

## ESTIMATED PROBABILITY OF TRAUMATIC ABDOMINAL INJURY DURING AN INTERNATIONAL SPACE STATION MISSION

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**INTRODUCTION:** The Integrated Medical Model (IMM) is a decision support tool that is useful to spaceflight mission planners and medical system designers when assessing risks and optimizing medical systems. The IMM project maintains a database of medical conditions that could occur during a spaceflight. The IMM project is in the process of assigning an incidence rate, the associated functional impairment, and a best and a worst case end state for each condition. The purpose of this work was to develop the IMM Abdominal Injury Module (AIM). The AIM calculates an incidence rate of traumatic abdominal injury per person-year of spaceflight on the International Space Station (ISS). The IMM project needs the incidence rate in the form of a probability density function, with the most likely incidence rate and the associated uncertainty determined. While the incidence rate for this medical event is low, the possible outcome (crew evacuation or loss of crew) is quite significant.

**METHODS:** A historical rate of in-flight, traumatic, abdominal injury is not available since such an injury has not occurred to date. Therefore, a combination of deterministic and probabilistic modeling was used to estimate an incidence rate. The initiating event for this injury is an impact to the abdomen. A rate of abdominal impact, as the astronauts work and live in space, was used within Poisson's equation to estimate the probability of impact. The severity of an injury resulting from an impact is dependent on the mass and velocity of the impactor. The masses of ISS equipment that could become an impactor and astronaut translational velocities were identified and used as input to a deterministic, lumped, mass-spring-damper, biomechanical model of the abdomen. The biomechanical model was built and used to calculate a response to the impact. The impact response of interest was abdominal compression and was the output of the biomechanical model. A relationship between compression and severity of injury was developed and used in a logistic equation to estimate the probability of injury severity. The probability of impact and the probability of injury severity were multiplied to determine the probability of abdominal injury per person-year of ISS spaceflight. The AIM parameters were characterized with distributions, so that the variability and uncertainty of each parameter was captured. Monte Carlo simulations were performed so that the output of the AIM is in the form of a probability distribution.

**RESULTS:** The probability distribution of traumatic abdominal injury during one year on ISS was determined to be a lognormal distribution with a mean of  $2.6 \times 10^{-4}$ , a standard deviation of  $1.3 \times 10^{-4}$  and 5<sup>th</sup> and 95<sup>th</sup> percent values of  $9.6 \times 10^{-5}$  and  $5.1 \times 10^{-4}$ , respectively. The most sensitive parameters of the model are, in order of sensitivity: 1) The intercept coefficient in the probability of an AIS 3 or greater injury equation; 2) The rate of impact; 3) The damping constant within the biomechanical model; 4) The velocity of the impactor.

**VERIFICATION AND VALIDATION (V&V):** The V&V performed for the AIM followed the IMM V&V plan, which is based upon the requirements outlined in NASA STD 7009. V&V for the AIM included an assessment of the pedigree of the data sets used to build the AIM and the data sets used as input data. The documentation maintained for the AIM includes source code comments and a technical report. The software code and documentation is under Subversion configuration management. Verification and validation included comparison of the AIM biomechanical output to the expected output. A sensitivity analysis was performed and the AIM report will undergo subject matter expert review.

**CONCLUSION:** The AIM was built so that the probability of traumatic abdominal injury during one year on ISS could be predicted. This result will be incorporated into the IMM Abdominal Injury Clinical Finding Form and used within the parent IMM model.



# Estimated Probability of Traumatic Abdominal Injury During an International Space Station Mission

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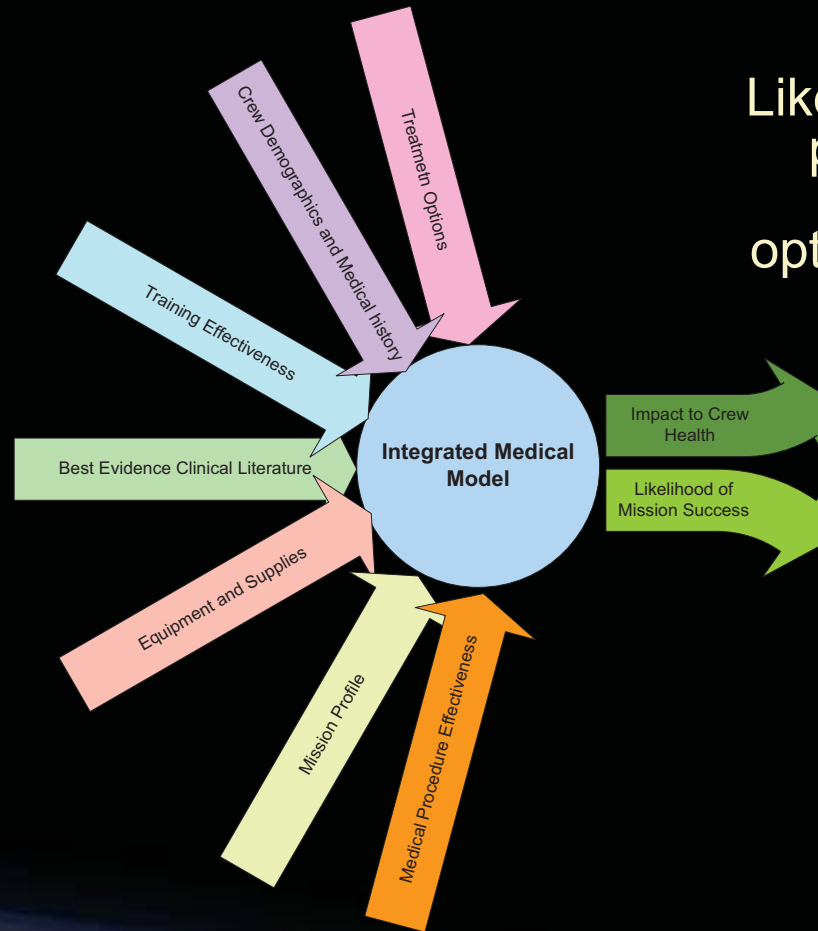


# Integrated Medical Model (IMM)

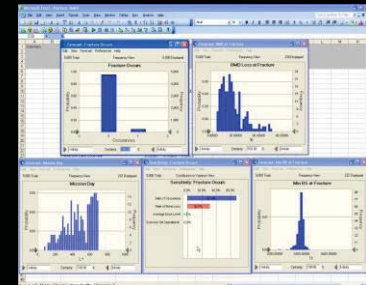
Potential Medical Condition



Evaluate with IMM



Likelihood of occurrence, probable severity of occurrence, and optimization of treatment and resources.



- Probability and consequences of medical risks
- Integrate best evidence in a quantifiable assessment of risk
- Identify medical resources necessary to optimize health and mission success



# Probabilistic Modeling of Rare Medical Events



- Event has not happened during a space mission
  - No incidence rate
  - Many unknowns
- Construct a computational model
  - Define the initiating event scenario and resulting injury
  - Determine available data and develop parameter distributions
  - Mathematically model the physiological response
  - Perform Verification and Validation
  - Relate the physiological response to probability of injury
  - Determine probability of occurrence
- Use probabilistic risk assessment methodology
  - Monte Carlo simulations
  - Estimate the most likely probability and confidence intervals





# Initiating Event Scenario and Injury Definition



- An astronaut translating with equipment too large to see around accidentally impacting another astronaut in the abdomen with attention focused elsewhere
- Traumatic abdominal injury defined as an injury with an Abbreviated Injury Scale (AIS) score of 3 or higher

## AIS definitions for abdominal injuries

AIS	Injury Severity	Description
1	Minor	skin/muscle contusion (hematoma)
2	Moderate	spleen or liver contusion (< 50% surface area)
3	Serious	major kidney contusion spleen rupture
4	Severe	abdominal aorta: minor laceration kidney/liver rupture
5	Critical	kidney: total destruction of organ and vasculature
6	Maximum	hepatic avulsion



Schmitt K-U et al., *Trauma Biomechanics: Accidental Injury in Traffic and Sports*, Heidelberg: Springer, 2010.



# Parameter Distributions

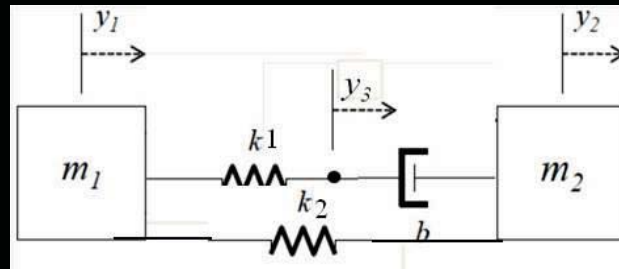
- Astronaut parameters
  - Astronaut mass
  - Abdominal depth
  - Translational velocity
- Mission parameters
  - ISS equipment masses
- Research data
  - Experimental impact response – impact force
  - Experimental impact response – normalized compression
  - Injury severity resulting from experimental impacts
- Spaceflight data
  - Impact rate



# Biomechanical Model of the Abdomen



- A lumped mass-spring-damper model of the abdomen was developed
- Force and deflection data from cadaver impact studies were used to estimate the parameters of a Kelvin mass-spring-damper model



**Equations of motion:**

$$m_1 \ddot{y}_1 + k_1 (y_1 - y_3) + k_2 (y_1 - y_2) = 0$$

$$m_2 \ddot{y}_2 + b (\dot{y}_2 - \dot{y}_3) + k_2 (y_2 - y_1) = 0$$

$$k (y_1 - y_3) = b (\dot{y}_3 - \dot{y}_2)$$

**Initial conditions:**

$$y_1(0) = y_2(0) = y_3(0) = 0$$

$$\dot{y}_1(0) = v_o$$

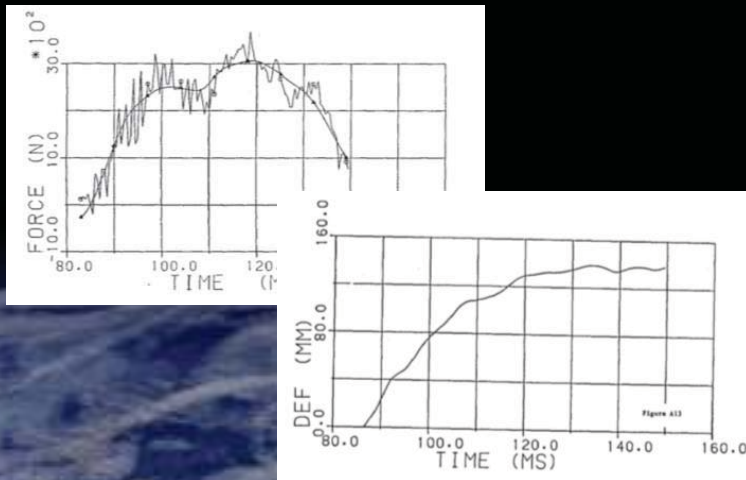
$$\dot{y}_2(0) = \dot{y}_3(0) = 0$$

**Output:**

$$d = y_1 - y_2$$

$$NC = \frac{d}{AD}$$

Parameter Name	Parameter Symbol
Impactor Mass	$m_1$
Body Mass	$m_2$
Spring Constant 1	$k_1$
Spring Constant 2	$k_2$
Damping Coefficient	$b$
Displacement of $m_1$	$y_1$
Velocity of $m_1$	$\dot{y}_1$
Acceleration of $m_1$	$\ddot{y}_1$
Displacement of $m_2$	$y_2$
Velocity of $m_2$	$\dot{y}_2$
Acceleration of $m_2$	$\ddot{y}_2$
Displacement between spring and damper	$y_3$
Velocity of between spring and damper	$\dot{y}_3$
Acceleration of between spring and damper	$\ddot{y}_3$
Initial Velocity	$v_o$
Abdominal Deflection	$d$
Normalized Compression	$NC$
Abdominal Depth	$AD$



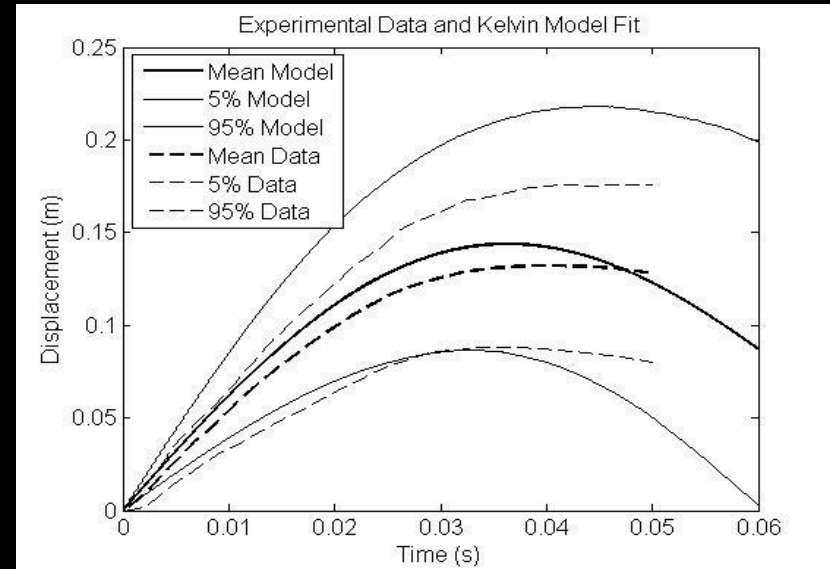
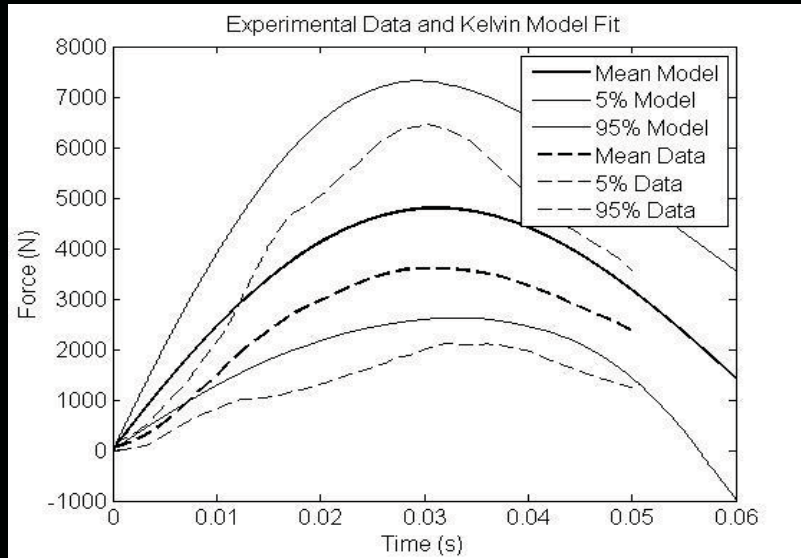
Example data: force vs. time and deflection vs. time

Cavanaugh et al., "Lower abdominal tolerance and response," SAE 861878, 1986.

Nusholtz et al., "Steering system abdominal impact trauma," UMTRI-88-19, 1988.



# Results of Parameter Estimation



Approximately 4.3 cm of error between measured and simulation

Cavanaugh et al., "Lower abdominal tolerance and response," SAE 861878, 1986.  
Nusholtz et al., "Steering system abdominal impact trauma," UMTRI-88-19, 1988.

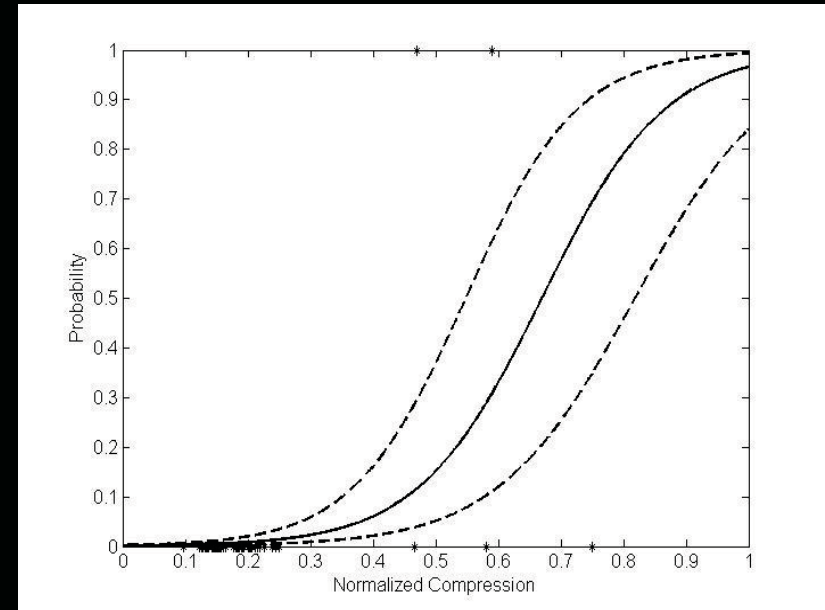




# Probability of Injury

- Translation between normalized compression and injury probability
  - Normalized compression and AIS score were from two impact studies
  - A 0 was given to an AIS of 2 or lower, a 1 was given to an AIS of 3 or higher
  - Matlab's glmfit was used to find the logistic regression coefficients (A & B) for the probability equation:

$$P_{Injury}(NC) = \frac{1}{1 + e^{-(A+B*NC)}}$$



Miller, "Tolerance to Steering Wheel-Induced Lower Abdominal Injury." *J. Trauma*, 31, 1332-9, 1991  
Cavanaugh et al., "Lower abdominal tolerance and response", SAE 861878, 1986.



# Probability of Impact

- Ideally, we would use a rate of the number of times an astronaut accidentally impacts a piece of equipment with his or her abdomen during a mission
- However, this data does not exist
- Instead, we know there have been 6 minor trunk injuries in 26.4 years of flight and 0 traumatic abdominal injuries
- Since an impact must have occurred to cause the minor injuries, we use it as our impact rate
- 6 impacts in 26.43 person-years was the rate used to update an arbitrary non-informed prior uniform distribution (0 to 12) using Bayesian analysis to develop a distribution for the impact rate ( $\lambda$ )

- The impact probability equation is:

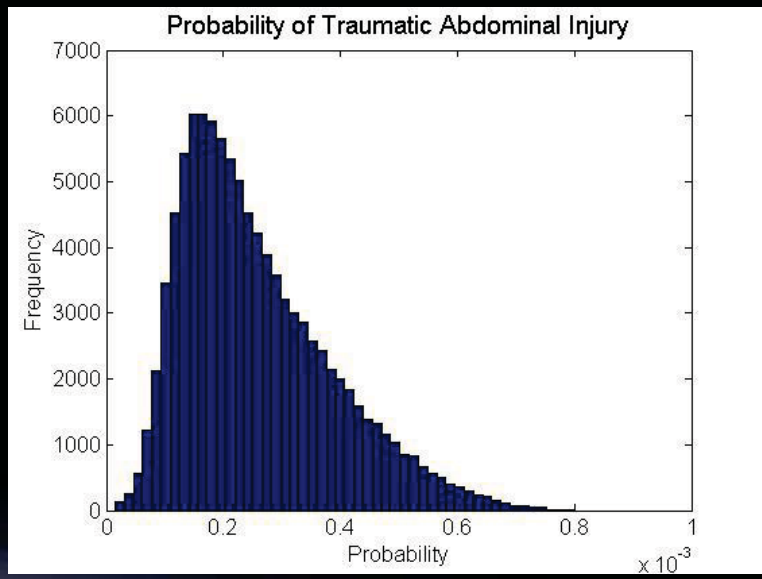
$$P_{Impact}(\lambda) = 1 - e^{-\lambda}$$

Scheuring et al, "Musculoskeletal injuries and minor trauma in space: incidence and injury mechanisms in US astronauts," *Aviat Space Environ Med*, 80(2), 117-24, 2009.



# Results

- Probability of impact and probability of injury are multiplied to obtain probability of traumatic abdominal injury
- 100,000 Monte Carlo simulation trials performed to obtain most likely probability of traumatic abdominal injury



Mean	Standard Deviation	5%	95%
$2.6 \times 10^{-4}$	$1.3 \times 10^{-4}$	$9.6 \times 10^{-5}$	$5.1 \times 10^{-4}$



# Sensitivity Analysis

- The intercept coefficient in the probability of an AIS 3 or greater injury equation and rate of impact are the two most sensitive parameters in the model
- Better estimates of these values could reduce the uncertainty in the probability estimate

Parameter	% Contribution to Variance
Probability coefficient, $A$	62.82
Rate of Impact, $\lambda$	37.17
Damping constant, $b_1$	0.00155
Velocity of the impactor, $v_0$	0.00154
Spring constant, $k_2$	0.0011
Spring constant, $k_1$	0.00091
Probability coefficient, $B$	0.00091
Astronaut Mass, $m_2$	0.00023
Abdominal depth, $AD$	0.00023
Mass of the impactor, $m_1$	$1.97 \times 10^{-7}$





# Conclusions

- A computational model has been developed to predict the probability of traumatic abdominal injury on ISS
- The risk is uncertain because the medical event hasn't happened, but the model bounds this uncertainty
- The estimated probability of traumatic abdominal injury is small, but the impact to the mission could be significant if it were to happen
- These results will be incorporated into the parent Integrated Medical Model and assessed relative to other potential medical events





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