INSTITUTE FOR DEFENSE ANALYSES

Guidance for Calculation of Risk of Significant Injury from Blunt Impact Projectiles

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IDA

INTEROFFICE MEMORANDUM

SCIENCE AND TECHNOLOGY DIVISION

18 October 2021

To: Wes Burgei, JIFCO

From: Sujeeta Bhatt, Jessica Swallow, Jeremy Teichman, Yevgeny (Jenya) Macheret

Subject: Guidance for Calculation of Risk of Significant Injury from Blunt Impact Projectiles

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IDA developed a framework and associated analysis for computing the risk of significant injury (RSI) from blunt impact projectiles. The attached package includes four documents describing that framework and how to employ it. The Joint Intermediate Force Capabilities Office (JIFCO) desired a way to estimate the RSI for any given projectile/employment combination incorporating such factors as targeting distance, aiming and delivery accuracy, impact velocity, reactive postures, and projectile and tissue properties. JIFCO has access to various models for different aspects of the analysis. The attached package describes how to employ and combine these models to build the overall risk estimate. A detailed analysis on the effect of reactive postures on projectile impact locations is contained in a separate IDA report (Bhatt, Cheng, Kramer, Swallow, & Teichman, 2021). The elements of this package have already been shared with the IDA working group, JIFCO, and Johns Hopkins University Applied Physics Laboratory (JHU/APL) subject matter experts as needed during the course of collaborative work. This bundled package represents a formalized delivery of those elements.

"Part 1 – Pose-dependent RSI Calculation with Uncertainty" (Appendix A) describes IDA's initial framework for connecting the necessary modules, their inputs and outputs, the sources from which the inputs should be drawn, and the way the modules get combined in order to calculate the RSI. The five modules captured are as follows:

1. The probability of hit (Phit) model to capture the scatter in projectile impact locations,
2. The pose-dependent segmented Phit model to capture the resulting impacted body locations,
3. The finite element model to associate hit locations with tissue-level effects,
4. The injury correlations to associate tissue-level effects with significant injury, and
5. The synthesis module for combining the outputs for multiple possible injury mechanisms and locations into a single aggregate RSI.

"Part 2 – RSI Calculation: Definitions, Models, and Equations" ("RSI Calculation") (Appendix B) is a refinement of the original RSI framework. This document provides greater mathematical detail regarding contributions to uncertainties in the resulting estimate and explicitly dictates the inputs, outputs, and connections of six modules to compute the aggregate RSI. The six modules are as follows:

1. The delivery model to capture statistical scatter of the projectile impact relative to the aim point,
2. The Phit model to convert each impact into a probability distribution over body segments (optionally including reactive postures),
3. The vulnerability model describing when and how to consider different injury mechanisms based on the areas of each body segment vulnerable to each type of injury,
4. The body response model for computing the tissue-level response to a given impact,
5. The injury model correlating tissue-level response with injury occurrence, and
6. The significance module describing the fraction of occurring injuries breaching the threshold of significance.

"Part 3 – Calculation of Risk of Significant Injury (RSI) Torso Example" (Appendix C) is a presentation for the expert user community that describes how to employ the models per the "RSI Calculation" document (Appendix B) using the torso as representative example. Because "RSI Calculation" does not explicitly dictate all possible employments of the modules, this document instructs users on how to select and employ procedures consistent with the structure of the "RSI Calculation" document.

"Part 4 – Calculation of Risk of Significant Injury (RSI) Hits to the Arm Example" (Appendix D) is a presentation that walks through the RSI calculation process for the arm. It shows how to handle distinct parts of a given body segment, such as the lower and upper arm, and distinct injury mechanisms within a single area, such as fractures to the radius and ulna. Critically, this document describes how to handle injuries that can and cannot occur in tandem. For instance, fractures to both the radius and humerus would not likely occur from a single impact location, but a single impact could fracture both the radius and ulna.

Glossary of common acronyms not explicitly defined everywhere in the package:

APL	Johns Hopkins University Applied Physics Laboratory
FEA	Finite Element Analysis
FEM	Finite Element Model
HEMAP	Human Effects Modeling Analysis Program

References

Bhatt, S., Cheng, E., Kramer, C., Swallow, J., & Teichman, J. (2021). The Role of Defensive Postures in Computing Probability of Hit for Projectile Blunt Impact Intermediate Force Capabilities (D-21534). Alexandria, VA: Institute for Defense Analyses.

Appendix A.
Part 1 - Pose-dependent RSI Calculation

Jeremy Teichman and Jessica Swallow
Institute for Defense Analyses
December 17, 2019

Introduction

The Human Effects Modeling Analysis Program (HEMAP) currently provides the probability of significant injury[1] for a discrete series of hit locations chosen to highlight different injury mechanisms. The locations do not represent a balanced probability distribution of likely hit locations. This document provides some guidance for calculation of overall risk of significant injury (RSI) using those injury probability data.

RSI Calculation

1. The probability of hit (Phit) model: Given a weapon aimpoint and accuracy, IDA model generates a distribution of hit locations via Monte Carlo simulation. Output: set of hit locations
2. Segmented Phit: Given a target pose, the IDA model generates the absolute probability of hitting each body segment as well as a standard deviation representing population variation and pose repeatability. Defined segments are: skull, face, neck, thorax, abdomen, pelvis, arm, and leg. Output: $P_{hit}(segment\ j)$
3. Advanced Total Body Model (ATBM) provides probability of significant injury for locations associated with different injury modalities. Output: $P(injury\ k\ given\ hit\ in\ segment\ j)$
4. Coarse allocation of segmented hit locations to injury modes based on ATBM locations: These are off-the-cuff approximations, best replaced by a more rigorous method if possible. Output: w_k, the weight given to injury mode k, where $P(injury\ given\ hit\ in\ segment\ j) = \sum_k w_k\, P(injury\ k\ given\ hit\ in\ segment\ j)$
    a. Leg: 50% femur fracture, 5% patella fracture, 30% tibia fracture, 15% fibula fracture

[1] The number provided may actually be the probability of injury rather than the probability of significant injury. If so, the appropriate conversion factors should be employed.

b. Arm: 50% humerus fracture, 25% radius fracture, 25% ulna fracture

c. Pelvis: 100% treat as abdomen

d. Face: 100% skull fracture

e. Neck: 100% skull fracture

f. Abdomen and thorax: treat injuries as if each could independently occur at each location, so probability of significant injury is $P(injury\ given\ hit\ in\ segment\ j) = 1 - \prod_k [1 - P(injury\ k\ given\ hit\ in\ segment\ j)]$ where $\prod_i$ indicates a product over all i injury mechanisms, each occurring with probability $P(injury\ i)$

g. Skull: 100% skull fracture

5. The overall RSI is given by the sum over all body segments of the product of the probability of hit (step 2 output) and the probability of injury-given-hit (weighted sums of step 3 output in accordance with step 4 allocations). Output: $RSI = \sum_j P_{hit}(segment\ j) P(injury\ given\ hit\ in\ segment\ j)$

Uncertainties

The body segmentation is currently done using an automated algorithm with hit probabilities generated from an ensemble of subjects and within-subject repetitions of each pose. Using manual segmentation of two images per pose, IDA estimated the error incurred by using the automated segmentation. This is a rather coarse error estimation approach but gives a sense of the error magnitude. IDA has not calculated covariances. The influence of the segmentation error on RSI error can aid in determining whether improvements to the segmentation approach would be useful.

Segmentation errors do not influence the probability of injury given a hit on a given body segment. So, the contribution to RSI error ϵ_{RSI} from segmentation error is given by

$$\epsilon_{RSI} = \sum_j \epsilon_{P_{hit\,j}} P(injury\ given\ hit\ in\ segment\ j)$$

The probability of injury given a hit in a given body segment is as described in the previous section. $\epsilon_{P_{hit\,j}}$, the error in P_{hit_j} stemming from segmentation error, is a function of the pose, aimpoint, and weapon impact spatial distribution. $\epsilon_{P_{hit\,j}}$ will be reported from the IDA model for each body segment, pose, aimpoint, and weapon impact spatial distribution. IDA computes this value as the root-mean-square difference between the P_{hit_j} computed on the auto-segmented image and the manually segmented image over all images of a single pose for which both segmentations are available (currently two per pose).

The resulting ϵ_{RSI} can be used to understand the uncertainty in RSI due to the body segmentation and/or to decide whether better segmentation meaningfully reduce the total RSI uncertainty.

Appendix B.
Part 2 - RSI Calculation: Definitions, Models, and Equations

Jeremy Teichman and Jessica Swallow
Institute for Defense Analyses
August 6, 2020

This document provides the framework for computation of risk of significant injury (RSI) for nonlethal blunt-impact projectiles when the projectile hits the target. The current construct for RSI computation comprises the following set of six serially connected models:

1. Delivery model: The weapon and scenario (including range) pair provides a probability distribution of the impact velocity *v* and the point of impact relative to the aimpoint $(\Delta x, \Delta y)$. We assume that the impact velocity does not vary appreciably with impact point and that the probability distribution about the aimpoint is a bi-variate normal distribution with range-independent angular standard deviations σ_x and σ_y in Δx and Δy. Thus, in general, the deterministic velocity *v* will be a function of range *R*, $v(R)$, and the distribution of hit locations relative to the aimpoint will be
$f(\Delta x, \Delta y; R, \sigma_x, \sigma_y) = \frac{1}{2\pi R\sqrt{\sigma_x \sigma_y}} e^{-\frac{\Delta x^2}{2R^2\sigma_x^2} - \frac{\Delta y^2}{2R^2\sigma_y^2}}$.
2. Probability of hit (Phit) model: Given an aimpoint, range, σ_x, and σ_y, there is a probability distribution of hit locations and angles of impact on the body given a distribution of postures and target body geometries. The current approach simplifies this as follows:
   a. All hits are assumed to be incident perpendicular to the local body surface.
   b. Hits are grouped by body segment (thorax, abdomen, leg, etc.), so the continuous distribution of hit locations is replaced by a set of discrete probabilities, $P_{hit_i} =$ probability of a hit in segment *i*. These will not sum to unity because there is some probability of a miss.
   c. The hit probability is tabulated and supplied for a series of poses, aimpoints, and accuracies $(R\sigma_x, R\sigma_y)$. $P_{hit_{i,k}}$ is the probability of a hit on segment *i* given pose *k*.
   d. $P_{hit_i} = \sum_k P_{pose_k} P_{hit_{i,k}}$, where P_{pose_k} is the probability of encountering pose *k* and is given by a uniform distribution over the front facing poses ($P_{pose_k} = \frac{1}{K}$ for *K* total

poses) or some other set of scenario-determined probabilities (for example, if the target is running away, there will be a different set of segment hit probabilities – in this special case the segments viewed from the rear would best be treated as different segments because they will have a different set of associated injury risks).

e. Within each body segment, the probability of a hit on any given location is considered uniformly distributed.

3. Vulnerability model: For each body segment, there will be a defined fraction of the presented cross-section vulnerable to each injury category (type, sub-type, or combination thereof). This will be based on the relative cross-sectional area of the affected organ(s). The fraction of hits to a segment exposing vulnerability j is given by w_j. Thus, the overall probability of a hit exposing vulnerability j in segment i is $w_j P_{hit_i}$. Let us denote the set of individual injuries ℓ in vulnerability j as $\ell \in j$, and the set of vulnerabilities j in segment i as $j \in i$.

4. Body response model: A finite element model (FEM) of the body is used to determine the mechanical response of the body to an impact of a given projectile at a given velocity, angle, and impact location. The body response is given in terms of stresses, strains, strain rates, moments, forces, pressures, momentum, or other mechanical characterizations. For each projectile and velocity, perpendicular incidence is assumed, and one or a limited set of FEM simulations is used to determine the mechanical response to impacts potentially causing injury ℓ. Using maximum stress $\sigma_{\max}$ as an example, the body response model would produce $\sigma_{\max}(v, x, y)$, where the impact positions would be selected to highlight the response associated with each injury. Let the general mechanical response be denoted $\mathcal{M}$. The body response model gives $\mathcal{M}(v, x, y)$.

5. Injury model: Models for individual injuries characterize the probability of an injury occurring given a mechanical response. For injury ℓ, the injury model takes the form $P_{I_\ell}(\mathcal{M})$.

f. The limited set of FEM simulation for injury ℓ are combined with $P_{I_\ell}(\mathcal{M})$ to give one single number $\bar{P}_{I_\ell}$ for the probability of injury ℓ given a hit to a body region vulnerable to injury ℓ.

6. Significance model: When there is no direct model for significant injury based on mechanical response, there must be a model providing the probability of significance given occurrence of an injury, $P_{SI|I_\ell}$. One impact location could produce multiple injury modalities (e.g., skull fracture and traumatic brain injury). The overall probability of significant injury for a given impact to body segment i exposing vulnerability j is $P_{SI_{i,j}} = 1 - \prod_{\ell \in j}(1 - P_{SI|I_\ell}\bar{P}_{I_\ell})$.

The total RSI is then given by the amalgam of these six models and normalization by the overall probability of a hit, $\sum_i P_{hit_i}$.

$$RSI = \frac{\sum_i \left[\left[\sum_k P_{pose_k} P_{hit_{i,k}}\left(R\sigma_x, R\sigma_y\right)\right] \sum_{j\in i} w_j \left(1 - \prod_{\ell\in j}\left(1 - P_{SI|I_\ell} \bar{P}_{I_\ell}\right)\right)\right]}{\sum_i \left[\left[\sum_k P_{pose_k} P_{hit_{i,k}}\left(R\sigma_x, R\sigma_y\right)\right]\right]}$$

or, more simply,

$$RSI = \frac{\sum_i \left[P_{hit_i} \sum_{j\in i} w_j P_{SI_{i,j}}\right]}{\sum_i P_{hit_i}}.$$

Appendix C.
Part 3 - Calculation of Risk of Significant Injury (RSI)
Torso Example

Part 3 - Calculation of Risk of Significant Injury (RSI)
Torso Example

Yevgeny (Jenya) Macheret
Jeremy Teichman

November 25, 2020

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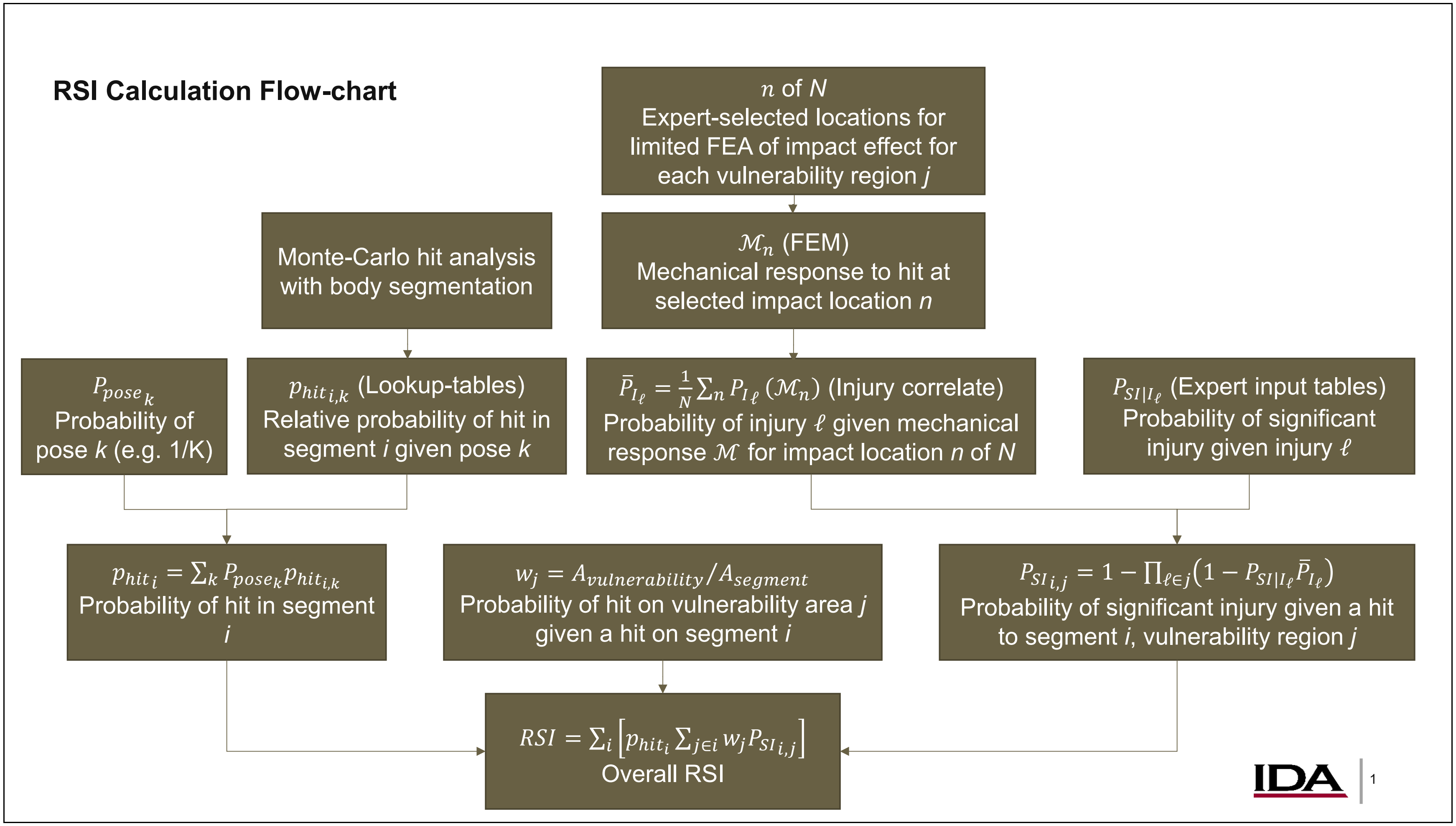
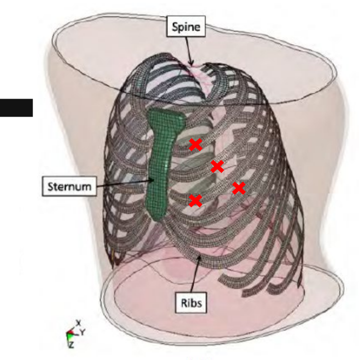

RSI Calculation Flow-chart
n of N
Expert-selected locations for limited FEA of impact effect for each vulnerability region j
$\mathcal{M}_n$ (FEM)
Mechanical response to hit at selected impact location n
Monte-Carlo hit analysis with body segmentation
P_{pose_k}
Probability of pose k (e.g. 1/K)
$p_{hit_{i,k}}$ (Lookup-tables)
Relative probability of hit in segment i given pose k
$\bar{P}_{I_\ell} = \frac{1}{N} \sum_n P_{I_\ell}(\mathcal{M}_n)$ (Injury correlate)
Probability of injury ℓ given mechanical response $\mathcal{M}$ for impact location n of N
$P_{SI|I_\ell}$ (Expert input tables)
Probability of significant injury given injury ℓ
$p_{hit_i} = \sum_k P_{pose_k} p_{hit_{i,k}}$
Probability of hit in segment i
$w_j = A_{vulnerability} / A_{segment}$
Probability of hit on vulnerability area j given a hit on segment i
$P_{SI_{i,j}} = 1 - \prod_{\ell \in j} \left(1 - P_{SI|I_\ell} \bar{P}_{I_\ell}\right)$
Probability of significant injury given a hit to segment i, vulnerability region j
$RSI = \sum_i \left[p_{hit_i} \sum_{j \in i} w_j P_{SI_{i,j}} \right]$
Overall RSI
IDA
1

This diagram defines the various segments in the flow-chart:

- Hits are grouped by body segment i (as defined in IDA D-21534) of which there are the following eight: thorax, skull, face, neck, thorax, abdomen, arms legs, pelvis.
- The hit probability is tabulated and supplied for a series of poses, aimpoints, and aiming accuracies.
- $p_{hit_{i,k}}$ is the relative probability of a hit on segment i given pose k and given that the body is hit.
- $p_{hit_i} = \sum_k P_{pose_k} p_{hit_{i,k}}$, where P_{pose_k} is the probability of encountering pose k (e.g., it could be assumed to be a uniform distribution over the front facing poses with $P_{pose_k} = \frac{1}{K}$ for K total poses or some other set of scenario-determined probabilities).
- In each segment i there are expert-selected vulnerability regions j, each associated with a particular set of injury types ℓ. For example, in the thorax segment there might be two regions, each with two injuries – rib cage with rib fracture and lung contusion injuries and sternum with heart contusion and cardiac arrest injuries.
- The fraction of hits to a vulnerability region j given a hit to segment i is defined by w_j, which is based on the relative cross-sectional area of the affected organ(s).
- The overall probability of hit to the region j is $w_j p_{hit_i}$.
- $\mathcal{M}(v, x, y)$ is the general mechanical response computed by the finite element model (FEM), where v is an impact velocity and x and y are impact location coordinates.
- $P_{I_\ell}(\mathcal{M})$ is the probability of an injury ℓ given $\mathcal{M}$.
- The limited number of FEM simulations N for an injury ℓ in a given vulnerability region j are averaged to give one single number $\bar{P}_{I_\ell}$ for the probability of injury ℓ given a hit to that body region.
- When there is no direct model for significant injury based on mechanical response, there must be a model providing the probability of significant injury given occurrence of an injury, $P_{SI|I_\ell}$. One impact location could produce multiple injury types ℓ (e.g., skull fracture, traumatic brain injury). The overall probability of significant injury for a given impact to body segment i in a vulnerability region j is $P_{SI\,i,j} = 1 - \prod_{\ell \in j}(1 - P_{SI|I_\ell} \bar{P}_{I_\ell})$.

RSI Calculation Flow-chart

n of N
Expert-selected locations for limited FEA of impact effect for each vulnerability region *j*



$\mathcal{M}_n$ (FEM)
Mechanical response to hit at selected impact location *n*

Monte-Carlo hit analysis with body segmentation

P_{pose_k}
Probability of pose *k* (e.g. 1/K)

$p_{hit_{i,k}}$ (Lookup-tables)
Relative probability of hit in segment *i* given pose *k*

$\bar{P}_{I_\ell} = \frac{1}{N}\sum_n P_{I_\ell}(\mathcal{M}_n)$ (Injury correlate)
Probability of injury ℓ given mechanical response $\mathcal{M}$ for impact location *n* of *N*

$P_{SI|I_\ell}$ (Expert input tables)
Probability of significant injury given injury ℓ

$p_{hit_i} = \sum_k P_{pose_k} p_{hit_{i,k}}$
Probability of hit in segment *i*

$w_j = A_{vulnerability}/A_{segment}$
Probability of hit on vulnerability area *j* given a hit on segment *i*

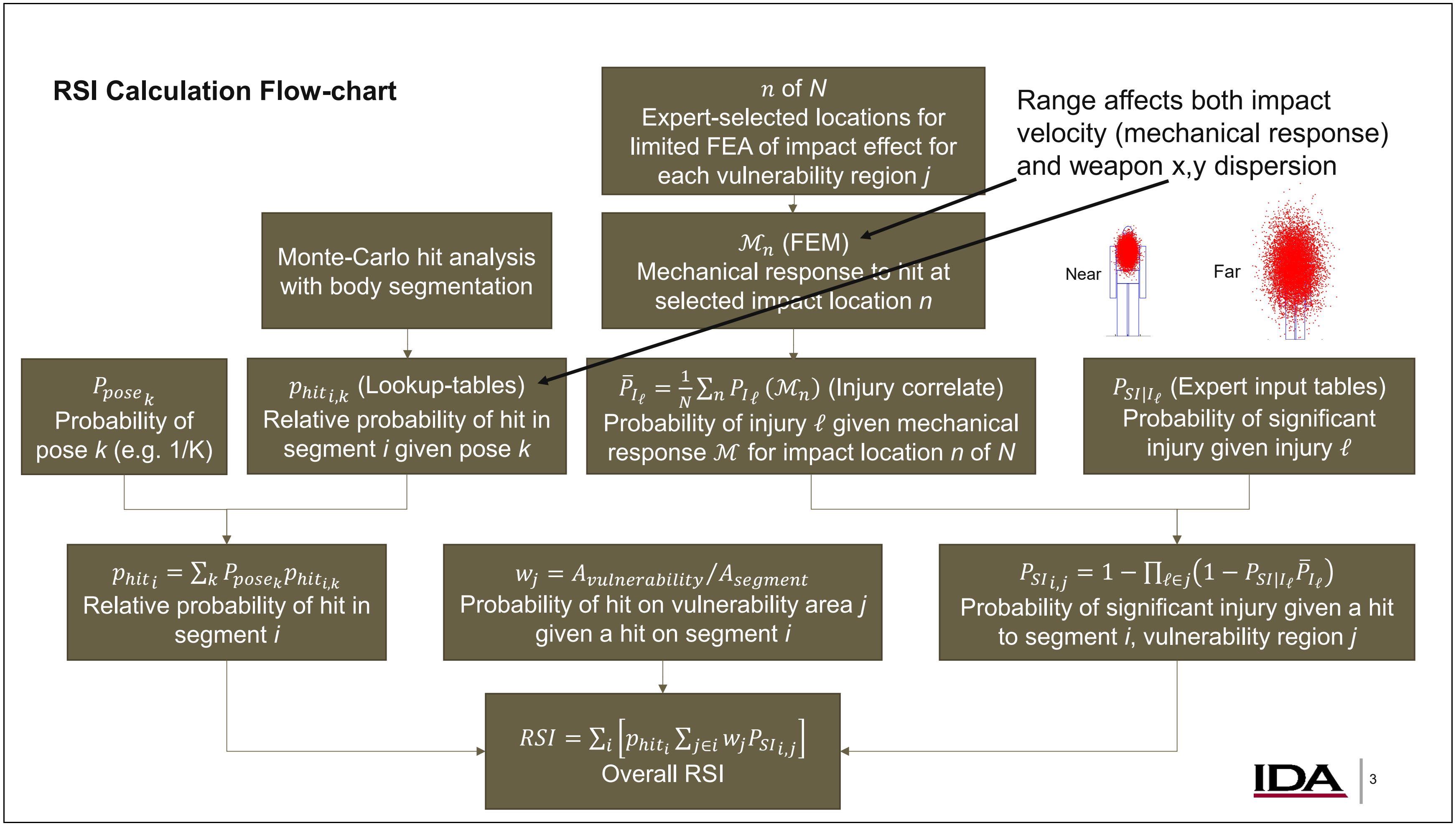
$P_{SI_{i,j}} = 1 - \prod_{\ell \in j}\left(1 - P_{SI|I_\ell}\bar{P}_{I_\ell}\right)$
Probability of significant injury given a hit to segment *i*, vulnerability region *j*

$RSI = \sum_i \left[p_{hit_i} \sum_{j \in i} w_j P_{SI_{i,j}}\right]$
Overall RSI

IDA 2

As shown here, for each vulnerability region, experts should judiciously choose a number of representative impact points such that averaging the probability of injury over these points will generate a representative mean probability of injury for that region. The probability of injury for the FEM-computed mechanical response is determined from the probability-of-injury correlation curve $P_{I_\ell}(\mathcal{M})$. The selection of vulnerability regions and their representative points will be done by subject matter experts.

Range and weapon characteristics are assumed known as inputs to the process described by the flowchart. These parameters determine the impact velocity, the probabilistic hit distribution, and the properties of the projectile and initial conditions in the finite element analysis. The hit distribution is characterized by the probability of hitting each defined body segment i (skull, face, neck, torso, abdomen, pelvis, arm, leg) as computed from a Monte Carlo hit analysis using the known aiming dispersion of the weapon and assumed body proportions and poses k, each occurring with probability P_{pose_k}. The probability of hitting vulnerability region j in segment i is determined based on the relative projected area of that region w_j. The next two slides show the RSI and probably of hit process.



RSI Calculation Flow-chart
n of N
Expert-selected locations for limited FEA of impact effect for each vulnerability region j
Range affects both impact velocity (mechanical response) and weapon x,y dispersion
Monte-Carlo hit analysis with body segmentation
$\mathcal{M}_n$ (FEM)
Mechanical response to hit at selected impact location n
Near
Far
P_{pose_k}
Probability of pose k (e.g. 1/K)
$p_{hit_{i,k}}$ (Lookup-tables)
Relative probability of hit in segment i given pose k
$\bar{P}_{I_\ell} = \frac{1}{N}\sum_n P_{I_\ell}(\mathcal{M}_n)$ (Injury correlate)
Probability of injury ℓ given mechanical response $\mathcal{M}$ for impact location n of N
$P_{SI|I_\ell}$ (Expert input tables)
Probability of significant injury given injury ℓ
$p_{hit_i} = \sum_k P_{pose_k} p_{hit_{i,k}}$
Relative probability of hit in segment i
$w_j = A_{vulnerability}/A_{segment}$
Probability of hit on vulnerability area j given a hit on segment i
$P_{SI_{i,j}} = 1 - \prod_{\ell \in j}\left(1 - P_{SI|I_\ell}\bar{P}_{I_\ell}\right)$
Probability of significant injury given a hit to segment i, vulnerability region j
$RSI = \sum_i \left[p_{hit_i} \sum_{j \in i} w_j P_{SI_{i,j}}\right]$
Overall RSI
IDA
3

P(hit) for each range and body segment

Monte-Carlo hit analysis with body segmentation

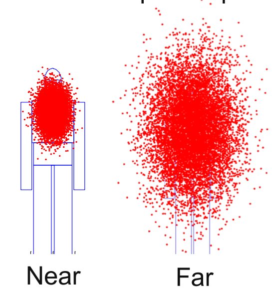
P_{pose_k}
Probability of pose *k* (e.g. 1/K)

$p_{hit_{i,k}}$ (Lookup-tables)
Relative probability of hit in segment *i* given pose *k*

$p_{hit_i} = \sum_k P_{pose_k} p_{hit_{i,k}}$
Probability of hit in segment *i*

$RSI = \sum_i \left[p_{hit_i} \sum_{j \in i} w_j P_{SI_{i,j}} \right]$
Overall RSI

Monte Carlo hit distribution as a function of weapon dispersion

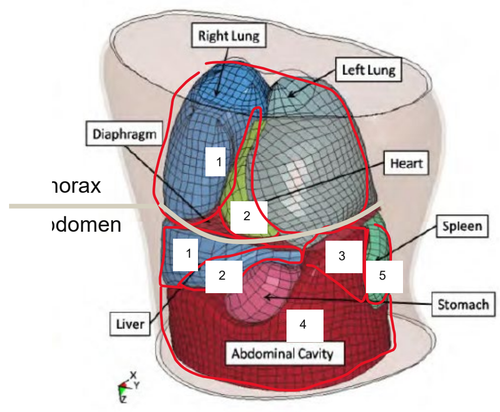


Map shots on body segments for each pose. Then calculate relative P(hit) for each body segment (e.g. thorax, abdomen, …) aggregated across poses. The relative P(hit) for each pose exists as a lookup table as a function of aimpoint and weapon horizontal and vertical dispersion.

For choice of weapon and range, lookup tables and pose distribution provide probability of hitting each body segment.

Segment	P(hit) to this segment
Thorax	82%
Abdomen	15%
…	…

IDA 4



i = 1: thorax
i = 2: abdomen
Vulnerability regions *j* as shown outlined in red and numbered

$w_j = A_{vulnerability}/A_{segment}$
Probability of hit on vulnerability area *j* given a hit on segment *i*

$RSI = \sum_i \left[p_{hit_i} \sum_{j \in i} w_j P_{SI_{i,j}} \right]$
Overall RSI

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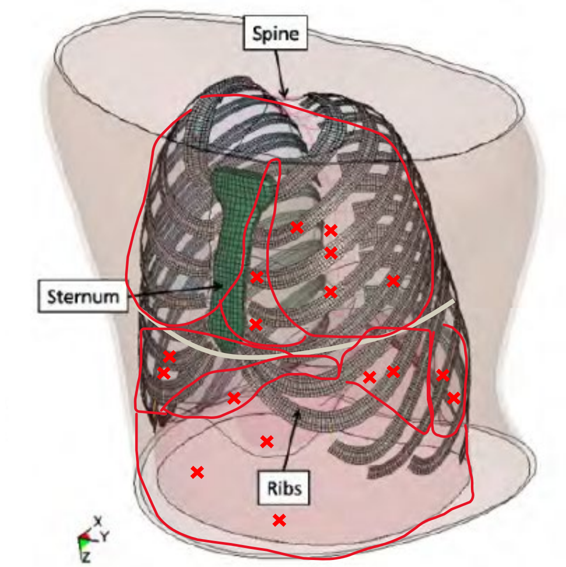
For each body segment, vulnerability regions are defined by subject matter experts in order to divide the body segment into areas with distinct sets of injury mechanisms. Taking the thorax (one of the body segments) as an example, a hit on the sternum might produce heart contusion but not rib fracture whereas a hit over the ribs might produce rib fracture but not heart contusion, although both might exhibit skin penetration. Therefore, experts might choose to define two separate vulnerability regions in the thorax, one for the sternum and one for the rib cage.

FEM sample points for each vulnerability region



For any projectile+velocity combination, each one of these impact points would require a finite element simulation. The results of FEM calculations would provide the risk of injury given a hit to that region.

n
Expert-selected locations for limited FEA of impact effect for each vulnerability region

$\mathcal{M}_n$ (FEM)
Mechanical response to hit at selected impact location *n*

$\bar{P}_{I_\ell} = \frac{1}{N}\sum_n P_{I_\ell}(\mathcal{M}_n)$ (Injury correlate)
Probability of injury ℓ given mechanical response $\mathcal{M}$ for impact location *n* of *N*

$P_{SI|I_\ell}$ (Expert input tables)
Probability of significant injury given injury ℓ

$P_{SI_{i,j}} = 1 - \prod_{\ell \in j}\left(1 - P_{SI|I_\ell}\bar{P}_{I_\ell}\right)$
Probability of significant injury given a hit to segment *i*, vulnerability region *j*

$RSI = \sum_i \left[p_{hit_i} \sum_{j \in i} w_j P_{SI_{i,j}}\right]$
Overall RSI

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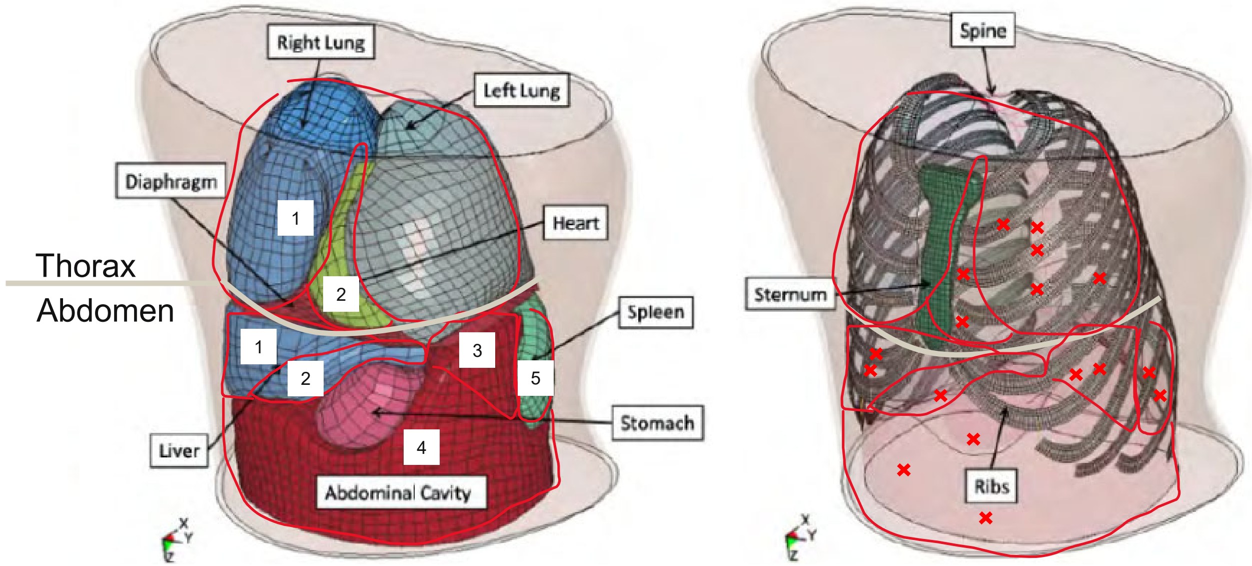
Each one of the vulnerability regions would be assigned some number of representative hit locations *N(i,j)* for finite element computations. The FEM would be used once for each of the *N* locations for a given vulnerability region to compute *N* mechanical responses. Each mechanical response $\mathcal{M}$ would be assessed for the probability of each associated injury ℓ using the appropriate injury correlations $P_{I_\ell}(\mathcal{M})$. The probabilities of injury thus calculated would be averaged to obtain the mean probability of each type of injury given a hit in this vulnerability region. For each such injury mechanism, the probability that it would qualify as serious given that it occurred, $P_{SI|I_\ell}$, would then be assessed based on expert input tables associating a probability that a given injury qualifies as serious by the JIFCO definitions. The injury mechanisms are considered statistically independent for the purpose of this calculation, so if two injury mechanisms are possible for a single vulnerability region, the probabilities of each occurring are computed independently both on a hit-location-by-hit-location basis and on a vulnerability-region-by-vulnerability-region basis. These probabilities are then fused to compute the overall probability $P_{SI_{i,j}}$ that a serious injury will occur given a hit to vulnerability region j in body segment i.

The results of the portions of the flowchart highlighted on each of the charts in this section are merged together in the final lower box using a weighted sum over vulnerability regions and body segments to form an overall risk of significant injury for a given projectile, velocity, and aiming accuracy.

Example calculation

Thorax and abdomen RSI calculation: Vulnerability regions and injury mechanisms



For any projectile+velocity combination, each one of these impact points would require a finite element simulation. The results of FEM calculations would provide the risk of injury given a hit to that region. RSI calculations would then utilize the range-dependent pose-aggregated hit distribution by body segment, the weights shown in the table, and the risk of injury given a hit to each region (from the FEM) to compute an overall RSI for the weapon/range combination.

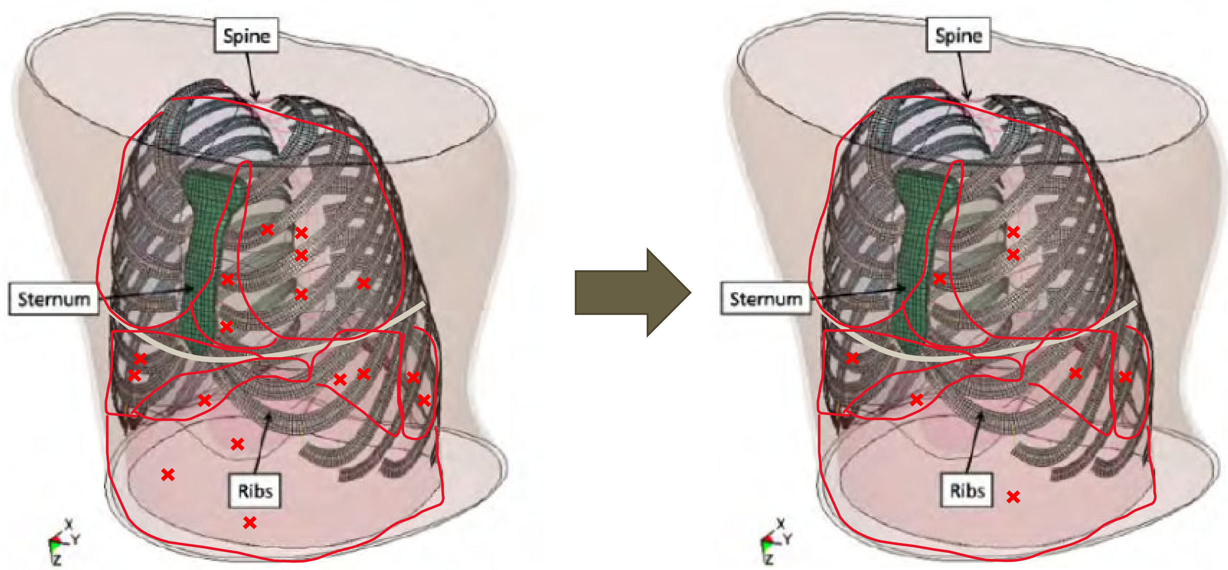
i = 1: thorax
i = 2: abdomen
Vulnerability regions *j* as shown outlined in red and numbered

Segment (*i*)	Region (*j*)	Weight (w_j)	Injury (ℓ)	Number of FEM runs
Thorax (1)	1	90%	Lung contusion + Rib fracture	5
Thorax (1)	2	10%	Heart contusion + Cardiac arrest	2
Abdomen (2)	1	10%	Liver laceration + Rib fracture	2
Abdomen (2)	2	10%	Liver laceration	1
Abdomen (2)	3	10%	Intestinal contusion + Rib fracture	2
Abdomen (2)	4	5%	Intestinal/stomach contusion	3
Abdomen (2)	5	65%	Spleen damage + Rib fracture	2

IDA 8

Using a notional set of vulnerability regions for two body segments, the thorax and abdomen (actual vulnerability regions would be chosen by subject matter experts executing this protocol), we walk through the process of calculating the RSI. This chart illustrates the tabulation of notional weights associated with each notional vulnerability region (given by their relative projected area w_j), associated injury mechanisms, and the number *N* of FEM runs for each region. All of the entries in this table would be defined by experts.

How many FEM runs are necessary? Where should the impact points be?



Segment (i)	Region (j)	Weight (w_j)	Injury (ℓ)	Number of FEM runs
Thorax (1)	1	90%	Lung contusion + Rib fracture	2
Thorax (1)	2	10%	Heart contusion + Cardiac arrest	1
Abdomen (2)	1	10%	Liver laceration + Rib fracture	1
Abdomen (2)	2	10%	Liver laceration	1
Abdomen (2)	3	10%	Intestinal contusion + Rib fracture	1
Abdomen (2)	4	5%	Intestinal/stomach contusion	1
Abdomen (2)	5	65%	Spleen damage + Rib fracture	1

IDA 9

This chart depicts a notional trade-off in choosing the number of FEM runs for each vulnerability region and the associated hit locations. This number should be sufficiently large to ensure coverage of the various injury types and should be a representative distribution such that the averaging would result in a meaningful mean probability of injury for the region. (For instance, for the thorax, projectiles might produce different mechanical responses depending on which rib underlies the hit location and whether the hit is directly over the rib or between ribs.) However, proliferating hit locations will cover more of these possibilities but lead to increased computation cost for a larger number of simulations.

Computing injury contribution from each vulnerability region

Segment (i)	Region (j)	Weight (w_j)	Injury (ℓ)	Number of FEM runs
Thorax (1)	1	90%	Lung contusion + Rib fracture	5
Thorax (1)	2	10%	Heart contusion + Cardiac arrest	2
Abdomen (2)	1	10%	Liver laceration + Rib fracture	2
Abdomen (2)	2	10%	Liver laceration	1
Abdomen (2)	3	10%	Intestinal contusion + Rib fracture	2
Abdomen (2)	4	5%	Intestinal/stomach contusion	3
Abdomen (2)	5	65%	Spleen damage + Rib fracture	2

FEM run for given velocity and designated impact point for that FEM run gives the mechanical response *M*. The injury correlation gives the probability of each injury given *M*. In this case P(rib fracture | *M*), P(lung contusion | *M*). The risk of significant injury is the product of the risk of injury and the probability of significant injury given injury: P(significant rib fracture) = P(significant rib fracture | rib fracture)*P(rib fracture | M). The overall risk of significant injury given a hit to this region is the average over the FEM runs of P(significant injury | hit) = 1-(1-P(significant rib fracture))*(1-P(significant lung contusion)).

FEM Run	Mechanical response	Lung contusion	Rib fracture	Significant lung contusion	Significant rib fracture	Overall probability of significant injury $P_{SI_{i,j}} = 1 - \prod_{\ell \in j}(1 - P_{SI\|I_\ell}\bar{P}_{I_\ell})$
1	M1	4%	18%			
2	M2	3%	12%			
3	M3	1%	30%			
4	M4	…	…			
5	M5	…	…			
Average		2.5%	21%	1.7%	14%	**15.5%**

IDA 10

The top table represents the outcome of the process of selecting the vulnerability regions. The lower table shows notional outputs from the FEM runs for each hit in the second column. The rows in the lower table are the *N* hit locations for a chosen vulnerability region (in this example, the thorax segment, vulnerability region 1, with 5 selected hit locations). Columns 3 and 4 show the independent probabilities of injury given the mechanical response in column 2, which are then averaged over the hit locations in the bottom row. These values are multiplied by the associated probability of serious injury given occurrence for the two injury modalities with results shown at the bottom of columns 5 and 6. The two injuries then have their probabilities fused to form the overall likelihood of serious injury at the bottom of column 7. The column 5 and column 6 probabilities are fused assuming they are statistically independent and that serious injury requires one or both of the serious injury modalities to occur.

Computation of RSI contribution from each body segment

Segment (i)	Region (j)	Weight (w_j)	Injury (ℓ)	Number of FEM runs
Thorax	1	90%	Lung contusion + Rib fracture	5
Thorax	2	10%	Heart contusion + Cardiac arrest	2
Abdomen	1	10%	Liver laceration + Rib fracture	2
Ab				
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Ab				
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FEM Run	Mechanical response	Heart contusion	Cardiac arrest	Significant heart contusion	Significant cardiac	Overall probability of significant injury
1						
2						
Ave						

FEM Run	Mechanical response	Lung contusion	Rib fracture	Significant lung contusion	Significant rib fracture	Overall probability of significant injury
1	M1	4%	18%			
2	M2	3%	12%			
3	M3	1%	30%			
4	M4	...	...			
5	M5	...	...			
Average		2.5%	21%	1.7%	14%	**15.5%**

$P_{SI\,i,j}$

For a given projectile and velocity (range) the overall probability of significant injury for the body segment is computed.

Segment (i)	Region (j)	Weight (w_j)	Injury (ℓ)	Number of FEM runs	Probability of significant injury given hit to this region
Thorax	1	90%	Lung contusion + Rib fracture	5	15.5%
Thorax	2	10%	Heart contusion + Cardiac arrest	2	6.3%
Thorax	Overall				14.6%

$\sum_{j \in i} w_j P_{SI\,i,j}$

IDA | 11

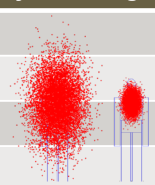
The table on the bottom of chart 10 would be computed for each vulnerability region for a given body segment. The cascade of tables on the top of the chart schematically illustrates the computation of the FEM simulations for the set of designated hit points in each vulnerability region leading to an overall probability of significant injury for that vulnerability region as shown circled at the bottom of the upper table cascade. The lower table shows how these injury probability values for each vulnerability region within a segment are assembled into an overall injury probability for that whole segment, which is computed as a weighted sum as shown on lower right.

Aggregate over segments for overall RSI

Segment (*i*)	Region (*j*)	Weight (w_j)	Injury (ℓ)	Number of FEM runs	Probability of significant injury given hit to this region
Thorax (1)	1	90%	Lung contusion + Rib fracture	5	14.5% $P_{SI_{1,1}}$
Thorax (1)	2	10%	Heart contusion + Cardiac arrest	2	6.3% $P_{SI_{1,2}}$
Thorax	Overall				14.6% $\sum_{j \in i} w_j P_{SI_{i,j}}$

Segment (*i*)	Region (*j*)	Weight (w_j)	Injury (ℓ)	Number of FEM runs	Probability of significant injury given hit to this region
Abdomen (2)	1	10%	Liver laceration + Rib fracture	2	$P_{SI_{2,1}}$
Abdomen (2)	2	10%	Liver laceration	1	…
Abdomen (2)	3	10%	Intestinal contusion + Rib fracture	2	…
Abdomen (2)	4	5%	Intestinal/stomach contusion	3	…
Abdomen (2)	5	65%	Spleen damage + Rib fracture	2	…
Abdomen (2)	Overall				19% $\sum_{j \in i} w_j P_{SI_{i,j}}$

Segment	Probability of hitting segment	Probability of significant injury given hit to this segment
Thorax	30%	14.6% $\sum_{j \in i} w_j P_{SI_{i,j}}, i = 1$
Abdomen	20%	19% $\sum_{j \in i} w_j P_{SI_{i,j}}, i = 2$
Leg	20%	…
…	…	…
Total RSI		$RSI = \sum_i \left[P_{hit_i} \sum_{j \in i} w_j P_{SI_{i,j}} \right]$



IDA | 12

Now the probability of significant injury for each segment must be aggregated into a single overall probability of significant injury over the entire body. The top table recaps chart 11 showing the aggregation of vulnerability regions in the thorax. That process would be repeated for each body segment, as shown for example for the abdomen in the center table on this chart. The yellow-highlighted line on the bottom of each of those tables shows the overall probability of significant injury for the associated body segment. The bottom table assembles the eight body segments, associating the probability of hitting the body segment (column 2) with the probability of significant injury given a hit to that body segment (in column 3). The column 3 values are taken from tables like those on the upper section of the chart but for all body segments. The total RSI in the bottom row of the lower table is given by a weighted sum over the body segments, where the weights are the relative probabilities of hitting the various segments taken from column 2.

To-do list

- Identify vulnerability regions
- Identify injury mechanisms
- Select FEM impact points
- Select ranges and associated velocities and dispersions

This chart provides a summarized list of the tasks required of the subject matter experts to execute the process described only notionally in this presentation.

Appendix D.
Part 4 - Calculation of Risk of Significant Injury (RSI)
Hits to the Arm Example

Part 4 - Calculation of Risk of Significant Injury (RSI)
Hits to the Arm Example

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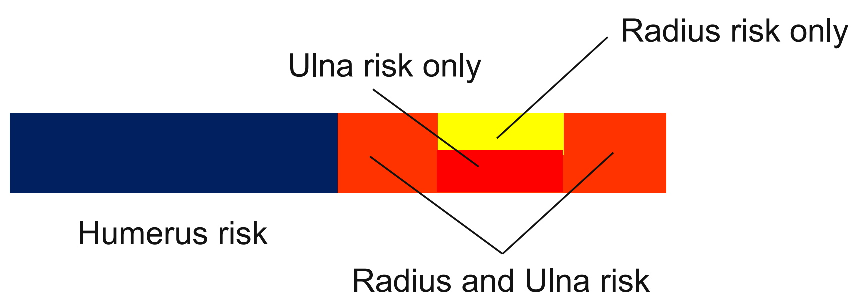
Vulnerability model

- Below is a simplified representation of the arm. The arm has 3 injury modes *I*: humerus, radius, and ulna fracture.
- Hits to the blue region in the schematic only risk humerus fracture.
- Hits to the yellow region only risk radius fracture
- Hits to the red region only risk ulna fracture
- Hits to the orange region could cause either ulna or radius fracture.
- These colored regions represent the 'vulnerabilities' described by the vulnerability model.



*This is a notional set of vulnerability regions – APL's input and some sensitivity analysis will help clarify what these regions should really be, particularly for the forearm.

IDA 2

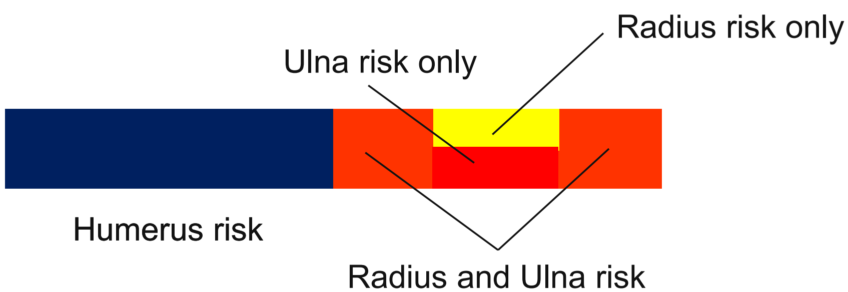
The next step is to apply the vulnerability model, where our goal is to understand the correspondence between cross-sectional area and injury types that may occur within a body region. In this worked example, we represent the arm schematically with the rectangle shown in the figure. The arm is divided in half, with the blue portion representing the section of the arm above the elbow, and the red, orange, and yellow sections combining to represent the portion of the arm below the elbow.

Within the arm, three injury types are modeled: humerus, radius, and ulna fracture. Therefore, we must understand which portions of the arm are at risk for which of these injuries. As explained on the slide, impacts to the upper arm (blue region) only risk humerus fracture. The lower arm is more complicated because of the presence of both radius and ulna. Based on the anatomy of these bones, we postulate that impacts near either the elbow or the wrist (where the radius and ulna are close together and/or in contact) could fracture either bone. This results in the orange regions in the diagram, which are considered vulnerable to either injury. Near the mid-section of the arm, where the radius and ulna are typically more separated, we assume that impacts are equally likely to be on the ‘humerus side’ or the ‘radius side,’ resulting in the yellow and red regions shown, corresponding to risk of radius fracture only or ulna fracture only, respectively.

Note that this is merely an example of how one might define these vulnerability regions for the arm. These should not be considered the ‘definitive’ regions for the final model. Each body region has its own set of modeled injuries, and the specific assignment of ‘vulnerability region’ and corresponding cross-sectional area must be informed by an understanding of anatomy.

Vulnerability model

- Each 'vulnerability' region is assigned a weight w_j based on its cross-sectional area
- For example, the blue region could be estimated to represent ½ of the arm's cross-sectional area, while the orange region represents 1/3 of the arm's cross-sectional area and the yellow and red regions each represent 1/12 of the arm's cross-sectional area.



Once we have identified the vulnerability regions, we must assign the weights w_j (as explained in step 3 of "RSI Calculation: Definitions, Models, and Equations"). The w_j for this example, subject to our schematic representation of the arm, are specified on the slide based on the relative cross-sectional area of each vulnerability region. Note that the w_j sum to one and form a partition of the arm body region.

Body response model

- Only a limited number of simulations will be done to compute the response variable (e.g., maximum stress) for the different vulnerabilities. Consider the set of hit positions denoted by numbers in the diagram.
- Positions 1, 2, and 3 could each cause humerus fracture.
- Positions 4 and 7 could cause either radius or ulna fracture
- Position 5 could cause radius fracture
- Position 6 could cause ulna fracture
- For each hit position, we use the finite element model to compute the body response *M* for each injury type corresponding to that hit location.

IDA 5

Now that we have determined the vulnerability regions and weights w_j, it is necessary to determine body responses for each injury type (step 4 of “RSI Calculation: Definitions, Models, and Equations”). As shown in this chart, only a limited number of finite element simulations will be conducted, which limits us to only a few impact locations. We have shown schematically an example of a possible set of hit locations that might be used for the arm. Response variables *M* will be extracted from simulations at each impact location. The vulnerability model tells us which response variables (corresponding to specific injuries) are needed in each case, as shown on the slide. In the case of fracture of the humerus, radius, and ulna, the relevant response variable is maximum principal stress in the corresponding bone.

Injury model & Vulnerability model

- Once we have computed the body response *M* for each injury type and hit location, we can compute a risk of injury for each *M*. Let all arm bone fractures be considered significant injuries.
- In this example, we have 4 vulnerability regions: blue, red, yellow, and orange
- The probability of injury given a hit to the arm is given by the sum of the probabilities of injury given a hit to each vulnerability region
- The probability of injury for the blue region is given by the average P(injury) over hit locations 1-3:
  - $P_{blue}=1/3*(P_{humerus\ fracture,\ 1} + P_{humerus\ fracture,\ 2} + P_{humerus\ fracture,\ 3})$
- The probability of injury for the yellow region and red region are simply the probabilities of injury for hit locations 5 and 6, respectively:
  - $P_{yellow}=P_{radius\ fracture,\ 5}$
  - $P_{red}=P_{ulna\ fracture,\ 6}$
- The probability of injury for the orange region is given by the probability of either ulna or radius fracture occurring given a hit to regions 4 and 7, assuming independence of the two injury types:
  - $P_{orange}= 1/2*(1-(1-P_{radius\ fracture,\ 4})(1-P_{ulna\ fracture,\ 4})) +1/2*(1-(1-P_{radius\ fracture,\ 7})(1-P_{ulna\ fracture,\ 7}))$

This is the same as 1-P(no injury for hit to location 7)

Humerus risk

Radius and Ulna risk

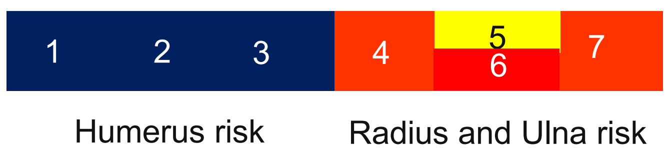
IDA 6

Once the body responses for each simulated impact location are computed, they must be converted to injury risk using the injury models available for each injury. This is step 5 of "RSI Calculation: Definitions, Models, and Equations."

Injury risk given a hit to each vulnerability region should be computed separately for each vulnerability region, as the risk of injury to the whole arm is the weighted sum of the risks given hits to the four vulnerability regions, where the weights are the w_j determined previously. In this example, we allow all impacts within a vulnerability region equal likelihood. Moreover, we apply an assumption of independence in computing injury risk for the orange vulnerability region, where more than one injury type may occur. This assumption means that in regions where multiple injury types are possible, we assume that whether or not a given impact causes one injury does not change the probability that the same impact causes another injury. Note that this is a simplifying assumption.

Injury model & Significance model

- If we had an additional factor denoting P(significant Injury)|injury type, then we would need to incorporate that into our calculation of the previous slide as follows (example for the blue region):
  - $P_{\text{significant injury, blue}}=1/3*(P_{\text{humerus fracture is significant}})(P_{\text{humerus fracture, 1}} + P_{\text{humerus fracture, 2}} + P_{\text{humerus fracture, 3}})$
- On the previous slide, we assumed that all arm bone fractures are significant, which sets the $P_{\text{fracture i is significant}}$ values to 1.



6

Some injuries may have a ‘significance model.’ In such cases, the injury may not always require medical treatment to prevent permanent disability or death, and therefore may not be considered a significant injury. An example of this is a minor tympanic membrane rupture, which can heal on its own without surgical intervention. Such significance models must be included when computing the risk of injury for each vulnerability region. This is step 6 of “RSI Calculation: Definitions, Models, and Equations.”

The application of this to the arm example is shown here; however, since we consider all arm bone fractures significant injuries, it has no effect on the overall calculation relative to what was shown on the previous slide.

Aggregation

- Now, compute the aggregated P(significant injury) for the whole arm region by summing the risk over the vulnerability regions and weighting each by their cross-sectional area
  - $P_{\text{significant injury, arm hit}} = 1/2*P_{\text{blue}} + 1/3*P_{\text{orange}} + 1/12*P_{\text{red}} + 1/12*P_{\text{blue}}$
- Finally, to aggregate full RSI to the body, we would apply a similar procedure to the other body regions and weight each body region's P(injury) according to its P_{hit_i}.

IDA 7

When the injury risk given a hit to each vulnerability region has been computed, the risk for injury to the arm given a hit to the arm is computed by weighting the injury risks in each vulnerability region by their corresponding w_j. This sum is shown on the slide for the arm example. This risk of injury given a hit to the arm would then be weighted by the overall risk of hitting the arm based on the P(hit) model and combined with corresponding calculations for the other body regions, resulting in the full RSI calculation. This is step 7 of "RSI Calculation: Definitions, Models, and Equations."

P(hit)-Weighted Risk of Individual Injury Types

- Once we have computed the body response *M* for each injury type and hit location, we can also compute the risk of each individual injury type, given an impact to the arm
- In this example, we have 3 injury modes: humerus fracture, ulna fracture, radius fracture
- The probability of humerus fracture given a hit to the arm is given by the average P(injury) over hit locations 1-3 weighted by the P(hit) to regions vulnerable to humerus fracture:
  - $P_{humerus\ fracture} = 1/2 * (1/3*(P_{humerus\ fracture,\ 1} + P_{humerus\ fracture,\ 2} + P_{humerus\ fracture,\ 3}))$
- The probability of radius fracture given a hit to the arm is given by the relative-area-weighted average of the orange and yellow regions' radius fracture injury risk:
  - $P_{radius\ fracture} = 1/12*P_{radius\ fracture,\ 5} + 1/6*P_{radius\ fracture,\ 4} + 1/6*P_{radius\ fracture,\ 7}$
- And similarly for ulna fracture:
  - $P_{ulna\ fracture} = 1/12*P_{ulna\ fracture,\ 6} + 1/6*P_{ulna\ fracture,\ 4} + 1/6*P_{ulna\ fracture,\ 7}$

IDA 8

Finally, we note that it is possible to compute risks of individual injury types given a hit to the arm using the procedure described on this slide. However, this is outside the chain of steps needed to compute risk of injury given a hit to the arm, which was described in the prior slides.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

IDA developed a framework and associated analysis for computing the risk of significant injury (RSI) from blunt impact projectiles. This document includes four appendices describing that framework and how to employ it. The Joint Intermediate Force Capabilities Office (JIFCO) desired a way to estimate the RSI for any given projectile/employment combination incorporating such factors as targeting distance, aiming and delivery accuracy, impact velocity, reactive postures, and projectile and tissue properties. JIFCO has access to various models for different aspects of the analysis, however, the current document describes how to employ and combine these models to build the overall risk estimate.

15. SUBJECT TERMS

Pose-dependent RSI calculation; Risk of Significant Injury (RSI); RSI calculation examples; RSI equations

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