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Verification and Validation Report for ATBM-LA v1.0 Finite Element Modeling and Injury Correlation

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Prepared by

Eugene Niu
Charles Webber

L-3 Applied Technologies, Inc.

10180 Barnes Canyon Rd. Ste 100
San Diego, California 92121

Prepared for

General Dynamics Information Technology
4141 Petroleum Drive, Bldg 3260
Fort Sam Houston, TX 78234
United States

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1 Executive Summary

This report documents the completed verification and validation (V&V) activities for the lower abdominal finite element model (FEM) and injury correlations as part of the blunt trauma Modeling and Simulation (M&S) program known as the Advanced Total Body Model (ATBM). The report details the specific requirements, acceptability criteria, and activities performed to validate the model's data, conceptual model, and results, as well as verify its data, design, and implementation. The report also summarizes the activities used to identify, evaluate, and quantify any limitations of the M&S as well as any risks associated with its use.

The ATBM program was developed in the mid-2000s for use by the Joint Non-Lethal Weapons Directorate (JNLWD) as an analytical tool to estimate the risk of injuries from Kinetic Energy NLWs (KE-NLWs). In 2006, a thoracic model was the first component of ATBM completed and included injury correlates for rib fracture and lung contusion. Models of the head, eye, upper abdomen, face, and extremities were developed in subsequent years. In 2014, creation of a lower abdomen FEM began.

The FEM was developed for the purpose of accurately predicting the responses to blunt impacts, including subject motion, stresses, and strains of the abdominal region spanning from the pelvis to the diaphragm. The model was formed from anatomically accurate geometry of the 50th percentile male, discretized at the organ level with finite elements, and assigned tissue material models based on literature sources and test data. Impacts between the abdomen body and a projectile can be simulated with the LS-Dyna nonlinear explicit solver, providing model responses that are then correlated to injury outcomes.

From literature sources describing the occurrence of certain organ injuries to blunt impacts, logistic regressions were calculated that associate model outputs with a likelihood of injury. Because the FEM provides a wealth of response data, several candidates were evaluated for their efficacy as injury predictors. In previous modeling efforts, the best predictors have been the mechanical field variables within the organ itself, such as stress and strain. Empirical correlations using other measures, such as peak force or maximum deformation, can be made; however, they tend to lose predictive power when applied to different impact locations and loading conditions.

The scope of the V&V Report covers the lower abdomen FEM and its associated injury correlates. The requirements of the M&S were determined by the subject matter experts (SMEs) developing the M&S to meet the capabilities needed by the M&S sponsor. The limitations and risks of the M&S are dependent upon the available resources, such as literature data, but are a consequence of the simplifications required by FEA. Because many of the V&V activities were conducted in parallel with the M&S development, these limits and risks were identified in the course of planned V&V activities, rather than prior to model development.

As part of the M&S development, a literature review was conducted to collect the suite of test data with which the FEM can be calibrated and validated. Verification and validation of the data was performed to ensure that the data is properly interpreted and that each source's results are consistent compared with other sources.

Concept validation is the process of confirming that the chosen abstraction types (in this case finite element modeling and logistic regressions) are adequate representations of the observed phenomena. Assessing the FEM's geometry, mesh quality, material models, and parameter sensitivity are all methods that can evaluate the choice of using the finite element method and reduce uncertainty in the model. When possible, the injury correlations were evaluated in two ways: first, by determining whether the response-injury outcome corresponds to a logistic regression model, and second by choosing the response that provides the best statistical fit to the injury data.

Two activities were performed as part of the FEM's design verification: 1) a check of the model's mass and inertial properties and 2) mesh convergence studies. The former activity tested whether the organ meshes occupy the intended region of space, while the latter confirmed that the mesh has the appropriate level of discretization, or *mesh density*. Mesh convergence studies reduce the computational cost of running the M&S by finding an optimal number of nodes and elements that produce satisfactory results.

Implementation verification activities were focused on ensuring that the FEM components have been integrated correctly. Various model checks, such as unconstrained modal analyses and energy checks were performed incrementally during the model development. Any problems that arose during these tests uncover problems in the model's design and were fixed prior to further development. Some of the model's test cases are performed in every instance of running the M&S and become the basis for defining the model's limitations.

Results validation is the final stage in the V&V process. Predictions from the two components of the M&S—the FEM and its injury correlations—were compared against test data. Force-deflection curves can be generated by the FEM and plotted against the response corridors established by other researchers. Postmortem Human Surrogates (PMHS) impacts that led to injuries can be simulated with the lower abdomen model and their outcomes compared to the M&S prediction.

The aforementioned V&V activities were completed in 2016. The greatest limiting factor for the V&V activities was finding enough viable data to conduct the results validation. This issue and additional technical hurdles in other V&V areas are documented in this report.

2 Problem Statement

The M&S was created to predict the *human effects* of blunt trauma to the lower abdomen and, more specifically, answer the following questions:

1. How does the lower abdomen of a human respond to the blunt impact of a KE-NLW?
2. What types of injuries will be incurred by blunt impact to the lower abdomen?
3. How severe will those injuries be to the lower abdomen?
4. What is the likelihood of incurring each injury type?

The M&S simulates the mechanical responses and interaction between the blunt impactor and the tissue of the lower abdomen. The body's responses to that impact, such as how the load becomes distributed, the internal deformation of each organ, and the stress state of those organs are computed by the M&S. That information is linked to empirically-derived dose-response curves to predict the type, severity, and likelihood of an injury to each organ.

The results of the M&S will guide decision-making at several stages of the acquisition process for KE-NLWs. During Development Test and Evaluation (DT&E), the M&S can evaluate the human effects of various KE-NLW design concepts or prototypes and indicate which design modifications yield the desired human effects. In the latter stages of the acquisition process, such as Operational Test and Evaluation (OT&E), the M&S can predict the cumulative Risk of Significant Injury (RSI) to an individual from a NLWS in various operational scenarios.

The results of this M&S are a critical part of the programmatic decisions made for a NLW system acquisition process; inaccurate predictions have several adverse consequences. An evaluation that overstates the injury risks may compel the developing agency into reengineering (in design, operation, or implementation) the NLWS to be safer. Likewise, if an evaluation understates the injury risks, a program could progress far into the latter stages of the acquisition process before discovering a critical design flaw. Mitigating these issues during OT&E or later would be significantly more costly. Furthermore, the deployment, operational usage, and training of the NLWS relies upon an accurate representation of the risks involved with its use. Significant inaccuracies could lead to the NLWS being rendered ineffective or excessively harmful when in actual use.

2.1 Intended Use

The M&S provides the capability to assess probability of injury to abdominal organs by simulating the impact between a NLW projectile and the lower abdomen. The probabilities of various injury occurrences are correlated to the abdomen's responses to a NLW impact and the damage limits of the associated tissues. The model is also intended to give guidance regarding the development of new non-lethal projectiles during their design phase, thereby allowing

developers to modify their designs to prevent unacceptable levels of injury while still yielding the desired effects on the targeted individuals.

2.2 M&S Overview

The M&S for which this report is written is a FEM that simulates the solid mechanics of a blunt impact to the lower abdomen combined with dose-response curves that use the FEM outputs to predict the probabilities of several types of abdominal injuries. The FEM includes the abdominal anatomy beginning from the diaphragm and extending downward beneath the small and large intestine, including the pelvis. Only key anatomical features have been incorporated into the FEM: the liver, kidneys, pancreas, spleen, intestines, gallbladder, pelvis, and a homogeneous tissue representing the skin, muscle, fat, and other viscera. All other anatomical features (e.g. tendons, ligaments, and blood vessels) were not included for simplicity. The dose-response curves are in the form of single parameter logistic regressions.

2.3 M&S Application

This subsection describes how the M&S will be used in the overall program and lists the program objectives that the M&S should meet in order to fulfill the intended use.

The M&S is one of several FEMs that model the biomechanics of blunt trauma, each dedicated to a specific region of the body. This collection, the Advanced Total Body Model, is itself part of a larger software application called the Human Effects Modeling Analysis Program (HEMAP), which is used to evaluate the human effects of all types of non-lethal stimuli including blast, thermal, auditory, flashblindness, and underwater acoustics.

The lower abdominal FEM, in conjunction with the rest of ATBM, can be used to conduct risk assessments of blunt impacts to various regions of the body. The output of ATBM is in the form of the probability of incurring certain injury types such as bone fractures or organ lacerations/ruptures. ATBM's output can then be aggregated into a final RSI that takes into account the relative severities of each injury type, the possibility of incurring more than one injury at a time, and the projectile's accuracy and velocity at a particular range.

2.4 Accreditation Scope

The interest of the JNLWD in assessing the NLWs procured in the future has led to the need to assess the injury risks of abdominal impacts. The scope of the accreditation effort will include a detailed review of the Accreditation Plan, the V&V Plan and this V&V report as well as supporting documentation to determine if the lower abdomen FEM and associated injury correlates are reliable, accurate, and appropriate for use in modeling abdominal impacts from the subject NLWS.

2.5 V&V Scope

This subsection describes the scope of the V&V effort based on the assessment of M&S requirements, acceptability criteria, and the availability of resources. The V&V establishes whether the M&S is implemented correctly, its abstractions are suitable to model the underlying physical phenomena, and that the M&S requirements have been acceptably met.

3 M&S Requirements and Acceptability Criteria

This section describes the M&S requirements defined for the intended use, the derived acceptability criteria that should be met to satisfy the requirements, the quantitative and qualitative metrics used to measure their success, and are sequenced in the order in which they are listed in the specifications document (Webber, Negus et al. 2014). Table 3-1 lists the relevant requirements and acceptability criteria for the components of the FEM (such as individual organs and referred to as sub-systems). Table 3-2 lists requirements and acceptability criteria for the FEM as a whole. Table 3-3 lists requirements for the dose-response injury regression curves that use FEM outputs to predict injury probabilities.

Table 3-1. List of requirements and acceptability criteria for M&S FEM sub-systems.

Req. #	Requirement	Necessary criteria	Preferred criteria
3.1.1.1	The sub-system must accurately represent the significant geometric features of the associated body part. Minor geometric details can be omitted.	FE mesh of each organ/part must match reference geometry volume within 5%	FE mesh of each organ/part must match reference geometry volume within 1%
3.1.1.2	The sub-system must accurately predict the biomechanical response to a stimulus for the strain rates of interest. Necessary strain rate ranges will be estimated according to iterative process of model development and availability of test data.	Model output falls within available response corridors for force-deflection curves for both high-mass/low-velocity impactors and low-mass/high-velocity projectiles.	Model output falls within available response corridors for field variables such as stress or strain time history for both high-mass/low-velocity impactors and low-mass/high-velocity projectiles.
3.1.1.3	The material properties of the organs should conform to the best available test data within the geometric size and strain-rate regimes of interest	The model of each organ material must be shown to agree within the corridors established from test data by simulating the tests and comparing the outcomes	Simulation results confirm that material properties produce matching responses (within established corridors) at several strain-rates and peak strains.
3.1.1.4	Model responses concur with injury mechanism (e.g. distribution of stress/strains	Qualitative comparison of shape and severity of damaged regions	Quantitative comparison of shape and volume of damaged regions

	match expected distribution or areas of damage based on test data)	between model and test data shows close agreement.	between test and model agree within 20%.
3.1.1.5	Geometry has been sufficiently discretized into an adequate number of elements.	Mesh convergence tests show displacement and force time-histories differ less than 5% at two consecutive levels of mesh density (defined as a baseline mesh and one where element size is halved).	Mesh convergence tests show displacement and force time-histories differ less than 2% at two consecutive levels of mesh density
3.1.1.6	Material model fully dissipates elastic strain energy and returns to a steady state. Necessary duration for simulation to run will be determined from analysis of time-to-steady-state figures found in literature review.	Test cases show that sub-system material model has dissipated 95% of all internal energy by the conclusion of the simulation.	Test cases show that sub-system material model has dissipated 100% of all internal energy by the conclusion of the simulation
3.1.1.7	Sub-system model maintains its integrity with a minimal number of deleted elements due to excessive deformation	Fewer than 5% of elements were deleted due to negative volume in all test cases	Fewer than 1% of elements were deleted due to negative volume in all test cases
3.1.1.8	Hourglass energy in the sub-system is minimal and limited throughout the simulation	Total hourglass energy never exceeds 10% of the initial system energy in any test case	Total hourglass energy never exceeds 5% of the initial system energy in any test case
3.1.1.9	Stable and numerically accurate elements are in use throughout the model	Tetrahedron or pentahedron elements comprise less than 5% of any organ.	Tetrahedron or pentahedron elements comprise less than 5% of any organ and are only used on posterior sides of organs.
3.1.1.10	Mesh quality of each sub-system is satisfactory	~~90% of the elements have a Jacobian between 0.9 and 1.0.~~ Mesh method delivers results within 10% of values achieved with mapped hex meshes	~~95% of the elements have a Jacobian between 0.9 and 1.0.~~ None.
3.1.1.11	Mesh is properly connected and does not have any artificial grounding	A free-free modal analysis of each sub-system yields precisely 6 rigid body modes and no unintended disconnected elements.	None.

Table 3-2. List of requirements and acceptability criteria for integrated FEM.

Req. #	Requirement	Necessary criteria	Preferred criteria
3.1.2.1	The integrated model must accurately predict the biomechanical response to a stimulus in the strain rates of interest.	Simulated force-deflection curves for high-mass/low-velocity impactors and low-mass/high-velocity projectiles must reside within tested response corridors	Additional model responses, such as strain or pressure also reside within established response corridors found in PMHS testing
3.1.2.2	Model responses concur with injury mechanism (e.g. distribution of stress/strains at or near failure level match expected distribution or areas of damage)	Qualitative comparison of shape and severity of damaged regions between models to test data shows close agreement	Quantitative comparison of shape and severity of damaged regions between test and model show close agreement
3.1.2.3	System model fully dissipates internal elastic energy and returns to steady state.	Test cases show that sub-system material model has dissipated 95% of all internal energy by the conclusion of the simulation	Test cases show that sub-system material model has dissipated 99% of all internal energy by the conclusion of the simulation
3.1.2.4	Model maintains its integrity with a minimal number of deleted elements due to excessive deformation	Fewer than 1% of elements were deleted due to negative volume in all test cases	Fewer than 0.1% of elements were deleted due to negative volume in all test cases
3.1.2.5	No spatial penetration exists between sub-systems	Complete model passes penetration checks by LS Pre-/Post	None
3.1.2.6	All contact and boundary conditions are properly initialized before the simulation	The model has no internal energy at the beginning of the simulation	None
3.1.2.7	Material model parameters proportionally affect simulation results	10% perturbations in critical material property parameters have proportional change in response (10% or less)	None
3.1.2.8	Hourglass energy is minimal and limited throughout the simulation	Total hourglass energy never exceeds 10% of the initial system energy in any test case	Total hourglass energy never exceeds 5% of the initial system energy in any test case
3.1.2.9	All contact parameters are implemented correctly	Adjacent parts slide together but do not penetrate	None

Table 3-3. List of requirements and acceptability criteria for injury regressions.

Req. #	Requirement	Necessary criteria	Preferred criteria
3.1.3.1	The probabilistic statistical classification model chosen is appropriate for each injury mode's actual statistical distribution.	The injury regression fits the trend of the data when plotted.	None
3.1.3.2	The chosen injury predictor is the model output that best predicts injury occurrence using the relevant goodness-of-fit statistics.	P-value < 0.05; Predictor's sensitivity to material properties is <10%; The predictor's chi-squared value is at or near the highest among other candidate predictors	None
3.1.3.3	The injury correlates predict the likelihood of injury at a rate similar to that of the original data set that derived the correlation.	The injury correlate predicts outcomes for an alternative set of data within 20% of the statistical fit measures used to develop the injury correlate (such as V50, chi-squared, percent correct prediction)	None

4 M&S Assumptions, Capabilities, Limitations, & Risks/Impacts

This section describes known factors that constrain the development and/or use of the M&S or that impede the VV&A effort, including the assumptions, capabilities, limitations, and risk factors affecting M&S development and risks associated with using the M&S for the intended use.

4.1 M&S Assumptions

This subsection describes the known assumptions about the M&S and the data used in support of the M&S in the context of the problem:

- The geometry is taken from the Zygote 3D Male Human Model (Zygote Media Group, American Fork, UT), which is assumed to be representative of a 50th percentile male.
- The FEM contains tissue (muscle, skin, organs, and bones). Each organ is treated as one continuum with uniform material properties contacting adjacent organs with sliding surface contact definitions.
- The necessary anatomical simplifications made to generate the FEM have a negligible effect on the relevant model outputs.
- Material properties are assigned based on available literature data, which are assumed to represent average tissue properties for the human population.

4.2 M&S Capabilities

The M&S can calculate both gross and micro-level dynamic responses of a 50th percentile male's lower abdomen under high-speed impacts. The responses are tied to model-specific injury correlates to predict the probability of injuries to the organs within the lower abdomen.

4.3 M&S Limitations

This subsection describes the known constraints and limitations associated with the development, testing, and/or use of the M&S. These constraints and limitations may be introduced as a result of an ongoing development process or may result from information garnered in previous VV&A efforts.

Since there are no yield, failure, or damage properties defined in the FEM, the model is limited to calculating the dynamic responses of impacts without material failure. Predicting the response of the lower abdomen after damage to an organ or the severity of the injury of the organ is beyond the present scope of the model in its current state.

The model either excludes or simplifies certain anatomical elements such as blood vessels, tendons, ligaments, and cartilage. Thus, predicting responses or injuries to these elements is outside the scope of the model's intended purpose.

Although the FEM is designed to complete all simulations during model construction and validation, abnormal termination due to element inversion or numerically infinite nodal velocities may be possible for more severe ballistic impacts. One of the V&V tasks in this report was performed to identify the range of initial conditions that do not cause the simulation to suffer any numerical problems.

The degree to which validation efforts can be undertaken is a function of the available resources, particularly the available data from post-mortem human subject (PMHS) tests. As the supply of data becomes exhausted, the validation of certain M&S components may remain incomplete or strictly qualitative.

4.4 M&S Risks/Impacts

This subsection describes the known risks associated with the development and/or use of the M&S within the context of the application. The model's capabilities are predicated on the available geometric and material properties as well as all necessary simplifying assumptions. In this case, the FEM is developed from a commercially-available geometry of a male abdomen and assigned properties based on available literature data.

The results are understandably most reliable for a person with the geometry and material properties that most closely match the FEM. Due to the large geometric and material variation in

these features within the global population, injury estimates may differ significantly on a case-by-case basis.

5 V&V Task Analysis

This section provides an overview of the results of the V&V inspection and testing activities, as outlined below. Included are details regarding any deviations from the V&V Plan and the justification for each change as well as all sources of data and any applicable quality-assurance documentation. Table 5-1 maps each requirement of the M&S to its associated V&V activity. Any modifications from the V&V Plan's method or acceptability criteria are summarized in the corresponding notes.

Table 5-1 V&V activity conducted for each requirement

Req. #	M&S Requirement Description	V&V Activity Type and Report Section	Notes	Status (Failed, Necessary, Preferred)
3.1.1.1	The sub-system must accurately represent the significant geometric features of the associated body part. Minor geometric details can be omitted.	Data Validation (Section 5.1.1.1)	No modification	Preferred
3.1.1.2	The sub-system must accurately predict the biomechanical response to a stimulus for the strain rates of interest. Necessary strain rate ranges will be estimated according to iterative process of model development and availability of test data.	Data Validation (Section 5.1.1.2.2) Result Validation (Section 5.5.1)	No modification	Necessary
3.1.1.3	The material properties of the organs should conform to the best available test data within the geometric size and strain-rate regimes of interest	Data Validation (Section 5.1.1.2, 5.1.1.2.2, 5.1.1.2.3)	Use available test to find suitable models	Necessary
3.1.1.4	Model responses concur with injury mechanism (e.g. distribution of stress/strains at or near the failure level match expected distribution or areas of damage based on test data)	Could not evaluate	Not conduct due to absent available test results	N/A
3.1.1.5	Geometry has been sufficiently discretized into an adequate number of elements.	Design Verification (Section 5.3.3)	No modification	Necessary
3.1.1.6	Material model fully dissipates elastic strain energy and returns to a steady state. Necessary duration for simulation to run will be determined from analysis of time-to-steady-state figures found in literature review.	Not evaluated	Not applicable	See below
3.1.1.7	Sub-system model maintains its integrity with a minimal number of deleted elements due to excessive deformation	Concept Validation (Section 5.2.2)	Setup erosion option at simulation to keep simulation stability	Necessary
3.1.1.8	Hourglass energy in the sub-system is minimal and limited	See below	Hourglass energy was less 15% in	See below

	throughout the simulation		high deformed organs	
3.1.1.9	Stable and numerically accurate elements are in use throughout the model	Concept Validation (Section 5.2.1)	All hexahedron	Preferred
3.1.1.10	Mesh quality of each sub-system is satisfactory	Concept Validation (Section 5.2.1)	Modified to create mesh with better minimum Jacobian	Necessary
3.1.1.11	Mesh is properly connected and does not have any artificial grounding	Design Verification (Section 5.3.3)	Model analysis of spleen and liver	Preferred
3.1.2.1	The integrated model must accurately predict the biomechanical response to a stimulus in the strain rates of interest.	Result Validation (Section 5.5.1)	On ballistic impacts	Necessary
3.1.2.2	Model responses concur with injury mechanism (e.g. distribution of stress/strains at or near failure level match expected distribution or areas of damage)	Could not evaluate	Not conduct since no available tests	N/A
3.1.2.3	System model fully dissipates internal elastic energy and returns to steady state.	See below	Damping was not considered for this application	See below
3.1.2.4	Model maintains its integrity with a minimal number of deleted elements due to excessive deformation	Concept Validation (Section 5.2.2)	Erosion to keep simulation stable	Necessary
3.1.2.5	No spatial penetration exists between sub-systems	Concept Validation (Section 5.4.2)	Segment-based contact formulation	Preferred
3.1.2.6	All contact and boundary conditions are properly initialized before the simulation	Implementation Verification (Section 5.4.2)	Zero initial internal energy	Preferred
3.1.2.7	Material model parameters proportionally affect simulation results	Design Verification (Section 5.3.1)	No modification	Preferred
3.1.2.8	Hourglass energy is minimal and limit throughout simulation	See below	Hourglass was less 15%	See below
3.1.2.9	All contact parameters are implemented correctly	Concept Validation (Section 5.4.2)		Preferred
3.1.3.1	The probabilistic statistical classification model chosen is appropriate for each injury	Results Validation (Section 5.5.2)	Segment-based contact	Necessary

	mode's actual statistical distribution.			
3.1.3.2	The chosen injury predictor is the model output that best predicts injury occurrence using the relevant goodness-of-fit statistics.	Results Validation (Section 5.5.2)		Necessary
3.1.3.3	The injury correlates predict the likelihood of injury at a rate similar to that of the original data set that derived the correlation.	Results Validation (Section 5.5.2)	Correlations were developed, validated and improved	Necessary

Four requirements pertaining to numerical stability (3.1.1.6, 3.1.1.8, 3.1.2.3, and 3.1.2.8) could not be fully addressed during model development. In some simulations, hourglass energy was found to exceed 10%, which will require further calibration of the hourglass parameters. The remaining two requirements intended to verify that simulations return to steady-state conditions after impact, which may involve the application and calibration of an artificial damping parameter.

5.1 Data V&V Task Analysis

5.1.1 Data Verification Task Analysis

This section describes data sources and any modifications made to the source data.

5.1.1.1 Anatomy

The proposed lower abdomen FE model includes skin, muscle, fat, liver, spleen, kidney, pancreas, gallbladder, intestines (small and large), stomach, spine and pelvis. The polygonal surfaces of geometry were exported from Zygote 3D Male Human Model (Zygote Media Group, American Fork, UT). The surfaces were imported into HyperMesh and smoothing was conducted to remove small complex details. Figure 5-1 depicted the exported liver, spleen and pancreas surfaces from Zygote Model. After small holes were filled and smoothed, the surfaces shown in Figure 5-2 were meshed in HyperMesh.

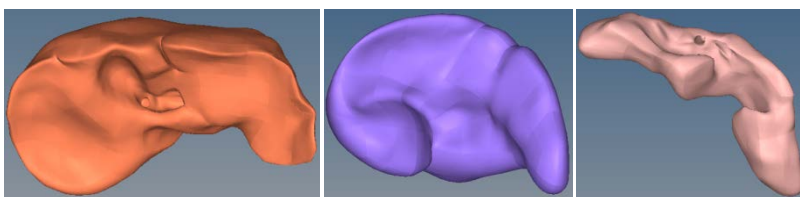


Figure 5-1. Exported liver, spleen and pancreas surfaces from Zygote.

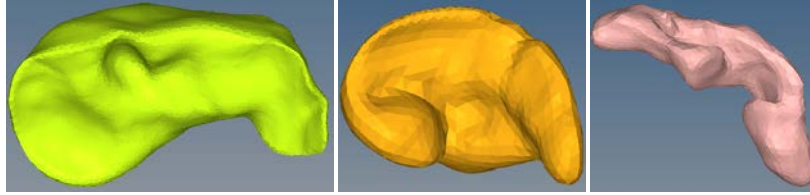


Figure 5-2. Detail removed liver, spleen and pancreas surfaces inside HyperMesh.

5.1.1.2 Organ Property Data

5.1.1.2.1 Muscle

The modified Split Hopkinson Pressure Bar (SHPB) system, shown in Figure 5-3, was used to test muscle properties under various strain rates (Song, Chen et al. 2007). The stress-strain curves along and perpendicular to the fiber direction are given in Figure 5-4. During high speed impacts, the large deformation will generally induce a maximum strain beyond the range of these stress-strain curves. An extrapolated stress-strain curve was used to model the hyperelastic property of general skin and muscle tissue. The average of the curves under a strain rate of 3700 s^{-1} and 1900 s^{-1} was used to model the stress-strain relationship for strains less than 0.5. The values for the range between 0.5 and 0.99 were extrapolated by fitting the lower strain values. The material models of skin, muscle, fat, pancreas and kidney were assumed to be a hyperelastic rubber (MAT_77_H in LS-Dyna, unit: kg, m, s) with a loading curve as shown in Figure 5-5 and other parameters listed in Table 5-2.

Table 5-2. Hyperelastic rubber parameters of skin.

$\rho \text{ (kg/m}^3\text{)}$	Poisson ratio	N	NV	G	SGL	SW	ST
1000	0.49	2	5	150	1	1	1

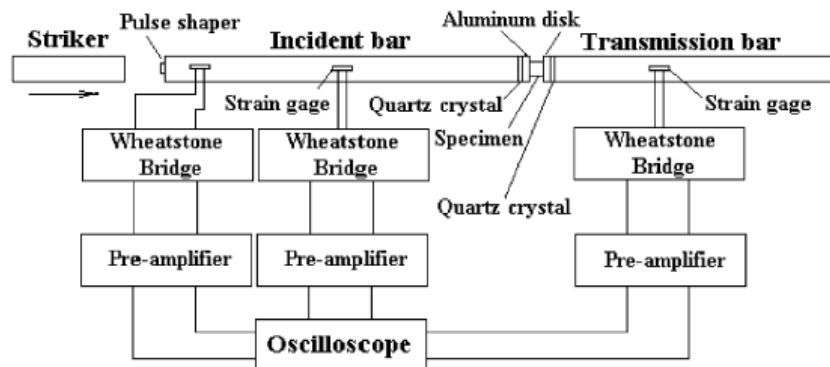


Figure 5-3. Schematic of a modified SHPB for testing soft biological tissue.

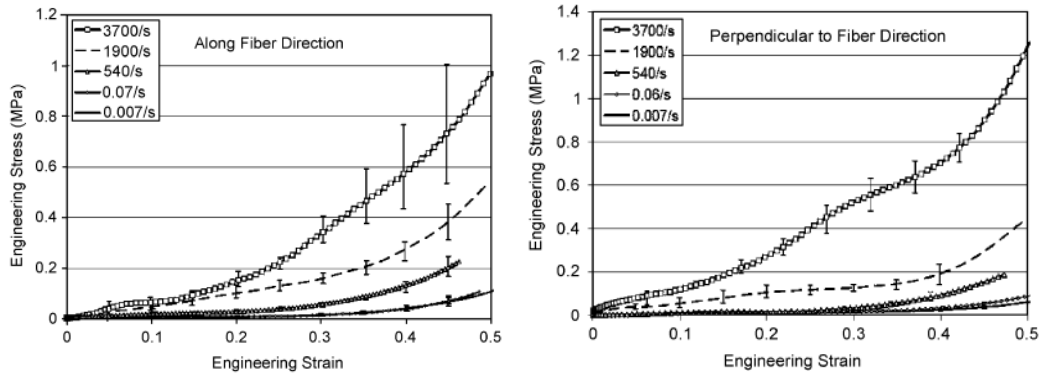


Figure 5-4. Stress-strain curves of muscle at various strain rates.

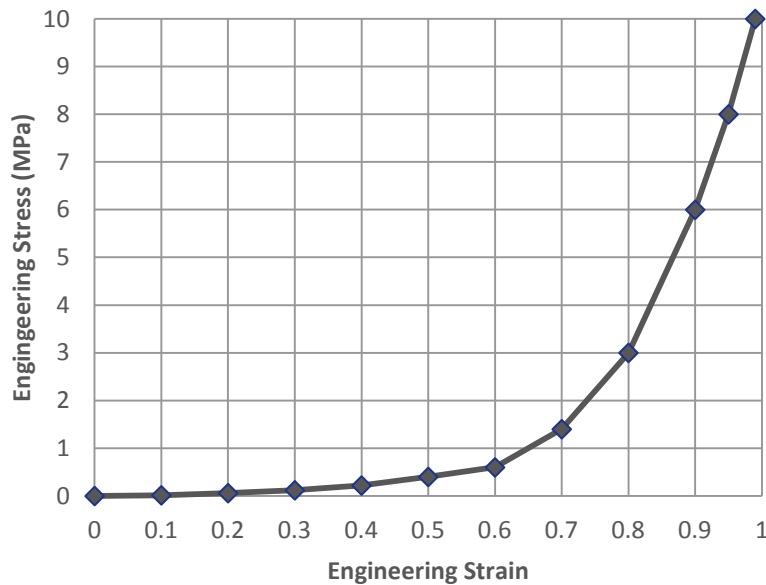


Figure 5-5. Extrapolated stress-strain curves for general muscle.

5.1.1.2.2 Liver and Spleen

Uniaxial compression tests were performed on cylindrical liver and spleen samples of constant thickness (Kemper, Santago et al. 2011). The results shown in Figure 5-6 from the liver and spleen compression tests demonstrate rate dependence, with strain decreasing and stress increasing with each increasing strain rate. The compressive failure stress for liver and spleen were 157.9~199.6 KPa and 35.0~62.3 KPa, strain were 0.456~0.607 and 0.369~0.404, respectively.

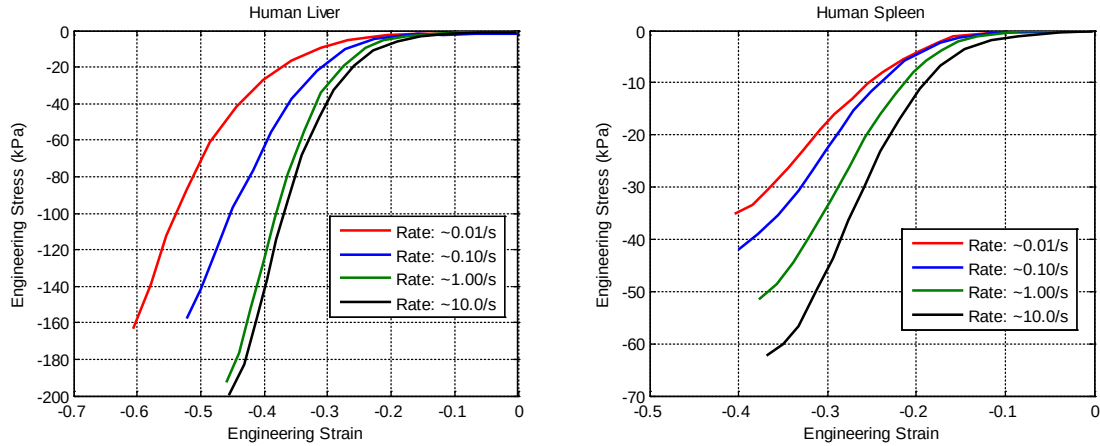


Figure 5-6. Characteristic averages for human liver and spleen in compression.

Ogden rubber models (MAT_77_O in LS-Dyna) were used to model the liver and spleen material properties by simulating the compression tests. Through a recursive optimization process, the model parameters were obtained for liver and spleen, shown in Table 5-3. The densities of liver and spleen were used the averages of reported data (Stingl, Baca et al. 2002).

Table 5-3. Ogden rubber model parameters for liver and spleen.

Organ	ρ (kg/m ³)	Poisson ratio	μ_i (kPa)	α_1	G_i (kPa)	β_i
Liver	1075	0.4995	6.7	8.8	190; 5000	0.33; 10000
Spleen	1044	0.4995	10	7.4	96; 5000	2.33; 10000

5.1.1.2.3 Stomach, Gallbladder, and Intestines

The hollow organs in lower abdomen include stomach, gallbladder and intestine (small and large were merged together). Using two type tools (Motorized Endoscopic Grasper and MTS setup), the tissue mechanical properties in vivo and postmortem for first and fifth cycle compression were measured by Rosen (Rosen, Brown et al. 2008) and shown in Figure 5-7. These results demonstrated the stress-strain relations were hyper elastic.

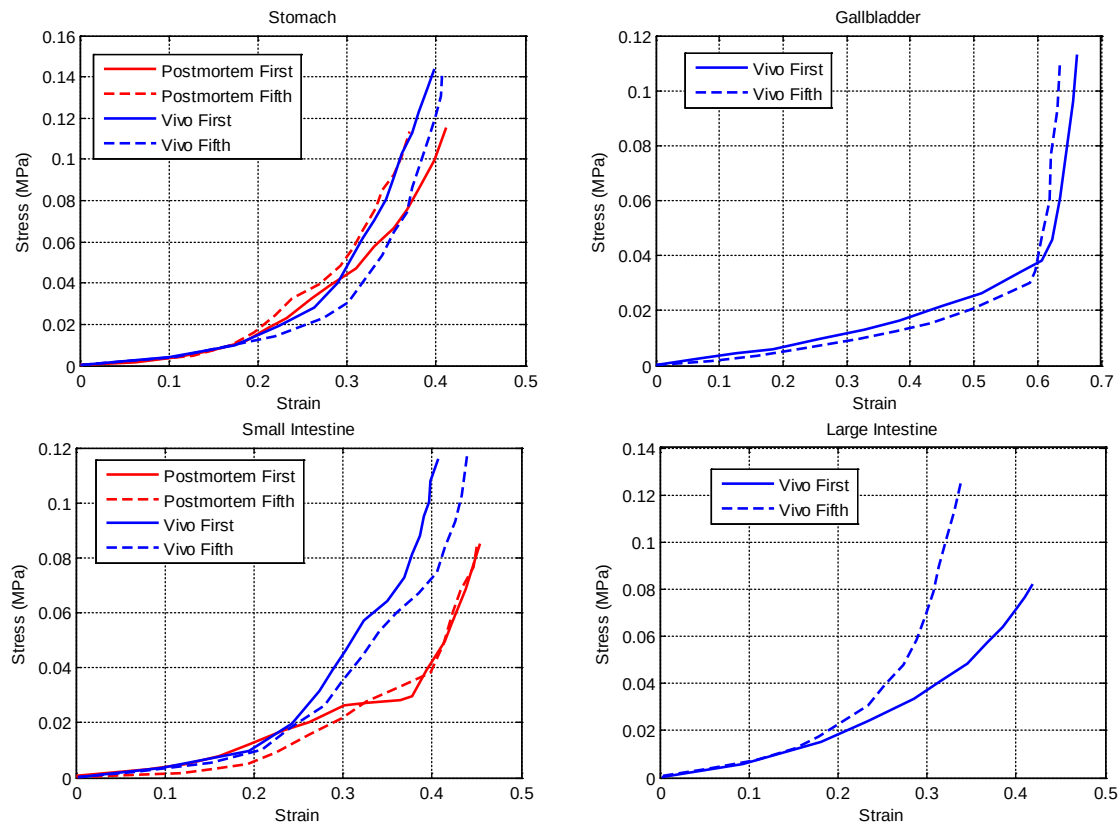


Figure 5-7. Hollow organ tissue stress-strain curves.

The stress-strain curves were first fitted by power formulations and then the maximum strain extended to 0.99. To reduce the model's complexity and save on simulation costs, hollow organs are assumed to behave like a simple elastic material (MAT 1 in LS-Dyna), and the modulus was selected to be 2 MPa for strains between 0.5 and 0.7.

5.1.1.3 Abdominal Impact Response Data

A total of six post-mortem human subjects (PMHS) were impacted with a rigid 37 mm diameter projectile weighing 45 grams at a speed of 60 m/s (Bir and Eck 2005). The force-deflection curves were shown in Figure 5-8. The average peak force was 4741 ± 553 N which occurred within 0.25ms. The average peak deflection of 22.9 ± 2.6 mm occurred over the first millisecond of the impact event.

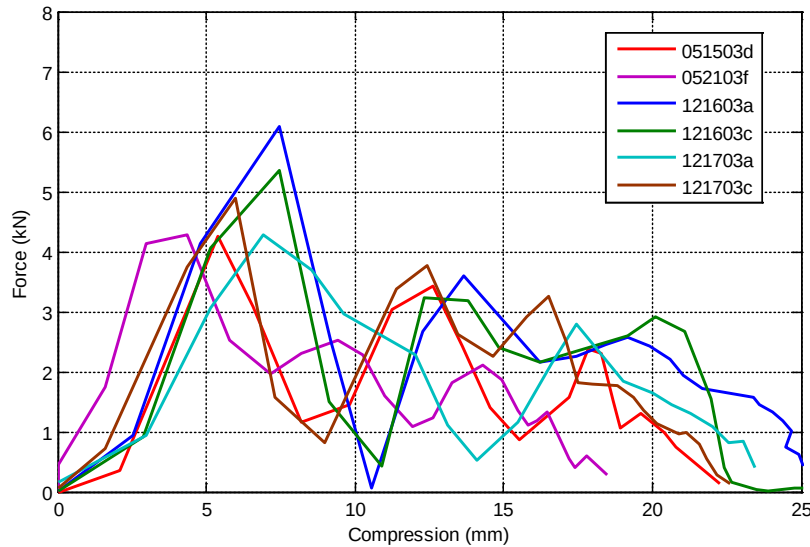


Figure 5-8. Force-deflection curves for six impact tests.

A series of eleven PMHS tests were conducted with a guided horizontal impactor at several speeds (Bouquet, Ramet et al. 1998). The rigid impactor was 200 x 200 mm flat and its weight was 12 or 16.2 kg. The impactor mass, speed, energy and measurements are listed in Table 5-4. The measured impact forces to pelvis are shown in Figure 5-9.

Table 5-4. Maximum measurements of PMHS pelvis impact tests.

Test N ^o	Impactor mass (kg)	Impactor speed (m/s)	Impact Energy (joule)	Max Result. accelerat (g)	F _s (N)	F _i (N)	Σ F (N)	Ratio F _s / Σ F %	Ratio F _i / Σ F %	(1) Measured Result. Force (N)	(2) Applied Force (N)
LCB 01	12.0	11.4	774		3 920	8 170	12 090	68	32	11 850	13 940
LCB 02	16.0	9.91	786	84	2 910	5 210	8 120	64	36	7 920	8 930
LCB 03	16.0	10.0	803	105	2 770	4 090	6 870	60	40	6 850	7 720
LCB 04	12.0	10.0	600	82	1 630	5 310	6 940	77	23	7 060	8 300
LCB 05	12.0	13.4	1077	107	3 560	6 170	9 730	63	37	10 020	11 790
LCB 06	12.0	13.7	1120	115	3 510	10 090	13 600	74	26	12 820	15 090
LCB 07	16.2	11.5	1073	86	3 290	11 660	14 950	78	22	14 310	16 120
LCB 08	16.2	11.8	1118	136	3 890	7 600	11 500	66	34	11 500	13 520
LCB 09	16.2	9.47	725	79	3 670	5 690	9 360	61	39	9 400	10 590
LCB 10	12.0	10.4	645	72	-	-	-	-	-	-	-
LCB 11	12.0	11.8	834	97	3 670	8 950	12 620	71	29	10 230	12 040
Mean								68%	32%		

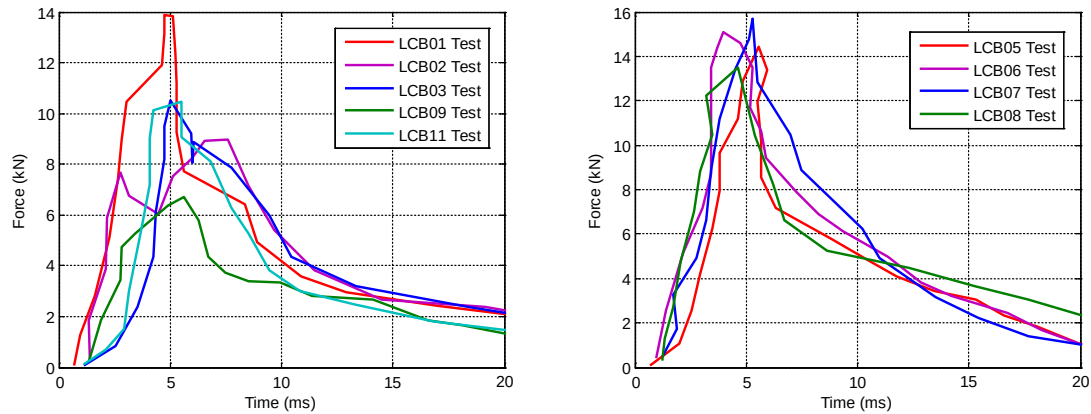


Figure 5-9. Applied force on PMHS pelvis impacts.

5.1.1.4 Abdominal Injury Data

Thirty-one impact tests were conducted on large white pigs of median weight 66kg (range 54~85kg) (Cripps and Cooper 1997). Five projectile masses were employed ranging from 52 gram to 377gram; impact velocities were range 15.9~85.8 m/s. The test matrix is provided in Table 5-5. Impacts were aimed 5 cm cranial to the prepuce in males and at an equivalent position in females. The injury outcomes are summarized in Table 5-6. It should be noted that animal weight was only reported in a range for each projectile in Table 5-6. To assign weight for individual subject, two hypotheses were tested: that injury occurred more easily for lower-weight subjects; and that a greater impact speed was necessary to create injury in the heavier subjects.

Table 5-5. Animal weight, projectile mass and impact velocity.

Group	Projectile mass (kg)	Projectile diameter (cm)	Number of animals	Body weight (kg)	Impact velocity	
					Median (m/s)	Range (m/s)
1	0.377	3.7	7	56–85	21.9	15.9–32.5
2	0.264	3.7	4	57–73	33.8	27.8–39.1
3	0.143	3.7	8	57–77	51.6	34.5–67.5
4	0.059	3.7	6	54–82	79.9	70.6–94.3
5	0.052	3	6	56–72	72.5	54.6–85.8

Table 5-6. Summary of biomechanical results from swine impact tests.

Test #	Animal Weight (kg)	Projectile Mass (gram)	Projectile Diameter (mm)	Impact Speed (m/s)	Intestinal Contusion
SH1	75.3	377	37	21.9	0
SH2	56	377	37	32.5	1
SH3	60.8	377	37	17.8	0
SH4	80.2	377	37	24.6	0
Sh5	85	377	37	29.5	0
SH6	70.5	377	37	15.9	0
SH7	65.7	377	37	19.3	0
SH8	57	264	37	38.4	1
SH9	62.3	264	37	39.1	1
SH10	67.7	264	37	27.8	0
SH11	73	264	37	28.4	0
SH12	71.3	143	37	49.8	1
SH13	77	143	37	53.4	0
SH14	65.6	143	37	58.8	1
SH15	68.4	143	37	46.2	1
SH16	59.9	143	37	52.4	1
SH17	74.1	143	37	34.5	0
SH18	57	143	37	56.2	1
SH19	62.7	143	37	44.4	1
SH20	59.6	59	37	76.2	1
SH21	70.8	59	37	91.6	1
SH22	65.2	59	37	94.3	1
SH23	76.4	59	37	70.6	0
SH24	54	59	37	80.1	1
SH25	82	59	37	79.6	0
SH26	65.6	52	30	74.3	1
SH27	62.4	52	30	85.8	1
SH28	72	52	30	54.6	0
SH29	68.8	52	30	59	1
SH30	56	52	30	70.2	1
SH31	59.2	52	30	74.4	1

5.1.1.4.1 Frontal Impact Injury

Three types of frontal abdominal loading were studied: rigid-bar impacts, seatbelt loading and close-proximity airbag deployments (Hardy, Schneider et al. 2001). Eleven rigid-bar free-back tests were performed into the mid and upper abdomens of PMHS using nominal impact speeds of 6 and 9 m/s. Table 5-7 outlines the subjects and conditions for free-back rigid-bar tests. The first

two tests involved a single subject and were used as proof-of concept and were excluded from calculation of the average values. The measured load histories for tests GI3-GI11 are given in Figure 5-10.

Table 5-7. Free-back rigid-bar test matrix of subjects and conditions.

Test	Region	Speed (m/s)	Gender	Age	Stature (cm)	Mass (kg)	Cadaver #
GI1*	mid	4.3	female	73	175	36	28594
GI2*	upper	4.3	female	73	175	36	28594
GI3	mid	6.3	male	87	173	73	28682
GI4	mid	6.6	female	93	165	58	28764
GI5	upper	6.0	female	65	164	61	28800
GI6	mid	6.1	male	85	165	91	28838
GI7	mid	9.1	male	74	181	77	28879
GI8	mid	9.0	male	71	182	64	28889
GI9	mid	9.6	female	85	155	51	28942
GI10	upper	8.9	male	64	180	65	29084
GI11	upper	6.2	male	74	168	75	29115
Average				78	170	68	

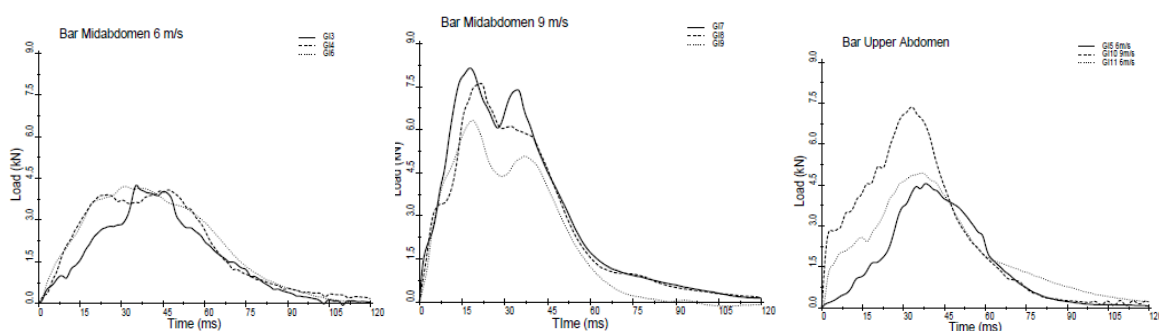


Figure 5-10. Load histories data for free-back rigid bar impacts.

Six seatbelt tests were conducted using three PMHS and a peak-loading rate of 3 m/s. The seatbelt loading tests were designed to maximize belt/abdomen interaction and were not necessarily representative of any real-world crashes. Table 5-8 outlines the matrix of subjects and test conditions that were used. Three PMHS were used in six tests, with each cadaver tested twice. The average subject's age, height, and mass were 81 years, 165 cm, and 59 kg, respectively. The seatbelt load histories are shown in Figure 5-11.

Table 5-8. Seatbelt loading test Matrix of subjects and conditions.

Test	Region	Type	Gender	Age	Stature (cm)	Mass (kg)	Cadaver #
CB1	mid	free	female	77	168	53	29311
CB2	mid	fixed					
CB3	mid	free	male	78	170	52	29116
CB4	lower	free					
CB5	mid	free	male	88	156	72	29131
CB6	lower	free					
Average				81	165	59	

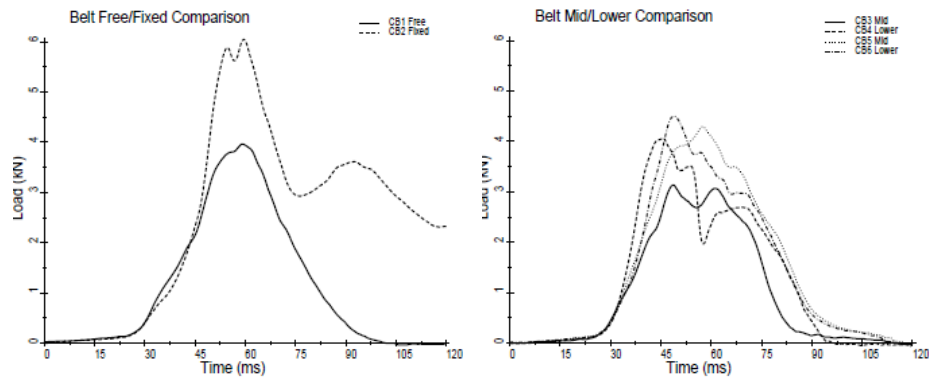


Figure 5-11. Load histories data for seatbelt loading.

Table 5-9 summarizes the test subjects and conditions used in the simulated airbag testing. The average PMHS age, stature, and mass were 75 years, 171 cm, and 72 kg, respectively. Three cadavers were used in six tests, with the first four tests performed on one cadaver. The first three of these tests were used to optimize the performance of the surrogate airbag device by adjusting the test setup. The first test was a free-back condition, while the second test used the same two-rung back support as in the fixed-back seatbelt test. The third test used the same rigid seat support used in the fixed-back rigid-bar tests. The fourth test was a repeat of the third test with a minor adjustment for peak abdominal penetration. The subsequent two tests were conducted in a similar fashion using two cadavers. The speed histories of airbag tests are given in Figure 5-12.

Table 5-9. Airbag loading test matrix of subjects and conditions.

Test	Airbag	Condition/ Spacing*	Gender	Age	Stature (cm)	Mass (kg)	Cadaver #
AA1	more aggressive	door/ 4 cm	male	83	160	73	29613
AA2	less aggressive	no door/ 0 cm	male	81	166	64	29739
AA3	less aggressive	no door/ 5 cm	female	79	169	64	29787
Average				81	165	67	

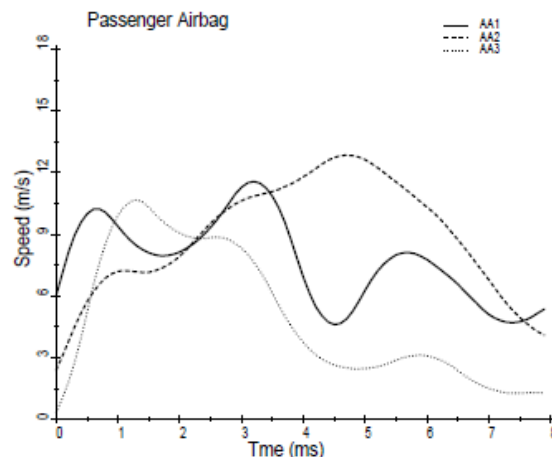


Figure 5-12. Time history for airbag loading.

Spleen laceration and intestinal contusion were recorded in these tests. Table 5-10 was the summary of tests results.

Table 5-10. Injury summary of spleen and intestine from three types of tests.

Test #	Weight (kg)	Loading Region	Load Condition	Spleen Laceration	Intestinal Contusion
GI3	73	Mid-abdomen	Rigid-bar	0	1
GI4	58	Mid-abdomen	Rigid-bar	0	0
GI5	61	Upper-abdomen	Rigid-bar	0	0
GI6	91	Mid-abdomen	Rigid-bar	1	0
GI7	77	Mid-abdomen	Rigid-bar	0	0
GI8	64	Mid-abdomen	Rigid-bar	0	0
GI9	51	Mid-abdomen	Rigid-bar	1	0
GI10	65	Upper-abdomen	Rigid-bar	1	0
GI11	75	Upper-abdomen	Rigid-bar	1	0
CB1	53	Mid-abdomen	Seatbelt	0	0
CB3	52	Mid-abdomen	Seatbelt	0	0
CB4	52	Lower-abdomen	Seatbelt	0	0
CB5	82	Mid-abdomen	Seatbelt	0	0
CB6	82	Lower-abdomen	Seatbelt	0	0
AA1	73	Mid-abdomen	Airbag	0	1
AA2	64	Mid-abdomen	Airbag	1	1
AA3	64	Mid-abdomen	Airbag	1	0

An additional series of tests using PMHS was conducted by Nusholtz, Kaiker et al. (1985) to investigate thoraco-abdominal impact response and kinematics secondary to steering wheel impact. The impact device, UMTRI Pneumatic Ballistic Pendulum Impact Device, consisted of either a 25 or 65 kg ballistic pendulum mechanically coupled with to the cannon which was used as the energy source. The PMHS was placed in a seated position on a mobile adjustable-height table covered with friction-reducing clear plastic sheets, and supported via a ceiling mounted rope cutter by the head and parachute harnesses. The lower aspect of the rim of steering wheel was positioned for impact 11 cm below the sternum (Figure 5-13a). More PMHS frontal abdominal impact tests were performed on new pendulum striker with weight 18 kg (Nusholtz, Kaiker et al. 1988). The striker is a physical model of the lower rim of a steering wheel, as shown in Figure 5-13b, attached to a rigid column support. It is not directly related to any production steering wheel assembly. Table 5-11 gives a summary of abdominal injuries included spleen, kidney, pancreas, and stomach under impact speed greater than 6 m/s. The heavy striker was impacted near the sternum, the intestines response will be affected significantly by ribcage. The intestinal injury was not considered since the developed lower abdomen FEM excluded ribcage.

Table 5-11. Abdominal injury summary for frontal impacts.

Test #	Subject Weight (kg)	Striker Mass (kg)	Impact Speed (m/s)	Spleen	Kidney	Pancreas	Stomach
83E121	75	25	9.5	1	0	0	0
83E131	75	25	12	0	0	0	1
84E142	75	65	11.8	1	0	0	1
84E153	75	65	11	0	0	0	0
84E163	75	65	12	0	1	1	0
84E173	75	65	7	0	0	0	0
84E181	75	65	9.3	0	1	1	0
85E193	75	65	11	0	0	0	0
86M001	70.1	18	10	0	1	0	0
86M010	40.2	18	6.5	0	0	0	1
86M020	57.5	18	7.5	0	1	0	1
86M040	50.0	18	10.8	0	0	0	0
86M050	70.3	18	9.3	0	0	0	0

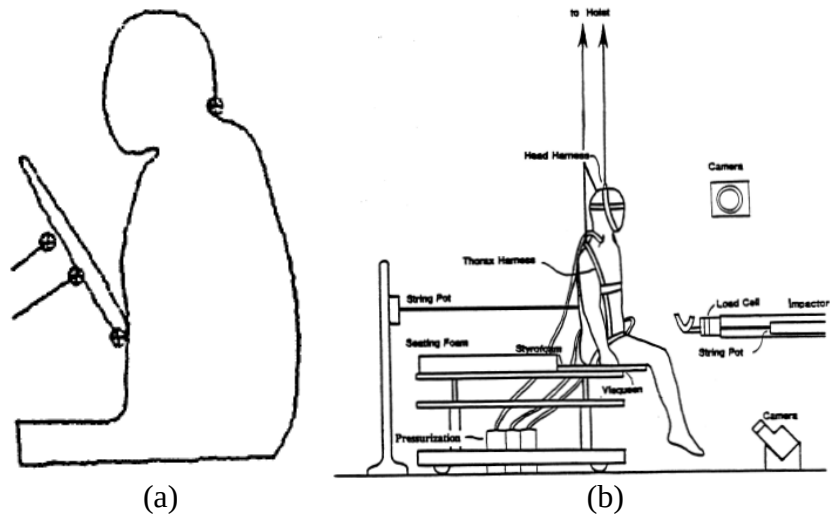


Figure 5-13. Frontal abdominal impact test setup by wheel and steering system.

5.1.1.4.2 Side Impact Injury

Flat-wall tests with PMHS were conducted by Cavanaugh at the WSU Bioengineering Center (Cavanaugh, Walilko et al. 1996). The tests utilized the WSU WHAM sled which was accelerated to 6.7 or 8.9 m/s and suddenly decelerated upon impacting a hydraulic snubber. During the deceleration, the subject slid across a Teflon seat into a wall instrumented with load cells. The summary of spleen lacerations was given in Table 5-12. The force histories of four types of flat wall tests: 6.7 m/s without padding, 9 m/s without padding, 9 m/s with soft and hard padding were shown in Figure 5-14.

Table 5-12. Spleen laceration summary under side impact by the flat-wall.

Test #	Padded	Subject Mass (kg)	Sled Speed (m/s)	Spleen Laceration
SIC04	No	57.6	9	1
SIC06	No	61.2	9	0
SIC05	No	44	6.7	0
SIC07	No	74.8	6.7	0
SIC08	No	73.9	6.7	1
SIC10	Soft	62.1	9	0
SIC11	Soft	55.3	9	0
SIC13	Soft	66.7	9	0
SIC15	Soft	68.9	9	0
SIC17	Soft	93	9	0
SIC09	Hard	54.9	9	0
SIC12	Hard	54.4	9	0
SIC14	Hard	55.3	9	1
SIC16	Hard	56.7	9	1

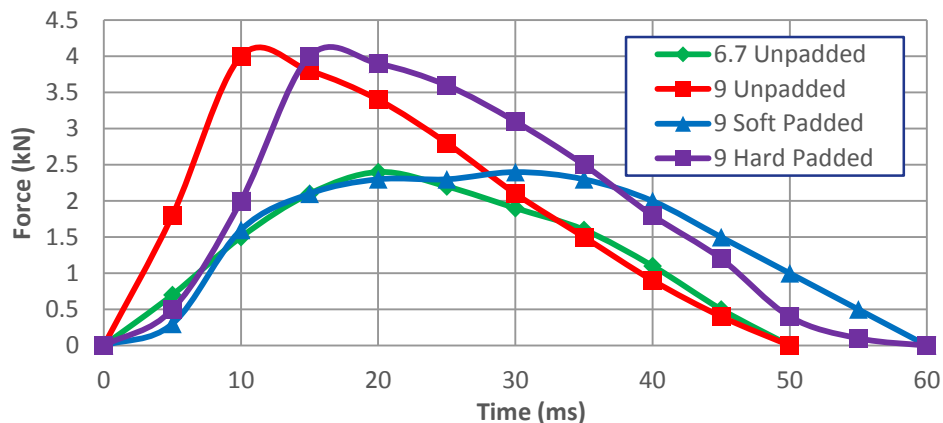


Figure 5-14. Force time history of abdominal load plate in flat-wall tests.

A series of lateral impacts was performed using seven PMHS at a custom-designed dual-sled test facility illustrated in Figure 5-15 (Miller and Rupp 2011). The test matrix is provided in Table 5-13. In five of the seven 3 m/s impacts, negligible or minimal skeletal injuries were observed, so higher severity tests with an initial impactor velocity of either 8 m/s or 10 m/s were conducted. Spleen laceration results for 5 high speed tests are shown in Table 5-14. The applied force histories for abdomen are illustrated in Figure 5-16.

Table 5-13. Test subjects and conditions.

Test Series ID	Age	Gender	Stature (cm)	Mass (kg)	t-score*	Tests Performed		
						3 m/s	8 m/s	10 m/s
NBA0901	86	M	170	77	-1.8	X		X
NBA0902	61	M	185	82	-0.9	X		
NBA0903	50	M	173	64	1.6	X		X
NBA1004	66	M	173	79	-	X	X	
NBA1005	51	M	183	98	2.6	X	X	
NBA1006	34	M	188	102	2.0	X	X	
NBA1107	87	M	175	73	-	X		

Table 5-14. Spleen laceration of side impacts.

Test #	Subject Weight (kg)	Impact Speed (m/s)	Spleen Laceration
NBA0901	77	10	0
NBA0903	64	10	1
NBA1004	79	8	0
NBA1005	98	8	0
NBA1006	102	8	0



Figure 5-15. Rendering of UMTRI's dual-sled impact facility.

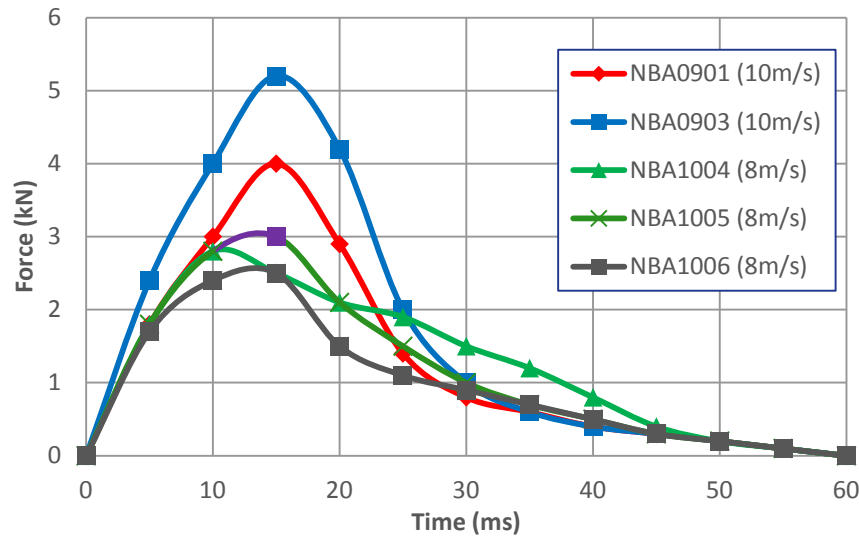


Figure 5-16. Applied force histories for abdomen for speeds 8 and 10 m/s.

Four side impacts on PMHS were performed by dynamic seat-mounted side airbag to observe the biomechanical and injury response to lateral interaction with a deployment torso airbag (Hallman, Yoganandan et al. 2010). The injuries of spleen and kidney were reported at Table 5-15. The measured abdomen force histories due to airbag deployment were given in Figure 5-17.

Table 5-15. Spleen and kidney injuries due to side airbag.

Test #	Subject Weight (kg)	Spleen	Kidney
D-1	50	1	0
D-2	84	0	1
D-3	56	0	0
D-4	108	1	0

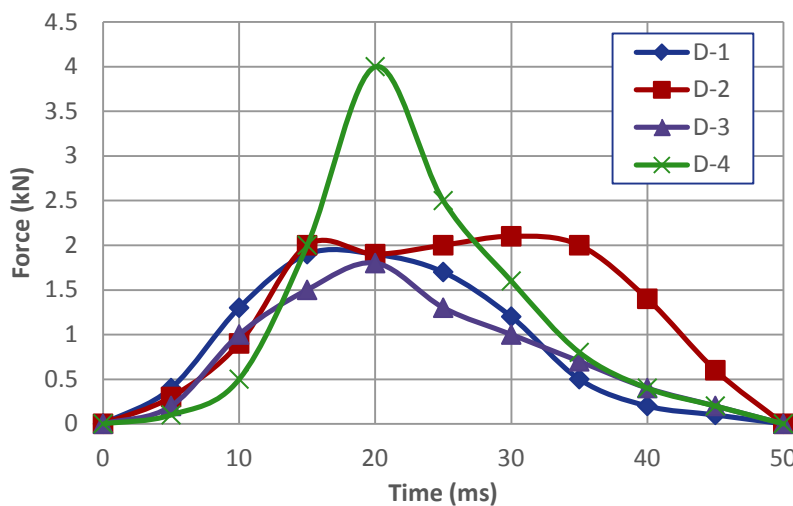


Figure 5-17. Abdomen force plate response history.

5.1.2 Data Validation Task Analysis

All source data was gathered from peer-reviewed literature sources and therefore an independent validation of the data was not performed.

5.2 Conceptual Model Validation Tasks Analysis

Several activities are performed to validate the conceptual models in use by this M&S. The geometric, FE meshing, and material model accuracy of the FE representation of the lower abdomen can be determined by standard model checks. Many of the FEM's concept validation activities shall be performed on each organ individually, while others will be conducted upon the FEM as a whole.

- **Geometric Accuracy:** Proof of which is obtained by comparing total volume and moments of inertia to the values found in the raw source geometry. This test satisfies requirement 3.1.1.1.
- **Mesh Quality:** Several statistics are available to quantify mesh quality, such as minimum angle and element Jacobians. This test satisfies requirement 3.1.1.10.
- **Material Models:** The applied material models can be evaluated according to how closely they can reproduce test data and the maximum loading rate for which the material model is stable. This test satisfies requirement 3.1.1.2.
- **Logistic Regression Empirical Model:** The incidence of particular injury modes for a specified model output will be examined to evaluate the validity of a logistic regression dose-response curve. This test satisfies requirement 3.1.3.1.
- **Injury Correlation:** Multiple model outputs can be chosen as candidate predictors for the injury predictions. Statistical measures of fit, such as chi-squared and p-value, will be reviewed to determine the best predictor of an injury type. This test satisfies requirement 3.1.3.2.

5.2.1 Geometry Abstraction

The lower abdomen anatomy was generated from the Zygote 3D Human Model of a 50th percentile male. The Zygote dataset contains a library of CAD models featuring detailed surface anatomy of the organs, musculoskeletal system, and vasculature. The anatomical surfaces of each organ, muscle, and bone in the lower abdomen were bounded into manifold volumes that comprised the most precise geometric definition available; however, the bounded volumes typically contain excessive physical detail. To avoid meshing the organs with excessively small elements at locations with high curvature, the volumes were first de-featured to remove unnecessary organ detail which allows for a consistent mesh size throughout.

To comply with requirement 3.1.1.1, the volume, center of gravity, and moments of inertia of the full-featured anatomy are compared to their counterparts from the de-featured anatomy. The comparison of part volumes in Table 5-16 indicates that the de-featured geometry differed from the original volume by an average of 2.9%. The center of gravity comparisons show that the position of the organs in the reference coordinate system has been relatively unchanged from the reference geometry (see Table 5-17). Lastly, Table 5-18 compares the principal moments of inertia of the original CAD and final FEM volumes to quantify how the organ's mass distribution was affected by the de-featuring process.

Table 5-16. Original CAD volume and final FEM volume for solid organs and bones.

Organ	Volume (m ³)		% Volume Difference
	CAD	FEM	
Kidney (Left)	1.76E-04	1.84E-04	4.0%
Kidney (Right)	1.58E-04	1.61E-04	2.1%
Liver	1.61E-03	1.63E-03	0.9%
Pancreas	1.07E-04	1.06E-04	-1.0%
Spleen	2.82E-04	2.80E-04	-0.8%
Pelvis (Left)	3.40E-04	3.24E-04	-4.8%
Pelvis (Right)	3.40E-04	3.24E-04	-4.8%
Spine T6	3.41E-05	3.17E-05	-7.0%
Spine T7	3.70E-05	3.51E-05	-5.1%
Spine T8	3.93E-05	3.75E-05	-4.4%
Spine T9	4.12E-05	3.88E-05	-5.8%
Spine T10	4.53E-05	4.35E-05	-4.1%
Spine T11	5.11E-05	4.95E-05	-3.1%
Spine T12	5.77E-05	5.54E-05	-4.0%
Spine L1	6.34E-05	6.07E-05	-4.1%
Spine L2	6.43E-05	6.18E-05	-3.9%
Spine L3	6.51E-05	6.26E-05	-3.8%
Spine L4	7.46E-05	7.20E-05	-3.4%
Spine L5	6.52E-05	6.31E-05	-3.1%
Sacrum	2.33E-04	2.29E-04	-1.4%
Average			-1.0%

Table 5-17. Center of gravity for original CAD and final FEM parts for solid organs and bones.

Organ	CAD Center of Gravity (m)			FEM Center of Gravity (m)			CG Diff (mm)
	X	Y	Z	X	Y	Z	
Kidney (Left)	0.0704	1.1329	-0.0159	0.0699	1.1327	-0.0151	0.99
Kidney (Right)	-0.0690	1.1246	-0.0057	-0.0685	1.1249	-0.0052	0.75
Liver	-0.0490	1.1986	0.0330	-0.0490	1.1987	0.0326	0.43
Pancreas	0.0199	1.1644	0.0324	0.0198	1.1645	0.0325	0.24
Spleen	0.0952	1.1866	-0.0029	0.0952	1.1867	-0.0030	0.13
Pelvis (Left)	0.0726	0.9490	-0.0179	0.0730	0.9493	-0.0180	0.52
Pelvis (Right)	-0.0726	0.9490	-0.0179	-0.0730	0.9493	-0.0180	0.52
Spine T6	0.0000	1.3605	-0.0705	0.0000	1.3606	-0.0699	0.62
Spine T7	0.0000	1.3343	-0.0691	0.0000	1.3346	-0.0683	0.87
Spine T8	0.0000	1.3089	-0.0644	0.0000	1.3091	-0.0638	0.68
Spine T9	0.0000	1.2834	-0.0579	0.0000	1.2838	-0.0570	1.02
Spine T10	0.0000	1.2565	-0.0508	0.0000	1.2567	-0.0502	0.63
Spine T11	0.0000	1.2275	-0.0413	0.0000	1.2276	-0.0408	0.50
Spine T12	0.0000	1.1963	-0.0319	0.0000	1.1965	-0.0313	0.61
Spine L1	0.0000	1.1636	-0.0239	0.0000	1.1638	-0.0234	0.55
Spine L2	0.0000	1.1307	-0.0154	0.0000	1.1309	-0.0145	0.99
Spine L3	0.0000	1.0966	-0.0102	0.0000	1.0967	-0.0094	0.86
Spine L4	0.0001	1.0625	-0.0084	0.0002	1.0623	-0.0077	0.76
Spine L5	0.0000	1.0302	-0.0133	0.0000	1.0300	-0.0128	0.61
Sacrum	0.0000	0.9840	-0.0488	-0.0001	0.9844	-0.0485	0.45
Average							0.64

Table 5-18. Principal moments of inertia for original CAD and final FEM parts for solid organs and bones.

Organ	Moments of Inertia (CAD)			Moments of Inertia (FEM)			% Diff		
	I ₁₁	I ₂₂	I ₃₃	I ₁₁	I ₂₂	I ₃₃	I ₁₁	I ₂₂	I ₃₃
Kidney (Left)	8.8E-05	2.3E-01	2.3E-01	9.6E-05	2.4E-01	2.4E-01	4%	4%	9%
Kidney (Right)	8.6E-05	2.0E-01	2.0E-01	8.6E-05	2.0E-01	2.0E-01	2%	2%	1%
Liver	5.9E-03	2.5E+00	2.5E+00	5.9E-03	2.5E+00	2.5E+00	1%	1%	-1%
Pancreas	1.5E-04	1.5E-01	1.5E-01	1.4E-04	1.4E-01	1.4E-01	-1%	-1%	-3%
Spleen	3.5E-04	4.2E-01	4.2E-01	3.4E-04	4.1E-01	4.2E-01	-1%	-1%	-2%
Pelvis (Left)	9.0E-04	5.6E-01	5.6E-01	8.1E-04	5.3E-01	5.3E-01	-5%	-5%	-10%
Pelvis (Right)	9.0E-04	5.6E-01	5.6E-01	8.1E-04	5.3E-01	5.3E-01	-5%	-5%	-10%
Spine T6	2.5E-05	1.2E-01	1.2E-01	2.2E-05	1.1E-01	1.1E-01	-7%	-7%	-12%
Spine T7	2.7E-05	1.3E-01	1.3E-01	2.4E-05	1.2E-01	1.2E-01	-5%	-5%	-10%
Spine T8	2.9E-05	1.3E-01	1.3E-01	2.7E-05	1.2E-01	1.2E-01	-4%	-4%	-9%
Spine T9	3.2E-05	1.3E-01	1.3E-01	2.8E-05	1.2E-01	1.2E-01	-6%	-6%	-12%
Spine T10	3.4E-05	1.4E-01	1.4E-01	3.1E-05	1.3E-01	1.3E-01	-4%	-4%	-9%
Spine T11	3.8E-05	1.5E-01	1.5E-01	3.5E-05	1.4E-01	1.4E-01	-3%	-3%	-7%
Spine T12	4.4E-05	1.6E-01	1.6E-01	4.0E-05	1.5E-01	1.5E-01	-4%	-4%	-9%
Spine L1	5.5E-05	1.6E-01	1.6E-01	5.0E-05	1.6E-01	1.6E-01	-4%	-4%	-8%
Spine L2	6.1E-05	1.6E-01	1.6E-01	5.5E-05	1.5E-01	1.5E-01	-4%	-4%	-10%
Spine L3	6.5E-05	1.5E-01	1.5E-01	5.8E-05	1.4E-01	1.4E-01	-4%	-4%	-10%
Spine L4	7.9E-05	1.6E-01	1.6E-01	7.3E-05	1.5E-01	1.5E-01	-3%	-3%	-8%
Spine L5	6.4E-05	1.3E-01	1.3E-01	6.0E-05	1.3E-01	1.3E-01	-3%	-3%	-7%
Sacrum	5.9E-04	4.3E-01	4.3E-01	5.8E-04	4.2E-01	4.2E-01	-1%	-1%	-3%
Average							-2.8%	-2.9%	-6.5%

5.2.2 Mesh Quality

The organ anatomy was extracted from Zygote 3D Male Human Model and the geometry was accurate enough to present human lower abdomen organs. In the initial plan, the organs were intended to be constructed from structured hexahedral meshes, which are more accurate and numerically robust than unstructured tetrahedral meshes for most applications. This method was employed for the left and right kidney using commercial meshing software (TrueGrid, XYZ Scientific, Inc., Livermore, CA). For highly curved geometry, however, the regularity of a structured, mapped mesh can only be achieved by sacrificing geometric accuracy and computational speed. Furthermore, structured hex meshes for some of the organs place the largest and most warped elements at the surface, leading to less discretization and accuracy precisely where injury risks are at their highest.

An alternative approach was developed to improve computational speed and element density at the surface for the remaining abdominal organs. Using HyperMesh, a tetrahedral mesh of the entire organ volume was generated. The tetrahedrons were then split into four hex elements each. While the tet-to-hex approach results in lower average element Jacobians, it provides other benefits:

- Elements have greater uniformity on the surface and gradually get larger near the interior;
- Computational speed is improved since the time step for explicit analysis is governed by the size of the smallest element;
- Fewer geometric abstractions are necessary, thus preserving the organ's anatomy.

A case study was conducted to evaluate the use of this approach (Figure 5-18). The liver and spleen were each meshed using both methods (structured hex and tet-to-hex) and were compared by simulating a direct impact to them from a rigid, 20-mm diameter, 20-gram cylinder at 20 m/s. The results in Table 5-19 indicate that peak stress, delivered energy, and peak impact force did not differ by more than 5%, while solve time was reduced by more than 20%.

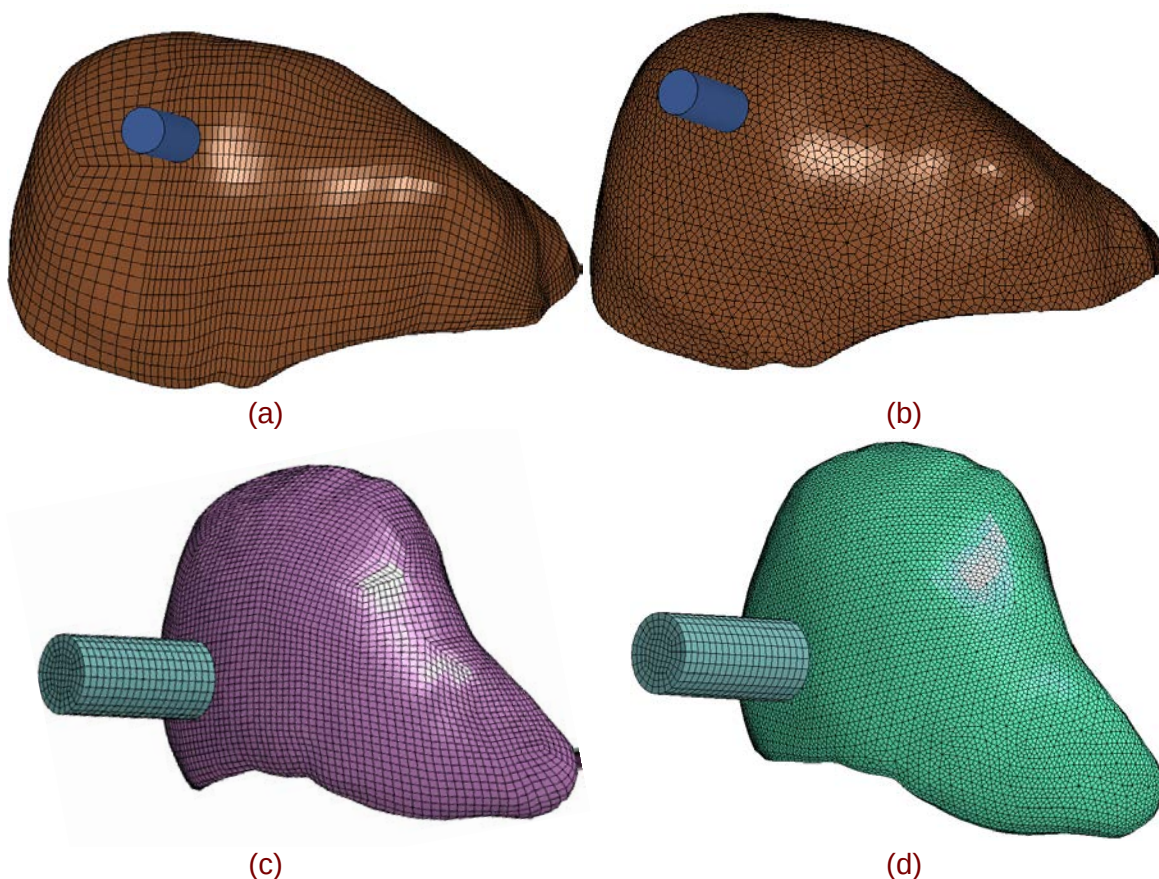


Figure 5-18. Simulation setup for mesh study of (a) structured hex mesh of liver, (b) tet-to-hex mesh of liver, (c) structured hex mesh of spleen, and (d) tet-to-hex mesh of spleen

Table 5-19. Comparison of meshing approaches for liver and spleen impacts.

Organ	Mesh Type	# Node	# Elems	Min. Jacob.	Solve Time (min)	Peak Stress (MPa)	Deliv. Energy (J)	Peak Impact Force (N)
Liver	Struct. Hex	66037	62847	0.03	15.1	8.43	14.75	2.34
	Tet-to-Hex	61617	52304	0.1	10.3	8.06	14.31	2.31
	% Difference				-31.8%	-4.4%	-3.1%	-1.3%
Spleen	Struct. Hex	117830	110592	0.1	28.5	2.44	3.81	0.98
	Tet-to-Hex	138599	119639	0.22	23.0	2.33	3.62	0.93
	% Difference				-19.3%	-4.5%	-5.0%	-5.1%

The spine included T6-T12, L1-L5 and sacral and was meshed as tetra elements. The beam elements were used to connect spine pieces together. The hollow organs were meshed as shell elements by taking the external face of hex elements and the solid elements will treated as filled fluid. The small and large intestines were merged into one part and only enclosed surface was mesh to avoid the details and internal contacts. A layer of fatty tissue, interior back muscles, and other viscera were inserted to fill gaps between the organs and muscle/skin layer. The minimum Jacobian shown in Table 5-20 was used to determine the simulation time steps and the reported values was good enough. Figure 5-19 gives the mesh of each organ.

Table 5-20. Mesh summary for lower abdominal organs.

Organ	Nodes	Elements	Min Length (mm)	Min Jacobian
Gallbladder	9389	Solid: 7628 Shell: 2148	0.50	0.22
Kidney	14786	13824	0.73	0.33
Liver	61617	52304	0.85	0.10
Pancreas	54948	45896	0.35	0.21
Spleen	39923	33568	0.52	0.12
Stomach	38641	Solid: 32252 Shell: 7113	0.49	0.22
Intestine	360021	Solid: 307124 Shell: 53553	0.40	0.22
Pelvis	32504	24856	0.76	0.21
Muscle/Skin	264772	225924	0.79	0.22

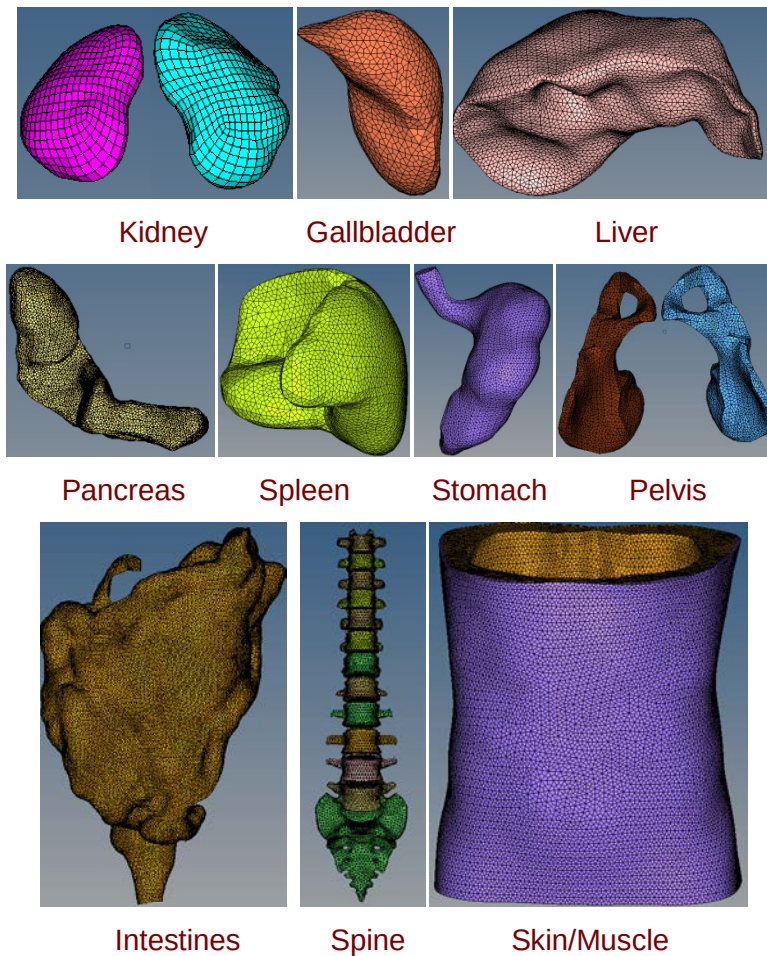


Figure 5-19. Lower abdomen mesh for each organ.

5.2.3 Material Models for Lower Abdomen Organs

A summary of the material models used in the lower abdomen is provided in Table 5-21. The hyper elastic rubber model described in Section 5.1.1.2 was determined to be an appropriate fit for the skin, muscle, fatty tissue, interior muscle, pancreas and kidney. The liver and spleen were assigned an Ogden rubber material models as described in Section 5.1.1.2.2. The hollow organs was assigned a simplified elastic model which is described in Section 5.1.1.2.3. The hollow organs are assumed to be filled with 50% water and 50% air, and modeled with an elastic fluid material. The density and bulk modulus were calculated based on percentages of water and air was 500.6 kg/m^3 ($0.5 \cdot 1000 + 1.26 \cdot 0.5$) and 1.1 GPa ($2.2 \cdot 0.5$), respectively.

The pelvis and spine were assigned simple models since the injuries of pelvis and spine were not considered in this study. A homogeneous elastic model was assigned for the pelvis, which the density and modulus were based on general bone properties. The values of modulus of cortical bones usually fall between 6 to 20 GPa (Coureau, Hobatho et al. 1998) (Zhao and Narwani 2007). For trabecular bones, the values of modulus were in the range of 0.01~6GPa. For

example, values between 0.4 and 3.6 GPa are reported by Ryan and Williams (1989), 3.81 and 5.72 GPa by Choi and Goldstein (1992), 0.01 and 0.291 GPa by Zhao and Narwani (2007). The modulus was selected to be 5 GPa with a density of 1800 kg/m³. To reduce computational cost, the vertebrae and sacral of spine were defined as rigid structures with correct bone density and connected by stiff elastic beams.

Table 5-21. Material models used in lower abdomen FEM

Material Model	Organs	Reference
Hyperelastic Rubber (MAT_77_H)	Muscle/Skin, Fatty Tissue, Interior Muscle, Pancreas, Kidney	Song, Chen et al. (2007)
Ogden Rubber (MAT_77_O)	Liver	Kemper, Santago et al. (2011)
Ogden Rubber (MAT_77_O)	Spleen	Kemper, Santago et al. (2011)
Elastic $\rho = 1000 \text{ kg/m}^3$, $E = 2 \text{ MPa}$, $\nu=0.49$	Shell of Intestine, Stomach, Gallbladder	Rosen, Brown et al. (2008)
Elastic Fluid $\rho = 500.6 \text{ kg/m}^3$, $K = 1.1 \text{ GPa}$, $\nu=0.35$	Filled Solid of Intestine, Stomach, Gallbladder	See section 5.2.3
Elastic $\rho = 1800 \text{ kg/m}^3$, $E = 5 \text{ GPa}$, $\nu=0.33$	Pelvis	See section 5.2.3
Rigid $\rho = 1900 \text{ kg/m}^3$, $E = 10 \text{ GPa}$, $\nu=0.33$	Spine	See section 5.2.3

5.3 Design Verification Task Analysis

This subsection describes the analysis of the results of each design verification task.

The design of the M&S will be verified through a series of checks intended to identify and remedy any improper numerical artifacts within the FEM. Furthermore, each task verifies that two or more aspects of the model are interacting together properly. These tasks are:

- **Mass and Inertial Properties:** A comparison of the mass and inertial properties of the model's organs will confirm correct application of the material density and geometric distribution. This test satisfies part of requirement 3.1.1.3.
- **Parameter Sensitivity:** Because the material properties will vary due to large differences in typical human tissue samples, response sensitivity to material property perturbations should be studied to ensure the output does not vary disproportionately to small changes in input properties. A secondary benefit will be that the output parameters that vary least are likely to be the best predictors of injury. This test satisfies requirement 3.1.2.7.
- **Mesh Convergence:** An appropriate level of mesh discretization must be determined to ensure that the FEM is capturing the phenomena it is intended to model. The simulation results from three meshes with different densities must be compared to identify the

appropriate element size to achieve converged results. This test satisfies requirement 3.1.1.5.

5.3.1 Mass and Inertial Properties

The mass of the abdominal organs in the mesh is compared in Table 5-22 with the ranges established for adult males by Molina and Dimaio (2012) and Caglar, Kumral et al. (2014).

Table 5-22. Organ mass comparisons from literature and FEM.

Organ	Literature Source	Literature Mass [g]			FEM Mass [g]
		Average	Min	Max	
Kidney	Molina (2012) (Right/Left)	129	79	223	161.0
		137	74	235	183.5
	Caglar (2014) – Average	150.7	85	309	172.2
Liver	Molina (2012)	1561	838	2584	1747.9
Pancreas	Caglar (2014)	87.3	41	174	105.8
Spleen	Molina (2012)	139	43	344	292.4
	Caglar (2014)	209	48	720	

5.3.2 Parameter Sensitivity

A material sensitivity study was to investigate the variation of model responses to material parameters, including density and modulus. In this study, the model responses were von-mises stress of liver, spleen, pancreas, intestine, stomach and gallbladder. The material variation included density offset by 80% and 120% of the original value, and stiffness offset by 80, and 120%, respectively. For elastic model, stiffness offset implemented by scaling modulus. For other complex models, the offset can be done by scaling defined loading curve or associated stiffness parameters. The interested organs were separated six group organs, muscle/skin/front fat, liver, spleen, pancreas/kidney, hollow organs shells (intestine, stomach, and gallbladder), and filled fluid.

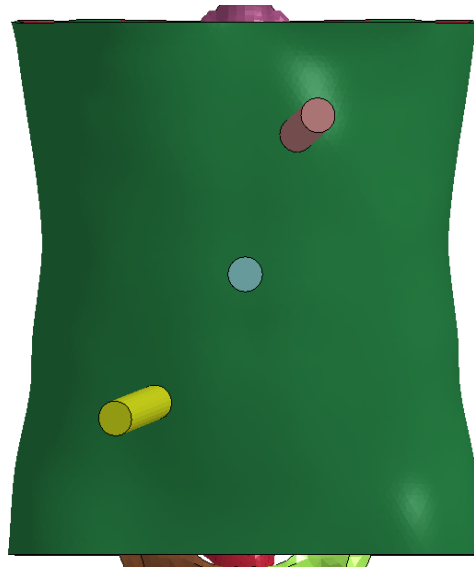


Figure 5-20. Simulation setup for material sensitivity study.

The sensitivity study was conducted by simulating the three 97 gram, 25 mm diameter projectiles frontal impacting at speed 50 m/s (Figure 5-20). For each simulation, only one group varied the density or stiffness. The sensitivity of density was listed in Table 5-24. It can be seen that the response variation (< 20%) was less density offset (40%) and the density effect was convergent. The density of muscle/skin/front fat has the most affects on response since higher density means larger mass were involved into impacting interaction, it will be less energy delivered to internal organs. Table 5-24 gives the stress variation under stiffness offsets. It was proved that the stiffness effect was also convergent since 40% offset only caused < 22% response variations. The hollow organs stiffness had the most effect on own responses. For filled fluid, the offsets were conducted by 50%, 75% and 100% water. Since the density and bulk were calculated by fraction percentages of water and air, the offset of density and stiffness was coupled together and the result was identical.

Table 5-23. Peak stress variation to density $\pm$ 20% offset.

Organ	Skin, Muscle & Front Fat	Liver	Spleen	Pancreas & Kidney	Hollow Organs	Filled Fluid
Liver	7.6	3.6	0.1	0.2	0.6	1.9
Spleen	4.5	0.9	0.3	0.4	0.7	1.1
Pancreas	11.9	2.0	0.3	3.7	2.0	2.0
Kidney	10.9	0.7	0.2	2.1	1.3	7.7
Gallbladder	17.6	3.3	0.8	2.1	3.8	13.3
Intestine	5.1	0.1	0.1	0.1	1.6	4.7
Stomach	9.3	4.7	0.3	1.2	2.4	7.6

Table 5-24. Peak stress variation to stiffness $\pm 20\%$ offset.

Organ	Skin, Muscle & Front Fat	Liver	Spleen	Pancreas & Kidney	Hollow Organs	Filled Fluid
Liver	1.1	10.5	0.1	0.1	0.1	1.9
Spleen	0.4	0.2	1.4	0.7	0.1	1.1
Pancreas	1.4	2.3	0.4	6.7	1.5	2.0
Kidney	4.7	0.7	0.3	5.2	1.6	7.7
Gallbladder	3.3	4.7	0.3	1.0	19.8	13.3
Intestine	0.9	0.2	0.1	0.1	11.7	4.7
Stomach	1.2	2.2	0.5	1.3	21.1	7.6

5.3.3 Mesh Convergence

Mesh sensitivity studies were conducted on the liver and spleen to investigate the response to mesh variable resolutions using a modal analysis as well as an explicit simulation of a blunt impact. The modal analysis was completed to calculate the natural frequencies of the spleen and liver. The blunt impact was simulated using a 20 gram, 20 mm diameter projectile at a speed of 40 m/s on the three meshes of spleen shown in Figure 5-21. Table 5-25 listed the mesh resolutions, natural frequencies and responses of three meshes. It showed that mesh 2 and 3 have enough resolution for accurate results which differences were less 5%.

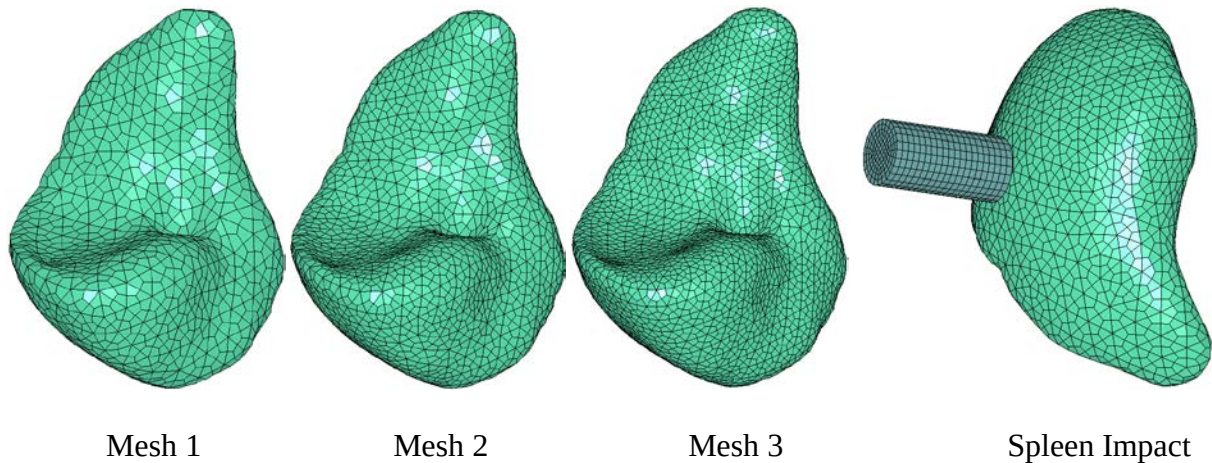


Figure 5-21. Three meshes of spleen for sensitivity study.

Table 5-25. Result of spleen mesh sensitivity study.

		Mesh 1	Mesh2	Mesh3	Diff 1-2	Diff 2-3
Mesh Resolution	Nodes	19039	22249	27019		
	Element	16724	19140	22795		
Modal Analysis	1 st Frequency	76.81	76.34	76.09	0.63%	0.33%
	2 nd Frequency	113.20	112.38	112.12	0.73%	0.23%
	3 rd Frequency	152.10	151.14	150.73	0.63%	0.27%
	4 th Frequency	171.20	170.03	169.73	0.69%	0.18%
	5 th Frequency	192.13	190.96	190.46	0.61%	0.26%
Responses	Peak Stress (MPa)	6.96	7.44	7.43	6.37%	0.02%
	Peak Pressure (MPa)	2.52	2.66	2.71	5.21%	2.13%
	Delivered Energy (J)	14.20	14.17	13.66	0.19%	3.78%
	Peak Impact Force (kN)	2.25	2.13	2.04	5.77%	4.43%
	Delivered Impulse (N.s)	0.98	0.99	1.00	1.12%	0.42%

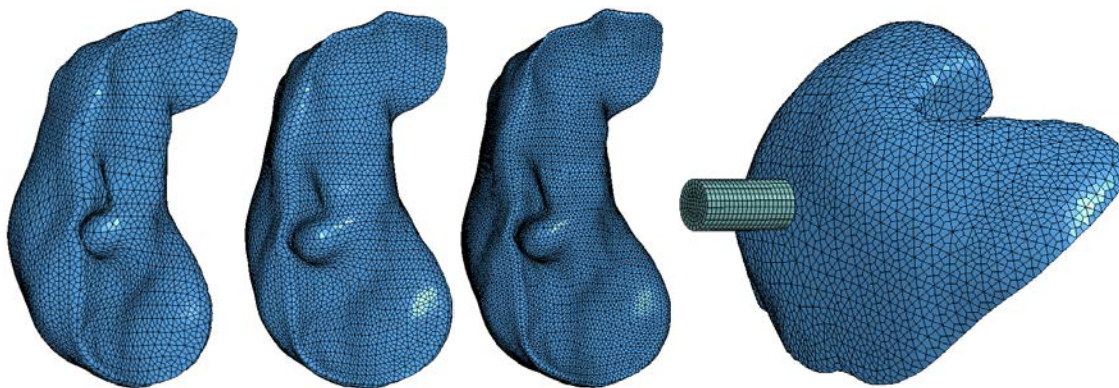


Figure 5-22. Three meshes of liver for mesh convergence study.

Figure 5-22 was illustrated three liver meshes and impact setup for mesh sensitivity study. The rigid projectile with 20 gram weight and 20 mm diameter impacted liver at speed 40 m/s. Table 5-26 presented the summary of sensitivity results. It can be seen that Mesh 2 has enough resolution comparing Mesh 2 which differences between Meshes 2 and 3 were less 4%.

Table 5-26. Summary of results of liver mesh sensitivity study.

		Mesh 1	Mesh2	Mesh3	Diff 1-2	Diff 2-3
Mesh Resolution	Nodes	37109	61617	80087		
	Element	31164	52304	69456		
Modal Analysis	1 st Frequency	48.70	48.58	48.54	0.24%	0.08%
	2 nd Frequency	59.09	58.84	58.71	0.42%	0.21%
	3 rd Frequency	74.84	74.59	74.50	0.33%	0.12%

Responses	4th Frequency	92.23	91.71	91.40	0.56%	0.35%
	5th Frequency	97.93	97.08	96.85	0.88%	0.23%
	Peak Stress (MPa)	8.07	8.84	9.18	8.71%	3.76%
	Peak Pressure (MPa)	2.34	2.37	2.38	1.22%	0.51%
	Delivered Energy (J)	14.25	14.39	14.70	0.96%	2.11%
	Peak Impact Force (kN)	2.12	2.12	2.19	0.04%	3.25%
	Delivered Impulse (N.s)	1.06	1.06	1.07	0.19%	0.66%

Comparing the mesh resolutions of lower abdomen FEM given in Table 5-20, other organ meshes have equal or smaller resolution than the meshes of liver and spleen used in this sensitivity study. Thus, the current mesh implemented in for the remaining organs of the lower abdomen FEM was considered to be adequately converged.

5.4 Implementation Verification Task Analysis

This subsection describes the analysis of the implementation verification test results. The overarching purpose of these tasks is to verify that the individual M&S components, such as material models, contact definitions, simulation parameters, geometry, and mesh, are incorporated into the M&S correctly. These tasks are:

- **Sub-System Modal Analysis:** The first ten eigenvalues and eigenvectors were computed for each part (organ) of the model by itself. The first six modal frequencies will be near zero, and their modal effective masses will sum to 100%. The remaining modes were viewed to verify that the organ mesh is connected properly throughout. This test satisfies part of requirement 3.1.1.11.
- **Part Penetration:** A penetration check was performed with LS Dyna to verify that no two organs intersect one another. This test satisfies requirement 3.1.2.5.
- **Contact Parameters:** The contact forces were viewed to verify that the contact definitions were applied correctly between adjacent parts. This test satisfies requirement 3.1.2.9.
- **Steady State Initial Conditions:** An explicit simulation was run for 1 ms to verify that no internal (deformation) energy exists within the system at the beginning of the simulation. This test satisfies requirement 3.1.2.6.
- **Numerical Stability:** An explicit impact simulation that lasts at least 2 ms after contact concludes between the impactor and abdomen were run to verify that element deletion due to large tissue deformations are not excessive. This test satisfies requirement 3.1.2.4.

5.4.1 Sub-System Modal Analysis

A free-free modal analysis was performed on each organ to verify the connectivity of its elements and ensure that there are no constraints applied to the organ's nodes. The organ should have exactly six rigid-body modes, which can be comparing the first six natural frequencies to

the seventh as well as confirming that the modal effective mass in all three directions are 100% by the sixth mode. Table 5-27 and Table 5-28 list the results of this analysis, which indicate that there are no incorrect constraints applied to the systems, and that the elements of each organ mesh are properly connected.

Table 5-27. The six rigid-body mode and first flexible-body mode frequencies.

Organ	Frequency (Hz)						
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7
Gallbladder	1.8	0.5	1.7	2.2	3.4	4.1	3333.4
Kidney (L)	0.4	0.3	0.3	0.1	0.3	0.4	156.3
Kidney (R)	0.5	0.4	0.4	0.1	0.2	0.3	151.0
Liver	0.2	0.2	0.1	0.1	0.1	0.1	10.3
Muscle	2.3E-02	1.9E-02	9.3E-03	1.1E-02	1.9E-02	2.6E-02	1.5
Pancreas	0.6	0.5	0.3	0.1	0.4	0.6	24.7
Spleen	0.3	0.2	0.1	0.1	0.3	0.4	12.5
Stomach	2.3	1.8	1.0	0.3	1.4	2.5	709.5
Skin	2.5E-01	2.2E-01	1.8E-01	1.4E-01	3.5E-02	1.5E-01	1.6

Table 5-28. Cumulative modal effective mass for the lower abdomen organs at the 6th mode.

Organ	Cumulative Sum of Modal Effective Mass at 6th mode					
	X-dir (kg)	(%)	Y-dir (kg)	(%)	Z-dir (kg)	(%)
Gallbladder	0.026	100%	0.026	100%	0.026	100%
Kidney (L)	0.184	100%	0.184	100%	0.184	100%
Kidney (R)	0.161	100%	0.161	100%	0.161	100%
Liver	1.748	100%	1.748	100%	1.748	100%
Muscle	8.855	100%	8.855	100%	8.855	100%
Pancreas	0.106	100%	0.106	100%	0.106	100%
Spleen	0.292	100%	0.292	100%	0.292	100%
Stomach	0.191	100%	0.191	100%	0.191	100%
Skin	1.652	100%	1.652	100%	1.651	100%

5.4.2 Part Penetration and Contact Parameters

Contact definitions between adjacent organs were manually checked for errors with the LS-Dyna solver and LS-PREPOST. A summary of the contact checks is shown below in Table 5-29. A simulation was also run involving no impact, and internal energy remained zero throughout.

Table 5-29. Contact pairs verified to have no penetrations or other instabilities at the start of the simulations.

Contact Pairs	Gallbladder	Left Kidney	Right Kidney	Liver	Pancreas	Spleen	Lg Intestines	Sm Intestines	Stomach	Front Fat	Back Muscle	Left Pelvis	Right Pelvis	Spine	Muscle
Gallbladder															
Left Kidney															
Right Kidney															
Liver															
Pancreas															
Spleen															
Lg Intestines															
Sm Intestines															
Stomach															
Front Fat															
Back Muscle															
Left Pelvis															
Right Pelvis															
Spine															
Muscle															

KEY

- No penetrations
- Penetrations
- Immediate crash
- No contact defined

5.4.3 Numerical Stability

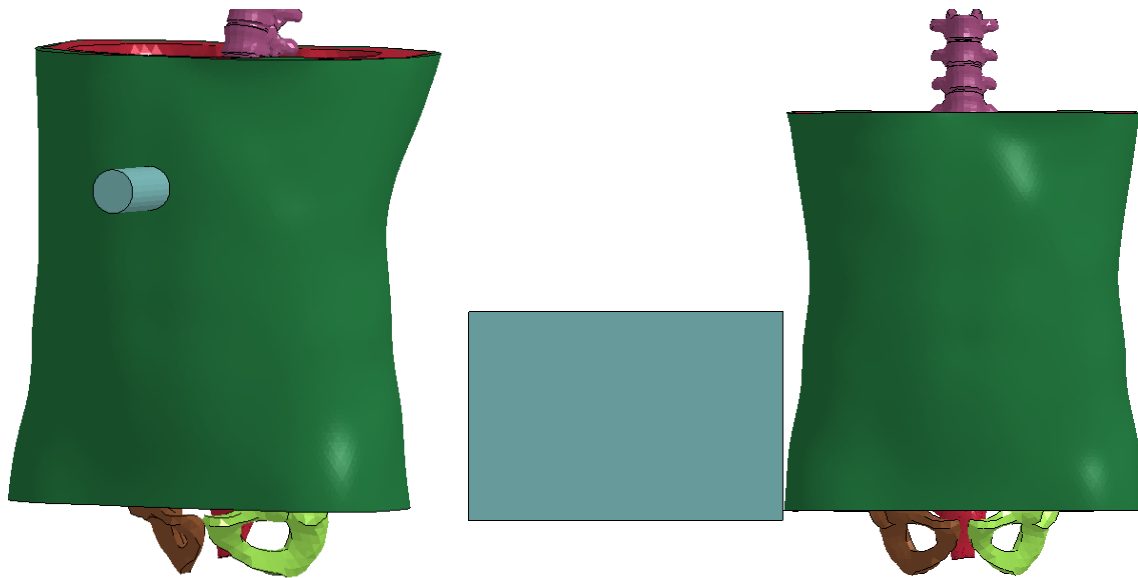
Element erosion control allows LS-DYNA to delete excessively deformed elements to prevent the simulation from crashing. When element erosion is minimal, it only negligibly affects the physics of the impact. In most of the analysis cases, no elements were eroded, however, in a few cases involving a large mass and high speed, the simulations had a trivial number—less than 1% of all elements—of eroded elements.

5.5 Results Validation Task Analysis

This subsection describes the analysis of the validation test results. It correlates M&S results with acceptability criteria and M&S requirements as well as identifies the authoritative resources to be used in evaluating the M&S results.

5.5.1 Lower Abdomen FEM Validation

The blunt impact tests described in Section 5.1.1.3 was simulated to validate the developed lower abdomen FEM, as shown in Figure 5-23(a). The projectile was 45 gram and 37 mm diameter and impact epigastria region at speed 60 m/s. The test data and simulation result were compared at the force-deflection curves plotted at Figure 5-25. The simulation produced the peak force 4703 N and peak deflection 20.7 mm which inside the test data range 4741 ± 553 N and 22.9 ± 2.6 mm, respectively.



(a) Projectile Blunt Impact

(b) Pelvis Impact

Figure 5-23. Simulations for lower abdomen FEM validation.

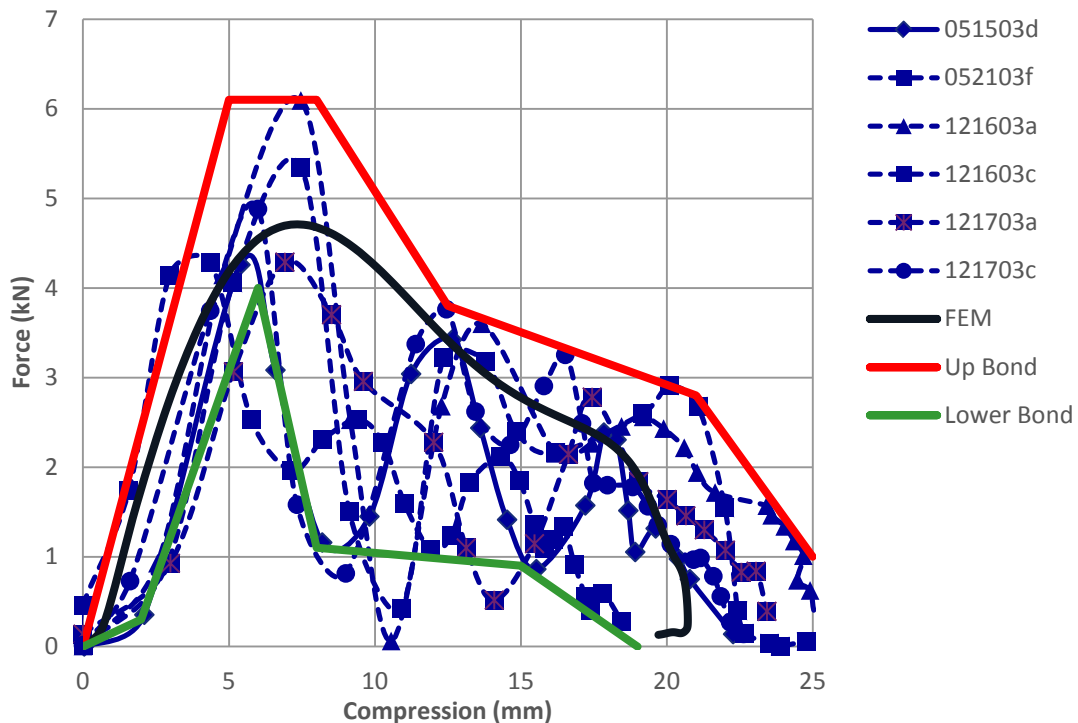


Figure 5-24. Force-deflection curve of test and simulation.

Pelvis impact tests (section 5.1.1.3) were also simulated to validate the lower abdomen FEM contact forces (Figure 5-23b). The rigid impactor was 200 x 200 mm flat block and its weight was 12-16 kg. It impacted the pelvis range at speed 10 m/s (Table 5-4). The force time histories of tests and simulation were illustrated at Figure 5-25. It should be notice that most simulations

only run to 10 ms (5 ms after reach peak force). The lower abdomen FEM was free at both connections to other body parts, while the whole PMHS body was used in tests. The differences will become larger after rigid motion of FEM appearing after 10 ms. The most simulation was conducted at less 10 ms range. The results were shown that the FEM result matched tests very well. These results from Figure 5-24 and Figure 5-25 demonstrated that the FEM can produce accurate biomechanical responses.

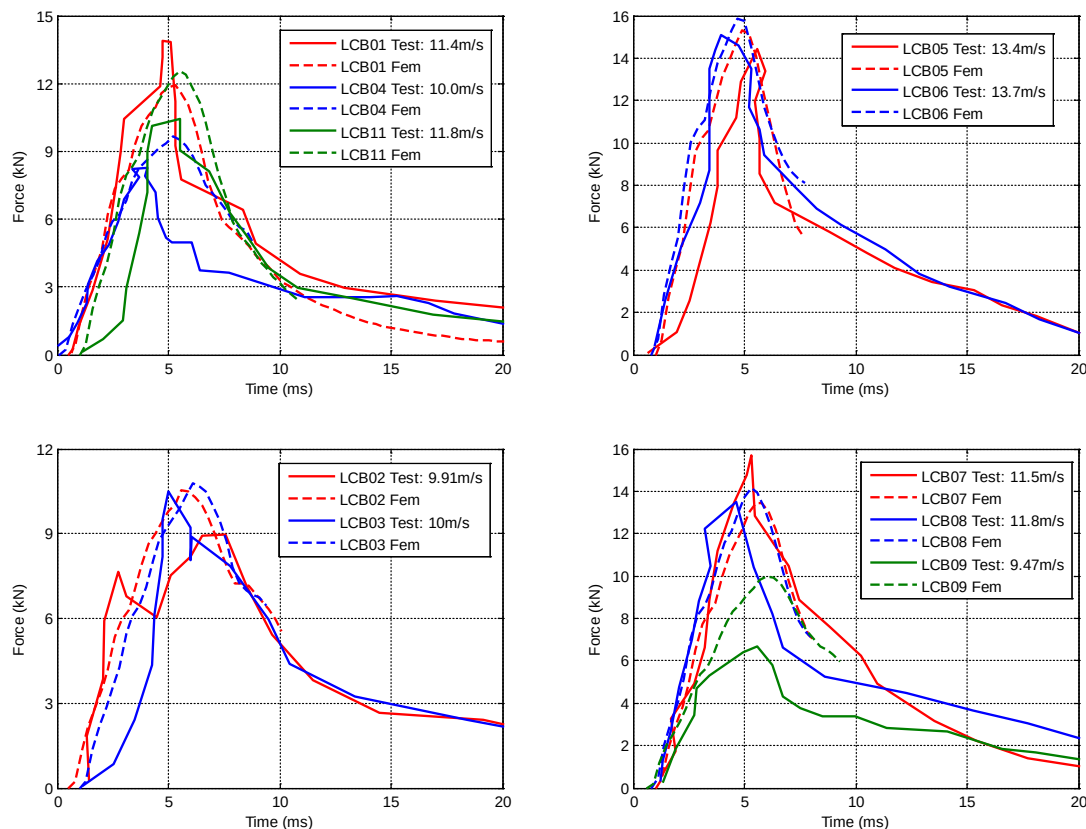


Figure 5-25 Forces histories of tests and simulations under pelvis impacts

5.5.2 Development and Validation FEM-Based Injury Correlations

The logistical regression has been used for all dose-response correlates of ATBM. Its formulation is expressed by:

$$\ln\left(\frac{P}{1-P}\right) = a + bx \quad (1)$$

where p is the probability of injury (dependent variable), a (interceptor) and b (slope) are the best-fit model parameters determined from a maximum-likelihood estimation, and x is the independent variable used for the regression.

Using the logistical regression method presented above and the test data described in section 5.1.1.4, FEM-based injury correlations were developed and validated for the lower abdomen. Six

model outputs were selected as candidates for evaluation to find the best one for predicting injury: strain energy density (SDEN), von Mises stress (VMST), equivalent von Mises strain (VMSS), pressure (PRES), maximum principal stress (PRST), and maximum principal strain (PRSS). The candidates were evaluated using five goodness-of-fit statistics: deviance, p-value, Chi-squared test (χ^2), McFadden's R^2 (McFR2), and percentage of correct prediction (PCP). The best candidates have a small deviance, a large χ^2 , a p-value less than 0.05, and a McFR2 nearest to one. Table 5-30 listed the summary of lower abdomen FEM-based injury correlations and regression curves were plotted at Figure 5-26.

Table 5-30. Summary of injury correlations for lower abdomen injuries.

Lower Abdomen Injury	Model Predictor	Alpha	Beta	V50	Test Data	Note
Intestinal Contusion	Principal strain	-49.292	136.118	0.362	Cripps, Hardy	Validated
Stomach Contusion	Von-mises stress (MPa)	-48.736	57.560	0.847	Nusholtz	Not validated
Spleen Laceration	Principal strain	-20.038	36.074	0.556	Cavanaugh, Hallman, Miller, Hardy, Nusholtz	Validated, Improved
Kidney Contusion	Principal strain	-16.224	43.620	0.372	Hallman, Nusholtz	Validated, Improved
Pancreas Rupture	Von-mises strain	-60.971	135.911	0.449	Nusholtz	Not validated

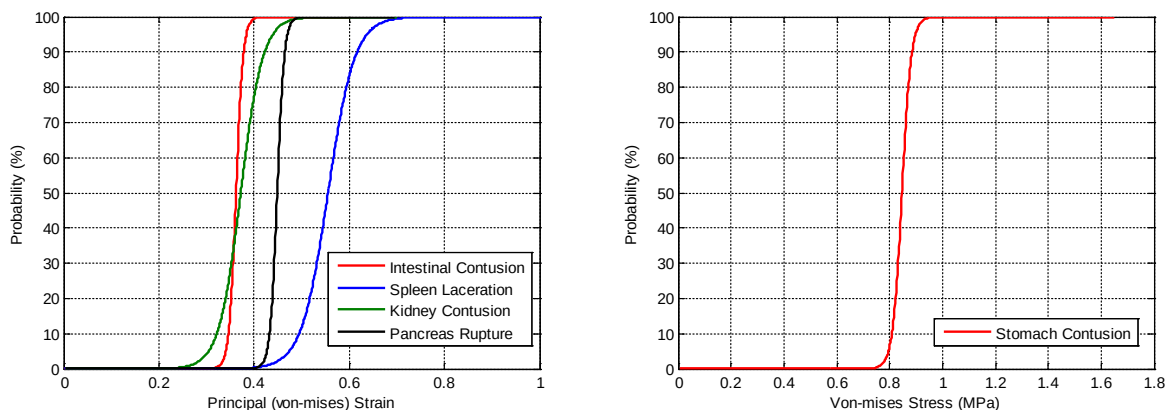


Figure 5-26. Logistical regression curves of lower abdomen injury.

5.5.2.1 FEM-based Correlation of Intestinal Contusion

Table 5-31 lists the calculated values of candidate predictors and intestinal contusion occurrence from the Cripps impact tests (section 5.1.1.4). Based on this data, the logistical regression results were obtained in Table 5-32. The candidates were VMSS, PRSS and VMST, which gave a 50%

failure level for equivalent von Mises strain of 0.571, principal strain of 0.362, and von Mises stress of 0.728 MPa. These V50 results were consistent with values reported in the literature. Yamada (1970) reported a transversal ultimate strength from 0.40 to 0.91MPa, a transversal ultimate strain of 81% to 121%, a longitudinal ultimate tensile strength varying from 0.42 to 1.00 MPa, and an longitudinal strain between 37 and 52%. Howes and Hardy (2012) gave the average maximum principal failure strain was 0.270 ± 0.083 under strain rate 86.7 s^{-1} . Since the intestine material was simplified as elastic shells and the difference between transverse and longitude was not considered, the failure strain should be consistent with the longitudinal test data.

Table 5-31. Cripps test data and calculated candidates values.

Test#	SDEN (kJ)	VMST (MPa)	VMSS	PRES (MPa)	PRST (MPa)	PRSS	Injured
SH1	70.230	0.660	0.502	0.205	0.577	0.312	0
SH2	134.226	0.797	0.600	0.240	0.834	0.385	1
SH3	75.276	0.698	0.531	0.189	0.550	0.329	0
SH4	94.695	0.639	0.480	0.151	0.712	0.300	0
Sh5	113.797	0.769	0.593	0.336	0.813	0.372	0
SH6	44.430	0.419	0.327	0.114	0.456	0.211	0
SH7	71.968	0.605	0.465	0.222	0.560	0.290	0
SH8	166.311	0.824	0.621	0.270	0.898	0.398	1
SH9	146.098	0.810	0.626	0.335	0.877	0.397	1
SH10	69.745	0.644	0.498	0.275	0.668	0.311	0
SH11	101.395	0.659	0.491	0.199	0.729	0.312	0
SH12	100.659	0.784	0.605	0.370	0.833	0.385	1
SH13	147.430	0.777	0.580	0.271	0.861	0.372	0
SH14	139.347	0.797	0.605	0.349	0.843	0.390	1
SH15	113.705	0.846	0.639	0.445	0.945	0.383	1
SH16	128.128	0.813	0.633	0.366	0.857	0.390	1
SH17	67.688	0.605	0.474	0.304	0.681	0.297	0
SH18	132.262	0.822	0.623	0.388	0.842	0.393	1
SH19	106.114	0.782	0.613	0.362	0.765	0.383	1
SH20	91.277	0.761	0.585	0.386	0.838	0.371	1
SH21	111.604	0.872	0.659	0.500	1.003	0.399	1
SH22	118.244	0.824	0.628	0.381	0.885	0.399	1
SH23	33.819	0.379	0.289	0.180	0.411	0.193	0
SH24	101.804	0.759	0.590	0.338	0.797	0.374	1
SH25	86.696	0.596	0.445	0.254	0.686	0.287	0
SH26	93.537	0.720	0.612	0.353	0.743	0.365	1
SH27	100.379	0.796	0.639	0.441	0.906	0.389	1
SH28	45.879	0.534	0.452	0.245	0.545	0.280	0
SH29	97.305	0.733	0.563	0.312	0.757	0.365	1
SH30	103.272	0.775	0.630	0.354	0.810	0.386	1
SH31	118.219	0.833	0.631	0.374	0.868	0.401	1

Note: 18 of 31 Injured (Yes=1, No=0)

Table 5-32. Regression results of six candidates from Cripps data.

Parameter	SDEN	VMST	VMSS	PRES	PRST	PRSS
Alpha	-6.143	-29.488	-42.149	-10.812	-19.505	-49.292
Beta	0.066	40.491	73.835	37.293	25.825	136.118
Deviance	27.871	14.086	10.000	17.521	18.050	10.085
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Chi2	14.295	28.079	32.165	24.645	24.115	32.080
McFadden's R^2	0.339	0.666	0.763	0.585	0.572	0.761
PCP	83.871	90.323	90.323	87.097	90.323	93.548
V50	93.446	0.728	0.571	0.290	0.755	0.362

Validation was conducted with the data found in Table 5-33 which represents the intestinal injury test data from Hardy. The V50 values in Table 5-32 were used to predict the occurrence of intestinal injury. The VMST, VMSS, and PRSS logistic regressions correctly predicted 70.6%, 76.5% and 88.2% of the injuries, respectively. The best predictor in both the calibrating and validating data set remained maximum principal strain and was thus selected for use in the prediction of intestinal contusion under projectile impacts. Since the Cripps tests were conducted by high speed projectiles, the derived regression is considered to quite suitable and representative of NLW threats.

Table 5-33. Hardy test data and calculated candidate values.

Test#	Injured	VMST (MPa)	Prediction By VMST	VMSS	Prediction By VMSS	PRSS	Prediction By PRSS
GI3	1	0.739	1	0.580	1	0.367	1
GI4	0	0.664	0	0.508	0	0.313	0
GI5	0	0.679	0	0.531	0	0.322	0
GI6	0	0.717	0	0.562	0	0.353	0
GI7	0	0.759	1	0.593	1	0.361	0
GI8	0	0.743	1	0.555	0	0.361	0
GI9	0	0.714	0	0.536	0	0.345	0
GI10	0	0.771	1	0.614	1	0.391	1
GI11	0	0.670	0	0.542	0	0.350	0
CB1	0	0.732	1	0.576	1	0.356	0
CB3	0	0.636	0	0.503	0	0.330	0
CB4	0	0.483	0	0.364	0	0.240	0
CB5	0	0.621	0	0.474	0	0.295	0
CB6	0	0.605	0	0.517	0	0.308	0
AA1	1	0.860	1	0.662	1	0.421	1
AA2	1	0.901	1	0.676	1	0.432	1
AA3	0	0.831	1	0.677	1	0.423	1
Correct Predictions (%)			70.6		76.5		88.2

5.5.2.2 FEM-based Correlation of Stomach Contusion

The logistic regression for stomach contusion was derived using injury data from Nusholtz, Kaiker et al. (1985), (1988). The regressions computed for the six candidates are listed in Table 5-35. The failure von Mises stress, equivalent von Mises strain and principal strain were 0.847 MPa, 0.632, and 0.408, respectively. Egorov, Schastlivtsev et al. (2002) reported the failure stress and strain for an axial sample as 0.70 MPa and 0.90 respectively, while a transversal sample failed at 0.5 MPa and 0.90, respectively. Yamada (1970) gave the tensile strength 0.34 to 0.54 MPa, ultimate strain of 0.83 to 1.24 and ultimate expansive strength 0.8 to 1.57 MPa, respectively. In the developed FEM, the stomach material was simplified as elastic model and the anisotropic and strain rate effects were not considered. The estimate V50 values were more realistic after comprised the rate effect (higher rate caused higher stress and less strain higher) and stomach anisotropic property (strength different at expansive and tensile). The von Mises stress was selected as the best predictor. It should be noted that the correlation was developed using high mass, low speed frontal impact tests. Validation of the injury correlate could not be conducted due to an absence of additional test data in the literature.

Table 5-34. Nusholtz stomach injury and candidates values.

Test #	SDEN (kJ)	VMST (MPa)	VMSS	PRES (MPa)	PRST (MPa)	PRSS	Injured
83E121	125.881	0.772	0.575	0.212	0.715	0.377	0
83E131	144.877	0.866	0.646	0.164	0.891	0.409	1
84E142	136.185	0.846	0.631	0.230	0.837	0.408	1
84E153	96.216	0.718	0.535	0.189	0.752	0.346	0
84E163	172.705	0.860	0.643	0.372	0.924	0.420	0
84E173	82.874	0.616	0.459	0.187	0.674	0.295	0
84E181	101.279	0.730	0.544	0.101	0.683	0.349	0
85E193	138.157	0.801	0.597	0.203	0.848	0.382	0
86M001	58.616	0.529	0.394	0.267	0.605	0.249	0
86M010	258.076	1.099	0.819	0.333	1.200	0.527	1
86M020	100.304	0.722	0.538	0.236	0.764	0.357	0
86M040	117.387	0.716	0.534	0.271	0.785	0.339	0
86M050	107.212	0.733	0.546	0.161	0.788	0.341	0

Table 5-35. Six candidates regressions for stomach contusion.

Parameter	SDEN	VMST	VMSS	PRES	PRST	PRSS
Alpha	-7.152	-48.736	-44.867	-2.240	-17.605	-32.295
Beta	0.044	57.560	70.978	4.487	19.628	79.235
Deviance	8.906	4.474	4.624	13.812	7.842	5.736
P-value	0.023	0.002	0.002	0.629	0.013	0.004
Chi2	5.139	9.572	9.421	0.234	6.203	8.310
McFadden's R ²	0.366	0.682	0.671	0.017	0.442	0.592
PCP	76.923	84.615	84.615	76.923	76.923	92.308
V50	162.255	0.847	0.632	0.499	0.897	0.408

5.5.2.3 FEM-based Correlation of Spleen Laceration

Side impact test data described in section 5.1.1.4 were used to develop the spleen laceration correlation. Table 5-36 was the simulation result of six and likelihood of spleen laceration. The logistical regression result was given in Table 5-37. The VMSS and PRSS were the useful candidates to estimate the injury and their V50s were 0.872 and 0.572, respectively. Tamura, Omori et al. (2002) reported the porcine average peak Cauchy stress 107.5, 114.6 and 146.3 kPa and peak strain 0.825, 0.809 and 0.834 for strain rate 0.005, 0.05 and 0.5 s⁻¹, respectively. Kemper, Santago et al. (2011) produced the compressive failure stresses and strains in spleens of 35.0 to 62.3 kPa and 0.369 to 0.404, respectively under strain rates between 0.01 to 10 s⁻¹. Hardy, Howes et al. (2015) summarized that the true failure stress under compression were 20.7, 25.3 32.3 and 39.1 kPa and true failure strains were 0.52, 0.51, 0.48 and 0.46 for loading rates of 0.01, 0.1, 1.0 and 10 s⁻¹, respectively. The thresholds of von Mises stress, strain and principal strain in Table 5-37 were 351.9 kPa, 0.872 and 0.572. These stress values significantly exceeded

the values found in reported test data, indicating that the artificial stiffening of the Ogden material model for the spleen affects the accuracy of stress results at high strain rates. Therefore, the stress candidate predictors were removed from consideration.

Table 5-36. Side impact (Cavanaugh, Hallman, Miller) spleen injury and candidates values.

Test#	SDEN (kJ)	VMST (kPa)	VMSS	PRES (kPa)	PRST (kPa)	PRSS	Injured
SIC04	72.153	332.220	0.903	286.837	379.179	0.597	1
SIC06	91.794	409.661	0.902	413.280	554.461	0.587	0
SIC05	57.681	291.738	0.802	281.986	353.516	0.522	0
SIC07	35.788	224.476	0.682	239.878	320.637	0.442	0
SIC08	56.239	274.650	0.841	269.345	325.010	0.557	1
SIC10	48.474	269.167	0.760	400.773	509.752	0.494	0
SIC11	52.509	275.391	0.782	271.237	390.746	0.508	0
SIC13	45.842	263.538	0.749	282.617	368.057	0.486	0
SIC15	43.932	263.266	0.743	256.037	336.595	0.483	0
SIC17	36.783	230.222	0.682	236.256	307.598	0.442	0
SIC09	38.990	256.806	0.726	267.223	371.289	0.460	0
SIC12	39.484	250.873	0.728	274.024	391.535	0.460	0
SIC14	81.701	361.661	0.949	218.317	402.450	0.628	1
SIC16	78.621	354.584	0.936	288.959	394.968	0.620	1
D-1	89.040	377.734	1.010	274.073	404.057	0.669	1
D-2	17.528	159.809	0.516	164.975	246.585	0.325	0
D-3	28.657	209.272	0.610	213.735	303.469	0.397	0
D-4	92.319	363.897	0.994	438.624	627.506	0.658	1
NBA0901	71.746	339.151	0.844	541.538	649.261	0.550	0
NBA0903	85.341	363.878	0.971	226.882	414.077	0.643	1
NBA1004	71.148	418.549	0.739	579.251	850.768	0.475	0
NBA1005	34.985	297.385	0.672	503.218	698.445	0.436	0
NBA1006	24.331	194.134	0.552	301.749	384.772	0.352	0

Table 5-37. Six regressions for spleen laceration from side impact tests.

Parameter	SDEN	VMST	VMSS	PRES	PRST	PRSS
Alpha	-7.209	-7.069	-31.689	0.393	-0.421	-34.266
Beta	0.099	0.020	36.357	-0.004	-0.001	59.880
Deviance	15.790	21.786	7.501	27.519	28.182	6.271
P-value	< 0.001	0.0109	< 0.001	0.3869	0.7704	< 0.001
Chi2	12.477	6.481	20.766	0.749	0.085	21.996
McfR2	0.441	0.229	0.735	0.027	0.003	0.778
PCP	86.957	82.609	91.304	69.565	69.565	91.304
V50	72.587	351.814	0.872	98.132	-445.591	0.572

The frontal loading tests in section 5.1.1.4 were used to validate the developed correlations. The von Mises strain regression correctly predicted the injury outcome in 90% of the tests while principal strain correctly predicted 93.3%. In the tests of side impacts of Cavanaugh, Walilko et al. (1996) and Hallman, Yoganandan et al. (2010), Miller and frontal loading tests of Hardy, Schneider et al. (2001) and Nusholtz, Kaiker et al. (1988), loading durations were about 50 ms and large deformation was occurred in large body area. The data in Table 5-36 and Table 5-39 can be merged together to improve correlations. Table 5-38 lists the improved regressions using all data. The best candidate for spleen laceration was found to be principal strain. Table 5-39 lists the injury, equivalent von Mises strain and principal strain values and prediction by these metrics.

Table 5-38. Regression of six candidates by test data.

Parameter	SDEN	VMST	VMSS	PRES	PRST	PRSS
Alpha	-4.663	-4.129	-18.940	-2.115	-2.360	-20.038
Beta	0.069	0.010	22.371	0.004	0.003	36.074
Deviance	40.696	49.645	25.847	58.507	58.061	22.883
P-value	< 0.001	< 0.001	< 0.001	0.0311	0.0240	< 0.001
Chi2	22.457	13.508	37.306	4.646	5.092	40.270
McfR2	0.356	0.214	0.591	0.074	0.081	0.638
PCP	84.906	75.472	88.679	69.811	71.698	94.340
V50	67.340	415.864	0.847	518.575	713.633	0.556

Table 5-39. Frontal loading tests (Hardy and Nusholtz), candidates and prediction.

Test	Injury	VMSS	Prediction by VMSS	PRSS	Prediction by PRSS
GI3	0	0.525	0	0.349	0
GI4	0	0.603	0	0.357	0
GI5	0	0.748	0	0.496	0
GI6	1	0.963	1	0.637	1
GI7	0	0.581	0	0.387	0
GI8	0	0.637	0	0.425	0
GI9	1	0.947	1	0.609	1
GI10	1	0.905	1	0.596	1
GI11	1	1.088	1	0.708	1
CB1	0	0.480	0	0.343	0
CB3	0	0.484	0	0.316	0
CB4	0	0.339	0	0.221	0
CB5	0	0.547	0	0.323	0
CB6	0	0.548	0	0.353	0
AA1	0	0.569	0	0.375	0
AA2	1	0.833	0	0.577	1
AA3	1	0.826	0	0.561	0
83E121	1	0.671	0	0.437	0
83E131	0	0.782	0	0.500	0
84E142	1	0.913	1	0.594	1
84E153	0	0.724	0	0.459	0
84E163	0	0.852	0	0.559	0
84E173	0	0.536	0	0.352	0
84E181	0	0.830	0	0.538	0
85E193	0	0.778	0	0.489	0
86M001	0	0.225	0	0.146	0
86M010	0	0.433	0	0.281	0
86M020	0	0.475	0	0.307	0
86M040	0	0.553	0	0.345	0
86M050	0	0.603	0	0.398	0
Prediction PCP (%)			90.0		93.3

5.5.2.4 FEM-based Correlation of Kidney Contusion

The logistic regressions for kidney contusion were derived using data from Hallman, Yoganandan et al. (2010) and Nusholtz, Kaiker et al. (1985), (1988). Table 5-40 lists the combined data from these two sources along with the candidate outputs from simulations;

however, only five of the 18 tests in the combined data set resulted in a kidney contusion. The regressions from the combined data sets are shown as Table 5-41. The thresholds of von Mises stress, equivalent von Mises strain, principal stress and principal strain were 2.55 MPa, 0.557, 2.32 MPa and 0.372, respectively.

Table 5-40. Kidney contusion of Hallman and Nusholtz tests and candidates values.

Test #	SDEN (kJ)	VMST (kPa)	VMSS	PRES (kPa)	PRST (kPa)	PRSS	Injured
D-1	32.7	781.4	0.429	593.4	873.3	0.284	0
D-2	55.6	555.1	0.494	569.9	817.7	0.326	1
D-3	39.3	522.9	0.444	460.6	656.6	0.294	0
D-4	27.0	765.3	0.396	486.7	752.4	0.261	0
83E121	61.9	1418.9	0.394	326.1	1395.1	0.266	0
83E131	73.3	1543.4	0.540	786.1	1641.6	0.362	0
84E142	90.1	1839.2	0.472	403.5	1468.2	0.315	0
84E153	74.9	1914.0	0.548	719.9	1756.3	0.364	0
84E163	97.3	2055.4	0.640	694.5	1696.7	0.431	1
84E173	65.1	1818.8	0.499	735.7	1858.3	0.332	0
84E181	67.4	1672.2	0.557	818.2	1439.2	0.376	1
85E193	81.0	2172.0	0.552	755.9	2043.1	0.368	0
86M001	284.0	3751.3	0.701	1153.7	3356.4	0.467	1
86M010	68.7	1335.6	0.376	275.4	1018.8	0.251	0
86M020	98.5	1822.1	0.548	745.1	1918.0	0.364	1
86M040	71.6	1903.8	0.533	773.8	1847.9	0.354	0
86M050	59.8	1401.1	0.494	656.8	1367.9	0.329	0

Table 5-41. Kidney contusion regressions by combined tests.

Parameter	SDEN	VMST	VMSS	PRES	PRST	PRSS
Alpha	-5.070	-2.562	-16.882	-5.721	-2.796	-16.224
Beta	0.056	0.001	30.329	0.007	0.001	43.620
Deviance	15.388	18.849	12.363	16.237	18.748	12.379
P-value	0.022	0.186	0.004	0.037	0.174	0.004
Chi2	5.209	1.748	8.234	4.360	1.850	8.219
McfR2	0.253	0.085	0.400	0.212	0.090	0.399
PCP	88.235	76.471	82.353	82.353	76.471	88.235
V50	91.333	2554.784	0.557	810.481	2316.674	0.372

Umale, Deck et al. (2013) found the ultimate stress and strain of the swine kidney capsule to be 4.78 ± 1.05 MPa and 0.361 ± 0.083 , respectively. Snedeker, Barbezat et al. (2005) reported the failure stress and strain of human kidney capsule were 9.0 ± 2.9 MPa and $33.4 \pm 6.6\%$, failure stress and strain of kidney renal parenchyma were 116 ± 28 kPa and $63 \pm 6.3\%$, respectively. Farshad, Barbezat et al. (1999) found the swine kidney overall failure stress and strain was 0.18

to 0.25 MPa and 0.5, respectively. Yamada found the renal capsule's ultimate strength and strain were 2.06 to 2.75 MPa and 0.28 to 0.30, respectively, while the renal parenchyma's ultimate strength and strain were 39.2 to 56.9 kPa and 0.46 to 0.62, respectively. In the FEM, the kidney material was modeled as one hyper elastic rubber as general tissue instead of separating the capsule and parenchyma. This material model does not consider the difference between capsule and parenchyma. The stress thresholds (2.55 MPa and 2.32 MPa) of regression were most consistent with the capsule strength, while the strain limits account for both the strength of the capsule and the parenchyma. Comparing the six regressions in Table 5-41, principal strain was identified as the best candidate predictor for kidney contusion.

5.5.2.5 FEM-based Correlation of Pancreas Rupture

Pancreas rupture data and predictor candidates are listed in Table 5-42 from simulations of the Nusholtz tests. The prospective regressions for each candidate are shown in Table 5-43. In the available data, there were only two pancreas ruptures which limits the confidence in any given injury correlate. The 50% probability thresholds were calculated at 1.27 MPa and 0.449 for von Mises stress and strain, respectively, and 1.12 MPa and 0.298 for principal stress and strain, respectively. Due to the limited amount of data available for validating these strain thresholds, these values were cross-referenced against stress thresholds found in literature. The stress thresholds were consistent with the reported average in vitro peak failure stress of 1.21 ± 0.27 MPa by Bradley and Vito (1984). The equivalent von Mises strain was selected as the best predictor of pancreas rupture.

Table 5-42. Pancreas rupture tests Nusholtz and candidate values.

Test#	SDEN (kJ)	VMST (kPa)	VMSS	PRES (kPa)	PRST (kPa)	PRSS	Injured
83E121	42.460	1034.708	0.411	235.476	891.740	0.274	0
83E131	44.363	1180.300	0.427	336.245	1034.100	0.284	0
84E142	41.281	1014.500	0.417	227.860	879.311	0.278	0
84E153	32.912	973.123	0.404	268.435	855.753	0.269	0
84E163	54.954	1297.343	0.463	258.544	1162.266	0.308	1
84E173	57.240	1282.400	0.451	375.306	1130.500	0.300	0
84E181	45.801	1119.178	0.441	241.251	1006.998	0.293	1
85E193	50.214	1168.110	0.436	259.539	1017.563	0.290	0
86M001	35.017	978.599	0.426	268.217	842.191	0.284	0
86M010	40.847	950.964	0.414	210.980	848.239	0.275	0
86M020	32.945	1018.800	0.403	307.012	878.738	0.269	0
86M040	27.243	806.261	0.356	170.339	701.645	0.236	0
86M050	39.441	947.690	0.397	217.627	835.637	0.264	0

Table 5-43. Pancreas rupture regressions of six candidates.

Parameter	SDEN	VMST	VMSS	PRES	PRST	PRSS
Alpha	-9.245	-14.490	-60.971	-0.556	-16.287	-59.827
Beta	0.166	0.011	135.911	-0.005	0.015	200.465
Deviance	8.622	8.155	5.272	11.076	7.296	5.391
P-value	0.111	0.083	0.015	0.768	0.049	0.016
Chi2	2.541	3.008	5.891	0.087	3.866	5.772
McfR2	0.228	0.269	0.528	0.008	0.346	0.517
PCP	76.923	84.615	84.615	84.615	84.615	84.615
V50	55.824	1274.422	0.449	-123.687	1115.029	0.298

5.6 V&V Reporting Task Analysis

This subsection describes how the V&V activities were documented and what documentation was delivered.

The M&S was evaluated by L-3/ATI according to the V&V Plan completed in February 2015. The results of the evaluation are provided by L-3/ATI within this report under Contract No. FA8650-13-D-6368.

6 V&V Issues

6.1 Material models

The material models used in lower abdomen FEM were listed in Table 5-21. The material of hollow organ was simplified as one elastic model based on test data described at section

5.1.1.2.3, which the anisotropy, hyper elasticity and strain rate dependence were not considered. The materials of spleen and liver were obtained by fitting test results (section 5.1.1.2.2) and it may over estimate the stiffness at high strain and high strain rate (section 5.5.2.3). The kidney and pancreas were assumed to be one hyper elastic model without considering the difference between capsule and parenchyma. This model was obtained by fitting and extending the average test at low strain range (section 5.1.1.2). It may over estimate the stiffness at high strain range (section 5.5.2.4). The following issues were included in the setup of material models:

- Each organ material model was based on only one source instead of multiples;
- The material anisotropy was not considered;
- Organ was assumed to be one type of material instead discriminate the capsule and parenchyma;

6.2 Large Mass Impacts

The FEM was used to predict blunt trauma under high speed projectiles. The M&S are intended to be used for localized effects to the body with minimal gross rigid motion. The model becomes less stable and more inaccurate when simulating large deformations, such as the example shown in Figure 6-1. In this case, the abdomen is rapidly compressed with a large impactor, causing soft tissue elements to collapse and crashing the simulation. This limitation is not expected to affect KE-NLWs which tend to be much lighter and create smaller, more localized effects.



Figure 6-1. Large compression of lower abdomen FEM.

6.3 FEM Validation and Injury Correlates

The lower abdomen FEM validation could only be performed by comparing external responses, such as impact forces and body deformation, to published data. Therefore, the accuracy of internal organ responses could only be evaluated indirectly by evaluating whether the organ failure thresholds were reasonably close to the V50 values of the injury correlates.

Additionally, some of the data used to develop or validate the injury correlates was gathered for applications different than the subject M&S' intended use. The correlation of intestinal contusion was developed based on high-speed, low-mass projectile impacts on swine, and validated by the slow frontal loadings on PMHS tests. The correlations of stomach contusion and pancreas rupture were developed from frontal wheel impact tests on PMHS and were not validated due to data absent. The correlations of spleen laceration and kidney contusion were also developed and validated by tests under automobile type loadings. Reasonable efforts were made to check the validity of these data to the M&S' validation, but future injury tests using PMHS or animals may be necessary to improve the correlates further.

7 Key Participants

This section identifies the participants involved in the VV&A effort, including the roles that they are assigned and their key responsibilities within that role. Roles and key responsibilities are defined during initial planning; names and contact information of the actual participants are added when they are determined.

7.1 Accreditation Participants

The accreditation roles of Accreditation Authority, Accreditation Agent, Accreditation Team, and SMEs have not yet been assigned.

7.2 V&V Participants

This subsection lists the participants involved in the V&V effort, including their contact information, assigned role, and the key responsibilities associated with that role. Typical V&V roles include M&S Proponent, V&V Agent, Validation Authority, Data Source, and SMEs.

Table 7-1. Participants in the V&V effort.

Level	Name	Company	Organization	Phone	E-mail
M&S Proponent		DoD	AFRL/RHD/HECOE		
M&S Developer	Charles Webber	L-3 Communications	Applied Technologies, Inc.	(858) 404-7966	charles.webber@L-3Com.com
V&V Agent	Charles Webber	L-3 Communications	Applied Technologies, Inc.	(858) 404-7966	charles.webber@L-3Com.com
Validation Authority	None assigned				
Data Source	None assigned				
SMEs	None assigned				

7.3 Other Participants

No other participants have been assigned at this time.

A. APPENDIX: M&S DESCRIPTION

This appendix contains pertinent detailed information about the M&S being assessed.

A.1 M&S Overview

The M&S is a FEM of a 50th percentile male lower abdomen whose outputs are used to determine a probability of suffering a blunt trauma injury to the abdominal organs. The injury correlates are empirically-derived logistic regressions based on the FEM responses. The M&S is intended to predict the risk of blunt trauma injuries from kinetic energy non-lethal weapons such as rubber bullets and sponge grenades.

The geometry of the lower abdomen spans from the diaphragm down to the pelvis and was generated from the Zygote 3D Male Human Model (Zygote Media Group, American Fork, UT) based on CT scans of 50th percentile males. The tissues and organs are meshed with TrueGrid (TrueGrid, XYZ Scientific, Inc., Livermore, CA) and HyperMesh (Altair Hyperworks, Troy, MI).

Material properties are identified from a variety of literature sources where extensive testing of material properties had been performed and applied to the appropriate FEM parts. Appropriate contact parameters are established so that the model would have accurate force transmission between adjacent parts. Several formal model checks are performed throughout each step of the model's development and are outlined in detail in this report.

Injury correlates are developed from fitting a logistic regression curve to available injury data. Validation is conducted by comparing the regressions with other literature data such as the 50% material failure thresholds of organ tissue or injury occurrence compared with the M&S prediction.

Only key anatomical features of the lower abdomen are incorporated into the FEM: the liver, kidneys, pancreas, spleen, gallbladder, intestines, stomach, lumbar spine, pelvis, and a homogeneous tissue representing the skin, muscle, and fat layers. All other anatomical features, such as tendons, ligaments, cartilage, and other joint connections, were not included for simplicity.

A.2 M&S Development and Structure

The M&S is currently under development at the time of this writing. The completed FEM will be a text file compatible with LS-Dyna. Once completed, the final structure, organization, hardware and software specifics (such as solver version), and technical statistics (such as runtime) can be provided. The paradigm being followed is a waterfall development process of sequential development steps. Figure A.2-1 is an example of this development process, though the actual process will have additional V&V steps.

FEM Development Life Cycle with V&V

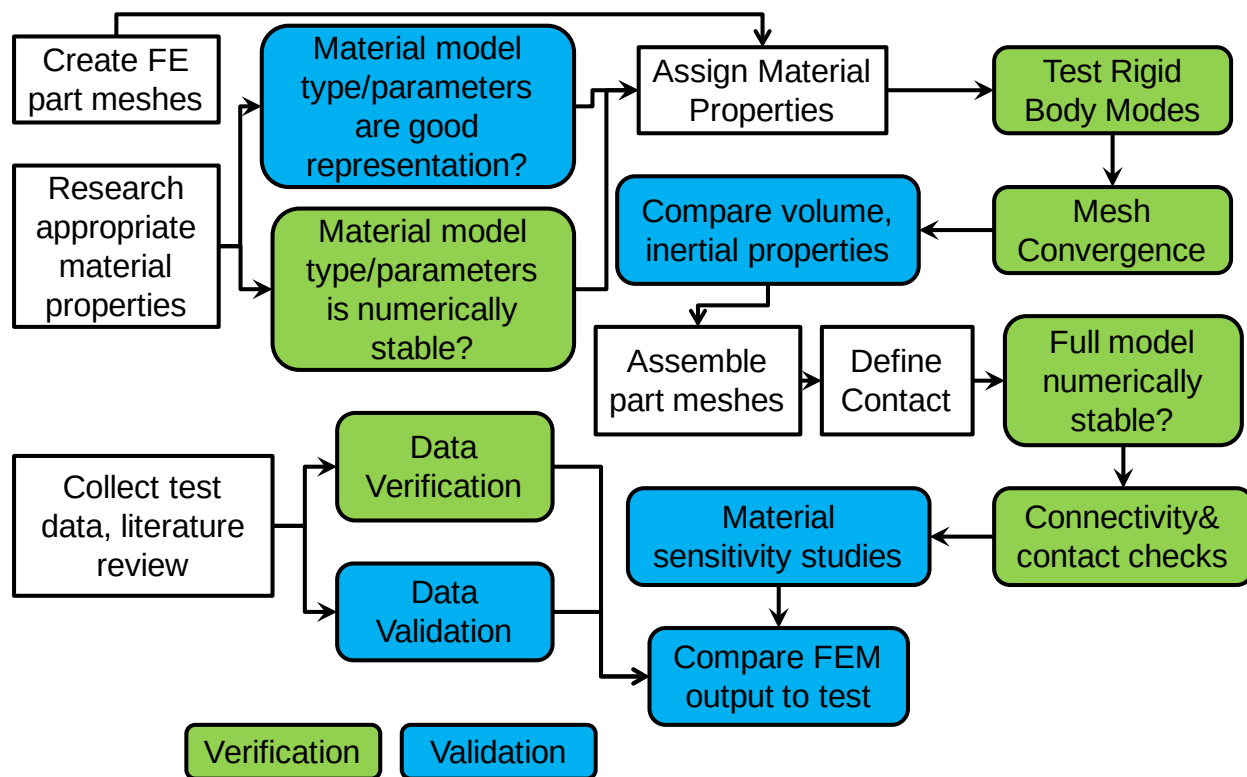


Figure A.2-1. An overview of the development cycle with V&V activities interspersed.

A.3 M&S Capabilities and Limitations

The M&S is intended to be a combination of a lower abdomen FEM and associated abdominal injury correlates. At this time, the M&S is still under development and therefore a complete list of its capabilities and limitations are not available.

A.4 M&S Use History

The M&S is still under development and has no use history at this time.

A.5 Data

A.5.1 Input Data

The input data necessary to run the M&S will be the necessary LS-Dyna files to run an impact simulation: the finished, unmodified lower abdomen FEM, a FEM of an impactor, the initial and boundary conditions, and the appropriate control settings to compute the appropriate simulation outputs. From these simulation outputs, the necessary data will be the logistic regressions that transform the FEM responses to injury probabilities.

A.5.2 Output Data

The M&S will produce intermediate outputs such as FEM responses like deformations, forces, stresses, and strains that will be necessary to compute the final outputs: injury probabilities. The FEM responses will be output in the same units as the FEM (SI) and the probabilities will be given in percentages.

A.6 Configuration Management

Configuration management for the M&S will be conducted by the M&S developer. Any changes to the FEM, injury correlations, and V&V results will be reported in the M&S documentation (e.g. V&V report, change log).

M&S Role	Name	Company	Organization	Phone	E-mail
M&S Developer	Charles Webber	L-3	Applied Technologies, Inc.	(858) 404-7966	charles.webber@L-3Com.com

B. APPENDIX: M&S REQUIREMENTS TRACEABILITY MATRIX

This appendix establishes the links between the M&S requirements, the acceptability criteria, and the evidence collected during the V&V processes. Building on Table 3-1 defined in Section 2, the traceability matrix provides a visual representation of the chain of information that evolves as the VV&A processes are implemented. As implementation progresses from the planning to reporting phases, the traceability matrix assists in the identification of information gaps that may result from VV&A activities neither performed, addressed, nor funded.

Table B-1 M&S requirements traceability matrix

	Accreditation Plan		V&V Plan	V&V Report	Accreditation Report
#	M&S Requirement	Acceptability Criterion	Relevant V&V Task/Activity Section	V&V Task Analysis	Accreditation Assessment
1	The sub-system must accurately represent the significant geometric features of the associated body part. Minor geometric details can be omitted.	FE mesh of each organ/part must match reference geometry volume within 5%	4.2	5.1.1.1	
2	The sub-system must accurately predict the biomechanical response to a stimulus for the strain rates of interest. Necessary strain rate ranges will be estimated according to iterative process of model development and availability of test data.	Model output falls within available response corridors for force-deflection curves for both high-mass/low-velocity impactors and low-mass/high-velocity projectiles.	4.2	5.1.1.2.2 5.5.1	
3	The material properties of the organs should conform to the best available test data within the geometric size and strain-rate regimes of interest	The model of each organ material must be shown to agree within the corridors established from test data by simulating the tests and comparing the outcomes	4.3	5.1.1.2 5.1.1.2.2 5.1.1.2.3	

4	Model responses concur with injury mechanism (e.g. distribution of stress/strains at or near failure level match expected distribution or areas of damage based on test data)	Qualitative comparison of shape and severity of damaged regions between model and test data shows close agreement.	4.2	Could not evaluate	
5	Geometry has been sufficiently discretized into an adequate number of elements.	Mesh convergence tests show displacement and force time-histories differ less than 5% at two consecutive levels of mesh density (defined as a baseline mesh and one where element size is halved).	4.3	5.3.3	
6	Material model fully dissipates elastic strain energy and returns to a steady state. Necessary duration for simulation to run will be determined from analysis of time-to-steady-state figures found in literature review.	Test cases show that sub-system material model has dissipated 95% of all internal energy by the conclusion of the simulation.	4.4	Not evaluated	
7	Sub-system model maintains its integrity with minimal number of deleted elements due to excessive deformation	Fewer than 5% of elements deleted due to negative volume in all test cases	4.4	5.2.2	
8	Hourglass energy in the sub-system is minimal and limited throughout the simulation	Total hourglass energy never exceeds 10% of the initial system energy in any test case	4.4	5.1	
9	Stable and numerically accurate elements are in use throughout the model	Tetrahedron or pentahedron elements comprise less than 5% of any organ.	4.4	5.3	
10	Mesh quality of each sub-system is satisfactory	90% of the elements have a Jacobian between 0.9 and 1.0.	4.2	5.3	
11	Mesh is properly connected and does not have any artificial grounding	A free-free modal analysis of each sub-system yields precisely 6 rigid body modes and no unintended	4.4	5.4	

		disconnected elements.			
12	The integrated model must accurately predict the biomechanical response to a stimulus in the strain rates of interest.	Simulated force-deflection curves for high-mass/low-velocity impactors and low-mass/high-velocity projectiles must reside within tested response corridors	4.5	5.5.1	
13	Model responses concur with injury mechanism (e.g. distribution of stress/strains at or near failure level match expected distribution or areas of damage)	Qualitative comparison of shape and severity of damaged regions between model to test data shows close agreement	4.5	Could not evaluate	
14	System model fully dissipates internal elastic energy and returns to steady state.	Test cases show that sub-system material model has dissipated 95% of all internal energy by the conclusion of the simulation	4.4	Not performed	
15	Model maintains its integrity with minimal number of deleted elements due to excessive deformation	Fewer than 1% of elements deleted due to negative volume in all test cases	4.4	5.2.2	
16	No spatial penetration exists between sub-systems	Complete model passes penetration checks by LS Pre-/Post	4.4	5.4	
17	All contact and boundary conditions are properly initialized before the simulation	The model has no internal energy at the beginning of the simulation	4.4	5.4	
18	Material model parameters proportionally affect simulation results	10% perturbations in critical material property parameters have proportional change in response (10% or less)	4.2	5.3.1	
19	Hourglass energy in the total system is minimal and limited throughout the simulation	Total hourglass energy never exceeds 10% of the initial system energy in any test case	4.4	5.4	
20	All contact parameters are implemented correctly	Adjacent parts slide together but do not penetrate	4.4	5.4	

21	The probabilistic statistical classification model chosen is appropriate for each injury mode's actual statistical distribution.	The injury regression fits the trend of the data when plotted.	4.4	5.5.2	
22	The chosen injury predictor is the model output that best predicts injury occurrence using the relevant goodness-of-fit statistics.	P-value less than 0.05; Predictor's sensitivity to material properties is <10%; The predictor's chi-squared value is at or near the highest among other candidate predictors	4.2	5.5.2	
23	The injury correlates predict the likelihood of injury at a rate similar to that of the original data set that derived the correlation.	The injury correlate predicts outcomes for an alternative set of data within 20% of the statistical fit measures used to develop the injury correlate (such as V50, chi-squared, percent correct prediction)	4.5	5.5.2	

C. APPENDIX: REFERENCES

This appendix identifies all of the references used in the development of this document.

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D. APPENDIX: ACRONYMS

This appendix identifies all acronyms used in this document.

ATBM	Advanced Total Body Model
DT&E	Development Test and Evaluation
FEM	Finite Element Model
HECOE	Human Effects Center of Excellence
JNLWD	Joint Non-Lethal Weapons Directorate
JNLWP	Joint Non-Lethal Weapon Program
M&S	Modeling and Simulation
MOE	Measures of Effectiveness
MOP	Measures of Performance
MOS	Measures of Suitability
NLWs	Non-Lethal Weapons
OT&E	Operational Test and Evaluation
PMHS	Post-Mortem Human Subject
SME	Subject Matter Expert
V&V	Verification and Validation
V50	Model response at which injury is 50% likely
VV&A	Verification, Validation, and Accreditation

E. APPENDIX: GLOSSARY

This appendix contains definitions that aid in the understanding of this document.

ACCEPTABILITY CRITERIA. A set of standards that an M&S must meet to be accredited for a specific purpose.

ACCREDITATION. The official certification that an M&S and its associated data are acceptable for use for a specific purpose.

ACCREDITATION AGENT. The individual, group, or organization designated by the Accreditation Authority to conduct an accreditation assessment for an M&S.

ACCREDITATION AUTHORITY. The organization/individual who approves the use of an M&S for a particular application.

CONCEPTUAL MODEL. The developer's description of what the model or simulation will represent, the assumptions limiting those representations, and other capabilities needed to satisfy the M&S User's requirements. A collection of assumptions, algorithms, relationships, and data that describe a developer's concept about the simulation.

DATA. A representation of facts, concepts, or instructions in a formalized manner suitable for communication, interpretation, or processing by humans or by automatic means. Assumed, given, measured, or otherwise determined facts or propositions used to draw a conclusion or make a decision.

DATA VERIFICATION AND VALIDATION. The process of verifying the internal consistency and correctness of data and validating that it represents real world entities appropriate for its intended purpose or an expected range of purposes.

INDEPENDENT REVIEW. In computer modeling and simulation, a review performed by competent, objective reviewers who are independent of the model developer. Independent review includes either: (a) a detailed verification and/or validation of the model or simulation; or (b) an examination of the verification and/or validation performed by the model or simulation developer.

INTENDED USE. The application of a model or simulation for a specific purpose.

M&S DEVELOPER. The individual, group or organization responsible for developing or modifying a simulation in accordance with a set of design requirements and specifications.

M&S PROPONENT. The organization that has primary responsibility for M&S planning and management that includes development, verification and validation, configuration management, maintenance, use of an M&S, and others as appropriate.

M&S LIFECYCLE. The period of time beginning when an M&S product is conceived and ending when the product is no longer available for use. The M&S lifecycle is typically broken into phases, such as requirements definition, design, development, test, and operation and maintenance.

M&S REQUIREMENTS. The collection of requirements that an M&S must meet to serve a particular purpose. M&S requirements include problem, M&S User, and simulation domain requirements.

M&S USER. The individual, group, or organization that uses the results or products from a specific application of an M&S. The M&S User is a Government entity.

REQUIREMENTS TRACEABILITY. The degree to which a relationship can be established between the M&S requirements, associated acceptability criteria for accreditation, and evidence collected during verification and validation implementation.

SIMULATION DOMAIN. Aspects of an M&S related to the implementation environment (e.g., time management, object interaction control, M&S User interfaces, databases, and report generators).

SUBJECT MATTER EXPERT. An individual who, by virtue of education, training, or experience, has expertise in a particular technical or operational discipline, system, or process.

M&S USER DOMAIN. The realm of knowledge describing an M&S User's environment to which an M&S will be applied.

VALIDATION. The process of determining the degree to which an M&S and its associated data are an accurate representation of the real world from the perspective of the intended uses of the model. The process of determining the fitness of an M&S and its associated data for a specific purpose.

VERIFICATION. The process of determining that an M&S implementation and its associated data accurately represent the developer's conceptual description and specifications. The process of determining that an M&S faithfully represents the developer's conceptual description and specifications. Verification evaluates the extent to which the M&S has been developed using sound and established software and system engineering techniques.

VERIFICATION AND VALIDATION (V&V) AGENT. The individual, group, or organization designated by the M&S Proponent to verify and validate an M&S. The V&V agent provides information to the Accreditation Agent to support the recommendation to accredit an M&S for a specific purpose. The organization designated by the M&S Proponent to perform verification and validation of an M&S.

F. APPENDIX: V&V PROGRAMMATICS

This appendix contains information regarding resource allocation and funding (Table F-1).

Table F-1. Estimated resources needed for V&V activities.

Actual Resource Allocations and Funding			
V&V Activity	Required Resources	Funding Source	FY15/16 \$K
Verification by M&S Developer	\$50k	JNLWD	\$50k
Validation by M&S Developer	\$50k	JNLWD	\$50k

G. APPENDIX: DISTRIBUTION LIST

This appendix provides the distribution list for hardcopies or digital copies of the approved document.

Joint Non-Lethal Weapons Directorate (1)

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