Mitigation of Underbody Blast Injuries to the Lower Extremity by Optimization of Combat Boot Properties

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Introduction

- 32 percent of soldiers wounded in underbody blast (UBB) events sustained foot/ankle fractures, 16 percent sustained both foot/ankle and tibia/fibula fractures [1]
- An objective injury criterion for high-rate UBB events for lower extremity injuries does not exist
- A layer of a prescribed injury mitigating material could provide sufficient protection for the lower extremity
- This study modifies an existing lumped-mass model by adding injury mitigating material properties to predict tibia and calcaneus loads [2]

Goals

- Benchmark the accuracy of the lumped-mass model with injury mitigating material properties
- Investigate effects of injury mitigating layers on the lower extremity using post mortem human specimens (PMHS)

Methods

Injury Mitigation Material

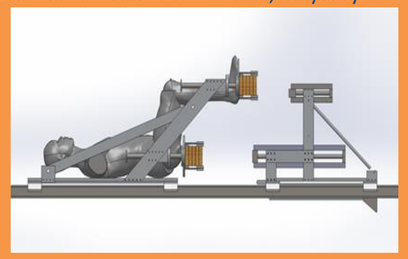
- Materials investigated: polyurethane-20, -40, -60, -80, Sorbothane®-50
- Polyurethane material properties obtained experimentally
- Sorbothane®-50 material properties are available [3]
- Materials characterized using viscoelastic theory to predict force response

Lumped-Mass Model

- A modified lumped-mass model of the human lower extremity was used to evaluate potential injury mitigation materials for [2]

PMHS Experiments

- Two whole body experiments were performed on the Center for Applied Biomechanics UBB simulator, Odyssey



- Each specimen tested three times:
  -Right foot in contact with Sorbothane®-50
  -Left foot in contact with plate

Test Matrix

Test	Specimen	Velocity (m/s)	Foot Hammer Mass (kg)	Max Foot Pan Acceleration: TTP (g, ms)
1	606	5.8	33.1	155.1, 0.337
2		7.2	32.4	508.2, 0.288
3		13.5	32.4	655.6, 0.270
4	622	6.0	33.1	123.9, 0.535
5		7.3	32.4	128.5, 1.091
6		13.4	32.4	507.5, 1.878

Results

Injury Mitigation Material

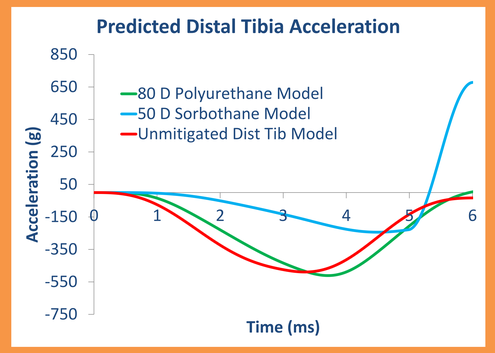
- Viscoelastic material parameters

Material Parameters

Material - Durometer	Model Type	Instantaneous Elastic Response Terms- A, B	Reduced Relaxation Parameters - G_i	Time Constants- τ_i (s)
Polyurethane-20	Non-linear elastic	1.245E6, 2.328	0	0
Polyurethane-40	Non-linear elastic	4.763E6, 1.490	0	0
Polyurethane-60	Quasi-linear viscoelastic	3.318E7, 2.297	G_1 = 0.870 G_∞ = 0.130	τ_1 = 2.686E-4
Polyurethane-80	Quasi-linear viscoelastic	6.166E7, 1.985	G_1 = 0.140 G_2 = 0.717 G_4 = 0.0242 G_∞ = 0.119	τ_1 = 1.001E-5 τ_2 = 4.005E-4 τ_4 = 1.634
Sorbothane®-50	Linear viscoelastic	7.407E6, 0	G_1 = 0.812 G_2 = 0.101 G_∞ = 0.087	τ_1 = 1E-3 τ_2 =1E-2

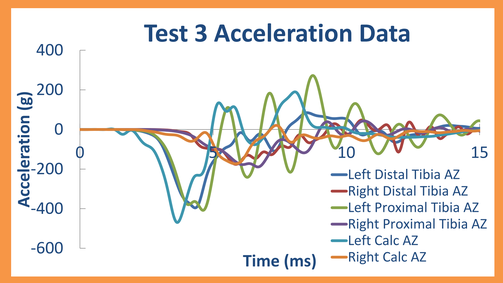
Lumped-Mass Model

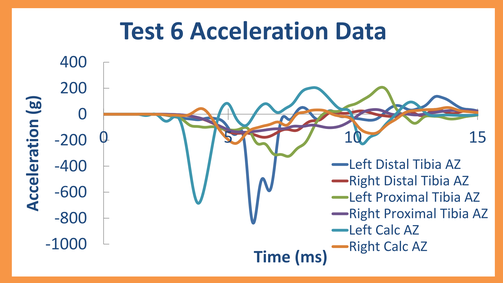
- Sorbothane®-50 was selected for PMHS testing



PMHS Experiments

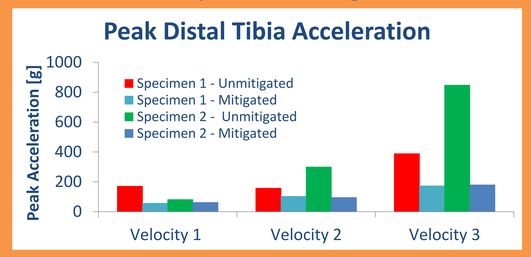
- Both specimens were tested with the left foot unmitigated and the right foot mitigated

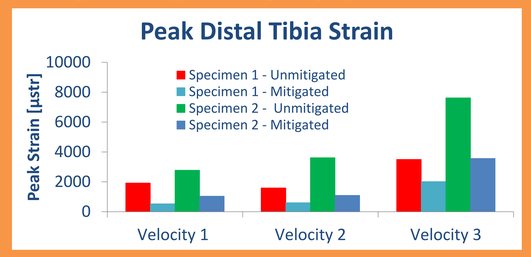




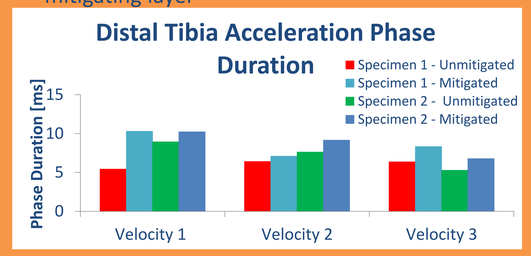
Discussion

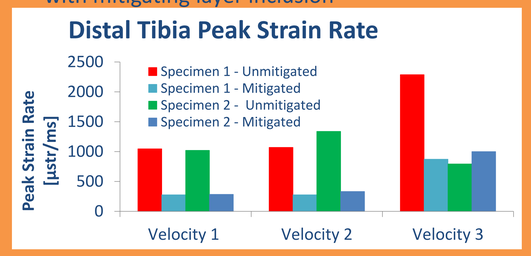
- Mitigated peak distal tibia accelerations are less severe when compared to unmitigated
- Distal tibia acceleration phase durations are lengthened by the mitigating layer





- Peak distal tibia strain was decreased by the mitigating layer
- In general, peak distal tibia strain rate is reduced with mitigating layer inclusion





Model Equations Used

Materials characterized using viscoelastic theory to predict force response:

$$F(\delta,t) = \int Gred_{(t-t')} \frac{dFe}{d\delta}\frac{d\delta}{dt'}dt'$$

G_{red} is the reduced relaxation function, F^e is the instantaneous elastic force, δ is displacement, t is time, t' is a dummy variable for integration

Model Equations

Model Type	$F^e(\delta)$	$G_{red(t)}$
Non-linear Elastic	$A[e^{B\delta}-1]$	G_∞
Linear Viscoelastic	$A\delta$	$G_\infty + \sum_{n=1}^{4} G_n e^{-t/\tau_n}$
Quasi-linear Viscoelastic	$A[e^{B\delta}-1]$	$G_\infty + \sum_{n=1}^{4} G_n e^{-t/\tau_n}$

A and *B* are instantaneous elastic parameters

$$G_1 + G_2 + G_3 + G_4 + G_\infty = 1$$

G_∞ is the steady-state relaxation coefficient, τ_n are time constants

Conclusion

- The lumped-mass model predicts a representative response change from the addition of an injury-mitigating layer
- Mitigating layer decreases severity of UBB events

Future Work

- Results from the lumped-mass model can be investigated using a finite element model of the lower extremity before PMHS testing

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References

[1] Vasquez K., Logsdon K., Shivers B., and Chancey C., Medical Injury Data 10, November, 2011.
[2] Henderson K., Bailey A., Christopher J., Brozoski F., and Salzar R., Biomechanical response of the lower leg under high rate loading, IRCOBI Conference on the Biomechanics of Impact, Gothenburg, Sweden, 11-13 September 2013, pp. 145-157.
[3] Sorbothane®, Inc, Kent, Ohio, http://www.sorbothane.com

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