



Applied Technologies

Swine Test Report for ATBM Injury Correlate Development and Validation

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Executive Summary

The Advanced Total Body Model (ATBM) is a series of models and injury correlates built to predict injury caused by blunt impact. The development and validation of these injury correlates is limited by the lack of injury outcome datasets. Historically, injury testing has been conducted primarily on post mortem human subjects (PMHS). PMHS testing provides a good anatomical representation for blunt impact injury, but may not properly exhibit live tissue inflammatory responses needed to observe blunt injury outcomes such as contusion, particularly in impacts to the thoracic and abdominal soft tissues. To address this need for live injury data, L-3 Applied Technologies, Inc (L-3 ATI) designed and conducted a series of impact tests in an anesthetized swine model in collaboration with the Medical College of Wisconsin (MCW).

Eleven swine test series (one cadaver and 10 live specimens) were conducted. These impact tests yielded non-injury and injury outcomes for three of four target areas: pneumothorax, liver laceration, and intestinal contusion. Impacts to the stomach only yielded non-injury outcomes, likely because the organ is hollow and not fixed to any rigid structure in the body. Additionally, stomach-targeted impact tests were almost always associated with other injuries such as liver laceration, spleen laceration, and intestinal contusion.

The data collected provides a significant portion of the results needed to complete the development and validation of the thoracic and abdominal soft tissue injury correlates based on the ATBM. Swine testing results also provide evidence that soft tissue injuries from blunt impact are best replicated by using live anesthetized subjects, where active inflammatory injury responses can be consistently observed. In addition, tissue compression tests were conducted at a variety of strain rates, allowing for a better understanding of the parameter range and experimental capabilities needed for future material property testing.

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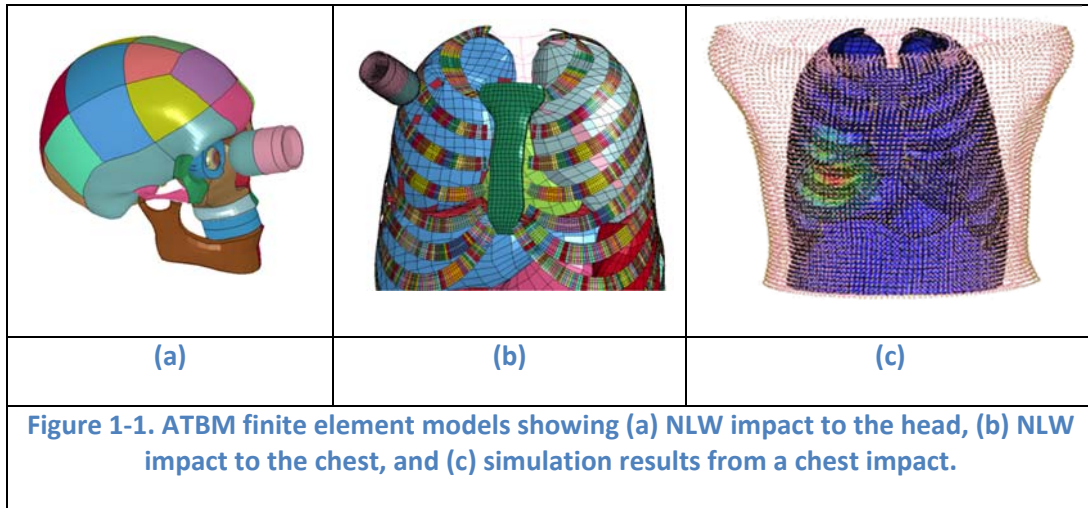
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1 Introduction

1.1 Background

L-3 ATI developed the Advanced Total Body Model (ATBM), a series of biomechanically accurate finite element models (FEM) of the human body and response-based injury correlates that best predict injury outcomes (Figure 1-1) [1].



1.2 Needs and Gaps

For each model, injury outcome data is required to develop and validate the injury correlates. Correlates that have been developed thus far have indicated broad agreement with test data found in journal articles; however, the quantity of available test data restricts the extent to which a model's responses and injury predictions can be validated for non-lethal weapon relevant impacts. Because a significant quantity of data is necessary at each stage of model development (calibration, model response validation, injury correlate development, and, lastly, injury correlate validation), the validation is often weakest when evaluating the injury correlates, particularly for non-lethal weapon relevant projectiles. Table 1-1 summarizes the validation status of each model prior to 2018 testing. This study focused on thoracic and abdominal impacts to complement the refined ATBM FEM of the lower abdomen [2] and thorax [1].

	Model	Status
THORAX	Rib Fracture	Complete
	Lung Contusion	Complete
	Pneumothorax	No Validation
	Liver Laceration	Partial
HEAD	Cranial Fracture	Complete
	Eye Injury	Complete
FACIAL BONES	Zygoma Fracture	Partial
	Maxilla Fracture	Partial
	Mandible Fracture	Partial
LIMBS	Arm Bone Fracture	Partial
	Leg Bone Fracture	Partial
LOWER ABDOMEN	Intestinal Contusion	Partial
	Stomach Contusion	No Validation
	Spleen Laceration	Partial
	Kidney Contusion	Partial
	Pancreas Rupture	No Validation

Table 1-1. Summary of injury correlate validation for ATBM injury types.

1.3 Objective

The objective of the testing efforts for this year is to generate the injury outcome data required to develop and validate injury correlates based on the ATBM, in particular for soft tissue injuries in the thoracic and lower abdominal regions, for non-lethal weapon relevant projectiles. The test plan describes impact tests conducted on a series of anesthetized swine specimens, where multiple target locations were impacted on each subject. The experimental conditions, including projectile mass and speed, would be closely controlled in relation to the subject's size and impact location to gather data across the range of injury probabilities (5-95%), with a focus on collecting data from the middle three quintiles of injury probabilities (20-80%).

2 Methods

2.1 Test Matrix Development

A power analysis was conducted to determine the number of tests needed to develop and validate each injury model, and is described in detail in the test plan for 2018 [3]. It was concluded that a minimum of 20 tests are needed for correlate development; and between 21 and 29 tests are needed for validation of those correlates, based on an estimate of each logistic regression and a desired statistical power of 0.8. The targets for testing in 2018 were narrowed down to those with higher probability of severe injury, based on injury occurrences reported in literature (summarized [4]). Table 2-1 summarizes targets chosen for 2018 testing, the data currently used for correlate development, and the minimum number of additional tests to complete the development and validation of correlates for each injury. Figures with an * next to them indicate correlates that require additional tests to achieve at least ten injury occurrences.

Table 2-1. Expected number of tests required to complete development and validation of injury correlates in swine model.

Model	# of Tests Used in Current Correlate	Minimum Additional Tests for Correlate Development	Minimum Number of Validation Tests (Power = 0.8)	Total Tests Needed
Thorax & Abdomen				
<i>Pneumothorax</i>	17	6*	29	35
<i>Liver Laceration</i>	20	0	21	21
Lower Abdomen				
<i>Intestinal Contusion</i>	31	0	21	21
<i>Stomach Contusion</i>	0	20	23	43
Minimum Required Tests				120

Table 3-1 provides target and test parameters for each impact test performed. Testing consisted of five main sections: calibration of the launcher system, specimen preparation, impact testing, injury identification, and tissue material testing, each of which is described below.

2.2 Equipment Design and Calibration

The projectile launcher, shown in Figure 2-1, is composed of a barrel connected to a pressure chamber that can be filled with helium up to a pressure of 1500 psi. When the device is triggered, a solenoid opens the valve between the pressure chamber and the barrel. The release of the pressure into the barrel accelerates the impactor forward to the test subject.

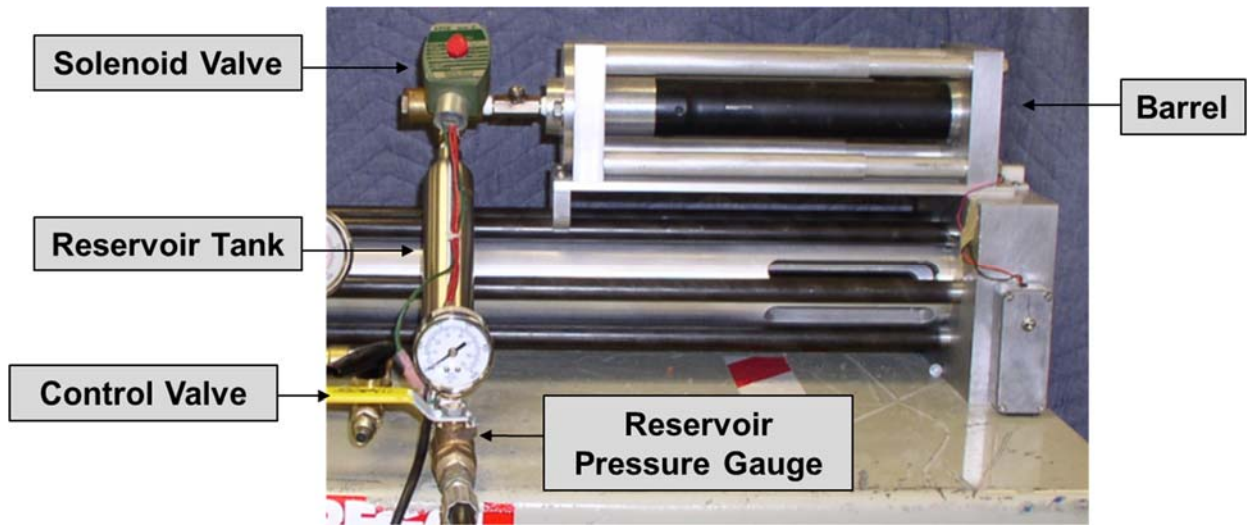


Figure 2-1. Helium driven pressurized impactor with labeled components.

The projectile (Figure 2-2) is a rigid impactor instrumented with a wired uniaxial accelerometer (PCB Piezoelectronics, model #350D02). The accelerometers have a measurement range of $\pm 50,000$ g and a frequency range of 2 to 25,000 Hz. Acceleration data was captured at a sampling rate of 100 kHz using a Synergy data acquisition system (Hi-Techniques, Inc.). The front of the projectile is a solid hemisphere with a diameter of 40 mm made from a stiff ABS-like plastic material created from a 3D printer. This piece is fastened to an aluminum base that houses the accelerometer. The aluminum housing is connected to a long pushrod before terminating at the base with a printed cylinder piece whose diameter matches that of the launcher's barrel. This design allows the projectile to remain closely horizontal with minimal angular deviations before striking the target.



Figure 2-2. (a) The original projectile from PMHS testing (2017) and (b) the modified design to minimize penetration risks in animal testing.

Between test series, minor changes in both the projectile launcher and projectile design were implemented to maximize achievable impact velocities and impact energies. The mass of the projectiles used over all tests ranged from 60 to 80 grams. Immediately before each test series, the projectile launcher system was calibrated by launching several projectiles at multiple pressure levels. A laser pointer and printed grids were used to aim and measure offsets from the aimed point. This ensured that the desired impact velocities and targeting could be achieved with accuracy and consistency. For each impact, the projectile rod was replaced to avoid any inconsistencies due to damage or warping caused in the previous test. The data from calibrations could then be used to assign target offsets and pressure levels for each impact test. During a test series, these values were adjusted as necessary to reflect any deviations observed. Figure 2-3 shows that over all tests, a high level of accuracy was maintained for both targeting and achieving desired velocities. For the majority of tests, impact sites were within a centimeter of the target point, and the projectile velocity was within 5% of the desired value.

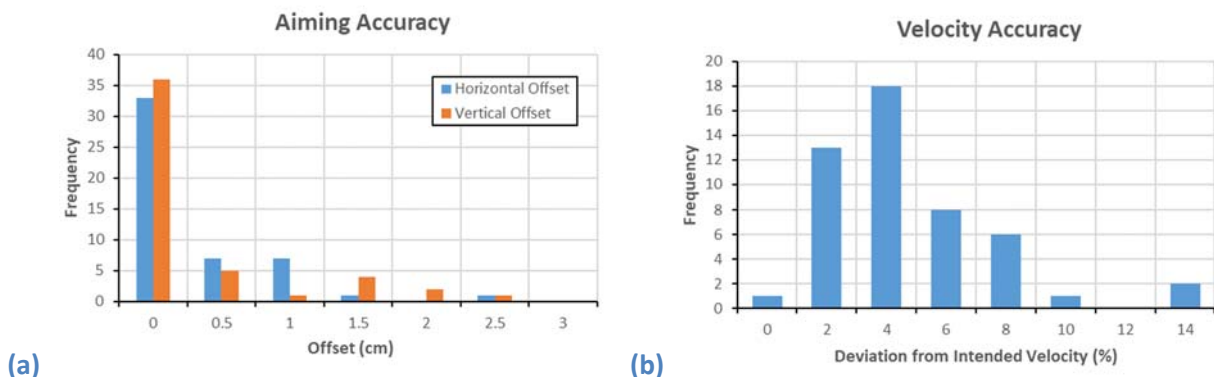


Figure 2-3. Results of launcher calibration tests over all test series for (a) accuracy of targeting and (b) achieving desired impact velocities.

2.3 Specimen Preparation

All animal testing protocols were reviewed and approved by the Zablocki Veterans Affairs Institutional Animal Care and Use Committee (IACUC) and the Department of Navy Bureau of Medicine and Surgery (BUMED) Veterinary Affairs Office prior to any testing. Impact tests were conducted on one cadaver and 10 live, anesthetized swine subjects at the Medical College of Wisconsin (MCW). A list of the specimens and test dates are shown below.

Table 2-2. Specimens selected for impact testing

Test Date	L-3 ID	Sex	Wt (kg)	Notes
6/13/2018	ATBMS-01	M	70.6	Sacrificed immediately prior to impact testing
6/14/2018	ATBMS-02	F	76.5	
6/27/2018	ATBMS-03	F	54	
7/10/2018	ATBMS-04	F	54.4	
7/11/2018	ATBMS-05	F	57.1	
8/01/2018	ATBMS-06	F	52.6	
8/02/2018	ATBMS-07	F	54.5	
8/07/2018	ATBMS-08	F	39.6	
8/09/2018	ATBMS-09	F	35.3	
10/23/2018	ATBMS-10	F	38.4	
10/24/2018	ATBMS-11	F	41.1	

Target locations were selected based on the specific subject characteristics. Figure 2-4 shows approximate anatomical locations for each possible target.

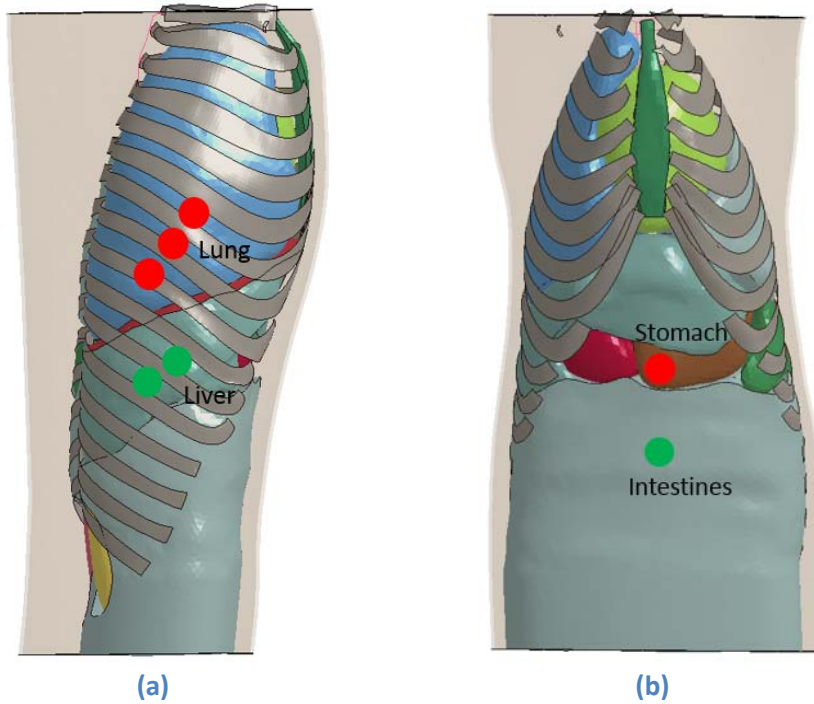


Figure 2-4. Impact locations for (a) thoracic and (b) lower abdominal tests

Prior to impact testing, anesthesia was induced using a cocktail of telazol (6mg/kg, IM) and xylazine (2.2mg/kg, IM). Once the anesthetic took effect, an intravenous catheter was placed in a peripheral extremity vein and the animal was intubated and connected to a respirator. Isoflurane gas (1-2%) was continuously administered and vitals (temperature, heart rate, pulse oxygen levels) were monitored regularly during as well as immediately before and after impact to ensure that the animal was never in distress. Before and after impact testing, a series of X-ray images were taken using a C-arm scanner, to aid in target location and possible injury identification.

2.4 Impact Testing

For each test, the subject was positioned such that the target was between 21 and 37 inches away from the projectile and would strike perpendicular to the body's surface. Projectiles were aimed at specific targets using the laser pointer and offset information determined by calibration tests. The tip of the projectile was covered with an oil-based paint to mark the impact site on the body.

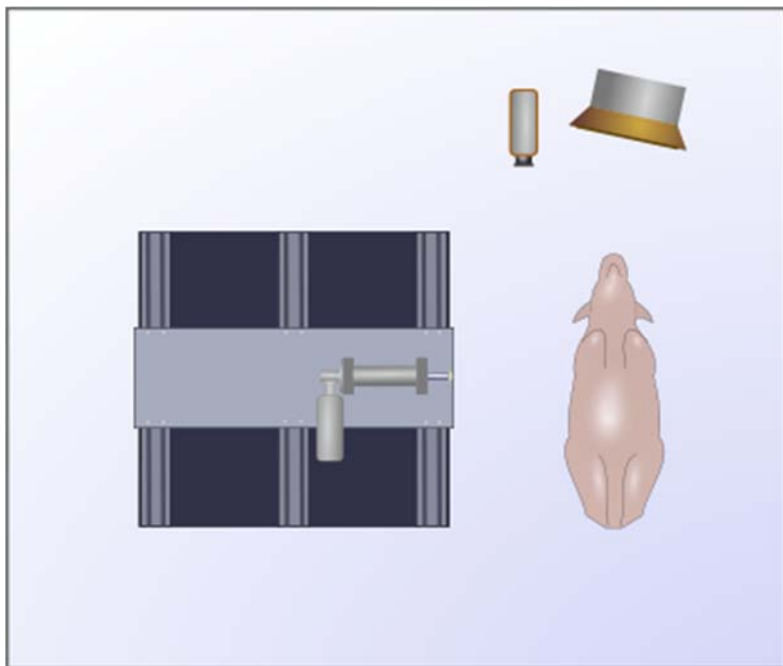


Figure 2-5. Top view of experimental layout of launcher, swine, and high-speed video camera.

Test subjects were subjected to impacts at up to 5 locations on the thorax or lower abdomen. For each impact test, projectile acceleration was recorded at 100 KHz. In addition to sensor recordings from the projectile instrumentation, high speed video of the projectile flight and impact was recorded at a 10-14 kHz framerate. Following an impact, a brief examination of the target site was performed to check impact accuracy and identify any immediate injuries. Approximately 30 minutes after the last impact test, the animal was sacrificed and a complete autopsy was performed by a medical examiner with assistance from MCW to identify and document the nature of any injuries caused.

2.5 Data Post-Processing

2.5.1 Projectile Acceleration Data Processing

Accelerometer data can be vulnerable to corruption by sources not related to the impact test. The data post-processing procedure developed from 2017 testing was used for the data collected in 2018, and is fully described in report J0511-17-716 [3]. Low-pass filtering with cut-off frequencies of 3 kHz and baseline offset corrections were applied to remove high frequency noise and correct any observed sensor drift. The data was then compared to reference measurements taken before each test and the high speed video, and a scaling factor calculated from the discrepancies between acceleration data and references measurements was applied to the full trace. With these corrections applied, the sensor data shows good agreement with references taken for each test. Figure 2-6 shows a comparison of projectile velocities measured

from the corrected acceleration data and high speed video, where the corrections applied to the acceleration reduce the root mean square (RMS) error from 13.3% to 3.87%. Figure 2-7 shows how the same data corrections affect the pre-launch distance calculation from acceleration data. Once the corrections have been applied, the impact trace from the accelerometer can be used with confidence to compare against simulated impacts.

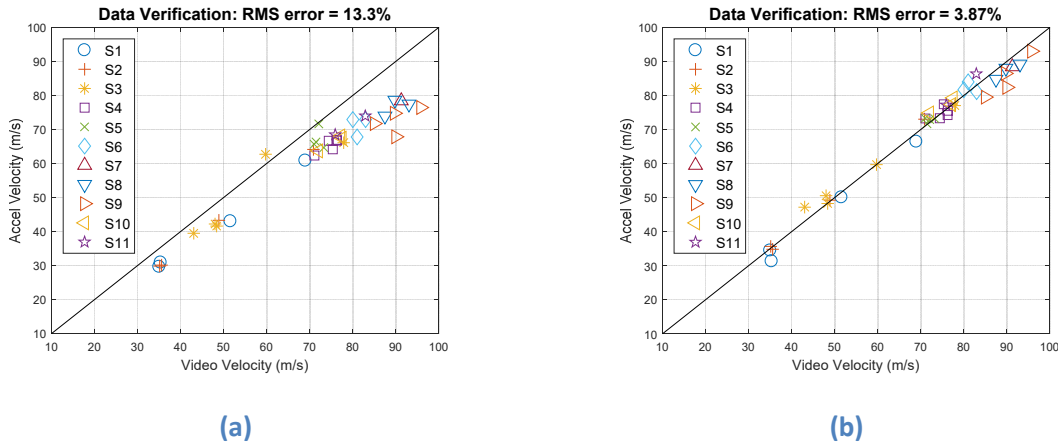


Figure 2-6. Scatter plots of projectile velocity calculated from the (a) raw and (b) corrected accelerometer data (y-axis) and high speed video (x-axis).

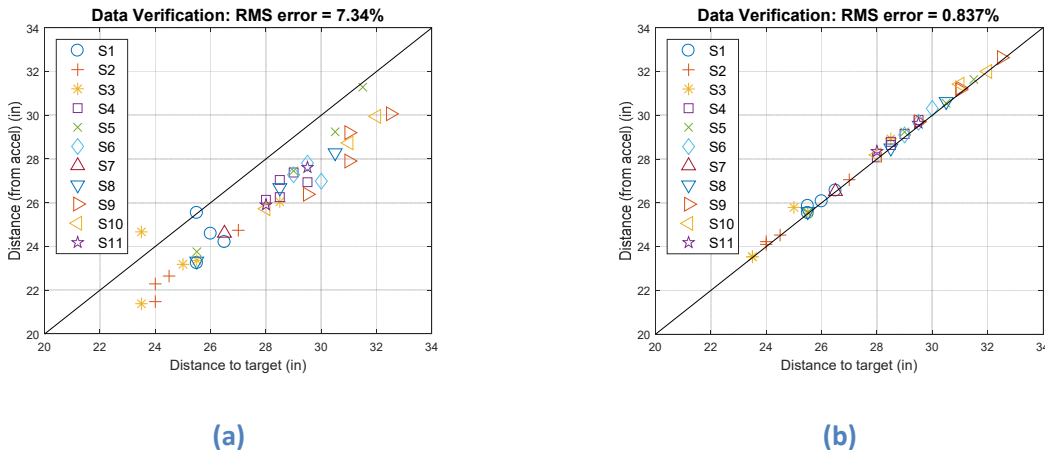


Figure 2-7. Scatter plots of projectile distance to target calculated from the (a) raw and (b) corrected accelerometer data (y-axis) and high speed video (x-axis).

2.6 Mechanical Tissue Sample Testing

After the animal was examined for any injuries, tissue samples were collected for material property testing. If testing did not occur immediately after collection, tissue samples were refrigerated until use. Otherwise, tissue samples were kept in an incubator at room temperature until tests were conducted. Compression tests were conducted using two different test set-ups based on the desired strain rates. For strain rates about 500 s^{-1} , a Split Hopkinson pressure bar was used. For strain rates of less than 50 s^{-1} , a piston set-up was used.

2.6.1 Split Hopkinson Pressure Bar Testing

A Split-Hopkinson bar set-up consisted of a piston that is driven into a transmitter bar and a receiver bar, each of which are instrumented with strain gauges, as depicted in Figure 2-8.

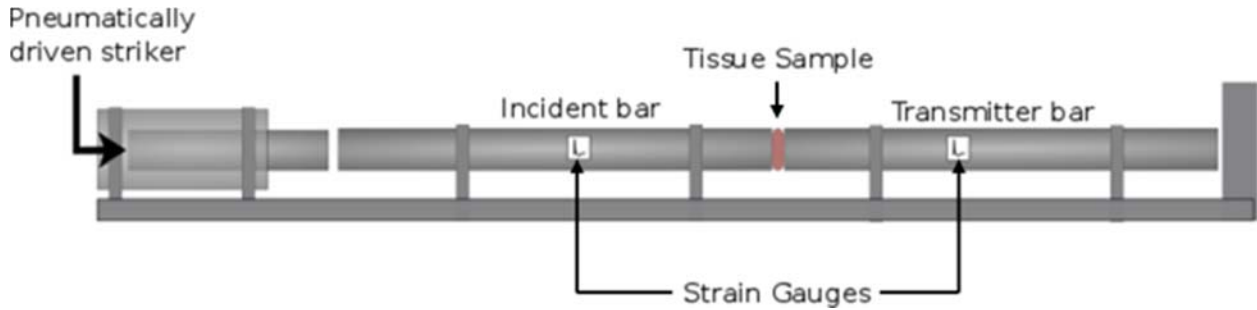


Figure 2-8. Illustration of Split-Hopkinson Pressure Bar used for high strain-rate tissue sample testing.

The tissue sample was first cut into a square piece with 1 cm edge length and a thickness of 2 mm. The thickness of the sample was verified in an uncompressed state, and then placed between the transmitter bar and receiver bar, such that minimal stress was applied to the tissue sample. High speed video was used to measure the compression of the tissue as the transmitter bar moved towards to receiver bar, to the point of tissue failure, and is used alongside the strains measured on each bar to calculate the stress-strain curves for the given sample.

2.6.2 Piston Compression Testing

A schematic of the lower strain-rate set up is shown in Figure 2-9. Specimens were cut into cubes with a thickness of approximately 2 cm using a scalpel and surgical scissors. Because of the larger sample required for piston testing, muscle samples were collected from both the chest wall and the forelegs of the subject, and intestinal wall tissue was not tested. The sample was placed on the table and a 1.5-inch piston-driven impactor was lowered until contact was just made. Specimen thickness was re-measured as the distance between the table and the impactor. The piston was set to compress the sample 70% of the measured thickness and run with goal velocity of approximately 1.5m/s, which corresponds to approximately 40 s⁻¹. A displacement sensor was used to measure the movement of the piston, and load cells on both the piston and table measured the force applied. Stress-strain curves were then derived from the force-displacement data.

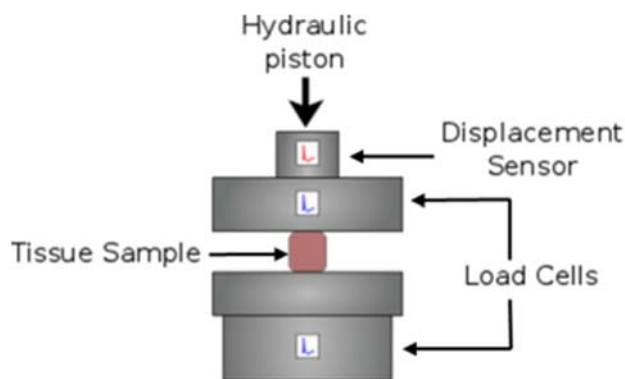


Figure 2-9. Illustration of piston test set up for low strain-rate compression tests.

3 Results

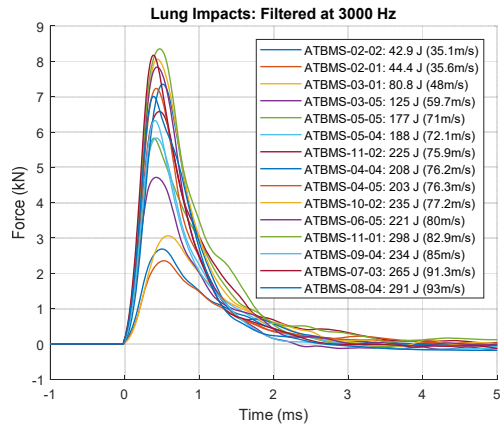
3.1 Data Collection

Table 3-1 provides a summary of usable data collected for all tests performed, organized by target site. For the majority of tests, all desired data was collected. In a few cases, however, data was lost as a result of improper triggering or damage to the instrumentation. The cadaver test data is not included here.

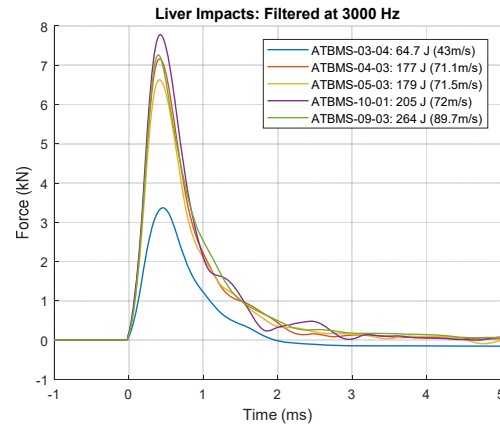
Table 3-1. Summary of data collected for each test, by target site.

Model	Target Location	Total Tests	High Speed Video	Projectile Acceleration
Thorax	Lung	14	12	12
	Liver	6	6	4
Lower Abdomen	Lower Intestines	8	7	8
	Stomach	7	7	6
Total		35	32	30

Figure 3-1 and Figure 3-2 show the impact force data from all test series overlaid for each target site. As expected, impacts to the same target site showed similar impact durations and waveform kinetics, although the peak force values did not necessarily relate directly to the impact energy.

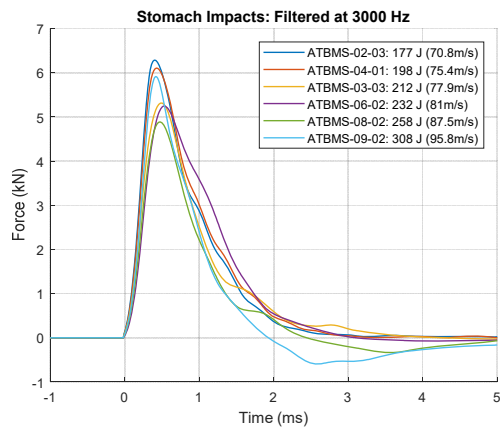


(a)

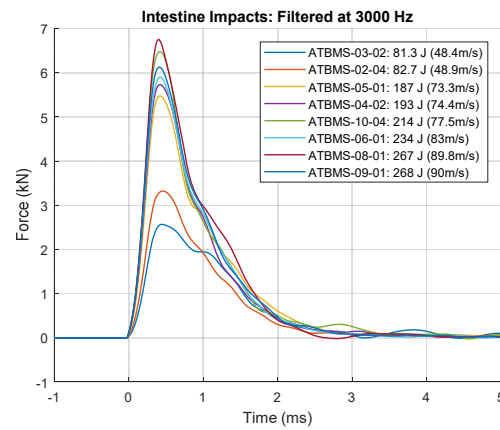


(b)

Figure 3-1. Force data for thoracic impacts to the (a) lungs and (b) liver.



(a)



(b)

Figure 3-2. Force data for abdominal impacts to the (a) stomach and (b) intestines. Intestinal impact that resulted in penetration is not included.

3.2 Injury Outcomes

One experiment was conducted on an animal that had been sacrificed immediately before impact testing, to compare tissue response between a live and cadaver specimen. Figure 3-3 shows a striking difference in tissue response between the two specimens after impacts of similar intensity, in which the cadaveric specimen shows no bruising while the live specimen produced almost immediate bruising around the impact location.



(a) (b)
Figure 3-3. Comparison of tissue response to a stomach impact on a (a) cadaver specimen (69 m/s) and a (b) live anesthetized specimen (71 m/s). Green paint was used to paint the projectile and marks the exact impact site.

A complete list of injury outcomes is included in Appendix A. Table 3-2 summarizes the impact tests performed and the resulting injury outcomes in live animal tests. In 2 of the 45 total tests performed, the projectile penetrated the body, and the data could not be used to validate blunt injury models. This test is not included in Table 3-2. The location of the liver in swine allows it to be impacted both through the ribs and from frontal impacts, resulting in several liver injuries caused by impacts targeting the stomach. These injuries are included in the liver injury outcomes as well.

Table 3-2. Impact tests and injury outcomes by injury model

Model	Injury Type	# Tests	Velocity Range (m/s)	# Injuries
THORAX	Pneumothorax	18	35 – 93	7
	Liver Laceration	15	43 – 93	12
LOWER ABDOMEN	Intestinal Contusion	9	48 – 90	6
	Stomach Contusion	8	70 – 96	0

Figure 3-4 provides a graphical representation of the injury outcome data by test, where each injury outcome is represented by a colored circle against the impact energy of that test. Both injured and non-injured outcomes were achieved in lung, liver, and intestinal impacts, but stomach impacts did not result in any injuries despite high velocity impacts.

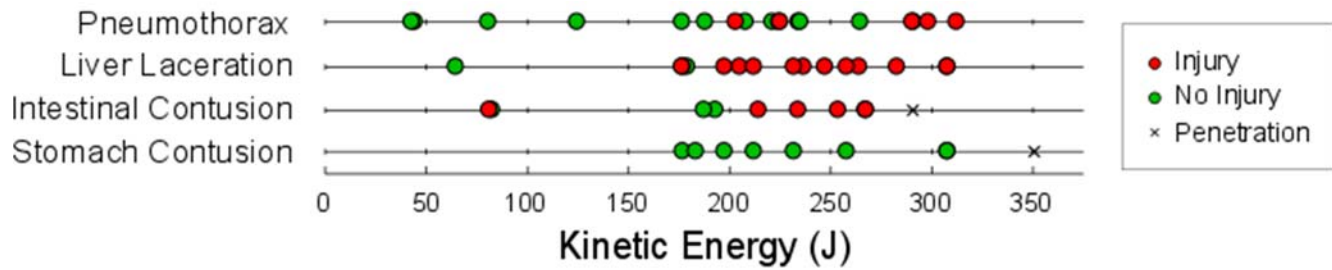


Figure 3-4. Injury outcome data by model.

3.3 Tissue Material Properties

Figure 3-5 shows the stress-strain curves from the high strain rate Split-Hopkinson compression tests ($700 - 1500 \text{ s}^{-1}$). Results across the same specimen and similar strain rates were consistent. As the strain rate of the tests decreased, stress-strain curves showed higher stiffness across a variety of organ tissues, which makes these results questionable in nature. Additionally, the magnitude of the stress-strain curve is orders of magnitude higher than that reported in literature.

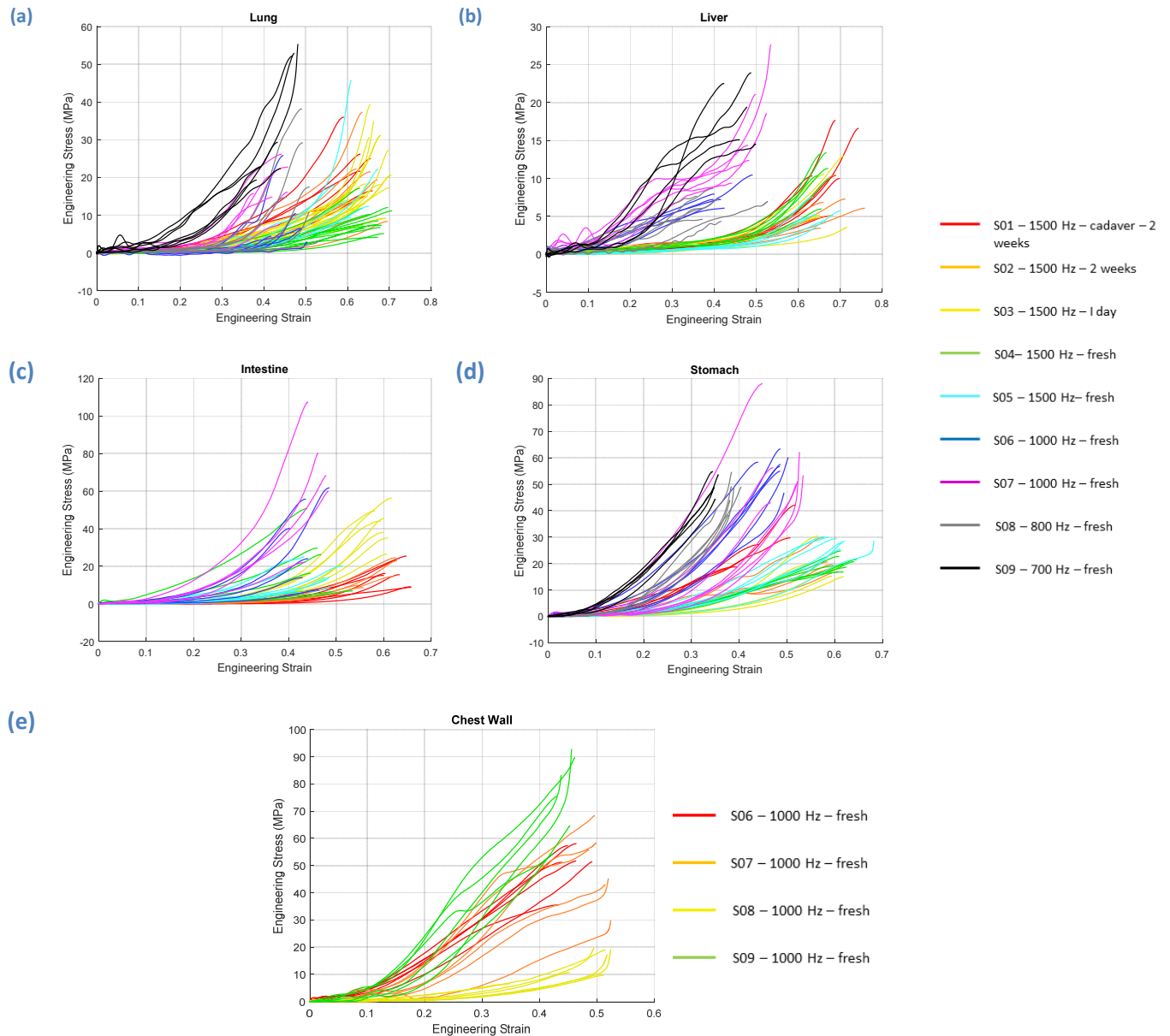


Figure 3-5. Stress-strain curves for high strain rate Split Hopkinson pressure bar tests ($700-1500 \text{ s}^{-1}$).

Figure 3-6 shows the stress-strain curves based on the lower strain rate compression tests using a piston instead of the Split-Hopkinson pressure bar. Stresses observed are an order of magnitude lower than those seen in Figure 3-5.

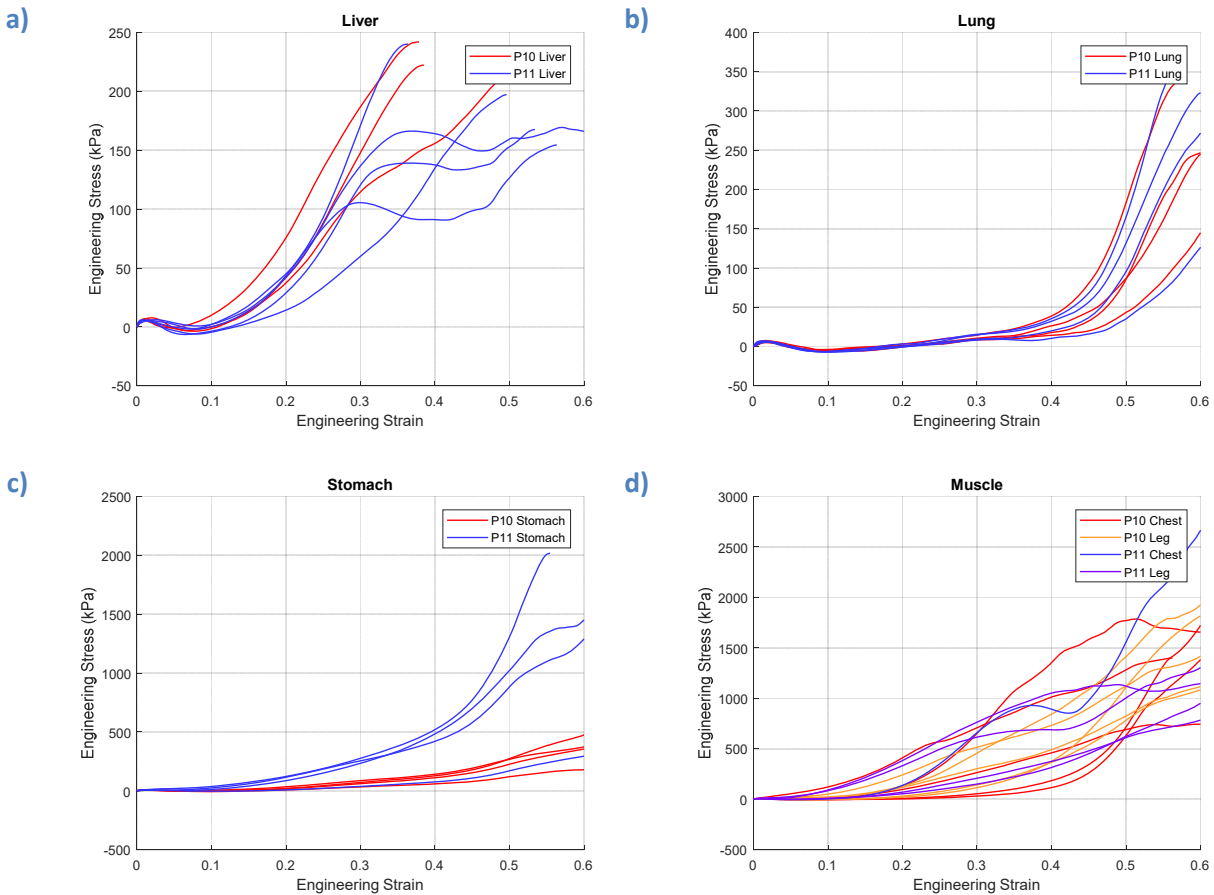


Figure 3-6. Stress-strain curves for low strain rate piston compression tests (40 s^{-1}).

4 Discussion

4.1 Impact Testing

The goal of the impact tests described in this report was to produce observable soft tissue injuries to be used for injury correlate development and validation. This proved to be a challenge during PMHS tests in 2017, and it was hypothesized based on lack of perfusion and from literature that this was largely due to the lack of dynamic injury response from live tissue and circulation in cadaver specimens [5]. This hypothesis proved to be true as injury response was not observed in the cadaver specimen whereas immediate bruising was apparent in the anesthetized specimen. Overall, live animal testing yielded a range of injury outcomes and sufficient data to develop the injury correlate for pneumothorax and provide a significant portion of the data required for validation of the other soft tissue injury correlates of interest.

Impact testing yielded consistent contact force data across most tests. Live animal testing, as hypothesized, yielded more visible soft tissue injury response than was observed in the human cadaver specimens. This was further confirmed by comparing impact sites on a live anesthetized specimen (ATBMS-01) and an animal that had been sacrificed immediately before impact testing (ATBMS-02). There was noticeably less bruising around the target site in the cadaver swine, as seen in Figure 3-3, suggesting that the lack of soft tissue injury observed in PMHS tests was likely due to the lack of circulation in cadaveric tissue. This is consistent with the fact that while PMHS specimens were perfused with a dye before impacts (as described in the 2017 test report [6]), the blue dye was not seen in organ tissue during the autopsy. Furthermore, only two out of the 49 tests conducted resulted in penetration of the abdomen. This is much lower than the 10 out of 39 thoracic or abdominal cadaver tests that resulted in penetration, and may suggest that muscle tone in a live subject also plays a role in protecting the body from impact trauma. These results suggest that live animal specimens are more appropriate to characterize soft tissue injuries than cadaver subjects.

While both injurious and non-injurious outcomes were achieved for three of the four target organs, no stomach contusion was observed. The threshold for stomach contusion is likely very high, due to its hollow structure and mobility within the body. Impacts with kinetic energies of up to 400 kJ were conducted. At these high energies, the probability of other injuries are likely higher than that of stomach contusion. In fact, in the swine tests, stomach-targeted impact tests were almost always associated with other injuries such as liver laceration, spleen laceration, and intestinal contusion. While this is dependent on the anatomy of the targeted subject, this suggests that stomach injury may be secondary to more vulnerable areas.

Table 4-1 and Table 4-2 show the number of tests required to complete correlate development and validation for each injury of interest. Datasets from previous testing and literature were included for injury correlate development of pneumothorax [7], liver laceration [7], and intestinal contusion [8], as these test parameters are similar to those used in the current experimental set-up. Only pneumothorax and stomach contusion required additional data for correlate development. All tests needed to complete pneumothorax correlate development were achieved, and nine of the 20 tests required to develop the stomach contusion correlate were completed. All impact tests targeting the stomach in 2018 will be used for correlate development and not validation. For correlate validation, 36 of the 71 tests needed for pneumothorax, liver laceration, and intestinal contusion correlate validations were completed. Focusing on these regions, 36 additional tests would be needed to for a statistically powerful correlate validation (Table 4-2), which can be completed with 12 additional animal specimens.

Currently, the data used for correlate development only includes tests whose parameters are similar to those described in this report (localized target sites, low projectile mass, high impact velocity). Theoretically, ATBM is capable of modeling a wide variety of impact parameters, such as injuries caused by vehicle related impacts. Using data reported from other types of impact tests may broaden the applicability of the injury correlate and lower the testing requirements for correlate development and validation.

Table 4-1. Tests required to complete injury correlate development.

Correlate Development									
Model	Minimum Tests Required			Tests Completed			Tests Needed (2019)		
	I	N	Total	I	N	Total	I	N	Total
<i>Pneumothorax</i>	6	0	6	6	0	6	0	0	0
<i>Stomach Contusion</i>	10	10	20	0	8	8	10	2	12
TOTAL	26			14			12		

I = injured outcome, N = non-injured outcome

Table 4-2. Tests required to complete injury correlate validation.

Correlate Validation									
Model	Minimum Tests Required			Tests Completed			Tests Needed (2019)		
	I	N	Total	I	N	Total	I	N	Total
<i>Pneumothorax</i>	15	14	29	1	11	12	14	3	17
<i>Liver Laceration</i>	11	10	21	12	3	15	0	7	7
<i>Intestinal Contusion</i>	11	10	21	6	3	9	5	7	12
<i>Stomach Contusion</i>	12	11	23	0	0	0	12	11	23
TOTAL	94 (*71)			36			59		

I = injured outcome, N = non-injured outcome
*Not including stomach contusion

4.2 Mechanical Tissue Testing

Split-Hopkinson bar tissue tests were conducted at very high strain rates (700-1500 s⁻¹). Stress-strain curves derived from these tests were fairly consistent across animals, despite differences in time between tissue collection and material testing. However, the high strain rate tests resulted in values that were at least an order of magnitude above those reported in literature, and seemed to show that stiffness increased as strain-rates were lowered. These results were unexpected and contrary to values reported in literature. Split-Hopkinson bar tests are typically used for much stiffer materials, such as measuring metals and polymers under parameters seen in explosive events, so it is likely that this experimental set-up is not appropriate for very soft materials such as organic tissue [9].

Lower strain rate compression tests were performed on tissue samples from two animals using a hydraulic piston experimental set-up. The stress-strain curves from these tests were similar to those reported in literature, which measured properties at similar strain rates. Based on the high speed videos from testing and the swine FE model, strain rates during blunt impact events similar to those replicated by the described impact tests are likely to be within the 100-600 s⁻¹ range. Future tissue tests should be designed to reflect such strain rates.

5 Conclusions

Over the last year, 11 swine test series (one cadaver and 10 live specimens) were conducted. These impact tests yielded non-injury and injury outcomes for three of four target areas: pneumothorax, liver laceration, and intestinal contusion. Impacts to the stomach only yielded non-injury outcomes, likely because the organ is hollow and not fixed to any rigid structure in the body. While this is dependent on the anatomy of the targeted subject, this suggests that stomach injury may be secondary to more vulnerable areas. The data collected provides a significant portion of the results needed to complete the development and validation of the thoracic and abdominal soft tissue injury correlates based on the ATBM. Swine testing results also provided evidence that soft tissue injuries from blunt impact are best replicated by using live anesthetized subjects, where dynamic tissue responses can be consistently observed. Tissue compression tests were conducted at a variety of strain rates, allowing for a better understanding of the parameter range and experimental capabilities needed for future material property testing. The following steps are recommended for future testing:

- 1. Complete high priority injury datasets for soft tissue injury correlates.*
Based on the the lack of injury outcomes for stomach targeted impacts, it is likely that any impact with high enough intensity to injure the stomach will cause more severe injuries to other organs as well. Similarly, injury to other abdominal organs, such as the kidneys, pancreas, and spleen, are also less likely, as they are more protected anatomically. Therefore, correlate validation should be prioritized to those injuries that are most likely to be caused by a blunt impact: pneumothorax, liver laceration, and intestinal contusion. The tests required to complete these correlate validations are described in Table 4-2 and require a minimum of 12 animals, only one more test series than was completed this year.
- 2. Conduct material testing with parameters that are more representative of localized blunt impacts.*
While a wide range of strain rate compression tests were completed this year, there remains a need to explore the range of strain rates that were not attainable with the current experimental set-ups. Specifically, tissue testing should be conducted at in the 100-600 s⁻¹ strain rate range. This will not only cover the relevant range for blunt impact injury, but may also provide information about the strain rate dependence of tissue material properties. Piston tests are suggested as the Split Hopkinson bar method proved to be difficult for very soft materials. The effect of muscle tone on tissue properties should also be considered.
- 3. Complete injury datasets for extremity and facial bone injury correlates.*
The ATBM has been advanced for the abdomen, thorax, and neck, and thus a finite small number of additional tests are needed to round out the injury development and validation dataset for these regions. This task relates to the PMHS tests that were conducted last year, in which a number of extremity and facial bone impact tests were completed in 2017 (7-8 impact tests per target) [6]. At least 12 more impacts per target are required to complete injury correlate validation. Because bone structure is less variable between live and cadaver specimens, these can be completed with cadaver specimens, allowing for a closer anatomical and structural representation of the injury.

6 References

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Appendix A. Impact Test Parameters and Injury Outcomes

Injury Outcomes: Y- injured, N – not injured, P – penetrative

*Estimated velocities based on previous tests and calibrations.

Test Name	Target	Projectile Mass (g)	Distance to Target (in)	Velocity (m/s)	Kinetic Energy (J)	Injury
ATMBS-01-01 (cadaver)	Right Lung	69.34	25.5	35.33	43.28	N
ATBMS-01-02 (cadaver)	Left Lung	69.32	25.5	35*	42.46	N
ATBMS-01-03 (cadaver)	Stomach	69.1	26	68.96	164.30	N
ATBMS-01-04 (cadaver)	Intestine	69.27	26.5	51.55	92.04	N
ATBMS-02-01	Left Lung	70.2	27	35.57	44.41	N
ATBMS-02-02	Right Lung	69.51	24	35.14	42.92	N
ATBMS-02-03	Stomach	70.51	24	70.85	176.97	N
ATBMS-02-04	Intestine	69.21	24.5	48.88	82.68	N
ATBMS-03-01	Left Lung	70.11	28.5	48*	80.77	N
ATBMS-03-02	Intestine	69.5	25.5	48.36	81.27	Y
ATBMS-03-03	Stomach	69.94	23.5	77.89	212.16	N
ATBMS-03-04	Liver	69.94	25	43.03	64.75	N
ATBMS-03-05	Right Lung	69.93	23.5	59.72	124.70	N
ATBMS-04-01	Stomach	69.59	29.5	75.36	197.61	N
ATBMS-04-02	Intestine	69.7	28.5	74.43	193.06	N
ATBMS-04-03	Liver	69.9	28.5	71.08	176.58	N
ATBMS-04-04	Right Lung	71.61	29	76.23	208.06	N
ATBMS-04-05	Left Lung	69.84	28	76.28	203.19	Y
ATBMS-05-01	Intestine	69.84	25.5	73.27	187.47	N
ATBMS-05-02	Stomach	70.74	26.5	72.02	183.46	N
ATBMS-05-03	Liver	70.19	30.5	71.45	179.16	N
ATBMS-05-04	Right Lung	72.39	31.5	72.09	188.10	N
ATBMS-05-05	Left Lung	70.08	29	71.01	176.69	N
ATBMS-06-01	Intestine	68.01	29	82.96	234.03	Y
ATBMS-06-02	Stomach	70.68	30	81.01	231.92	N
ATBMS-06-03	Liver	69.62	30	82.46	236.70	Y
ATBMS-06-04	Right Lung	70.13	29	80.04	224.64	Y
ATBMS-06-05	Left Lung	69.16	29.5	80.01	221.37	N
ATBMS-07-01	Intestine	69.68	28.5	91.33	290.61	P
ATBMS-07-02	Right Lung	70.28	27.5	91*	290.99	N
ATBMS-07-03	Left Lung	63.57	26.5	91.26	264.72	N
ATBMS-08-01	Intestine	66.34	28.5	89.78	267.37	Y
ATBMS-08-02	Stomach	67.44	30.5	87.48	258.05	N
ATBMS-08-03	Liver	66.05	30.5	92.56	282.94	Y
ATBMS-08-04	Left Lung	67.13	25.5	93.04	290.55	Y
ATBMS-09-01	Intestine	66.07	29.5	90*	267.58	Y
ATBMS-09-02	Stomach	67.13	31	95.77	307.85	N
ATBMS-09-03	Liver	65.73	32.5	89.66	264.20	Y

Test Name	Target	Projectile Mass (g)	Distance to Target (in)	Velocity (m/s)	Kinetic Energy (J)	Injury
ATBMS-09-04	Left Lung	64.83	31	85*	234.20	Y
ATBMS-10-01	Liver	79.16	31	72*	205.18	Y
ATBMS-10-02	Right Lung	78.96	32	77.16	235.05	N
ATBMS-10-03	Left Lung	78.11	29.5	89.44	312.42	Y
ATBMS-10-04	Intestine	71.35	28	77.53	214.44	Y
ATBMS-10-05	Stomach	72.27	29	98.5	350.59	P
ATBMS-11-01	Left Lung	86.84	28	82.9	298.40	Y
ATBMS-11-02	Right Lung	78.12	29.5	75.92	225.14	Y
ATBMS-11-03	Liver	80.32	29	78.48	247.35	Y
ATBMS-11-04	Intestine	79.24	25.5	80.04	253.82	Y
ATBMS-11-05	Stomach	78.39	25	88.63	307.89	N