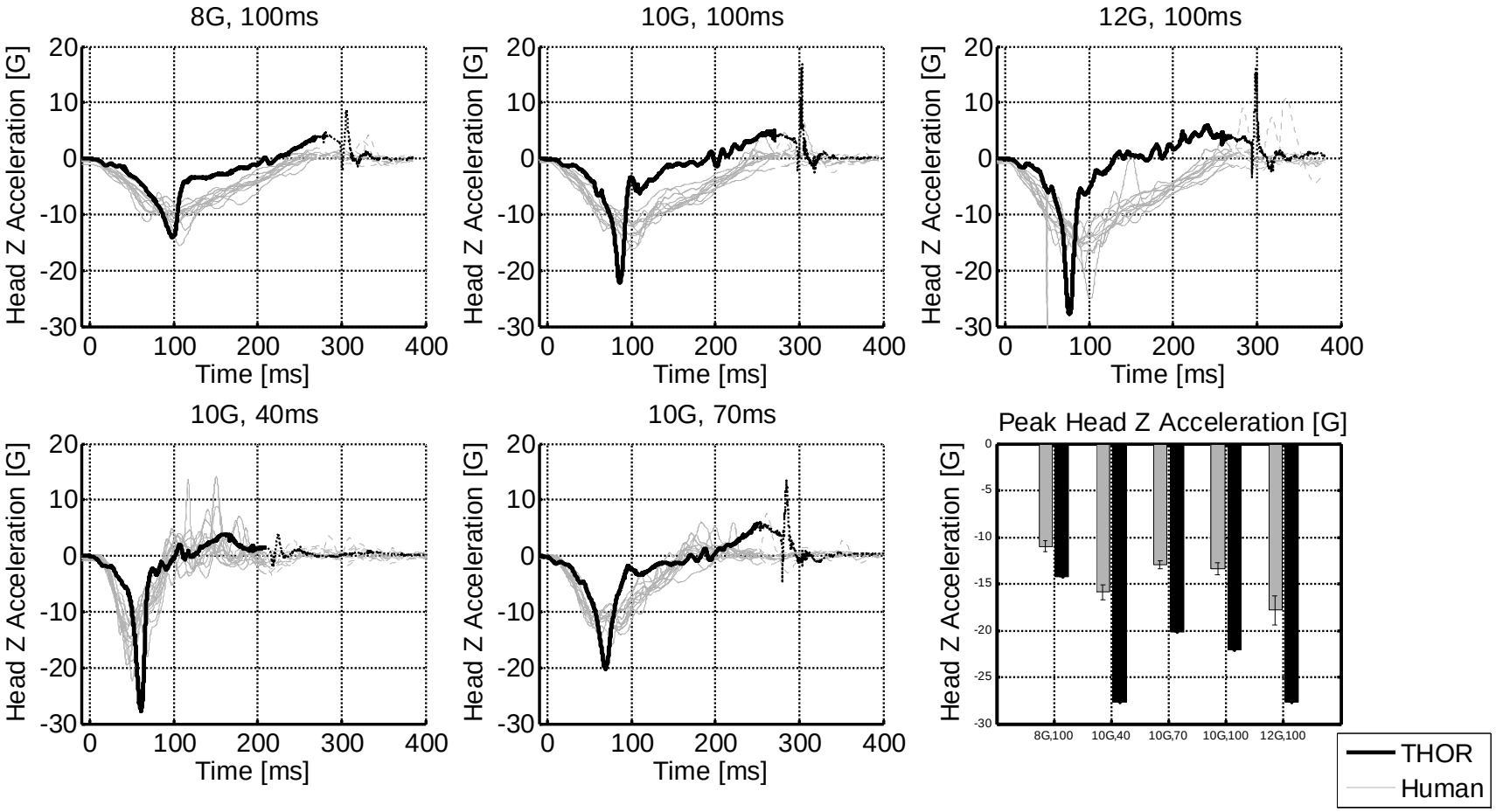


Figure 23. THOR and human head z-axis acceleration responses to spinal (-z) impacts. Dotted line portions of the THOR trace indicate data that were not included in the time period of CORA analysis.

Results: Spinal Impacts

Chest z-axis Acceleration

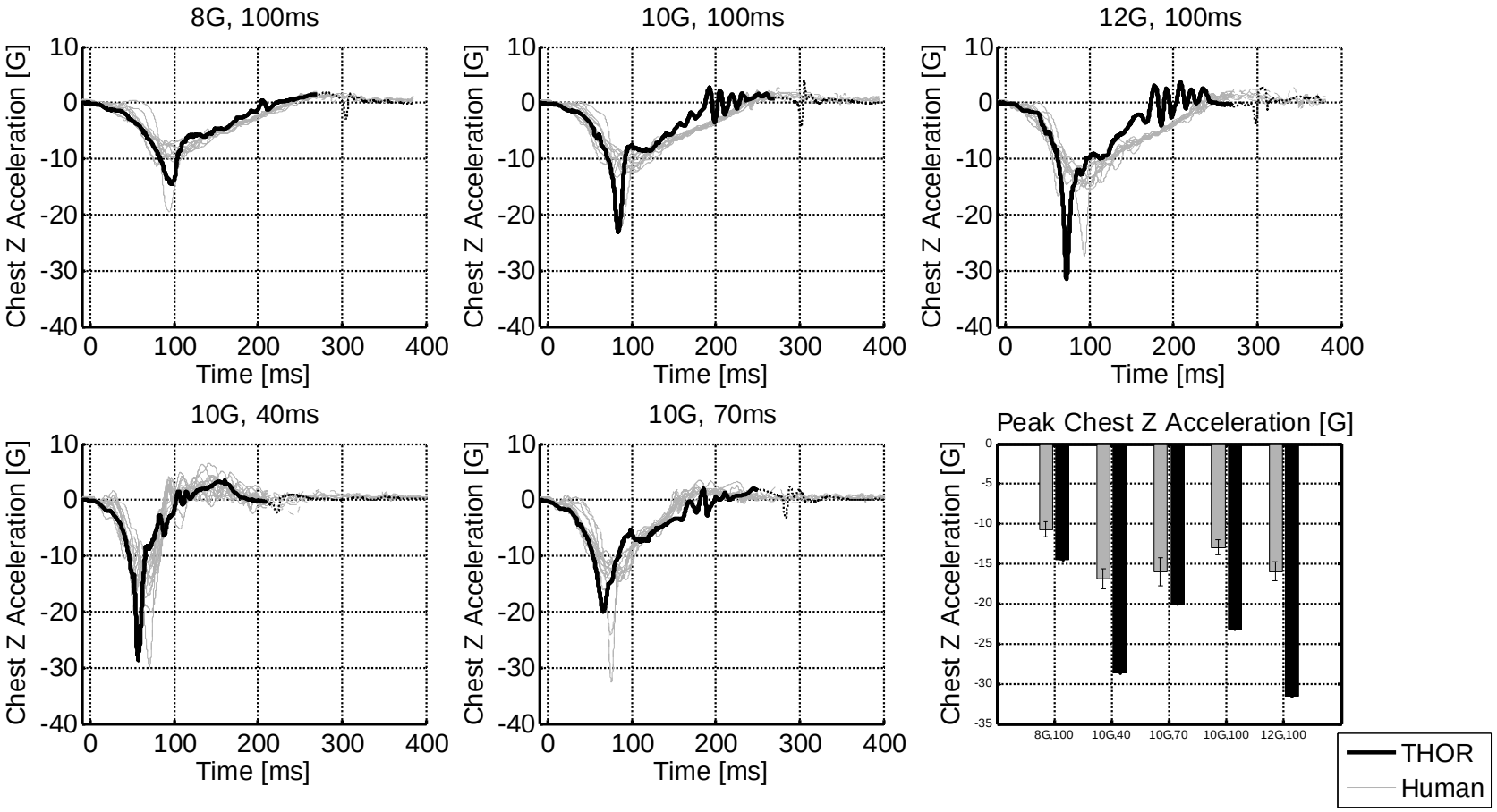


Figure 25. THOR and human chest z-axis acceleration responses to spinal (-z) impacts. Dotted line portions of the THOR trace indicate data that were not included in the time period of CORA analysis.

Results: Spinal Impacts

Shoulder z-axis Displacement

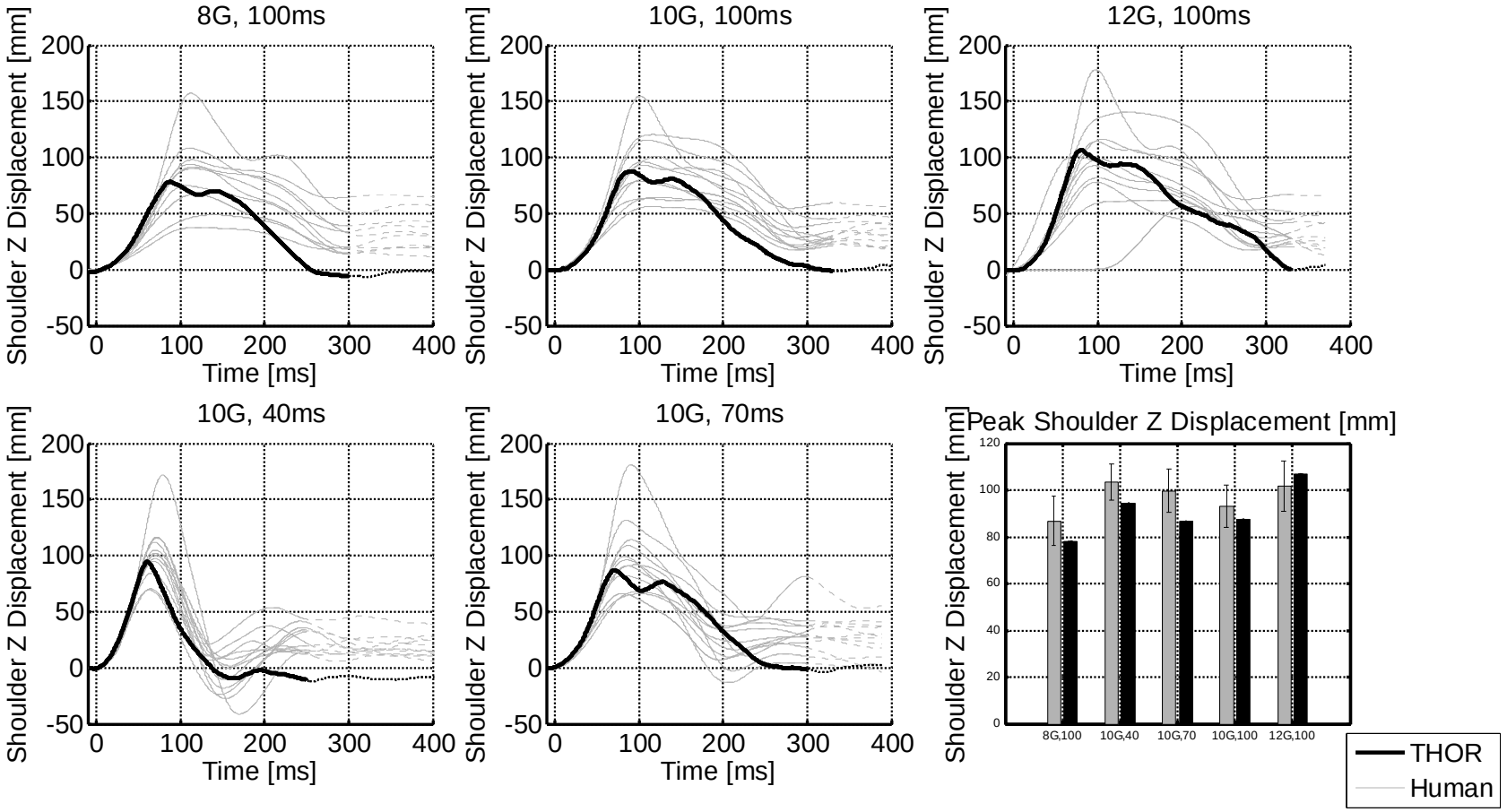


Figure 31. THOR and human shoulder z-axis displacement responses to spinal (-z) impacts. Dotted line portions of the THOR trace indicate data that was not included in the time period of CORA analysis.

Results: Spinal Impacts

Head x-axis Displacement

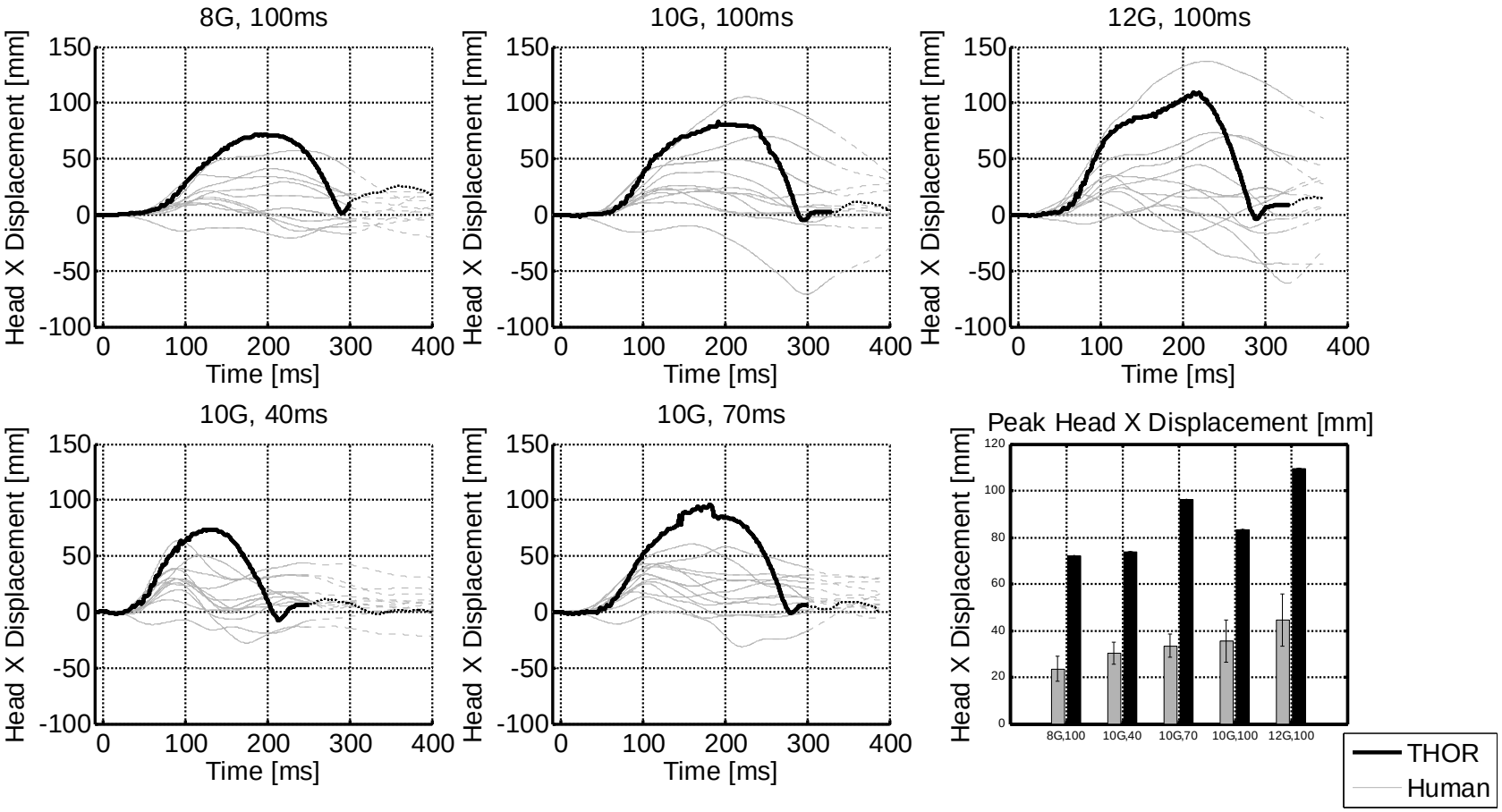


Figure 27. THOR and human head x-axis displacement responses to spinal (-z) impacts. Dotted line portions of the THOR trace indicate data that were not included in the time period of CORA analysis.

Results: Spinal Impacts

Head z-axis Displacement

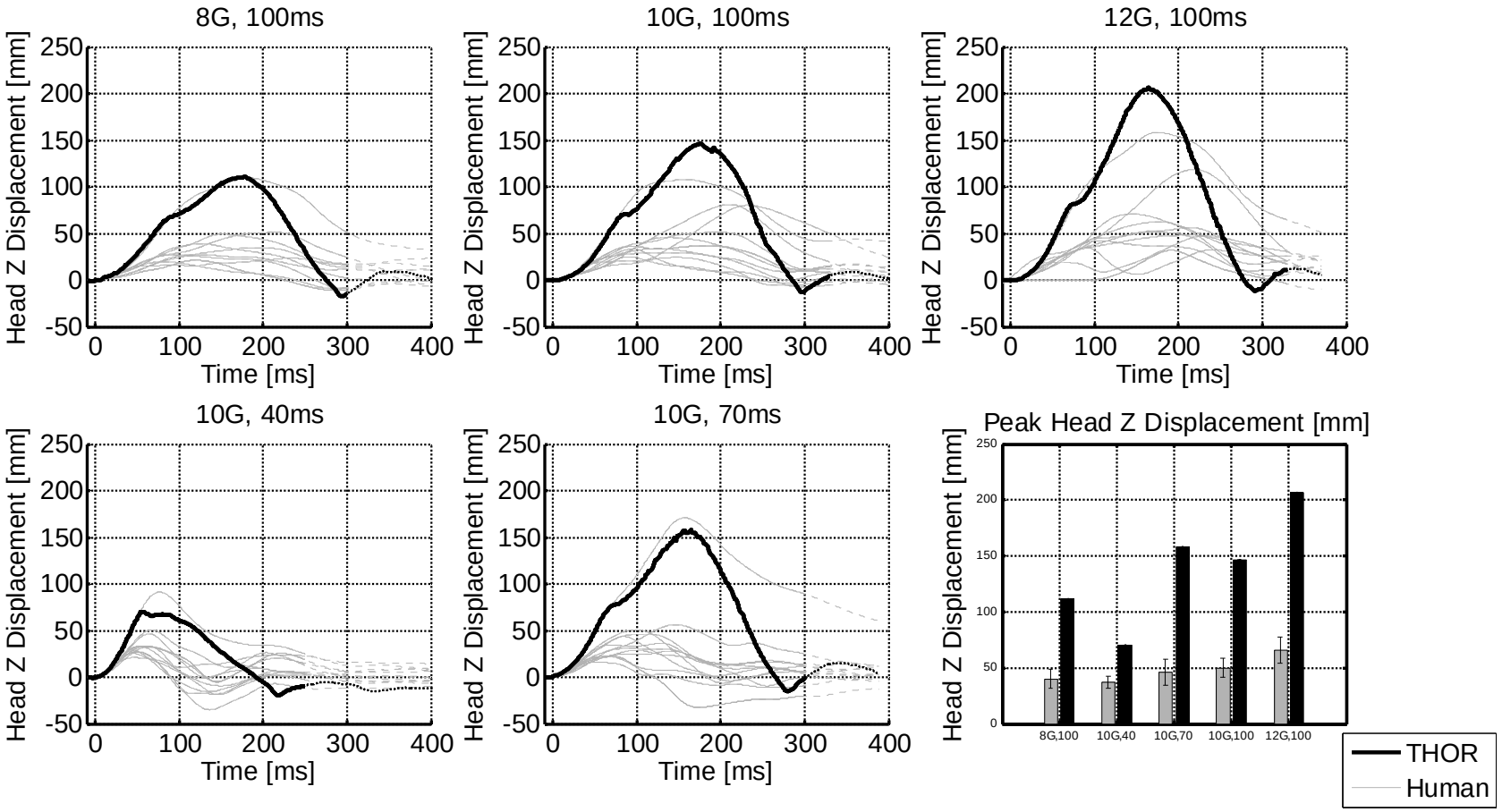


Figure 29. THOR and human head z-axis displacement responses to spinal (-z) impacts. Dotted line portions of the THOR trace indicate data that were not included in the time period of CORA analysis.

Results: Spinal Impacts

Seat pan Force

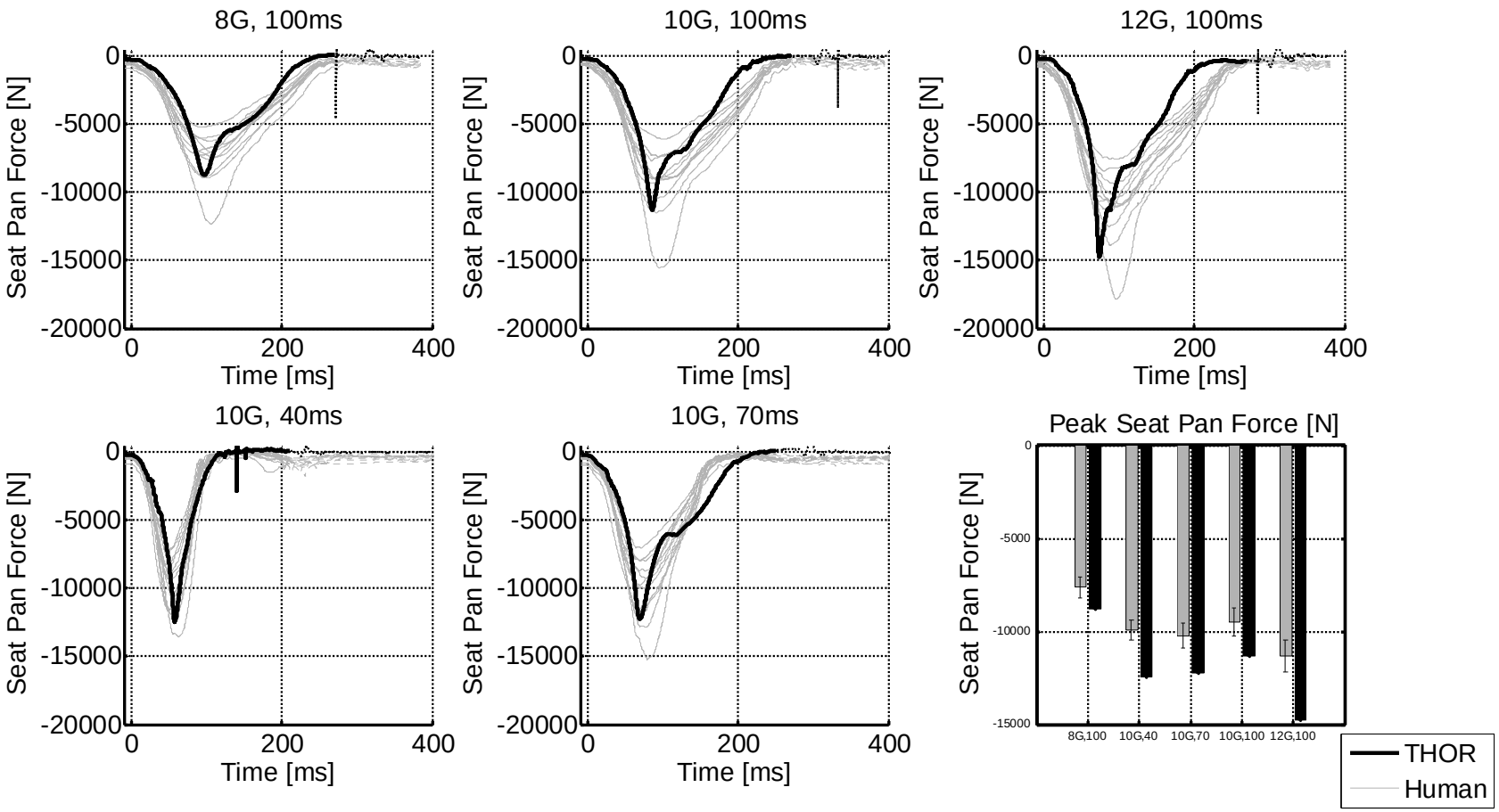


Figure 33. THOR and human seat pan force reactions to spinal (-z) impacts. Dotted line portions of the THOR trace indicate data that were not included in the time period of CORA analysis.