NHTSA

NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION

Evaluation of sex specific abdominal injury risk functions

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Background

- Abdominal injuries in motor vehicle crashes
  - Nearly 15,000 occupants sustain AIS 2+ abdominal injuries each year [Klinich 2010]
  - Spleen and liver are most frequently injured for drivers, while jejunum-ileum, spleen and liver for front passengers [Frampton 2012]

- In PMHS testing, several measurements have been correlated to abdominal injury
  - Compression, C_{max}
  - Force, F_{max}
  - $F_{max}C_{max}$
  - Velocity, V_{max}
  - $V_{max}C_{max}$
  - VC_{max}

Background

- PMHS Abdominal Injury Criterion ($AIC_{PMHS}=V_{max}*C_{max}$)
  - Best predictor of AIS3+ abdominal injury [Rouhana 1985, 2010; Ramachandra 2016]
- Difficulty in measuring velocity and compression in the soft abdomen component in an ATD
  - Abdomen Pressure Twin Sensors (APTS) in ATD abdomen (THOR-05F, LODC, Q-series)
- Abdominal pressure-based metrics correlated with injury [Sparks 2007, Kremer 2011, Ramachandra 2016]
  - Maximum rate of pressure change ($\dot{P}_{max}$)
  - Product of the maximum pressure and maximum rate of pressure change ($P_{max}*\dot{P}_{max}$)

Motivation

- Abdomen injury risk functions evaluated in our previous studies included both male and female PMHS
  - Other abdomen studies included more male than female PMHS [Hardy 2001, Foster 2006, Lamielle 2008]
  - Need for more female PMHS abdomen data
- Females may be at greater risk of AIS 2+ and AIS 3+ injury compared to males in identical accident scenarios [Forman 2019, Kahane 2013, Parenteau 2013]
  - It is unknown if higher risk to females, specifically to abdominal organs, is related to injury tolerance or mechanism leading to injuries, such as submarining
- THOR 5^{th} Female vs 50^{th} Male
  - Determine if we can use same IRFs or metrics for both dummies

Objective

I. Measure biomechanical responses of small female PMHS subjected to abdominal loading

- Belt-pull and rigid bar impact

II. Evaluate sex specific abdominal injury risk functions

- Update and expand upon previously created IRFs [Ramachandra 2016]

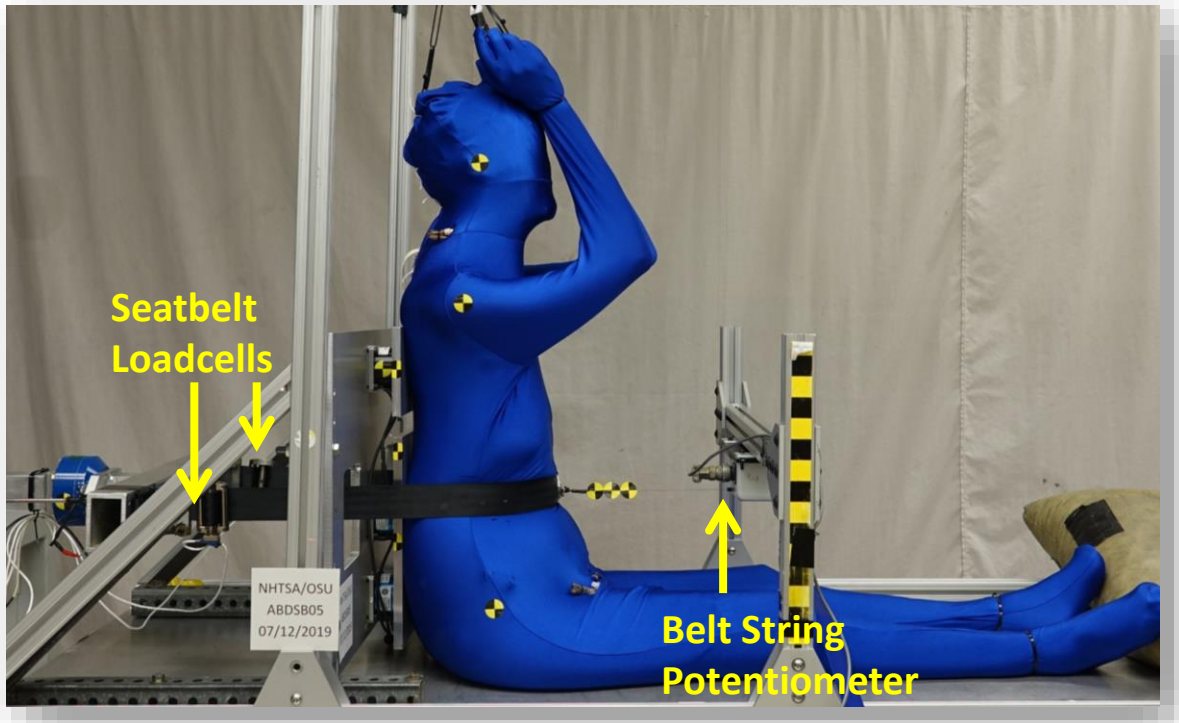
Content Warning

The following slides include cadaveric images that are graphic and may be considered disturbing to some viewers!

Methods – Test Setup

Belt loading

- Fixed-back upright configuration
- Mid-abdominal
- Approximately 4 m/s
- Non-injurious and Injurious (3 each)
  - Non-injurious: 27% compression [Lamielle 2008]
  - Injurious: 50% compression
- Perfused abdominal vasculature



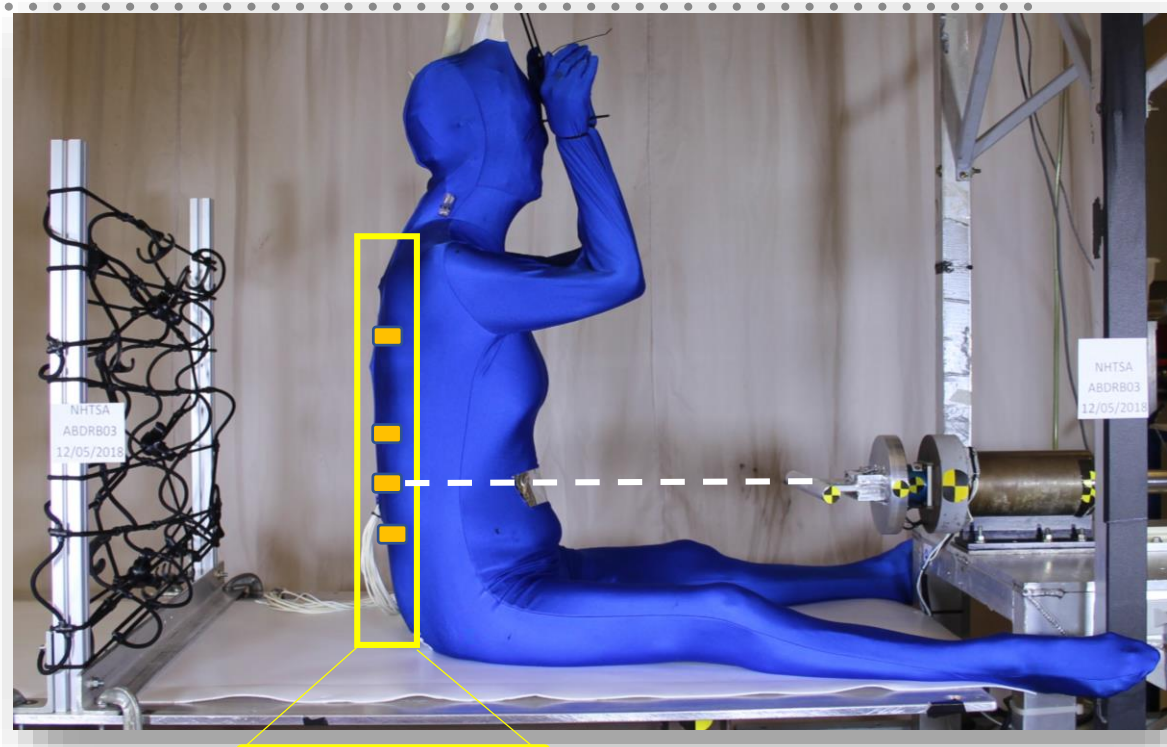
Abdomen Penetration

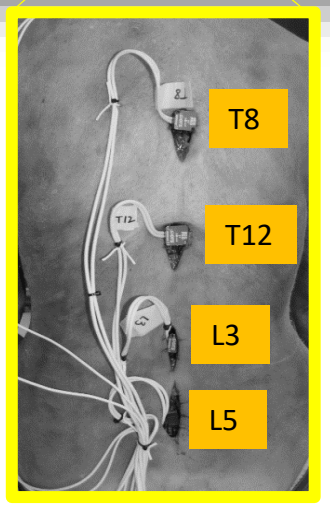
$$\delta_{Abd} = \delta_{Belt}$$

Methods – Test Setup

Rigid bar loading

- Free-back upright configuration
- Mid-abdominal
- Impactor: 23kg, 2.5cm diameter
- Approximately 6 m/s
- Non-injurious (3)
- Perfused abdominal vasculature

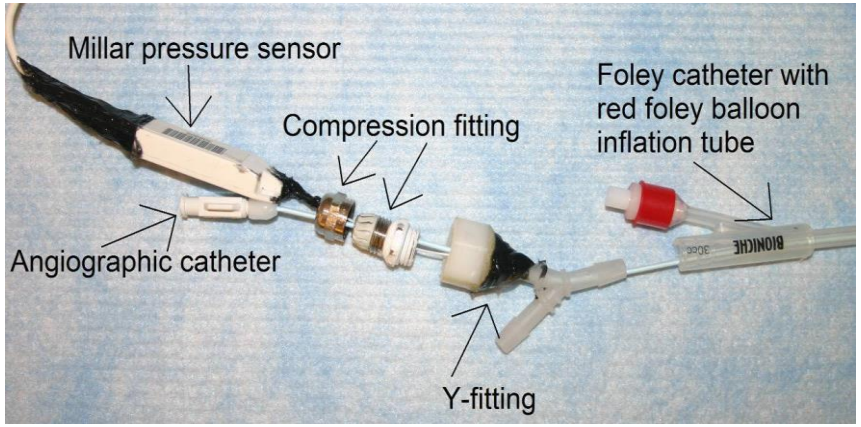




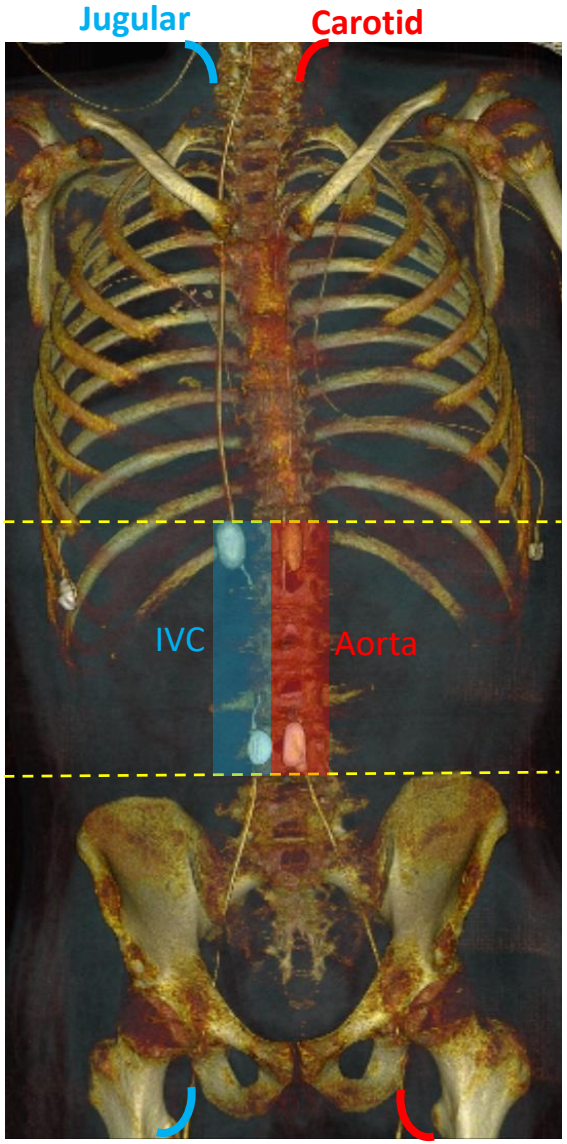
Abdomen Penetration

$$\delta_{Abd} = \delta_{Ram} - \iint a_{X(L3)}$$

Methods – Vascular Instrumentation



Foley balloon and pressure transducers



Superior

Diaphragm

Bifurcation to common iliac a. and v.

Inferior

Kremer 2011, Ramachandra 2016

Methods – Data Processing

- Time zero
  - 0.5g acceleration of the pneumatic ram [belt pull]
  - Contact switch [rigid bar]
- Filtering
  - Standard SAE-J211
  - Channel filter classes (CFC) 60 to 180
- Normalization approach
  - Equal stress equal velocity [Eppinger, 1976]

Methods – Injury Metrics

Injury Metrics	Belt-pull Tests	Rigid Bar Tests
V_{max}	Max. belt penetration velocity	Max. impact velocity
C_{max}	Max. compression = Max. abdomen penetration/depth	
F_{max}	Max. belt force (sum of left and right)	Max. inertially compensated bar force
$(VC)_{max}$	Viscous Criterion, Max. value of product of velocity and compression	
$V_{max} * C_{max}$	Abdominal Injury Criterion, AIC, Product of V_{max} and C_{max}	
$F_{max} * C_{max}$	Product of F_{max} and C_{max}	
P_{max}	Max. pressure in abdominal vasculature (positive maximum)	
$\dot{P}_{max}$	Max. rate of pressure change in abdominal vasculature	
$P_{max} * \dot{P}_{max}$	Product of P_{max} and $\dot{P}_{max}$	

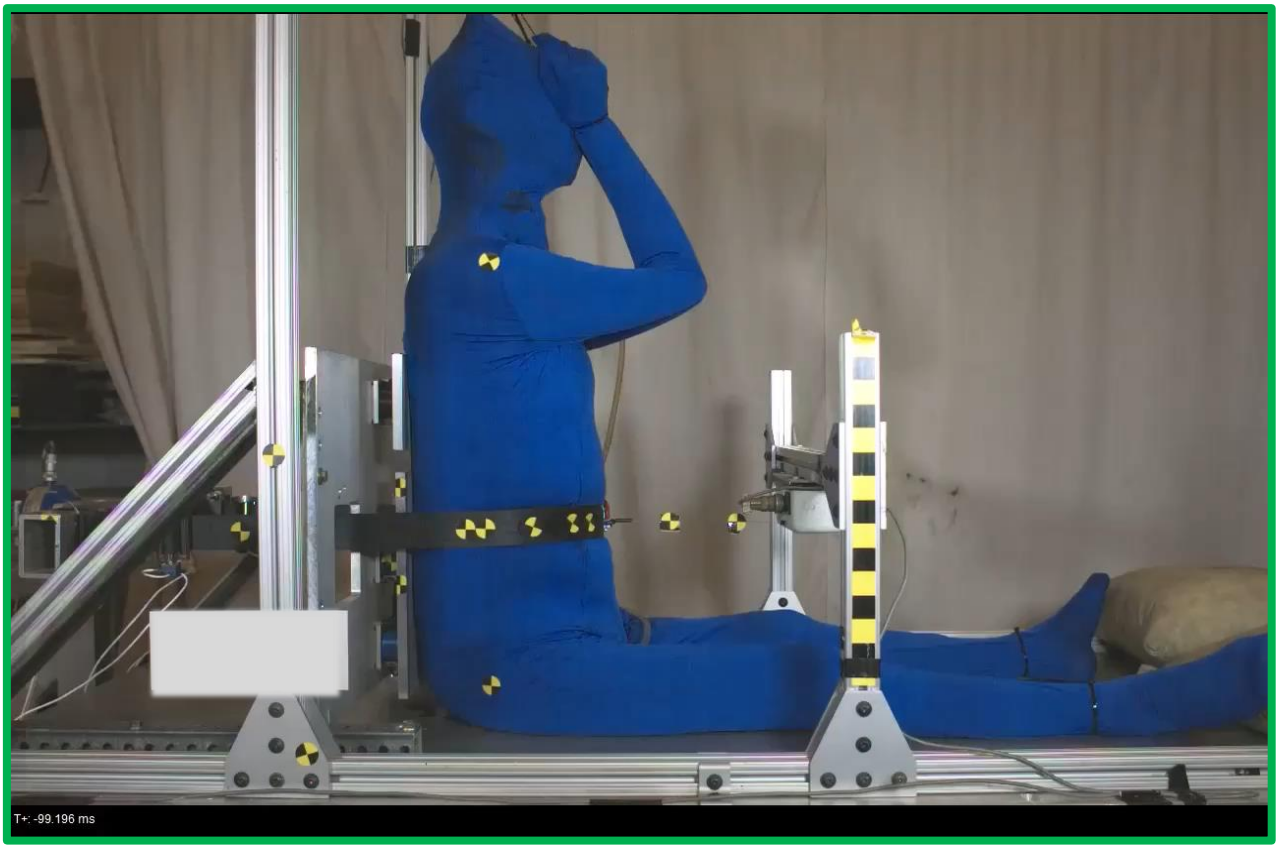
Results – Subject Information

Nine PMHS obtained through The Ohio State University's Body Donor Program

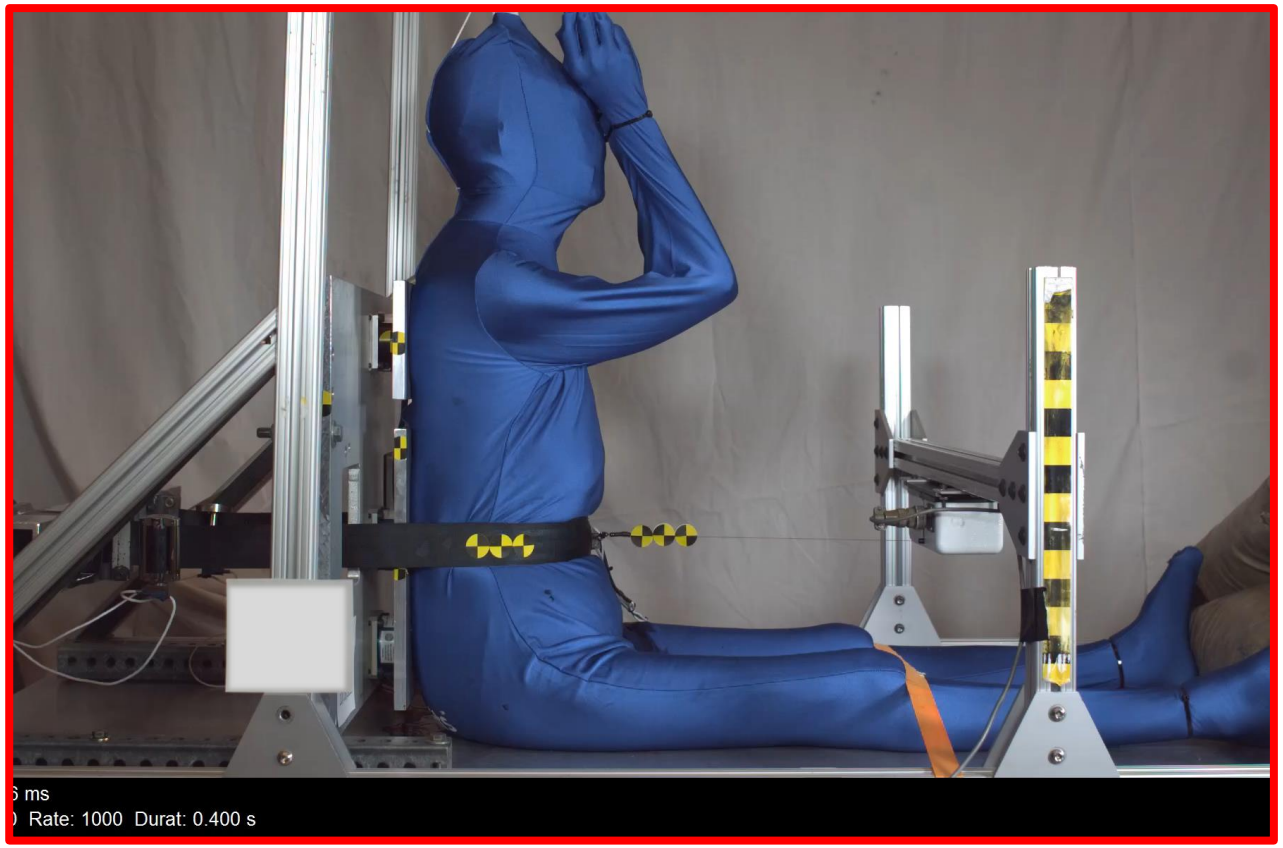
- Fresh never frozen (within 72 to 120 hours)
  - Except ABDSB01, fresh frozen

Test	Test Condition	Age/Sex	Mass (kg)	Stature (cm)	Abd C'ference (cm)	Seated Abd Depth (cm)	BMI (kg/m^2)
ABDSB01	Fixed Back Belt	38F	54	172.0	72.5	21.8	18.3
ABDSB02	Fixed Back Belt	73M	61	175.0	76.0	20.5	21.6
ABDSB03	Fixed Back Belt	86F	43	154.5	71.5	26.5	18.0
ABDSB05	Fixed Back Belt	83F	55	175.5	68.0	21.8	17.9
ABDSB06	Fixed Back Belt	95F	55	156.0	90.0	25.0	22.6
ABDSB07	Fixed Back Belt	102F	37	152.4	60.8	21.2	15.9
ABDRB01	Rigid Bar	80F	61	165.1	81.0	24.3	22.3
ABDRB02	Rigid Bar	77F	45	160.0	73.5	18.5	17.6
ABDRB03	Rigid Bar	57F	51	159.0	78.5	23.3	20.2
Average ± 1 Std Dev		**77±19.5**	**51±8.1**	**163.3±9.0**	**74.6±8.3**	**22.5±2.5**	**19.3±2.4**
THOR-05F			*50*	*151.0*	*86.5*	*22.5*	*21.9*

Results – Belt Pull Video



Non-injurious



Injurious

Results – Belt Pull

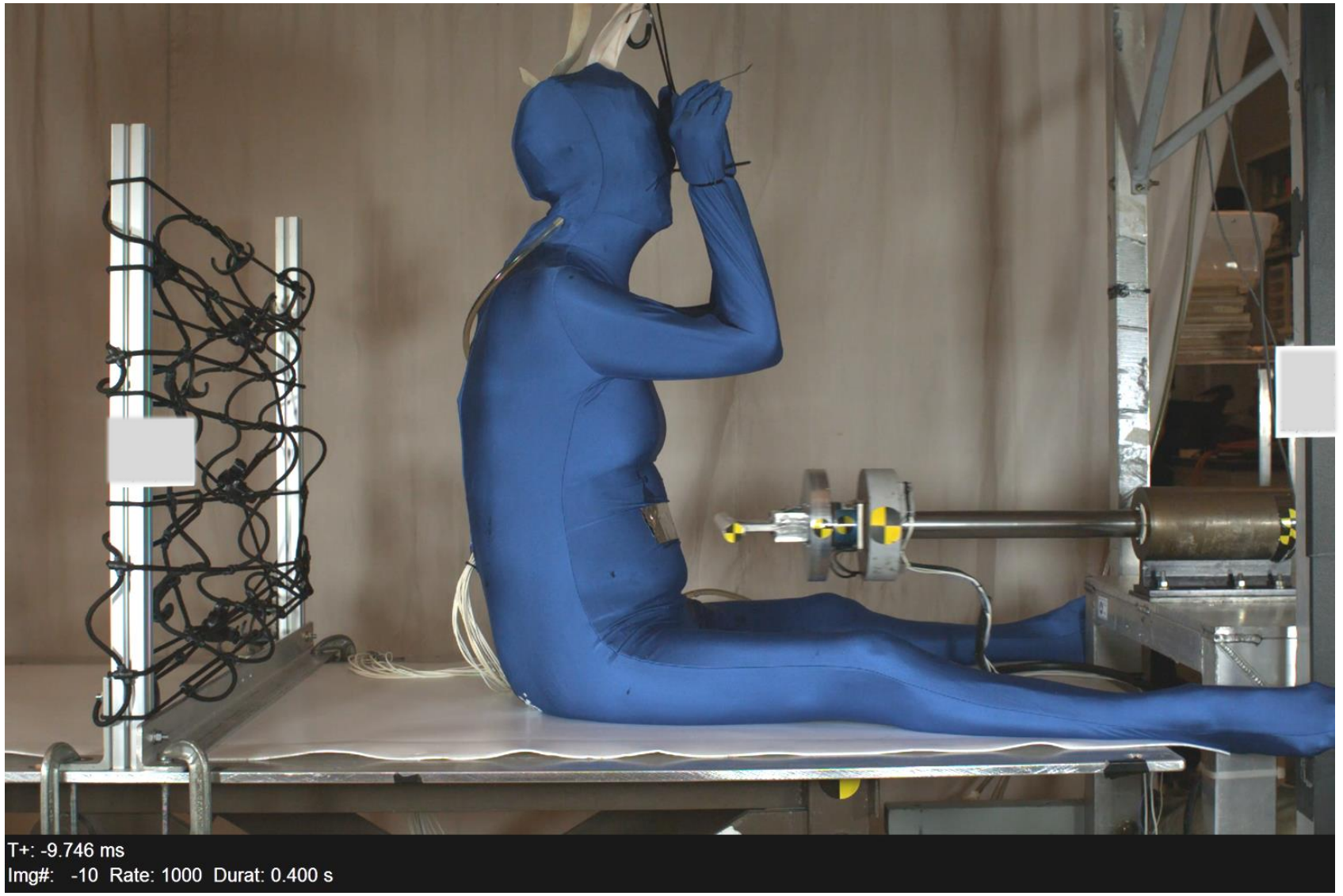
Test	V_{max}	C_{max}	F_{max}	$(VC)_{max}$	$V_{max} * C_{max}$	$F_{max} * C_{max}$	P_{max}	$\dot{P}_{max}$	$P_{max} * \dot{P}_{max}$	Abdominal Damages (AIS Severity)
	m/s	*%*	*kN*	*m/s*	*m/s*	*kN*	*kPa*	*kPa/ms*	*kPa^2/ms*	*Description*
ABDSB01	4.10	34	2.45	1.22	1.39	0.08	99.2	8.02	795.6	None
ABDSB02	3.68	30	2.67	0.94	1.10	0.08	50.4	3.58	180.4	None
ABDSB03	3.12	26	1.93	0.74	0.81	0.05	53.3	4.91	261.7	None
ABDSB05	3.28	45	4.3	0.83	1.48	0.19	104.5	5.80	606.1	Ruptured kidney (4) Partial tear jejunum (3) Splenic capsule tear (2)
ABDSB06	3.78	50	4.88	1.1	1.89	0.24	127.5	12.90	1644.8	Ruptured kidney (4) Full tear ileum (4) Full tear duodenum (4) Partial tear jejunum (3)
ABDSB07	3.12	36	5.45	1.04	1.12	0.20	245.0	31.50	7717.5	None
Average	**3.85**	**37**	**3.61**	**0.98**	**1.30**	**0.14**	**113.3**	**11.12**	**1867.7**	
1 Std Dev	**0.40**	**9.1**	**1.45**	**0.18**	**0.37**	**0.07**	**71.2**	**10.50**	**2913.3**	

Results – Belt Pull

Test	V_{max}	C_{max}	F_{max}	$(VC)_{max}$	$V_{max} * C_{max}$	$F_{max} * C_{max}$	P_{max}	$\dot{P}_{max}$	$P_{max} * \dot{P}_{max}$	Abdominal Damages (AIS Severity)
	m/s	*%*	*kN*	*m/s*	*m/s*	*kN*	*kPa*	*kPa/ms*	*kPa^2/ms*	*Description*
ABDSB01	4.10	34	2.45	1.22	1.39	0.08	99.2	8.02	795.6	None
ABDSB02	3.68	30	2.67	0.94	1.10	0.08	50.4	3.58	180.4	None
ABDSB03	3.12	26	1.93	0.74	0.81	0.05	53.3	4.91	261.7	None
ABDSB05	3.28	45	4.3	0.83	1.48	0.19	104.5	5.80	606.1	Ruptured kidney (4) Partial tear jejunum (3) Splenic capsule tear (2)
ABDSB06	3.78	50	4.88	1.1	1.89	0.24	127.5	12.90	1644.8	Ruptured kidney (4) Full tear ileum (4) Full tear duodenum (4) Partial tear jejunum (3)
~~ABDSB07~~	~~3.12~~	~~36~~	~~5.45~~	~~1.04~~	~~1.12~~	~~0.20~~	~~245.0~~	~~31.50~~	~~7717.5~~	None
Average	**3.59**	**37**	**3.25**	**0.97**	**1.33**	**0.13**	**86.9**	**7.04**	**697.7**	
1 Std Dev	**0.39**	**10.1**	**1.27**	**0.19**	**0.40**	**0.08**	**33.8**	**3.65**	**585.8**	

ABDSB07 was determined to be an outlier based on Grubbs test, and therefore was not included in further analyses

Results – Rigid Bar Video



Results – Rigid Bar

Test	V_{max}	C_{max}	F_{max}	$(VC)_{max}$	$V_{max} * C_{max}$	$F_{max} * C_{max}$	P_{max}	$\dot{P}_{max}$	$P_{max} * \dot{P}_{max}$	Abdominal Damages (AIS Severity)
	m/s	*%*	*kN*	*m/s*	*m/s*	*kN*	*kPa*	*kPa/ms*	*kPa^2/ms*	*Description*
ABDRB01	5.94	49	1.45	1.73	2.99	0.71	43.4	2.52	109.4	None
ABDRB02	5.88	38	1.07	1.56	2.25	0.41	24.7	2.88	71.1	None
ABDRB03	6.12	40	1.08	1.66	2.35	0.43	17.6	5.47	96.3	None
Average	**5.98**	**42**	**1.20**	**1.65**	**2.53**	**0.52**	**28.6**	**3.63**	**92.3**	
1 Std Dev	**0.12**	**5.8**	**0.21**	**0.08**	**0.40**	**0.16**	**13.3**	**1.60**	**19.4**	

Objective

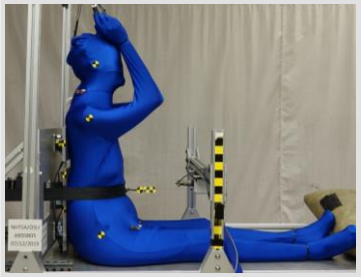
I. Measure biomechanical responses of small female PMHS subjected to abdominal loading

- Belt-pull and rigid bar impact

II. Evaluate sex specific abdominal injury risk functions

- Update and expand upon previously created IRFs [Ramachandra 2016]

Abdomen Test Data Summary

PMHS	Oblique Hub	Lateral Hub	Belt Free Back	Belt Fixed Back	Rigid Bar	Total
	 Kremer 2011	 Kremer 2011	 Ramachandra 2016	 Ramachandra 2021*	 Ramachandra 2021*	
Male	2	3	5	1	0	**11**
Female	3	2	2	4	3	**14**
Total	**5**	**5**	**7**	**5**	**3**	**25**

** Technical paper under construction*

Methods – Overview

- Statistical analysis of updated dataset
  - Compare injury metrics [Studentized T-tests]
    - AIS2+ vs. AIS3+
    - Male only vs. Female only vs. Combined Male/Female
    - Non-injurious vs. injurious
- Injury risk function development and comparison
  - Reliability/survival analyses
    - Identify best model fit for the predictor variables

Results – Statistical Analyses

	V_{max}	C_{max}	F_{max}	$(VC)_{max}$	V_{max}* C_{max}	F_{max}* C_{max}	P_{max}	$\dot{P}_{max}$	P_{max}* $\dot{P}_{max}$
Female vs. Male AIS<2	0.550	0.971	**0.044**	0.408	0.574	0.414	0.087	0.458	0.331
Female vs. Male AIS≥2	0.811	0.989	0.439	0.578	0.731	**0.017**	0.471	0.976	0.687
Female AIS<2 vs. AIS≥2	0.697	0.700	**0.013**	0.194	0.925	0.713	0.058	**0.046**	0.102
Male AIS<2 vs. AIS≥2	0.245	0.732	0.261	0.949	0.450	0.733	0.265	0.463	0.309
Combined AIS<2 vs. AIS>2	0.238	0.585	**0.003**	0.301	0.653	0.509	**0.011**	**0.030**	**0.020**
Female vs. Male AIS<3	0.855	0.931	**0.009**	0.264	0.632	0.180	**0.023**	0.260	0.156
Female vs. Male AIS≥3	0.753	0.926	0.619	0.498	0.659	**0.034**	0.198	0.935	0.514
Female AIS<3 vs. AIS≥3	0.929	0.987	**0.028**	0.339	0.759	0.482	0.055	0.052	0.108
Male AIS<3 vs. AIS≥3	0.651	0.973	0.375	0.527	0.527	0.576	0.635	0.433	0.665
Combined AIS<3 vs. AIS>3	0.819	0.960	**0.011**	0.785	0.900	0.925	0.071	**0.041**	0.061

- Using two-tail T-test, assuming unequal variances
- Significance level = 0.05
- P-value < 0.05 indicates the means are different

Results – Female vs. Male

	V_{max}	C_{max}	F_{max}	$(VC)_{max}$	V_{max}* C_{max}	F_{max}* C_{max}	P_{max}	$\dot{P}_{max}$	P_{max}* $\dot{P}_{max}$
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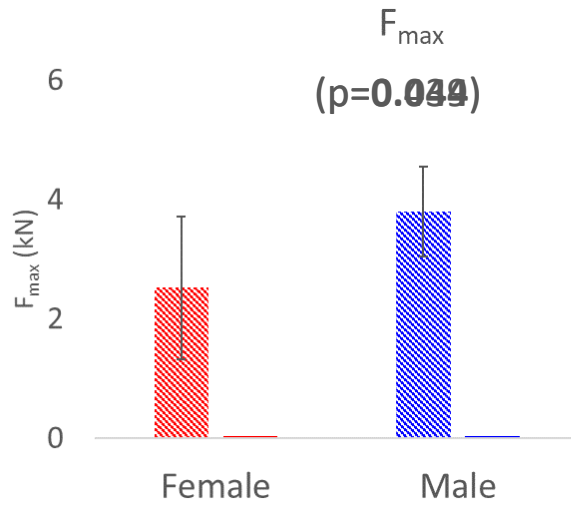
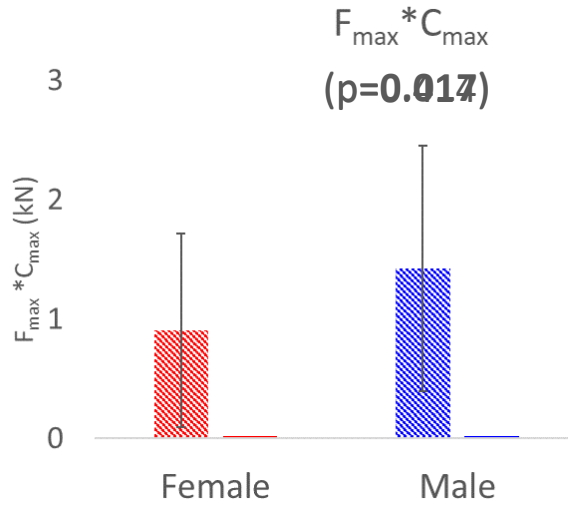
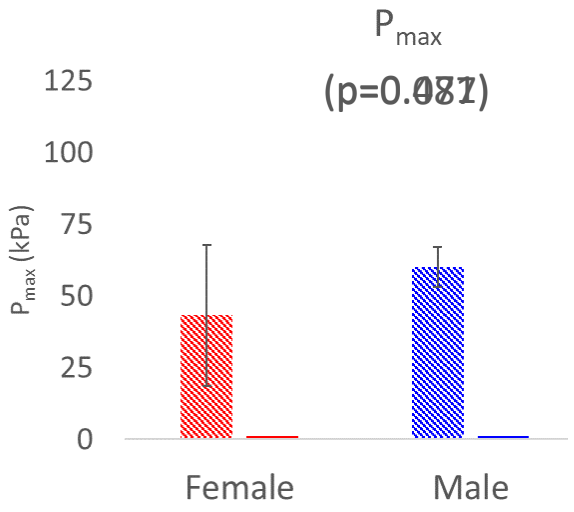
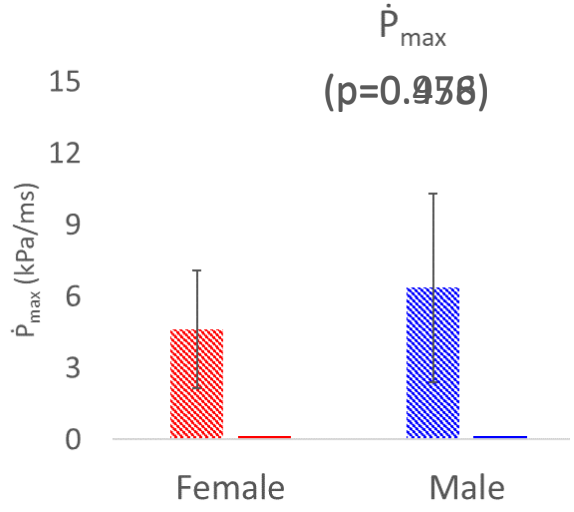
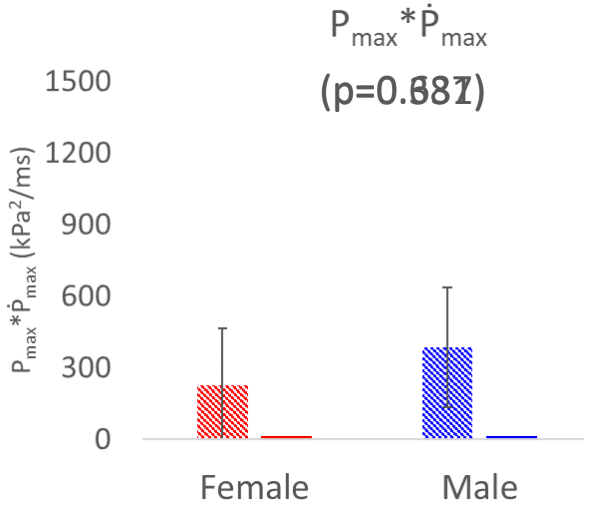


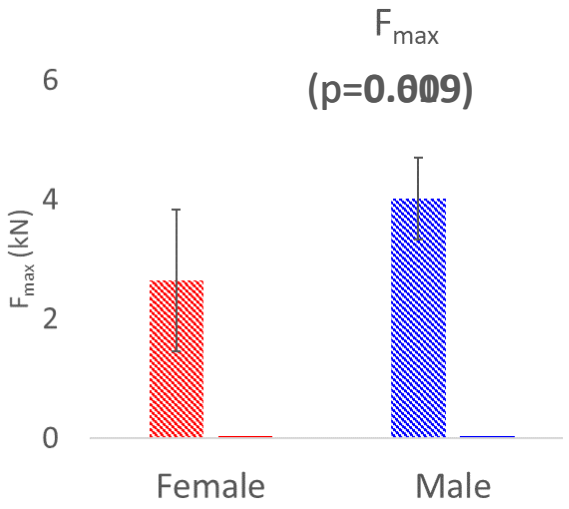


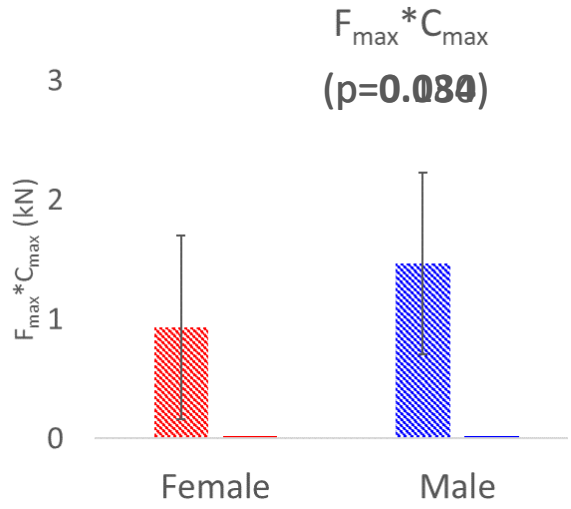


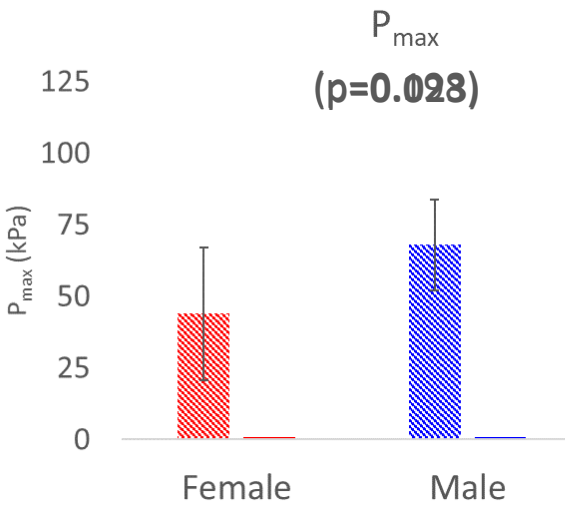


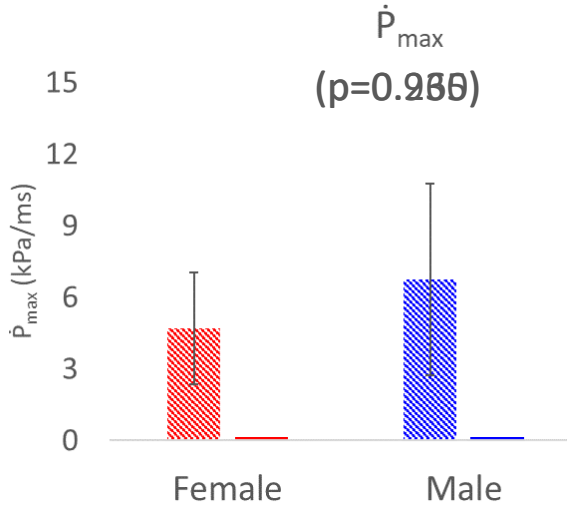


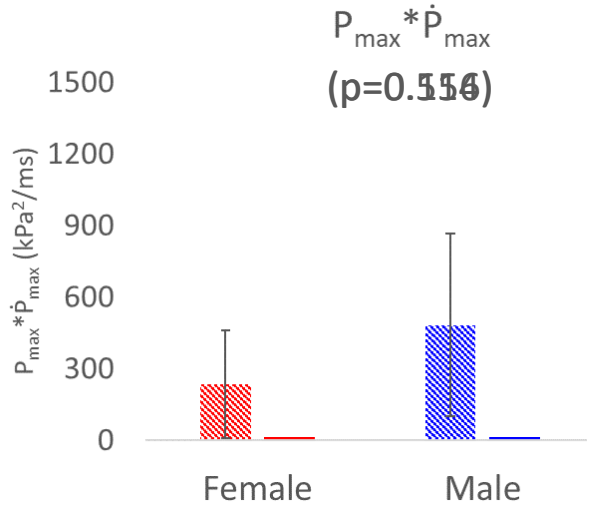
Results – Female vs. Male











Results – Injury vs. No-Injury

	V_{max}	C_{max}	F_{max}	$(VC)_{max}$	$V_{max}*C_{max}$	$F_{max}*C_{max}$	P_{max}	$\dot{P}_{max}$	$P_{max}*\dot{P}_{max}$
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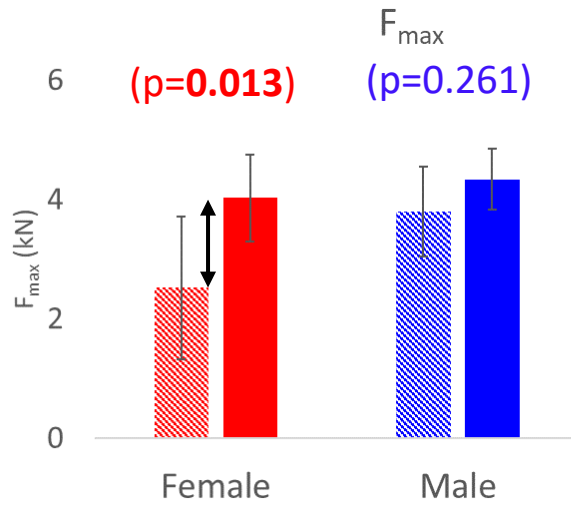
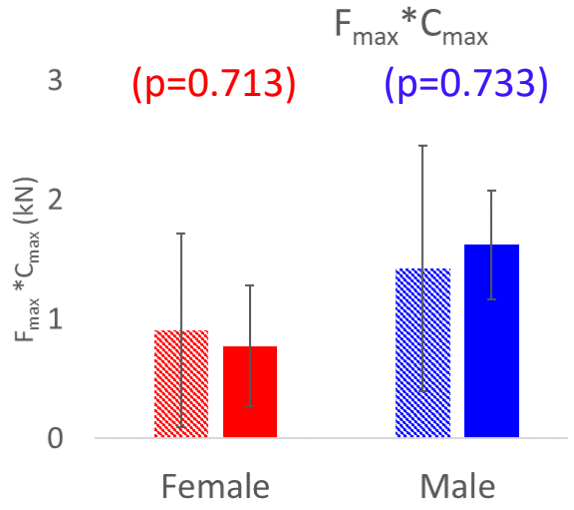
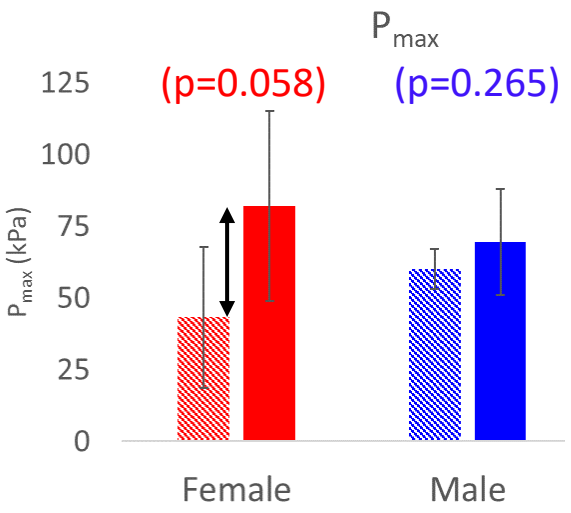
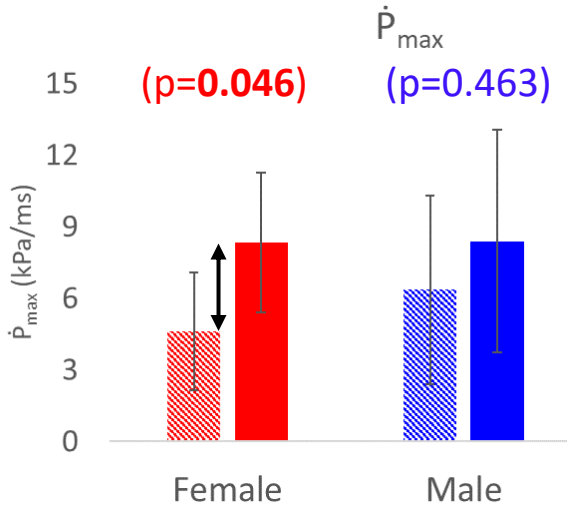
- P-value < 0.05 indicates the means are different

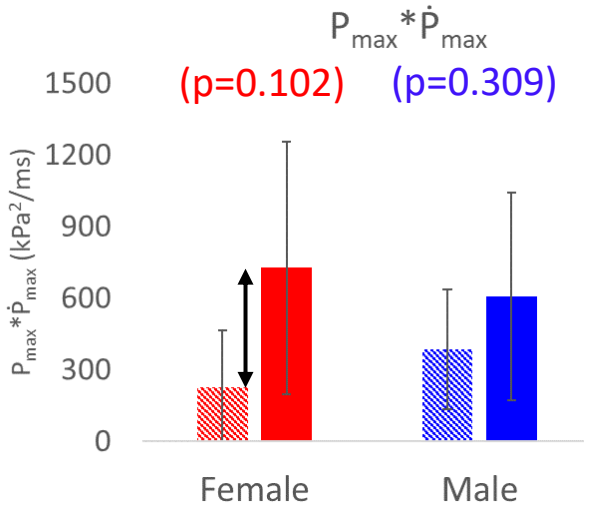
Results – Injury vs. No-Injury







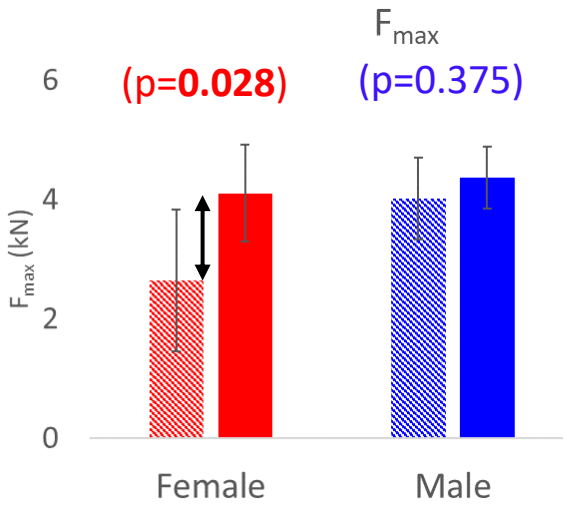


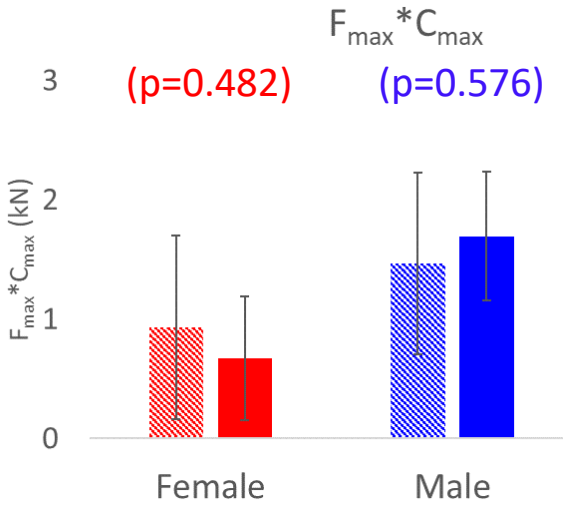


AIS<2

AIS≥2

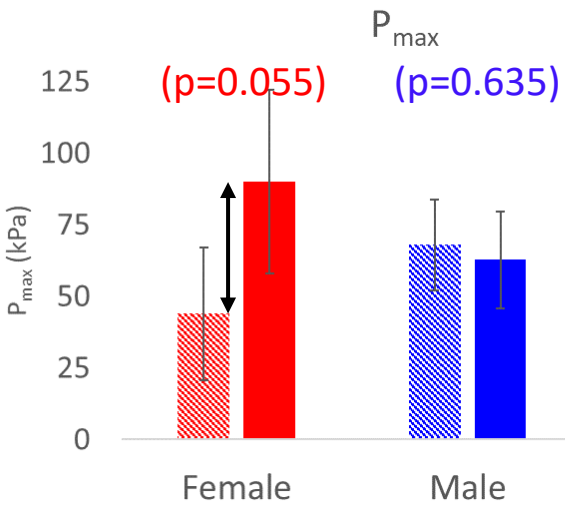
Results – Injury vs. No-Injury

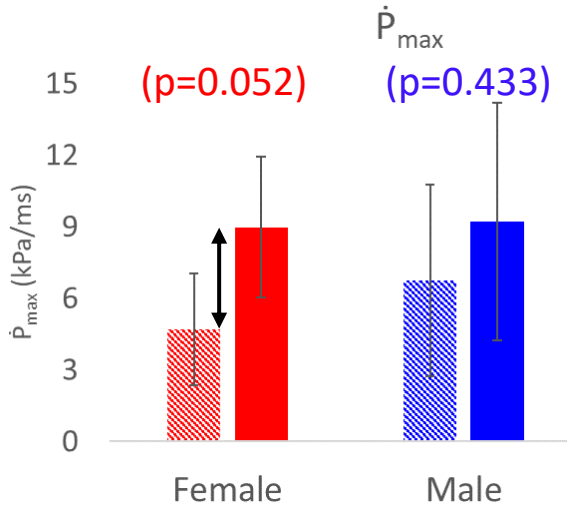


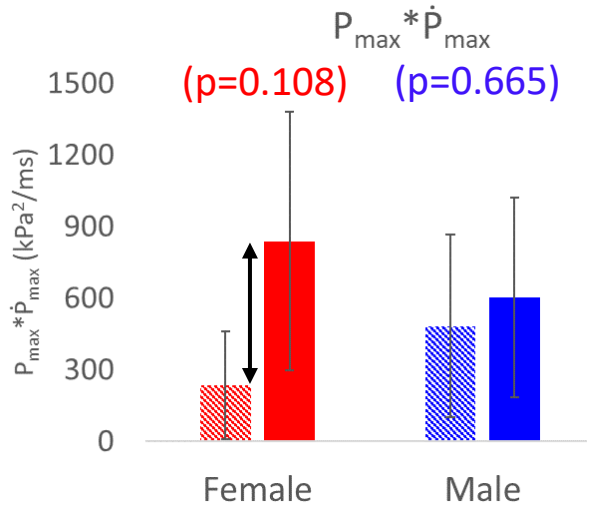


AIS<3

AIS≥3





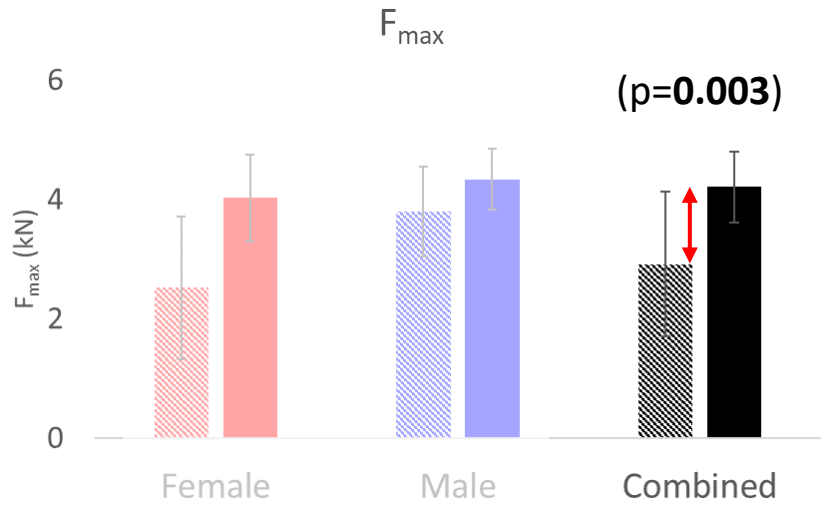


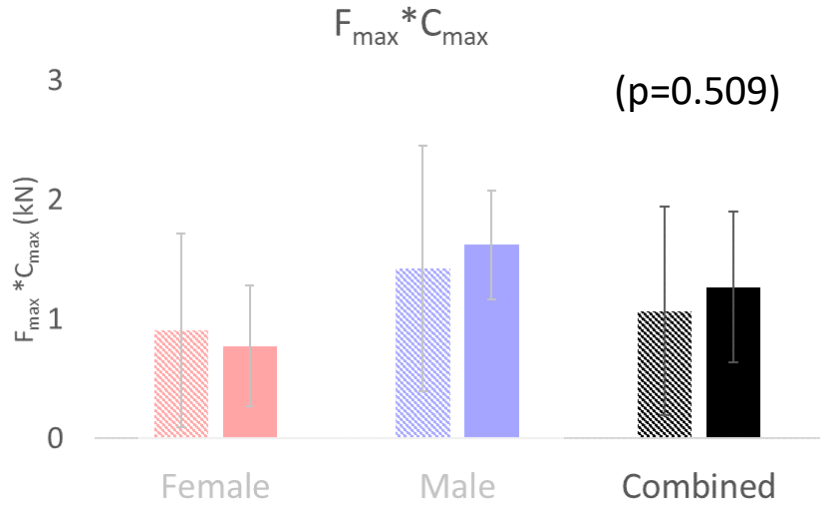
Results – Injury vs. No-Injury (Combined M+F)

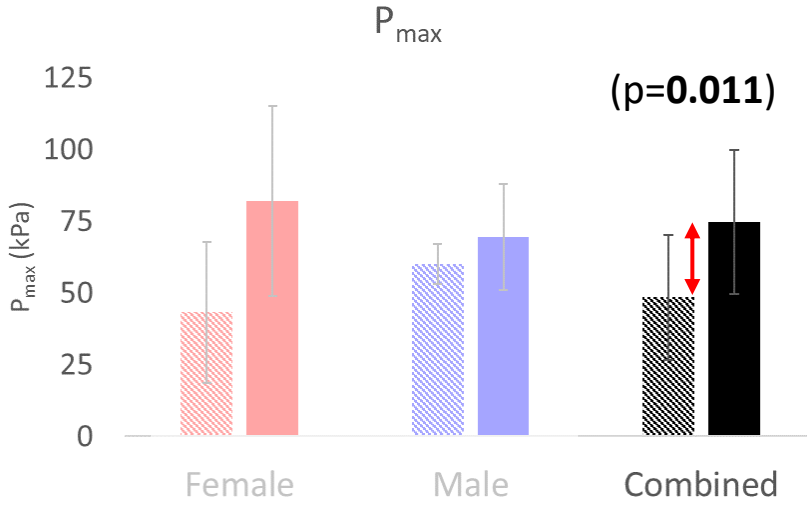
	V_{max}	C_{max}	F_{max}	$(VC)_{max}$	$V_{max}^* C_{max}$	$F_{max}^* C_{max}$	P_{max}	$\dot{P}_{max}$	$P_{max}^* \dot{P}_{max}$
Female vs. Male AIS<2	0.550	0.971	**0.044**	0.408	0.574	0.414	0.087	0.458	0.331
Female vs. Male AIS≥2	0.811	0.989	0.439	0.578	0.731	**0.017**	0.471	0.976	0.687
Female AIS<2 vs. AIS≥2	0.697	0.700	**0.013**	0.194	0.925	0.713	0.058	**0.046**	0.102
Male AIS<2 vs. AIS≥2	0.245	0.732	0.261	0.949	0.450	0.733	0.265	0.463	0.309
Combined AIS<2 vs. AIS>2	0.238	0.585	**0.003**	0.301	0.653	0.509	**0.011**	**0.030**	**0.020**
Female vs. Male AIS<3	0.855	0.931	**0.009**	0.264	0.632	0.180	**0.023**	0.260	0.156
Female vs. Male AIS≥3	0.753	0.926	0.619	0.498	0.659	**0.034**	0.198	0.935	0.514
Female AIS<3 vs. AIS≥3	0.929	0.987	**0.028**	0.339	0.759	0.482	0.055	0.052	0.108
Male AIS<3 vs. AIS≥3	0.651	0.973	0.375	0.527	0.527	0.576	0.635	0.433	0.665
Combined AIS<3 vs. AIS>3	0.819	0.960	**0.011**	0.785	0.900	0.925	0.071	**0.041**	0.061

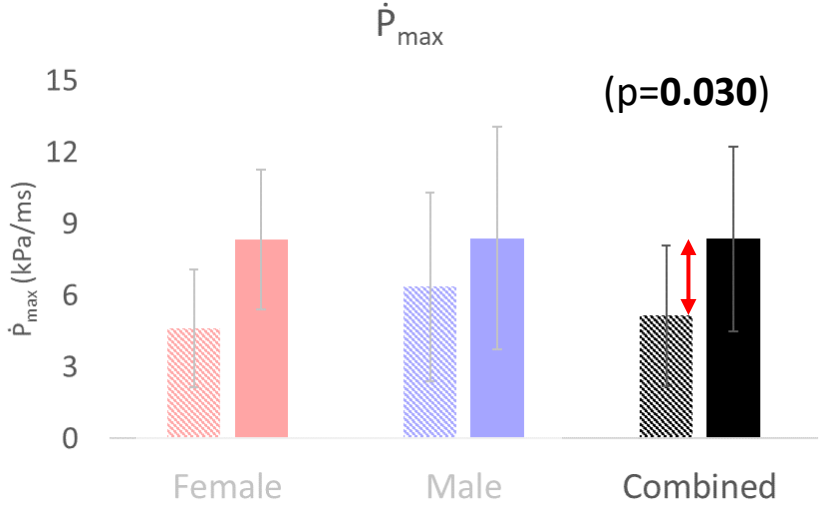
- Using two-tail T-test, assuming unequal variances
- Significance level = 0.05
- P-value < 0.05 indicates the means are different

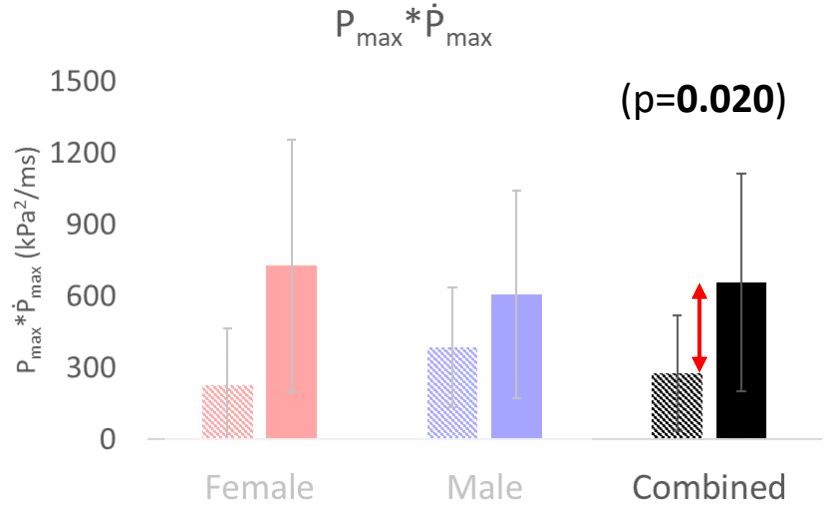
Results – Injury vs. No-Injury (Combined M+F)



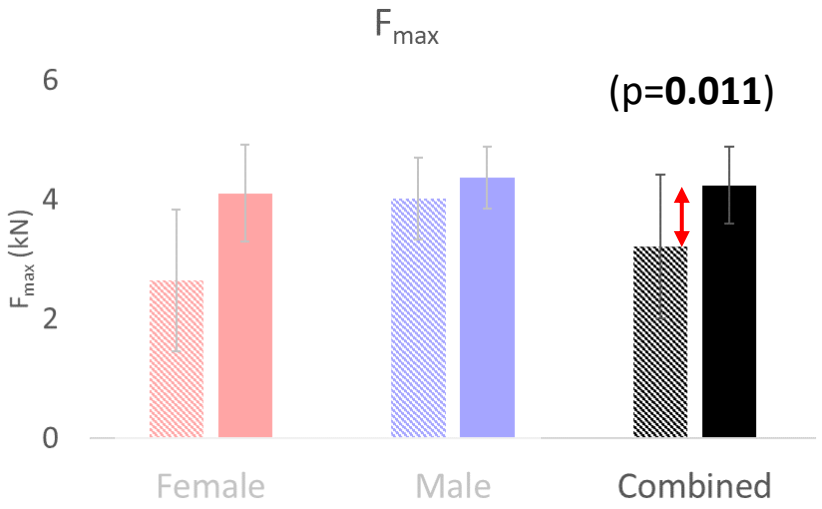


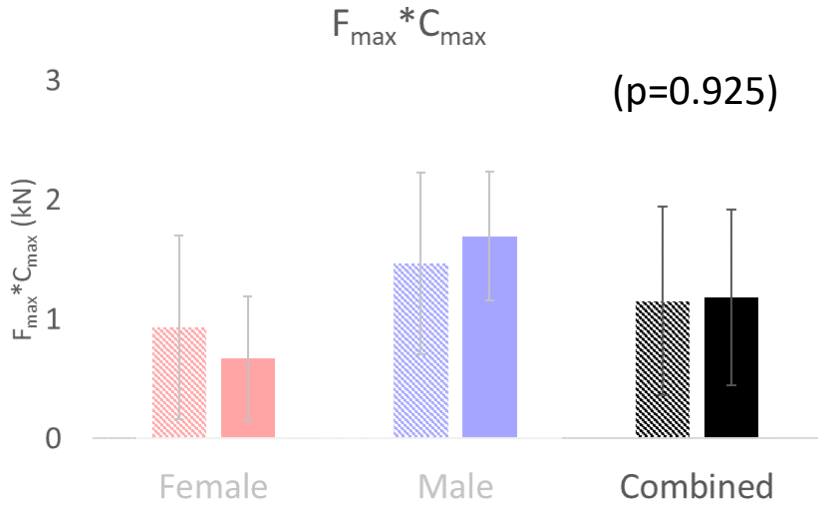


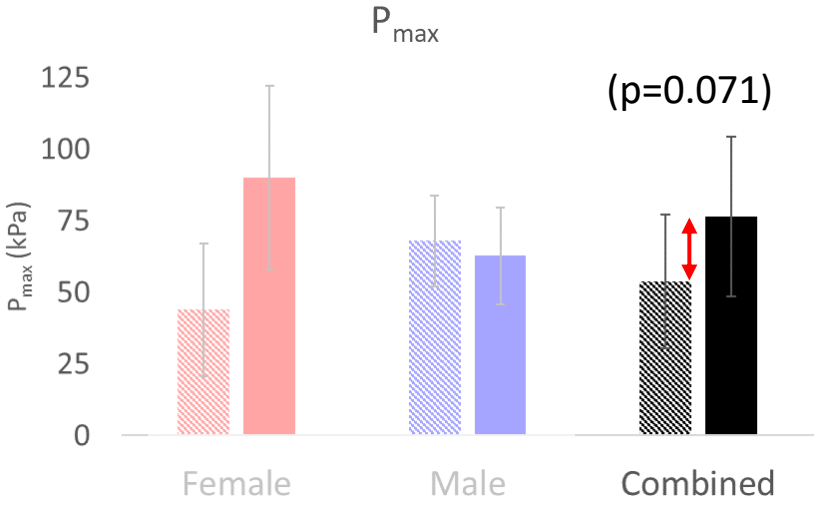


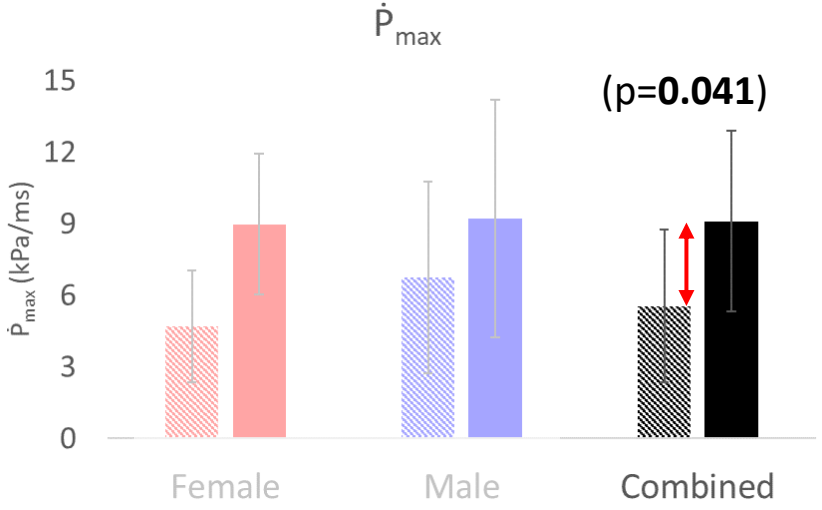


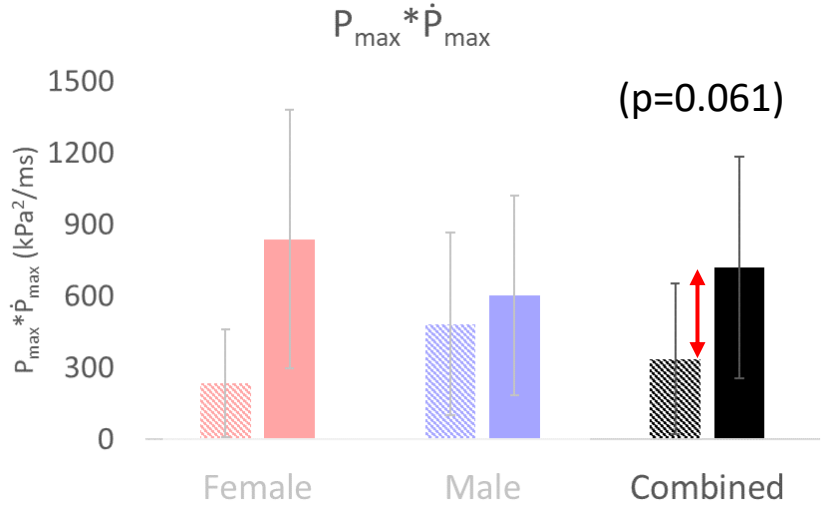
Results – Injury vs. No-Injury (Combined M+F)











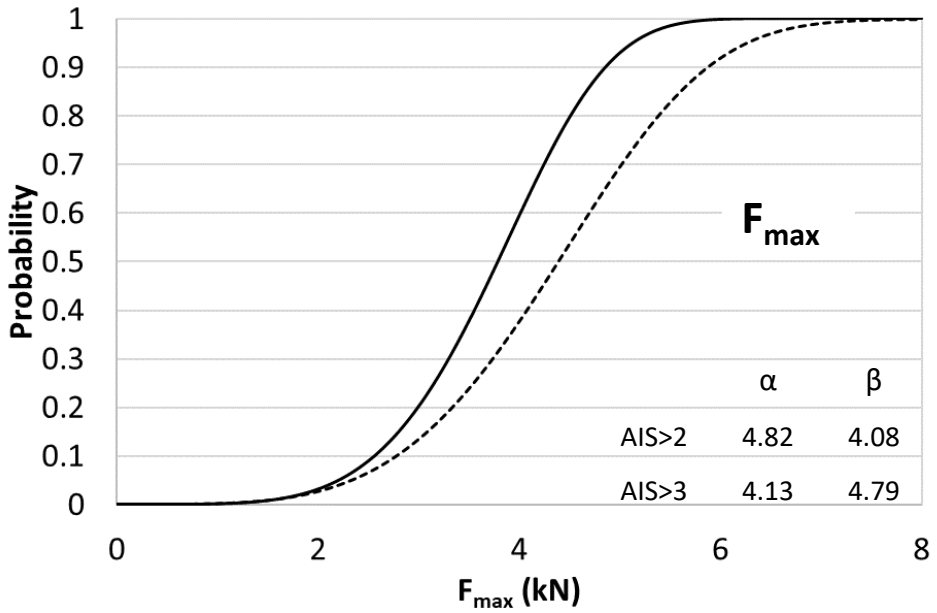
Results – Regression Analyses (Combined M+F)

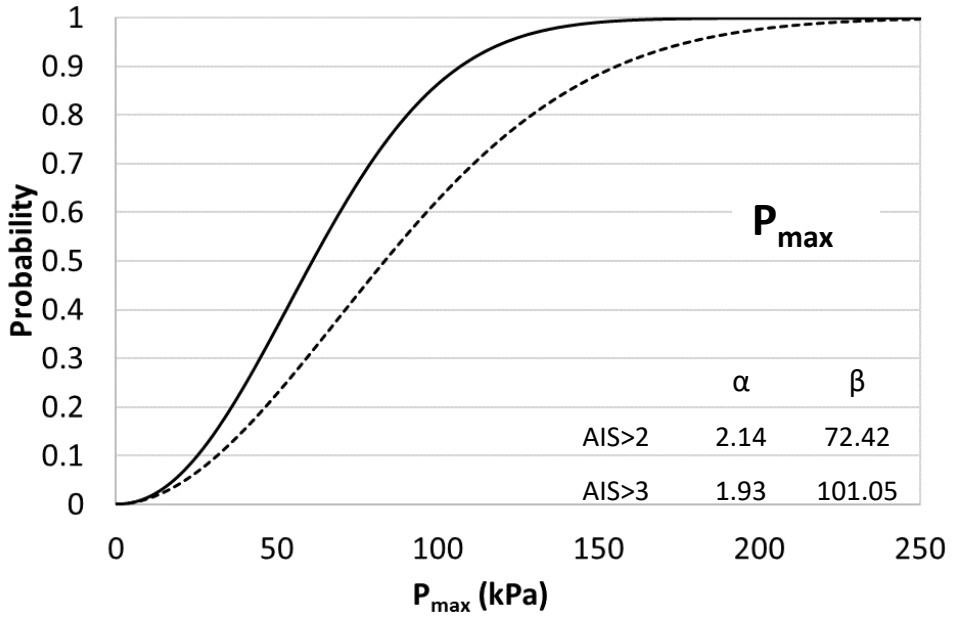
		V_{max}	C_{max}	F_{max}	$(VC)_{max}$	V_{max}* C_{max}	F_{max}* C_{max}	P_{max}	$\dot{P}_{max}$	P_{max}* $\dot{P}_{max}$
AIS 2+	**P-value**	0.21	0.56	**0.00**	0.28	0.64	0.49	**0.01**	**0.02**	**0.01**
	GKG	0.30	0.09	**0.74**	0.25	0.02	0.23	**0.63**	0.48	**0.63**
	AUROC	0.63	0.56	**0.87**	0.63	0.5	0.61	**0.81**	0.74	**0.82**
AIS 3+	**P-value**	0.79	0.96	**0.01**	0.76	0.90	0.92	**0.04**	**0.02**	**0.02**
	GKG	0.09	-0.09	**0.65**	0.10	-0.07	0.03	**0.54**	**0.57**	**0.62**
	AUROC	0.53	0.47	**0.82**	0.54	0.47	0.44	**0.77**	**0.78**	**0.81**

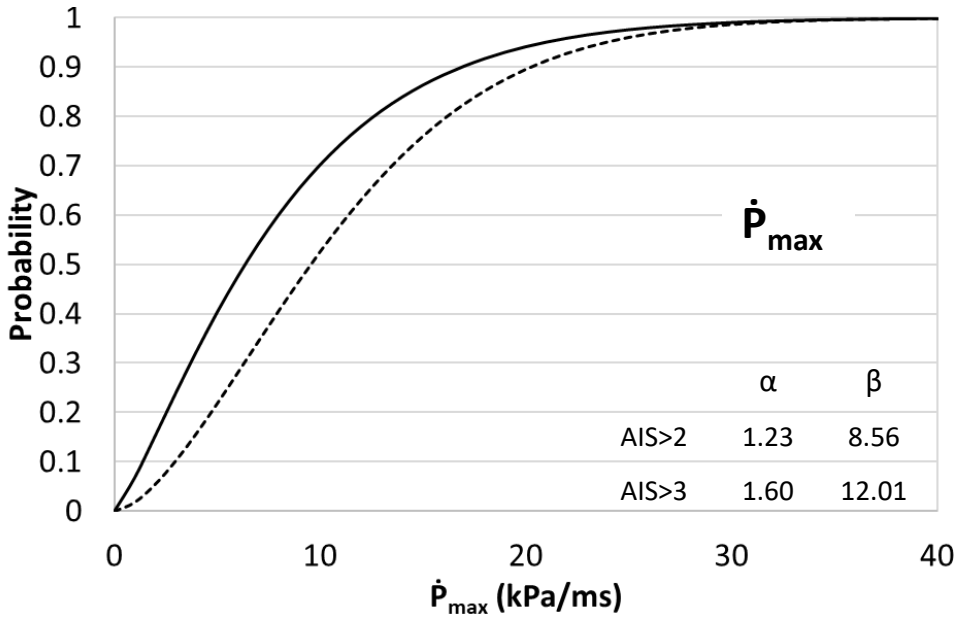
GKG→Goodman-Kruskal Gamma; AUROC→Area under receiver operating characteristic

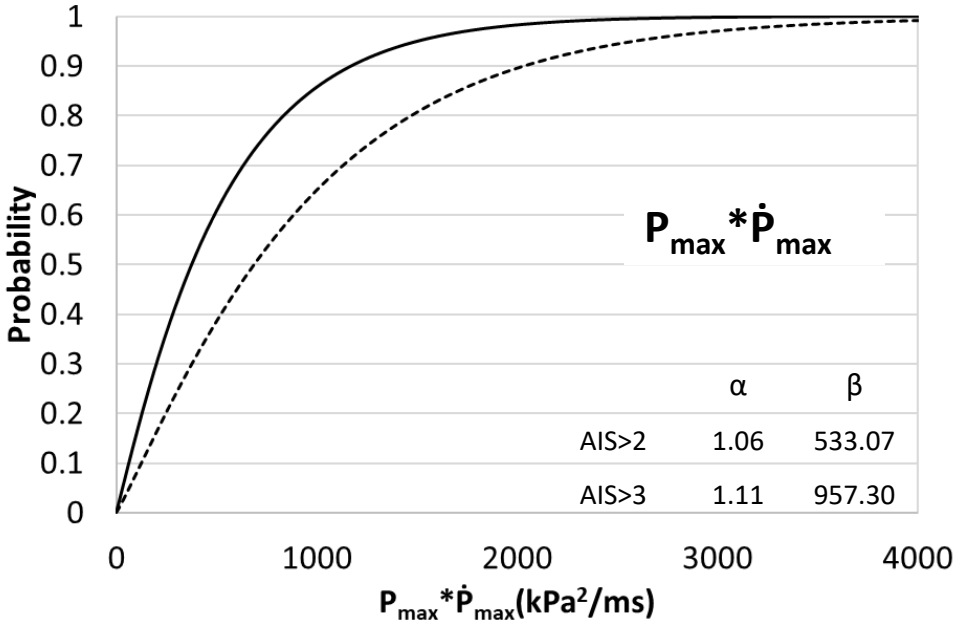
Assumptions: Good correlation when p<0.05, GKG between 0.5 and 1.0, AUROC between 0.75 and 1.0

Results – Injury Risk Functions (Combined M+F)









AIS≥2

AIS≥3

Weibull

$F(x;\alpha,\beta)=1-e^{-(x/\beta)^{\alpha}}$

Summary

- Performed nine table-top abdomen tests on small 5th female size subjects
  - Belt pull and rigid bar impacts
  - Added this data to update the PMHS dataset
- Statistics performed to identify strongest predictors of abdomen injury
  - Peak force and pressure-based metrics
  - No significant difference found between male and female injury tolerance
- Constructed combined IRFs for AIS2+ and AIS3+
  - Still examining other statistical methods and predictor variables
- We recognize that the pressure and force magnitudes are different for ATDs and PMHS (different sensors, biofidelity, etc.)
  - This PMHS study suggests that pressure is appropriate for both female and male ATD abdomens

NHTSA

NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION

Evaluation of sex specific abdominal injury risk functions

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