GHBMC PEDESTRIAN MODEL OVERVIEW

Full Body Model Center of Expertise

Wake Forest and Virginia Tech

Global Human Body Models Consortium

September 15th, 2020

Center for Injury Biomechanics

Wake Forest School of Medicine

CIB

Virginia Tech Wake Forest University School of Biomedical Engineering and Sciences

GHBMC Introduction
- Objective & Mission

Founded in 2006, GHBMC is an international consortium established to advance human body modeling technologies for crash simulations.

MEMBERS

OBJECTIVE:
To consolidate world-wide HBM R&D effort into a single global effort

MISSION:
To develop and maintain high fidelity FE human body models for crash simulations

SPONSOR

PARTICIPANTS

GHBMC Introduction
- GHBMC COEs (Center Of Expertise)

BRM (Body Region Model) COE

Head Model COE
PI: Dr. Liying Zhang; Leader: Dr. Jesse Ruan (Ford)

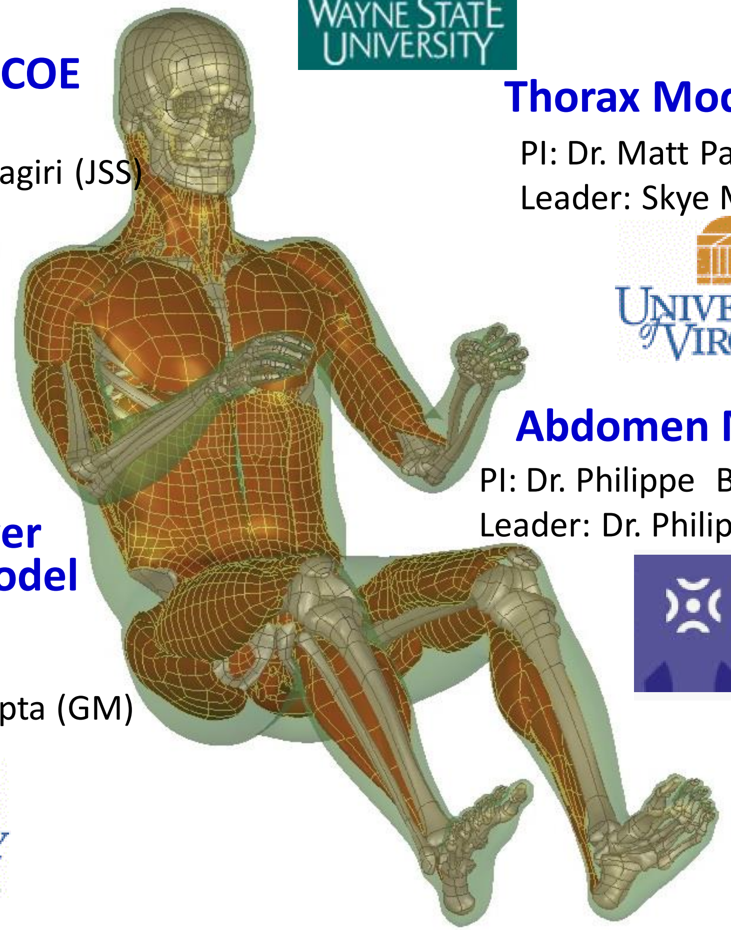
Wayne State University

Neck Model COE
PI: Dr. Duane Cronin
Leader: Dr. Maika Katagiri (JSS)

University of Waterloo

Thorax Model COE
PI: Dr. Matt Panzer
Leader: Skye Malcolm (Honda)

University of Virginia



Abdomen Model COE
PI: Dr. Philippe Beillas
Leader: Dr. Philippe Petit (Renault)

Université Gustave Eiffel

Pelvis & Lower Extremities Model COE
PI: Dr. Matt Panzer
Leader: Dr. Vishal Gupta (GM)

University of Virginia

FBM (Full Body Model) COE
Co-PIs: Dr. Scott Gayzik
Dr. Joel Stitzel
Leader: Dr. Jay Zhao (JSS)

Wake Forest University

Pedestrian & Active Model Test COE
PIs: Dr. Costin Untaroiu
Dr. Andrew Kemper
Leader: Dr. Eric Song (PSA), Dr. Jay Zhao (JSS)

Virginia Tech

Models Conversion COE
PIs: Dr. Hyung Yun Choi
Leader: Dr. Eric Song (PSA)

Hongik University

Responsibilities:

FBM COE
- CAD mesh interface body regions
- Full Body Validation

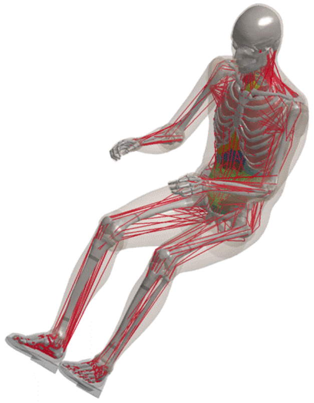
BRM COEs
- Body region validation
- Suggest model design modifications
- Updates

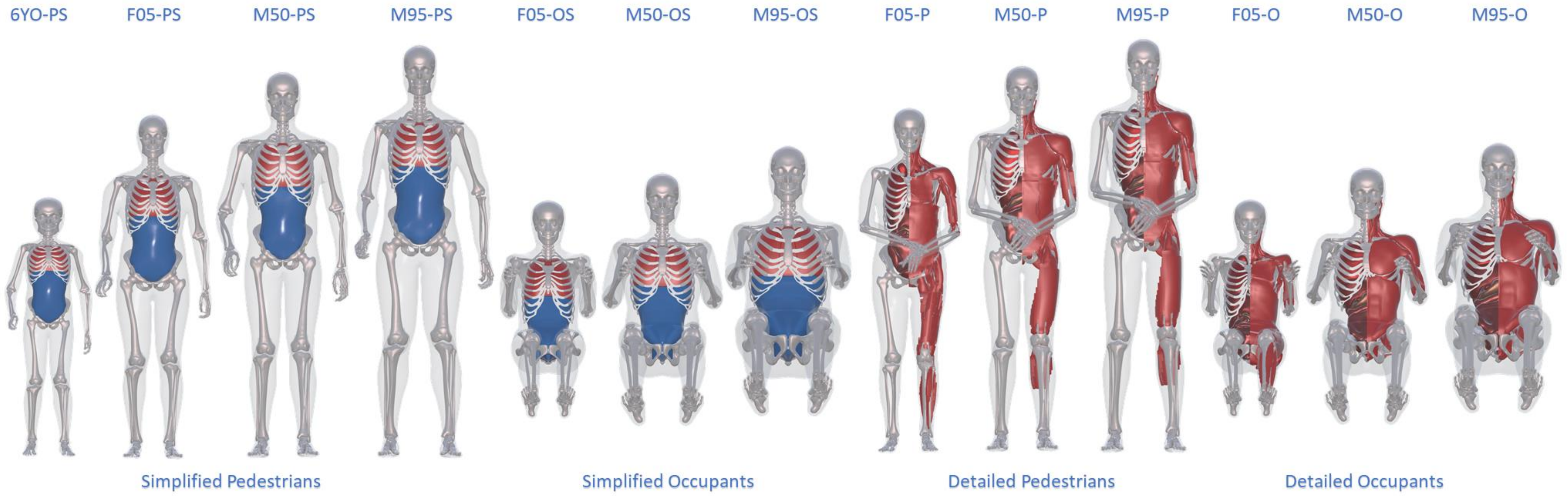
Global Human Body Models Consortium

The GHBMC Family

13 Base Models in the Family
Developed in LS-Dyna, VPS, and Radioss

Active Models Available

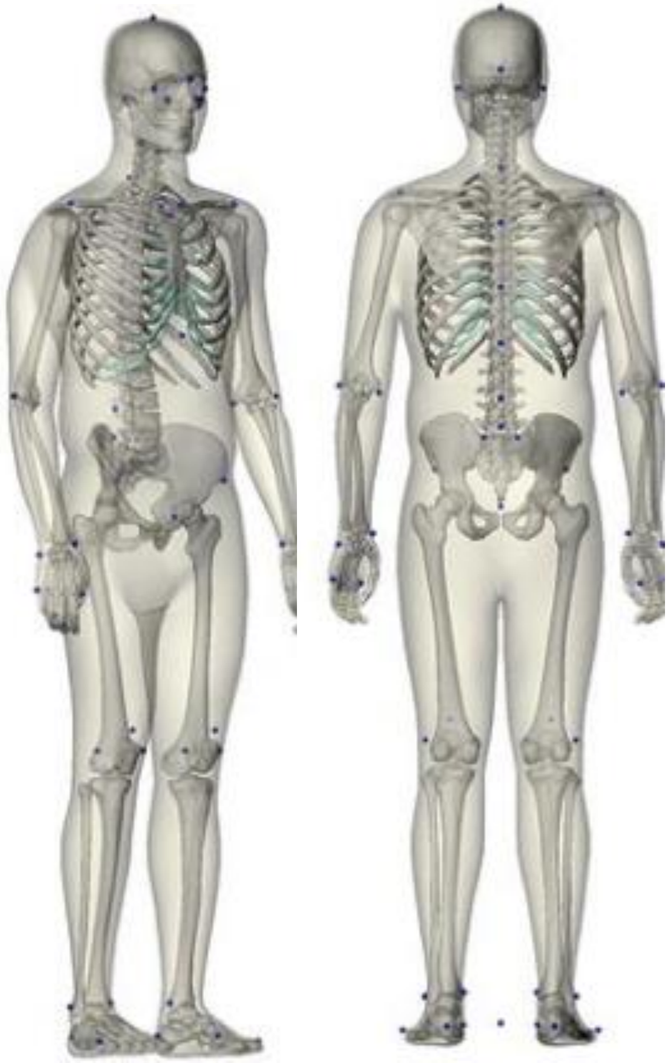




GEOMETRY DEVELOPMENT

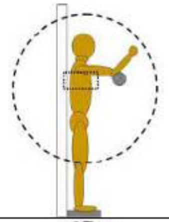
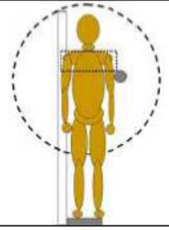
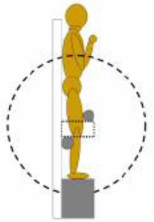
External Geometry Development

- Procedures for determining external shape of body:
- https://www.ncbi.nlm.nih.gov/pubmed/22441664
- Gayzik et al. 2012, "**External landmark, body surface, and volume data of a mid-sized male in seated and standing postures**"
- We took landmark and surface data on living subjects who met sizes of interest



Imaging Procedures: Upright MRI (aka uMRI)

- **We used upright MRI to scan the knee in the standing posture**
- We are not aware of other FEM human models that have used upright data for model development
- The subjects were recruited and scanned for the purpose of human model development

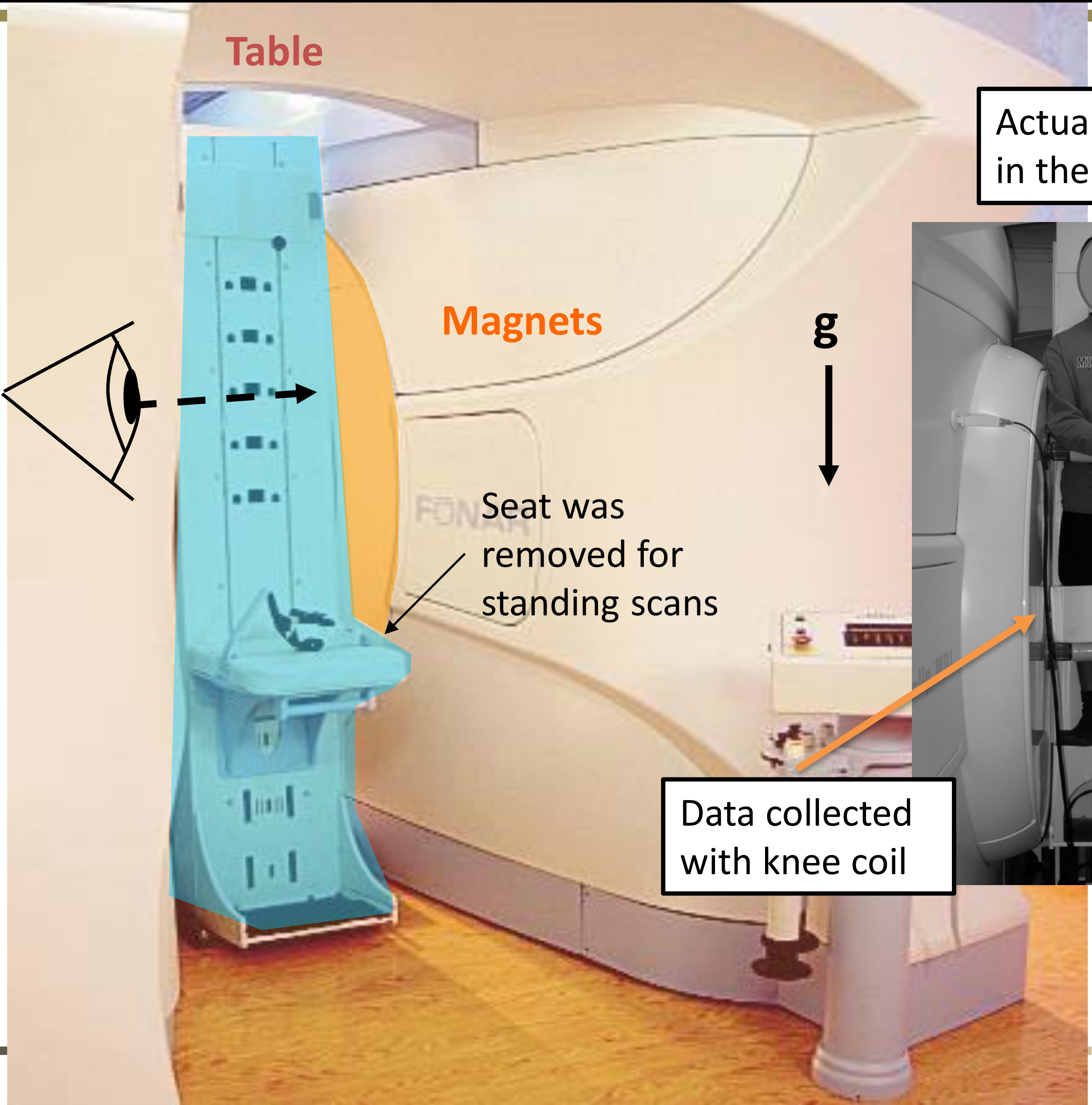
Standing			
Body Region	Number of Slabs	Resolution / Slice Thickness	Posture Schematic
Thorax and Abdomen	3 – 5	2.15 / 2	
Chest and Shoulder	1 – 2	2 / 2	
Loaded knee	1 – 2	1.5 / 1.6	

Gayzik, FS, Moreno, D.P., Hamilton, C.A., Tan, J.C., McNally, C., Duma, S.M., Klinich, K.D., Stitzel, J.D., A multi-modality image data collection protocol for full body finite element analysis model development, *SAE Technical Paper* 2009-01-2261, doi:10.4271/2009-01-2261

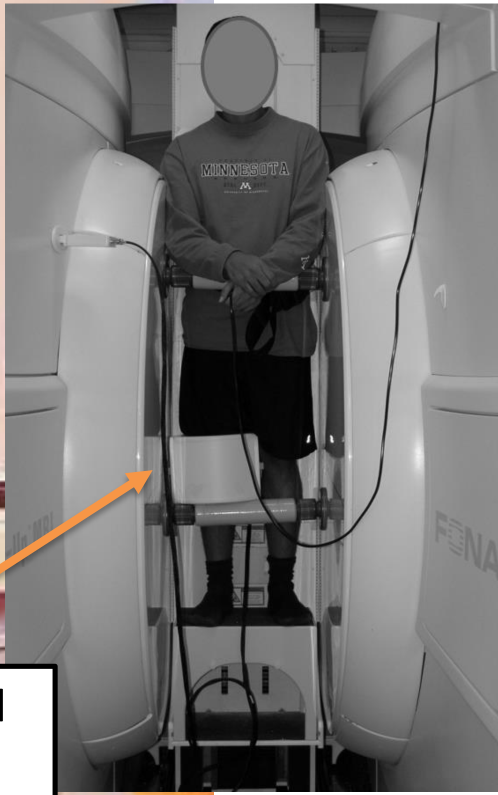
Upright MRI

- Provides unique ability to image oriented with gravity

- Protocol sequence:
  - Head
  - Cervical
  - Seated Chest & Abd.
  - Standing Chest & Abd.
  - **Standing Knee**



Actual M50-O in the scanner



Data collected with knee coil

Paper on M50-PS in Literature

- 2.1 **Development of the Finite Element Model of 50th Percentile Pedestrian Male.**
  - The geometric data were obtained from a living 50th percentile male who met selection criteria for 15 external anthropomorphic measurements [9].
  - The same subject (26 year old, 175 cm height, 78.6 kg weight) [10] was used as the basis for the GHBMC 50th percentile detailed occupant model.
  - A multimodality protocol was used to acquire data in a pedestrian posture [9].
  - External anthropometry was collected via a three-dimensional scanner (Faro, Platinum Model arm, 8 ft. (2.4 m), Lake Mary, FL)
  - The medical scans and external anthropometry were integrated to develop CAD.
  - The final full-body CAD was composed of 410 components, including bones, organs, muscles, vessels, ligaments, and tendons.

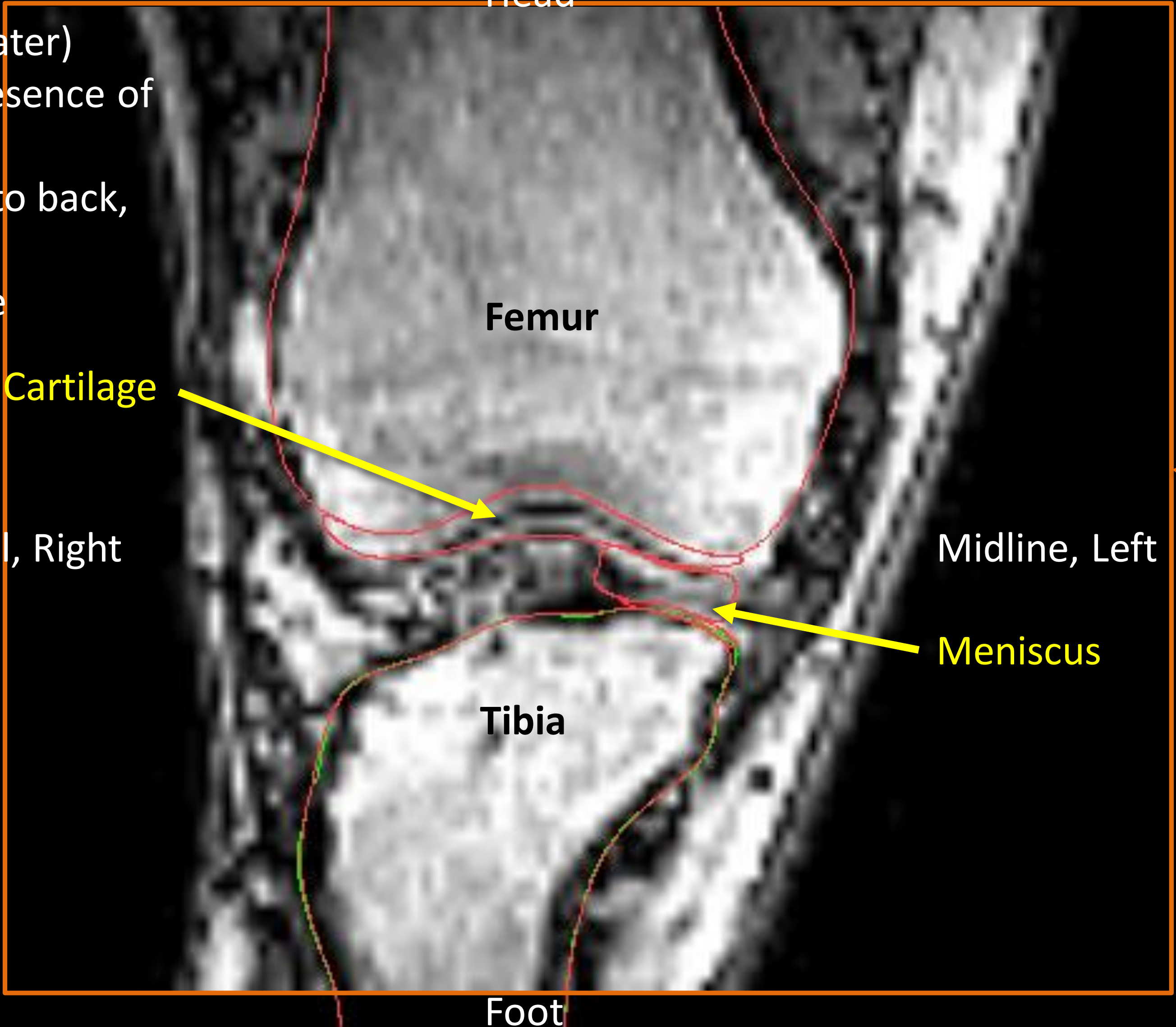
Untaroiu, C.D., Pak, W., Meng, Y., Schap, J., Koya, B., **Gayzik, F.S**. A Finite Element Model of a Mid-Size Male for Simulating Pedestrian Accidents, J Biomech Eng. 2018 Jan 1;140(1). doi: 10.1115/1.4037854.

Methods: M50-PS Standing Knee Geometry Check

- Both the M50-P and M50-PS have the same source data.
- CAD of the knee was **aligned to the upright MRI (uMRI) knee** using tibia only (CAD tibia, femur, ligaments, cartilage, etc. were moved as a whole) with no relative motion or adjustment
- We did not “tune” these to match scans, this is a blinded test to see how well they match.
- The scans and CAD match!

M50-PS Standing Right Knee Geometry Check (Anterior)

- These scans are MRI of M50
- Cortical bone is dark (little water)
- Trabecular bone is bright (presence of water)
- Scans go in order from front to back, several coronal planes
- Ligaments are not easy to see



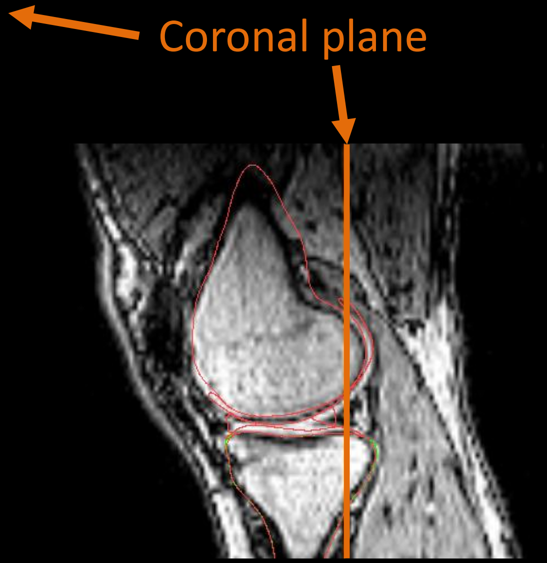
1. Red outlines are GHBMC bones in CAD
2. Green is FEA mesh
3. Only difference from these and the FEA models is the stanced posture, which is a small angle adjustment.

Coronal plane

M50-PS Standing Right Knee Geometry Check (Mid)

- This subjects is standing for the MRI.
- The knee shows a diagonally downward posture.

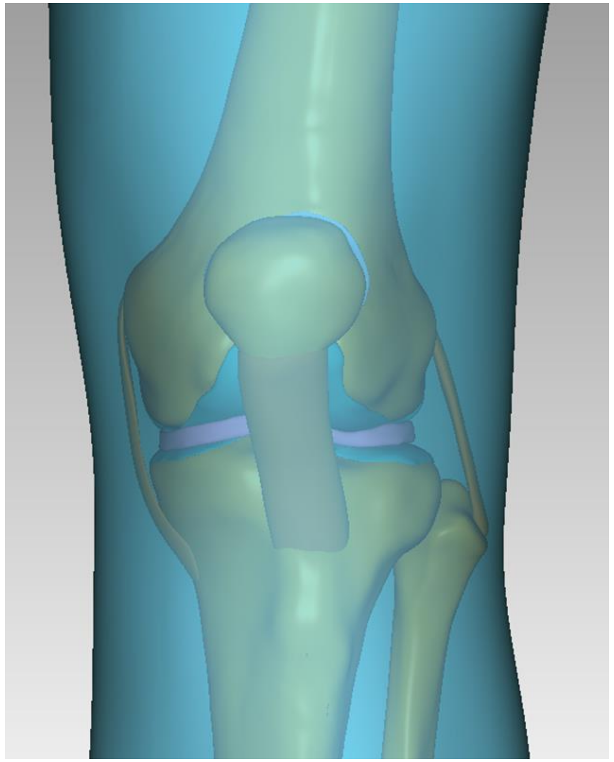
M50-PS Standing Right Knee Geometry Check (Posterior)



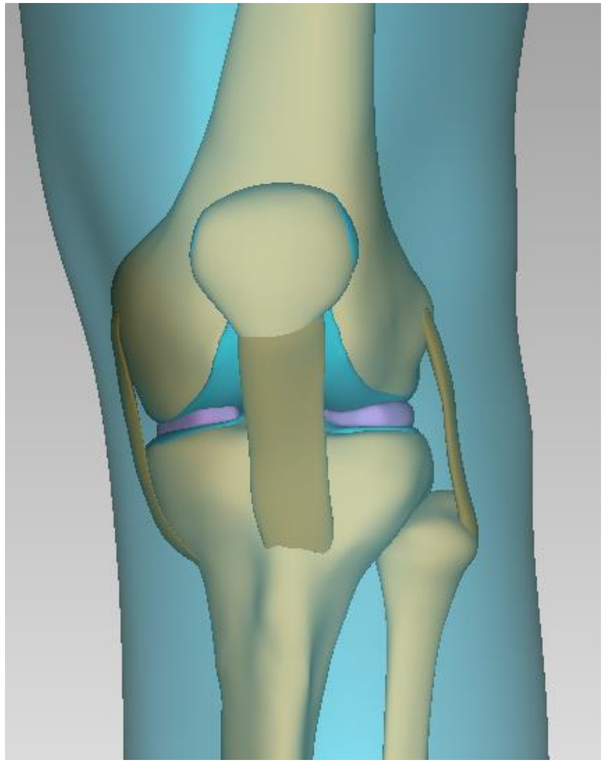
Reference Points of Overall Knee in Standing Posture

- GHBMC CAD Reconstructions show similar trends

M50-P CAD



F05-P CAD



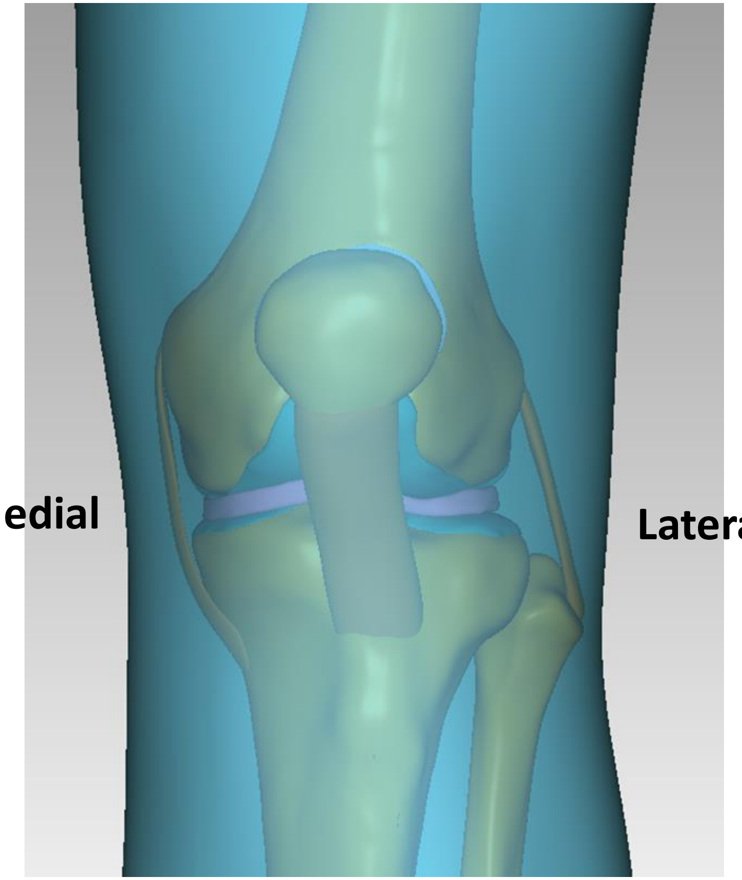
Anterior View of CAD (Straight Leg) and M50-PS Stance

M50-P & PS CAD

M50-PS v. 1.5.1 Left Knee with all structures and thicknesses visualized (LS-PrePost)

Superior

Medial

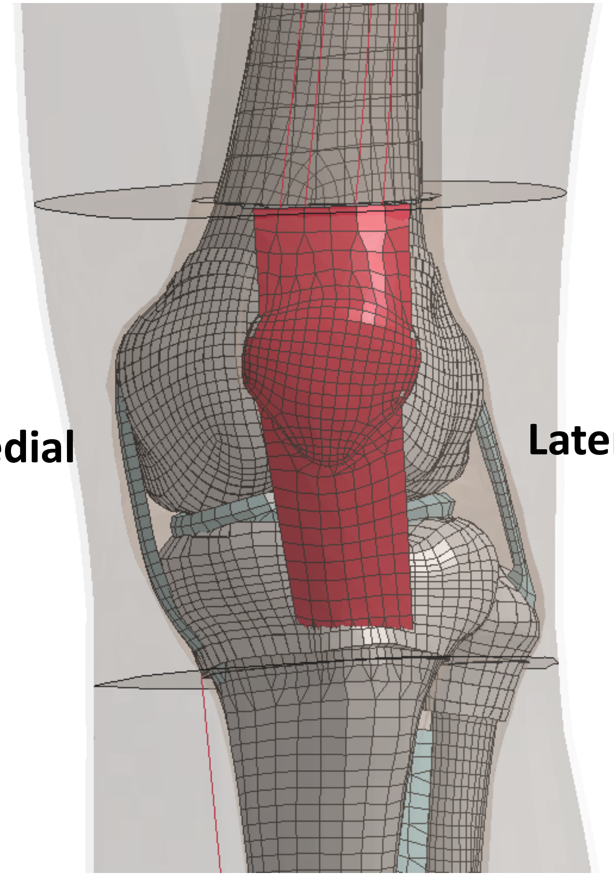


Lateral

Inferior

Superior

Medial

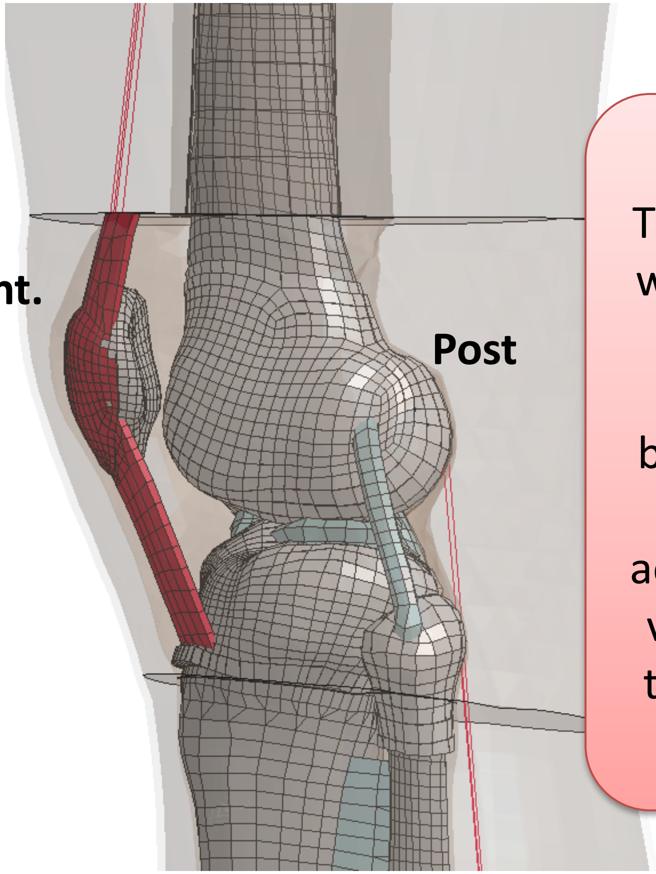


Lateral

Inferior

Superior

Ant.



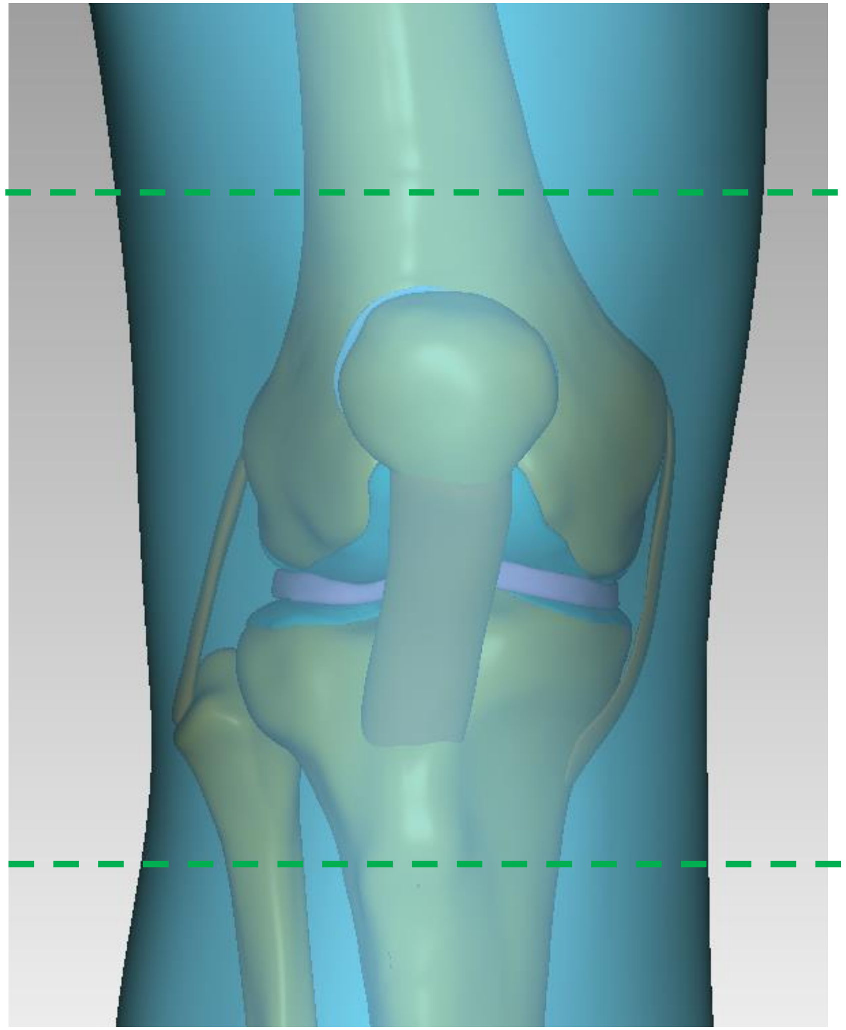
Post

Inferior

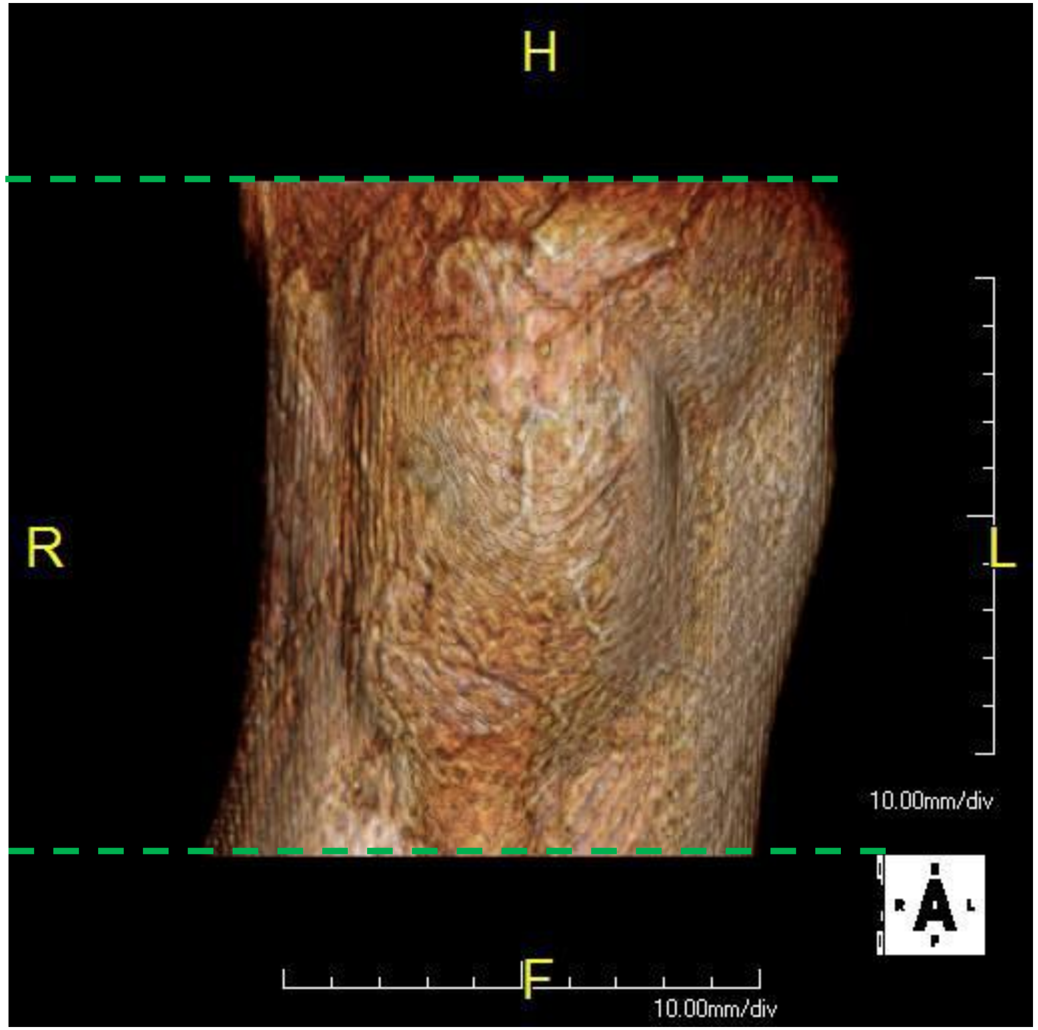
There are parts with thickness, like shell elements for bone and solid menisci that account for any visible gaps in these pictures

M50-P Standing Knee Geometry Check (3D not 2D)

Straight Leg CAD

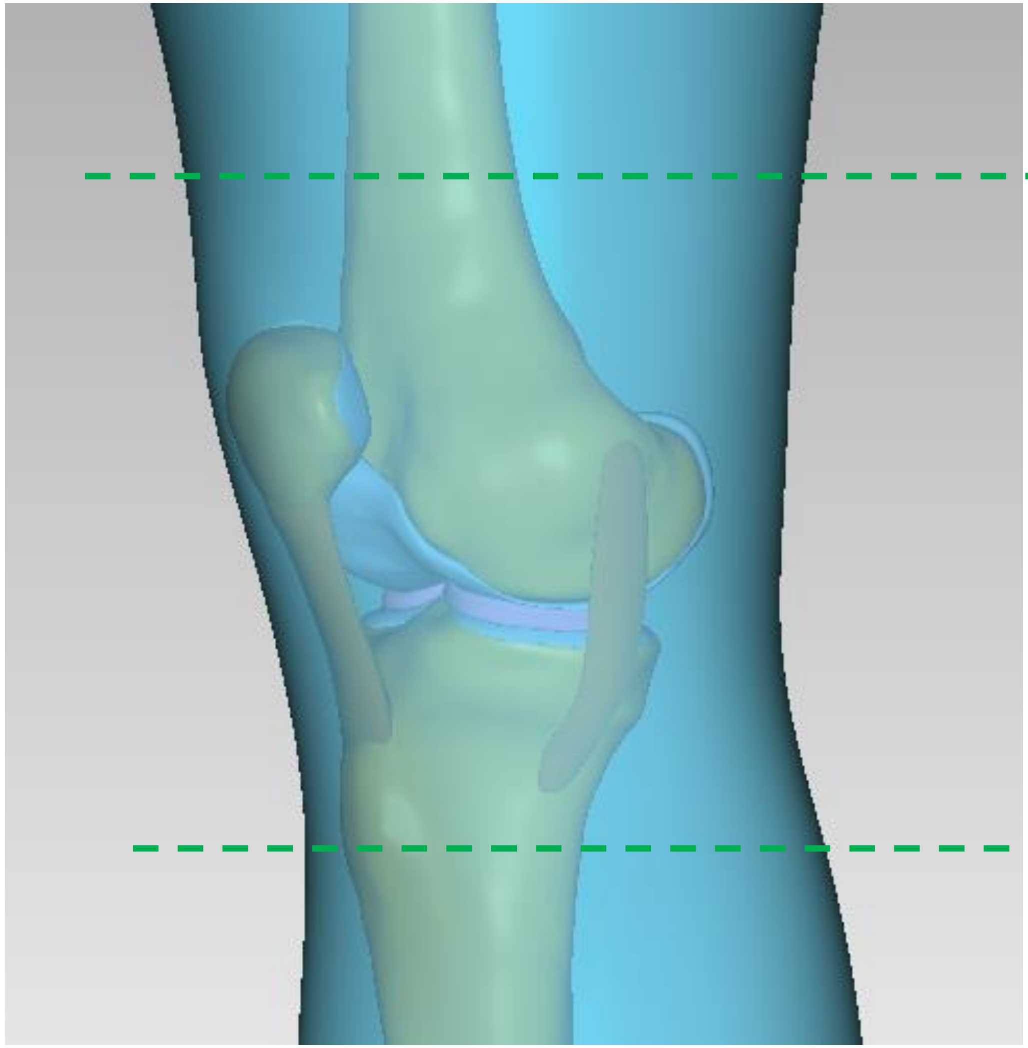


3D Render of actual patient knee standing in MRI

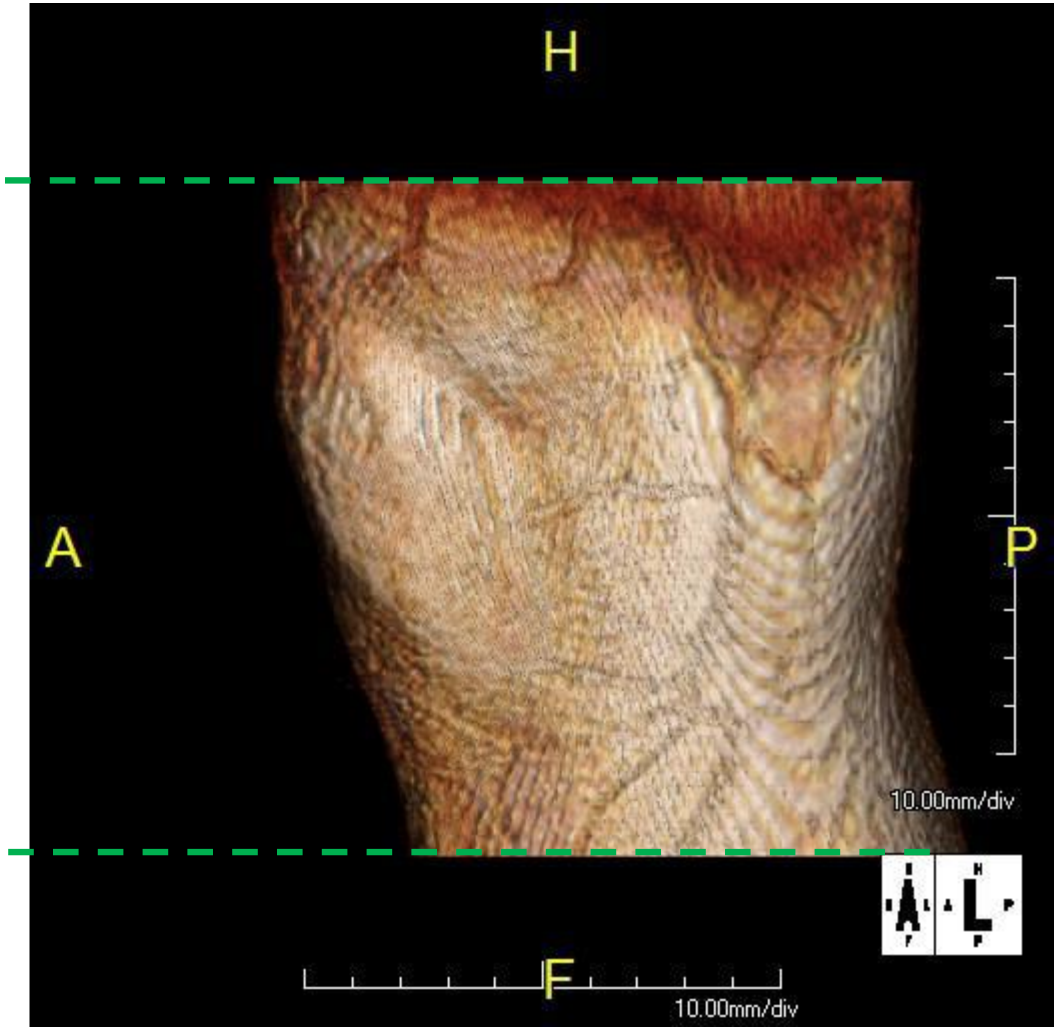


3D M50-P Standing Knee Geometry Check: Oblique View

Straight Leg CAD



3D Render of actual patient knee standing in MRI



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Ligament Cross Sections and Lengths based on Literature

- Ligaments do not show well on scans, we used literature to reconstruct them

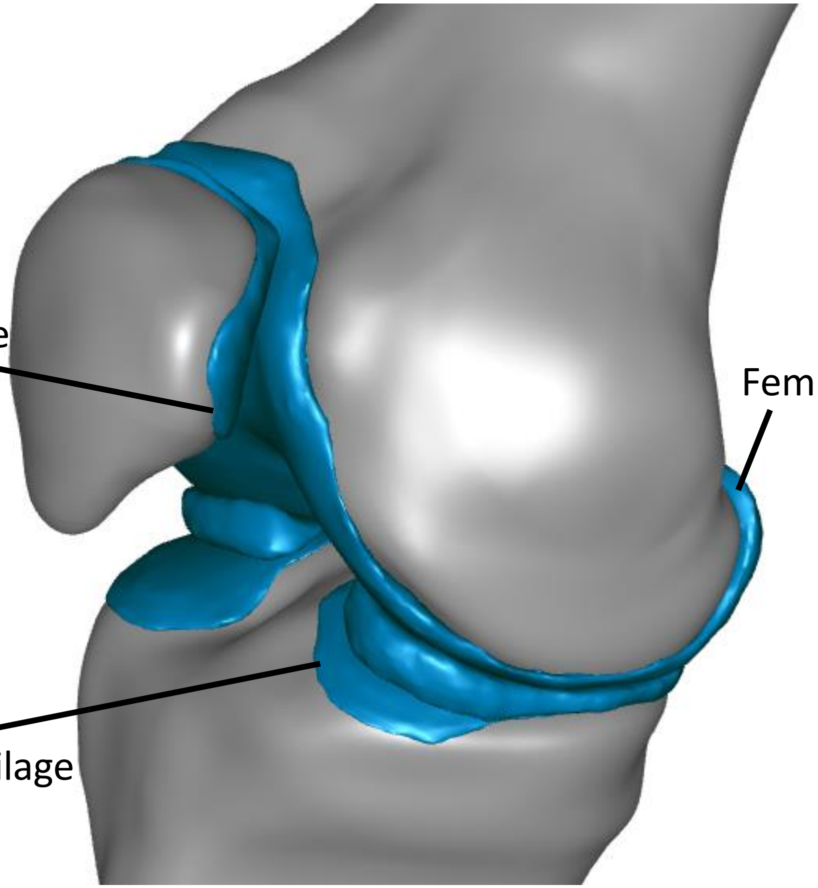
Table 8. Lengths and cross sectional areas of ligaments and tendons of the M50 lower extremity.

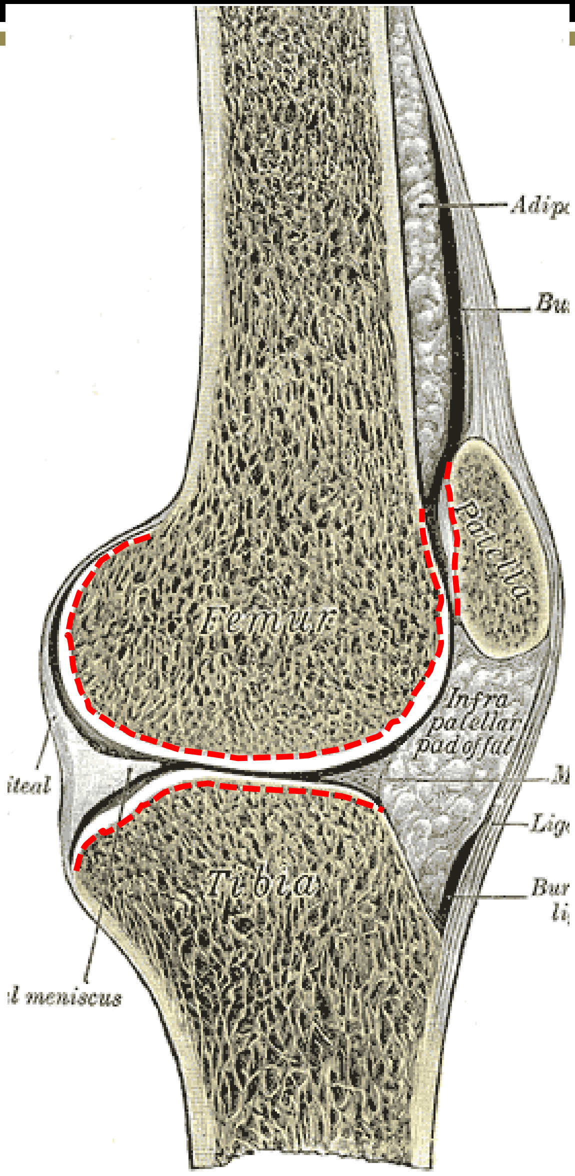
Structure	M50 value: Max Length (L, mm), Mid-length cross sectional area (CSA, mm^2)	Literature Range
ACL	L: 34.9 mm	25.5 – 41 mm [145-147]
	CSA: 34.3 mm^2	31 ± 5 mm2 [148]
PCL	L: 38.9 mm	29 -42 mm [149, 150]
	CSA: 49.0 mm^2	40 – 77 mm^2 [148, 151]
MCL	L: 90 mm	77.5 – 93.5 mm [151, 152]
	CSA: 35.6 mm^2	27.0 – 37.0 mm^2 [151, 153]
LCL	L: 58 mm	46 – 68 mm [151, 152, 154, 155]
	CSA: 20.4 mm^2	18 – 29.0 mm^2 [151, 153]
Patellar ligament	L: 46.0 mm	36.5 – 58.5 mm [156-158]
	CSA: 119.0 mm^2	90 – 128.6 mm^2 [159, 160]
Quadriceps tendon†	L: 81.9 mm	67 – 97 mm [156, 161]
	CSA: 265 mm^2	213 ± 20 mm^2 [162]*
Calcaneal tendon†	L: 247 mm	200 – 280 mm [163, 164]
	CSA: 58.9 mm^2	49 – 75 mm [165, 166]

ACL Ref 148: Harner, C., et al., *Quantitative Analysis of Human Cruciate Ligament Insertions.* J. Arthrooscopic and Rel. Surg., 1999. **15**(7): p. 741-749.

PCL Ref 148 and 151: Takahashi, Y., et al., *Development and Validation of the Finite Element Model for the Human Lower Limb of Pedestrians.* Stapp Car Crash J, 2000. **44**.

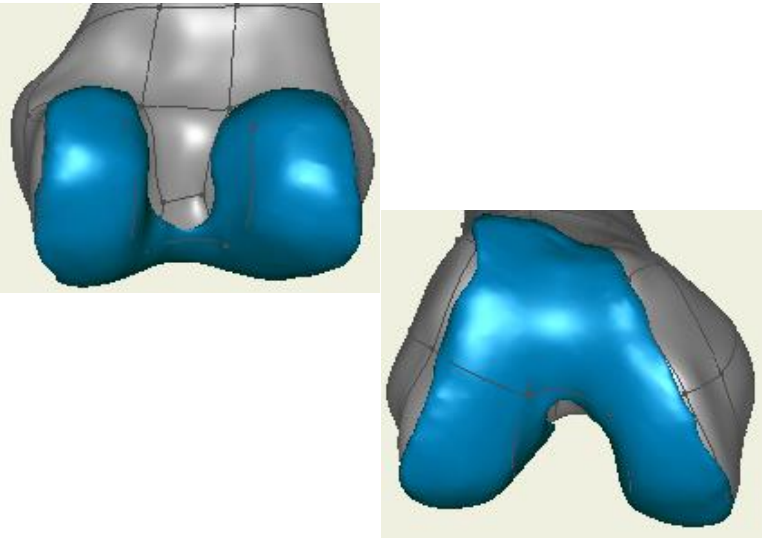
Knee Articular Cartilage

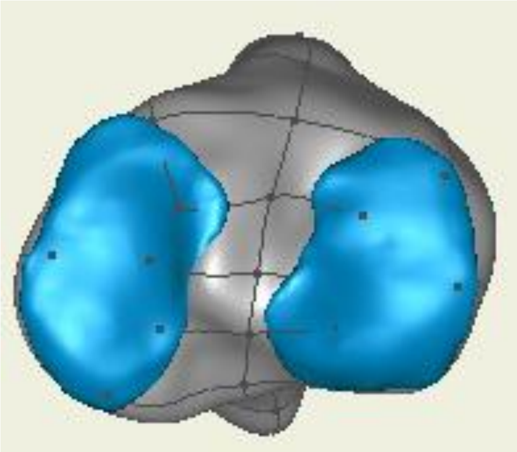




www.bartleby.com

Femur Cartilage | Tibia Cartilage | Patella Cartilage





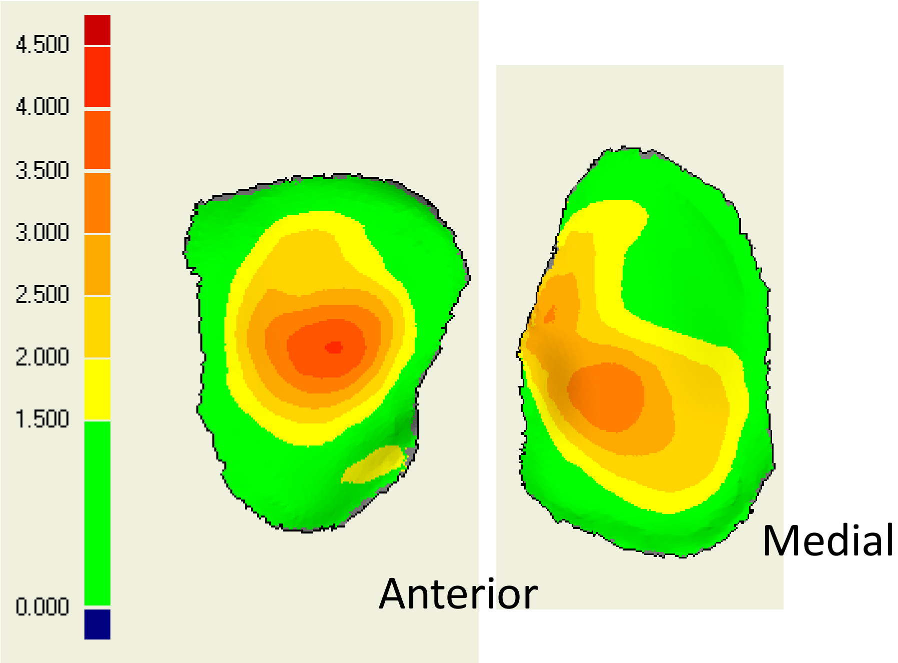
	Femur Cartilage	Tibia Cartilage		Patella Cartilage
Measured Values	---	medial	Lateral	---
Volume (mm^3)	13680	1988	1804	3487
Avg Thickness (mm)	2.18	1.71	1.63	2.46
Ref 1 Literature Values		Average - Both Sides		
Thickness (mm)	2.14+/-0.53	2.38+/-0.90		3.08+/-0.94
Ref 2 Literature Values		medial	Lateral	
Volume (mm^3)	15000+/-2600	1920+/-490	2550+/-510	3560+/-480
Thickness (mm)	1.88+/-0.29	1.36+/-0.15	1.76+/-0.27	2.39+/-0.42

Good thickness and volume agreement between CAD and Lit

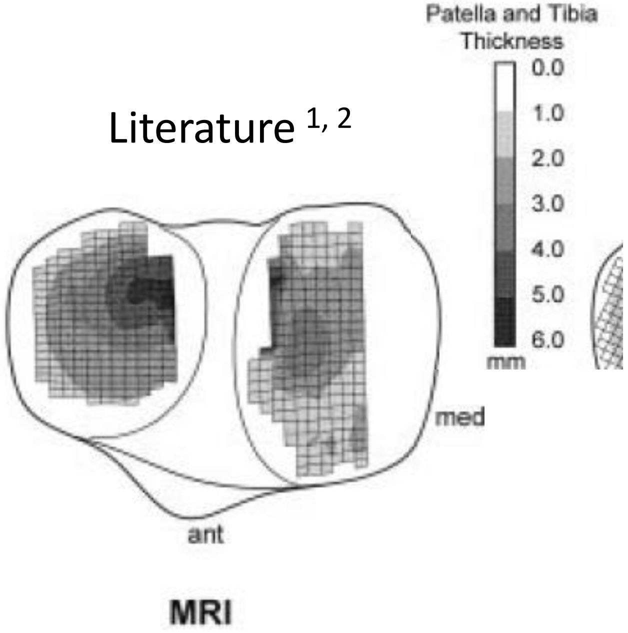
[1] Cohen et al., Osteoarthritis and Cartilage, 1999; [2] Faber et al., Skeletal Radiol, 2001

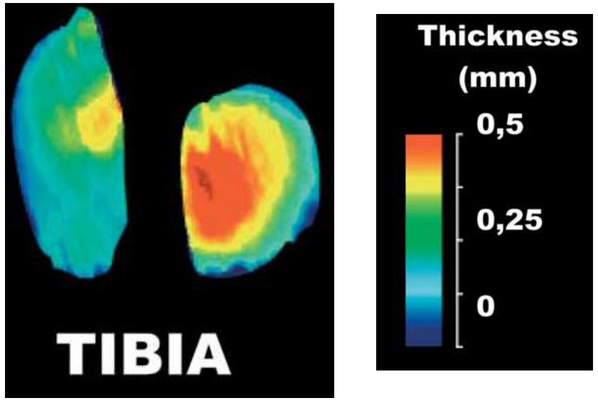
Tibial Plateau Cartilage vs. Literature

CAD



Literature [1, 2]



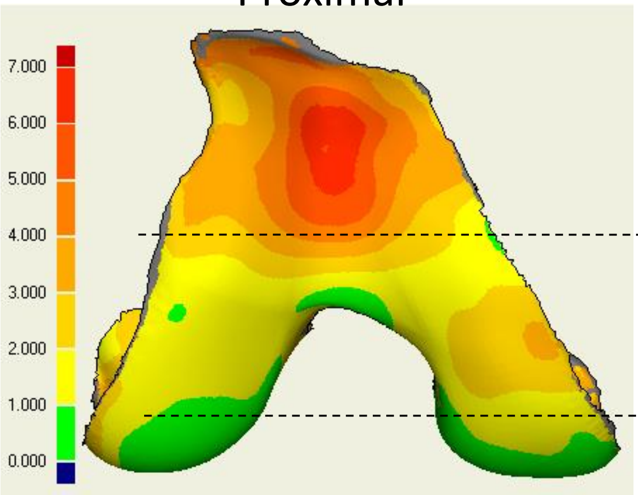


Good match between CAD and Literature thickness distribution

[1] Zohara et al., J Osteoarthritis Res Soc Int, 1999; Raynauld et al., Osteoarthritis and Cartilage, 2003

Femur Cartilage vs. Literature

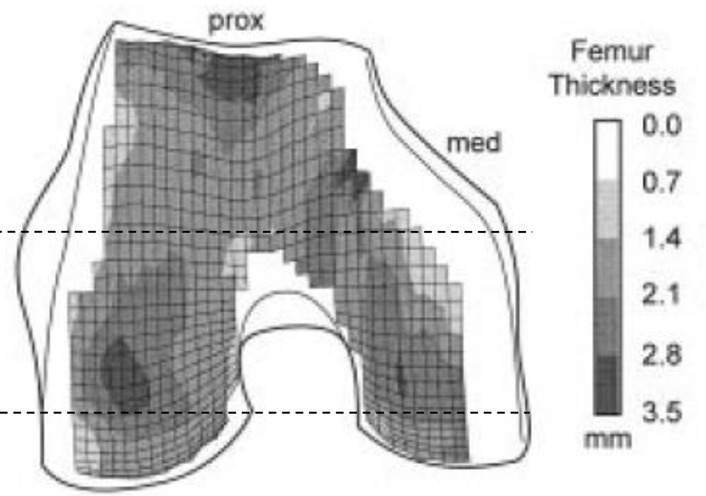
Proximal

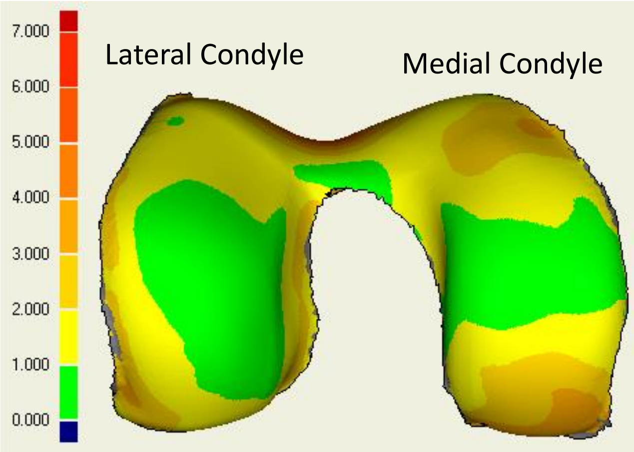


Trochlea cartilage

Condylar cartilage

Literature [1]





Posterior

Good match between CAD and Literature thickness distribution

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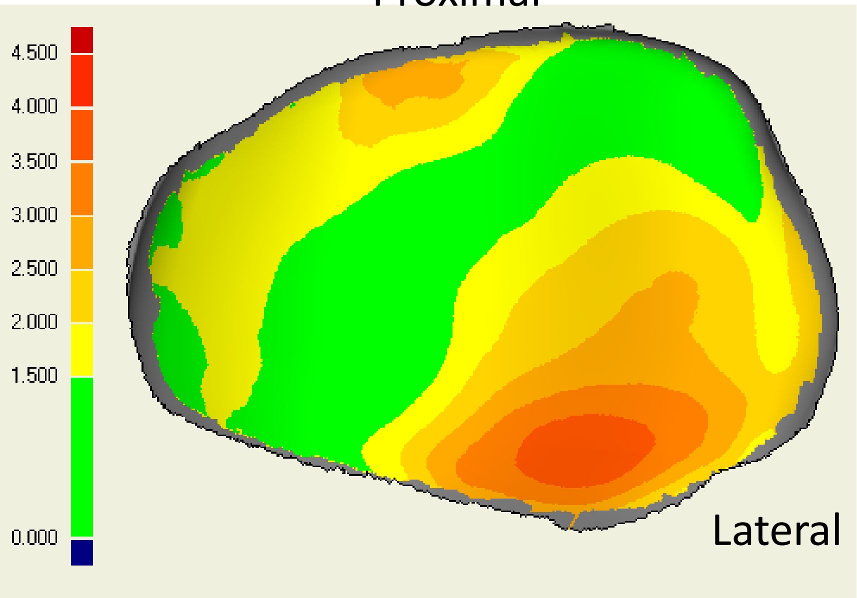
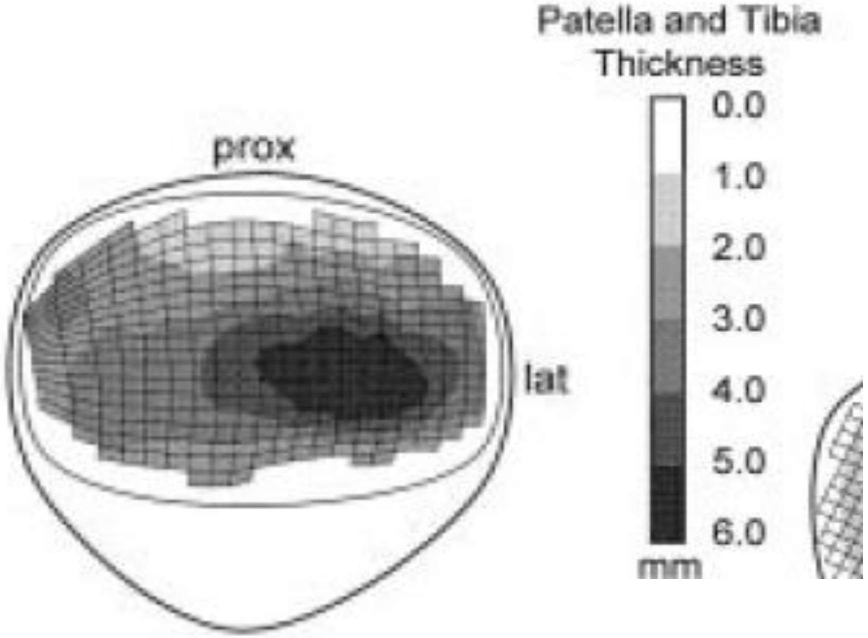
[1] Zohara et al., J Osteoarthritis Res Soc Int, 1999

Patellar Cartilage vs. Literature

Proximal



Literature [1]

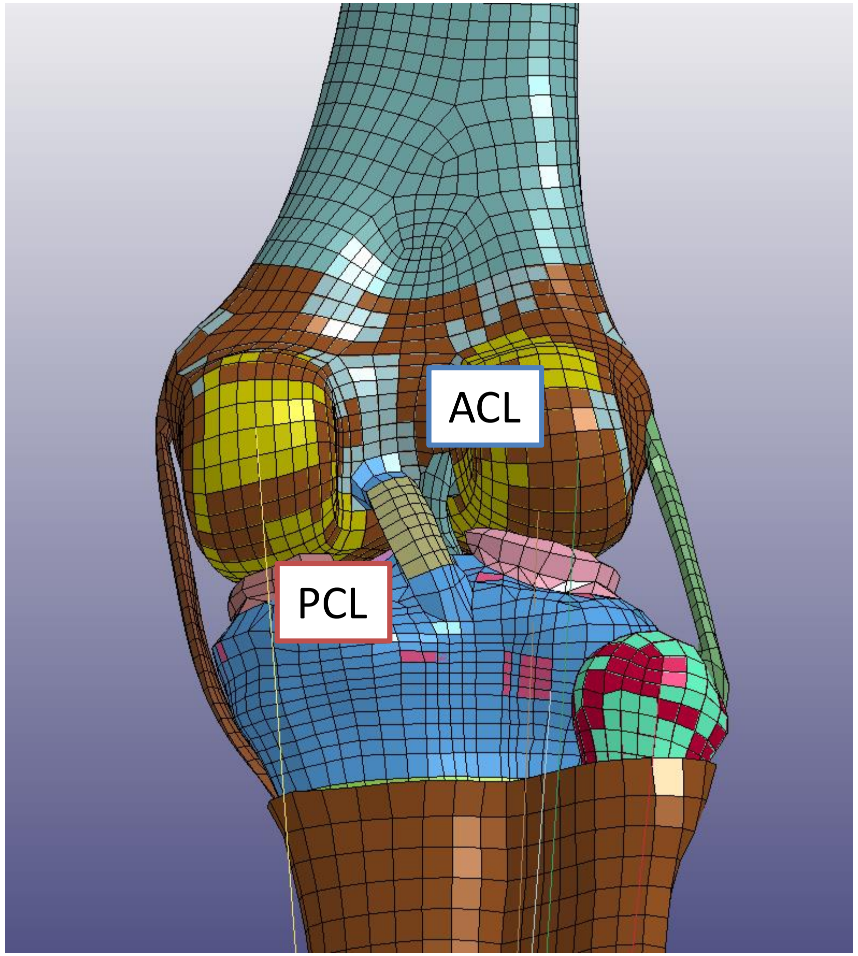


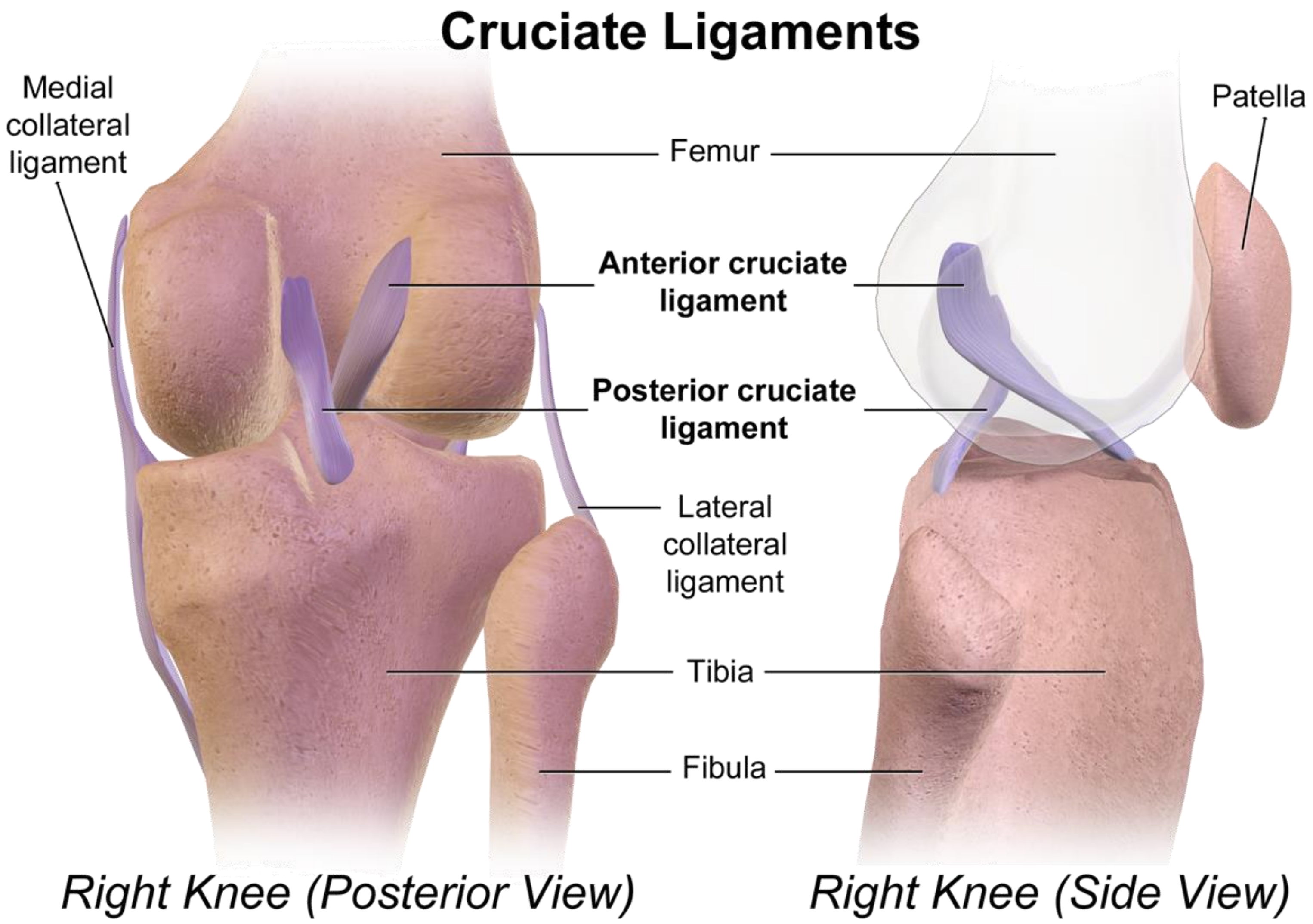
Good match between CAD and Literature thickness distribution

[1] Zohara et al., J Osteoarthritis Res Soc Int, 1999

Diagram of the knee vs. the M50-PS

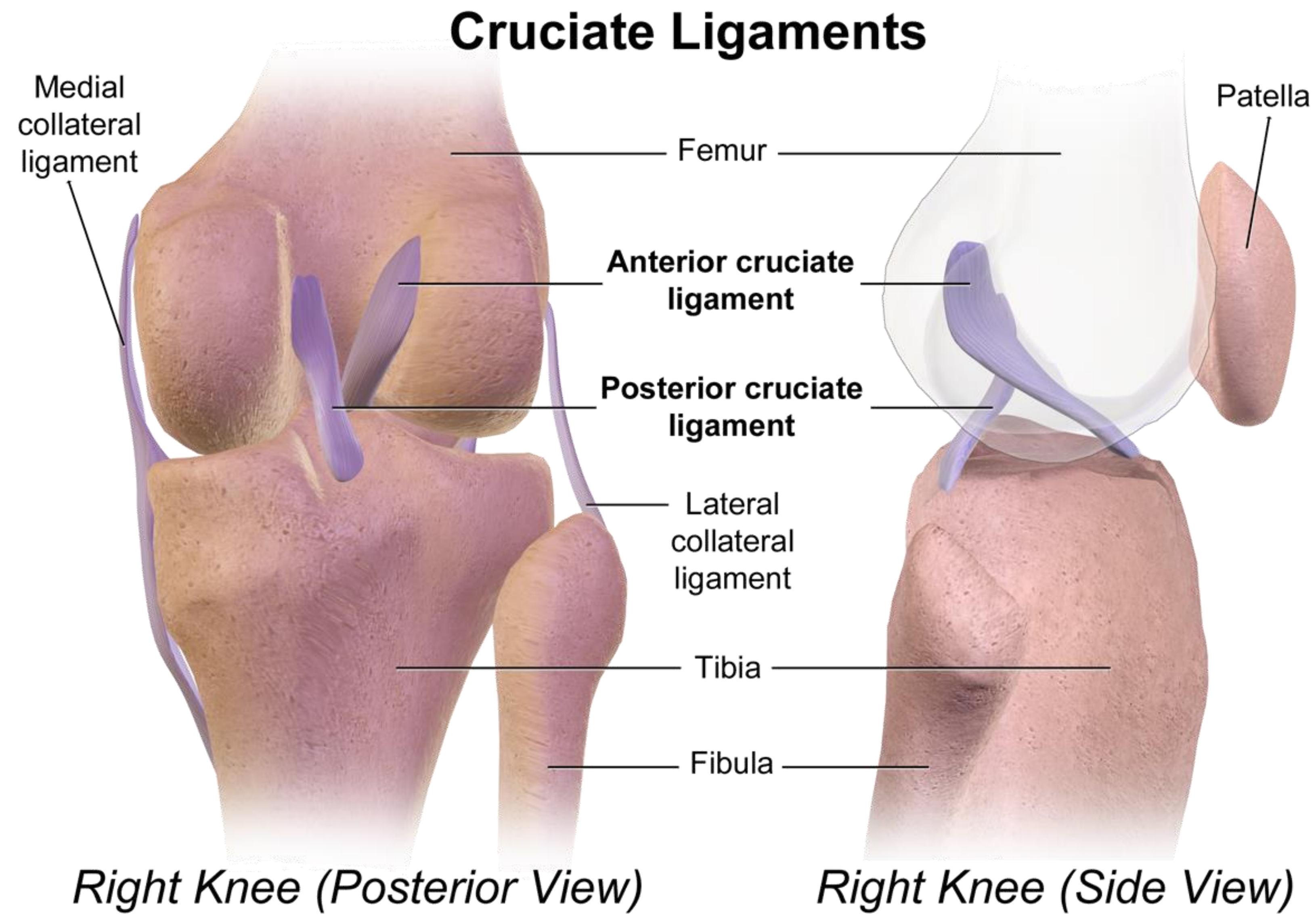
Posterior View of Right Leg



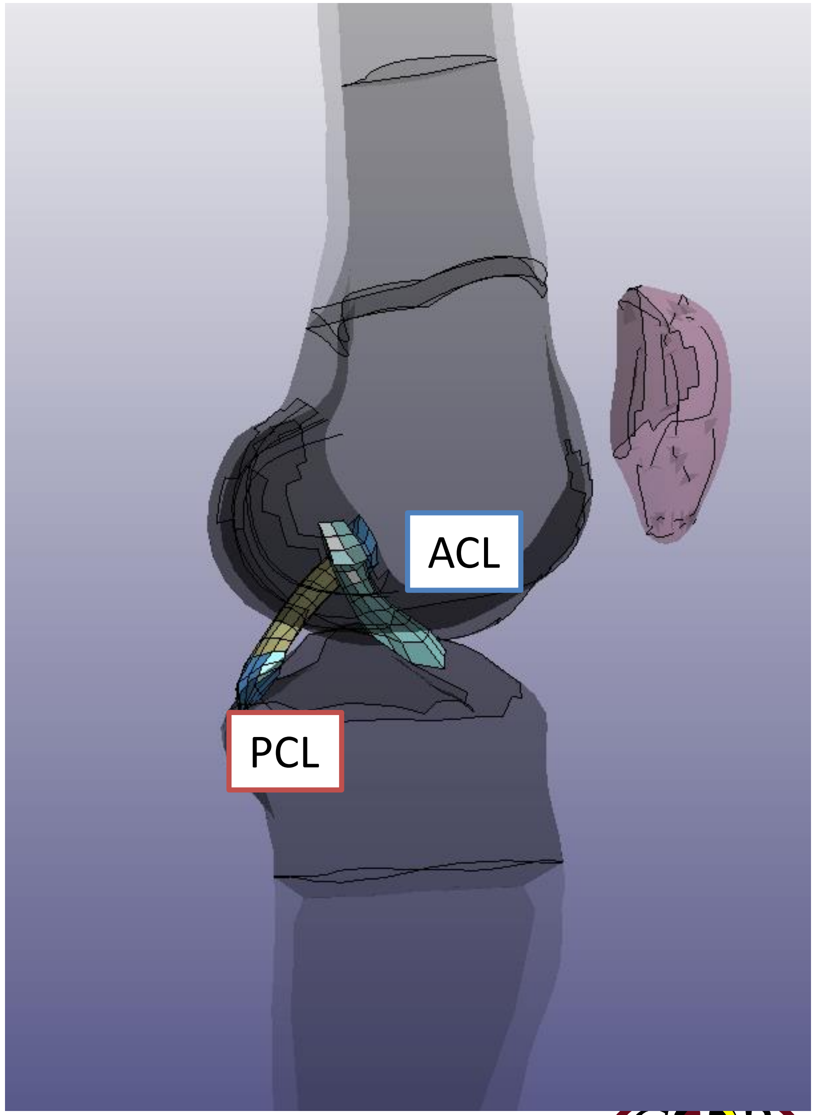


https://www.wikiwand.com/en/Cruciate_ligament

Diagram of the knee vs. M50-PS



Lateral View of Right Leg



https://www.wikiwand.com/en/Cruciate_ligament

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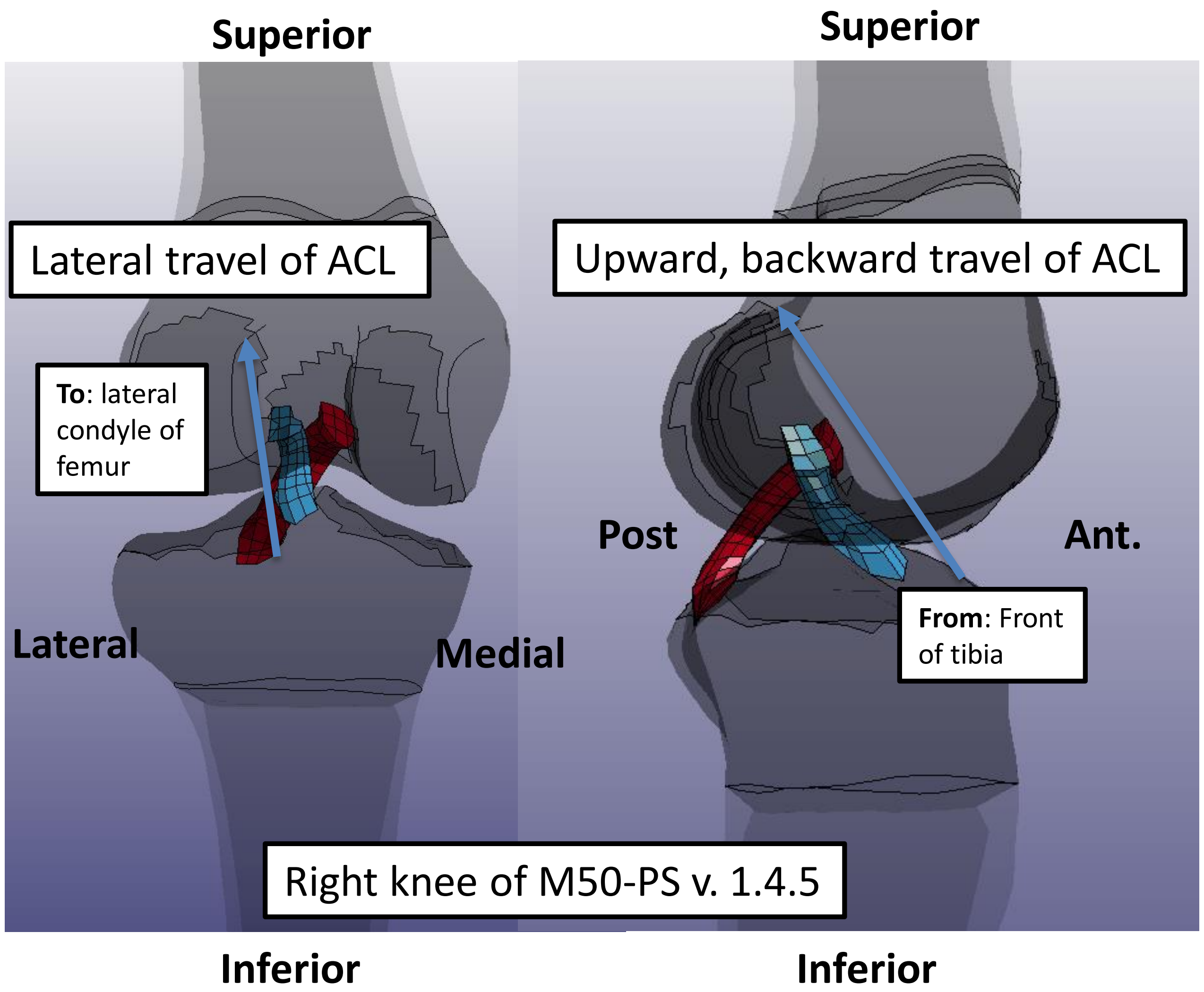
Description of ACL from Gray's Anatomy

- **"The ACL (Blue)** is attached to the depression in front of the intercondyloid eminence of the tibia, being blended with the anterior extremity of the lateral meniscus; it passes upward, backward, and lateral ward, and is fixed into the medial and back part of the lateral condyle of the femur"

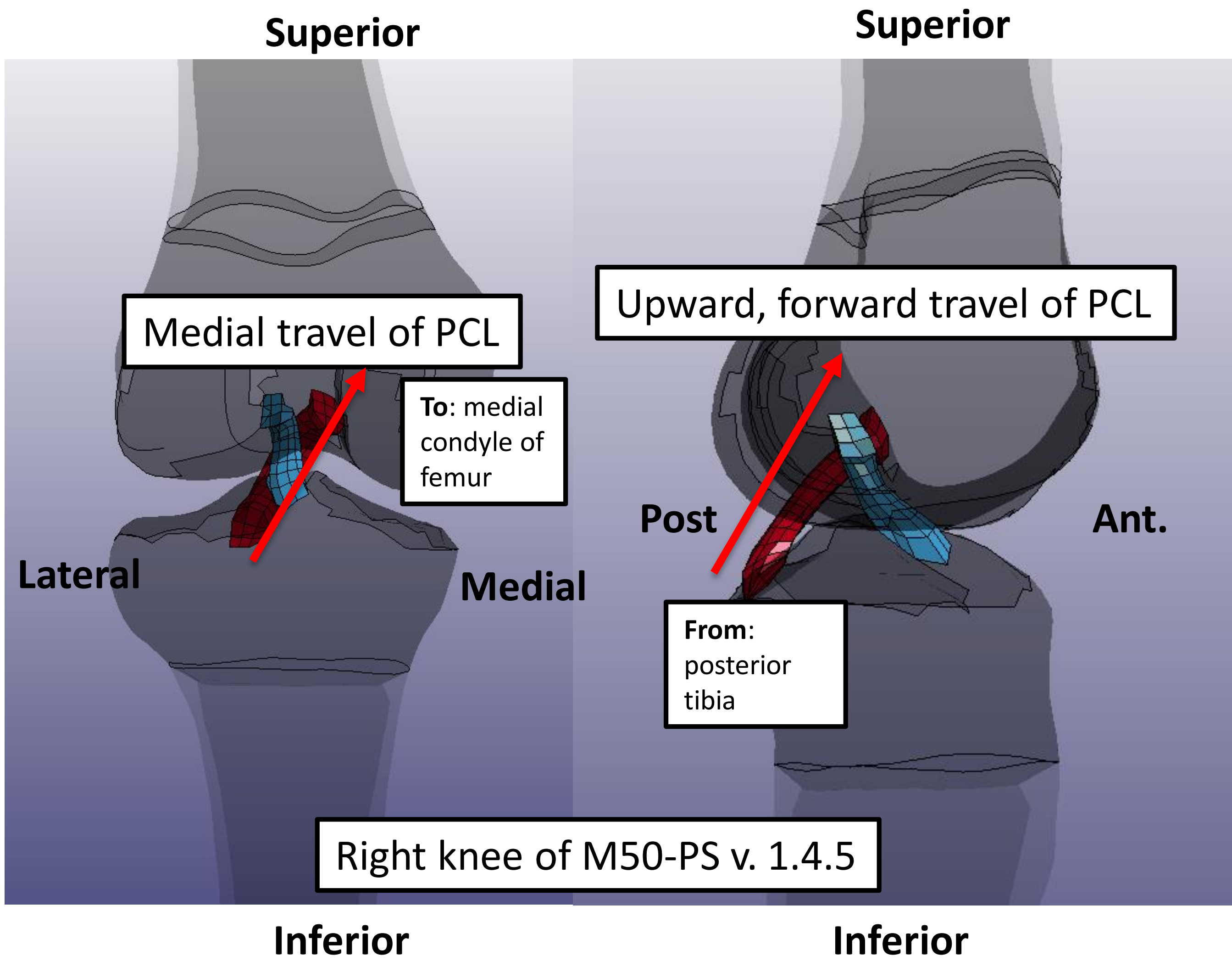
https://www.bartleby.com/107/93.html



Description of MCL from Gray's Anatomy

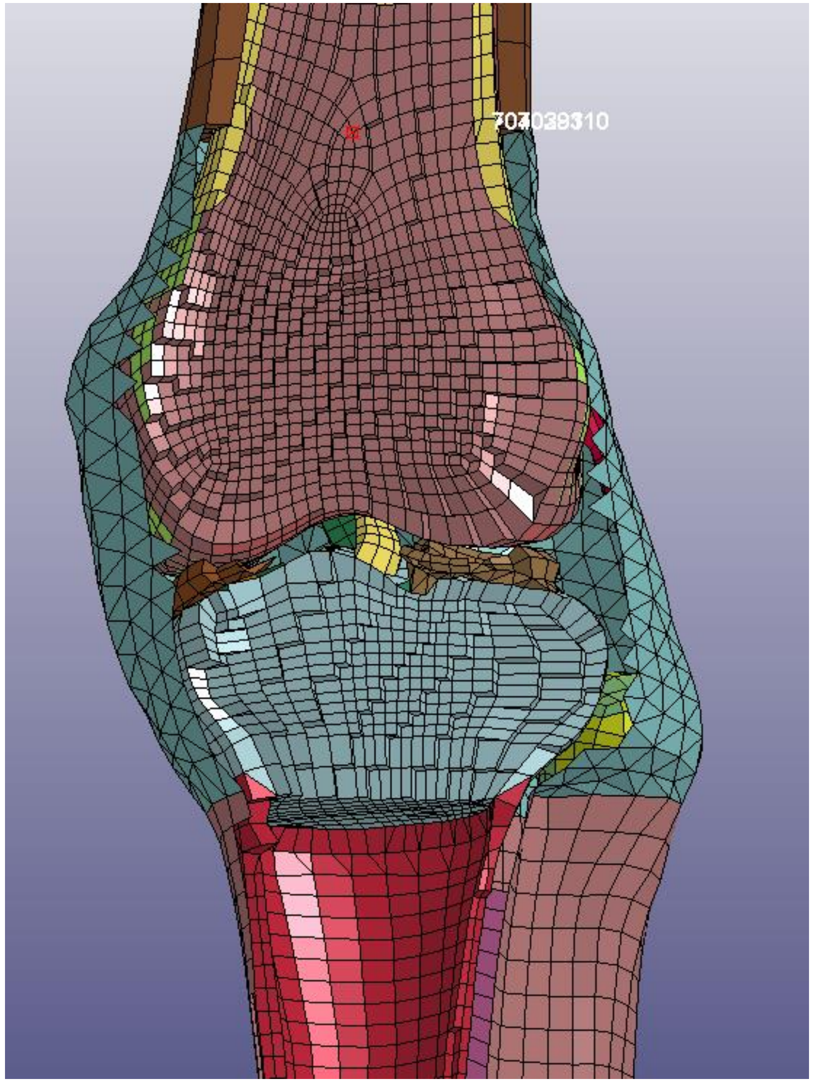
- **The PCL (Red)** is stronger, but shorter and less oblique in its direction, than the anterior. It is attached to the posterior intercondyloid fossa of the tibia, and to the posterior extremity of the lateral meniscus; and passes upward, forward, and medialward, to be fixed into the lateral and front part of the medial condyle of the femur.

https://www.bartleby.com/107/93.html



Knee Interior

- The outer surface of the knee is not an anatomical capsule, rather the “knee interior 2D surface”
- It was made for contact implementation for this simplified knee, this is rationale for including the patella
- The detailed pedestrian model knee follows the knee anatomy



GHBMC M50-PS AND –PS FAMILY IN EURONCAP CERTIFICATION PROCESS

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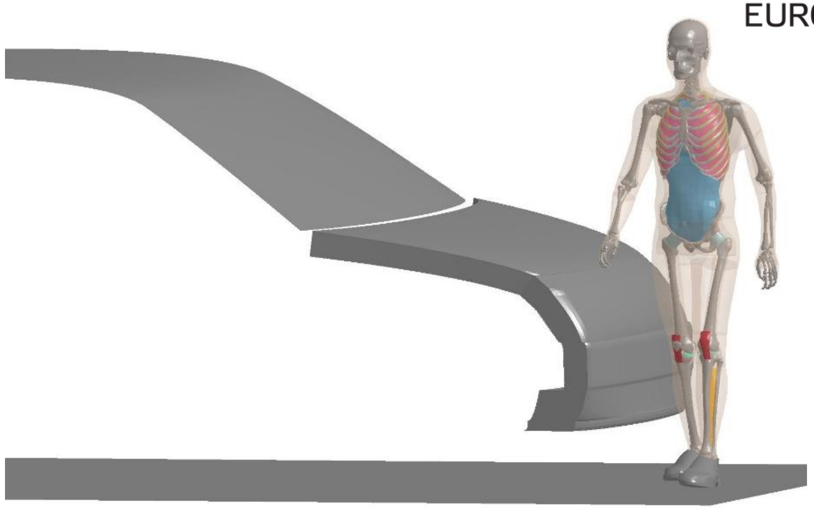
Methods: Euro NCAP Setup

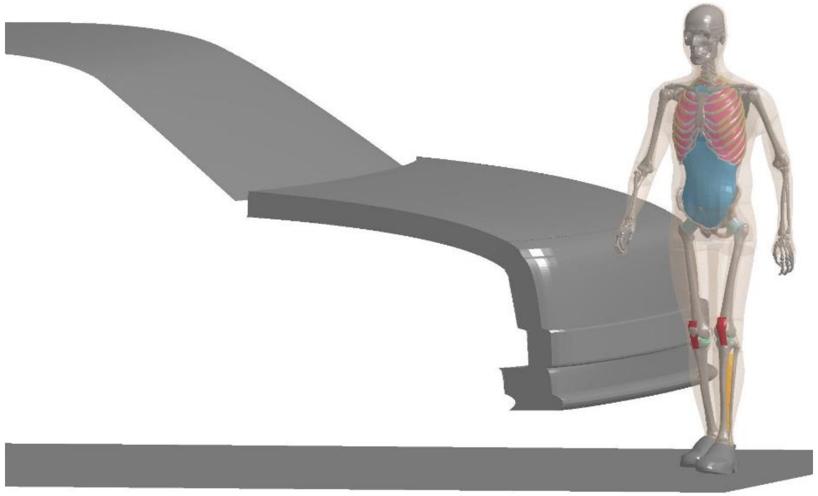
Family Car (FCR)

Multi-Purpose Vehicle (MPV)



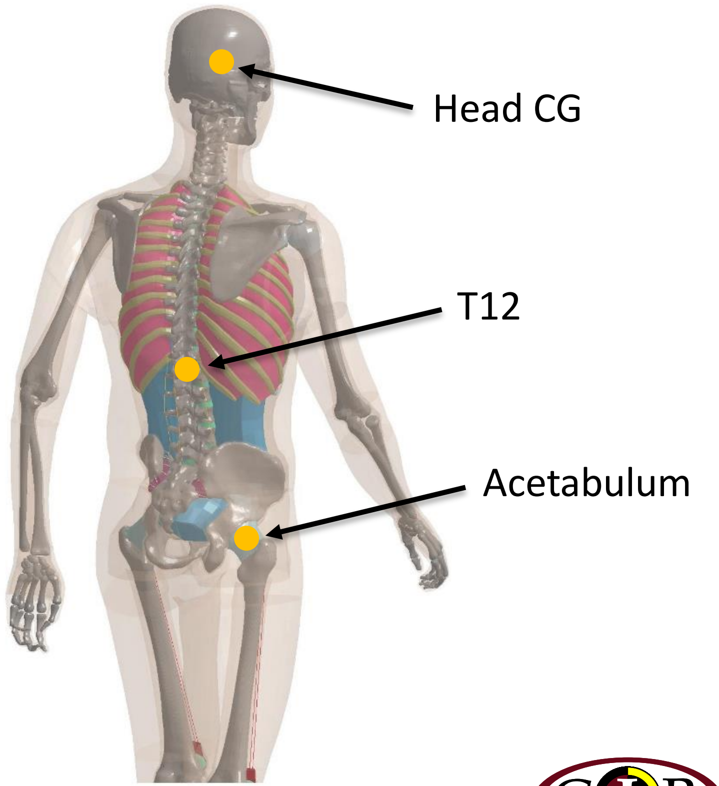
Roadster (RDS)

Sport Utility Vehicle (SUV)



30 kph | 40 kph | 50 kph
4 Vehicle Geometries
12 simulations per HBM
48 Total Simulations

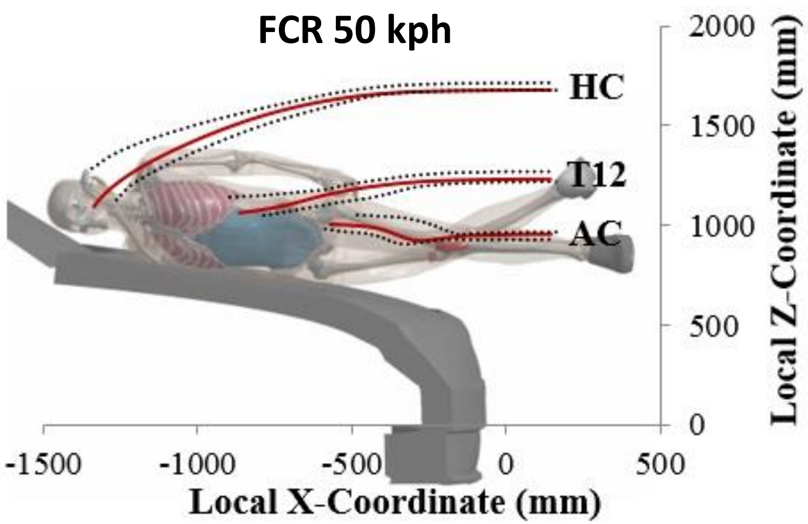
M50-PS Sensor Locations



Development of Generic Vehicles was completed under Coherent Project **(Klug et al. 2017)**

Results: M50-P Certification

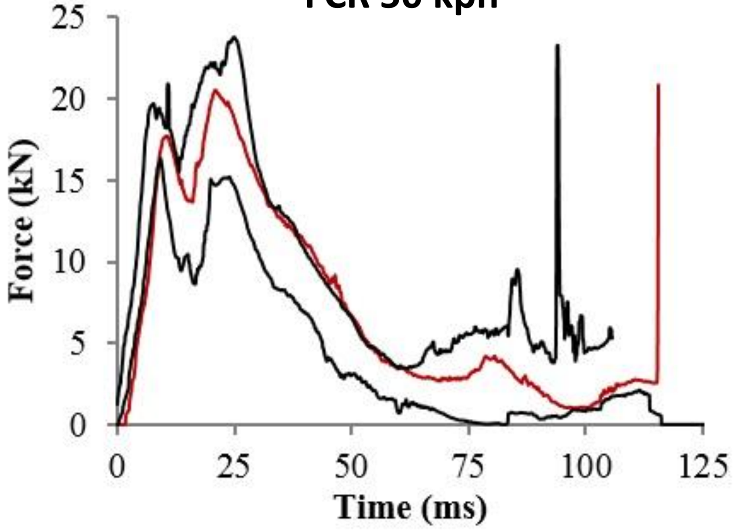
- Pre – Post Simulation Check
- **50th male certification**
  - Kinematic response corridors
  - Time of head impact (HIT)
  - *Force monitored for stability*
- All sizes to be simulated for HIT assessn and stability

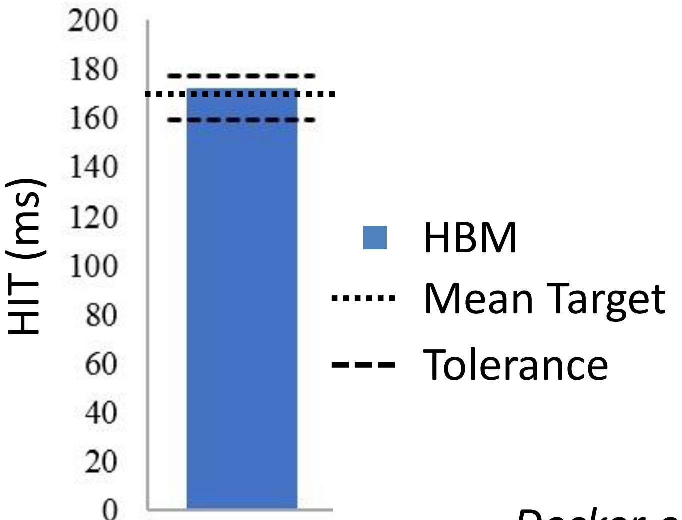


······ Corridors

Corridors created from response data from 18 proposed HBMs for the study

Tolerance : 50 mm





HIT tolerance interval of +3.5% and -7% of mean target

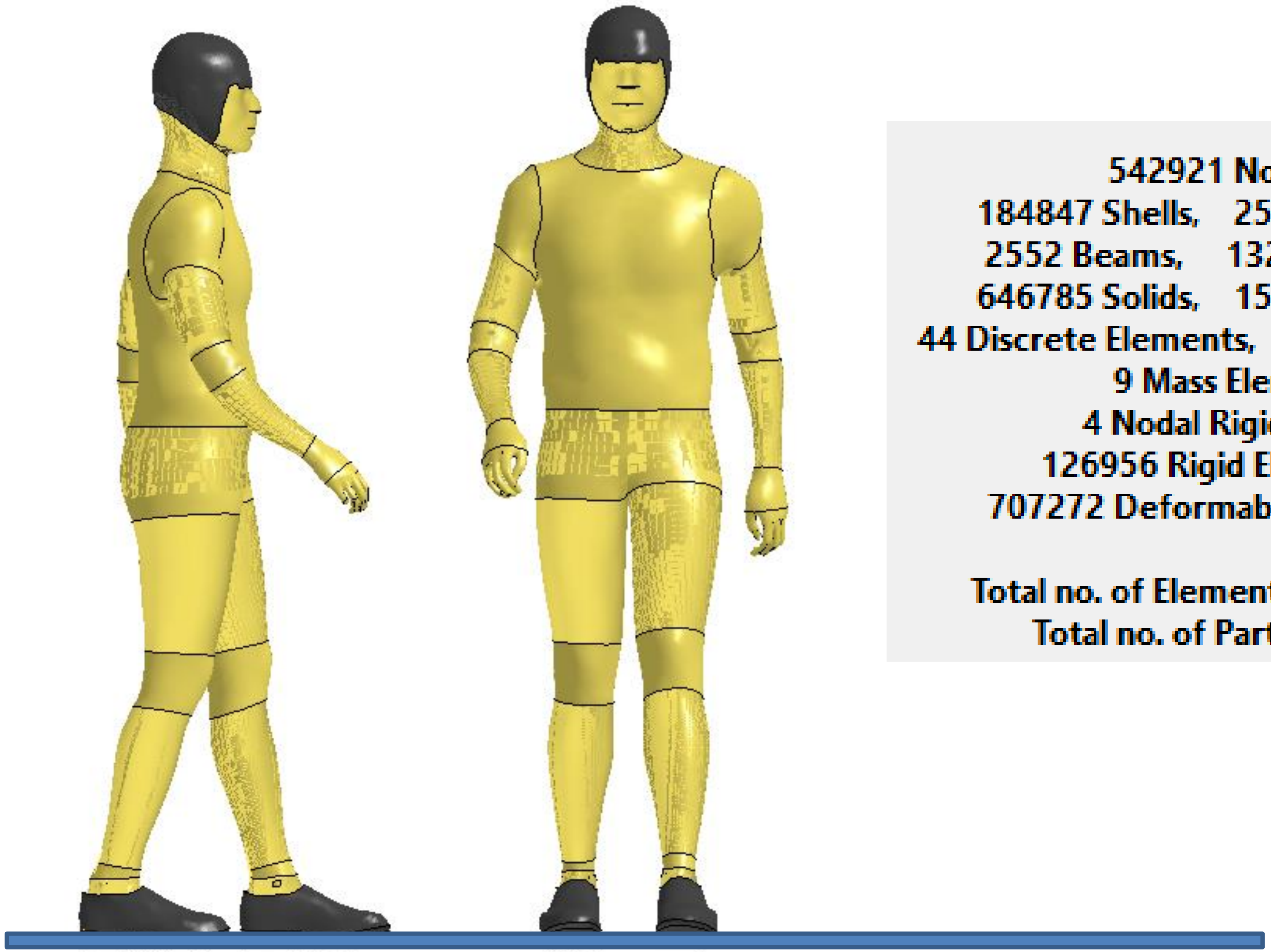
Decker et al. 2019, Traffic Inj Prev

MODELING SUPPORT SLIDES

Pedestrian Modelling

1. GHBMC Pedestrian Model (PS- Simplified Version) - Overview
2. GHBMC Model Validation
3. GHBMC Knee Model – Component Validation
4. GHBMC Knee Model – CTP Validation

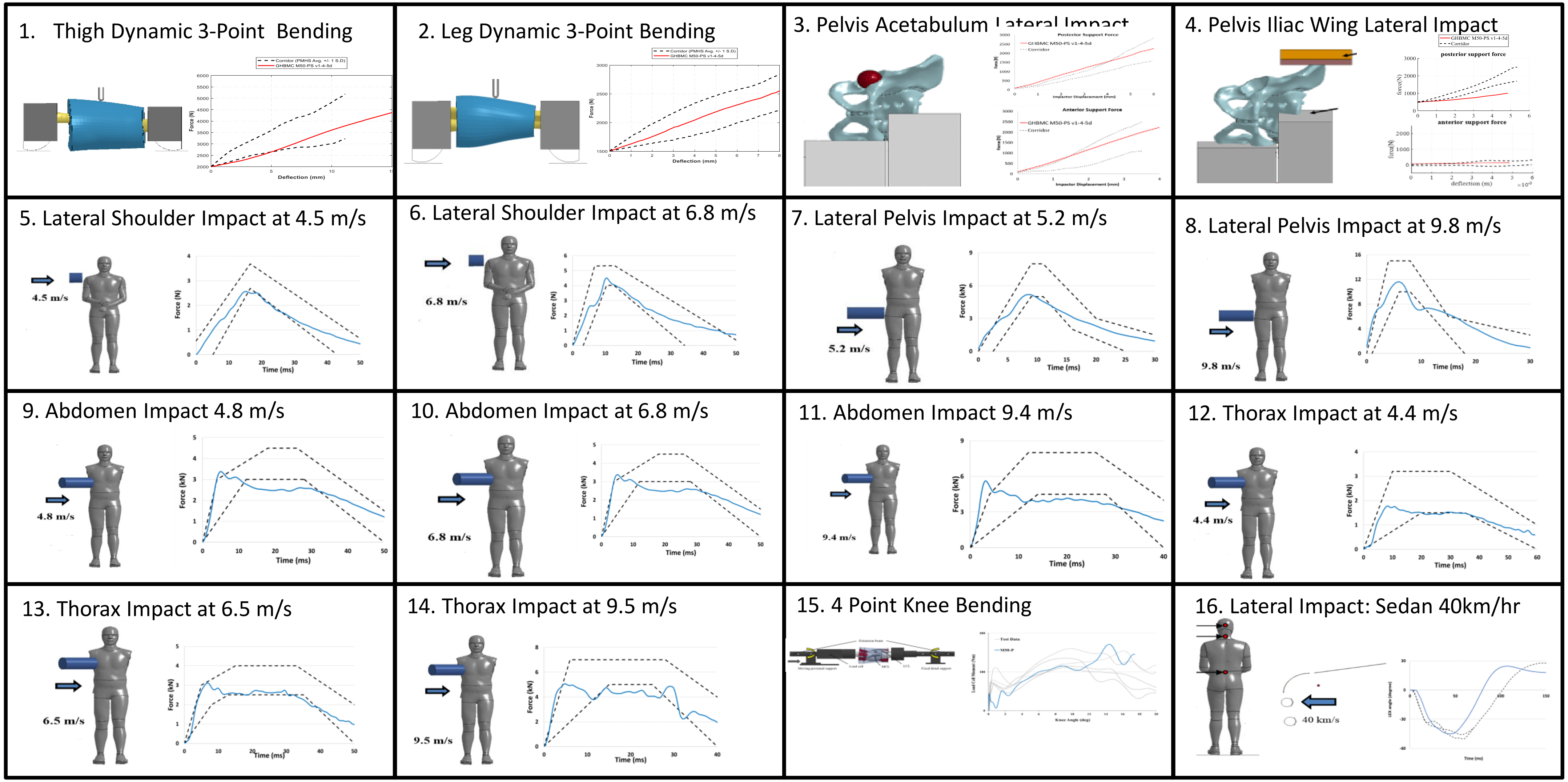
GHBMC 50th PS Model



542921 Nodes
184847 Shells, 253 Shell Parts
2552 Beams, 132 Beam Parts
646785 Solids, 158 Solid Parts
44 Discrete Elements, 44 Discrete Parts
9 Mass Elements
4 Nodal Rigid Bodies
126956 Rigid Elements
707272 Deformable Elements

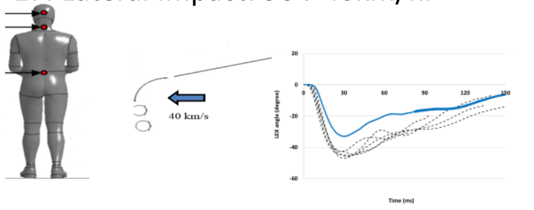
Total no. of Elements = 834228
Total no. of Parts = 590

GHBMC Pedestrian Validations (1)

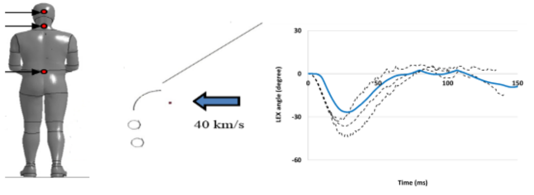


GHBMC Pedestrian Validations (2)

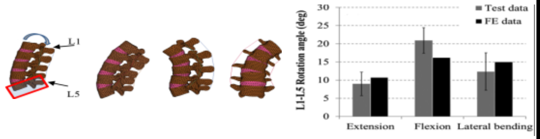
17. Lateral Impact: SUV 40km/hr



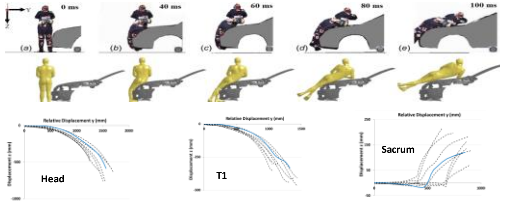
18. Lateral Impact: Van 40km/hr



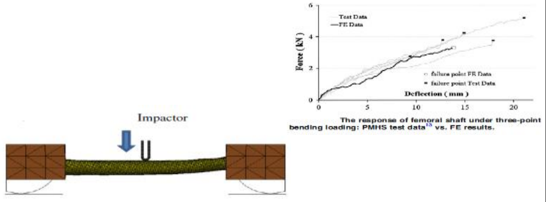
19. Lumbar Spine Bending



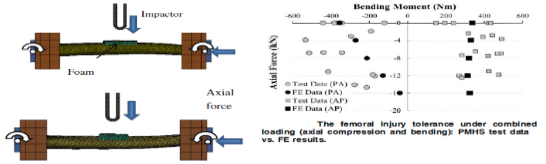
20. Kerrigan lateral impact



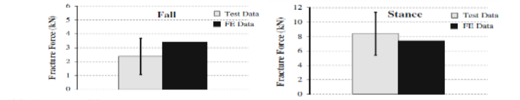
21. Femur 3 Point Bending -Unloaded

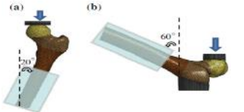


22. Femur bending under Anterior/Posterior Loading



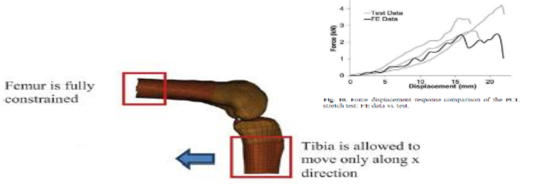
23. Femur Head Fracture In Stance and Fall



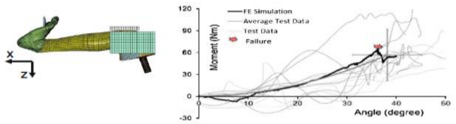


The fracture locations and the fracture force companions of the proximal femur compression tests and FE simulations in both (a) stance and (b) fall configurations

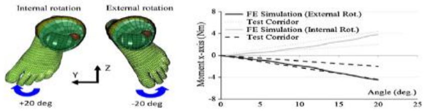
24. PCL Stretch Test



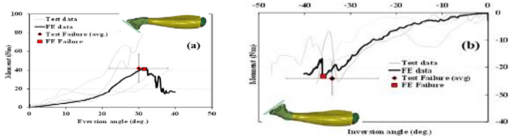
25. Dorsiflexion loading at 30ms



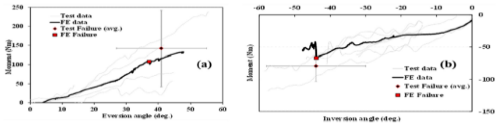
26. Foot rotation



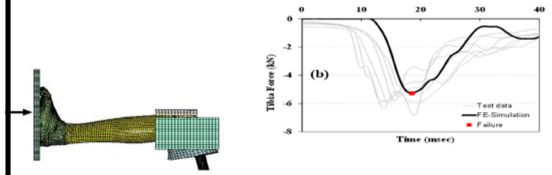
27. Foot-Ankle-Leg Inversion/Eversion Loading



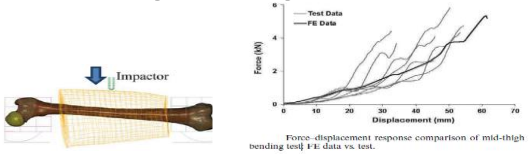
28. Foot-Ankle-Leg Inversion/Eversion Loading and Axial Loading



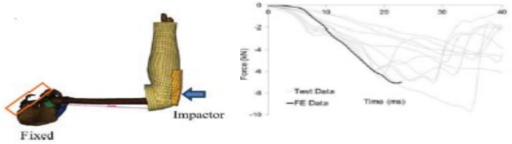
29. Foot-Ankle-Leg Axial Impact



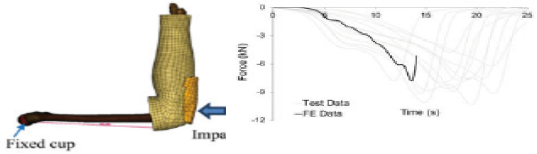
30. Mid Thigh Bending Test



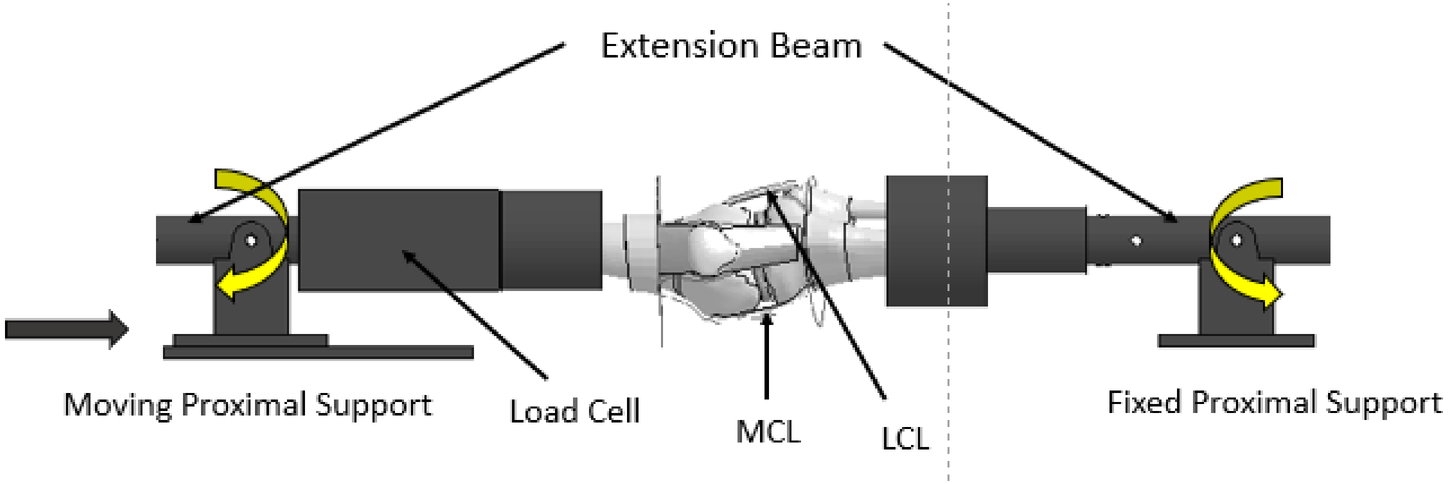
31. Knee-Thigh-Hip Impact

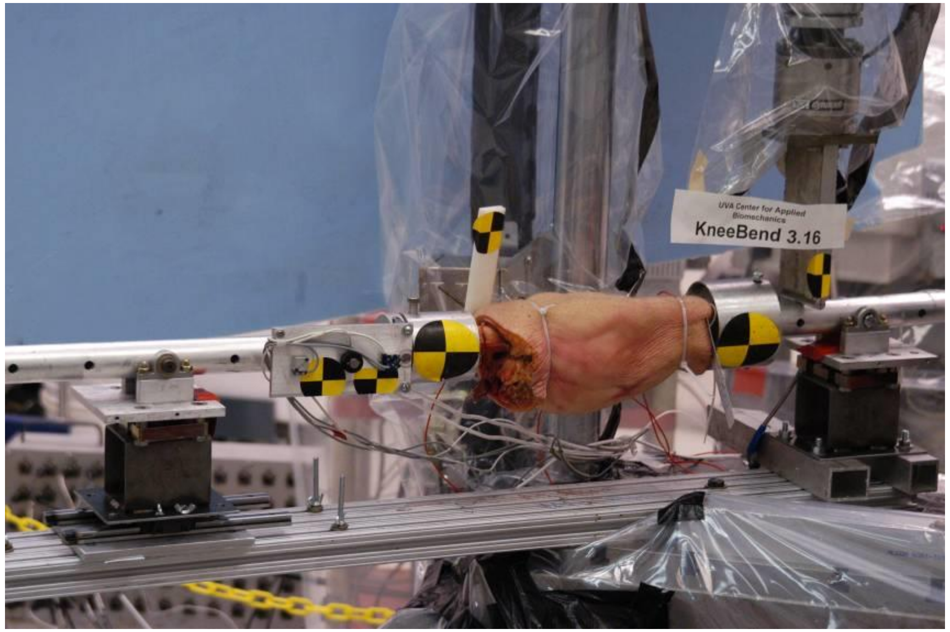


32. Knee-Thigh Impact



Validation: Lower extremities (knee joint)

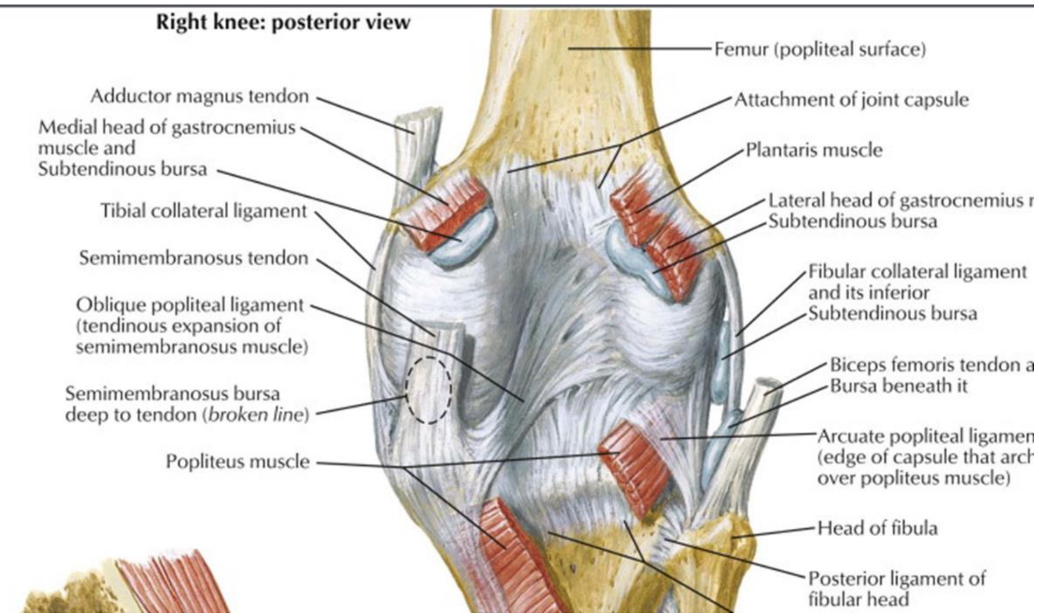


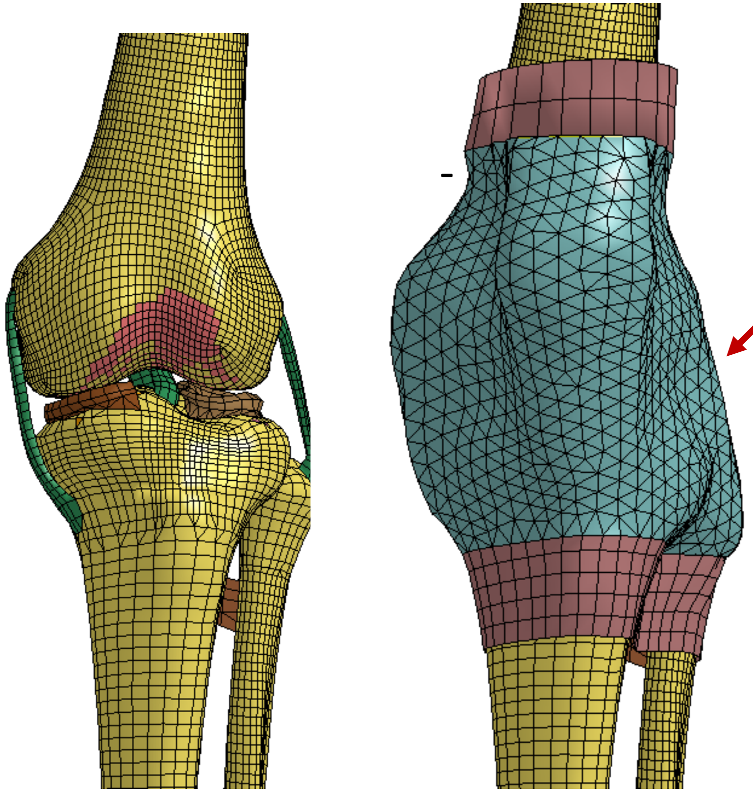


- Knee joint was loaded under valgus bending[1]
- Extension beams rotated about 1 °/ms (approximately 40 km/h impact velocity)
- **Bending moment vs degree** was recorded at the load cell

[1] Bose et al. 2008

Knee FE Model

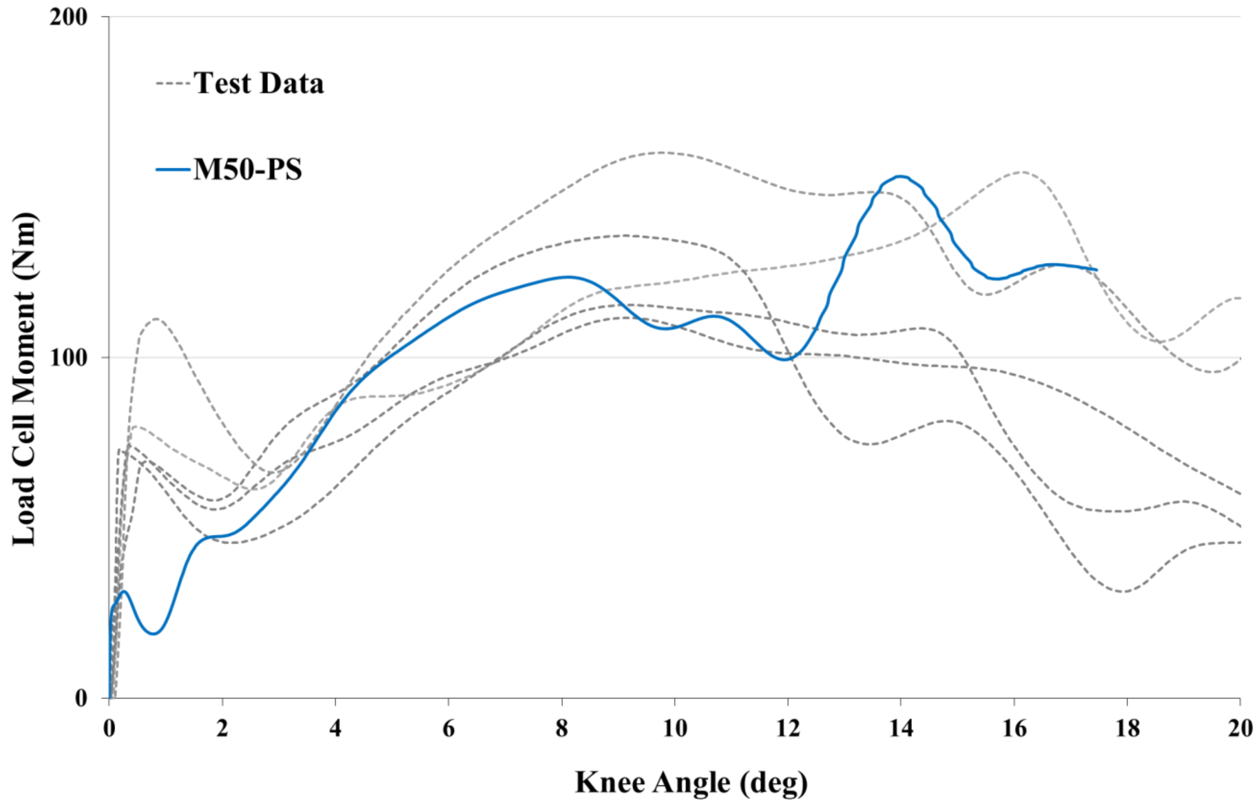




The part **Knee-Interior_2D** is not designed to simulate the knee capsule, but to globally represent multiple missing anatomical components (ligaments, tendons, capsule, synovial liquid) in the knee.

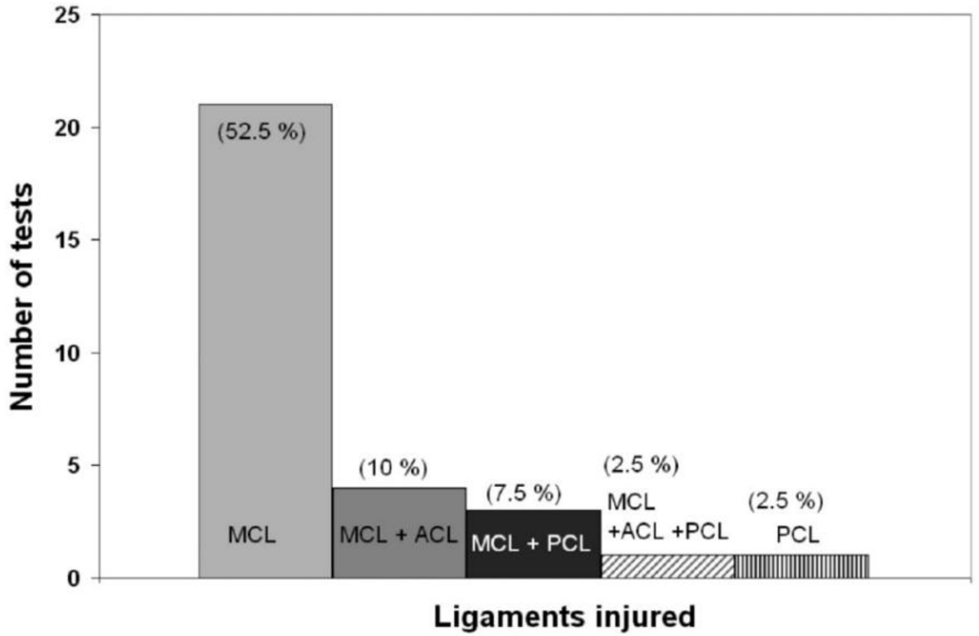
The thickness and material (0.2 mm / 850 MPa) properties of this part are not relevant. They are just obtained from calibration and depend of the Boundary Conditions chosen for this part.

Lower extremities (knee joint)

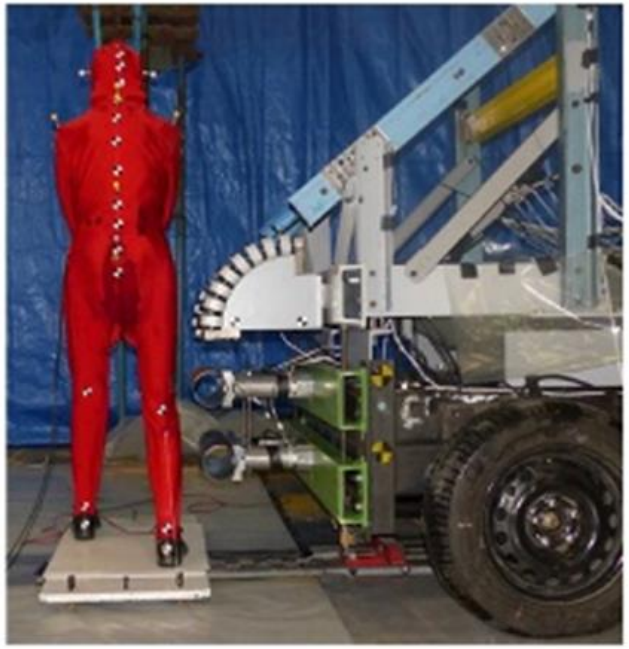


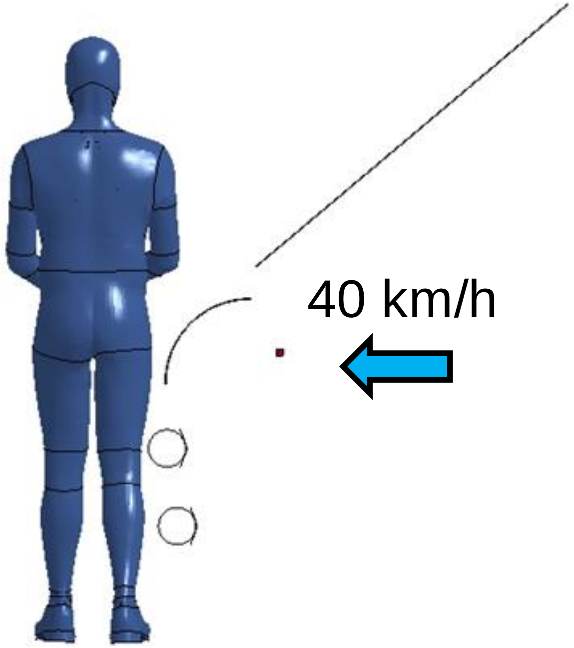
MCL: Medial collateral ligament
ACL: Anterior cruciate ligament

- **Similar trend** as the curves corresponding to PMHS tests[1]
- **ACL** and **MCL** were **ruptured**
  - MCL (52.5 %), MCL+ACL (10 %)[1]

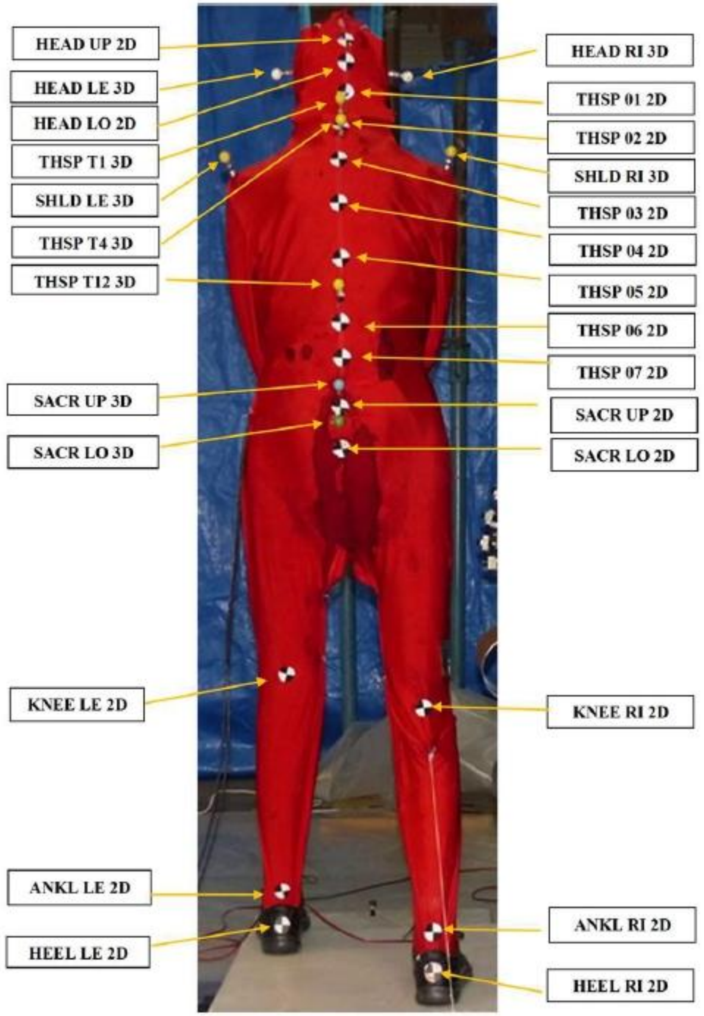


LAB PMHS Test Data



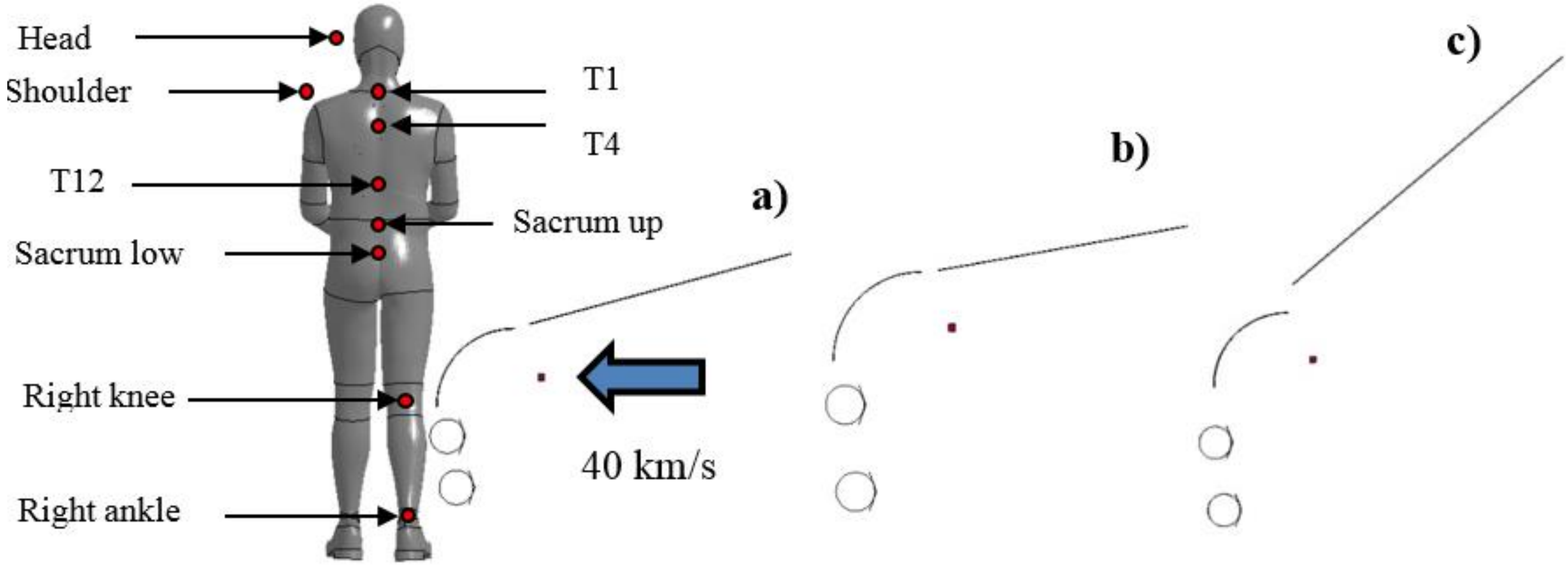


Experimental and simulation set-up[1]



[1] Song et al. 2017

LAB PMHS Test Data



Whole-body validation setup with simplified generic vehicles; a) sedan (3), b) SUV (5) and c) Van (3)

PMHS Knee Angle Update

A: Femur Head
B: Greater trochanter Bone Surface

Goal: Calculate Knee Angle in PMHS tests using the Femur Head as a reference point rather than the bone surface of the Greater Trochanter

Available Data:

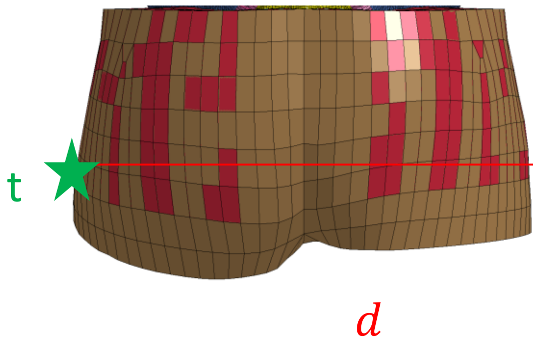
- Initial Coordinates
    - Skin surface of left & right Greater Trochanters (GT)
- Continuous Coordinates
    - Two sacral points
    - Both Knees
    - Both Ankle

Key Assumptions: Sacrum and femur head are effectively rigidly connected, suggesting the distance between them doesn't change

Procedure:

1. Estimate coordinates of femur head using PMHS hip width and dimensions from GHBMC M50P-v1.6 model
2. "Track" femur head location using coordinates of sacrum

Step 1. Estimate location of Femur Head

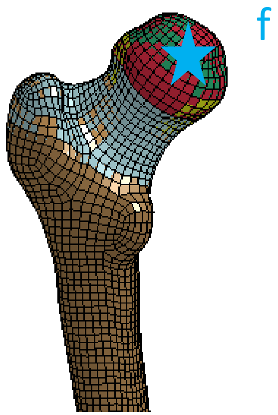


1. Calculate the ratios ($\boldsymbol{\gamma_x}, \boldsymbol{\gamma_y}$) of outer hip diameter **(d)** to horizontal and vertical distance from the greater trochanter skin surface (**t**) to the tip of the femur head (**f**) using dimensions from the GHBMC M50P-v1.6 model.

$$\frac{f_x - t_x}{d} = \gamma_x = 0.31 \qquad \frac{f_z - t}{d} = \gamma_z = 0.10$$

2. Estimate PMHS femur head initial coordinates (**F**) using the initial location of the greater trochanter skin surface (**T**) and hip width (**D**)

$$F_x = D * \gamma_x + T_x \qquad F_z = D * \gamma_z + T_z$$



Step 2. Track the Femur Head

Reminder: PMHS testing records the location of **two** points on the sacrum

1. Assume the sacrum and femur head are rigidly attached, meaning the length between the two sacral points and the femur head remains constant (L_1, L_2)
2. Plot a circle for both sacrum points moving through time, radius L_1 or L_2
3. The intersection point of the circles is the femur head location

Step 3. Calculate Knee Angle

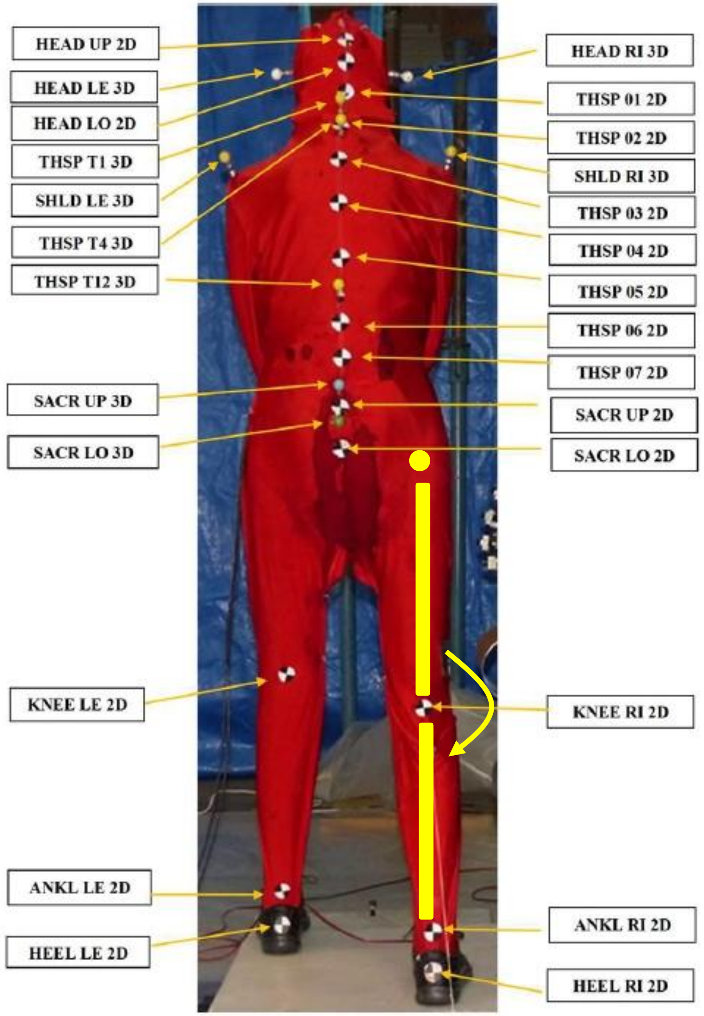
Reminder: PMHS testing continuously records the location of the knee and ankle

1. Create vectors between the Ankle-Knee and Knee-Greater Trochanter
2. Calculate knee angle using the dot product between the two vectors

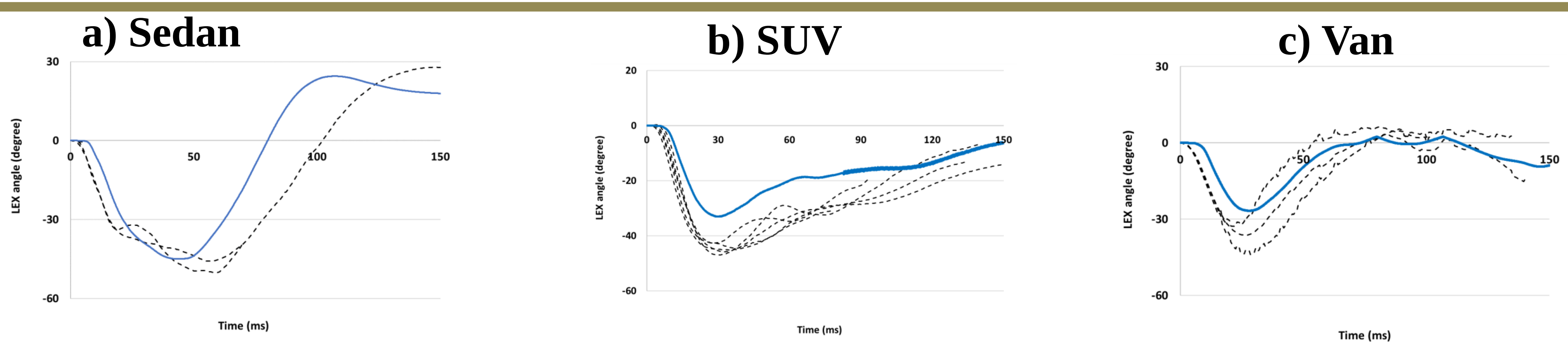
Step 3. Calculate Knee Angle

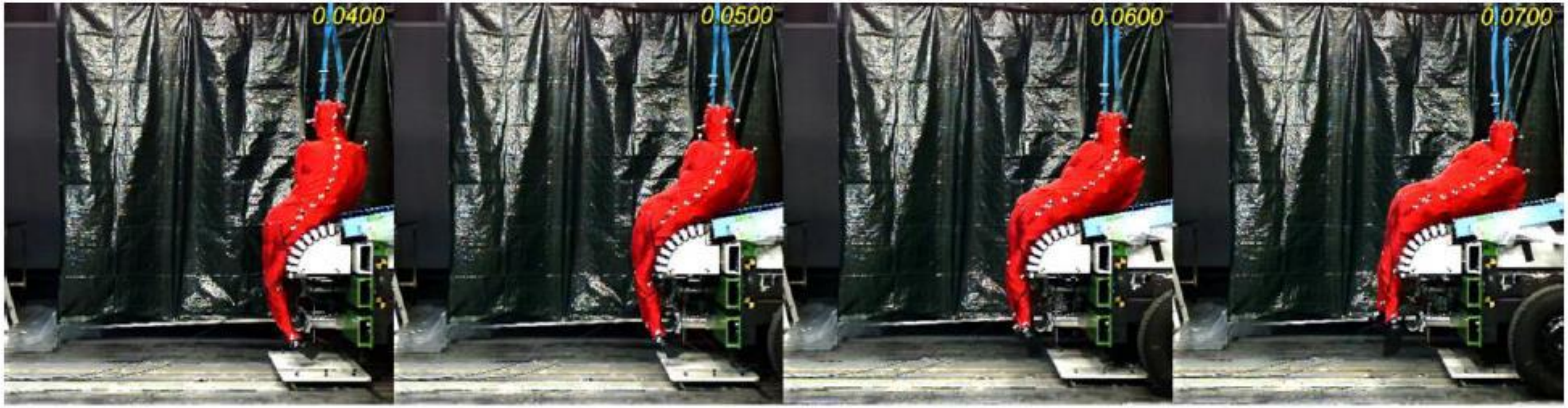
Reminder: PMHS testing continuously records the location of the knee and ankle

1. Create vectors between the Ankle-Knee and Knee-Greater Trochanter
2. Calculate knee angle using the dot product between the two vectors



Model validation – LAB tests/Coronal plane knee angle

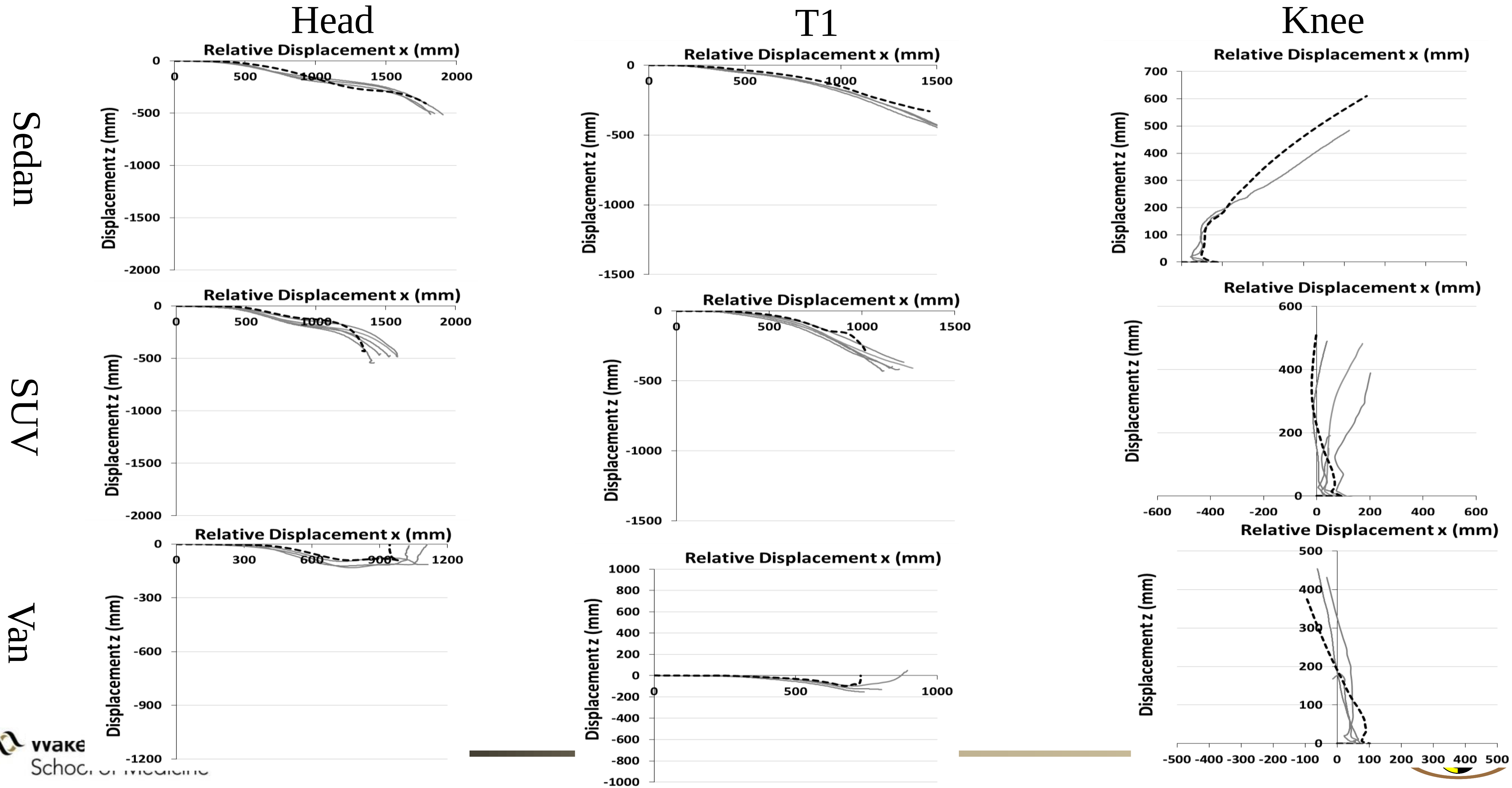




40 ms | 50 ms | 60 ms | 70 ms

Test TIR04-MS700 (SUV configuration – 1/2).

Model validation – LAB tests/Kinematics



Conclusions

- The development process of the GHBMC M50-PS knee used ad hoc scans from recruited subjects
- There is high confidence in the placement of the knee bones and the gaps between bones for soft tissues, models are based on subject upright MRI data
- The ligament placement is based on anatomical texts
- The knee “capsule” in the simplified models was designed for contact control, and is not meant to be anatomically based
- The simplified pedestrian models meet the EuroNCAP pedestrian protocol
- Validation data were presented

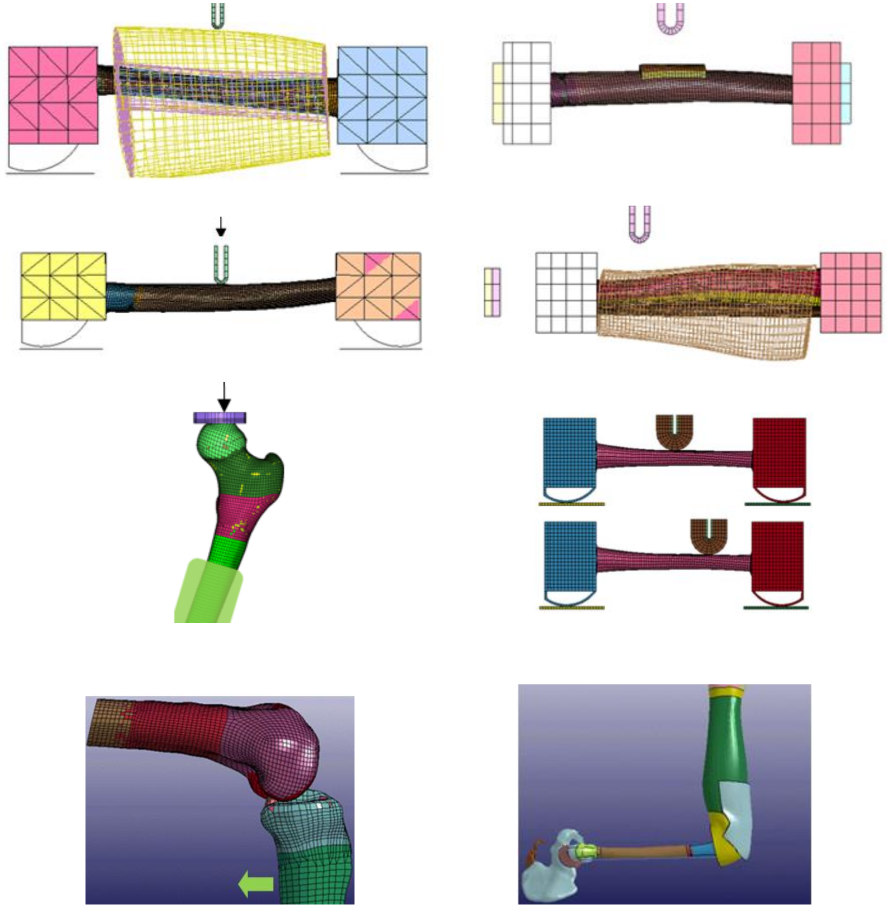
Acknowledgements

- GHBMC and the FBM COE at Wake Forest and Virginia Tech would like to thank IWG-DPPS for and providing us with an opportunity to present today

SUPPLEMENTAL

Lower Extremity Cases

- Thigh Model in Medial Side Impact (Kerrigan et al. 2004)
- Femoral Shaft Model in Bending Load (Funk et al. 2004)
- Femoral Shaft Model in Combined Loading (bending and compression) (Ivarsson et al. 2009)
- Femoral Head Model in Compression Loading (Keyak et al. 1998)
- PCL Model in Knee Shear Loading (Balasubramanian et al. 2004)
- Tibial Shaft Bending in Lateral and Medial Direction
- Limb Model in Knee-Thigh (KT) Impact (Rupp et al. 2003)
- Lower Limb in Knee-Thigh-Hip (KTH) Impact (Rupp et al. 2002, 03)



Regional Validation
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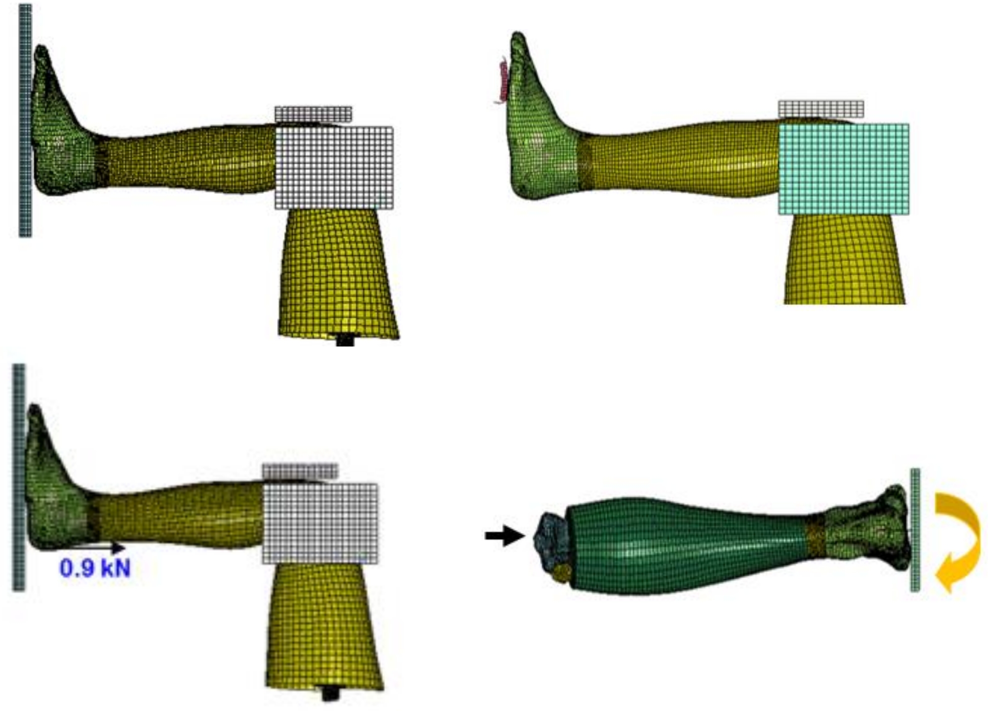
Dr. Jeff Crandall

University of Virginia Engineering

Foot ankle cases

- Foof, Axial Impact Loading (Funk 2000)
- Foot, Dorsiflexion Loading (Rudd 2004)
- Foot, Xversion Loading (Funk 2002)
- Foot, Axial Impact with Achilles Tension (Funk 2000)
- Foot, Combined loading (Funk 2002)



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