Predicting Head Injury Risk During International Space Station Increments

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Weaver AS, Zakrajsek AD, Lewandowski BE, Brooker JE, Myers JG Jr. ***Predicting head injury risk during International Space Station increments.*** **Aviat Space Environ Med 2013; 84:38–46.**

Introduction: NASA's Human Research Program is using a probabilistic risk assessment approach to identify acute and chronic medical risks to manned spaceflight. The objective of this project was to estimate the likelihood of a neurological head injury to a crewmember severe enough to require medical assessment, treatment, or evacuation during a typical International Space Station (ISS) increment. ***Methods:*** A 2 degree-of-freedom analytical model of the human head was created to allow for analysis of the impact response. The output of the model is acceleration of the head, which was used to determine the probability that the simulated impact resulted in a head injury with an Abbreviated Injury Scale (AIS) score of 3 or greater. These data were then integrated into a probabilistic risk assessment, which outputs a likelihood of injury with a representative measure of the uncertainty. ***Results:*** A Monte Carlo simulation was performed to vary input parameters over their defined distributions. The mean probability of a moderate neurological injury (AIS 3 or greater) occurring due to a head impact by a crewmember translating through the ISS is 1.16×10^{-4} per 6-mo mission increment (2.32×10^{-4} per year). ***Discussion:*** Our head injury prediction model has shown that there is a low, yet not insignificant, probability of neurological head injury of AIS score 3 or greater. The results from this simulation will be input into the parent Integrated Medical Model, which incorporates the risks of over 80 different medical events in order to inform mission planning scenarios.

Keywords: probabilistic risk assessment, Monte Carlo methods, head injury.

DESPITE OVER HALF A century of manned spaceflight, the spaceflight community is only now fully assessing the short- and long-term medical dangers of exposure to reduced gravity environments. Further, as new manned, long-duration missions are pursued and with the advent of commercial flight capabilities available to the general public, a full understanding of medical risk becomes even more critical for maintaining and understanding mission safety and crew health. To address these critical issues, NASA's Human Research Program is using a probabilistic risk assessment approach to identify acute and chronic medical risks and to estimate the consequences of their occurrence to manned spaceflight.

The Integrated Medical Model (IMM) is a probabilistic risk assessment based decision support tool that is useful to mission planners and medical staff to help quantify and assess risks and plan for possible medical events during extended duration spaceflight missions (10,16). IMM provides an evidence-based approach for optimizing medical resources and minimizing risks within spaceflight operational constraints. The IMM model relies primarily on observed medical events to estimate the likelihood of future medical events during International Space Station (ISS) missions. In areas where data are lacking, the IMM project relies on derived probability distributions developed from probabilistic simulations of the events and conditions that contribute to the incidence of the medical event. These probabilistic simulations are enhanced by using deterministic models that integrate physical principles and physiological responses to supplement the observed statistical data. Currently, the IMM model has 85 different medical event probabilities (1). The data from all of these potential medical conditions are integrated using Monte Carlo methods to quantify the most likely utilization of medical resources for the given scenario, estimates of crew impairment, mission impact, and the likelihood of crew evacuation.

Predicting the incidence rates of injuries and illness on ISS is difficult because of the very limited data pool that exists. As of yet, there have not been enough incidences in the limited number of flight person-years to adequately assess the likelihood of most injury modalities during space mission scenarios. Hence, there is a need for a predictive tool. Appropriately derived and developed deterministic models providing input to probabilistic simulations fill this need for the IMM project. The IMM Head Injury Module developed in this study is designed to provide the most likely probability of head injury, with associated uncertainty, for baseline ISS mission scenarios. Head injury is one of the conditions on the Space Medicine Exploration Medical Condition List (32) that lacks observational data or appropriate Earth analogue data to derive a representative in-flight rate of occurrence.

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This manuscript was received for review in May 2012. It was accepted for publication in August 2012.

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DOI: 10.3357/ASEM.3429.2013

The Head Injury Module is one step toward quantification of medical hazards presenting the highest risks during space missions. The module addresses the head injury risk encountered by ISS crewmembers during spaceflight. Specifically, this module examines the likelihood of moderate neurologic injury to ISS crewmembers not wearing headgear, resulting from head impacts during 180-d ISS increments. The probability of head injury from the Head Injury Module will directly feed into the Human Research Program's parent IMM model. These results will then help to determine supplies and procedures required to prepare for treating such injuries during ISS increments.

METHODS

Mission Scenario

The model was designed to assess the likelihood of head impacts onboard the ISS and assumes the ISS mission length to be 180 d. The model also assumes that any impact to the head of a crewmember is directed through the center of gravity of the head, which creates maximal lateral translation without imparting any head rotation. In the model, the crewmember is not wearing a helmet and the head is assumed to impact a fixed, rigid structure inside the ISS.

Injury Definition

This analysis identifies the probability of head injury of moderate or more severe neurological level. Moderate neurological injury is used as the minimum threshold injury criteria in this model since the observed rate of minor ISS head injury (lacerations and bruising) has been previously reported (21). For this case, a moderate neurological injury is defined as anterograde amnesia of 30 min to 24 h, a score between 9 and 12 on the Glasgow scale, and an Abbreviated Injury Scale (AIS) score between 3 and 4.

Lumped Parameter Mathematical Model

The IMM Head Injury Module uses a model of head acceleration response developed by Deb and Ali (6), and modifies it for the ISS head impact scenario. This model includes a mass to represent the head, a spring to represent the rotation of the neck, and a Voigt viscoelastic unit to represent contact of the head with an object (**Fig. 1**). A Voigt viscoelastic unit is an elastic element (a spring with nonzero rest length) in parallel with a viscous element (a dashpot or damper) whose parameters are selected, in this case, to represent the viscoelastic response of a head impact. The benefit of this model is its relative simplicity while still allowing for the examination of both head translation and rotation if desired. Rotation is not considered in this current examination because the mission scenario directs the impact vector through the center of gravity.

The response to impact of the system illustrated in Fig. 1 can be deterministically represented by a set of simultaneous equations that describe the linear and rotational force balance. These equations are integrated in time, with the initial conditions of velocity and orientation of impact, and using model parameters appropriately selected to represent the system under analysis. The equations of motion for the model shown in Fig. 1 are:

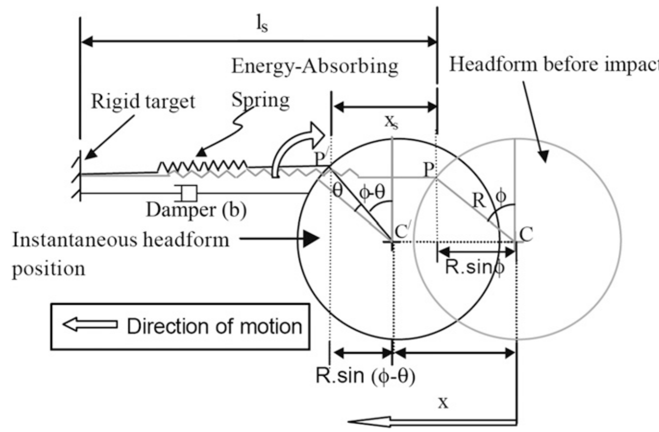

Fig. 1. Head impact, modified from Deb and Ali (6), is modeled using a circular mass translating toward a rigid target connected by a spring and damper (Voigt) system.

$$m\ddot{x} + F_{sb} = 0 \quad \text{Eq. 1}$$

$$I_c\ddot{\theta} + K_r\theta - F_{sb}Rcos(\theta - \varphi) = 0 \quad \text{Eq. 2}$$

where m is the mass of the head, F_{sb} is the force imparted by the spring and damper to the head, I_c is the moment of inertia of the head, K_r is the rotational stiffness constraining the head, R is the radius of the head, and φ is the angle at which the impact occurred in relation to the top of the head. The direction of motion is into the rigid object; therefore, the sign convention is positive into the object.

To determine the properties for the spring and damper that make up F_{sb}, experimental data derived from Sulzer et al. (23) were used. In these experiments, moderate impact forces and acceleration profiles were measured by dropping an International Harmonization Research Activity head form (dummy head analogue) onto a rigid target. The loading and unloading stiffness characteristics of the head form's vinyl skin were assumed to have an analogous response congruent with human tissue. Curves representing these characteristics were digitized (Engauge Digitizer 4.1, digitizer.sourceforge.net) from the published data (23) for implementation in Eqs. 1 and 2.

In order to capture the effects of the skin, the impact model was split into an impacting and a rebound phase. During the impacting phase, the combined force from the spring and damper elements was described by a third order function, fit to the data from Sulzer et al. (23). This total force was scaled by the ratio of the energy in the modeled system to the energy in the referent system. This ratio can be simplified to:

$$\frac{J_{model}}{J_o} = \frac{m(v_f - v_i)_{model}}{m(v_f - v_i)_o} = \frac{e \times (v_i - v_i)_{model}}{(v_f - v_i)_o} \quad \text{Eq. 3}$$

where m is the mass of the head or head form, v_i is the initial velocity, v_f is the final velocity, and e is the coefficient of restitution.

During the rebounding phase, the stiffness and damping elements were separated into individual components to capture the contribution of the rebounding velocity on the damping force. As there is a change in the viscoelastic properties of the head during the impact and rebound phase of the impact event, there is the potential for the model to produce a physically unrealistic, discontinuous impact force that will affect the assessment of the injury scoring. If the stiffnesses as defined for both the loading and the unloading portions of the curve are not equal at this transition point, there will be a discontinuity in the acceleration profile. To avoid a discontinuity in the acceleration curves between the impacting and rebounding phases of motion, the curves for the loading and unloading spring forces are forced to intersect at the rebound point. The new unloading curve is created by fitting an exponential function to the original unloading data points and one data point on the loading curve at the rebound displacement. The modified curve and the spring force are dependent on the maximal displacement during the impact and are independent of impact velocity.

Data for the damping characteristics of the head form during the rebound phase were taken from the same source as the spring stiffness. Instead of a constant damping coefficient, the damping is defined as a linear function of velocity. For this model, the damping force during rebound is defined as:

$$F_b = b \times \dot{x} + (u_0/2.71) \times C \qquad \text{Eq. 4}$$

where the damping coefficient, b, is 737 N-s/m, the constant, C, is defined as 2272 N, and u_0 is the initial velocity (see 23 and note the reversed sign convention).

Calculation of Acceleration

To calculate the acceleration at each time point, Eqs. 1 and 2 are solved for $\ddot{x}$ and $\ddot{\theta}$, respectively. F_{sb} is calculated from the initial conditions. F_{sb} and the initial conditions are used as inputs to the variable step Runge-Kutta solver (ODE45) in Matlab (MathWorks, Natick, MA). For each time step, displacements and velocities are calculated and used to update F_{sb}. Finally, the derivative of the output velocity vector with respect to time is calculated to arrive at the acceleration vector.

Head Injury Metric

The Head Injury Criteria, or HIC score, was proposed in 1972 by the National Highway Traffic Safety Administration as a way of grading the relative severity of head injuries in automobile crashes (14). The HIC score is a contact-dependent metric that uses a formula dependent on peak linear acceleration to determine risk of injury with no regard to the mode of injury. Since the HIC score is based on contact forces, it may not be used to quantify the risk of injury due to inertial loads, such as whiplash. The HIC score is calculated as:

$$HIC = \max_{(t_1,t_2)} \left\{ (t_2 - t_1) \left[\frac{1}{(t_2 - t_1)} \left(\int_{t_1}^{t_2} \ddot{x}\, dt \right) \right]^{2.5} \right\} \qquad \text{Eq. 5}$$

where times t_1 and t_2 are chosen to maximize the HIC value (14).

Model Parameters

A summary of the distributions used as model inputs is given in **Table I**. Data from numerous sources (3,5,8,19,20,22,24,25,33–35) were compiled and a distribution in terms of either mean and SD (for normal distributions) or minimum and maximum (for uniform distributions) was determined. The range of the data was checked for congruency with astronaut anthropometric data found in NASA Standard 3000 (17).

Impact Model Velocity Input Data

The input velocity distribution was created using data from Scheuring et al. (21) and NASA-STD-3000 (17). There are three velocity categories defined in NASA-STD-3000: moving equipment (0.15–0.30 $m \cdot s^{-1}$), translating through the cabin (0.40–0.60 $m \cdot s^{-1}$), and gymnastic motion (1.8 $m \cdot s^{-1}$). To capture the uncertainty in the gymnastic velocity, a combination of videos from onboard the ISS and data from previous studies (2,12,27–31) was used to develop an input range with bounds of 1.5–2.0 $m \cdot s^{-1}$. From the activity list in Scheuring et al. (21), it is known that there were 13 injuries caused by either transferring or stowing equipment, 8 injuries from translating through the spacecraft, 12 injuries from impacting structures, and 17 unknown causes of injury. In this approach, it is assumed that only these injury scenarios (50 total injuries) could have caused a head injury. From these data, upper and lower bounds were constructed for the velocity distributions, and then they were used to determine how often the model samples from each distribution. Using the lower bound as an example, 45.3% of the time the model would choose a value within the uniform distribution of 0.15–0.30 $m \cdot s^{-1}$. The bounds are created by the uncertainty in the velocities from the impacting structures and the unknown injury categories.

Lower bounds:

$$0.15 - 0.30\frac{m}{s} \rightarrow \frac{Transferring + Stowing + \frac{1}{3}(Impacting + Unknown)}{Total\ Injuries} = \frac{5 + 8 + \frac{1}{3}(12+17)}{50} = 45.3\%$$

$$0.40 - 0.60\frac{m}{s} \rightarrow \frac{Translating + \frac{1}{3}(Impacting + Unknown)}{Total\ Injuries} = \frac{8 + \frac{1}{3}(12+17)}{50} = 35.3\%$$

$$1.5 - 2.0\frac{m}{s} \rightarrow \frac{\frac{1}{3}(Impacting + Unknown)}{Total\ Injuries} = \frac{\frac{1}{3}(12+17)}{50} = 19.3\%$$

TABLE I. A SUMMARY OF THE DISTRIBUTIONS INPUT INTO THE MODEL.

	Normal Distributions		Uniform Distributions	
	Mean	SD	Min	Max
Mass (kg)	4.56	0.419	——	——
Radius (m)	0.0894	0.0026	——	——
Moment of Inertia (kg-m^2)	0.0242	0.0047	——	——
Stiffness, Torsion (N-m · rad^{-1})	14.99	5.51	——	——
Stiffness, Flex/Ext (N-m · rad^{-1})	27.21	11.67	——	——
Stiffness, Lat Bend (N-m · rad^{-1})	29.01	15.43	——	——
Velocity (moving equipment) (m · s^{-1})	——	——	0.15	0.30
Velocity (translating) (m · s^{-1})	——	——	0.40	0.60
Velocity ("gymnastic") (m · s^{-1})	——	——	1.5	2.0
Injury Coefficient a	——	——	−10.753	−10.588
Injury Coefficient b	——	——	0.0147	0.0317

The distributions were treated as either normal or uniform as indicated by the table. The data for the distribution was taken from Refs. 3, 5, 8, 19, 20, 22, 24, 25, and 33–35 and then checked against values (if applicable) stated in NASA-STD-3000 (17) in order to ensure that they were in the correct range for the astronaut population.

Upper bounds:

$$0.15-0.30\frac{m}{s}\rightarrow\frac{Transferring+Stowing}{Total\ Injuries}=\frac{5+8}{50}=26.0\%$$

$$0.40-0.60\frac{m}{s}\rightarrow\frac{Translating}{Total\ Injuries}=\frac{8}{50}=16.0\%$$

$$1.5-2.0\frac{m}{s}\rightarrow\frac{Impacting+Unknown}{Total\ Injuries}=\frac{12+17}{50}=58.0\%$$

Probability of Injury

The probability of injury can be defined as a sigmoid curve following the form

$$P(x)=\frac{1}{1+e^{-(a+bx)}} \qquad \text{Eq. 6}$$

where P is the probability of injury for the given value of x (HIC score), which is the injury predictor in the described model. The a and b parameters are determined using the maximum likelihood method (14). Digitizing the data from Marjoux et al. (14) for moderate neurological injury, the parameters for a and b were found as: 5th percentile: a = −10.753, b = 0.0317; 95th percentile: a = −10.588, b = 0.0147. These values were then used to create uniform distributions of a and b to define a probability of injury function to relate HIC score to injuries of AIS three or greater, which was bounded by the 5th and 95th percentile curves.

Historical Rate of Head Injury

The rate of head injuries during spaceflight found in Scheuring et al. (21) was used to determine how often a head impact that could potentially cause injury might occur. It is known that there were 82 injuries caused by crew activity, but it is not known which activities led to head injuries. Of the 82 total injuries, 37 of them could have been caused by translating through the vehicle. Those injury sources were classified as translating through spacecraft (N = 8), impacting structures (N = 12), and unknown (N = 17). Assuming that any of the 82 crew activities reported have an equal chance of causing a head injury, the data can be used to construct an upper and lower bound for the number of head injuries that may have been caused by translating through the vehicle.

$$Lower\ bd.=\left(\frac{Translating}{Total\ Injuries}\right)\times(Total\ Head\ Injuries)$$
$$=\left(\frac{8}{82}\right)\times(9)=0.88\cong 1$$

$$Upper\ bd.=\left(\frac{Translating+Impacting+Unknown}{Total\ Injuries}\right)\times$$
$$(Total\ Head\ Injuries)=\left(\frac{8+12+17}{82}\right)\times(9)=4.1\cong 4$$

To implement this data in the impact model, it was assumed that the distribution of head injuries caused by crewmember translation between the lower bound (one injury) and upper bound (four injuries) is unknown. To capture the uncertainty in this estimate, a Bayesian uninformed prior approach was used to generate a gamma distribution with the properties:

$$lambda=gamma(\#\ of\ events, time)=gamma(2.5, 52.87)$$

The number of events was chosen as a mean of 2.0 + 0.5 (to account for uncertainty in the mean) and the time was chosen as 52.87 6-mo periods, which represents the 231,724.7 person-hours of spaceflight reported in Scheuring et al. (21).

Monte Carlo Simulation

A Monte Carlo simulation of 100,000 trials was performed to calculate the probability of head injury. This process is described here and in **Fig. 2**. During each trial, Eqs. 1 and 2 were solved for acceleration with parameters sampled from the distributions that describe them. During each iteration, the HIC score was calculated from the acceleration. Next, the injury probability due to an impact was calculated using Eq. 6, the HIC score, and the values of a and b, sampled from their respective distributions. Finally, the injury probability was multiplied

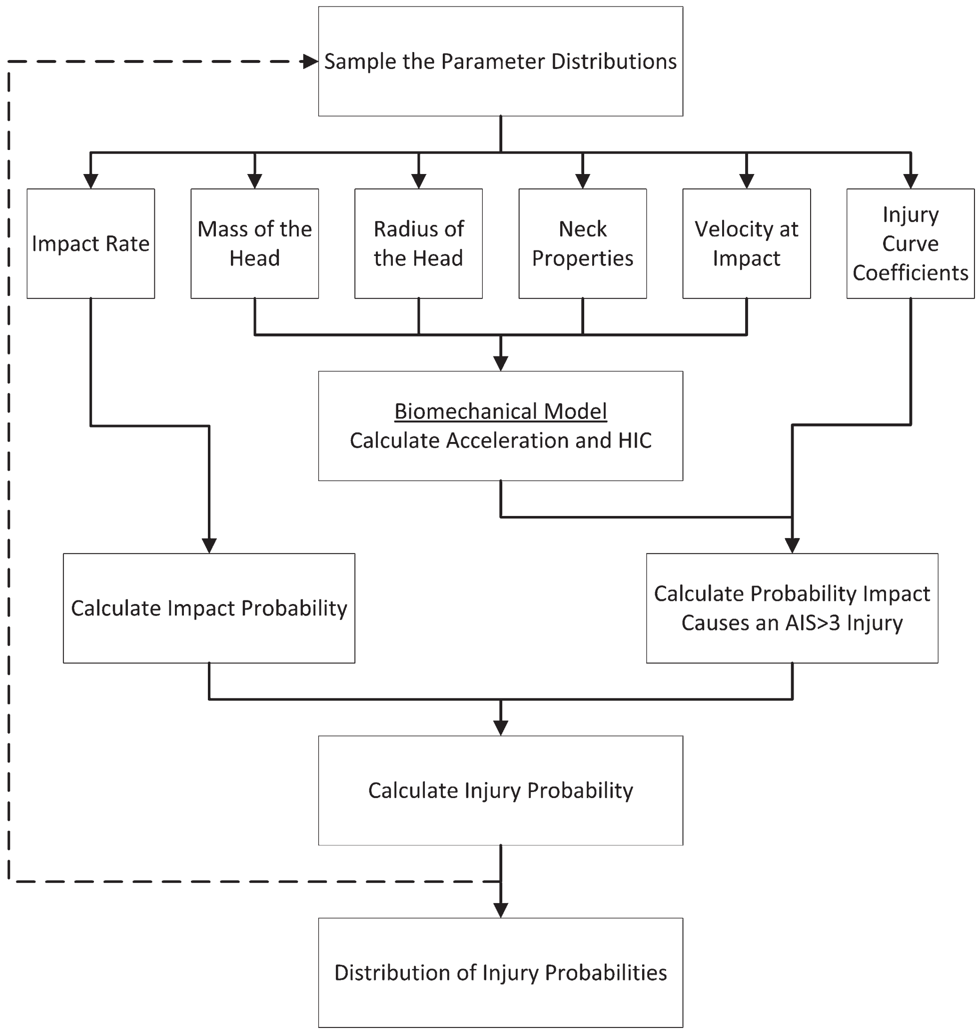

Fig. 2. The possibility of an AIS 3 or greater head injury occurring during ISS operations is determined by a probabilistic model simulating a head striking a rigid object. The model samples the input parameter distributions, which include the impact rate, the mass of the head, the radius of the head, neck properties, the velocity at impact, and coefficients that define the shape of the curve relating Head Injury Criteria to the risk of injury. The probability of impact and the probability that impact caused an injury are then calculated and used to determine total injury probability for one model iteration. That value is stored to create a distribution of injury probabilities, and the process is repeated.

by the historical injury rate probability to estimate the overall probability of head injury during a 6-mo ISS mission. The mean, SD, and 5th and 95th percentile values for the 100,000 probability calculations were found. Model convergence was verified by analysis of the difference in the SD over intervals of 1000 iterations. The mean probability is the most likely probability of head injury during an ISS simulation.

Sensitivity Analysis

The sensitivity analysis relates the contribution of the uncertainty of each input variable to the probability of injury. Sensitivity of the analysis to the variables in the model state space was determined using correlation coefficients. The correlation coefficients were squared and divided by the sum of the squared correlation coefficients. This analysis provides the percentage that each input variable contributes to the variability in the probabilistic output (13).

RESULTS

Few definitive studies have been identified in the archival literature with regard to head impacts at the low velocities that are applicable to validating this model. The data that has been found to be most suitable for validation is from dummy head-drop tests. These tests are routine impact tests to calibrate the properties of crash test dummies that are specifically designed to mimic aspects of the biomechanical impact responses of human subjects (26). They are performed in a controlled environment and provide reproducible results.

To validate the output of the model, the referent acceleration data from the head-drop test that was compared to the model output was taken from Sulzer et al. (23). The acceleration profile and the HIC score from the head-drop test, the model presented in Sulzer et al., and the model presented here were compared for a drop height of 376 mm, which corresponds to an impact velocity of 2.71 $m \cdot s^{-1}$. At this velocity, the error between the IMM model and the drop test was +1.2% for acceleration and −1.0% for HIC score. The acceleration profiles of the drop test and the current model using an input velocity of 2.71 $m \cdot s^{-1}$ are shown in **Fig. 3**. Data for a higher input velocity case, 3.13 $m \cdot s^{-1}$, were also compared against the model output (23). For this input velocity, the model shows a −4.7% error in peak acceleration and a −2.5% error in HIC.

A summary of the results of the model run with 100,000 Monte Carlo iterations is shown in **Table II**, and the distribution of probability of injury is shown in **Fig. 4**. Data indicate the most likely probability of a moderate neurological injury (AIS 3 or greater) occurring due to a head impact by a crewmember translating through the ISS is 1.16×10^{-4} per 6-mo mission increment (2.32×10^{-4} per year).

The results of the sensitivity analysis are shown in **Table III**. The data show that the velocity distribution contributes to the majority of the output variability. This is expected since the velocity is a major input to the deterministic model. Also, the true velocity distribution is unknown and was created from three separate distributions for moving equipment, normal translation, and gymnastic translation. The next most sensitive parameters are the distribution for the probability of injury coefficient, b, which is one of the coefficients used to define the injury risk curve, and the historical head injury incidence rate.

DISCUSSION

The rate of minor head injuries can be quantified from existing ISS injury data (21). However, such efforts are insufficient in helping to quantify the likelihood of much more severe head injuries, as direct evidence is lacking for the space mission environment. The results of the mathematical model show that the 90th percentile confidence interval for probability of a moderate head injury (AIS > 3) occurring onboard the ISS during a typical 6-mo mission is less than 5×10^{-4} per person-year. This is considered to be low, yet not insignificant in comparison to several of the other astronaut medical conditions included in the IMM probabilistic risk assessment model. Any injury below this level would not result in the need for an immediate return to Earth for medical treatment. Although those minor injuries may require treatments such as bandages, antibiotic ointments, and other common medical kit items, the rate of injury for those situations is not covered by this model. The rate of minor head injuries has already been quantified from existing ISS injury data (21).

Numerous biomechanical models of the head/neck system have been developed to study head and neck injury. These range from very simple one-mass, one-spring systems to more complex mass-spring-damper systems that represent the integrated biomechanics of the head, each individual vertebra, and each supporting muscle, ligament, and tendon (4,9,15). The IMM Head Injury Module modified a model of head acceleration response developed by Deb and Ali (6) for the ISS head impact scenario. This is a relatively simple mathematical representation that incorporates elements of the forehead, the head, and rotational components of the neck. The goal of this model was to create a validated representation of the physical response to low impact loads ample enough to capture the uncertainty in the head injury event scenario. This was done to provide reliable information for medical mission planning without adding computational burden from unnecessary model complexities.

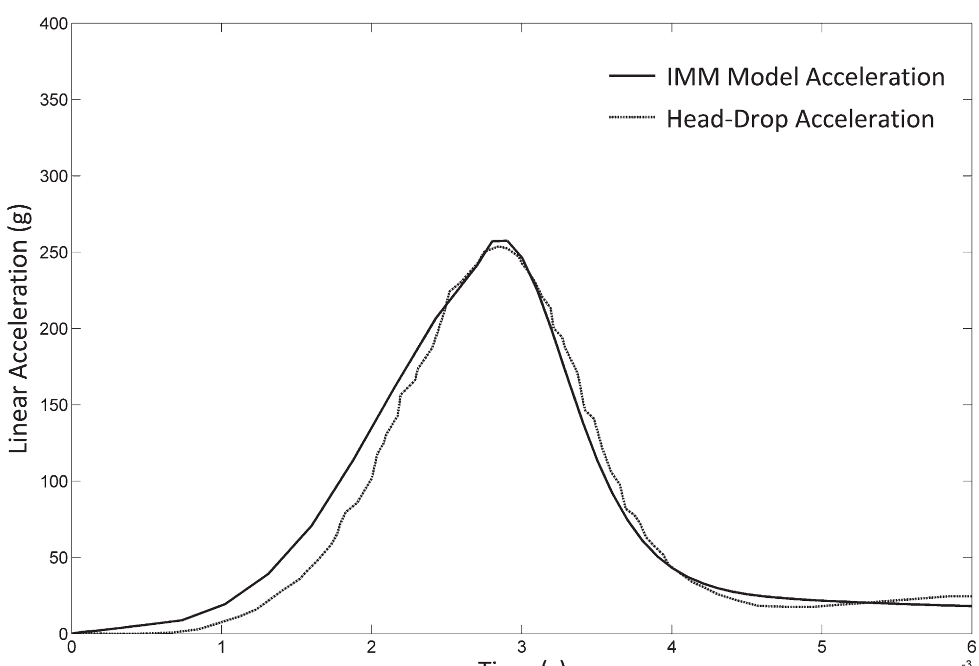

Fig. 3. A comparison of the acceleration from a head-drop test (dashed line) and the acceleration output of the head injury model (solid line). The plots show that the shape and the magnitude of the model curve closely matched the test data for an input velocity of 2.71 $m \cdot s^{-1}$.

TABLE II. THE RATE OF HEAD INJURY OF AIS SCORE 3 OR GREATER AS PREDICTED BY THE HEAD INJURY MODEL COMBINING BOTH THE MODIFIED INCIDENCE RATE AND THE MODIFIED VELOCITY DISTRIBUTION.

	Mean	SD	5th Percentile	95th Percentile
Probability of Moderate Neurological Injury per 6 mo (per year)	1.16×10^{-4} (2.32×10^{-4})	5.48×10^{-4} (1.10×10^{-3})	3.26×10^{-7} (6.52×10^{-7})	4.94×10^{-4} (9.88×10^{-4})

All values are reported for one astronaut as either per 6-mo increment or 1 person-year (1-yr statistics in parenthesis).

This model uses the HIC score as the predictor of moderate head injury. The HIC score is calculated using only translational acceleration without accounting for any rotational acceleration. The mathematical model in this analysis has the capability to predict rotational acceleration, which may be an important aspect of neurological trauma (7,18). However, other injury criterion, like head impact power, that depend on rotational components have not been validated or accepted by the biomechanics community (11). Therefore, rotational dynamics and head impact power injury criterion were not incorporated into this model at this time. Due to the HIC score calculation, a more conservative (i.e., higher) HIC score resulted when only translation was considered and the rotation was disregarded. For medical planning for ISS missions, this conservative approach is preferred.

Another limitation of this model is that the head impact is mathematically represented as a head striking a rigid, stationary object. This type of model and experimental data are used by the automobile industry to examine the effectiveness of countermeasures to prevent head injuries during motor vehicle accidents. The head impact model described here uses a distribution for the mass of a human head as the input mass. A higher incidence of injury would result if the estimated mass were to account for a greater fraction of the entire body mass. However, it would not be biomechanically correct to represent the entire body mass within the model of the head. To accommodate the potential for more severe impacts from whole body translations, additional mechanical components would need to be included in the impact model to account for the additional body mechanics. The mechanics would include the physical properties of other parts of the body, as well as relationships describing how those parts would behave with respect to each other. This approach would add complexity, uncertainty, and a level of detail that is not justified at this time. It is expected that the current model encompasses the output range of the more complex formulation within acceptable bounds.

Totaling data from all U.S. spaceflight missions through ISS Expedition 13, there were nine reported minor head injuries reported in 231,724.7 person-hours of spaceflight (21), which provides a reasonable estimate of the incidence rate at which head impacts resulting in injury during spaceflight onboard the ISS occurred. This conservative rate of head impact was used to derive the probability of occurrence within the impact model event tree. This probability of occurrence was then multiplied by the probability of injury due to the impact (Eq. 6) to estimate the overall probability of head injury during an ISS mission.

The deterministic model was validated using a head-drop test with an impact velocity of 2.71 $m \cdot s^{-1}$. This speed is faster than the highest impact speed considered for the given scenario, but it was not possible to find data for slower velocity tests. Even though the model was unable to be validated at a velocity of 2.0 $m \cdot s^{-1}$ or less it is still considered reliable, as higher impact velocities show reasonable validity and with diminishing differences in peak response as velocity is reduced. Even though these relationships should hold true for the cases with velocities of 2.0 $m \cdot s^{-1}$ or less, it still adds a level of

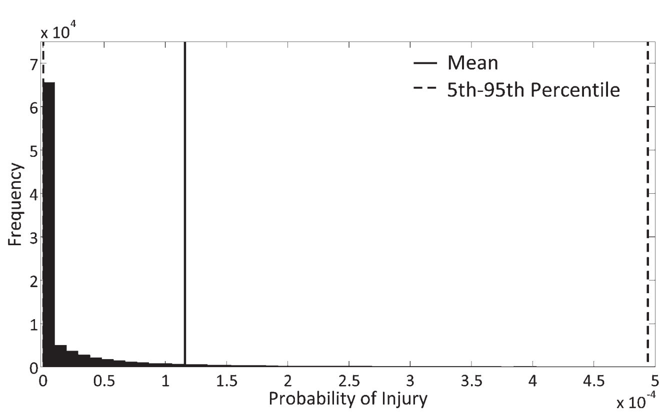

Fig. 4. The histogram of the frequency of probability of injury for the 100,000 model iterations, which was truncated between the 5th and 95th percentile data in order to clearly see the shape of the distribution. The histogram shows that the most frequent outcome was a very low injury probability. Data exist to 0.024 on the x-axis, but the frequencies were too low to be seen on the plot.

TABLE III. THE SENSITIVITY OF THE OUTPUT VARIANCE TO THE UNCERTAINTY IN THE INPUT DISTRIBUTIONS.

Input Parameter	Percentage Contribution to Output Variance
Impact Velocity	64.80
Injury Coefficient, b	23.58
Incidence Rate	10.66
Head Mass	0.94
Injury Coefficient, a	0.01
Head Radius	0.01
Moment of Inertia	0.00
Neck Stiffness	0.00

The sensitivity analysis shows that the probability of a head injury of AIS score 3 or greater is most sensitive to the impact velocity, a coefficient that defines the risk of injury curve, and the incidence rate.

uncertainty to the result. As an example of the uncertainty and to illustrate that the model validates against varying input velocity cases, an additional validation case was performed. Head-drop test data at a 3.13 m · s^{-1} input velocity compared well to the model output with a −4.7% error in peak acceleration and a −2.5% error in HIC. Even though this is for a higher velocity case than expected on the ISS, it provides confidence that the model adequately represents varying input velocity scenarios.

In conclusion, this head injury model was developed to evaluate the probability of a moderate head injury occurring due to crewmembers translating through the ISS. The probabilistic simulation has shown that there is a low probability of neurological head injury of AIS score 3 or greater, and the velocity of impact is the most important factor in the model. The results from this simulation will be input into NASA's Integrated Medical Model, which currently incorporates the risks of 85 different medical events in order to inform mission planning scenarios. This will allow for more informed medical planning for future space missions.

ACKNOWLEDGMENTS

The authors would like to thank DeVon Griffin, Eric Milo, Michael McRae, and Elise Griffin for their invaluable contribution to this work. The authors would also like to acknowledge support from the Exploration Medical Capabilities Element of NASA's Human Research Program.

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