CAVEMAN FE Model: Consideration to Biological Variabilities in the Computational Evaluation of Lower Leg Injuries during Underbody Blast Loading Conditions

Ryan Neice, Matthew Panzer, Kevin Lister, Kent Butz, Chad Spurlock, Rajarshi Roy

Introduction

- The use of IED's against U.S. military vehicles has led to an increased need to accurately predict mounted warfighter injuries, particularly in the lower limbs.
- The Corvid Technologies CAVEMAN (Computational Anthropomorphic Virtual Experiment Man) lower leg model is a highly detailed FE model based on a 50th percentile man designed to predict fracture location and severity as well as soft tissue damage.

Objective

1. Perform an injury sensitivity study on biological variabilities such as positioning, material properties, and anatomical geometry.
2. Compare the injury prediction capabilities of the CAVEMAN model to an injurious PMHS data set (Bailey 2016).

Methodology

CAVEMAN Model Details

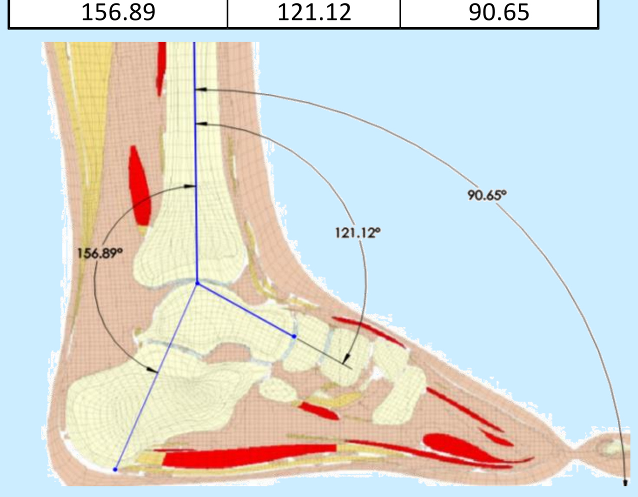
- Developed to run on Velodyne, an explicit finite element solver developed by Corvid. Limits simplifications and assumptions, all structural components of the body are explicitly modeled.
- Lower extremity model consists of 28 bones, 26 muscles, 40 ligaments, fascia, cartilage, and skin, and its bio-fidelity has been validated with 14 sub-injurious PMHS data sets.
- Currently utilizes primarily low rate human tissue material models derived from literature, but model will be updated in the future to reflect high rate material characterizations.

PMHS Data Set Description

- Specimen: 12 (Medium and High Impacts); Sex: Male; Average Age: 57.75 years; Average Leg Length: 476 mm; Average Body Mass: 86.76 kg
- Calcaneus fractures occurred in over 95% of the 24 impacts. Pilon and Talus fractures were also observed, but in less than half of the tests.

Average Medium Impact Positioning Angles

Tibia-Calcaneus Angle	Tibia-Talus Angle	Ankle Flexion Angle
156.89	121.12	90.65



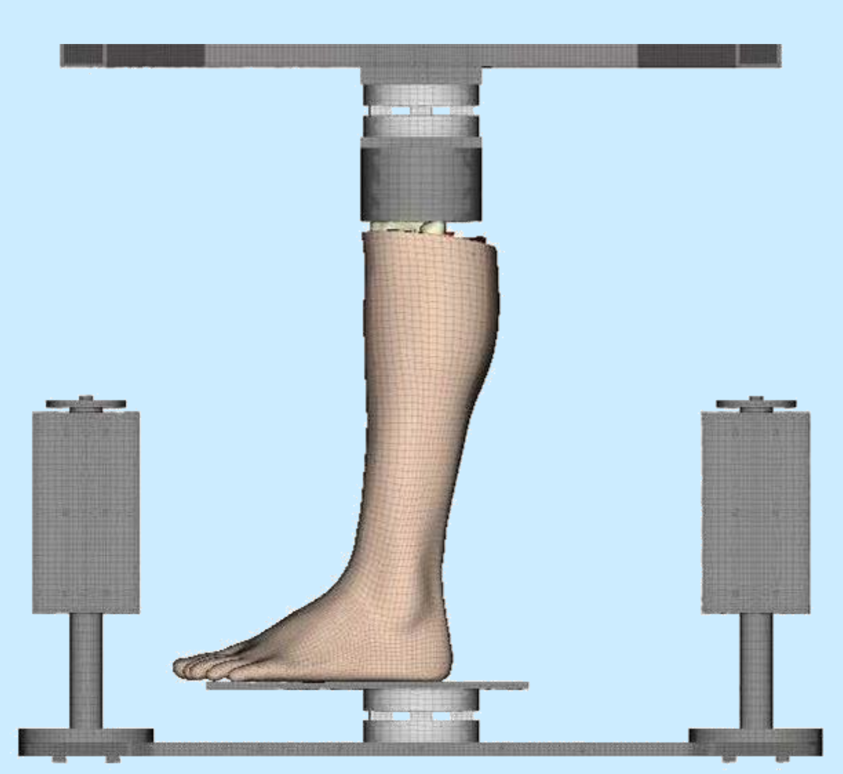
Model Set-up

- The CAVEMAN leg was positioned to match the average alignment angles measured from CAD via pre-impact x-ray scans of the 2 impact conditions. (left)
- Leg is rigidly potted at proximal tibia, input acceleration from dataset trace prescribed on impactor.
- Below table compares peak tibia forces and fracture times for PMHS and CAVEMAN. (standard error)

Impact Condition	Peak Velocity (m/s)	Proximal Tibia Force at Fracture (kN)	Time at Fracture (ms)
CAVEMAN Medium	2.4	6.83	6.73
CAVEMAN High	4.3	8.95	6.41
PMHS Avg. Medium	2.4	8.29 (0.670)	7.43 (0.39)
PMHS Avg. High	4.5	9.98 (0.62)	5.16 (0.17)

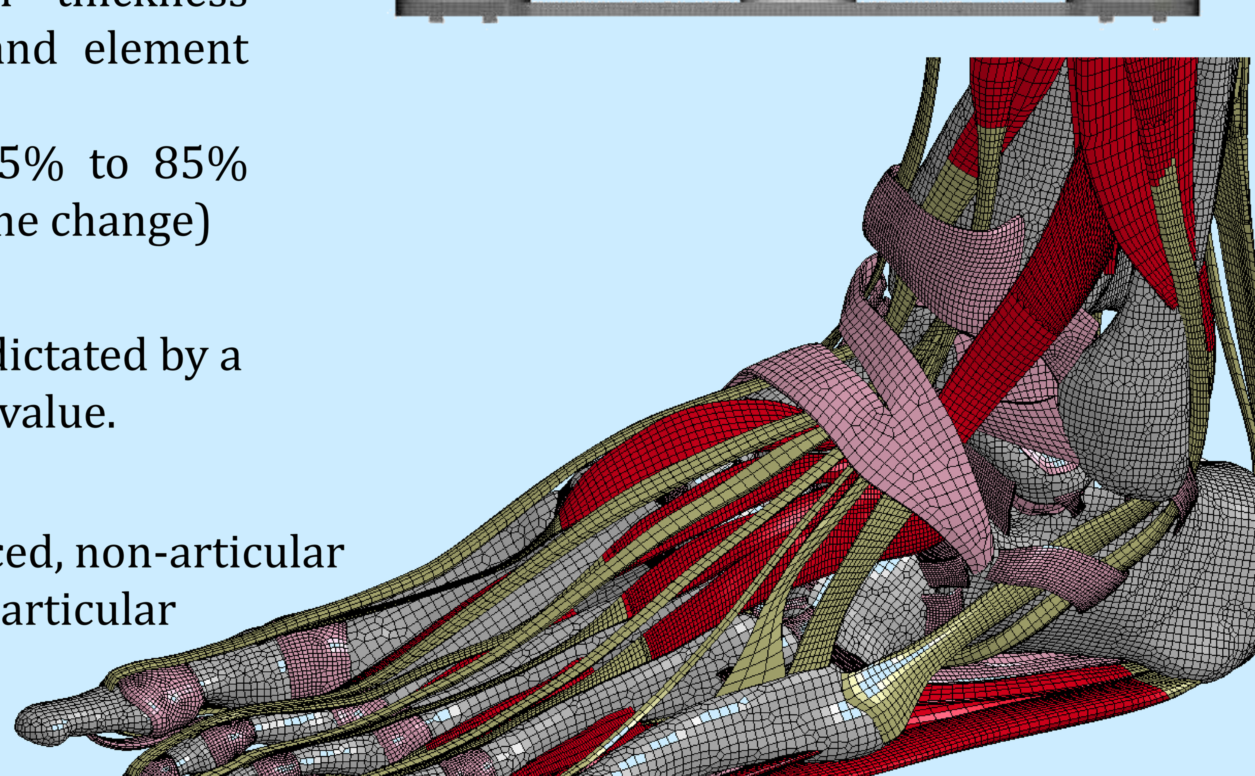
Sensitivity Study Parameters

- Positioning:
  - Ankle-Flexion angle altered by 4.6 degrees for each impact condition (86 to 90.6 degrees)
- Material Stiffness:
  - Muscle x 0.1 , x 10
  - Tendon x 0.1 , x 10
  - Ligament x 0.1 , x 10
  - Heel pad x 0.1 , x 10
  - Cortical Bone + - 25%
  - Cancellous Bone x 0.1 , x 10
- Anatomical Geometry:
  - Calcaneus cortical thickness shifted by 3mm and element layer assignment. (Ranges from a 15% to 85% cortical bone volume change)

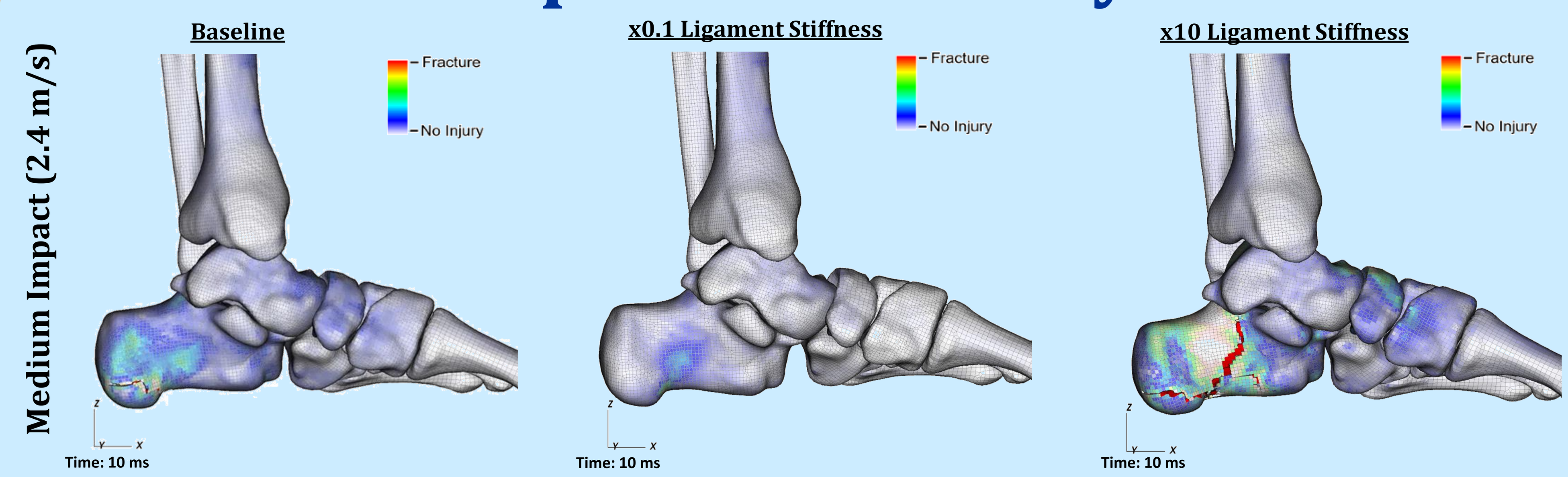


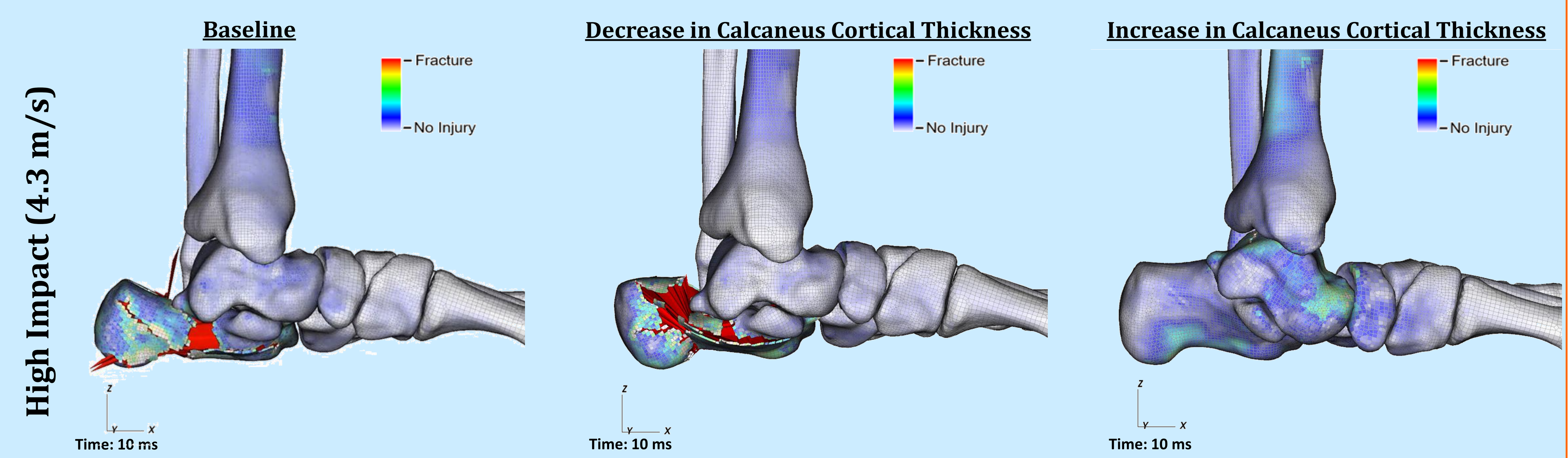
Injury Evaluation

- Cortical bone failure dictated by a 2.2% principal strain value.
- Failure Description:
  - Minor: Non-displaced, non-articular
  - Severe: Displaced , articular

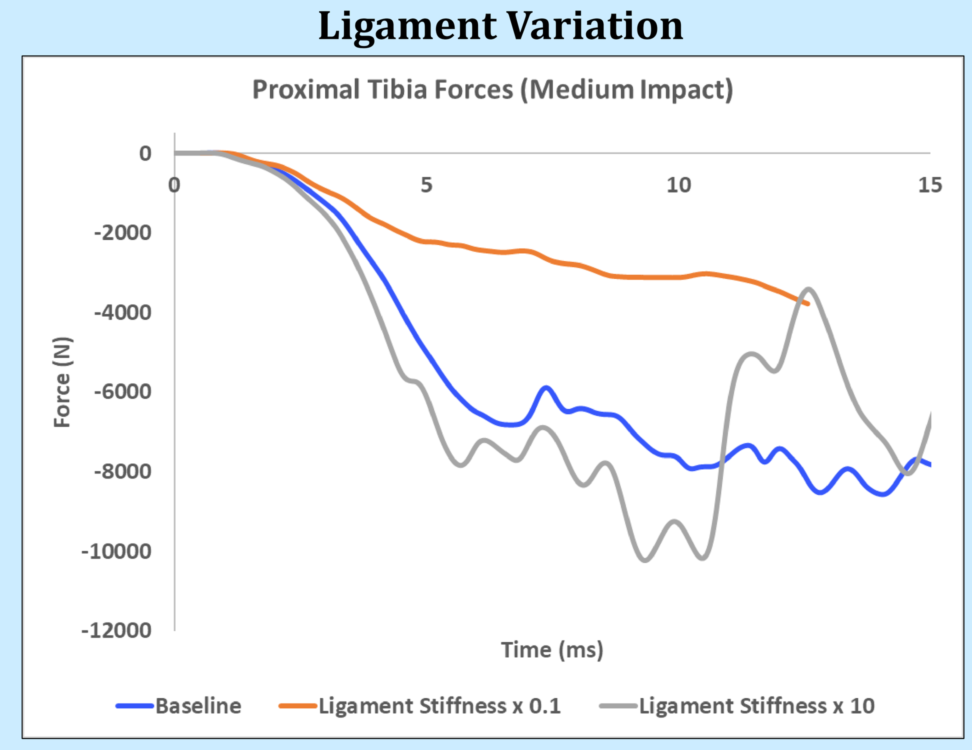


Computational Analysis

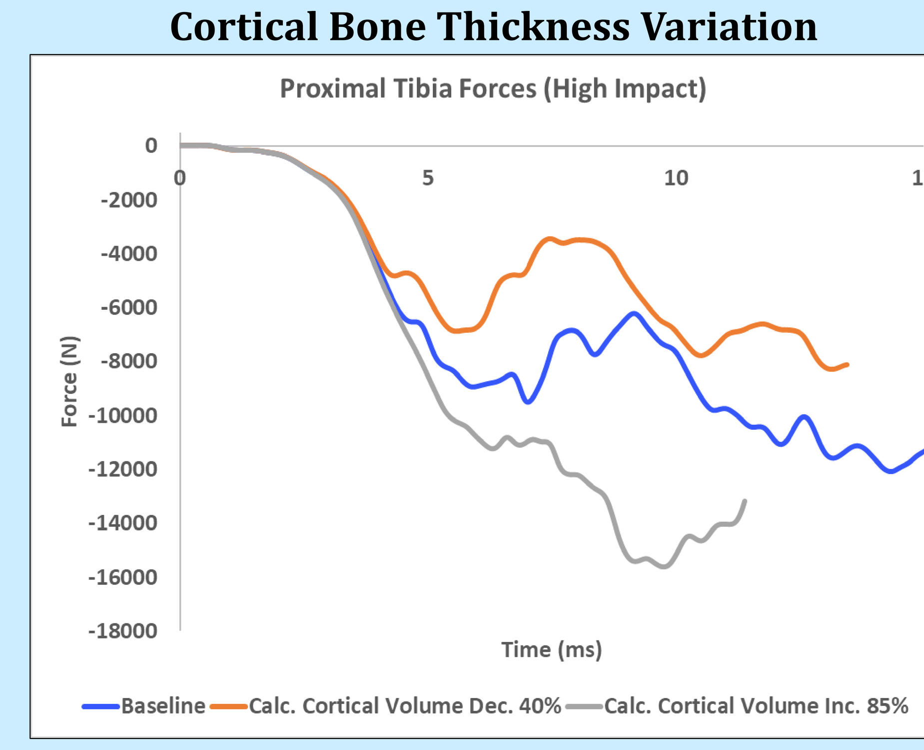




Medium Impact Force Response Ligament Variation



High Impact Force Response Cortical Bone Thickness Variation



Medium Impacts Summary

Impact	Variation Description	Change in Force Response	Change in Fracture
Medium	Muscle Stiffness x 0.1	N	N
	Muscle Stiffness x 10	N	N
	Tendon Stiffness x 0.1	N	Y (no fracture)
	Tendon Stiffness x 10	N	N
	Heel Pad Stiffness x 0.1	N	N
	Heel Pad Stiffness x 10	N	N
	Ligament Stiffness x 0.1	Y	Y (no fracture)
	Ligament Stiffness x 10	Y	Y (severe fracture)
	Cancellous Bone Stiffness x 0.1	N	N
	Cancellous Bone Stiffness x 10	N	N
	Cortical Bone Stiffness - 25%	N	Y (no fracture)
	Cortical Bone Stiffness + 25%	N	N
Medium	"High" Allignment (4 Deg Dif.)	N	N
Medium	Cortical Thickness Element Inc.	N	Y (no fracture)
	Cortical Thickness Element Dec.	Y	Y (severe fracture)
	Cortical Thickness 3mm Inc.	N	Y (no fracture)
	Cortical Thickness 3mm Dec.	N	N

High Impacts Summary

Impact	Variation Description	Change in Force Response	Change in Fracture
High	Muscle Stiffness x 0.1	N	N
	Muscle Stiffness x 10	N	N
	Tendon Stiffness x 0.1	Y	N
	Tendon Stiffness x 10	N	N
	Heel Pad Stiffness x 0.1	N	N
	Heel Pad Stiffness x 10	N	N
	Ligament Stiffness x 0.1	Y	Y (no fracture)
	Ligament Stiffness x 10	Y	N
	Cancellous Bone Stiffness x 0.1	Y	N
	Cancellous Bone Stiffness x 10	N	N
	Cortical Bone Stiffness - 25%	Y	Y (minor fracture)
	Cortical Bone Stiffness + 25%	N	N
High	"Medium" Allignment (4 Deg Dif.)	N	N
High	Cortical Thickness Element Inc.	Y	Y (no fracture)
	Cortical Thickness Element Dec.	Y	N
	Cortical Thickness 3mm Inc.	N	N
	Cortical Thickness 3mm Dec.	N	N

Discussion

- The force transmission through the foot changed when ligament stiffness was reduced. Notice the gap that emerges between the calcaneus and cuboid. The ligaments between the calcaneus and cuboid are especially consequential to load path through foot/leg.
- The variations in cortical bone stiffness and thickness suggests that ideal cortical bone to prevent fracture would be flexible and thick. This could lead to an aging based study to see how aged based changes to bone material properties and thickness effect injury, since aging affects cortical bone thickness and causes bones to become more brittle.

Conclusions

1. The CAVEMAN lower leg model shows most significant injury sensitivity to the variation in ligament material properties and cortical bone thickness. A lesser sensitivity was found with changes to tendon and bone material properties.
2. Ligaments that connect the calcaneus and cuboid appear especially important for the force transmission and injury likelihood for axial loading.
3. The CAVEMAN lower extremity model's prediction of calcaneus fracture occurrence and severity compares favorably to the PMHS dataset.

[1] Butz, K., Spurlock, C., Roy, R., Bell, C., Barrett, P., Ward, A., Xiao, X., Shirley, A., Welch, C., and Lister, K. (2017). Development of the CAVEMAN Human Body Model: Validation of Lower Extremity Sub-Injurious Response to Vertical Accelerative Loading. Stapp Car Crash Journal, Vol. 61

[2] Bailey, A. (2016). Injury Assessment for the Human Leg Exposed to Axial Impact Loading. University of Virginia, Department of Mechanical and Aerospace Engineering, PHD..

University of Virginia - Center for Applied Biomechanics

CORVID

Ryan Neice, rjn7df@Virginia.edu
4040 Lewis and Clark Drive
Charlottesville, VA 22911