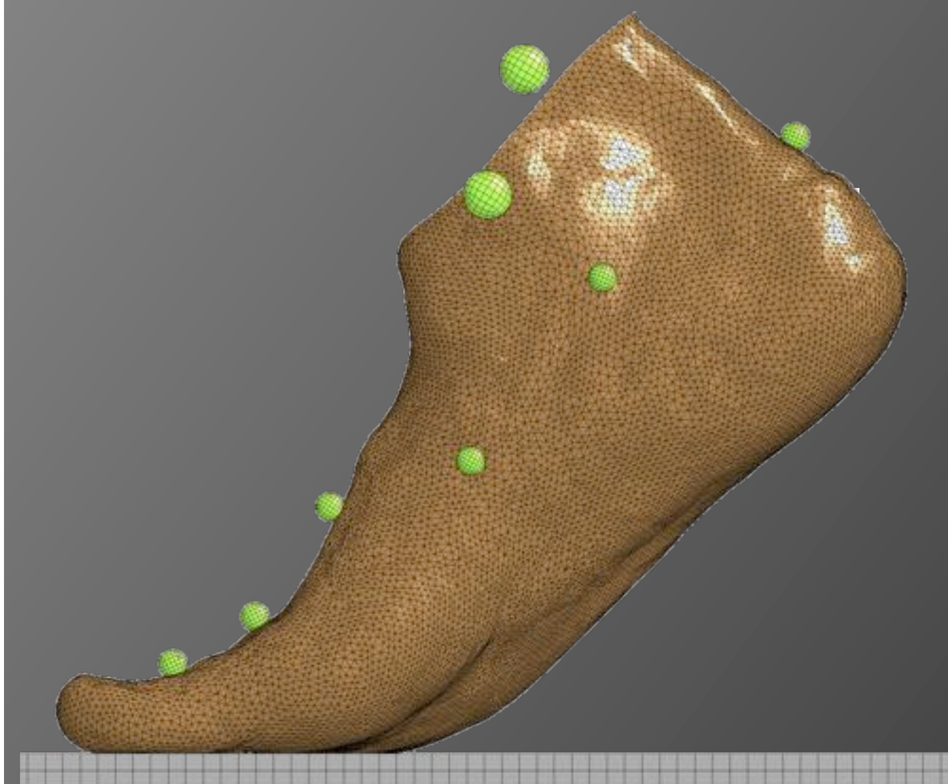
FINITE ELEMENT MODELING OF THE FOOT



PhD FINAL EXAMINATION
03/11/2015

Vara Isvilanonda

Objective

To develop and validate two subject-specific FE foot models (normal and diabetic), to explore the plantar pressure and internal soft tissue stress during quiet stance and the stance phase of gait, and to investigate the effect of soft tissue assumptions.

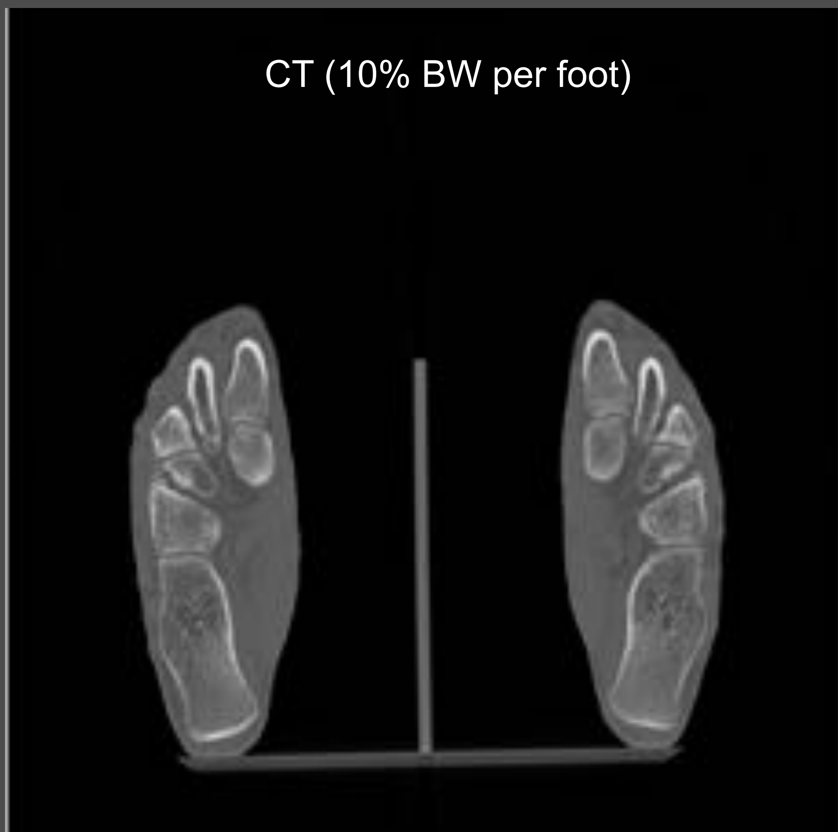
Normal and diabetic subjects

- Normal subject
  - Age 43 year-old (male)
  - Body weight 945 N

- Diabetic subject
  - Age 31 year-old (male)
  - Body weight 688 N
  - Duration of diabetes > 25 years

FE foot model development

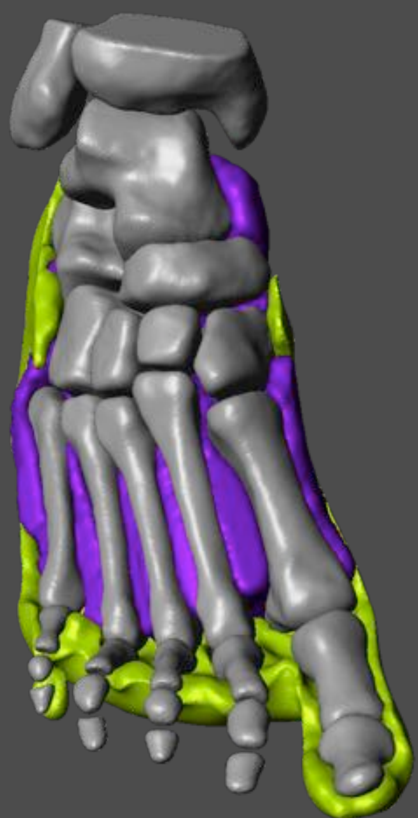
Obtain imaging data

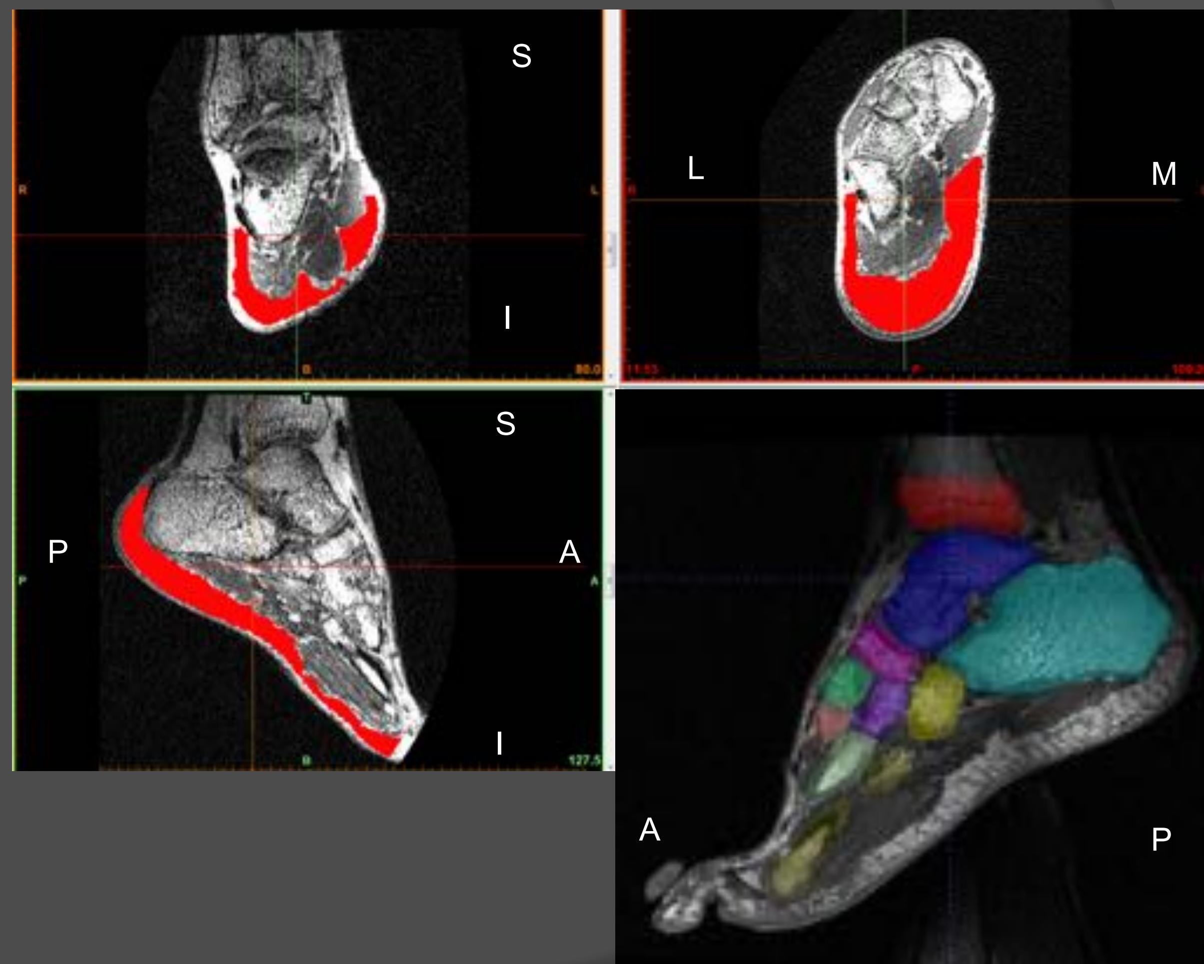


Bone anatomy

Skin, fat and muscle anatomy

Segmentation





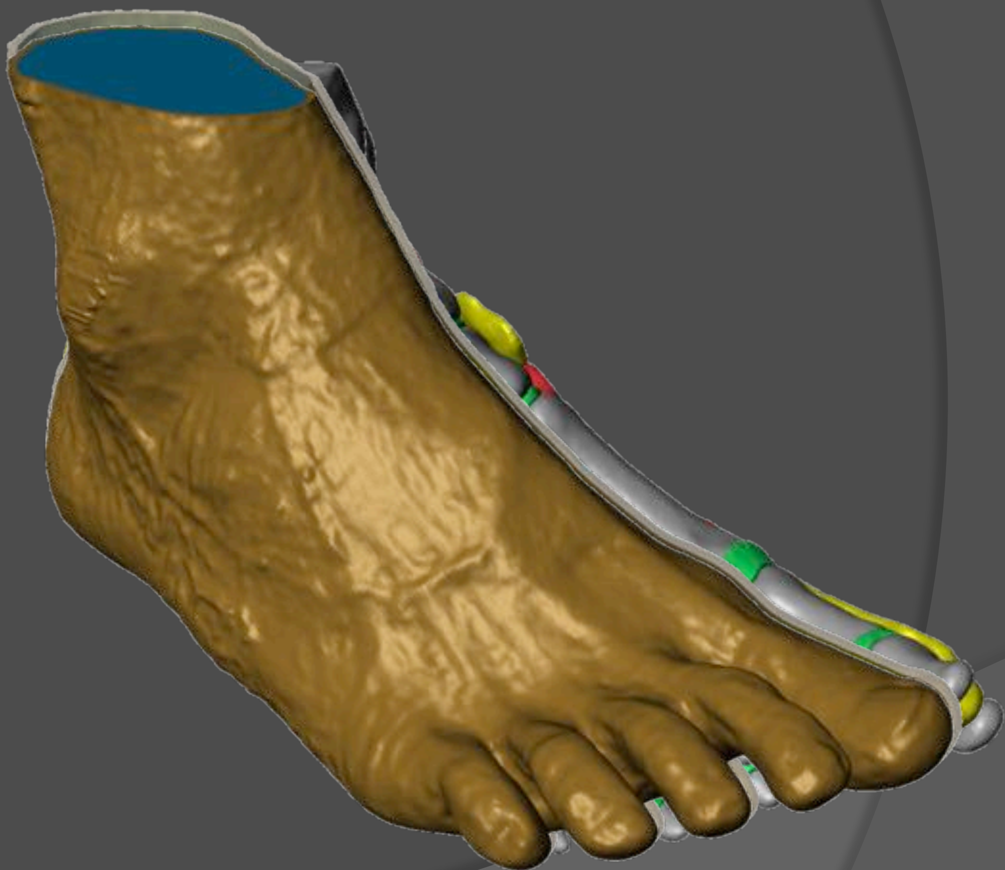
Boolean operations

Generate joint cavities

Generate skin thickness

Smoothen surfaces

Eliminate gaps/overlaps



FE model pre-processing

- Mesh with tetrahedral elements
- Element size (2.5mm), type (ELFORM13) determined from mesh convergence analysis
- Bone-soft tissue share nodes

Material properties

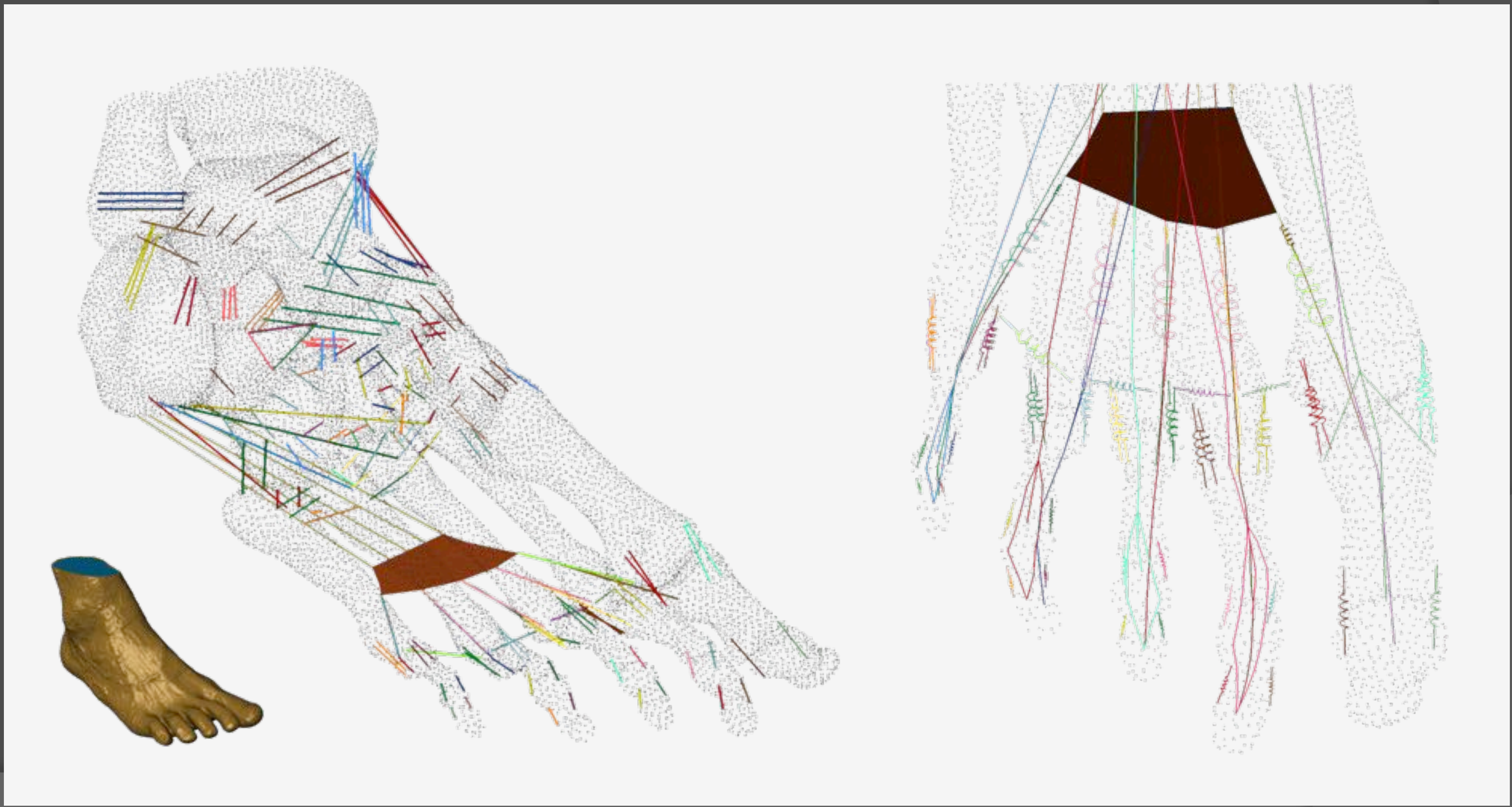
- Materials: rigid bone, Ogden hyperelastic soft tissue

$$W(\lambda_1,\lambda_2,\lambda_3)=\frac{\mu}{\alpha}\left(\tilde{\lambda}_1^{\alpha}+\tilde{\lambda}_2^{\alpha}+\tilde{\lambda}_3^{\alpha}-3\right)+\frac{1}{2}K(J-1)^2 \qquad \tilde{\lambda}_i=\frac{\lambda_i}{J^{1/3}}$$

  - *(μ_S, α_S), (μ_F, α_F)* and *(μ_M, α_M)* are subject-specific skin, fat and muscle material properties determined *in vivo* (Specific Aim 2)
  - Dorsal soft tissue modeled with subject-specific generic soft tissue *(μ_G, α_G)*

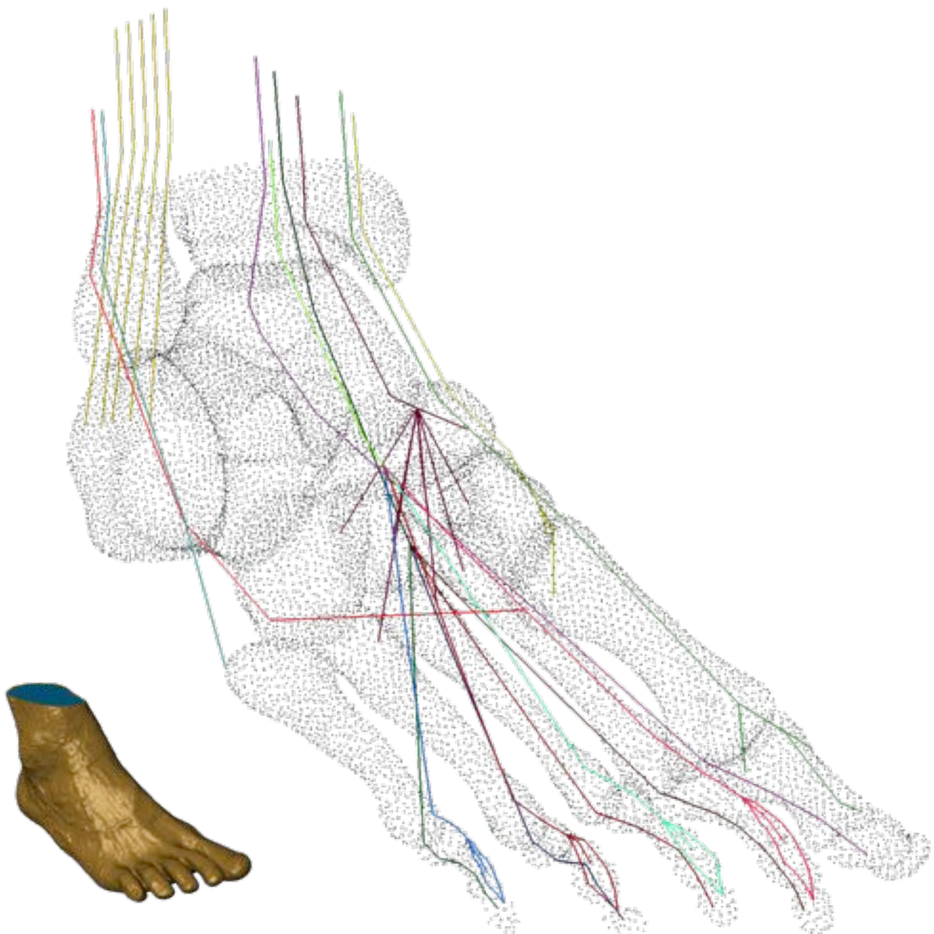
Ligament

- 102 non-linear, tension only ligaments



Tendon

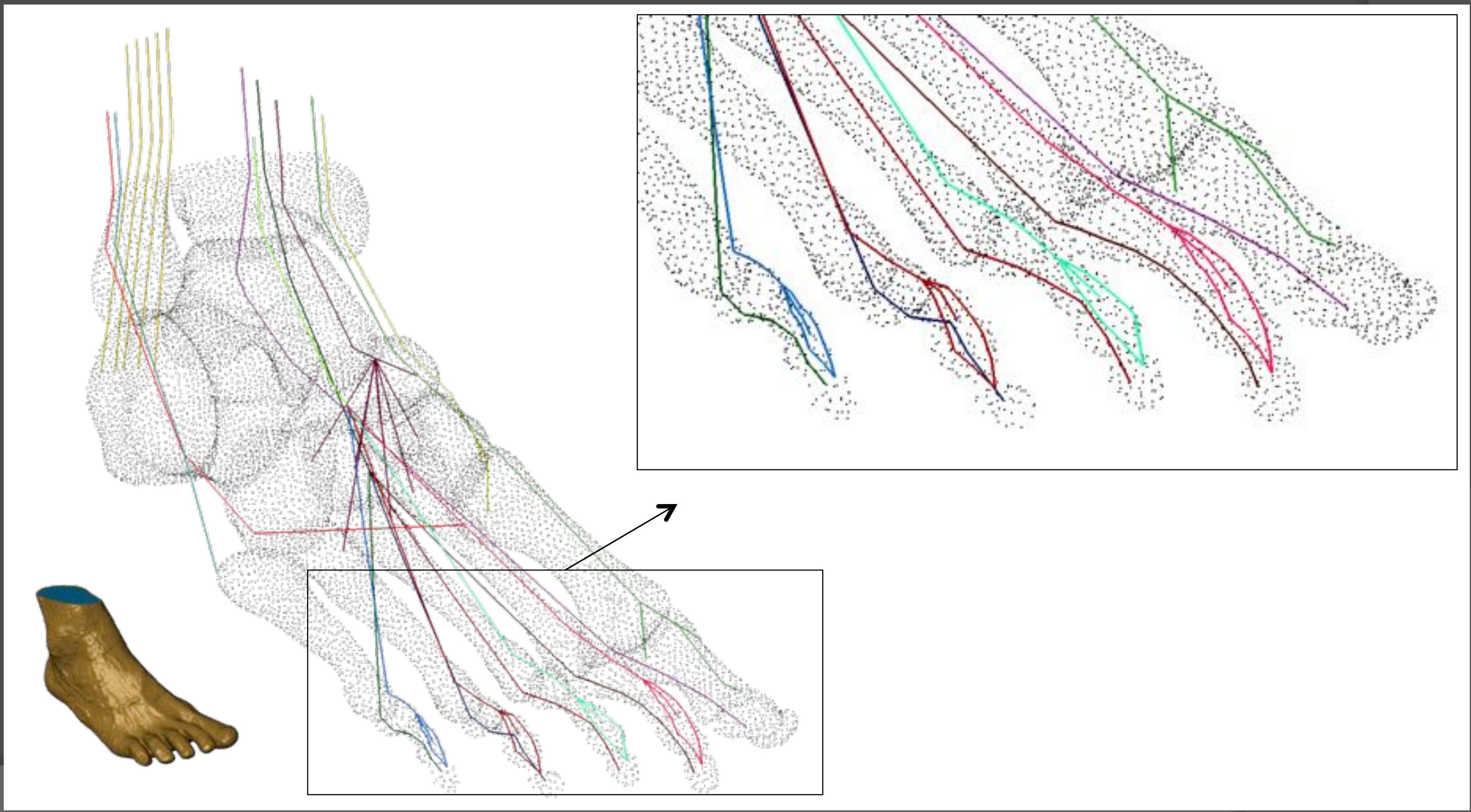
- 9 extrinsic muscle tendons (seatbelts – slip rings)



9Tendons are:
-Achilles
-Tibialis anterior
-Tibialis posterior
-Peroneus longus
-Peroneus brevis
-Extensor hallucis longus
-Externso digitorum longus
-Flexor hallucis longus
-Flexor digitorum longus

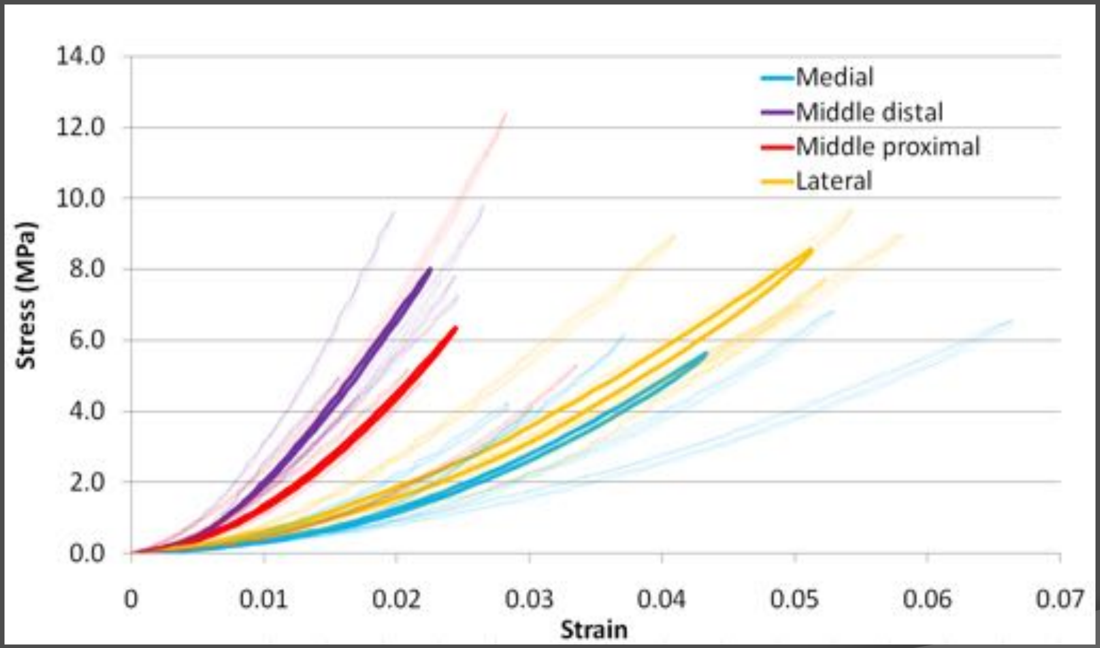
Tendon

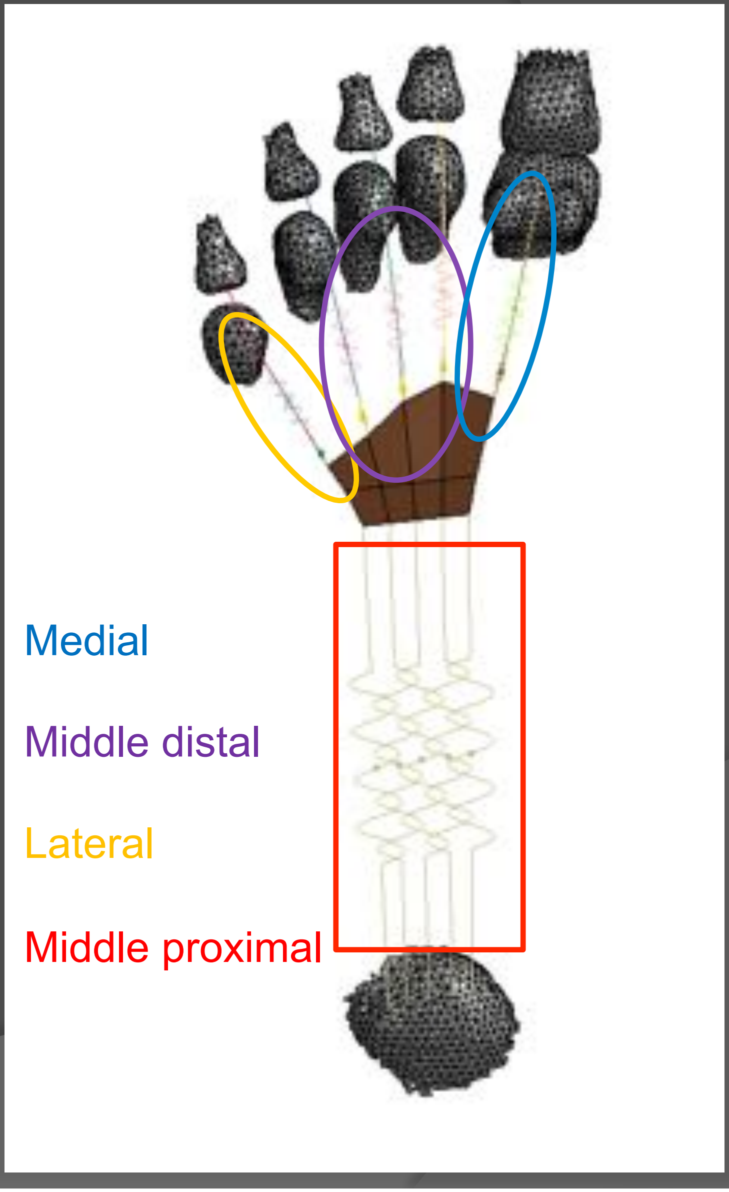
- 9 extrinsic muscle tendons (seatbelts – slip rings)



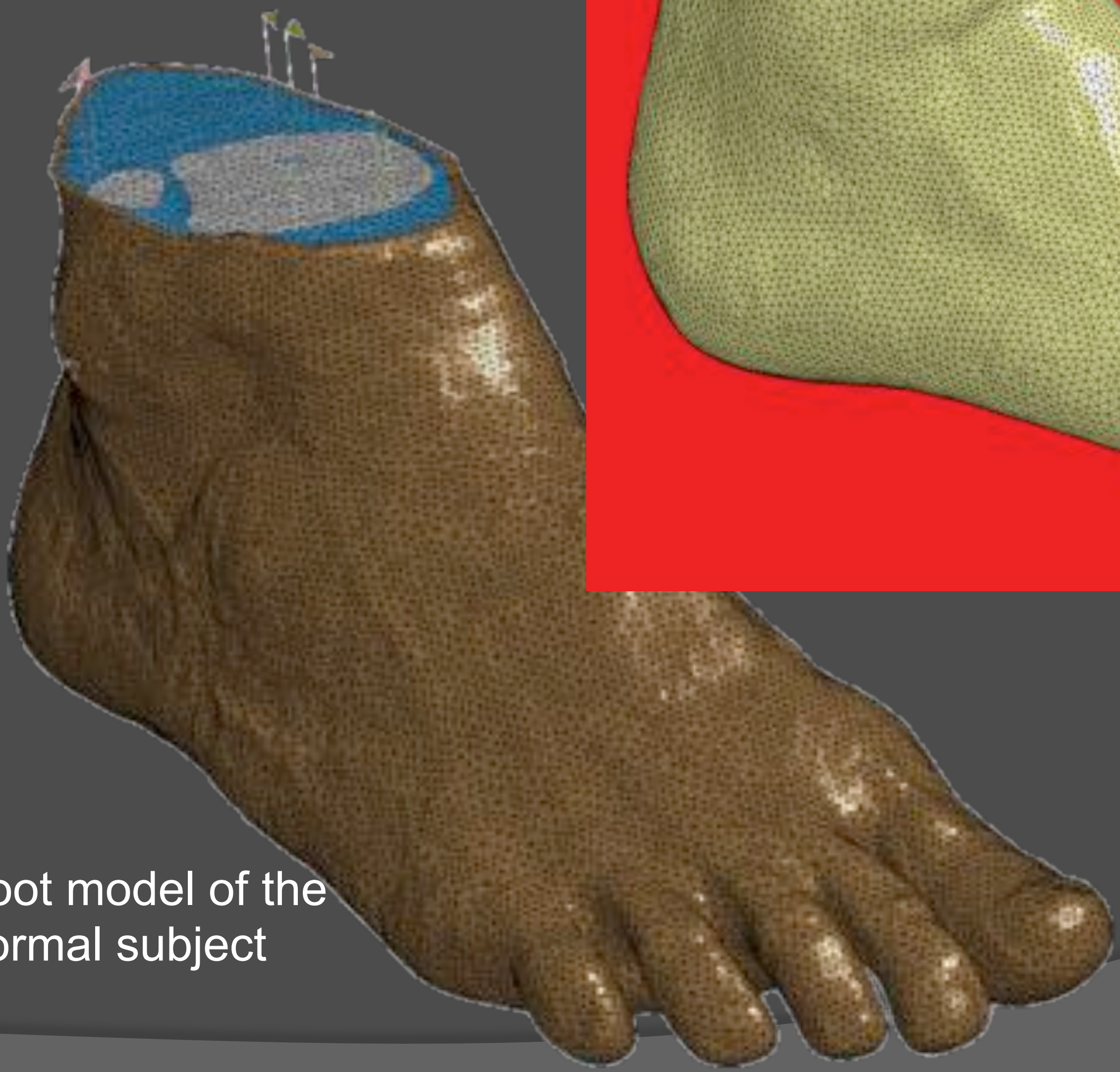
Plantar fascia

- Material properties in 4 regions from cadaveric tests from 3rd Specific Aim





Specific Aim 4: Method



Foot model of the diabetic subject

Foot model of the normal subject

Experimental Validation

3 validation conditions

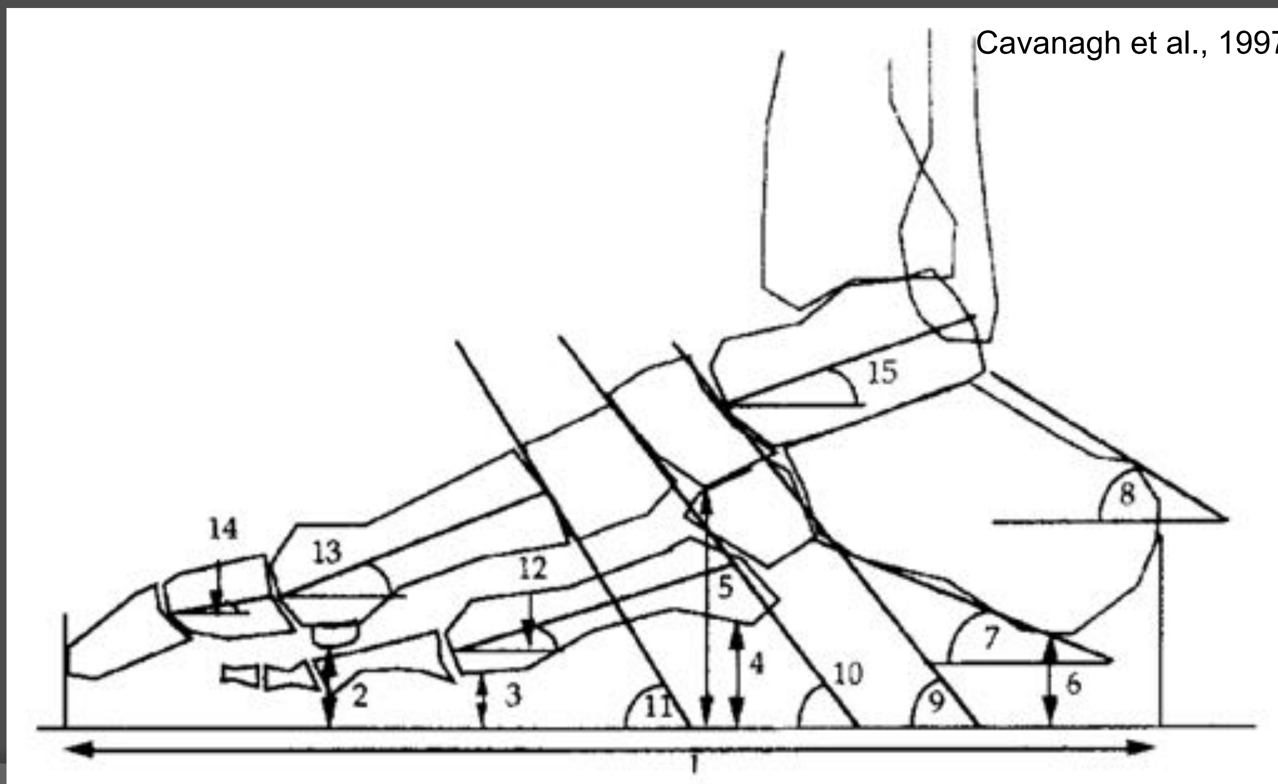
- Quasi static: Passive 10% BW foot compression
- Quasi static: Quiet stance
- Dynamic: Stance phase of gait

Validation 1: passive compression

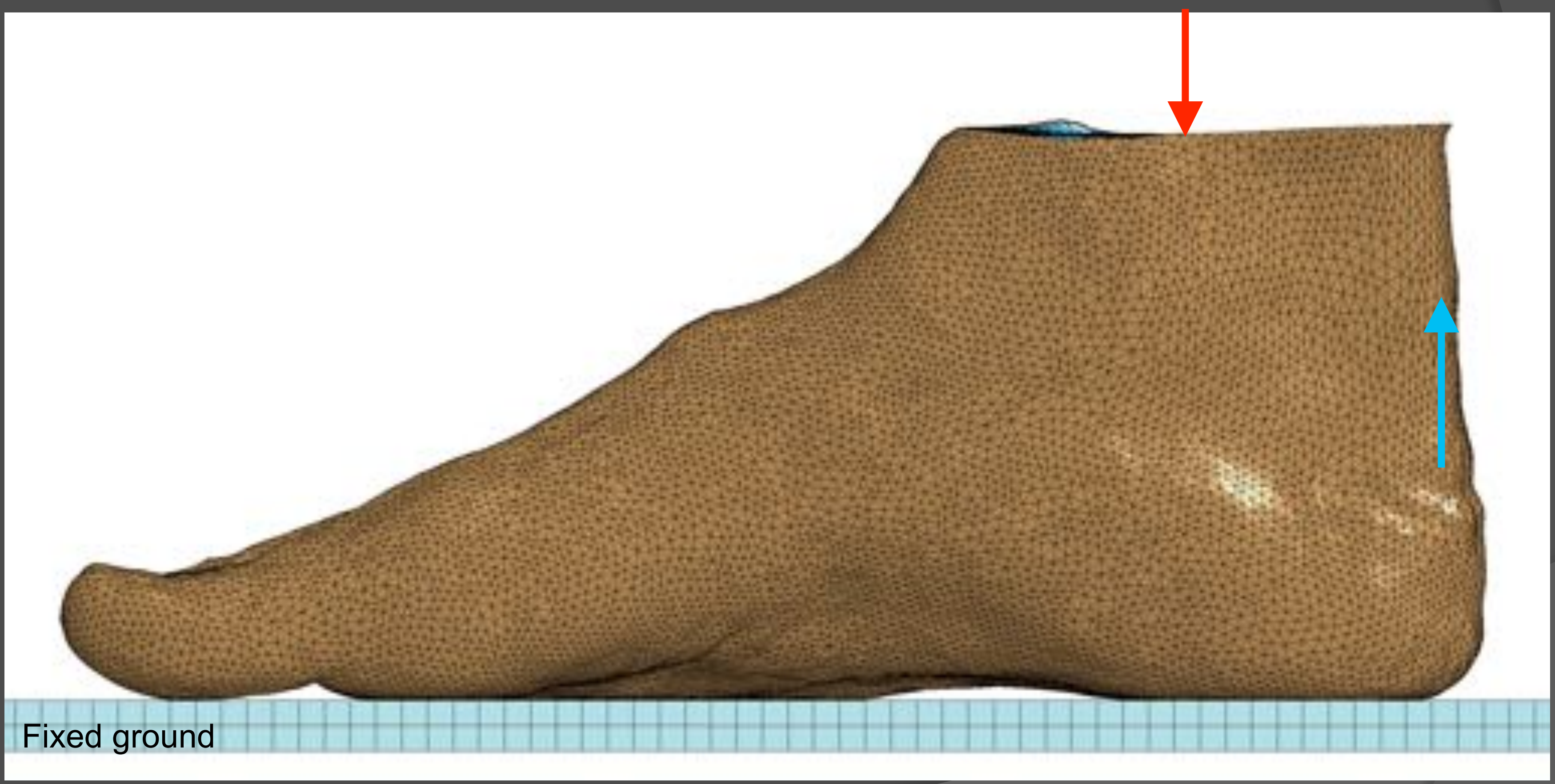
- Bony alignments from 10% BW CT data are compared to simulation

Validation 1: passive compression

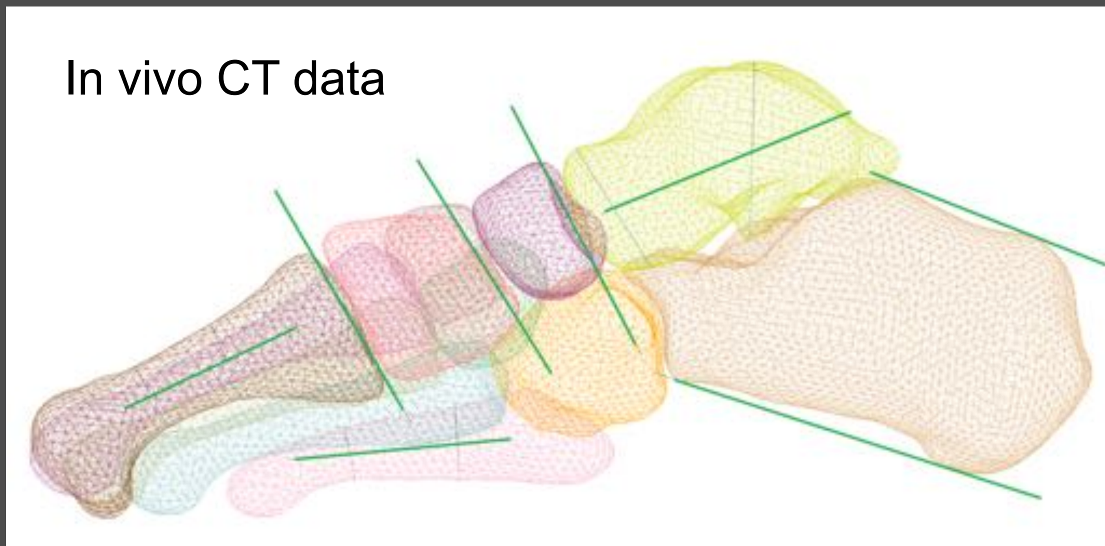
- Bony alignments from 10% BW CT data are compared to simulation

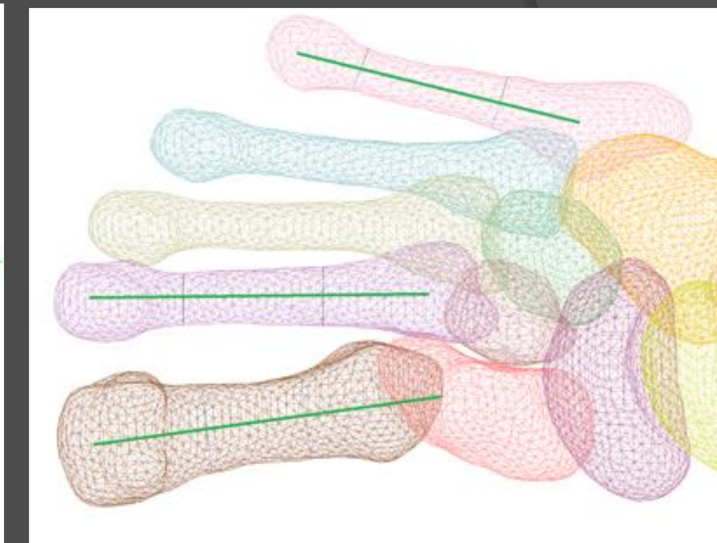


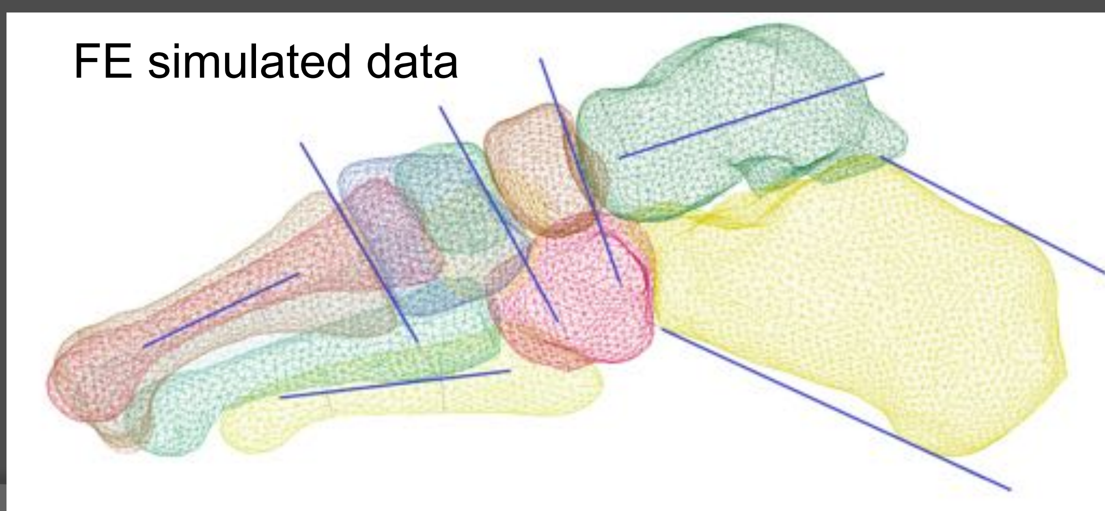
Passive compression FE simulation

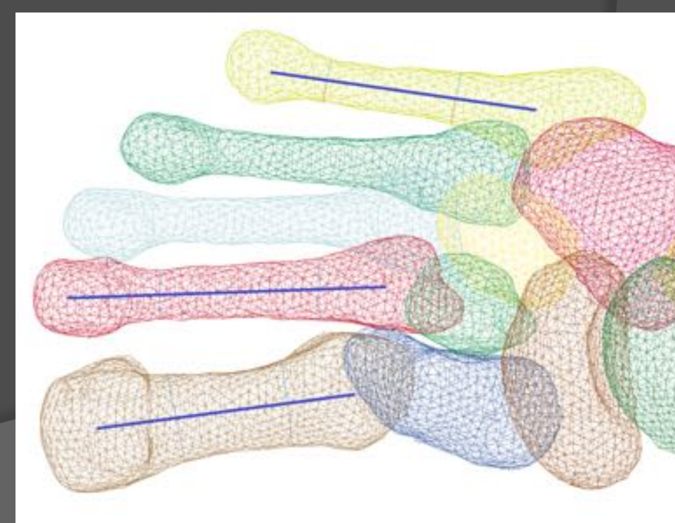


Passive compression FE simulation

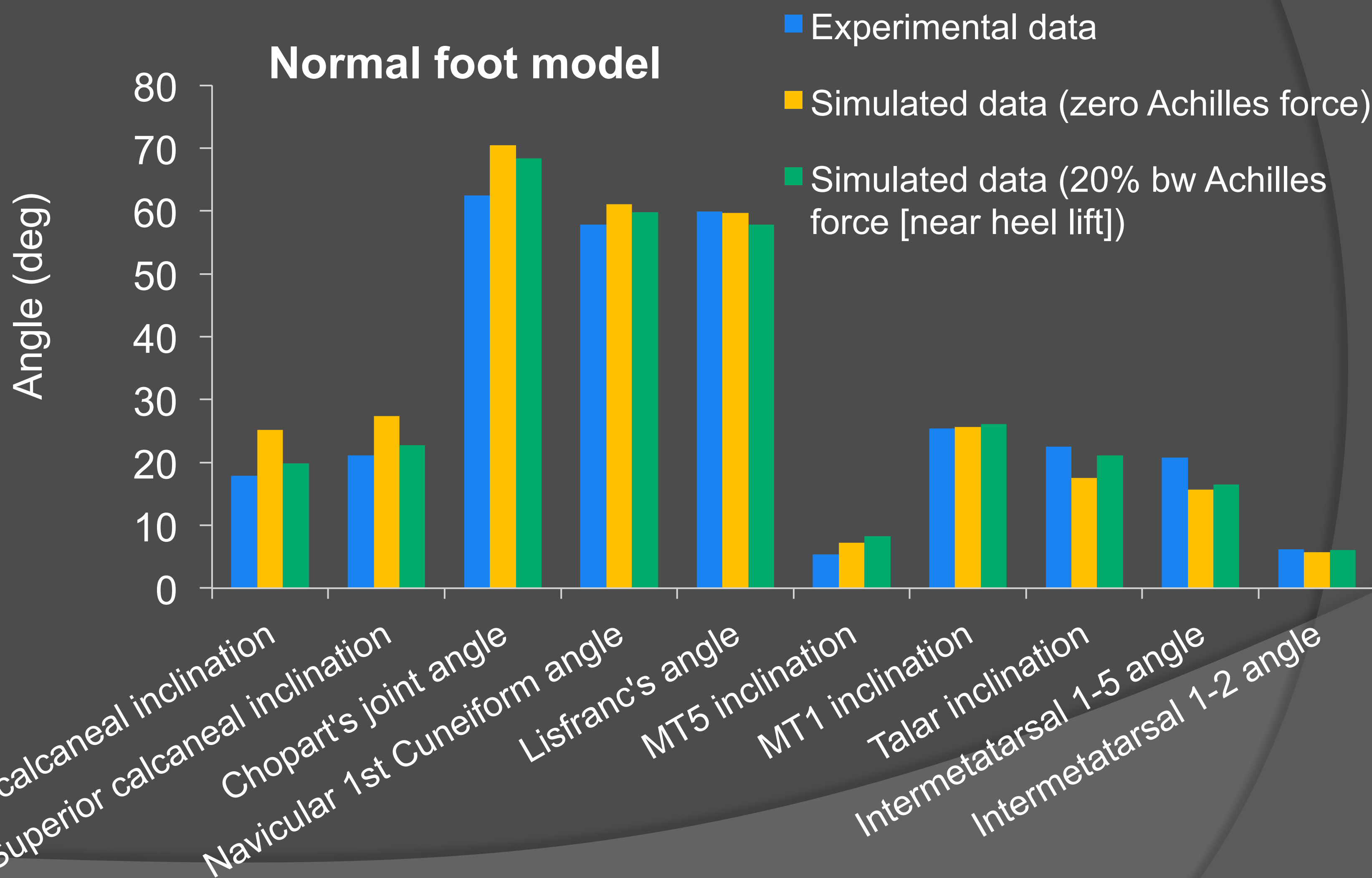




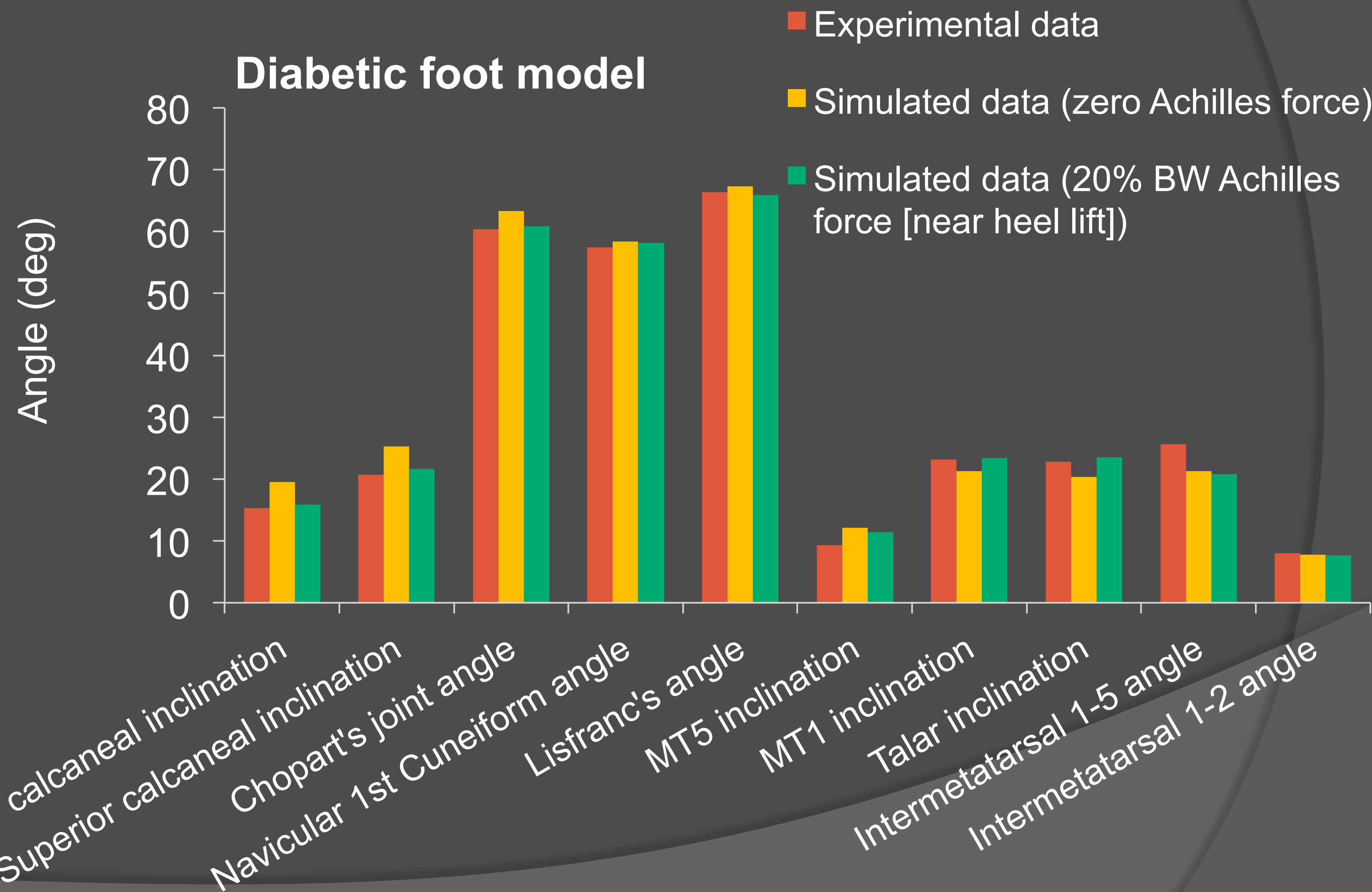




Passive compression validation results

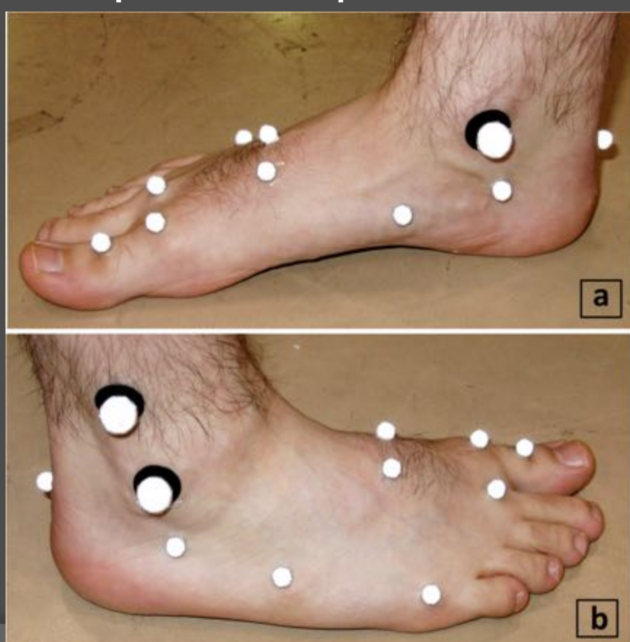


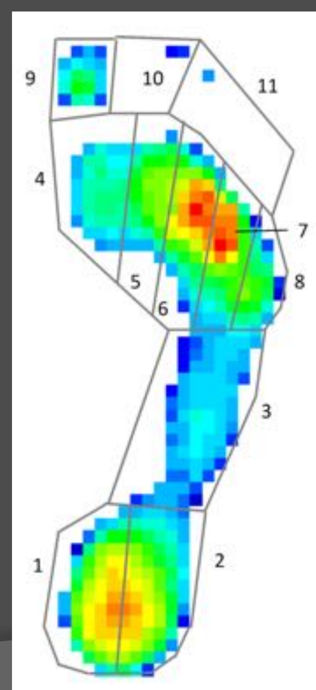
Passive compression validation results



Validation 2: Quiet stance

- Recorded 14 foot retro-reflective markers [1] using 12-camera Vicon system
- Recorded plantar pressure on an emed-x pressure platform

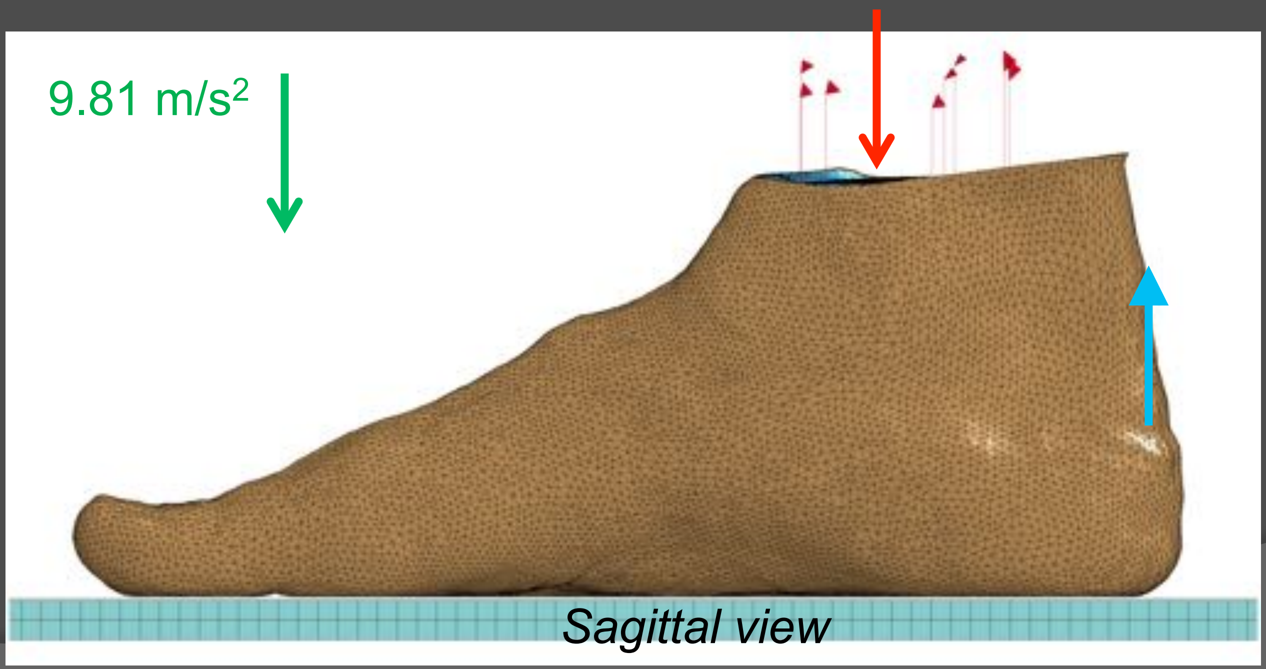




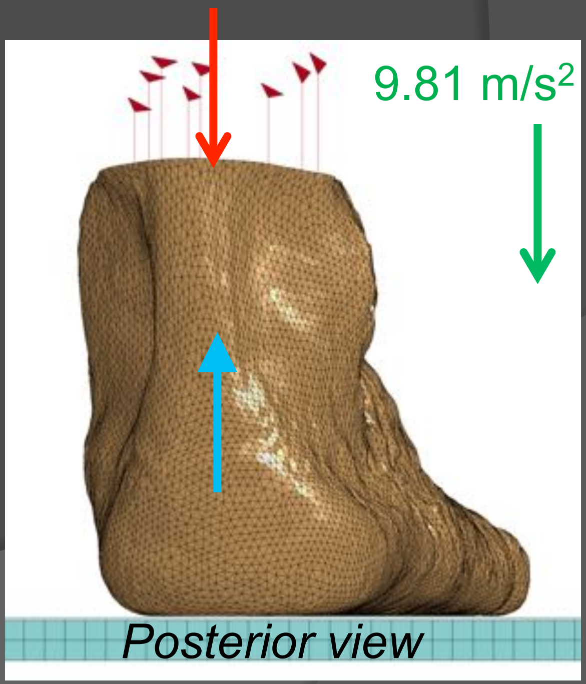
1 [Leardini et al., *Gati & Posture*, 25: 453-462

Quiet stance FE simulation

- Prescribed tibia orientation from motion capture data
- Tibial force + Achilles tendon force + gravitational force = **50% BW**
- Tune Achilles tendon force to match *in vivo* COP location

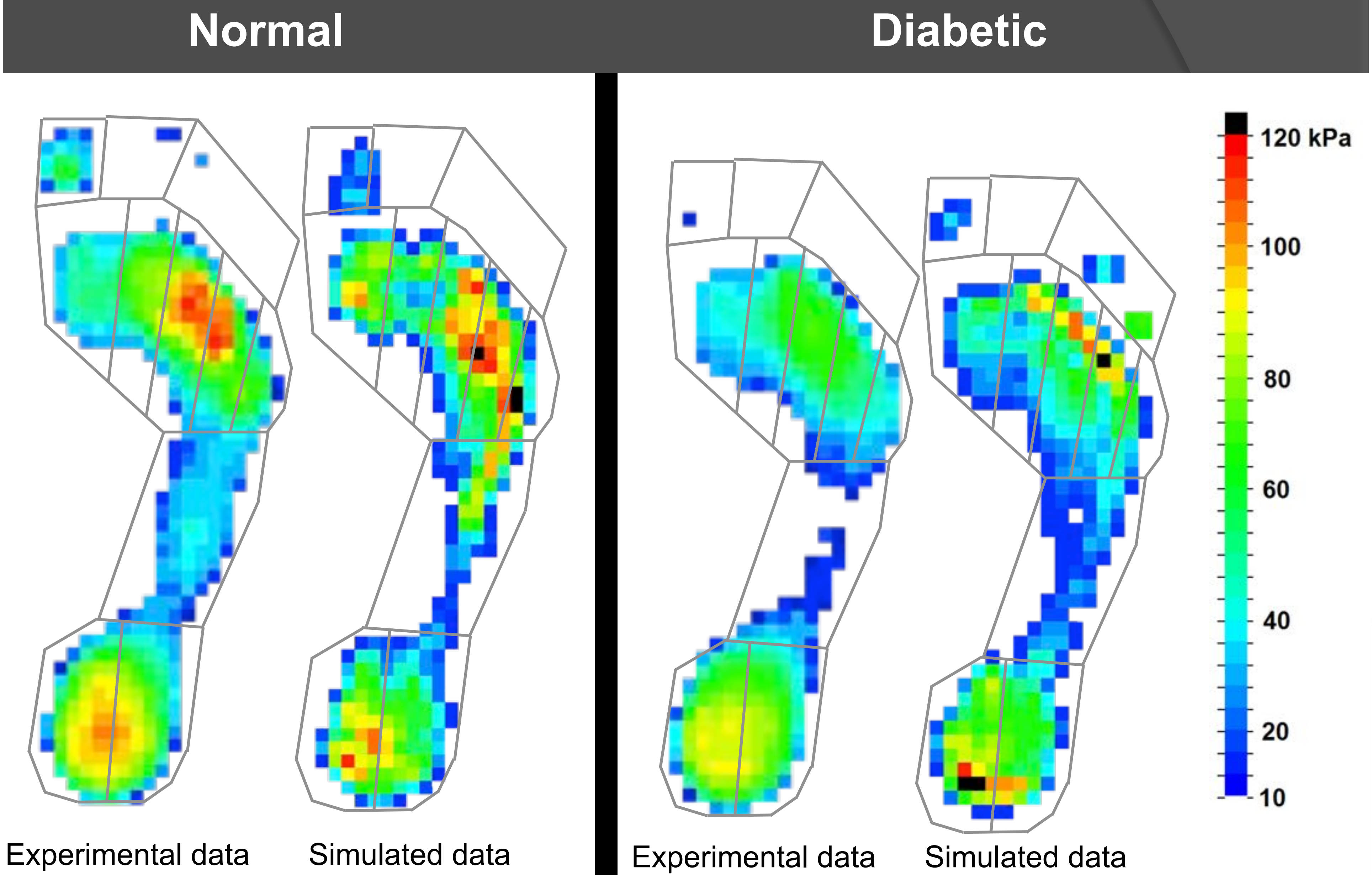


Sagittal view



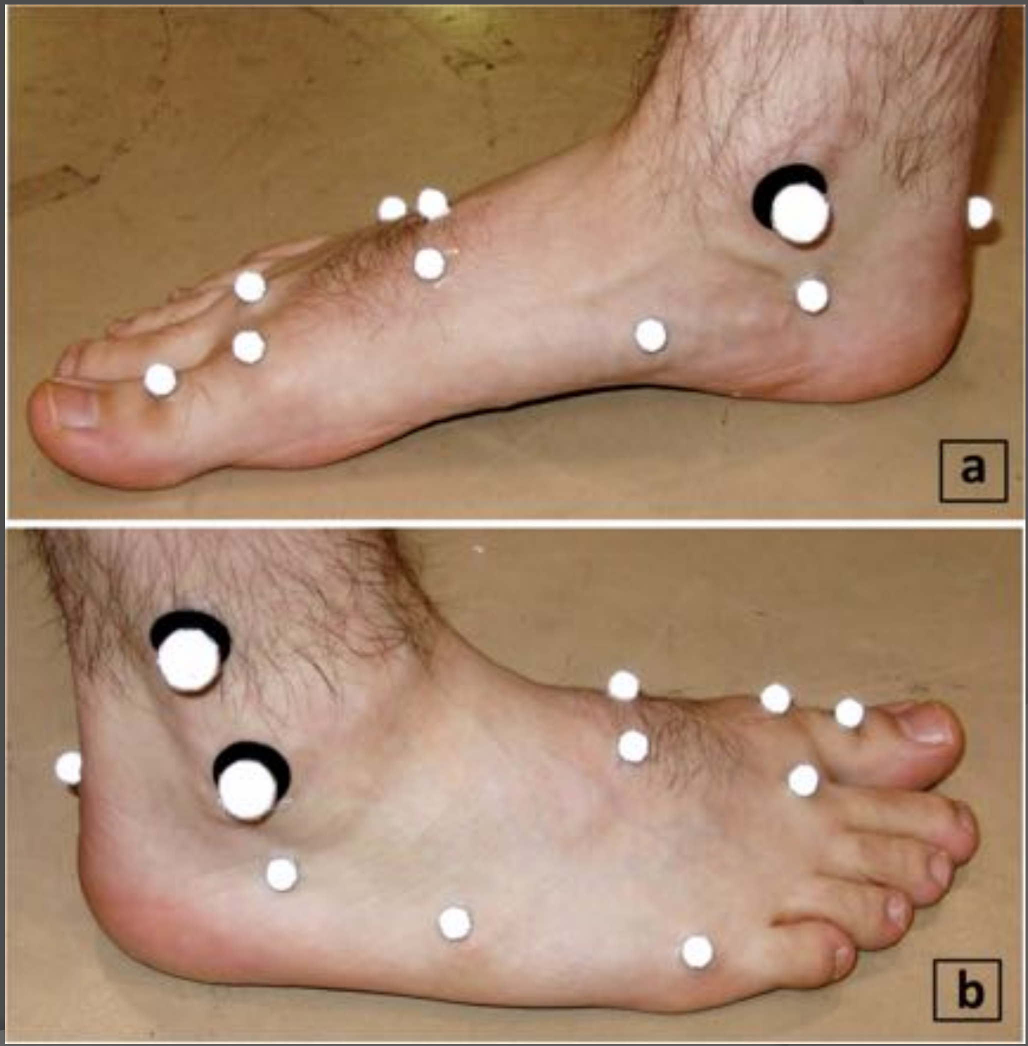
Posterior view

Specific Aim 4: Results – Validation2



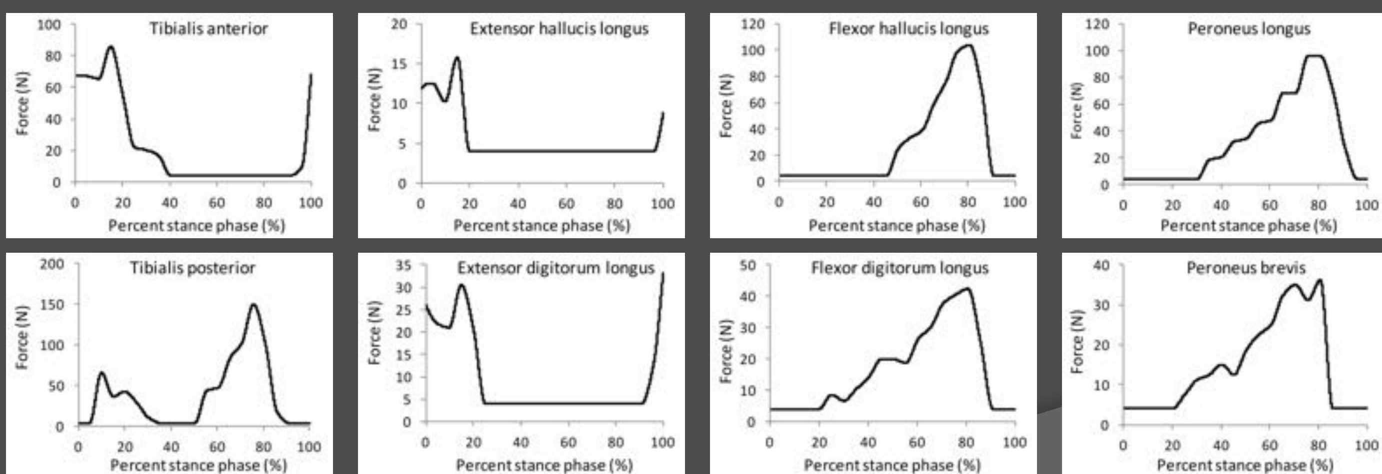
Validation 3: Dynamic gait

- Self-selected speed
- Right foot strike
- 7 force plate trials
- 7 pressure platform trials



Gait FE simulation

- Different simulation for force plate and pressure platform trials
- Prescribe tibial kinematics-time history (series of 4x4 transformation matrices)
- Prescribe tendon force-time history from literature [1]



1 [Aubin et al., 2012, *IEEE T. Robot*, **28**: 246-255

Gait FE simulation

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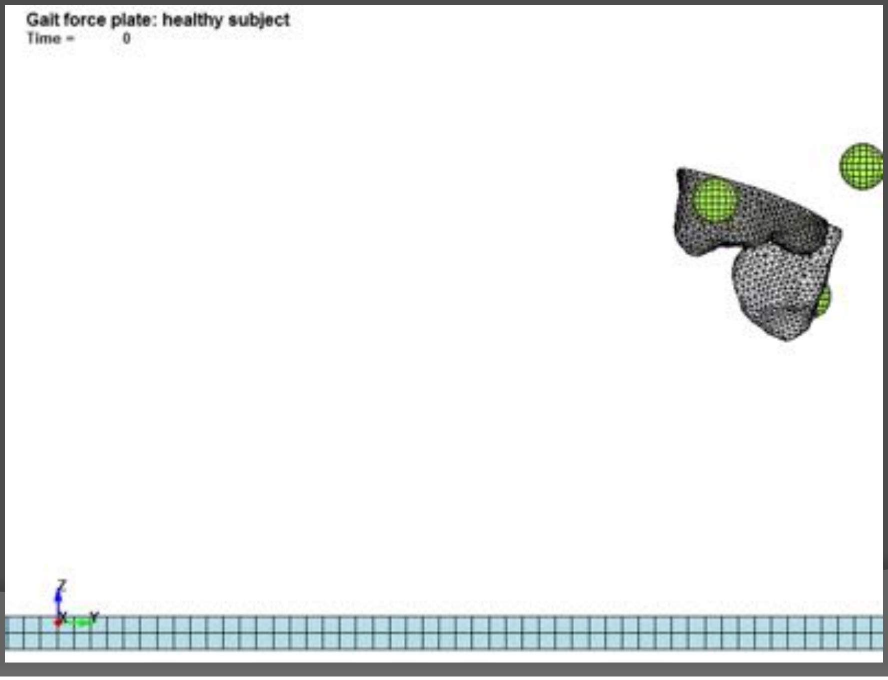
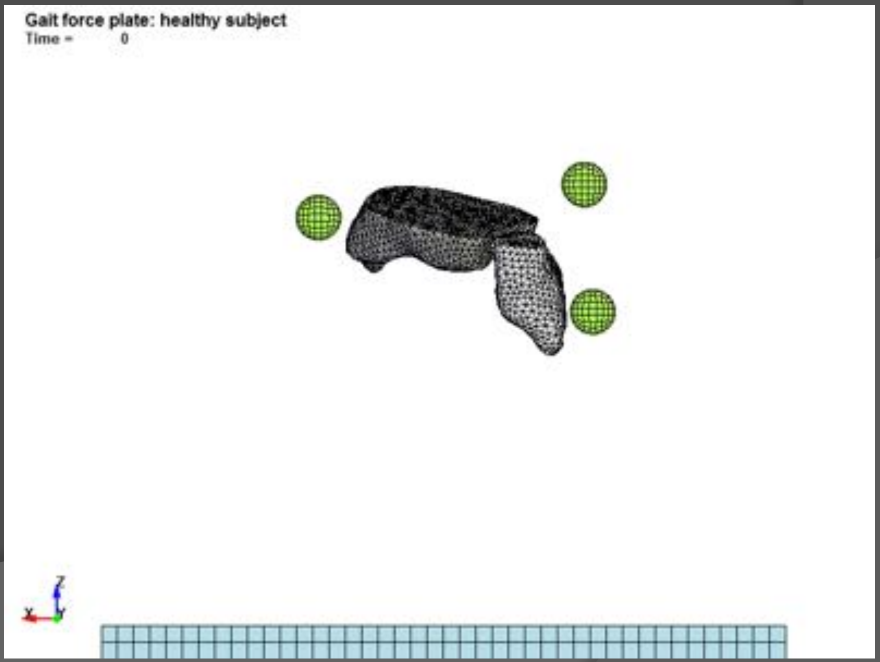


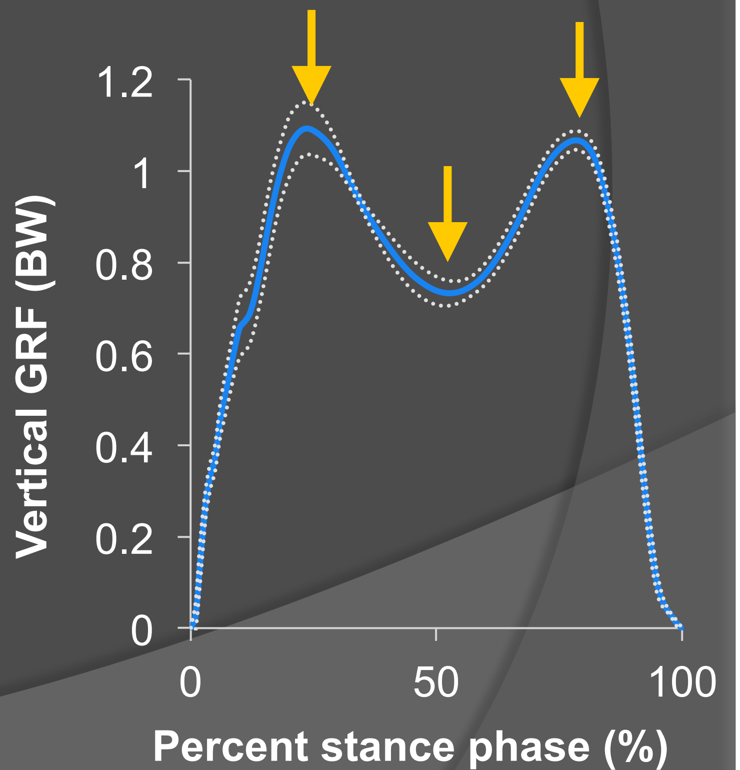


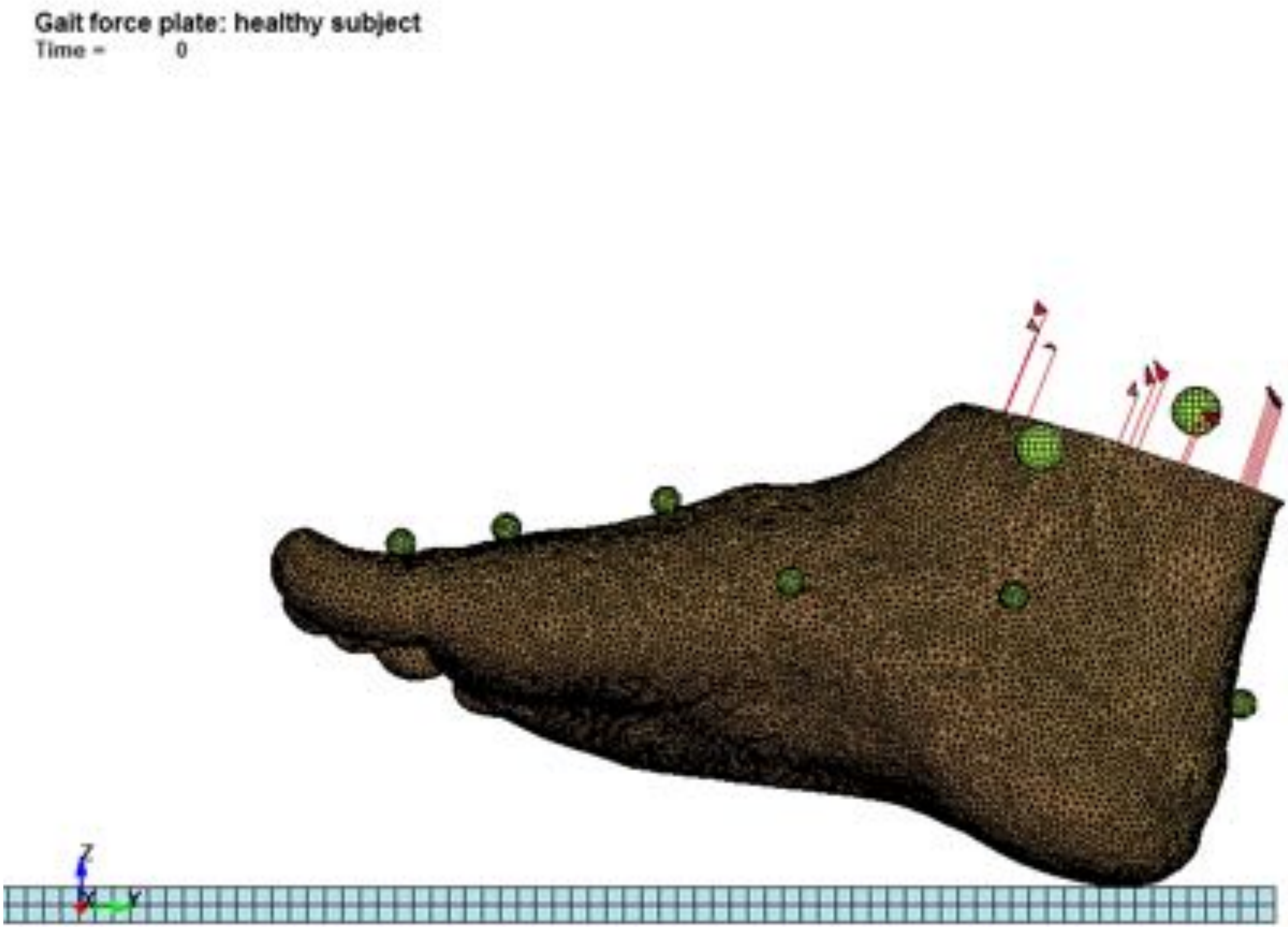
Gait FE simulation: protocol

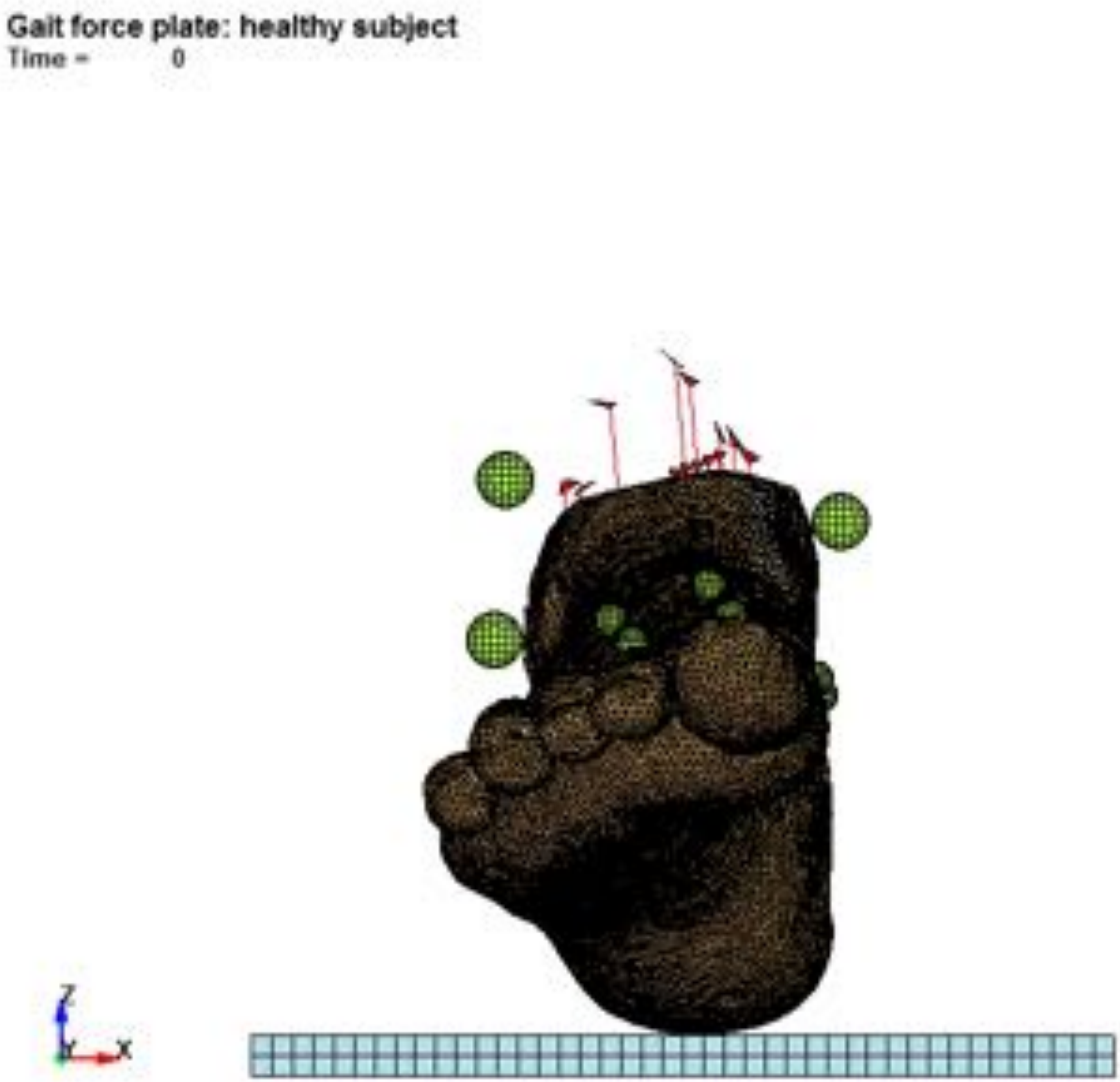
- Initialize tendon forces, dorsiflex ankle before heel strike (0.0s to 0.2s)
- At 0.2s, switched to prescribed tibial kinematics
- Stance phase of gait ~0.215s to push off

Model tuning to achieve target vertical GRF

- Floor position (1-7mm)
- Achilles tendon force

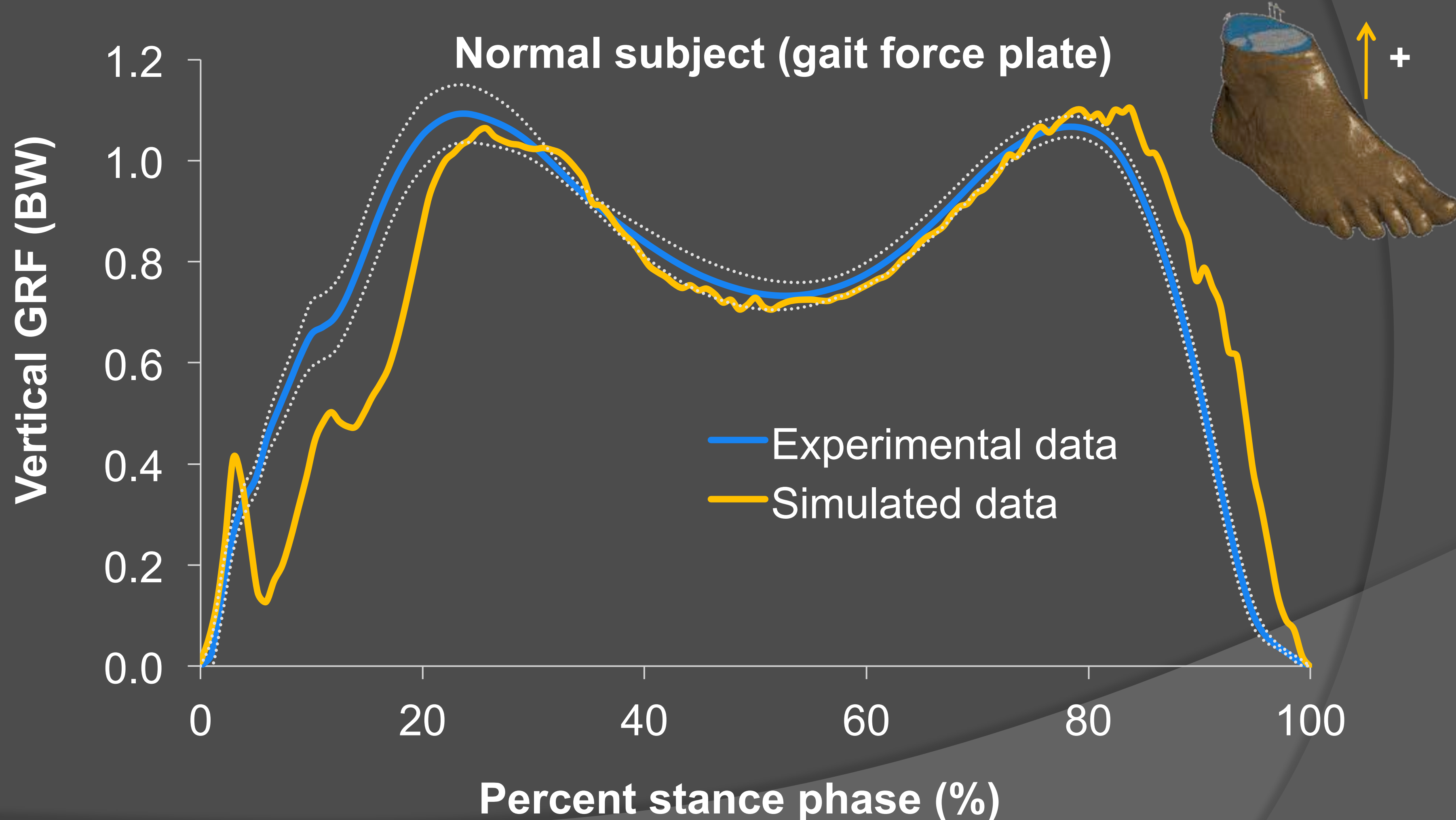



Gait force plate: healthy subject
Time = 0
Z
Y

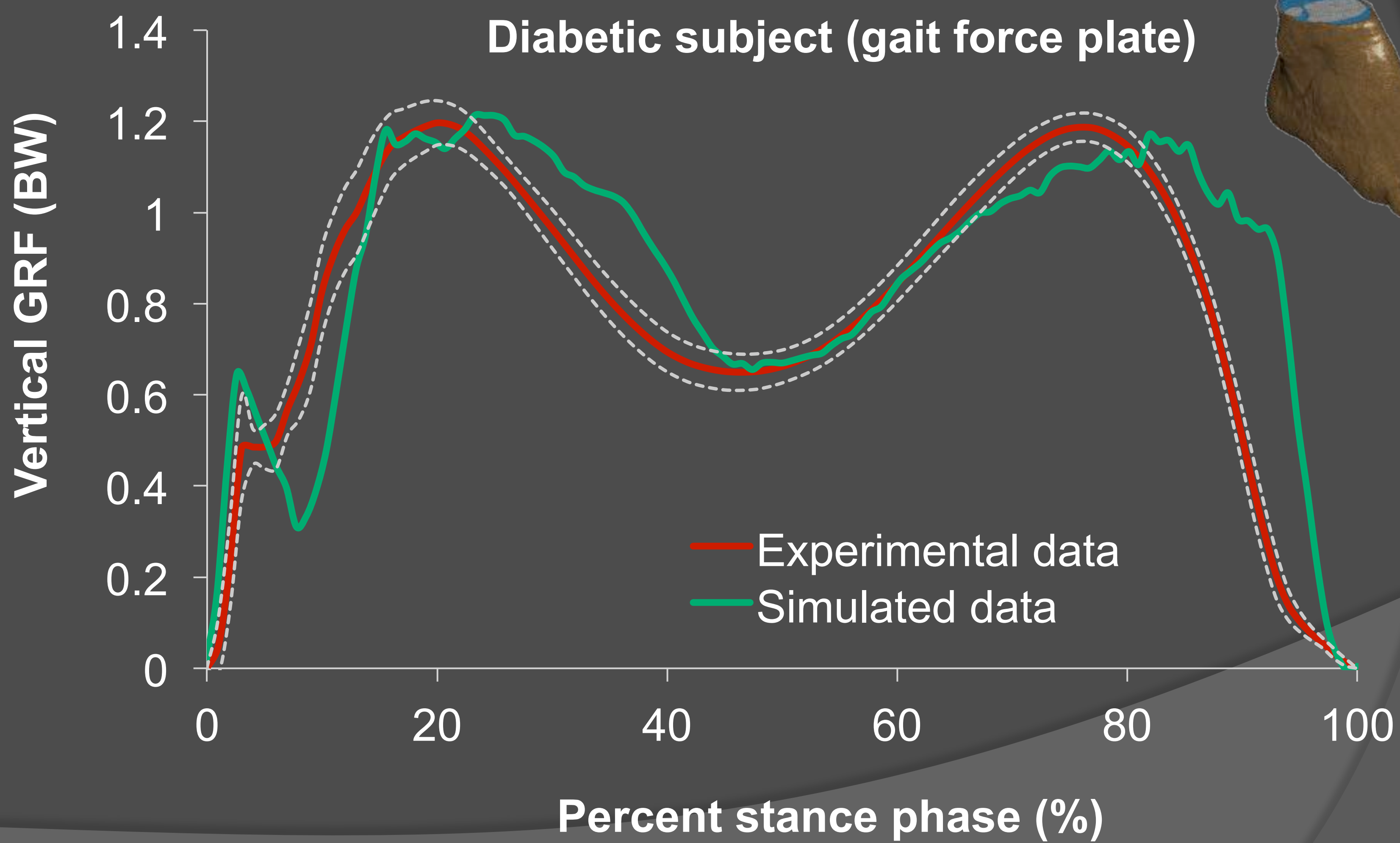


Gait force plate: healthy subject
Time = 0
Z
X

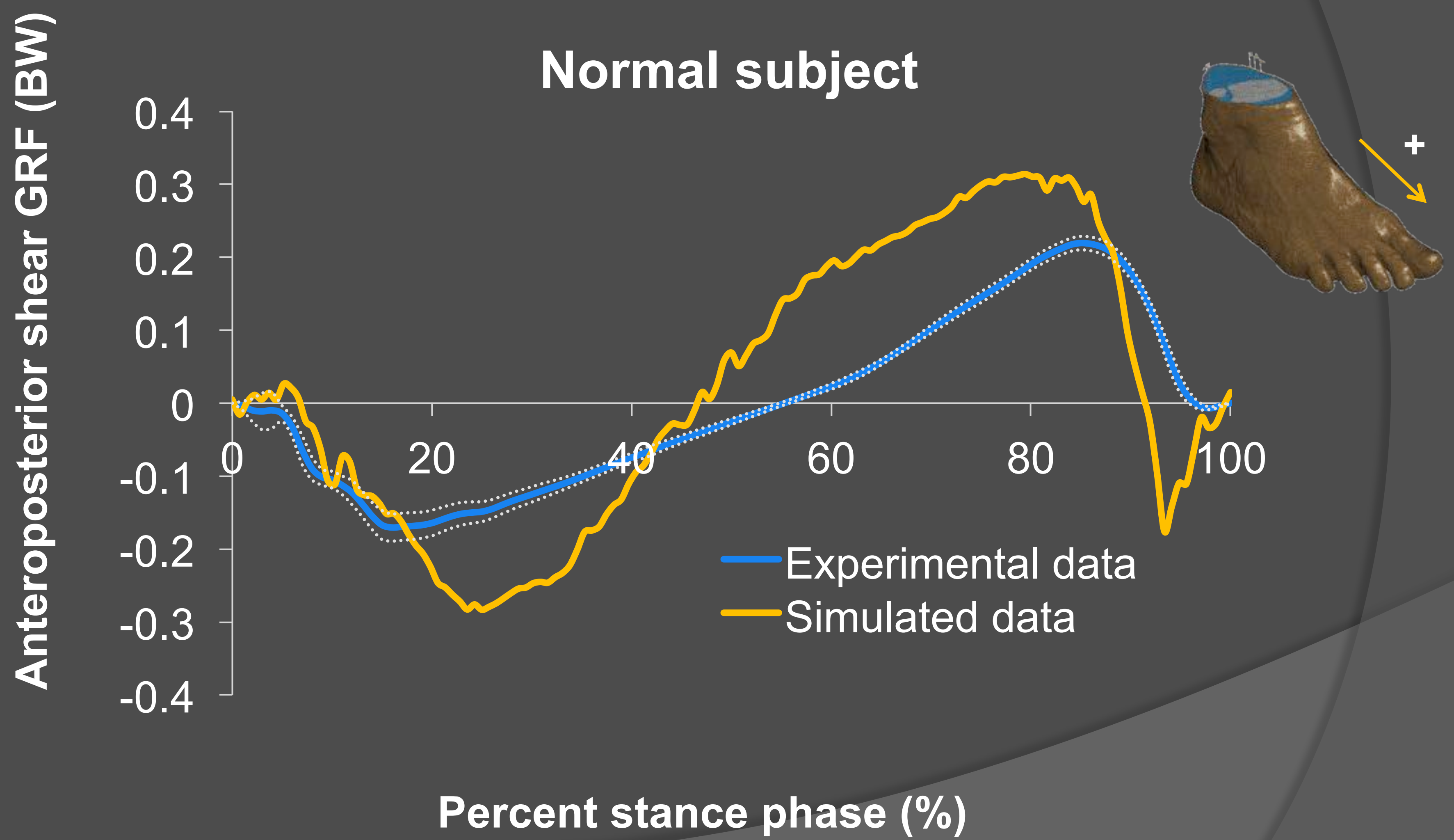
Gait: Vertical ground reaction force



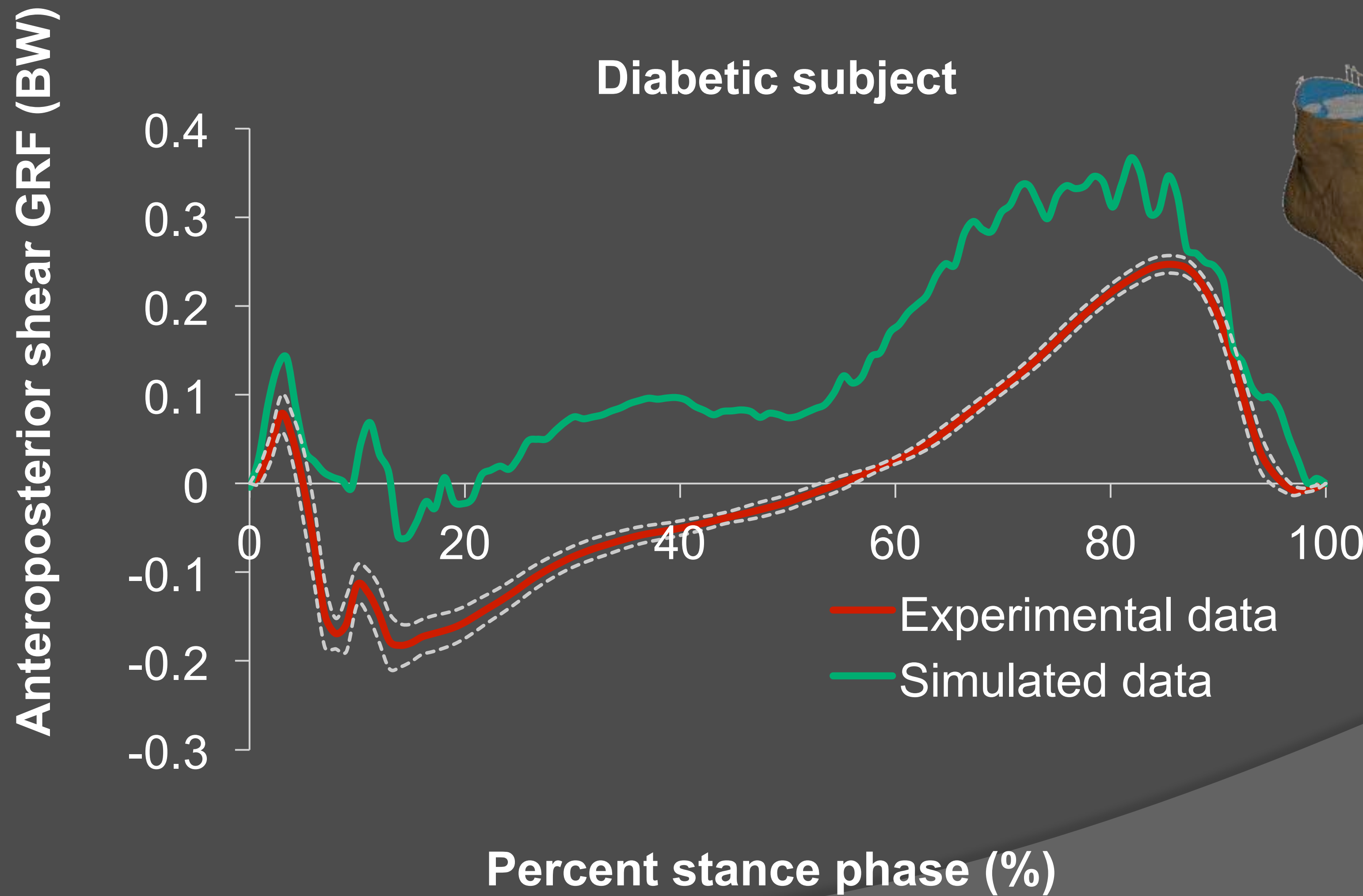
Gait: Vertical ground reaction force



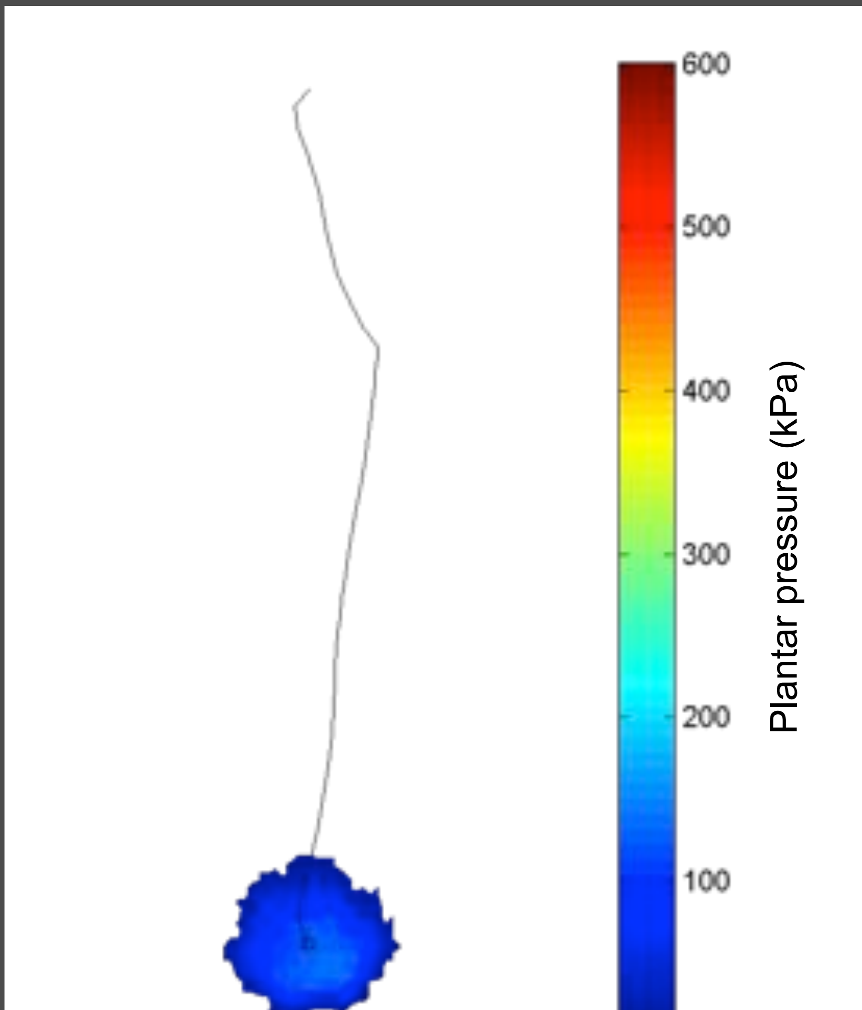
Gait: AP shear ground reaction force



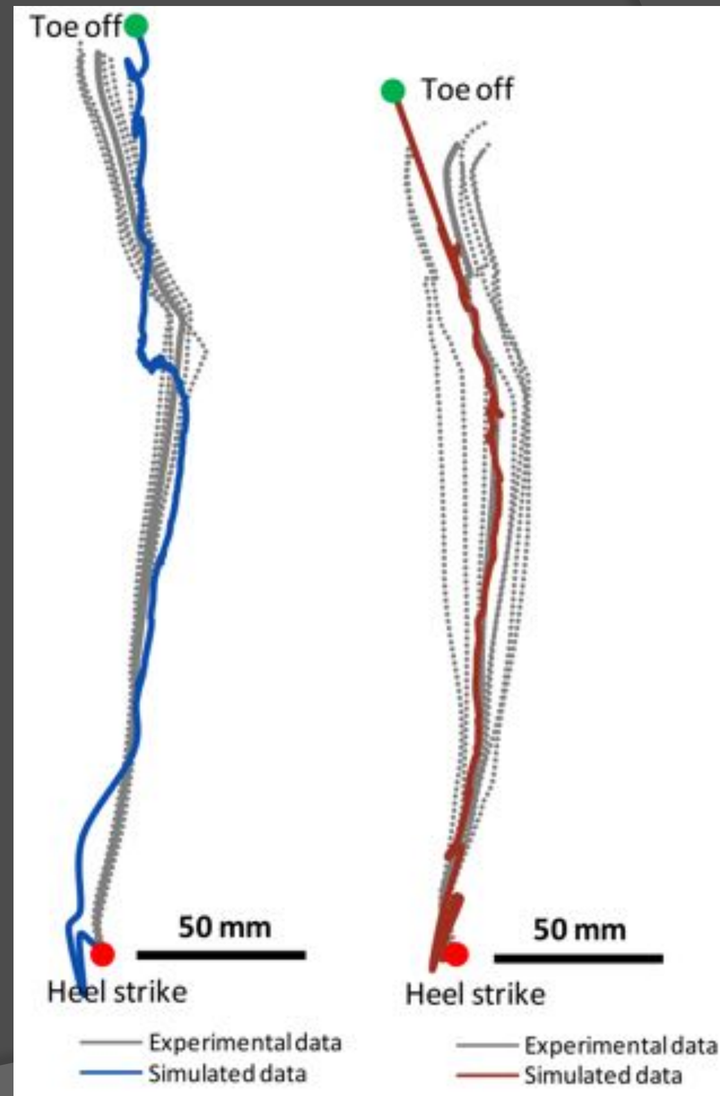
Gait: AP shear ground reaction force



Gait: Center of pressure



Experimental plantar pressure and COP progression from emed pressure platform (normal subject data)

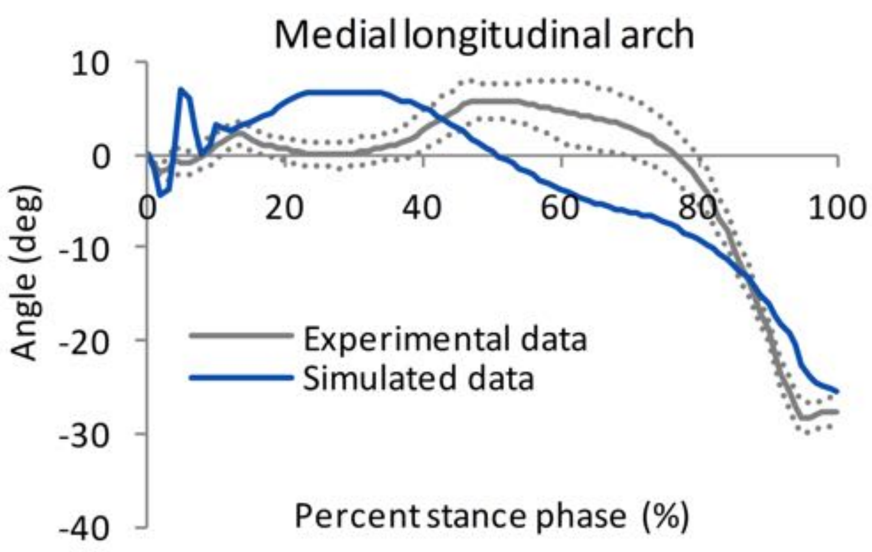


Normal **Diabetic**

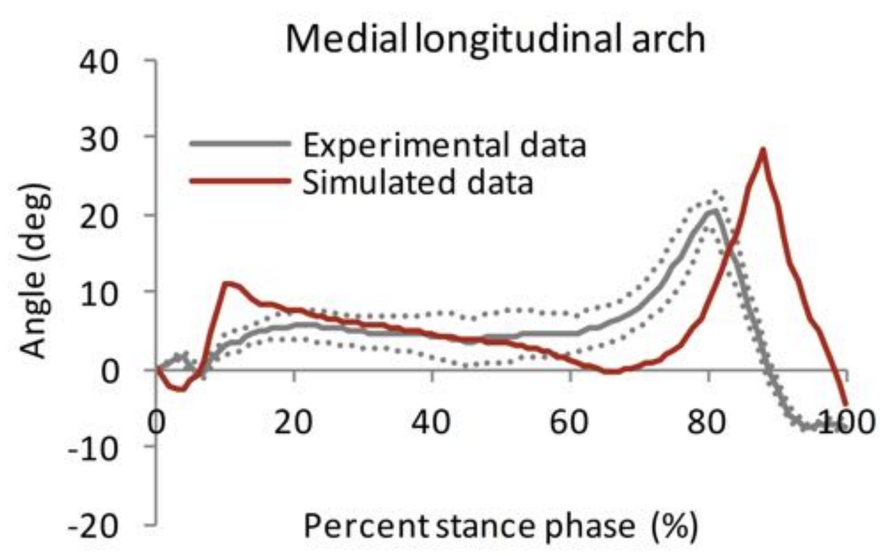
Gait: Bone kinematics

- Measurements are based on foot model described by Leardini et al., 2007
- 10 bone angle validations showed small RMS error relative to peak

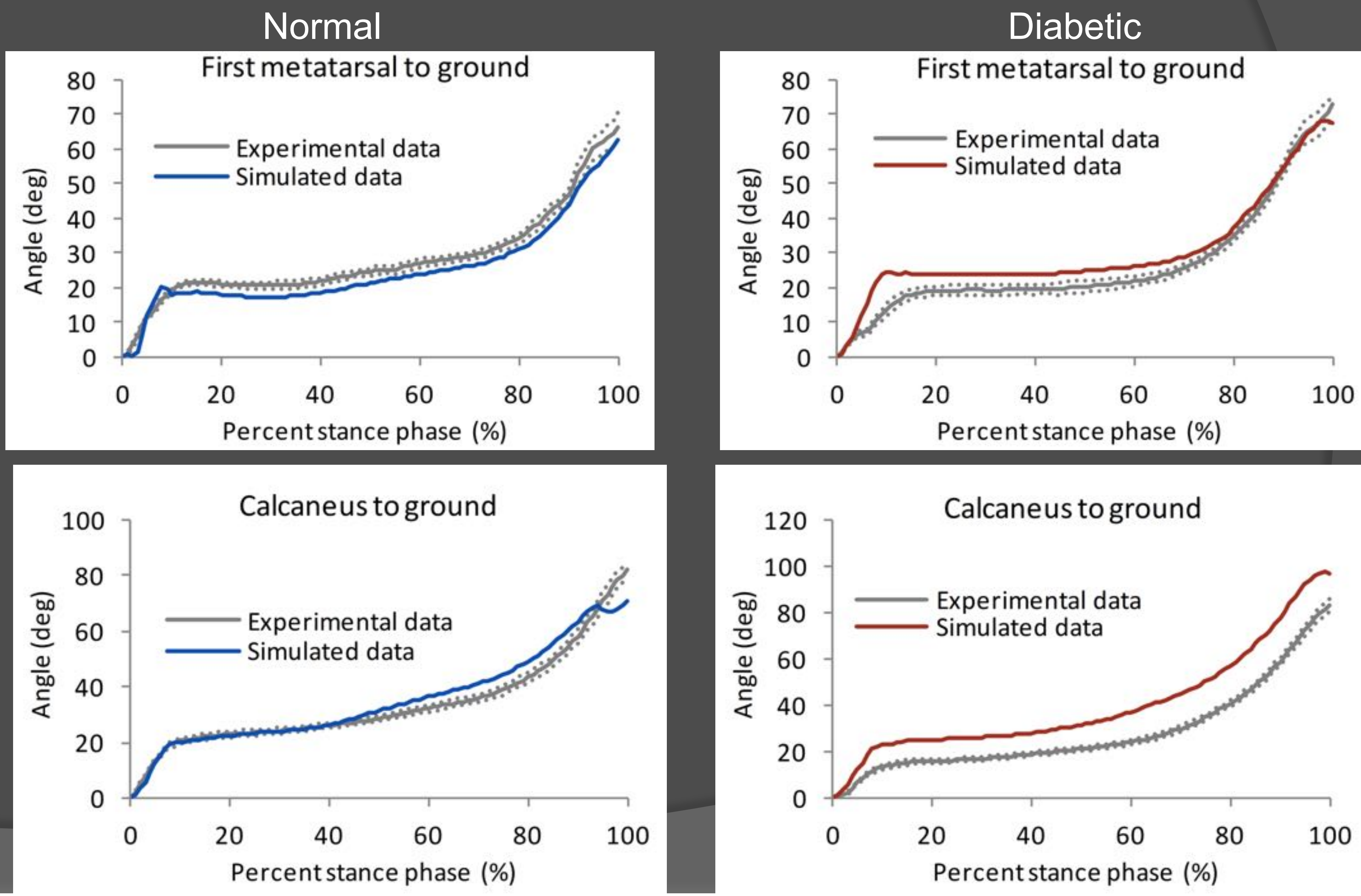
Normal



Diabetic

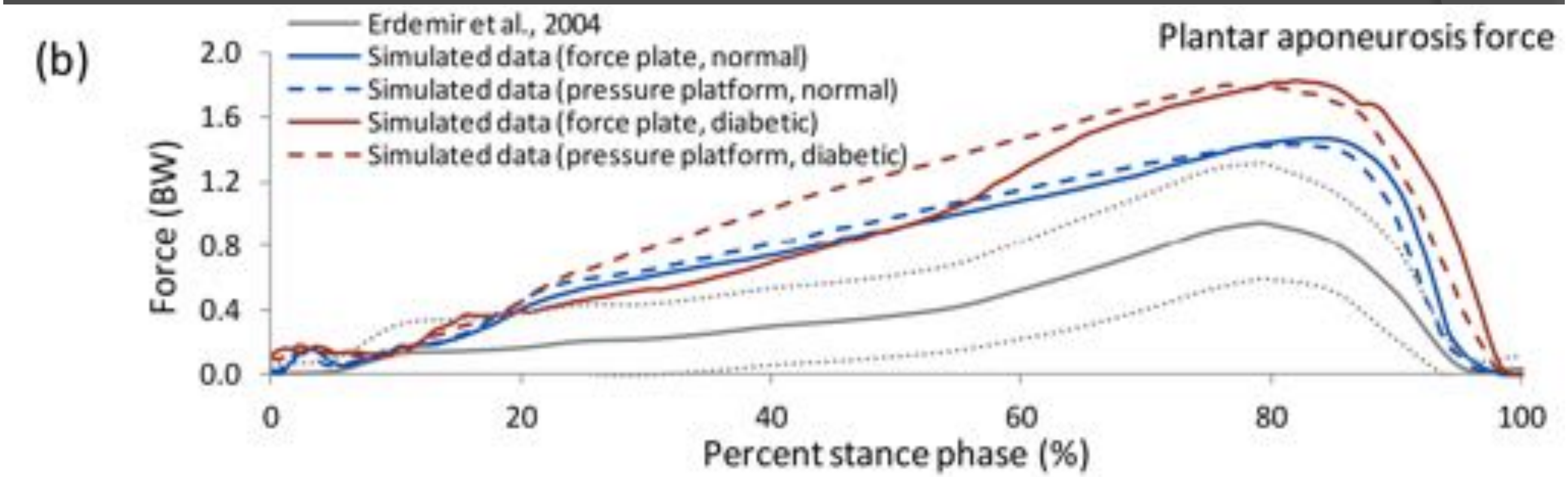


Gait: Bone-to-ground angles



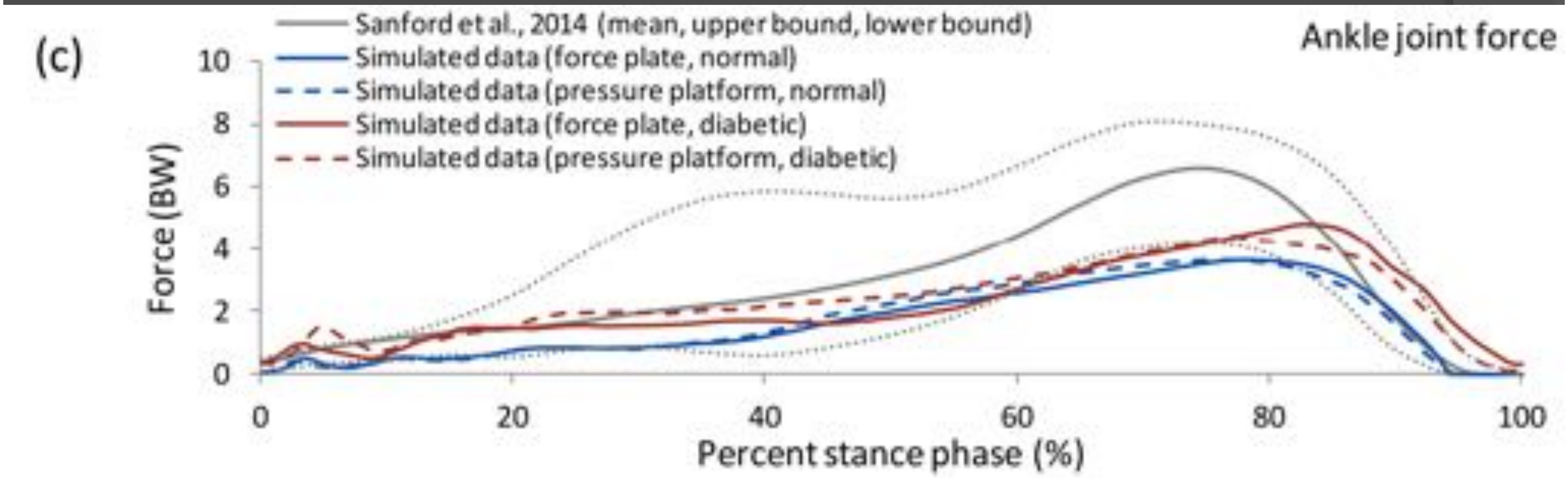
Gait: Plantar fascia force

- Cadaveric experimental results vs FE model



Gait: Ankle joint force

- In vivo inverse dynamic results vs FE model

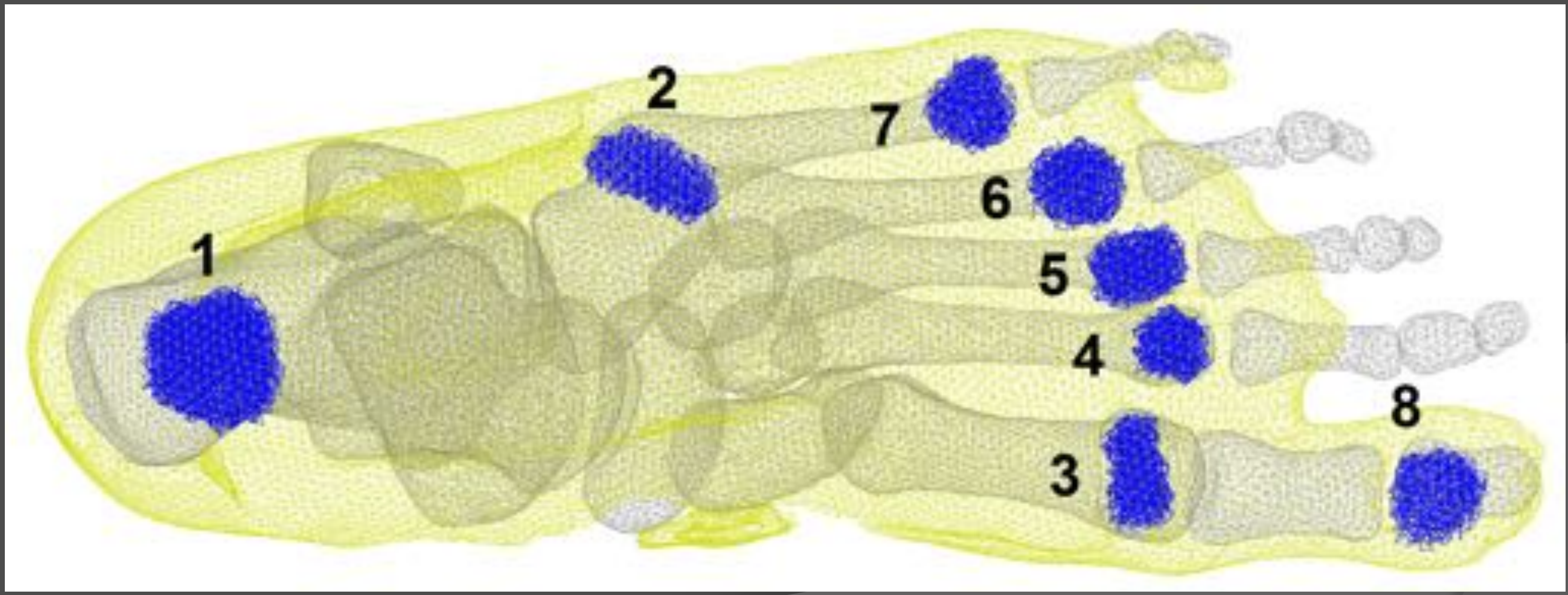


Model prediction

- Internal stress
- Parametric analysis on the effect of soft tissue assumptions on plantar pressure and internal stress

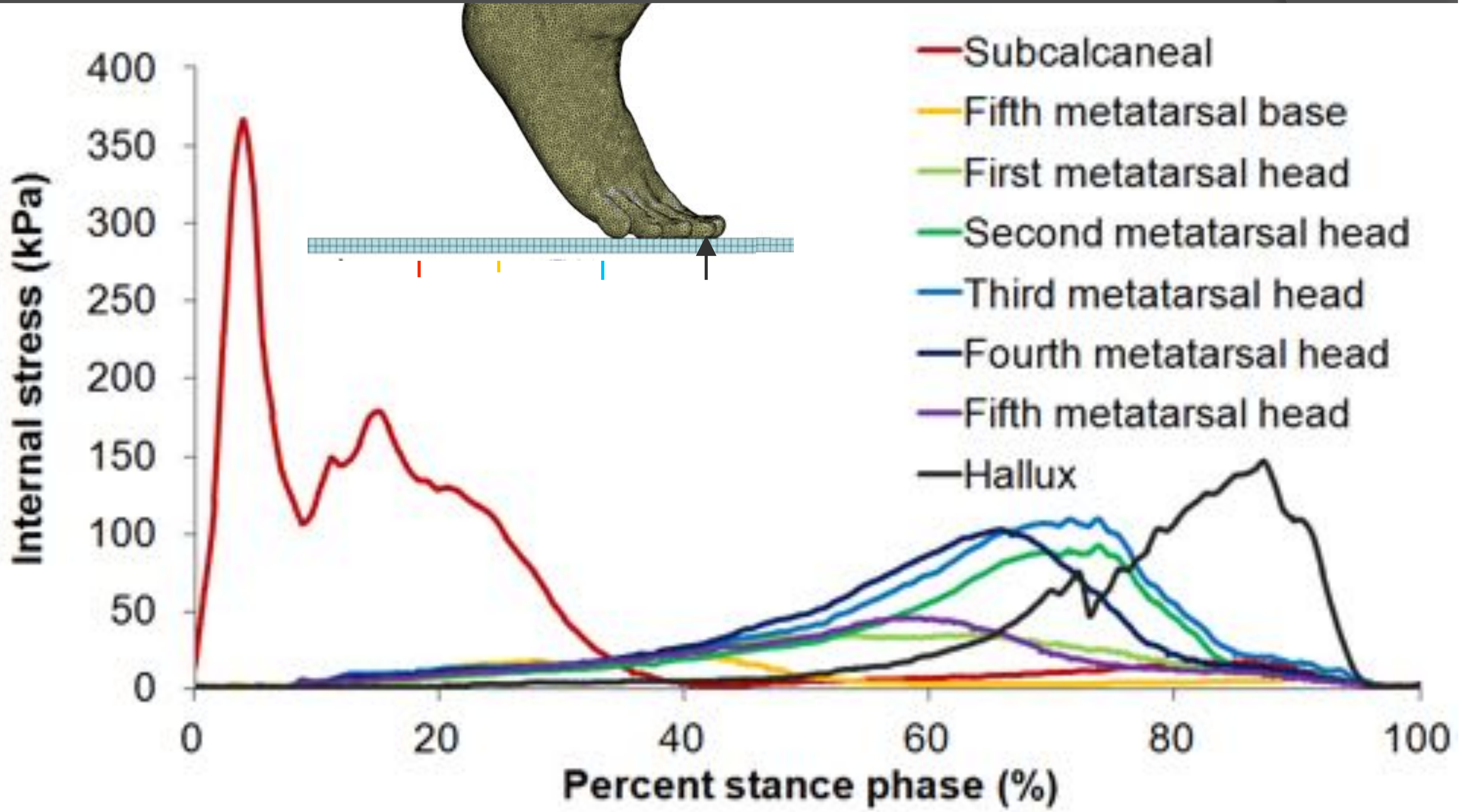
Model prediction: Internal stress

- 8 locations in the plantar fat (ulcer risk locations)
- Calculated stress in terms of mean Von Mises stress[1]
- 1000 elements/region (3000 at the subcalcaneus)

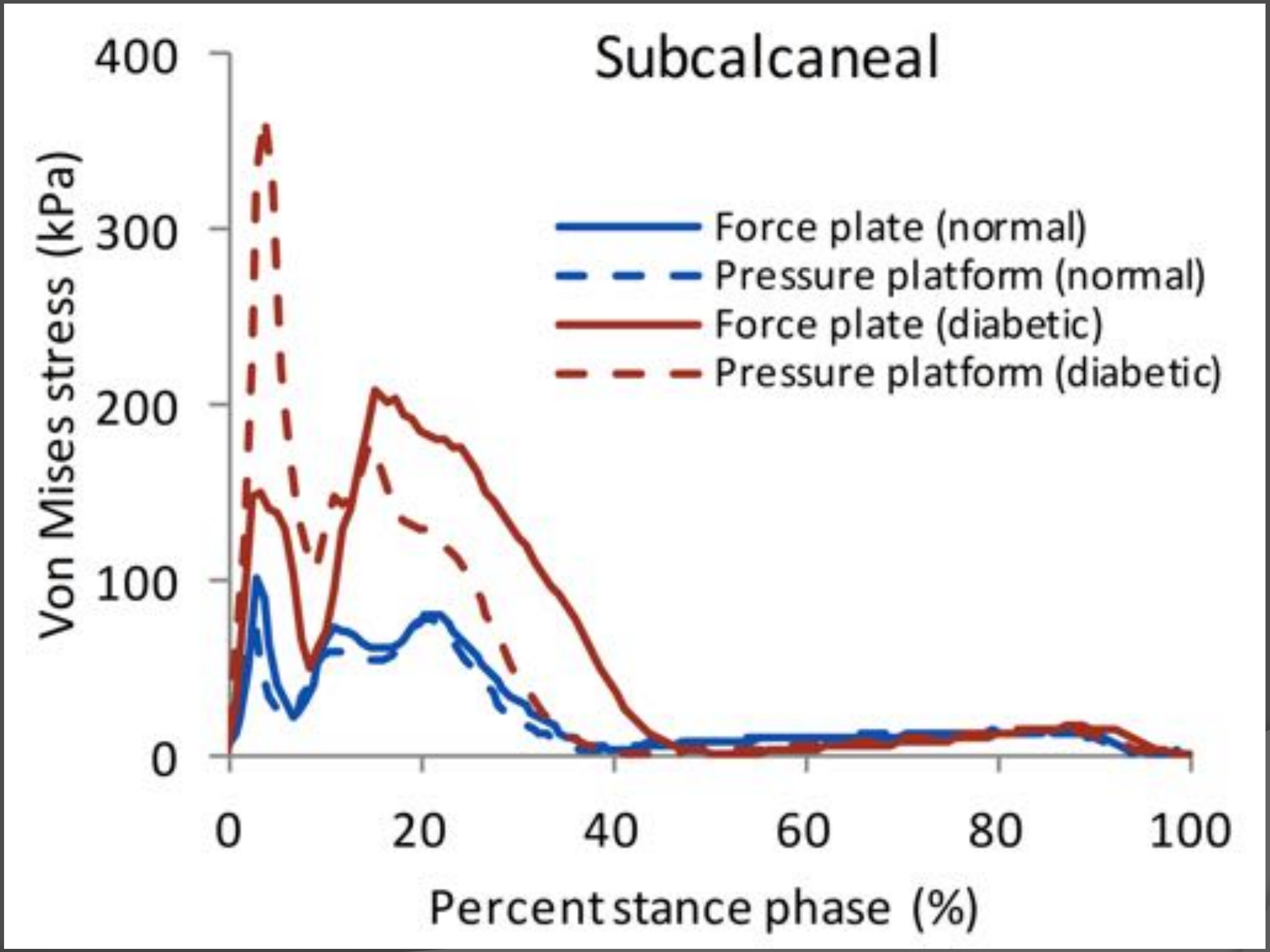


1 [Gefen et al., 2003, *Med. Eng. Phys.*, **6**: 491-499

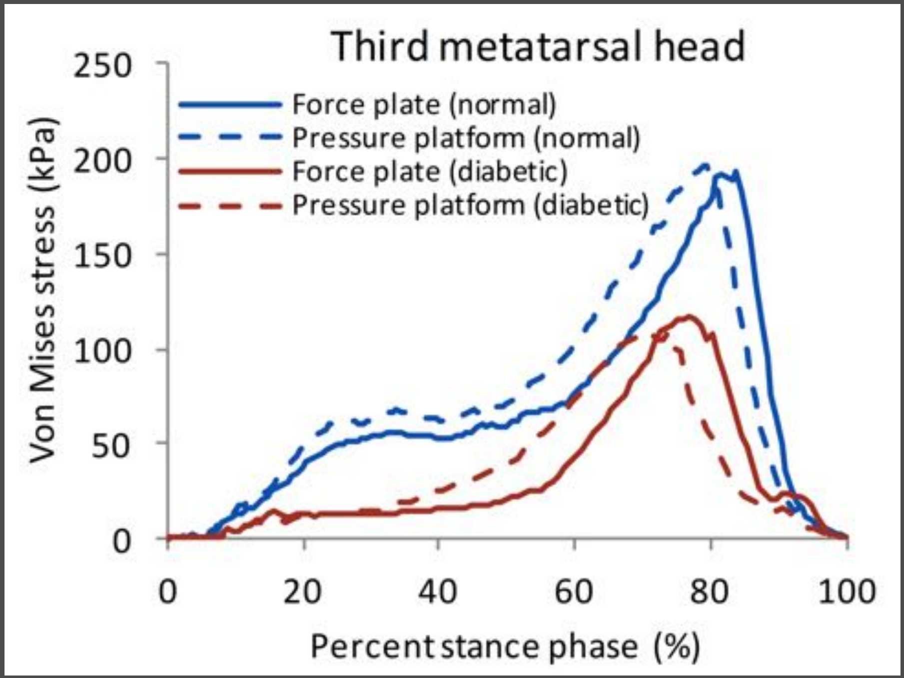
Model prediction: Internal stress

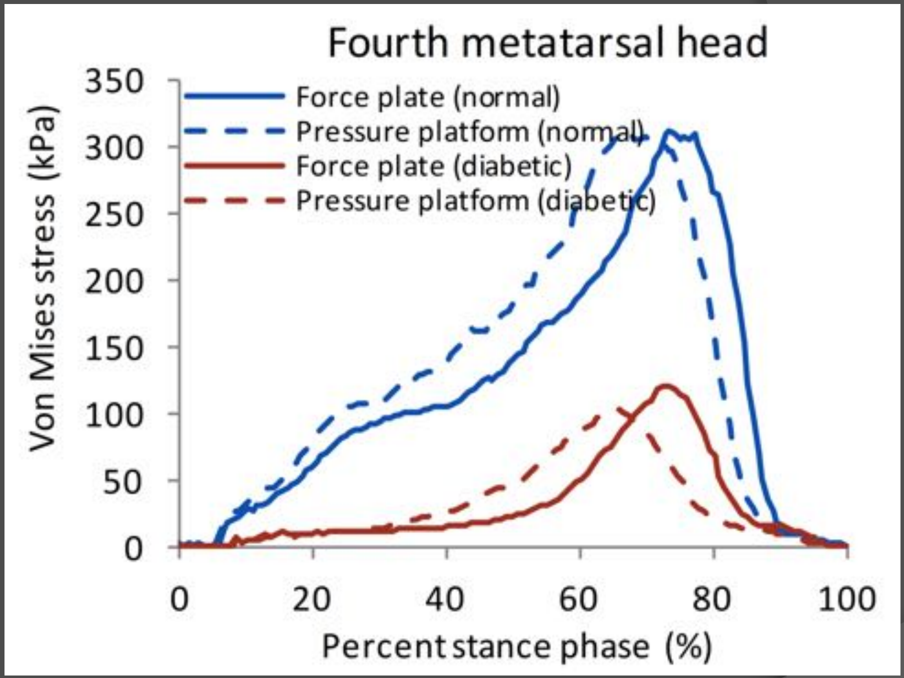


Model prediction: Internal stress

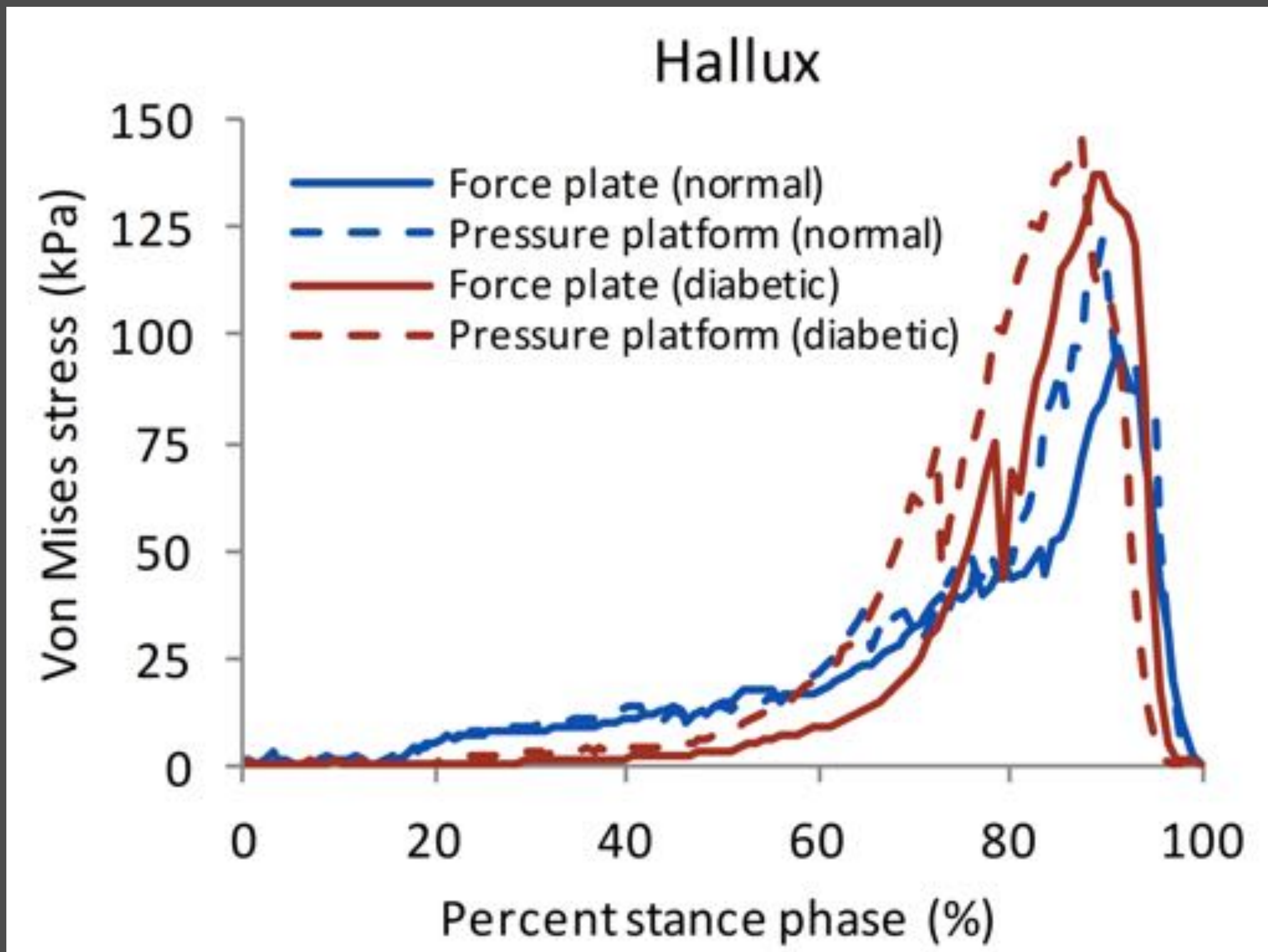


Model prediction: Internal stress





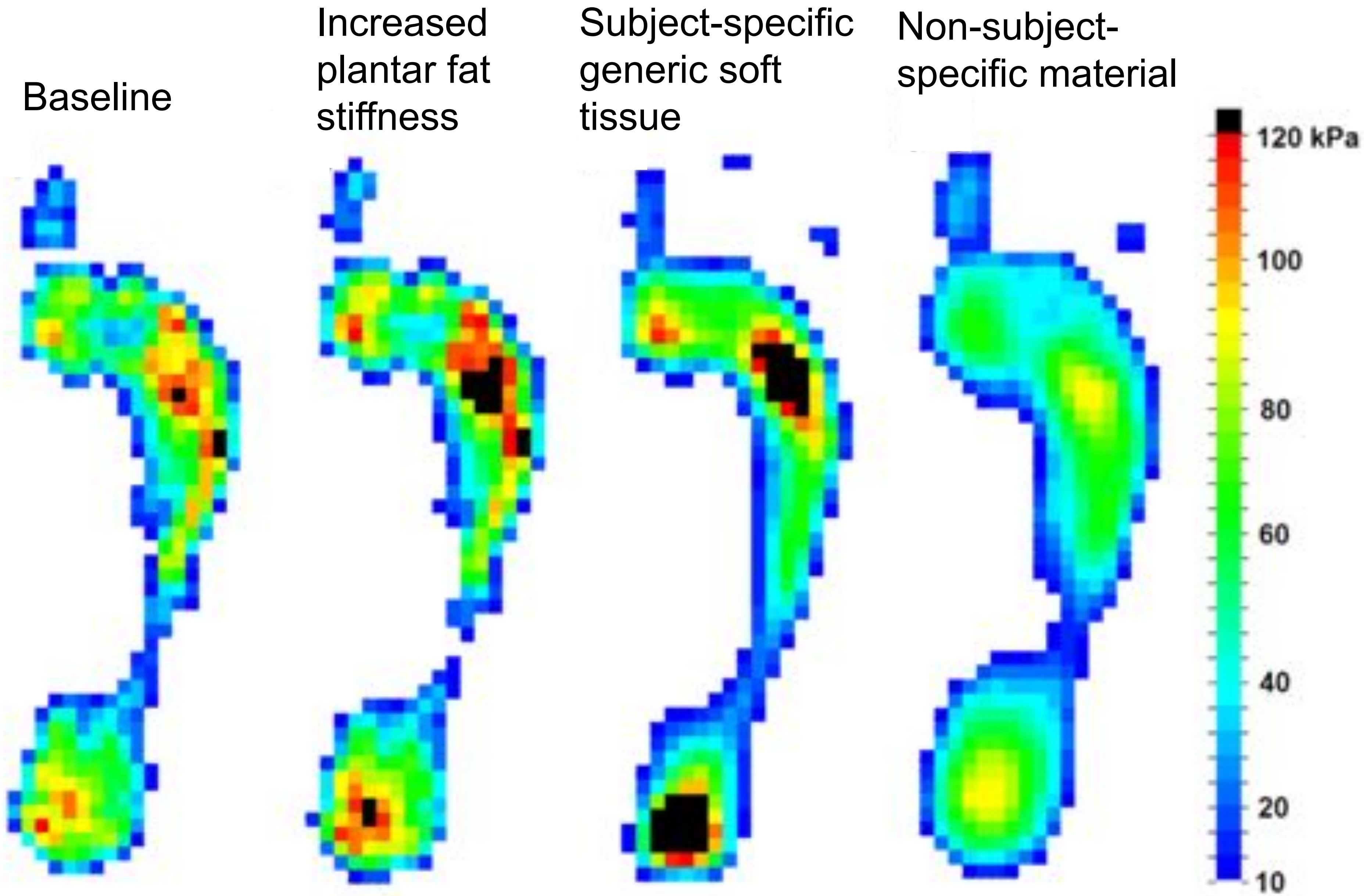
Model prediction: Internal stress



Model prediction: Parametric study

- The effect of soft tissue material properties on plantar pressure and internal stress in quiet stance
  - 2X increased plantar fat stiffness
  - Generic soft tissue assumption
  - Non-subject-specific soft tissue assumption

Quiet stance plantar pressure



Conclusion

- Subject-specific FE foot models
  - Subject-specific anatomy, soft tissue material properties and tibial kinematics
  - Improved plantar fascia component
  - Improved ligament, tendon structures and joint cavity
  - Extensive static and dynamic model validations