

Modifying an Automotive based Finite Element Model of the Lower Extremity with High-Rate Heel Properties for Simulating a Blast Loading Condition

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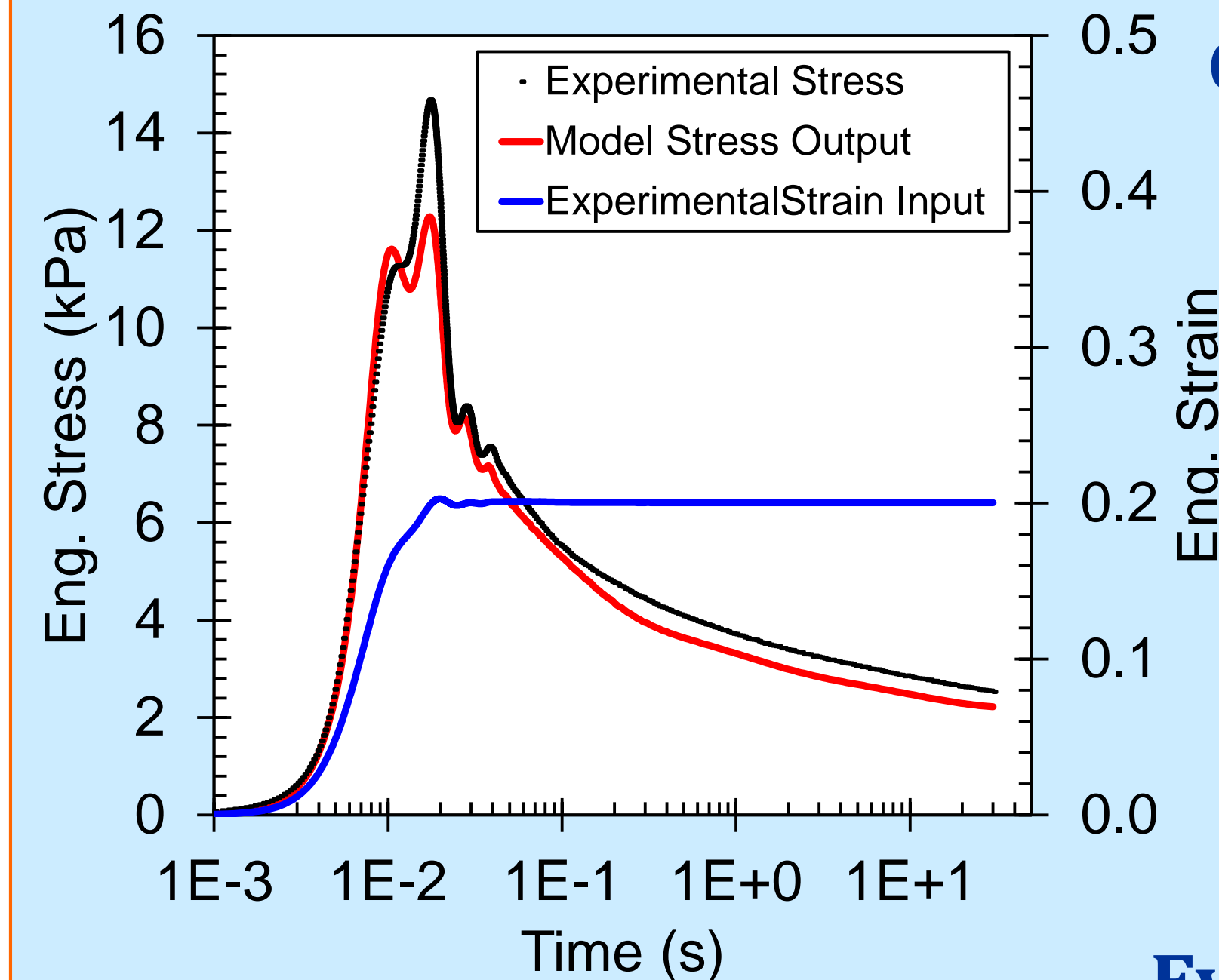
Introduction

- ❖ Severe lower extremity injuries are a major concern for military personnel exposed to blast loading in armored vehicles. These injuries include foot, ankle, and tibia fractures and account for more than 80% of all skeletal injuries observed in underbody blast (UBB) events [1].
- ❖ Severe foot and ankle injuries caused by axial loading to the lower limb are also one of the most frequent injuries sustained in frontal automotive crashes.
- ❖ Finite element (FE) models of the lower extremity originally designed for the automotive loading environment can be used for blast loading simulations, however modifications are needed to improve fidelity for high-rate loading conditions typical of UBB.

Objectives

1. Evaluate the mechanical response of the current automotive lower extremity FE model under high-rate axial loading to the heel.
2. Modify the lower extremity FE model to improve biofidelity for high-rate events by incorporating rate-dependent mechanical properties into the heel pad, refining the mesh of various bony structures, and improving the material properties of many tissues.

QLV modeling of ramp and hold tests performed on cadaveric heel pads

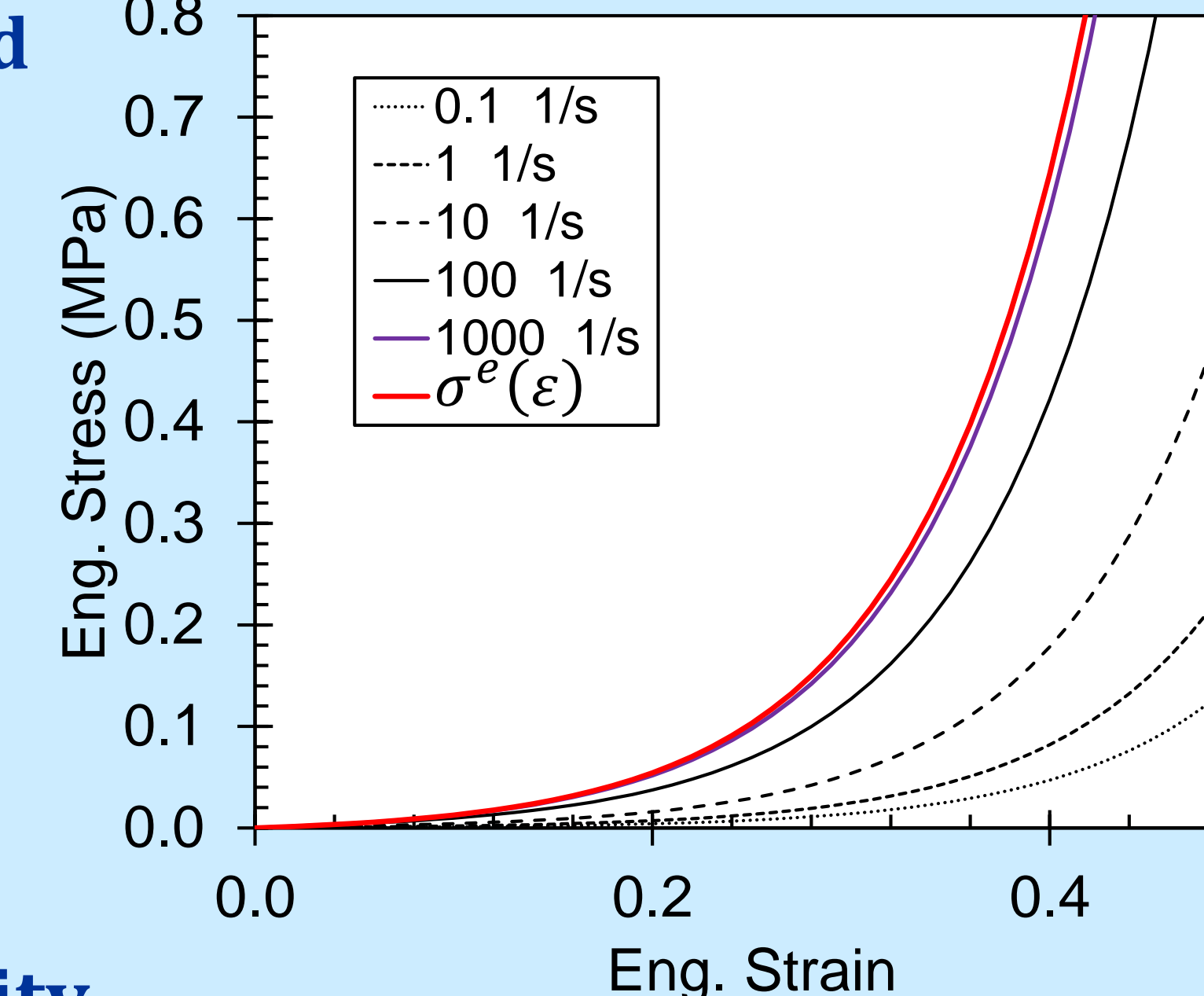


Results

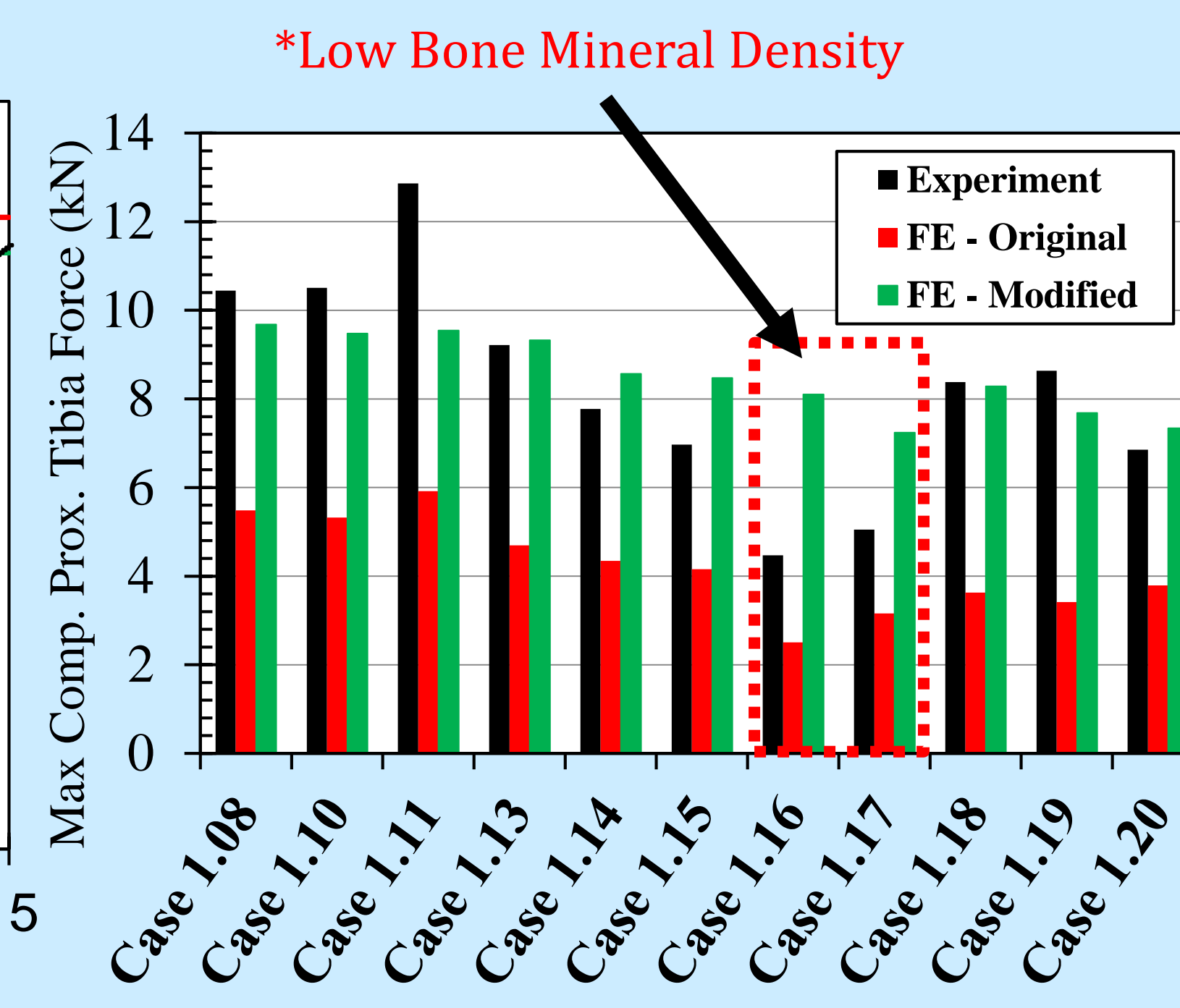
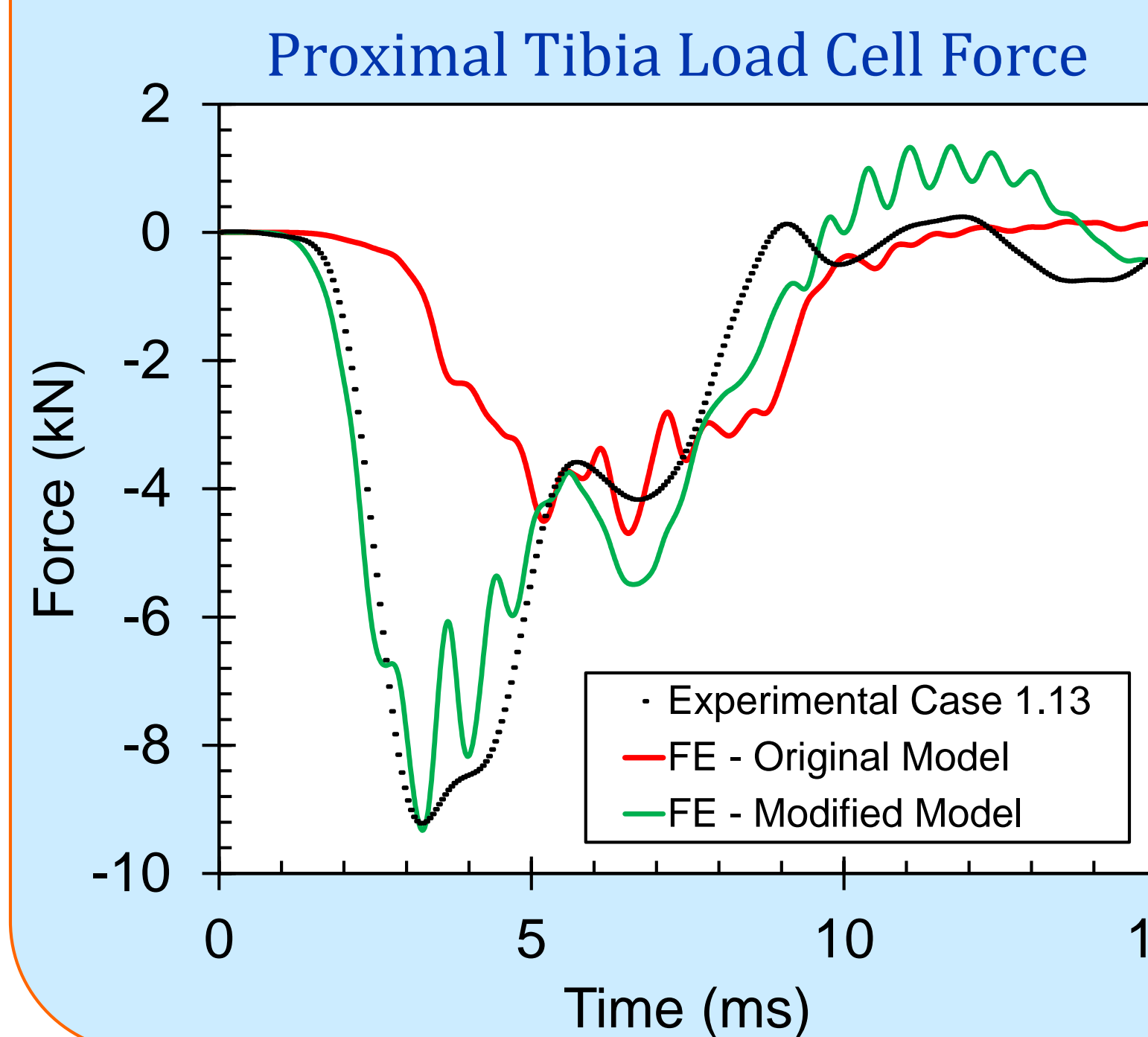
Constitutive model for heel pad

QLV Model Coefficients	Fitted Values
A	5.51kPa
B	11.9
$G_1(\tau_1 = 0.001s)$	0.741
$G_2(\tau_2 = 0.01s)$	0.125
$G_3(\tau_3 = 0.1s)$	0.059
$G_4(\tau_4 = 1s)$	0.020
$G_5(\tau_5 = 10s)$	0.015
$G_\infty(\tau \rightarrow \infty)$	0.040

Load curves for GHBM FOOT-FLESH generated using the QLV heel pad model



Evaluating FE model Biofidelity



Mean correlation and analysis (CORA) scores across 11 experimental cases

Scoring	Original Model	Modified Model
Overall	(0.53±0.05)	(0.90±0.08)
Phase	(0.30±0.18)	(0.98±0.02)
Size	(0.34±0.12)	(0.74±0.22)
Shape	(0.96±0.02)	(0.97±0.02)

- ❖ Model accuracy to the experimental data was assessed using the cross-correlation methods of CORA. Phase, size, and shape parameters were equally weighted to form the overall CORA score. Scores range from 0 to 1; 1 being a better fit.

Discussion

- ❖ The original FE model underestimated the proximal tibia force; peak compressive forces were severely attenuated and a significant phase delay was observed when compared to the 11 experimental cases.
- ❖ A parametric analysis was performed on case 1.13 and a general linear model (GLM) was used to evaluate the contribution of each modification on prox. tibia force.

GLM coefficients for proximal tibia force

Modification	Overall	Phase	Size	Shape
Mesh	0.111*	-0.004	0.333*	0.003
Bone	-0.015	0.013	-0.064	0.006
Heel	0.305*	0.575*	0.336*	0.005
R ²	0.957	0.999	0.858	0.724

*Indicates a statistically significant result (p<0.05)

- ❖ Alterations to the heel pad considerably improved force phasing, and both heel pad and mesh refinement improved the force magnitude correlation (size). Bone modifications did not statistically improve results.

Future Work

- ❖ Incorporating patient-specific biometrics may improve correlations between the model and experiment.
- ❖ Rate-dependent material properties for bone may improve biofidelity of stress wave propagation and energy dissipation along the tibia.
- ❖ Testing heel pad at higher strain rates, closer to those calculated from the FE model (250s⁻¹) may further improve model biofidelity.

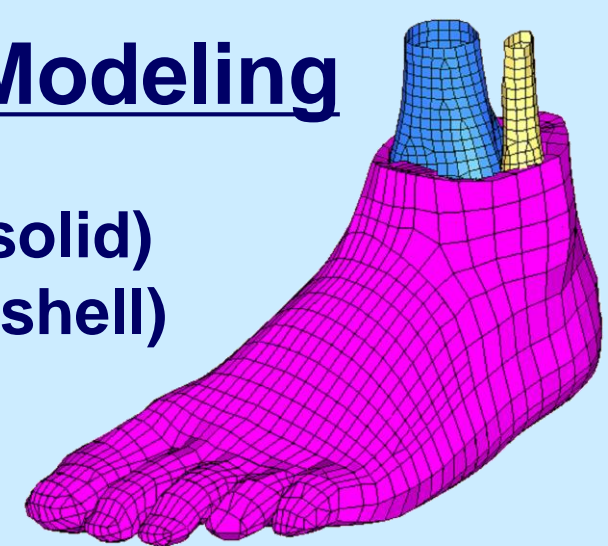
Original Automotive FE model

Global Human Body Model Consortium (GHBM) Phase 1 Lower Extremity

- 50thile Male
- Mass: 4.17 kg
- Parts: 115
- Nodes: 38,172
- Elements: 44,548

Flesh Modeling

Flesh (solid) & Skin (shell)

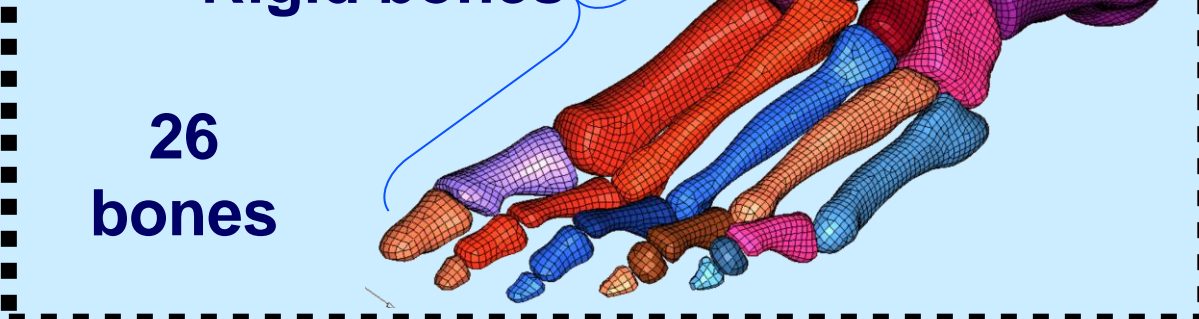


Foot Modeling

Deformable bones

Rigid bones

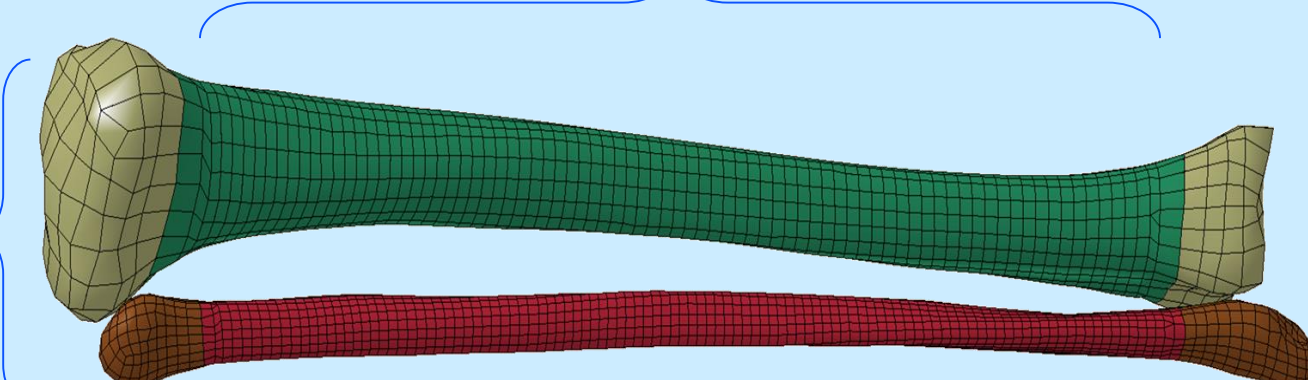
26 bones



Tibia & Fibula Modeling

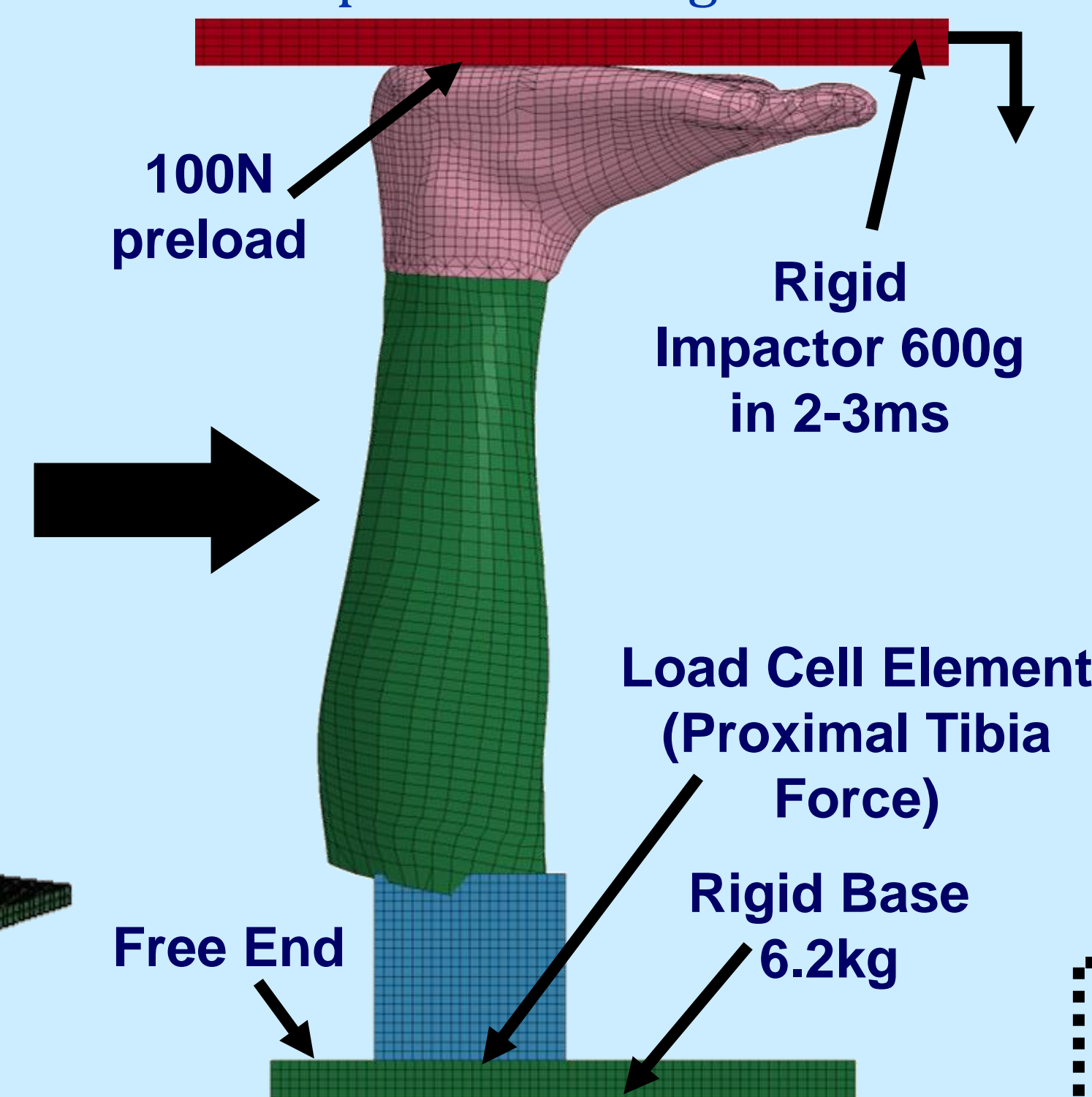
Solid cortical shaft

Solid cancellous end with cortical shell



Methods

GHBM FE model in an experimental drop tower configuration



- ❖ The GHBM FE model (left) was integrated into a FE model of a drop-tower impact system (above) and reproduced experimental drop-tower tests on 11 cadaveric lower limbs [2]. Model biofidelity was evaluated using this condition which is comparable to an UBB.

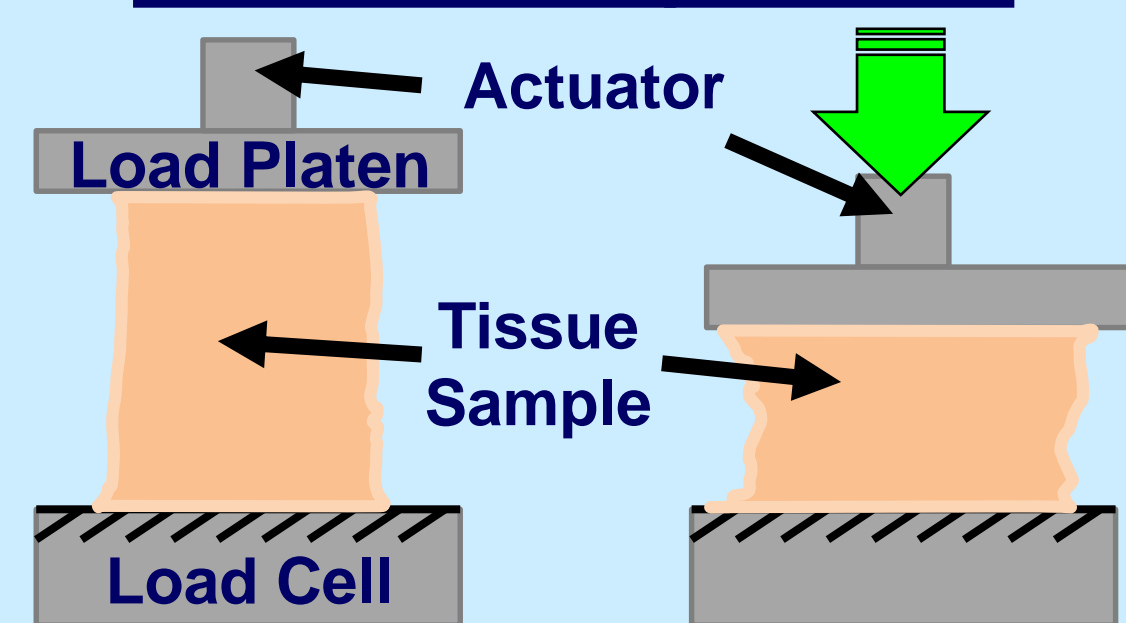
Modifications to the FE model

1. Experimental testing of cadaveric heel pad and constitutive modeling using Quasi-linear Viscoelasticity (QLV) [3]

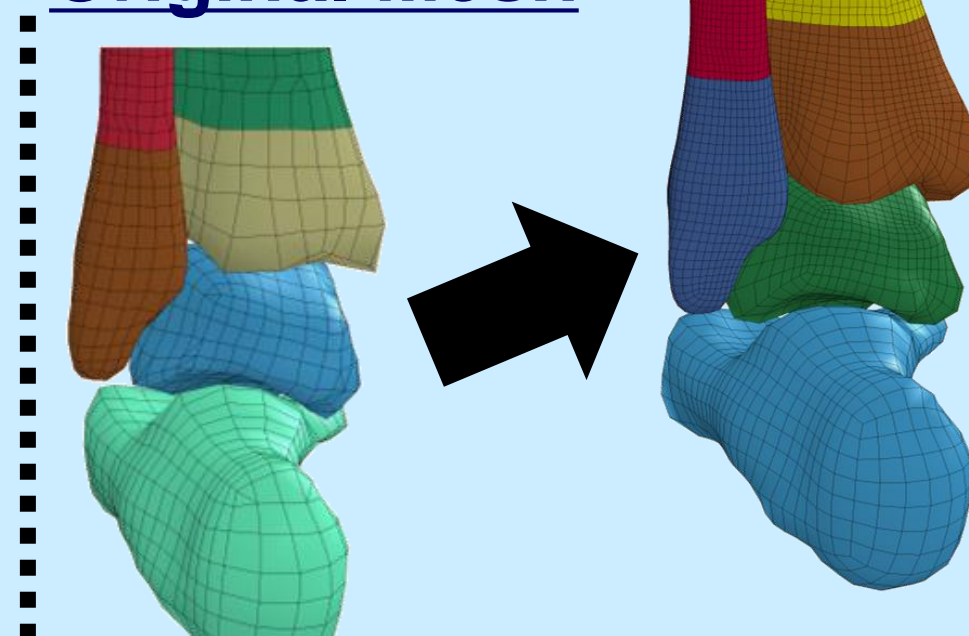
Ramp and hold tests

- 17 Cubic samples
- $\epsilon = (10-45)\%$ Compression
- Avg/Peak $\dot{\epsilon} = 25s^{-1}/60s^{-1}$

Uniaxial compression



Original Mesh



Modified Mesh

Structure (GHBM) LSDYNA V971, LSTC	Original (*MAT)	Modified (*MAT)
FOOT-FLESH	OGDEN_RUBBER ($\nu = 0.49$)	SIMPLIFIED_RUBBER/FOAM ($K = 2GPa$) Load curves generated using QLV model (above)
Tibia/Fibula (Cortical)	STRAIN_RATE_DEPENDENT_PLASTICITY ($\sigma_y = 125MPa$)	PIECEWISE_LINEAR_PLASTICITY $\sigma_y = 140MPa$, $\sigma_u = 214$, $\epsilon_u = 2.2\%$
Tibia/Fibula (Cancellous)	*MAT_PLASTIC_KINEMATIC $E = 455MPa$, $\sigma_y = 5.3MPa$, $\nu = 0.3$	PIECEWISE_LINEAR_PLASTICITY $E = 1.07GPa$, $\sigma_y = 8.56MPa$, $\nu = 0.1$, $\sigma_u = 8.564$, $\epsilon_u = 13.4\%$
Talus/Calcaneus (Cortical)	*MAT_PLASTIC_KINEMATIC $\sigma_y = 165MPa$, $\nu = 0.29$, $\sigma_u = (-)/178MPa$, $\epsilon_u = (-)/2.2\%$	PIECEWISE_LINEAR_PLASTICITY $\sigma_y = 140MPa$, $\nu = 0.3$, $\sigma_u = 214$, $\epsilon_u = 2.2\%$
Talus/Calcaneus (Cancellous)	*MAT_PLASTIC_KINEMATIC $E = 455MPa$, $\sigma_y = 5.3MPa$, $\nu = 0.3$	PIECEWISE_LINEAR_PLASTICITY $E = 1.07/0.068GPa$, $\sigma_y = 8.56/0.544MPa$, $\nu = 0.1$, $\sigma_u = 8.564/0.824MPa$, $\epsilon_u = 13.4\%$

Conclusions

1. FE models of the lower limb developed and validated for automotive type loading applications can be modified for high-rate loading conditions typical of UBB.
2. Rate-dependent mechanical properties for the heel pad significantly improved model biofidelity in the areas of phasing and magnitude and should be incorporated into the FOOT-FLESH for high-rate axial loading applications.
3. This work establishes preliminary efforts required to develop a more effective and biofidelic modeling tool that may be used to evaluate future systems designed to mitigate injury in blast type loading events.

- [1] Ramasamy A, Masouros SD, et al. In-vehicle extremity injuries from improvised explosive devices: current and future foci. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 2011, 366(1562):160-170.
- [2] Henderson K, Bailey A, Christopher J, Brozowski F, Salzar R. Biomechanical response of the lower leg under high rate loading. *Proceedings of IRCOBI Conference*, 2013, Gothenburg, Sweden.
- [3] Fung YC, Biomechanics: Mechanical Properties of Living Tissues, 277-280, Springer, New York, NY, 1993.