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Developing an Empirical Model to Estimate Tibia Injury

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Agenda

- Introduction
- Approach
- Results
- Discussion
- Caveats
- Conclusion

Introduction

Issue/background

- Under-body blast (UBB) can induce lower extremity fractures to seated occupants.
- The test and evaluation community currently lacks reduced-order (RO) tools capable of accurately and efficiently estimating these injuries.
- Assessing occupant injury from data from anthropomorphic test devices (ATDs) in live-fire (LF) tests is the most common method of evaluating occupant injury.
- But it is also important to interpret the vehicle's structural response in terms of injury-causing potential.

Introduction

Objective: Can empirical models be developed to estimate lower-leg injuries based on structural response data?

Overall approach: Perform a correlation analysis between floor accelerometer data and lower-leg responses of associated ATDs from LF test events.

Approach: Test Data

Floor response ∝ Assessed injuries

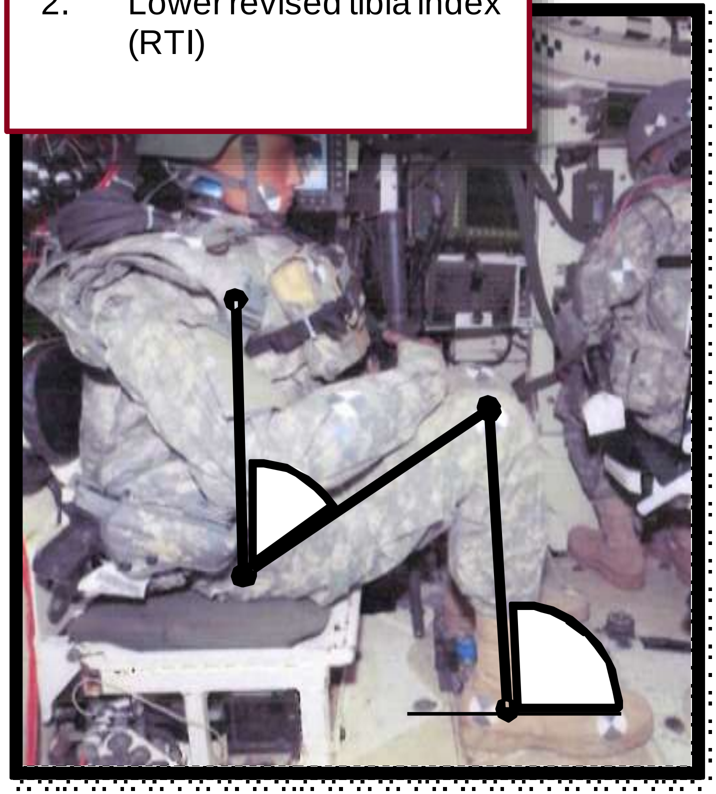
Four dataset variations:
1. Raw
2. Filtered
3. Raw adjusted
4. Filtered & adjusted

Metrics:

1. Peak acceleration
2. Peak velocity
3. Floor response metric
4. Peak jerk
5. Effective-G
6. 5% Effective-G
7. 10% Effective-G
8. Sine wave avg. acceleration
9. Triangle wave avg. acceleration
10. PVSS plateau
11. Rigid body velocity
12. Local velocity
13. Local displacement
14. Global displacement

Assessed injuries:

1. Lower tibia compressive force
2. Lower revised tibia index (RTI)



Approach: Correlation Analysis

- Simple linear regression analyses conducted for one- (linear) and two-predictor (quadratic) models as a function of each response
  - Coefficient of determination, R^2, was calculated for each model
  - Prediction intervals (PIs) calculated around the models using a student t-distribution of the data
  - Response plots (actual versus model) generated
- Logistic regression analyses performed to identify the probability of exceeding the injury threshold value (confidence intervals calculated as well)

Results: Predicting Force and RTI

- Quadratic models with predictors, ***raw peak velocity*** and ***adjusted local displacement***, were found to yield the best relationship with lower tibia compressive force and RTI.
- The model to estimate lower tibia force and RTI is described by:

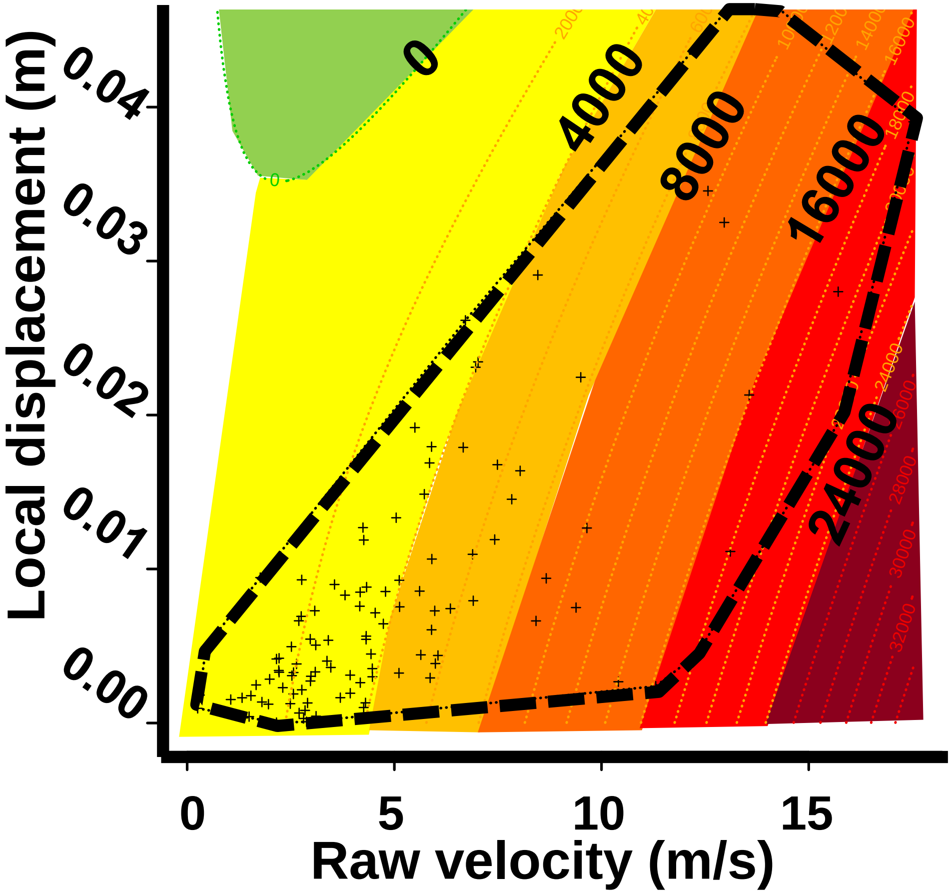
$$z = \boldsymbol{v}^T \boldsymbol{b} \pm \gamma s \sqrt{1 + \boldsymbol{v}^T \boldsymbol{U} \boldsymbol{v}}$$

Results: Predicting Tibia Force

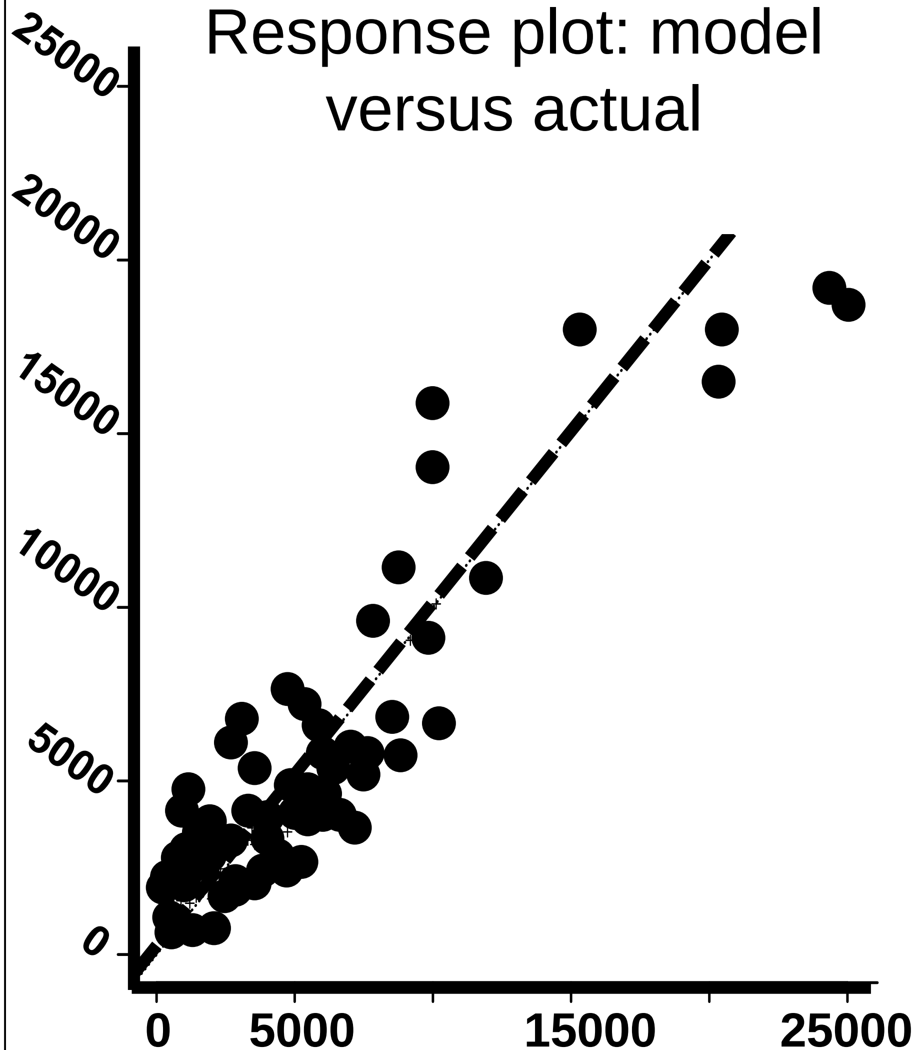
- The best two-predictor model for lower tibia compressive force resulted in an R^2 value of 0.84 on a set of 109 data points.
- The 90% PIs yield a variation in model results of about +/- 3500 N.

Results: Predicting Tibia Force

Tibia force (N) as a function of local displacement and peak velocity



Response plot: model versus actual

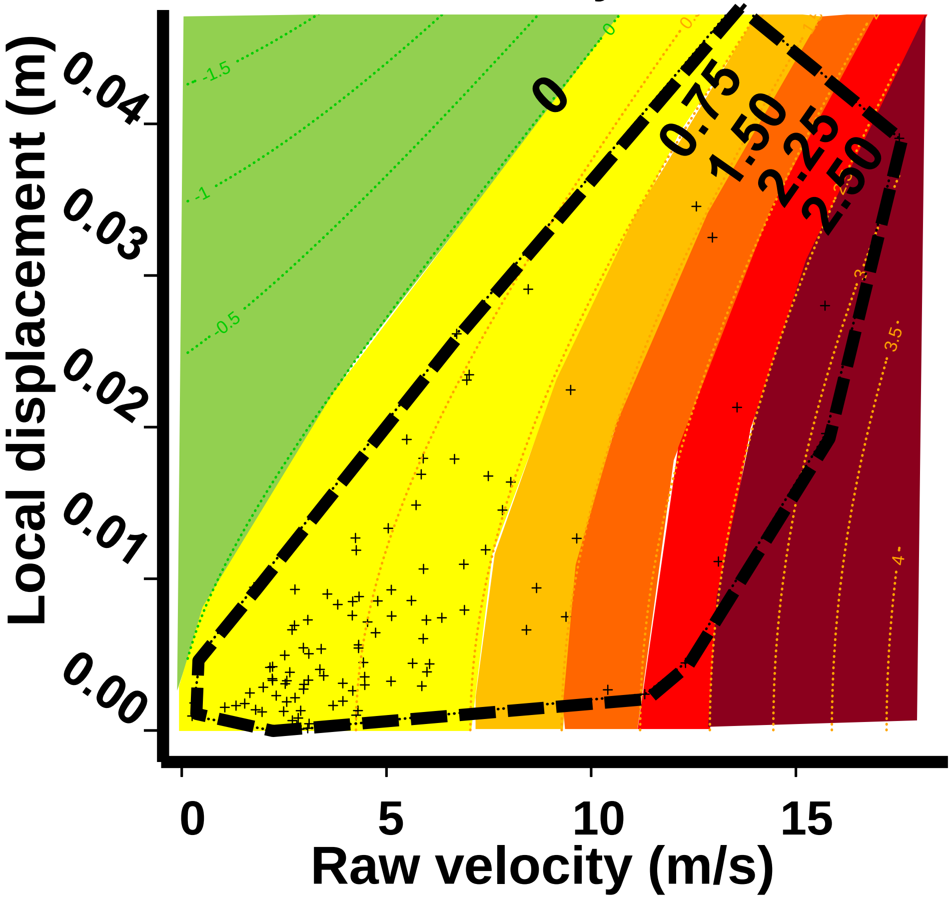


Results: Predicting Tibia RTI

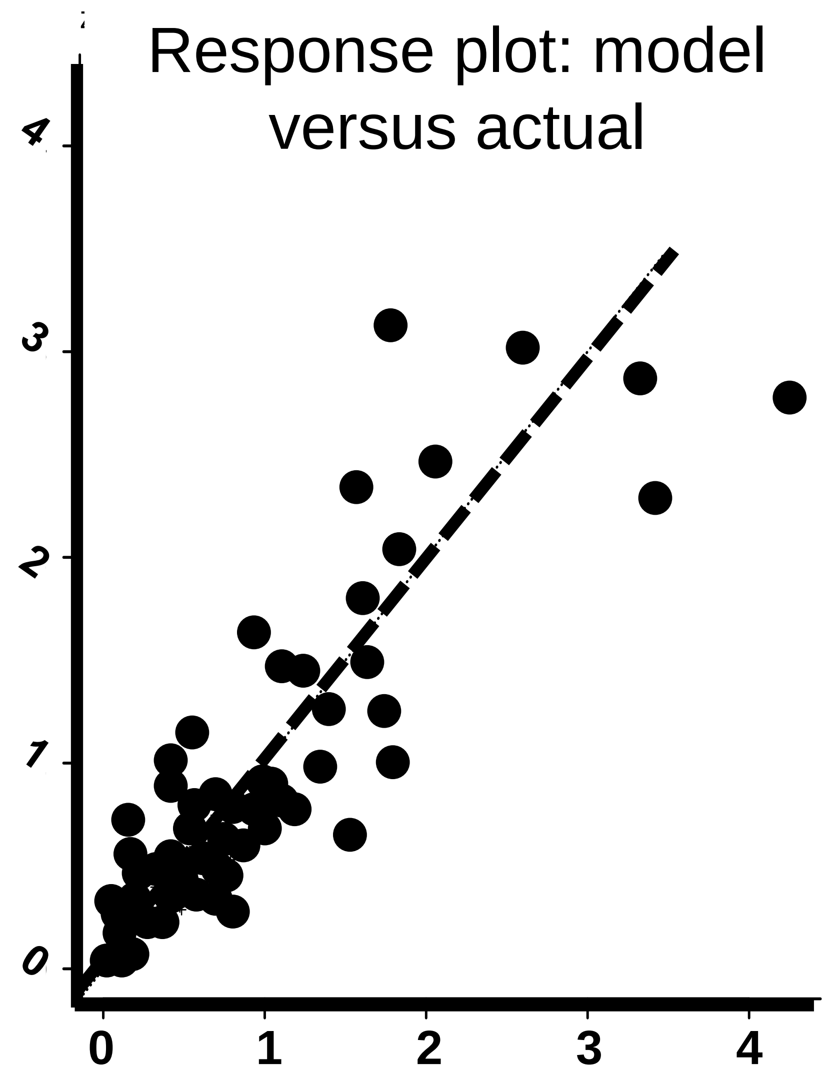
- The best two-predictor model for lower tibia RTI resulted in an R^2 value of 0.77 on a set of 109 data points.
- The 90% PIs on this model yield a variation of about +/-0.57.

Results: Predicting Tibia RTI

RTI as a function of local displacement and peak velocity



Response plot: model versus actual



Results: Logistic Regression

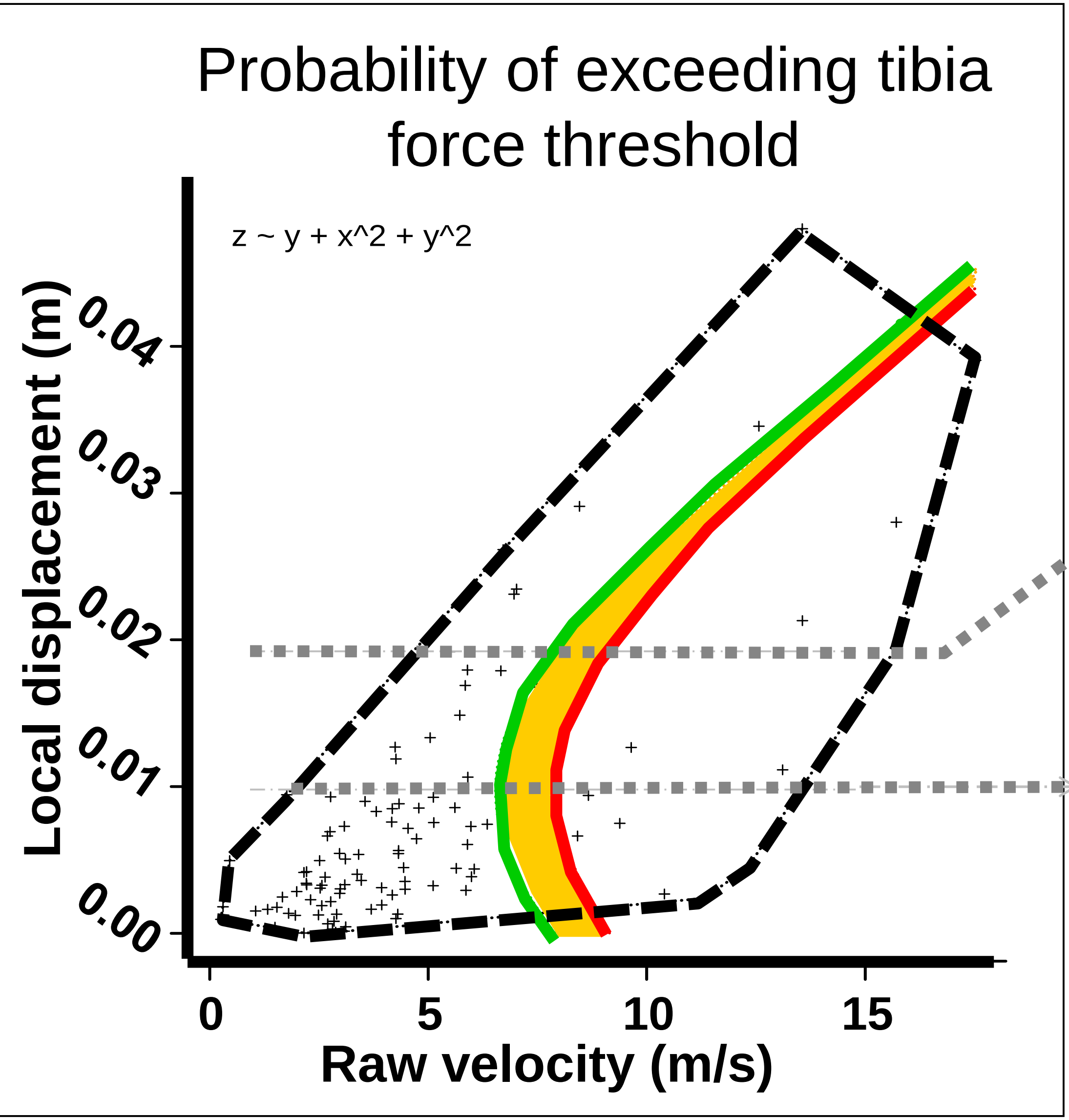
- The logistic regression analysis for the best two predictors was performed based on the compressive force and RTI values relative to their appropriate injury threshold.
- Tibia force: {no-injury < 7980 N ≤ injury}
- Tibia RTI: {no-injury < 0.75 ≤ injury}

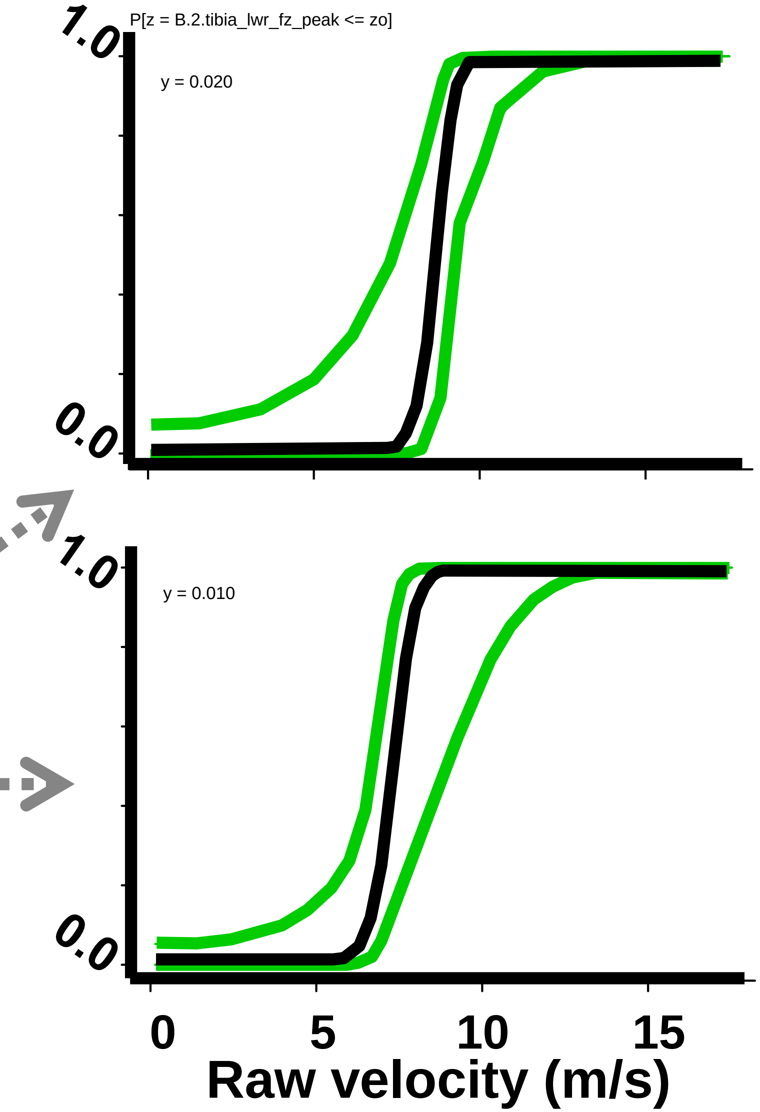
Results: Logistic Regression

The model to estimate the probability of exceeding the injury threshold is described by:

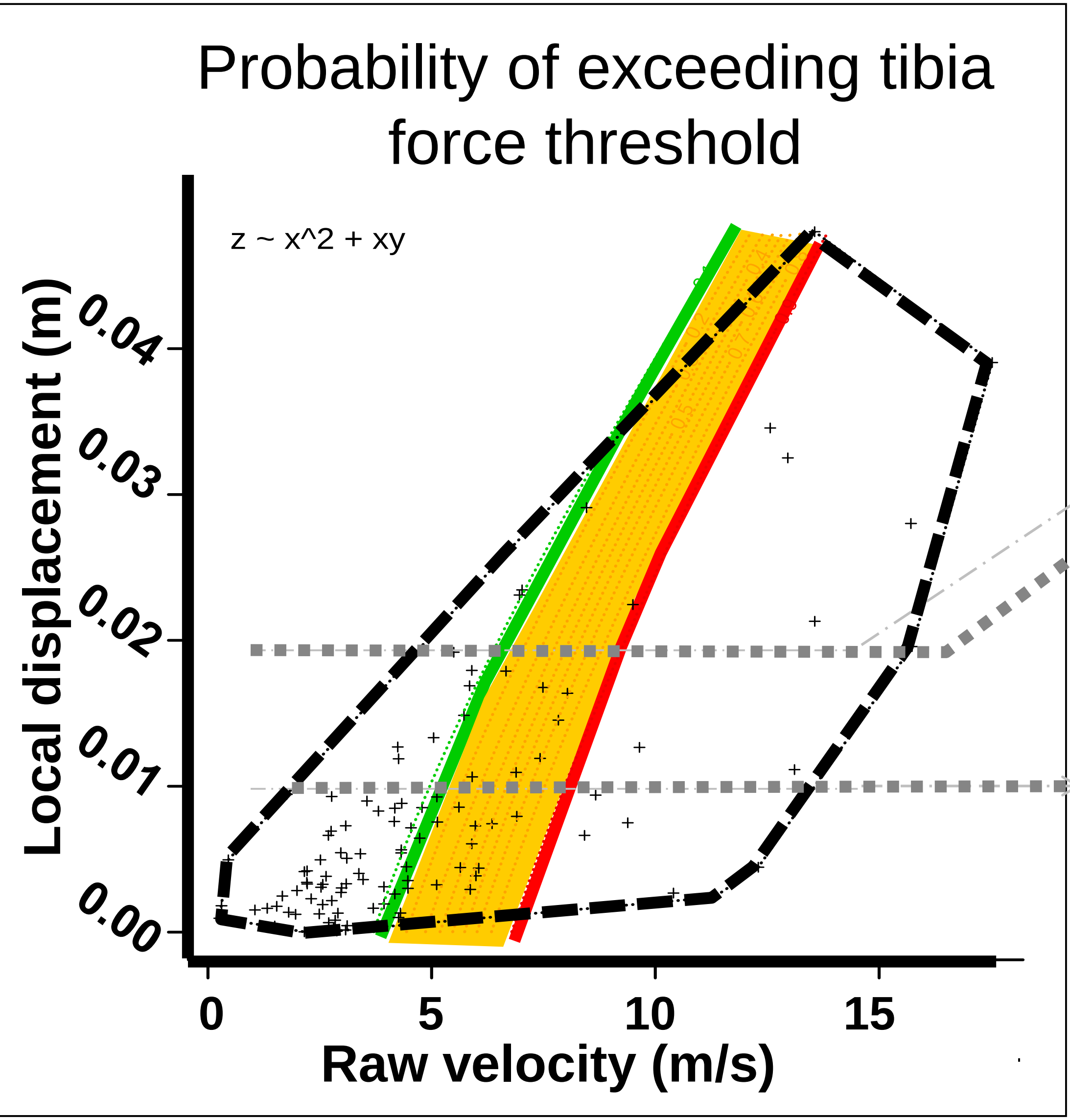
$$P(z > z_o) = \left(1 + e^{-\boldsymbol{v}^T \boldsymbol{b} \pm \gamma \sqrt{\boldsymbol{v}^T \boldsymbol{U} \boldsymbol{v}}}\right)^{-1}$$

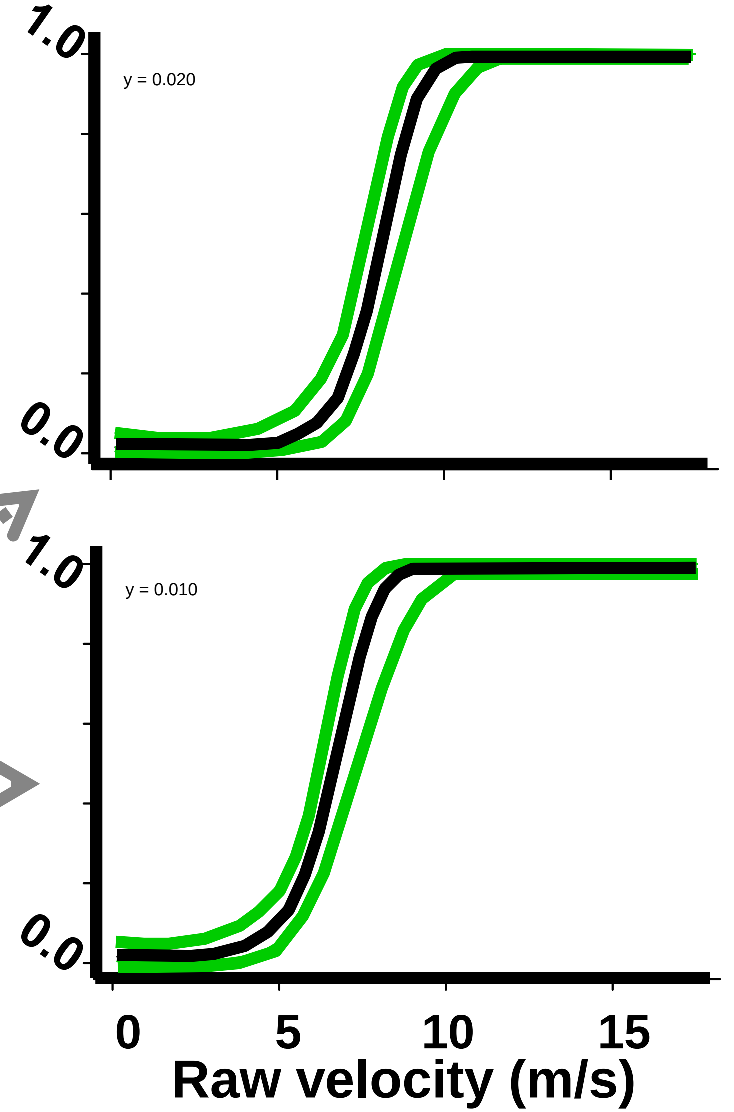
Results: Probability of Tibia Force Injury





Results: Probability of Tibia RTI Injury





Discussion

- Models with greater than two predictors were not pursued because there is a diminishing return on R^2 relative to model complexity, the number of data points decreases, the domain of data becomes more sparse, and the quality of the model is hard to visually assess.
- Raw and filtered peak velocities were nearly identical; raw, filtered, and adjusted local displacements were nearly identical.
- Lower tibia compressive force and lower RTI are closely correlated with an R^2 value of 0.90.
- Force and RTI increases as velocity increases and local displacement decreases (i.e., a short duration velocity pulse is more severe than a longer duration velocity).

Caveats

- In order to utilize the empirical models, predictor data should be comparable to that obtained from floor-mounted accelerometers placed in armored ground vehicles subjected to an under-body blast.
  - The velocity and local displacement should lie within the dashed boundary lines shown in many of the earlier plots.
  - Using these models with predictor data different than this would be considered extrapolation.
- The results of these models provide estimates of lower leg injury responses for ATDs with booted feet placed flat on the same floor panel as the accelerometer, within about six inches of the accelerometer, and with the ATD hip and knee angles in normal positions.

Conclusion

- Empirical models were developed to estimate lower tibia compressive force and RTI injuries as a function of floor accelerometers' peak velocity and local displacement.
- These models can also serve as methods to assess severity of floor response from an under-body blast in terms of lower-leg injury potential and, at the very least, indicate the significance of peak velocity and local displacement to lower-leg injury assessed using ATDs.
- Future work will consist of performing controlled laboratory tests to further refine this correlation.

Back-up: Variables for Empirical Models

Variables for Predicting Lower Tibia Compressive Force

$$\boldsymbol{b} = [429.86 \quad 454.76 \quad 88.32 \quad -24025.45]$$

$$\boldsymbol{v} = \begin{bmatrix} 1 \\ x \\ x^2 \\ xy \end{bmatrix} \qquad \boldsymbol{U} = \begin{bmatrix} 0.084966346 & -0.02515397 & 0.001426337 & -0.02115971 \\ -0.02515397 & 0.0088744756 & -0.000551537 & 0.012066885 \\ 0.001426337 & -0.000551537 & 0.0000455201 & -.005319462 \\ -0.021159706 & 0.0120668852 & -0.005319462 & 2.516150808 \end{bmatrix}$$

$s = 1953.06 \quad d = 105$

Variables for Predicting Lower Tibia RTI

$$\boldsymbol{b} = [0.007357148 \quad 0.07766773 \quad 0.008960343 \quad -836.4894]$$

$$\boldsymbol{v} = \begin{bmatrix} 1 \\ x \\ x^2 \\ y^2 \end{bmatrix} \qquad \boldsymbol{U} = \begin{bmatrix} 0.084790813 & -0.0250513072 & 0.001378975 & 0.6321994 \\ -0.025051307 & 0.0088171913 & -0.0005273214 & 0.3116409 \\ 0.001378975 & -0.0005273214 & 0.00003713892 & -0.689211 \\ 0.632199403 & 0.3116409264 & -0.689211 & 165806.4 \end{bmatrix}$$

$s = 0.341250 \qquad d = 105$

Variables for Probability of Lower Tibia Compressive Injury

$$\boldsymbol{b} = [-15.22553 \quad 839.1152 \quad 0.2085131 \quad -0.00043104]$$

$$\boldsymbol{v} = \begin{bmatrix} 1 \\ y \\ x^2 \\ y^2 \end{bmatrix} \qquad \boldsymbol{U} = \begin{bmatrix} 48.91427 & -0.003368215 & -0.5689323 & 148979.951 \\ -0.003368215 & 297588.7 & 25.64374 & -10417496.1 \\ -0.5689323 & 25.64374 & 0..01029503 & -1861.699 \\ 148980.0 & -10417500 & -1861.699 & 487118696 \end{bmatrix}$$

Variables for Probability of Lower Tibia Compressive Injury

$$\boldsymbol{b} = [-4.0637062 \quad 0.1359171 \quad -29.8084320]$$

$$\boldsymbol{v} = \begin{bmatrix} 1 \\ x^2 \\ xy \end{bmatrix} \qquad \boldsymbol{U} = \begin{bmatrix} 0.52464665 & -0.019929853 & 4.5431797 \\ -0.01992985 & 0.001134127 & -0.3056993 \\ 4.54317967 & -0.305699303 & 95.5931828 \end{bmatrix}$$