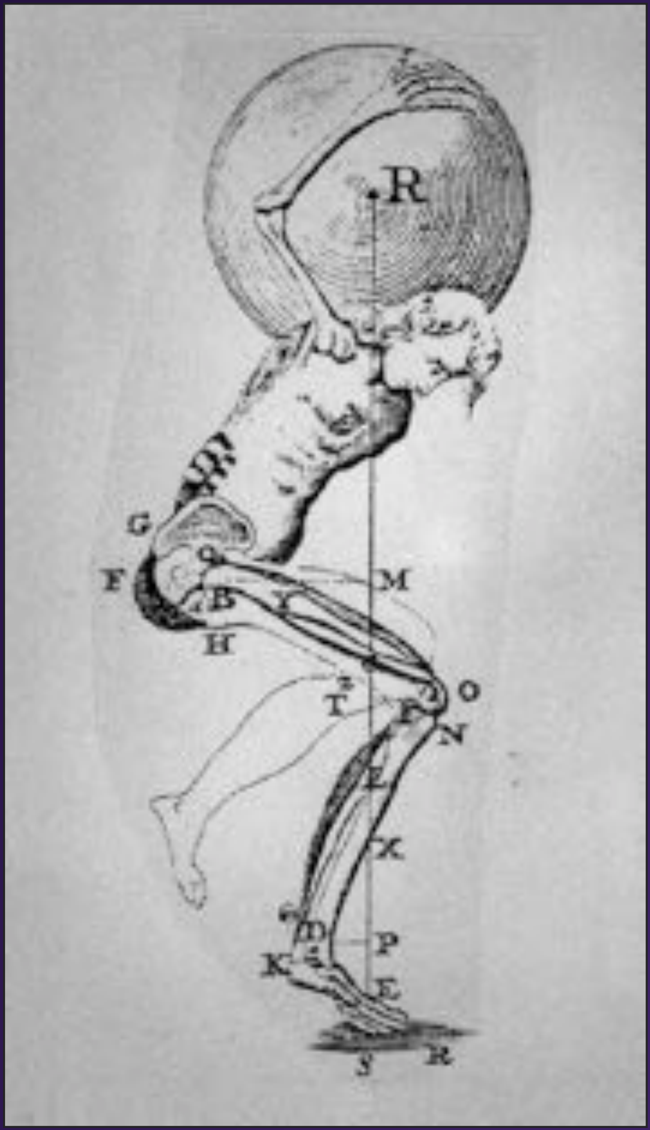


Musculoskeletal Biomechanics

BIOEN 520 | ME 527

Session 16A

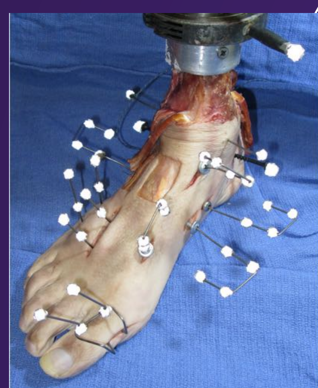
Biomechanics of the Foot and Ankle

Session 16A Overview...

- Foot and ankle
- Anatomy
- General function
- Pathology

Quantifying Foot Function

There are three ways to study part of the body: living subjects, cadavers, and computation models. Our group employs all three.



Foot

Limb Loss Prevention

- Functional limb loss
  - Relevant pathologies:
    - Ankle OA (arthrodesis vs. arthroplasty)
    - Foot type (high arch v. neutral v. flatfoot)
  - Research thrusts:
    - Robotic gait simulation
    - Biplane fluoroscopy

Limb Loss Prevention

- Functional limb loss
  - Ankle osteoarthritis:
    - Affects ~6% of the population, $370M per year
    - Veterans have a higher incidence of ankle OA
      - Huch 1997, Health Care Utilization Proj., Shibuya 2011
  - Foot types:
    - Veterans have a higher incidence of flatfoot
    - 308M Americans (2010), 21.8M Veterans, 9M older 65 years
    - Foot pathologies are more prevalent in older populations
      - Shibuya 2011, www.census.gov, Gould 1980

Limb Loss Prevention

- Anatomical limb loss
  - Relevant pathologies:
    - Diabetes
  - Research thrusts:
    - Cadaveric tissue testing (diabetic v. non-diabetic)
    - MRI-compatible loading device
    - Patient-specific computational modeling

Limb Loss Prevention

- Anatomical limb loss
  - Despite declining amputation rates among diabetic subjects and Veterans, amputations are still an important problem
    - Li 2012, Tseng 2011
  - In 2010, 8% of population has diabetes, but had over 60% of non-traumatic amputations. Over 65,000 amputations in 2006.
    - CDCP 2011
  - Veterans have 2x to 3x incidence of diabetes
    - VHA 2004

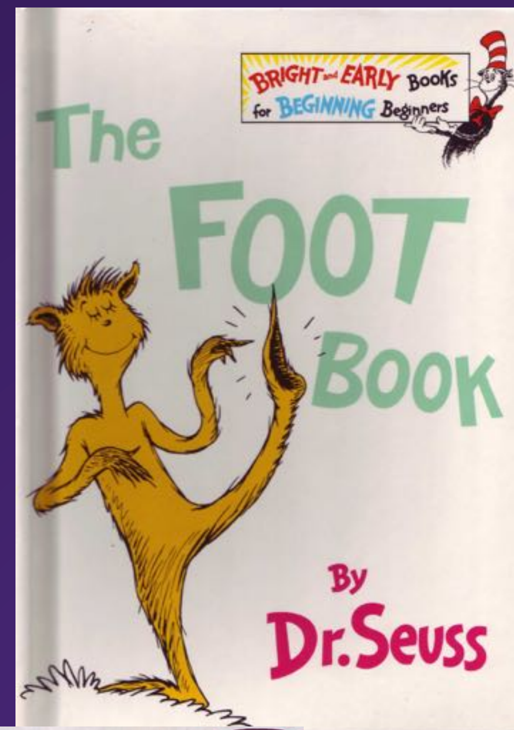
Why Study Feet?

"Although peripheral vascular disease has long been implicated in lower limb problems in the diabetic patient, it is now well-recognized that the majority of injuries to the foot, principally ulcers, are a consequence of mechanical trauma not recognized by the patient because of neuropathy."

Cavanagh, 2001, The Diabetic Foot

Why Study Feet?

"Left foot, Right foot, Left foot, Right.
Feet in the morning, Feet at night.
Left foot, Right foot, Left foot, Right.
Wet foot, Dry foot, Low foot, High foot.
Front feet, Back feet, Red feet, Black feet.
Left foot, Right foot, Feet, Feet, Feet.
How many, many feet you meet.
Slow feet, Quick feet, Trick feet, Sick feet.
Up feet, Down feet, Here come clown feet.
Small feet, Big feet, Here come pig feet.
His feet, Her feet, Fuzzy fur feet.
In the house, and on the street,
how many, many feet you meet.
Up in the air feet, Over a chair feet.
More and more feet, Twenty-four feet.
Here come more and more and more feet.
Left foot, Right foot, Feet, Feet, Feet.
Oh, how many feet you meet!"



Why Study Feet?

"If you want to make someone forget the troubles of the world, have them wear tight shoes."

- Confucious (via Bruce Sangeorzan)

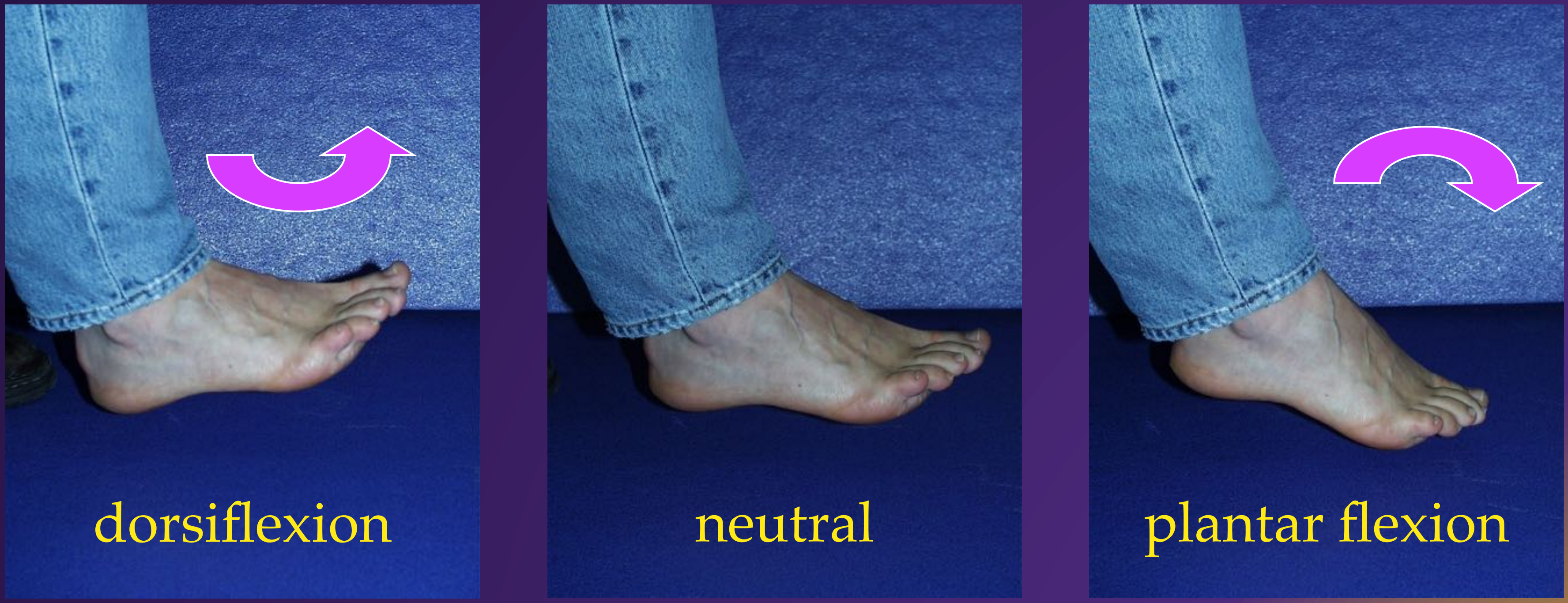
Why Study Feet?

“To address all of these issues, you need valid, objective, 3D tools.”

- William Ledoux (just now)

Foot: motion

sagittal plane

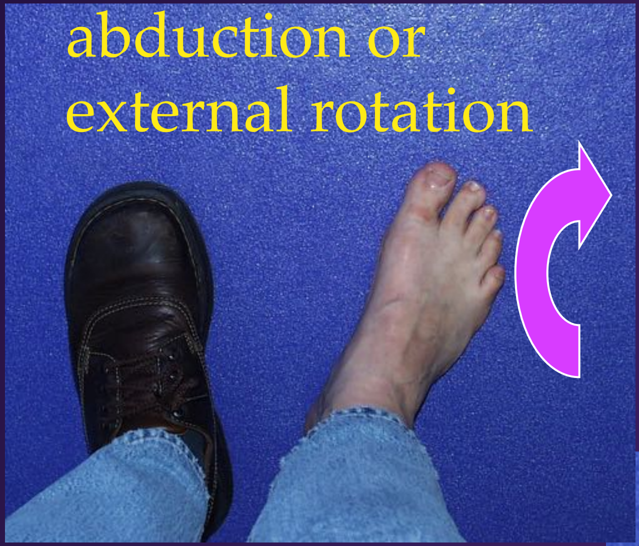


Foot: motion

frontal plane

Foot: motion

transverse plane



Foot: motion

- Pronation
  - dorsiflexion
  - abduction/external rotation
  - eversion/valgus
  - flat foot
- Supination
  - plantar flexion
  - adduction/internal rotation
  - inversion/varus
  - high arched foot

- issues with pronation and supination:
  - works well for hand, but not for foot due to 90˚ ankle
  - neutral position vs. anatomic position
  - in some texts, refers to pure frontal plane motion
  - in flat foot (hyperpronated foot or pes planus), forefoot actually supinated relative to hindfoot

Foot and ankle anatomical terms

- Discuss the foot with ankle at 90˚ (i.e., neutral position) and not with the ankle plantar flexed (i.e., anatomical position), except if we are taking about the toes.
- Avoid use of pronation/supination (see last slide); instead discuss motion/position in specific cardinal planes.
- Coronal rather than frontal (minor point)

Foot and ankle anatomical terms

- Sagittal plane motion at all joints is referred to as dorsiflexion/plantar flexion.
- Hindfoot (calcaneus to tibia, calcaneus to talus, talus to tibia) ankle at 90˚
  - coronal plane motion = inversion/eversion (and position varus/valgus)
  - transverse plane motion = adduction/abduction or internal/external rotation

Foot and ankle anatomical terms

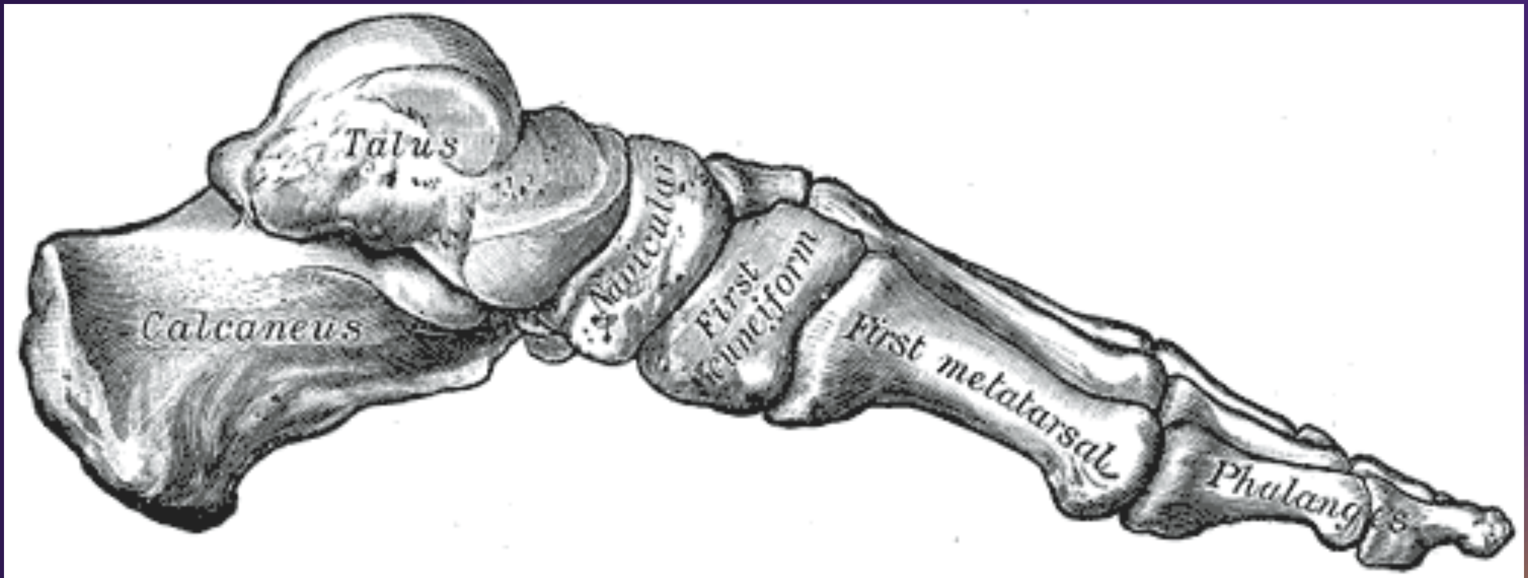
- Forefoot to hindfoot (first metatarsal to talus) ankle at 90˚
  - coronal plane motion = inversion/eversion (and position varus/valgus)
  - transverse plane motion = adduction/abduction or internal/external rotation
- Hallux to first metatarsal
  - coronal plane motion = inversion/eversion
  - transverse plane motion = varus/valgus
    - hallux valgus = bunion

Foot and ankle anatomical terms

- Use hindfoot not rearfoot
- Use neutrally aligned not rectus
- Can not say “pes planus foot type”, as that literally means “foot flat foot type”. Say “pes planus” or “planus foot type”.

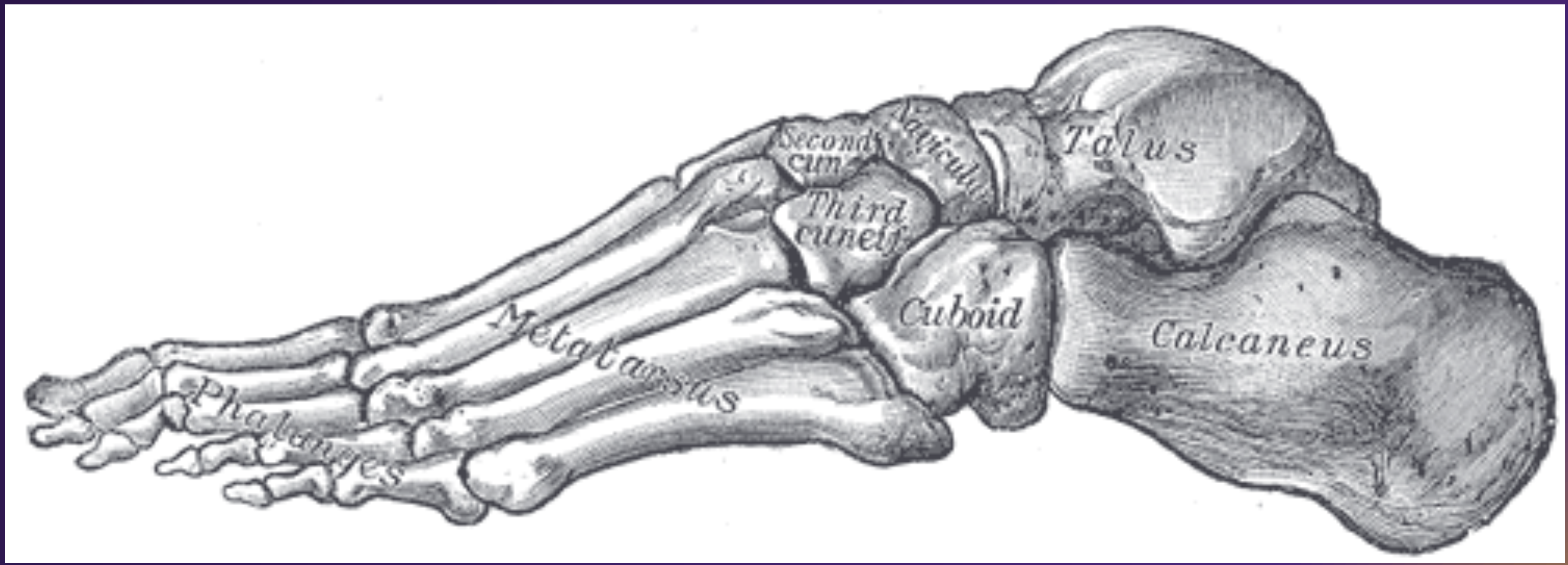
Foot: bony anatomy

medial column: calcaneus, talus, navicular, medial cuneiform, first metatarsal

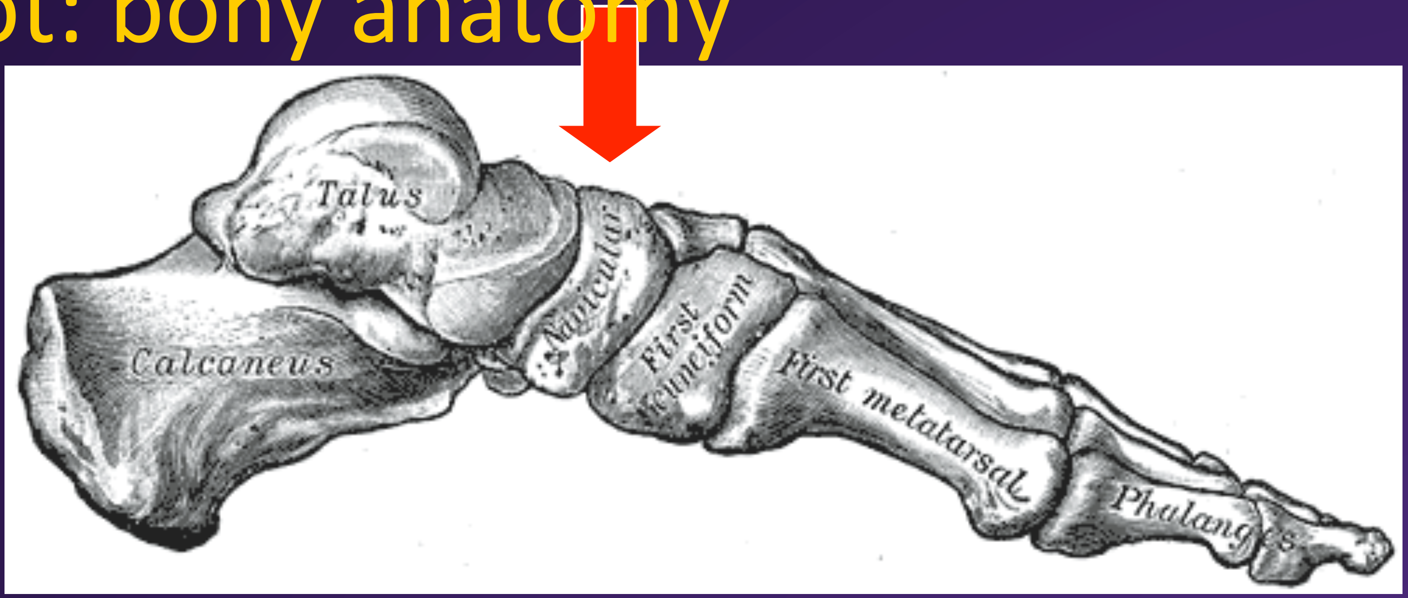


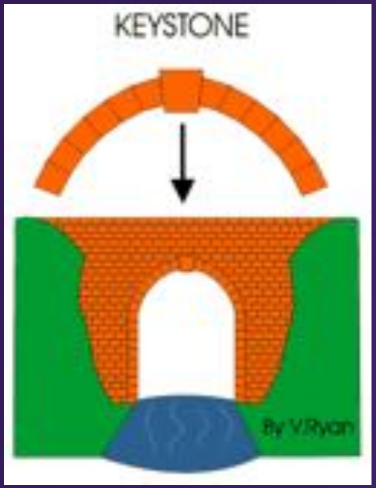
Foot: bony anatomy

lateral column: calcaneus, cuboid, fifth metatarsal



Foot: bony anatomy



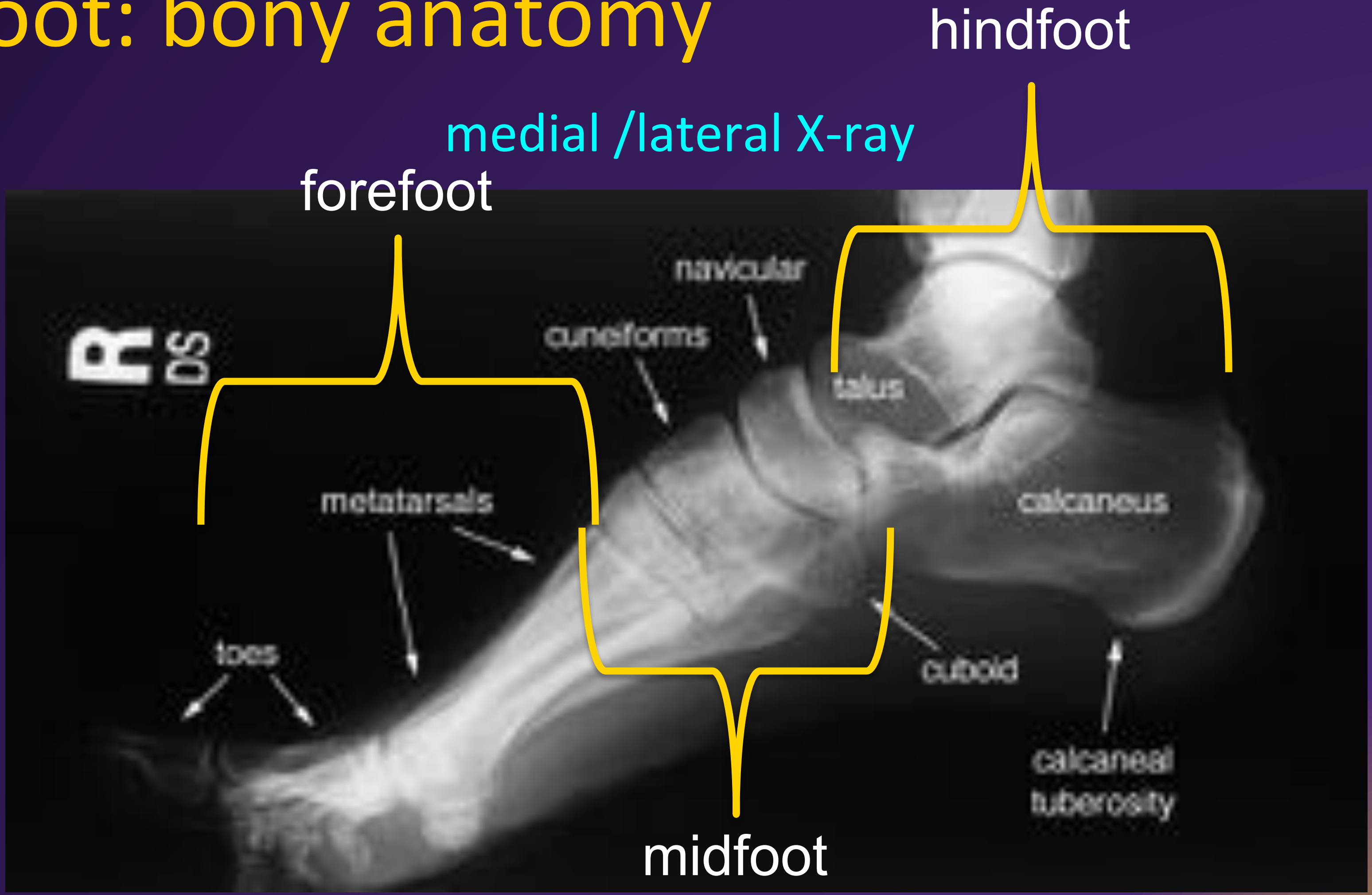


POND DE GARD (South of France)

http://www.technologystudent.com/struct1/arch1.htm

Foot: bony anatomy

medial /lateral X-ray



Radiographic Anatomy of the Skeleton, Michael L. Richardson, M.D.
http://www.rad.washington.edu/radanat/Foot.html

Foot: bony anatomy

anterior/posterior
or dorsal/plantar
X-ray

Radiographic Anatomy of the Skeleton,
Michael L. Richardson, M.D.
http://www.rad.washington.edu/radanat/Foot.html

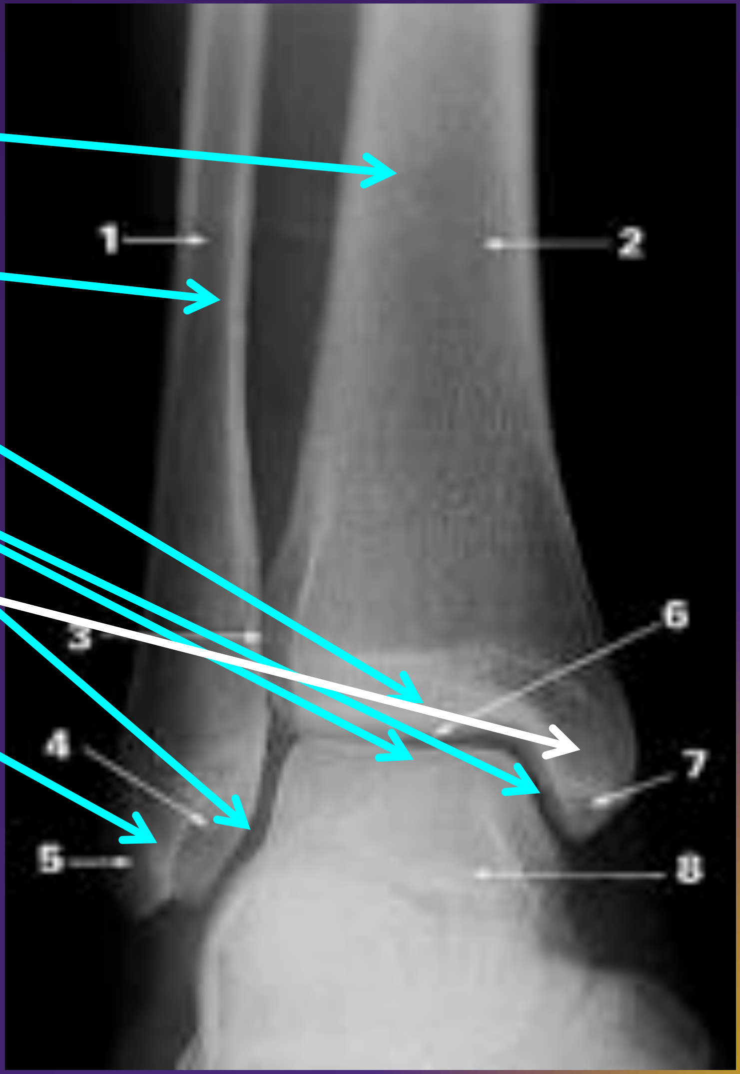
Foot: bony anatomy (n=28)

- hindfoot: calcaneus, talus, (tibia, fibula)
- midfoot: navicular, cuboid, and medial, intermediate and lateral cuneiform
- forefoot: metatarsals (n=5) and phalanges (n=14)
- ¼ of bones in the body (n=206)

Foot: bony anatomy

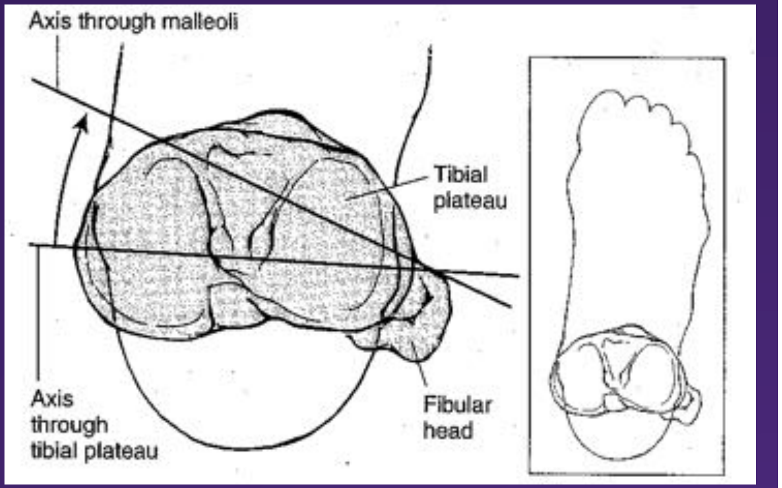
Foot & Ankle: Anatomy

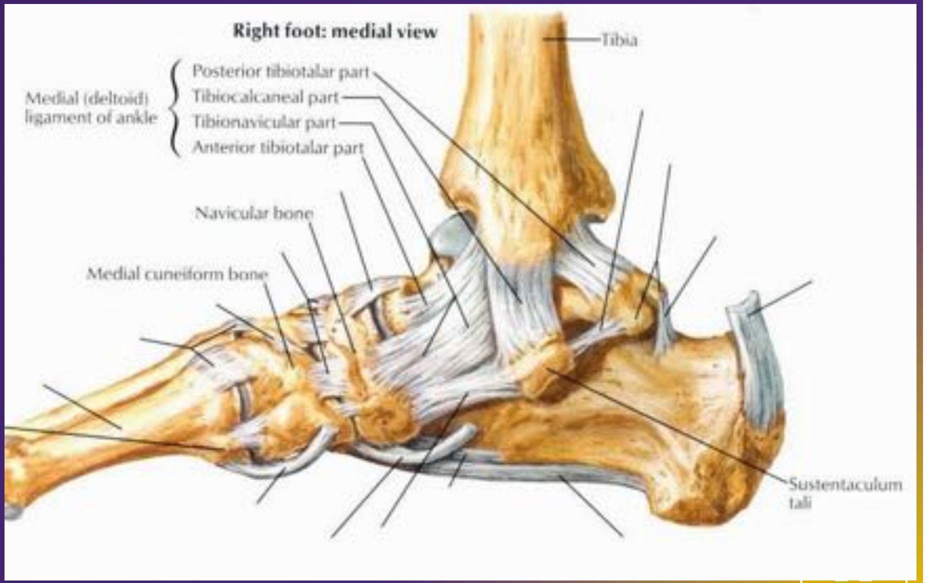
- distal leg:
  - tibia
  - fibula
  - tibial plafond
  - ankle mortise
  - medial malleolus
  - lateral malleolus
  - tibia = 85% load



Foot & Ankle: Anatomy

- ankle (talotibial) joint:
  - 20˚ - 40˚ tibial torsion
  - lateral ankle ligaments
  - medial ankle ligaments





Foot & Ankle: Anatomy

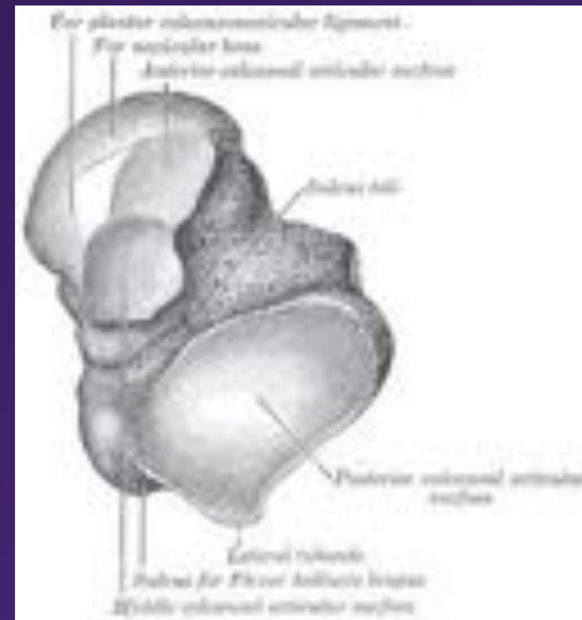
- talus

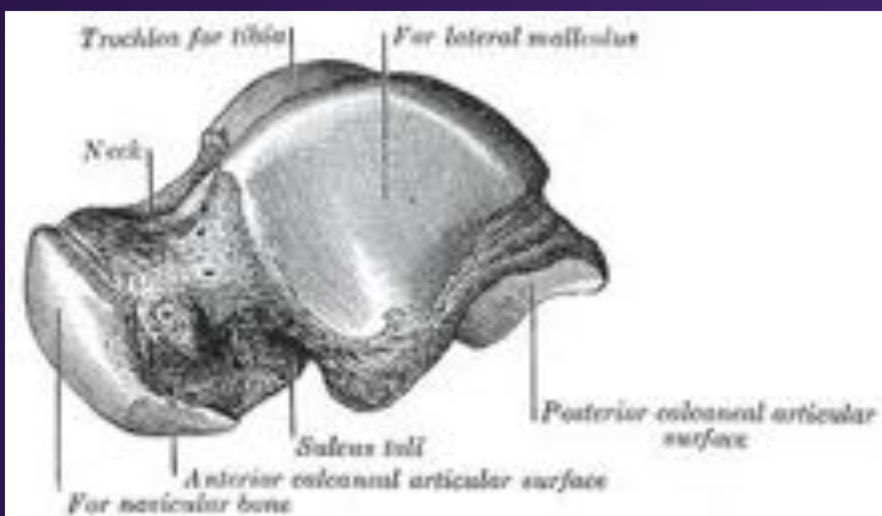
  "It's all about the talus."

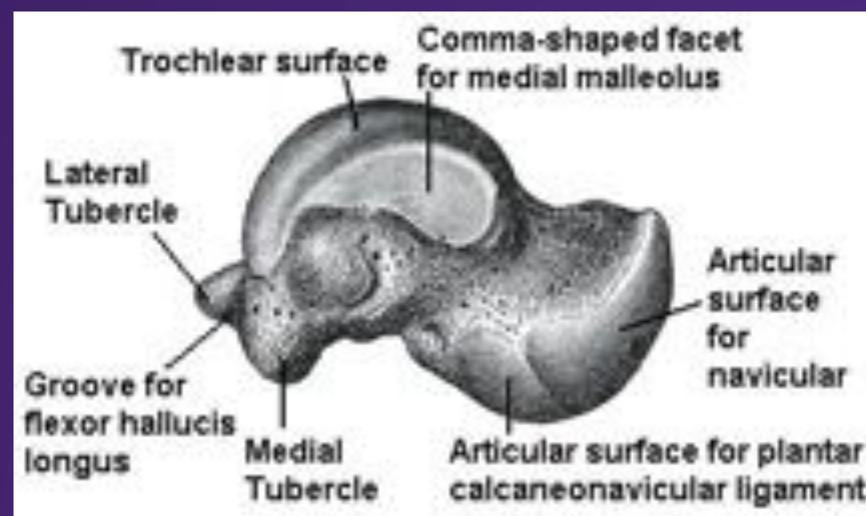
  vertical and horizontal load

  no muscles!

  dictates foot type



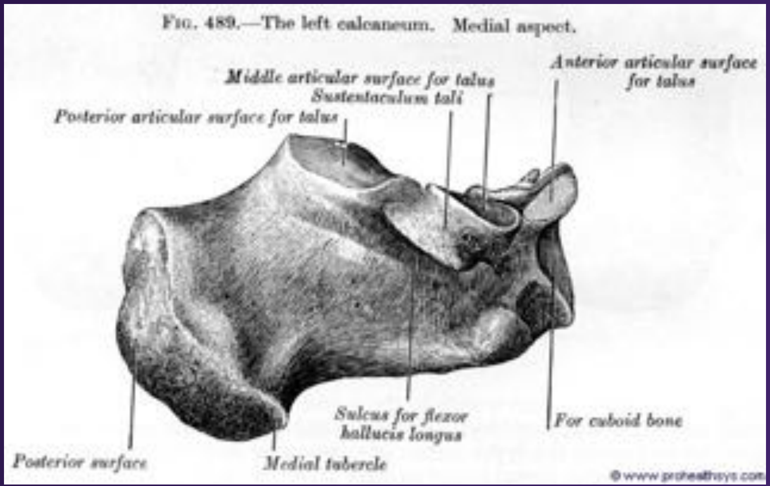


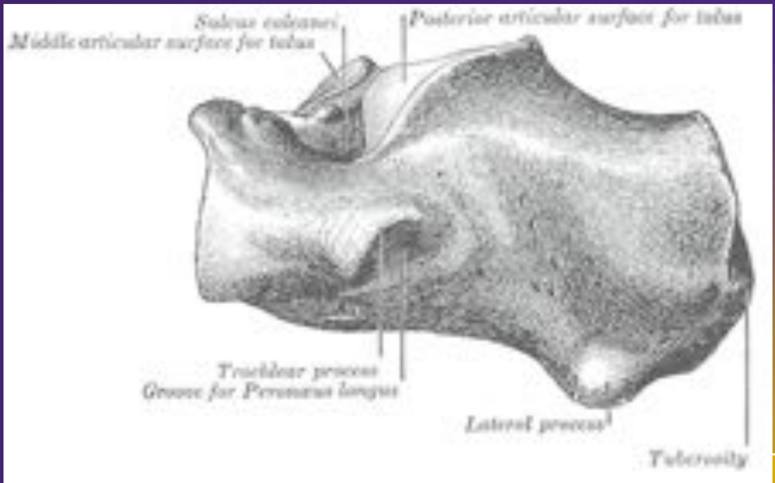


Foot & Ankle: Anatomy

- calcaneus
  - heel bone, largest foot bone
  - Achilles tendon
  - calcaneal tuberosity
  - sustentaculum tali

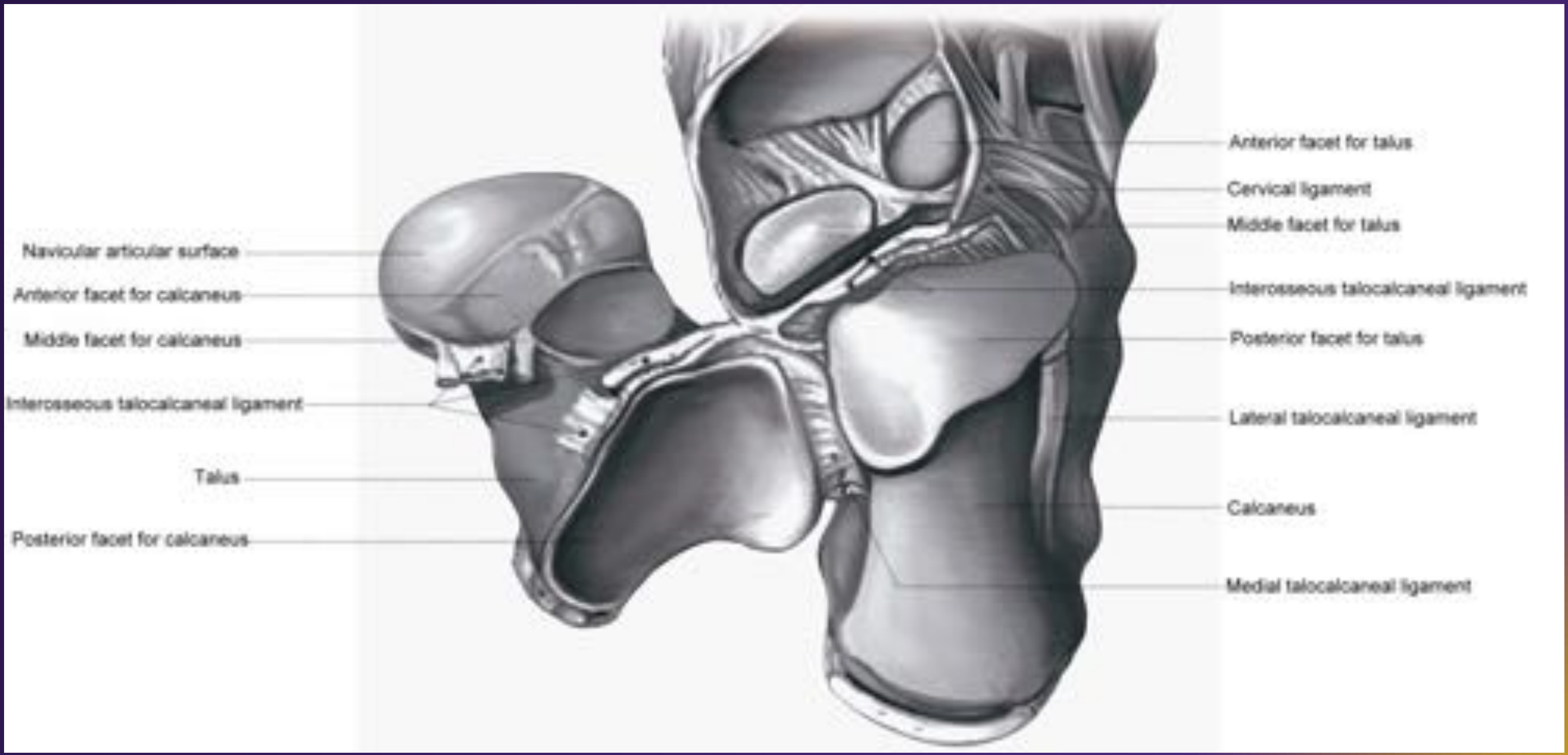
Fig. 489.—The left calcaneum. Medial aspect.





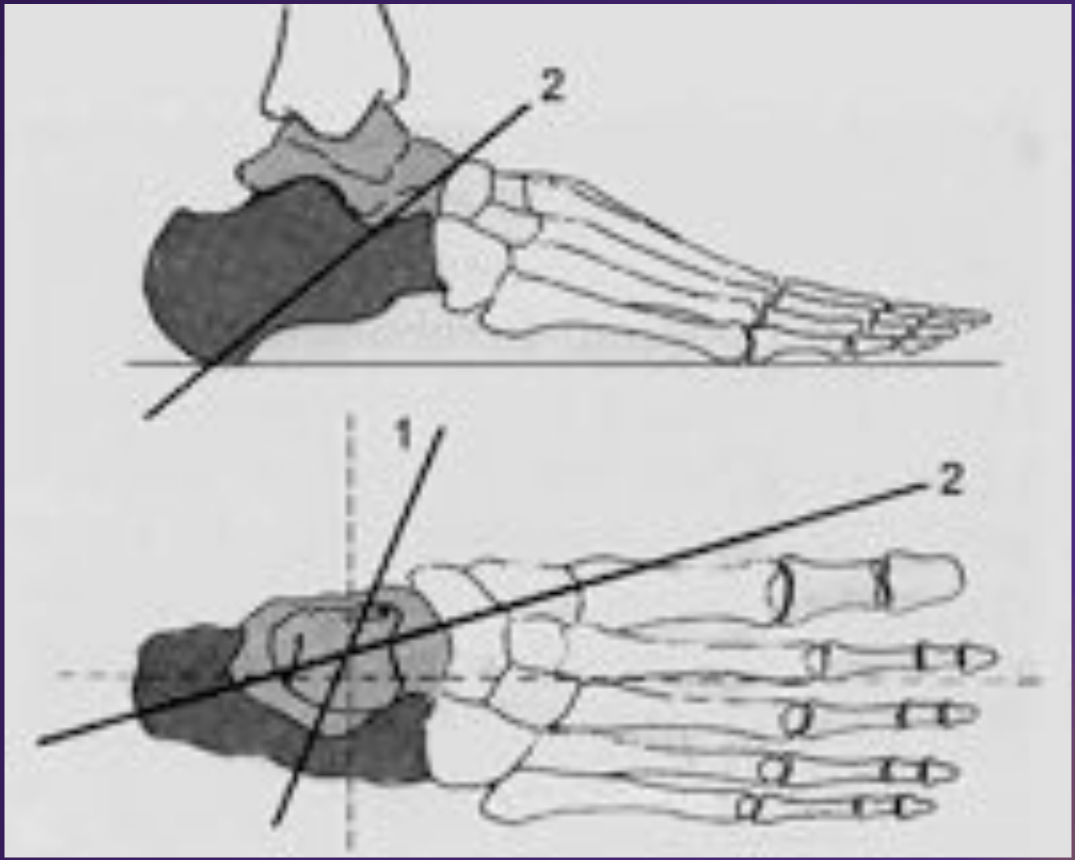
Foot & Ankle: Anatomy

- subtalar (talocalcaneal) joint:



Foot & Ankle: Anatomy

- subtalar (talocalcaneal) joint:
  43˚ in sagittal, 19˚ in transverse



Foot: joints (n=19 major, n=57 total)

- talocrural (ankle)
- talocalcaneal (subtalar)

Foot: joints (n=19 major, n=57 total)

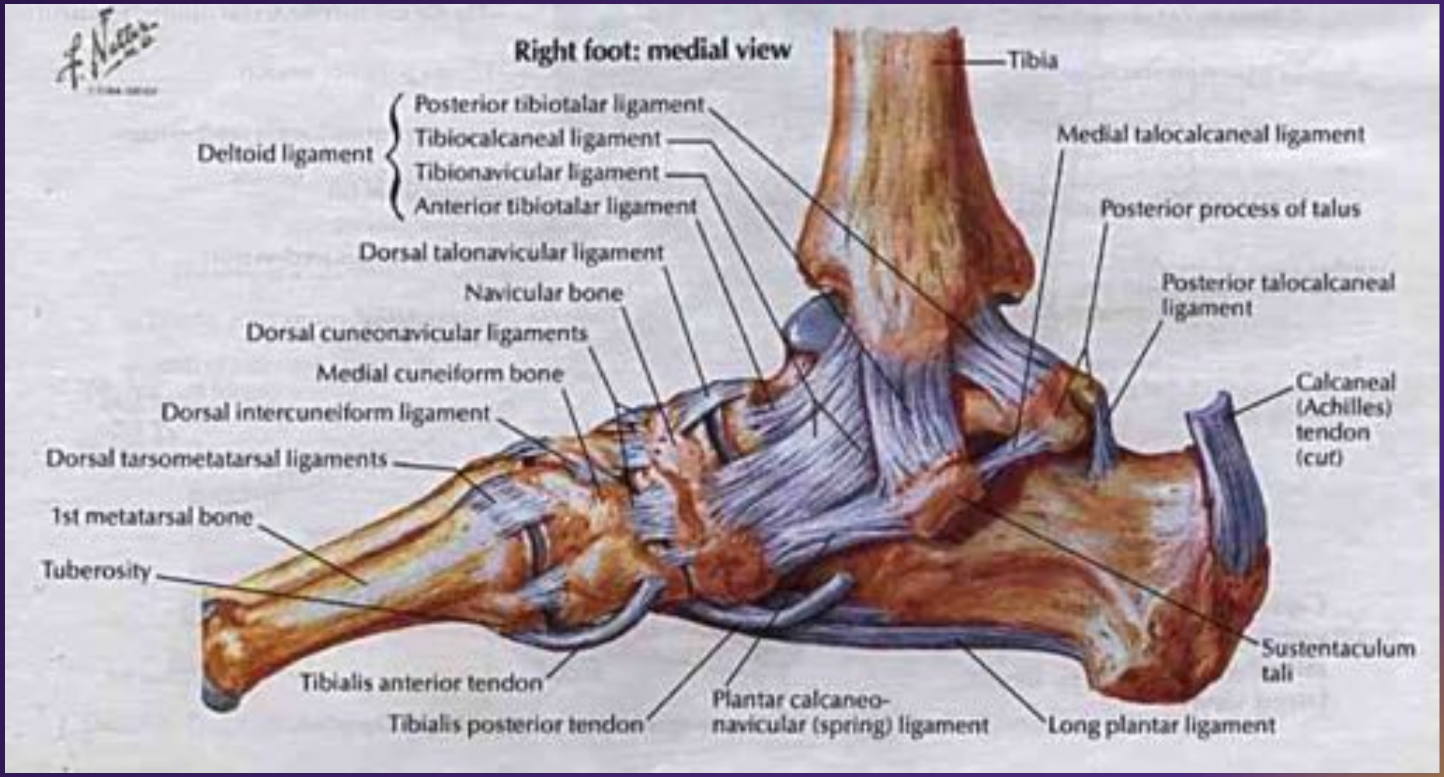
- talonavicular (Chopart's)
- calcaneocuboid (Chopart's)

Foot: joints (n=19 major,

- tarsometatarsal (Lisfranc's)
- first metatarsophalangeal

Foot: ligaments (n=108)

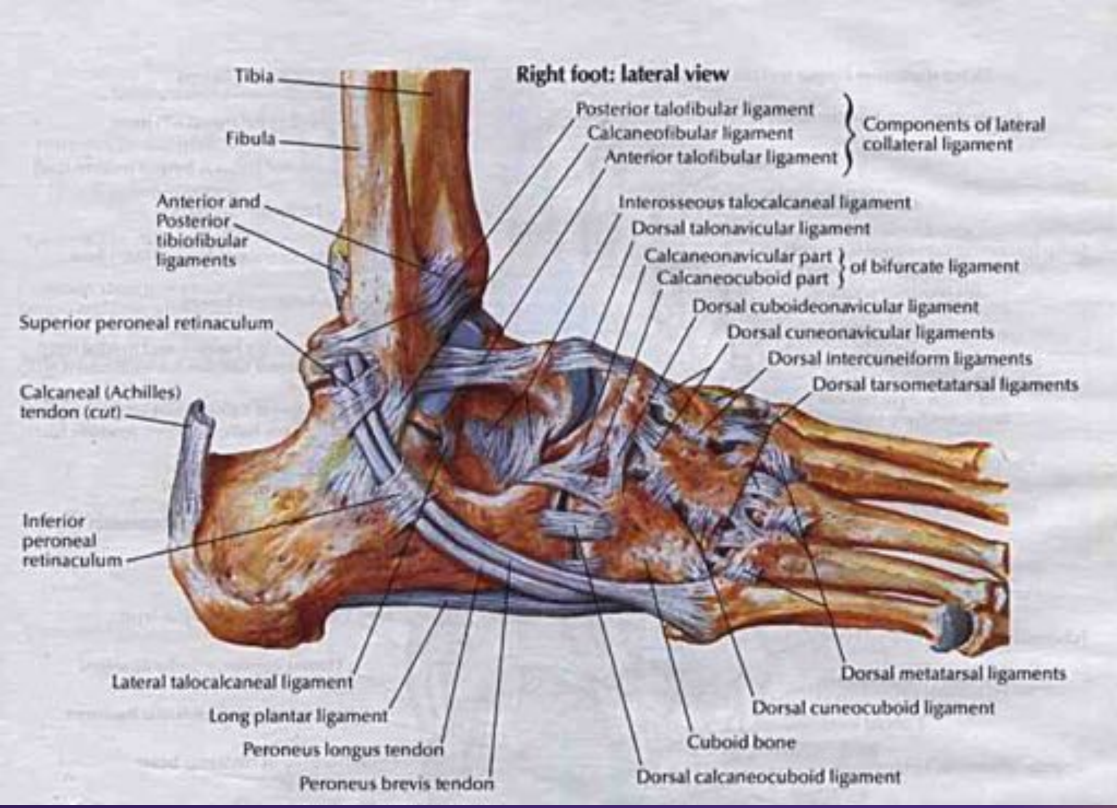
medial ligaments: deltoid



Frank Netter, Atlas of Human Anatomy

Foot: ligaments (n=108)

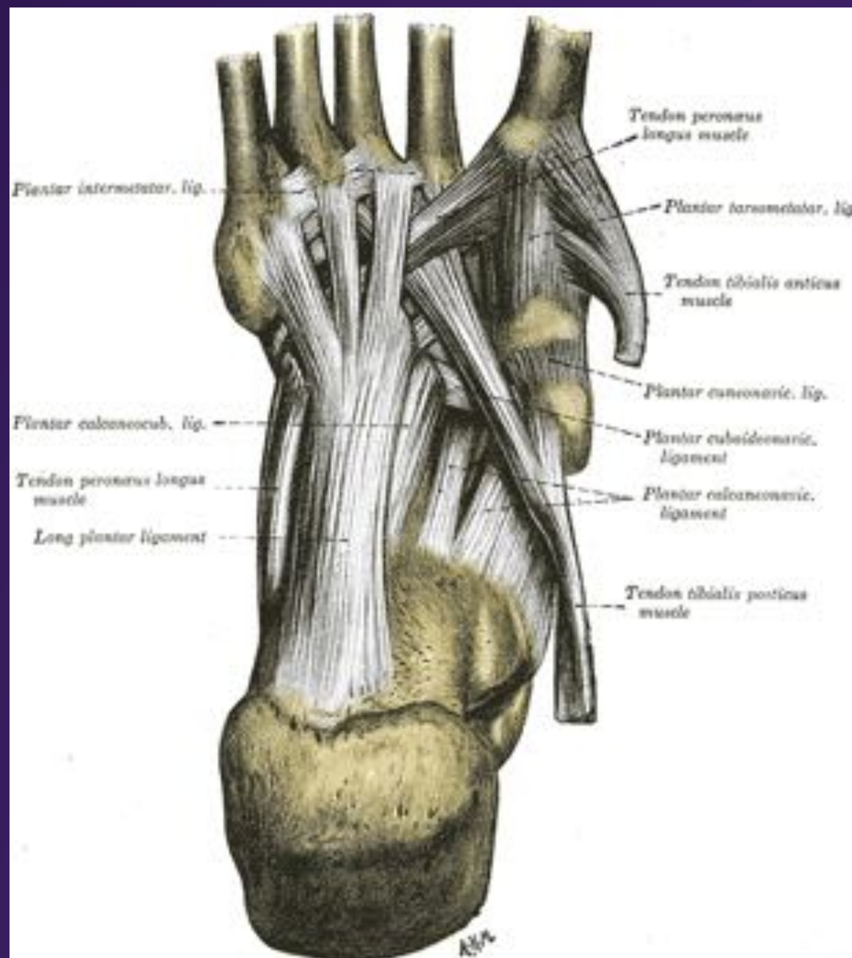
lateral ligaments: lateral collateral ligament



Frank Netter, Atlas of Human Anatomy

Foot: ligaments (n=108)

plantar ligaments: long plantar and spring

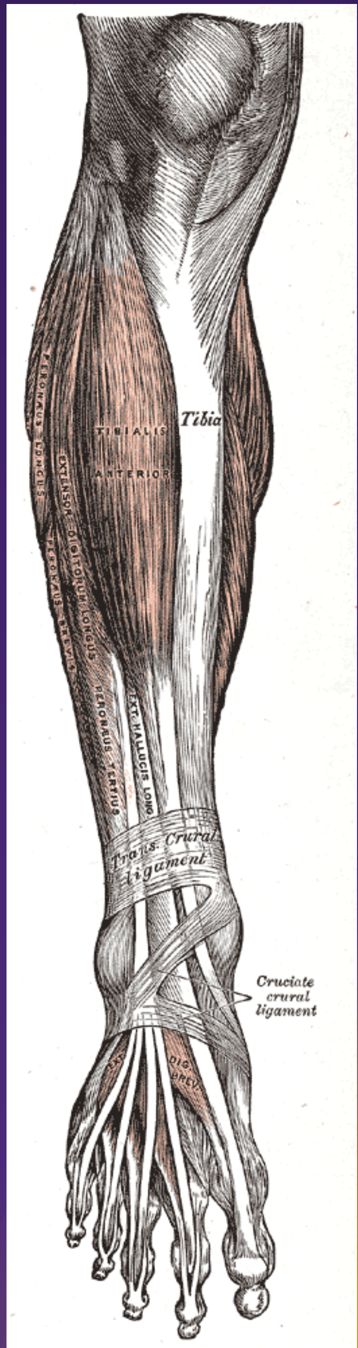


Gray's Anatomy, www.bartleby.com/107/

Foot: extrinsic muscles (n=12)

anterior extrinsic muscles (extra credit)

- tibialis anterior
- extensor hallucis longus
- extensor digitorum longus
- peronius brevis
- peronius longus
- peronius tertius



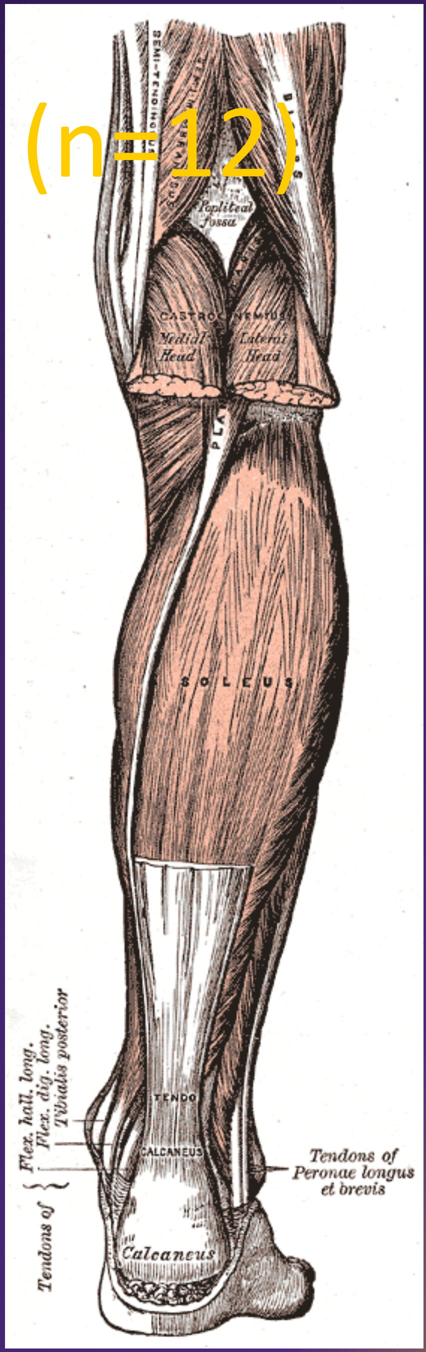
Gray's Anatomy, www.bartleby.com/107/

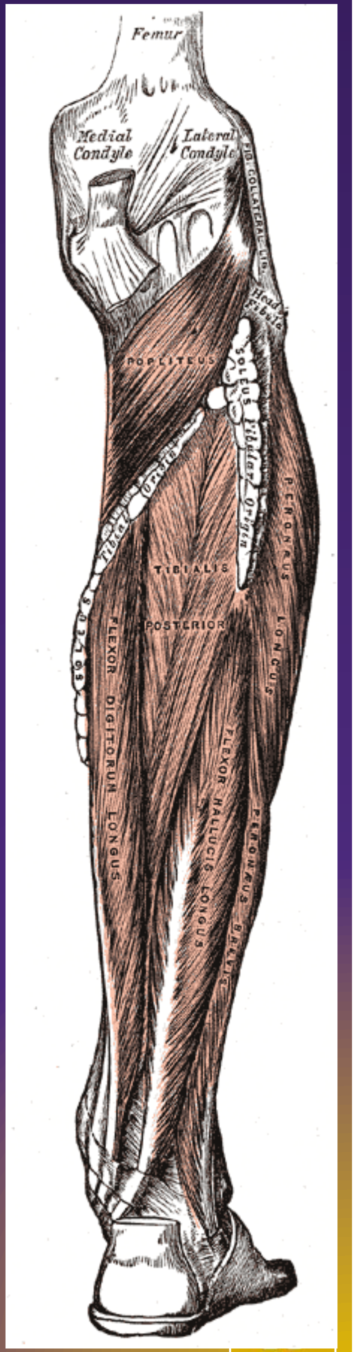
Foot: extrinsic muscles (n=12)

posterior extrinsic muscles (extra credit)

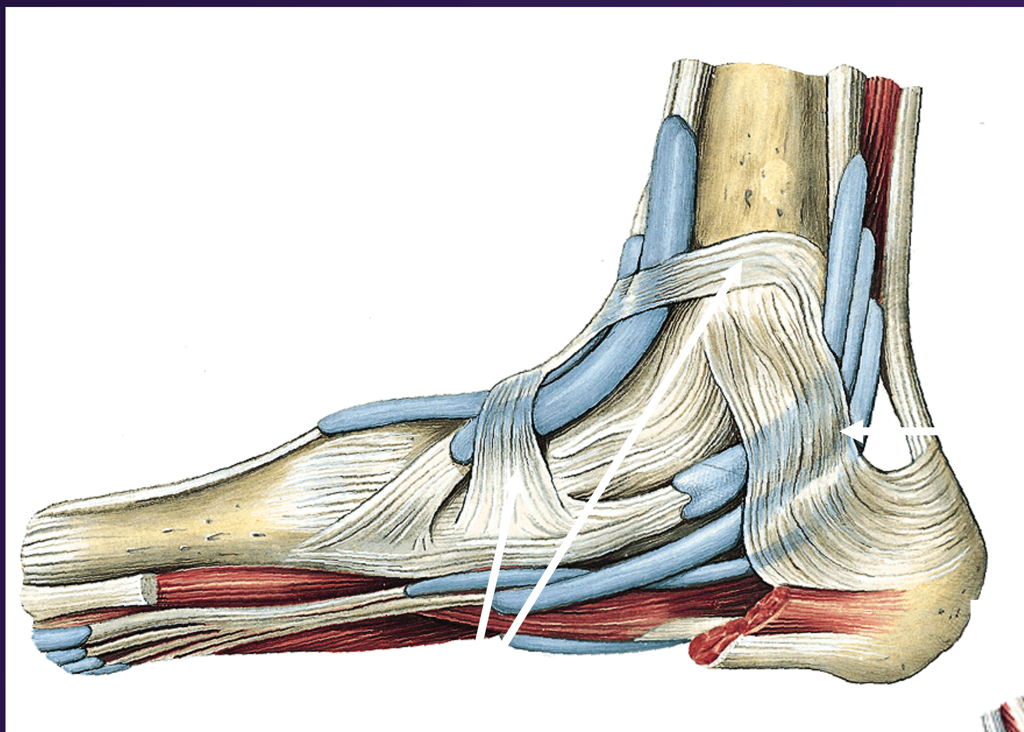
- soleus
- gastronemius
- tibialis posterior
- flexor hallucis longus
- flexor digitorum longus
- plantaris

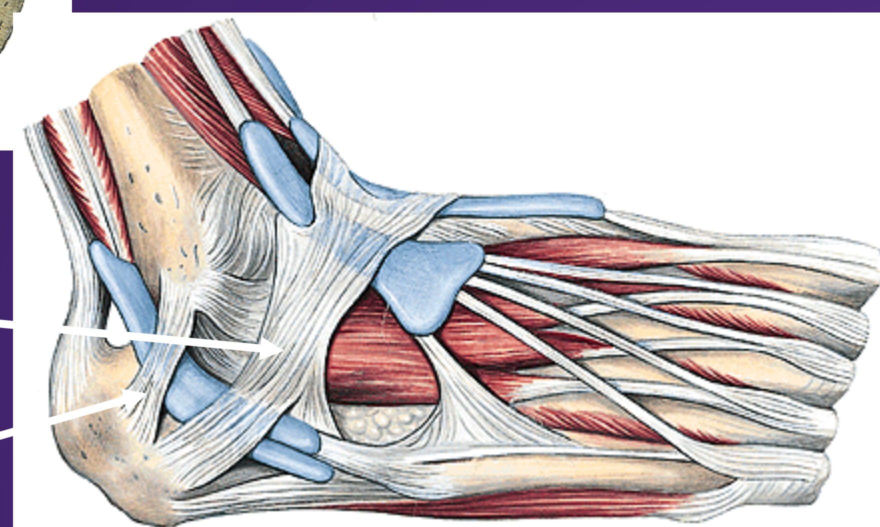
Gray's Anatomy, www.bartleby.com/107/





Foot: retinaculum





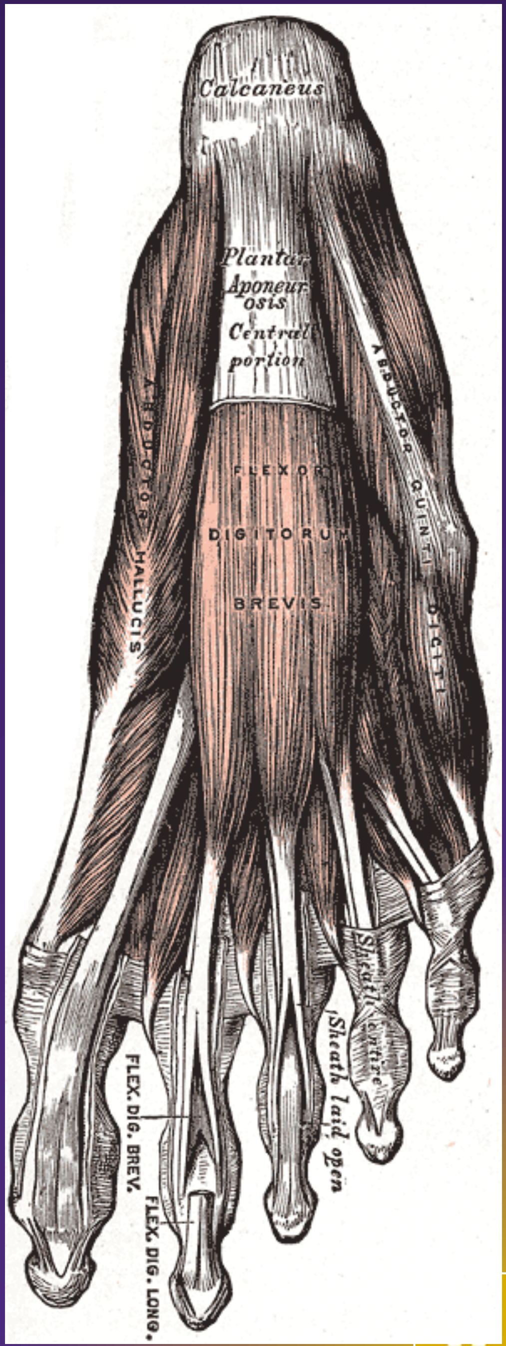
Flexor retinaculum

Extensor retinaculum

Peroneal (Fibular) retinaculum

Foot: intrinsic muscles (n=20)

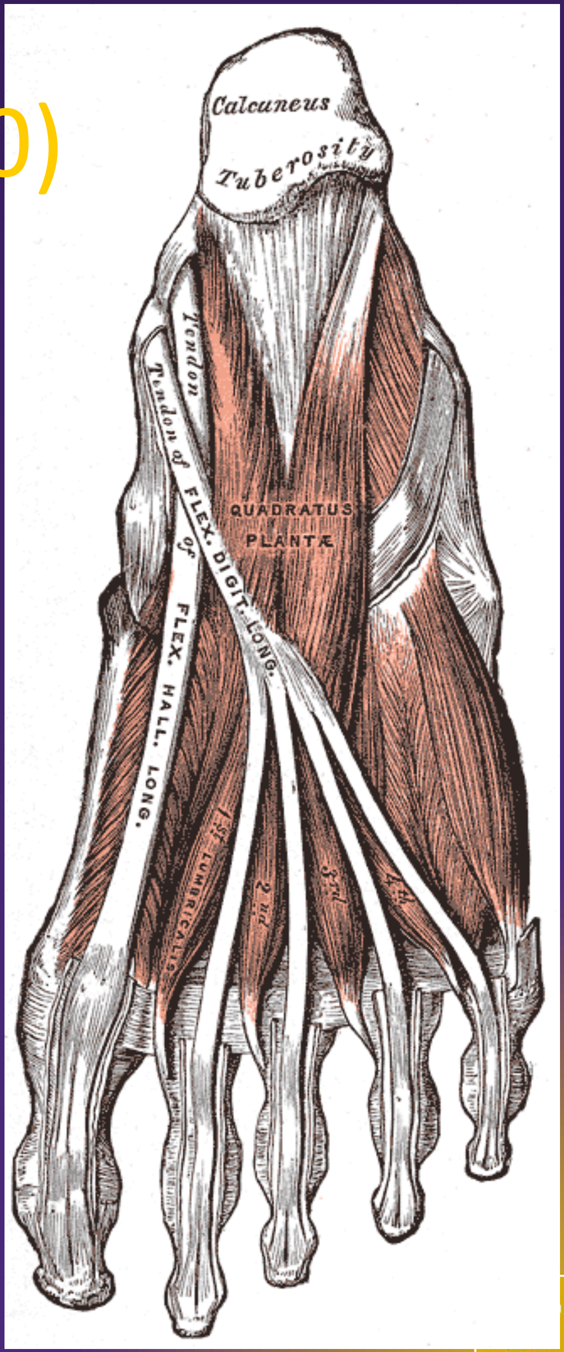
intrinsic muscles - layer 1



Gray's Anatomy, www.bartleby.com/107/

Foot: intrinsic muscles (n=20)

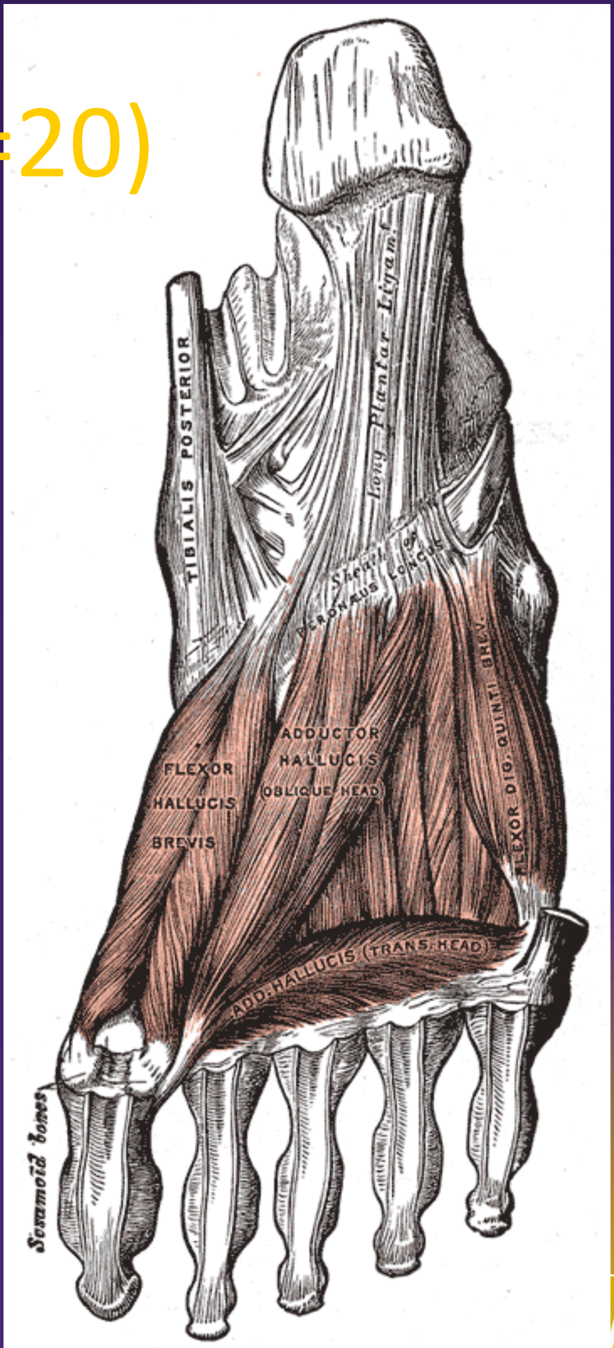
intrinsic muscles - layer 2



Gray's Anatomy, www.bartleby.com/107/

Foot: intrinsic muscles (n=20)

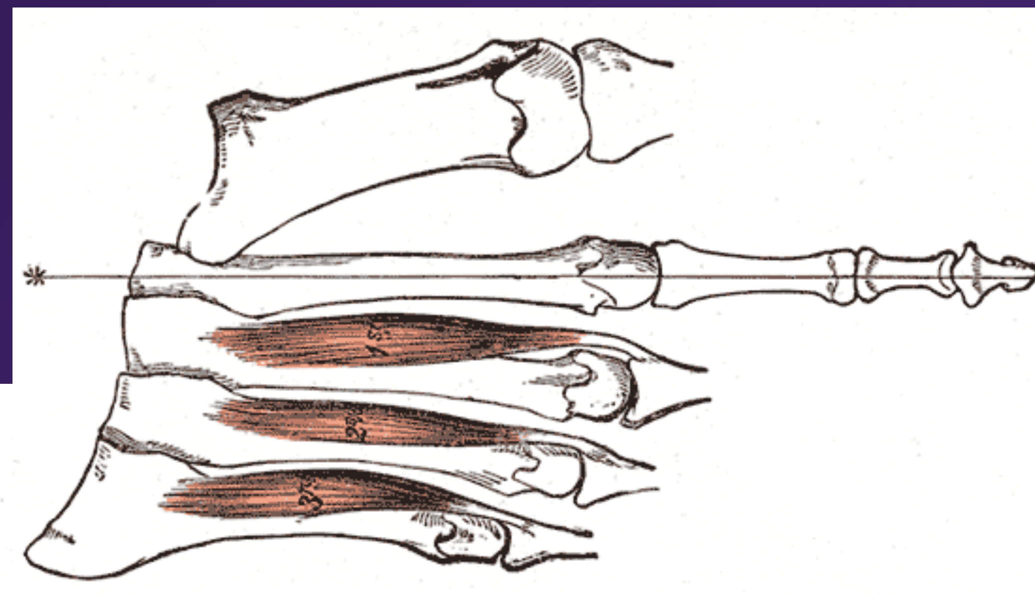
intrinsic muscles - layer 3

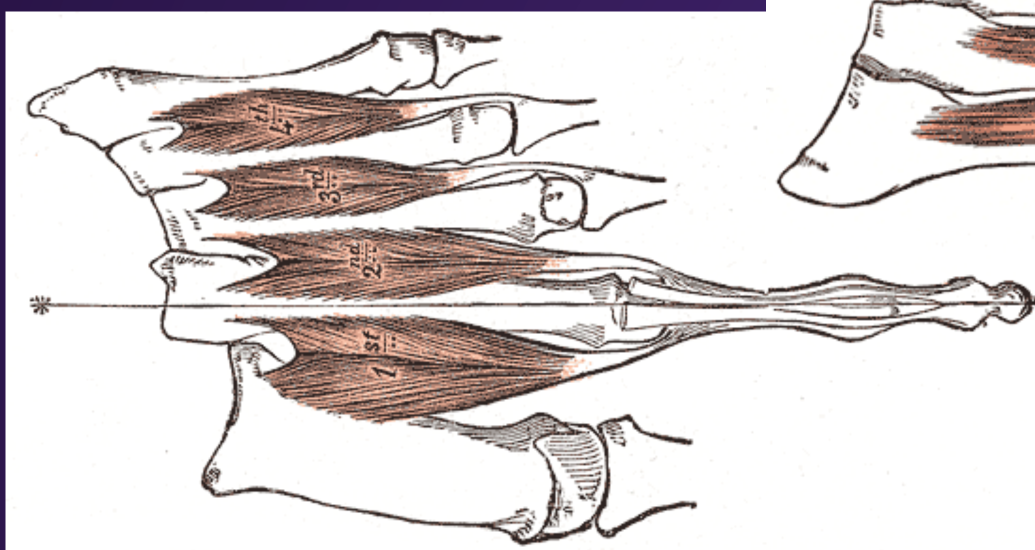


Gray's Anatomy, www.bartleby.com/107/

Foot: intrinsic muscles (n=20)

intrinsic muscles - layer 4

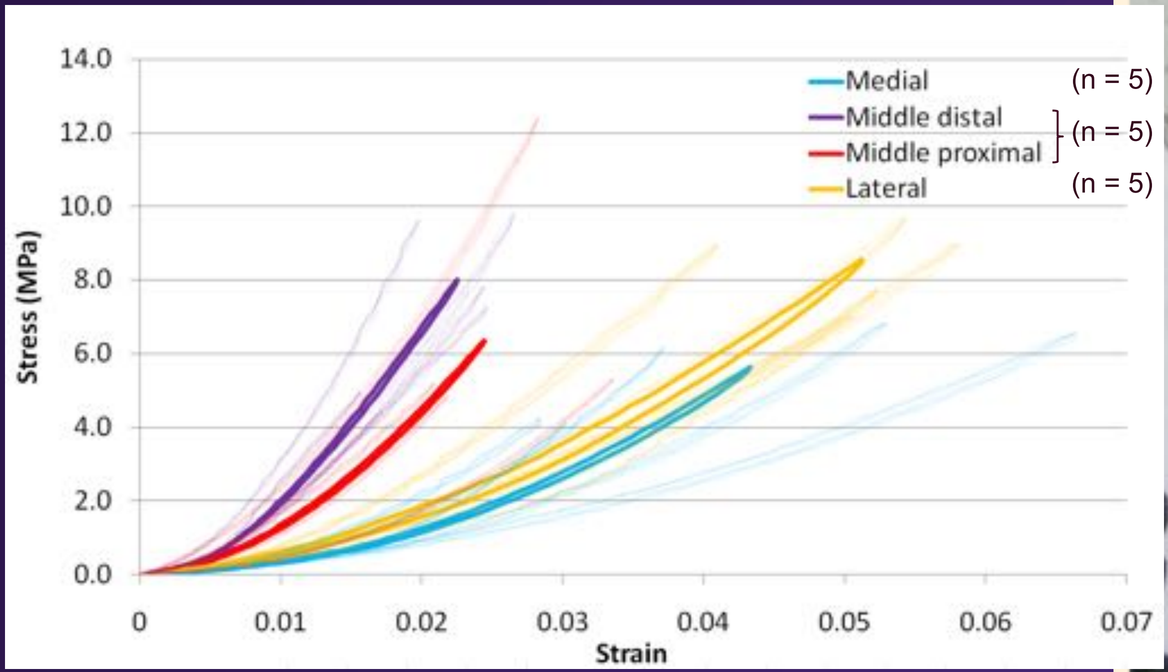




Gray's Anatomy, www.bartleby.com/107/

Foot & Ankle: Anatomy

- plantar aponeurosis



Foot function

- Transfers load from body to ground
- Balance in sagittal plane
- Mobile adaptor vs. rigid level arm
- Absorb shock
  - Heel pad
  - Subtalar joint

Session 16A Overview…

- Foot and ankle
- Anatomy
- General function
- Pathology
    - Flat foot reconstruction

Foot & Ankle: Flat foot reconstruction

- Surgery often required for symptomatic feet
- Stage II: flexor digitorum longus transfer and lateral column lengthening (LCL)

Evans calcaneal lengthening

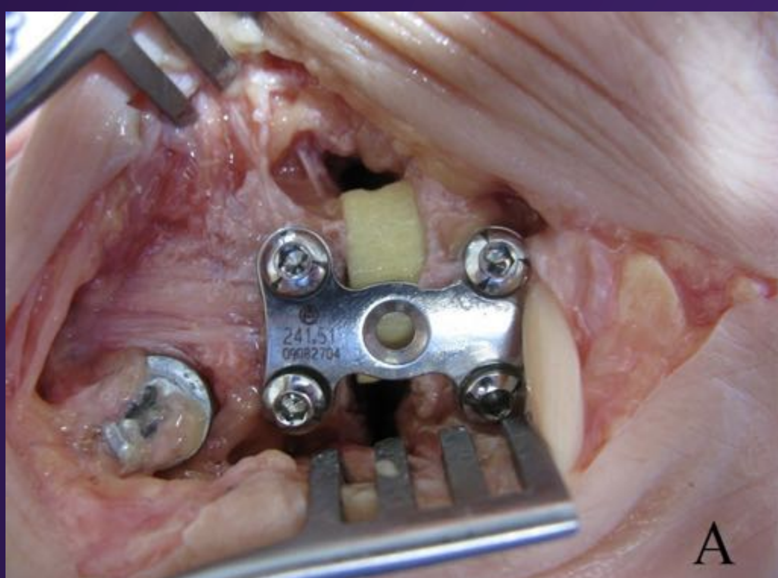
Evans, JBJS, 1975

Z-osteotomy

vander Griend, Tech FAS, 2008

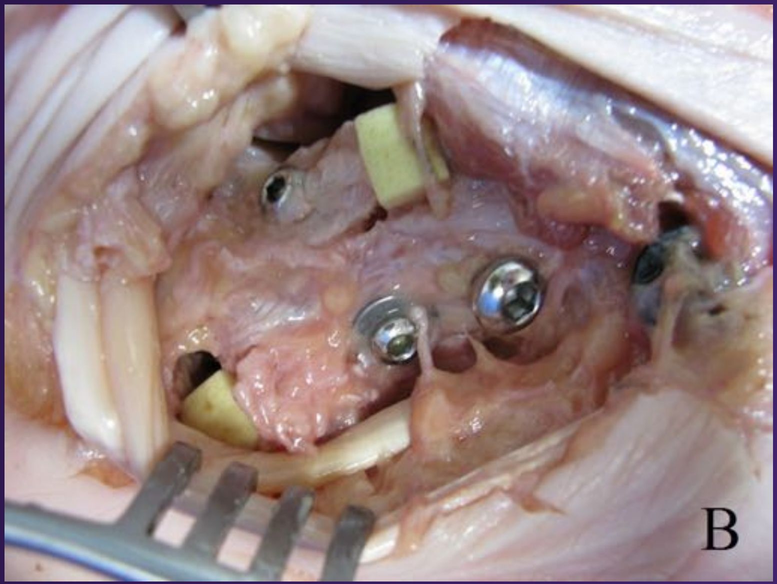
Evans calcaneal osteotomy

- Calcaneal neck, 1 cm proximal to cuboid
  - 8 to 10 mm gap, bone graft, H-plate
- High lat. pressure post surg. (Ellis et al., JBJS, 2010)
- Bone graft complications, may over correct



Z-osteotomy

- Distal and proximal vertical partial cuts
- Longitudinal cut connecting them
- Improved bone-to-bone contact
  - Bone graft not required (but used to strength)



X-ray measure of foot type

- Faxitron X-ray cabinet and digital scanner
- All specimens loaded to 25% body weight and standard clinical X-rays taken

Hindfoot Alignment

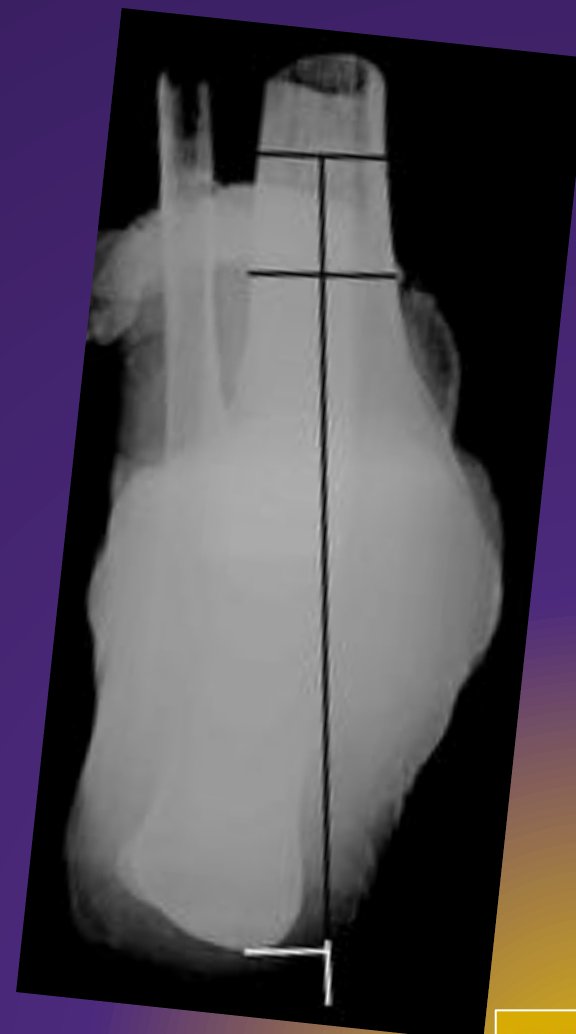
Anterior-Posterior (AP)

X-ray measure of foot type

- Lateral view
  - Lateral talometatarsal angle (LTMA) (Sangeorzan et al, Foot & Ankle, 1993)
  - Calcaneal pitch angle (CPA) (Sangeoran et al, Foot & Ankle, 1993)
  - Navicular height (Ellis et al., JBJS, 2000)

X-ray measure of foot type

- AP view
  - Talonavicular coverage angle (TNCA) (Sangeorzan et al, Foot & Ankle, 1993)
- Hindfoot alignment view
  - Calcaneal eversion distance (CED) (Saltzman and el-Khoury, FAI, 1995)

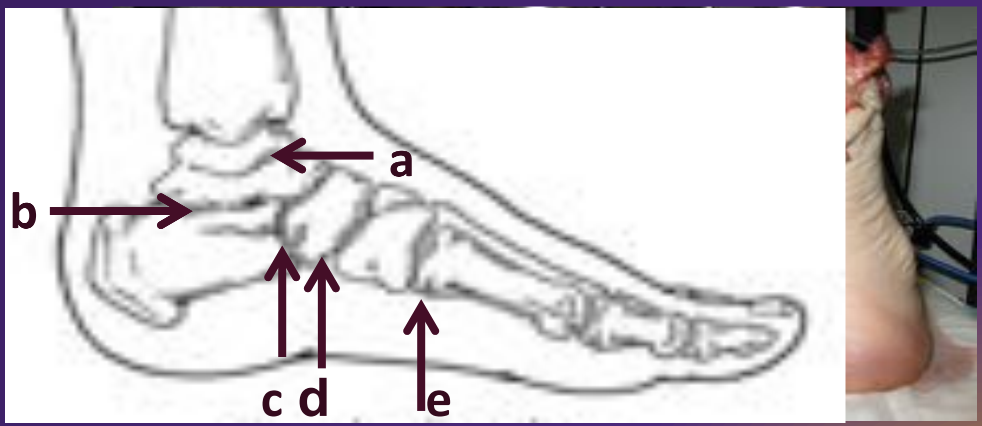


Clinical foot and ankle X-rays with cadaveric specimens , Roush et

Cadaveric flatfoot model

- Ligaments disrupted in flatfoot (Deland et al., FAI, 2005)
- Involved ligaments attenuated (Blackman et al., JOR, 2009)
  - Small cuts parallel to ligament fibers

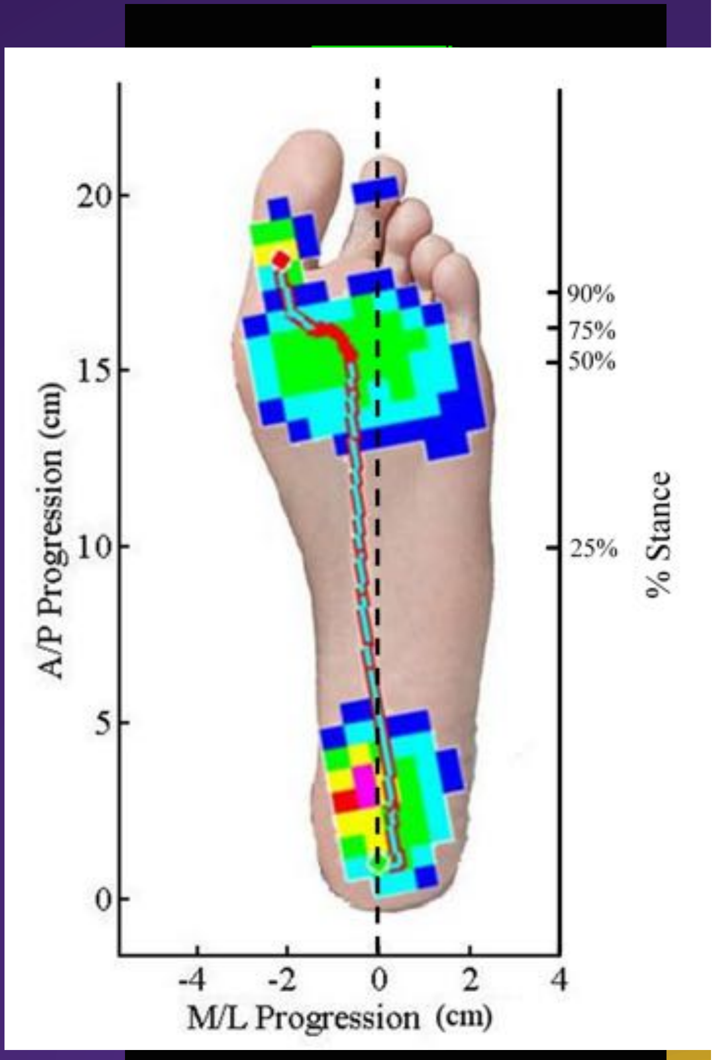
a) Anterior superficial deltoid
b) Talocalcaneal interosseous
c) Calcaneonavicular (spring)
d) Plantar naviculocuneiform
e) Plantar metatarsocuneiform



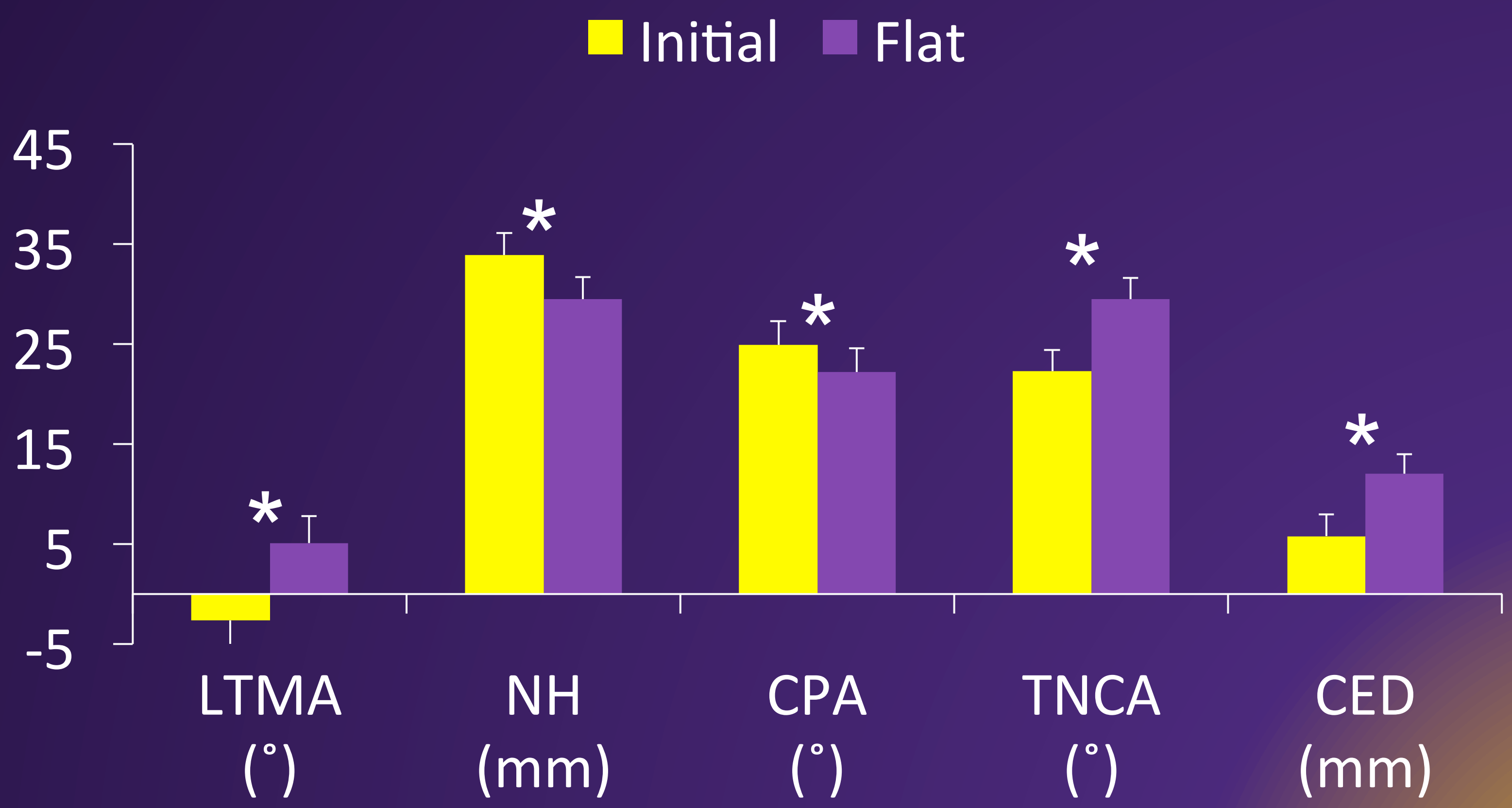
- Cycled at 2 Hz up to 35,000 times on MTS machine with a 40˚ wedge to promote eversion

Plantar pressure

- Peak plantar pressure
  - 7 locations beneath the foot
- Center of pressure progression (De Cock et al., G&P, 2008)
- M/L displacements from the longitudinal axis of the foot were compared at four points in stance:
  - 25%, 50%, 75%, 90%

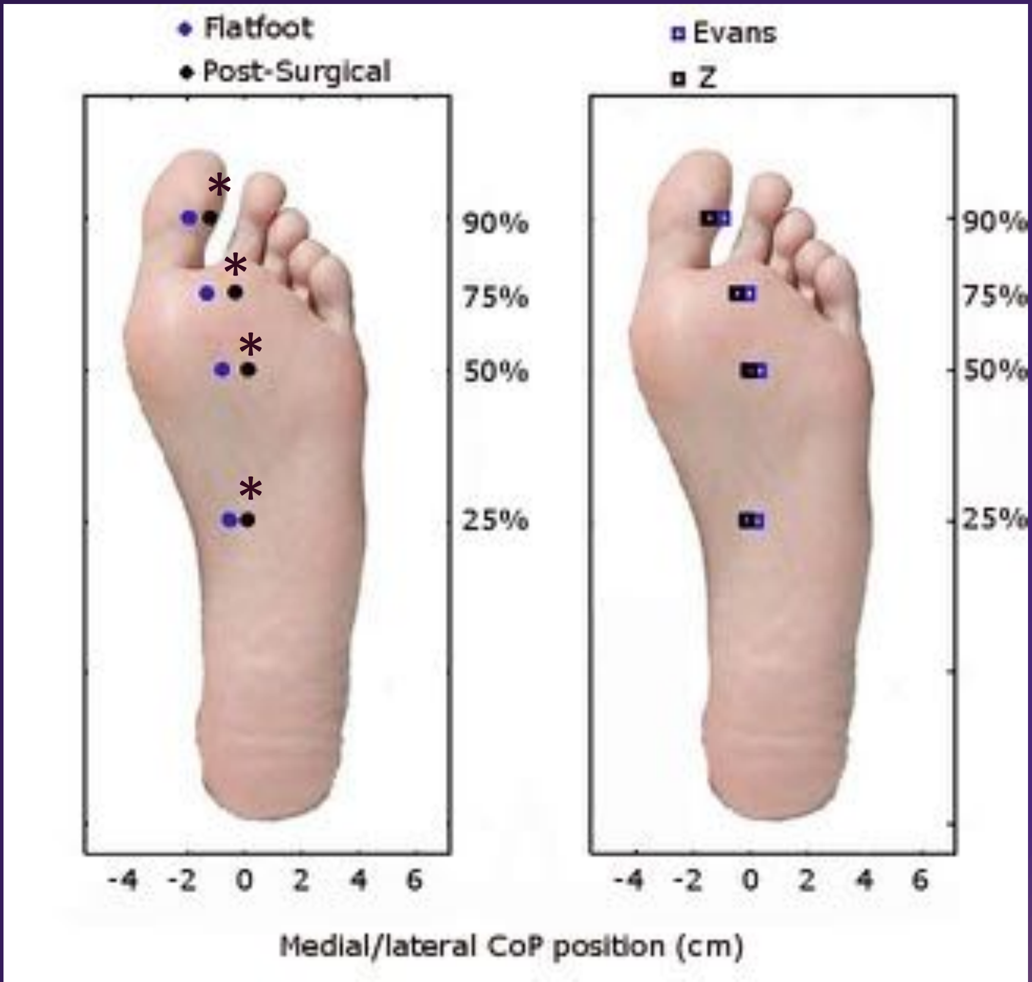


X-ray: Initial vs. Flat



* All are significant differences indicative of flatfoot ($p < 0.05$)

Pressure: Flat vs. Surgery, Evans vs. Z



*Significant difference seen at $p < 0.05$

Foot: Function – Range of Motion

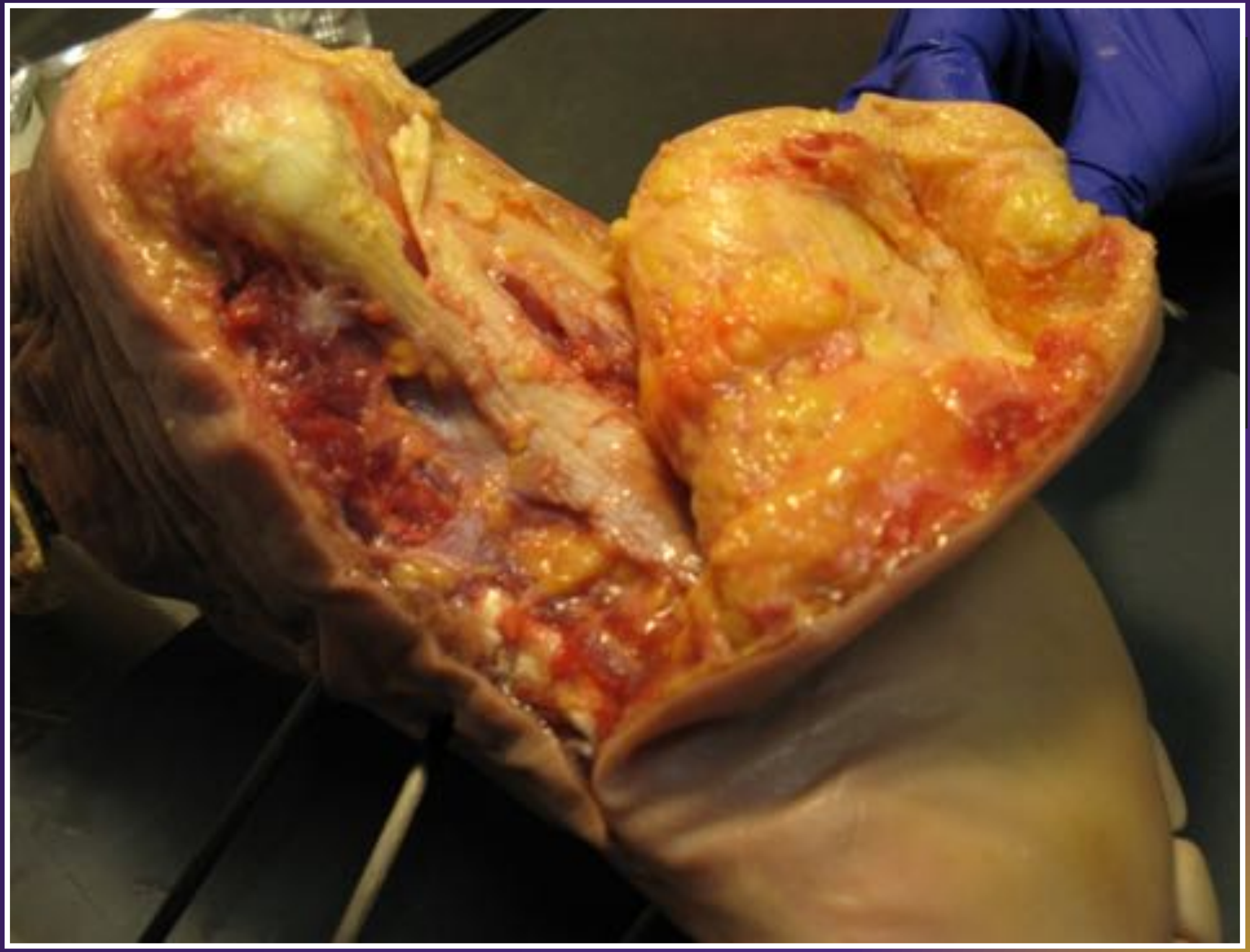
- ankle: dorsiflexion – 20˚
- ankle: plantar flexion – 50˚
- great toe: dorsiflexion – 90˚
- great toe: plantar flexion – 10˚
- subtalar: eversion – 15˚
- subtalar: inversion – 35˚

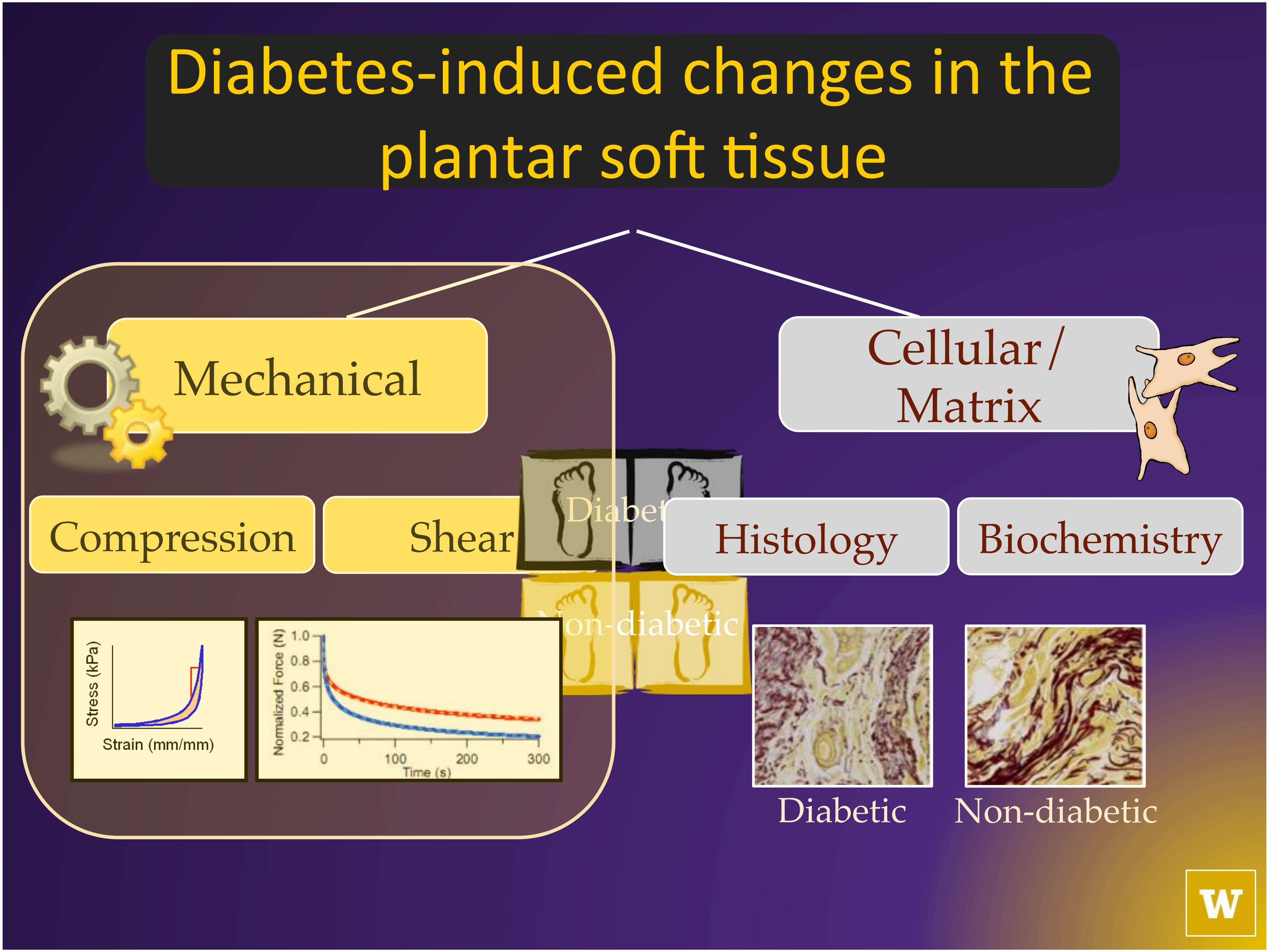
Session 16A Overview...

- Foot and ankle
- Anatomy
- General function
- Pathology
  - Flat foot reconstruction
  - Diabetic plantar soft tissue

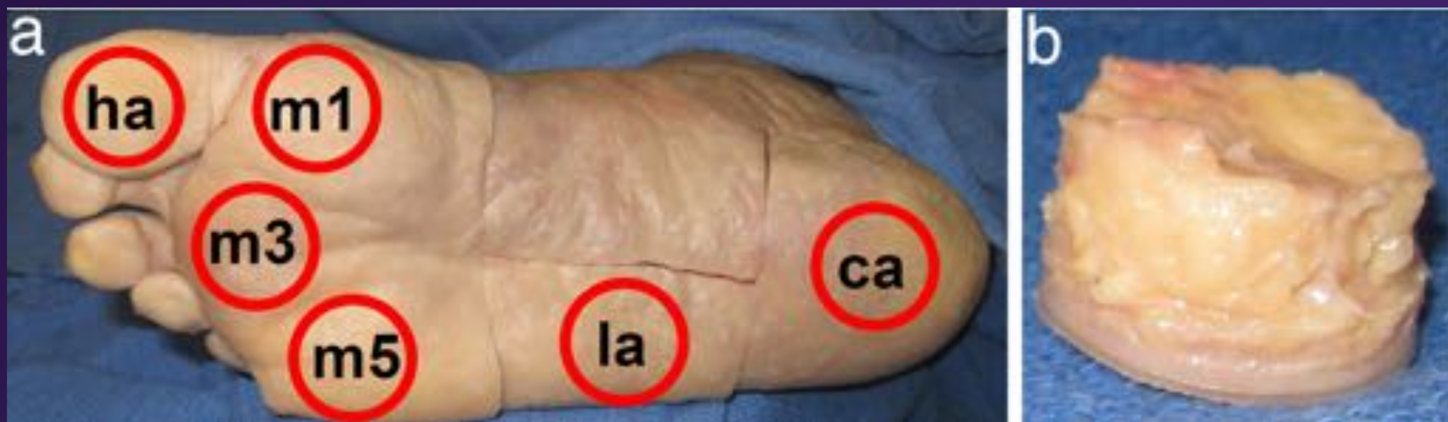
Foot & Ankle: Plantar soft tissue?

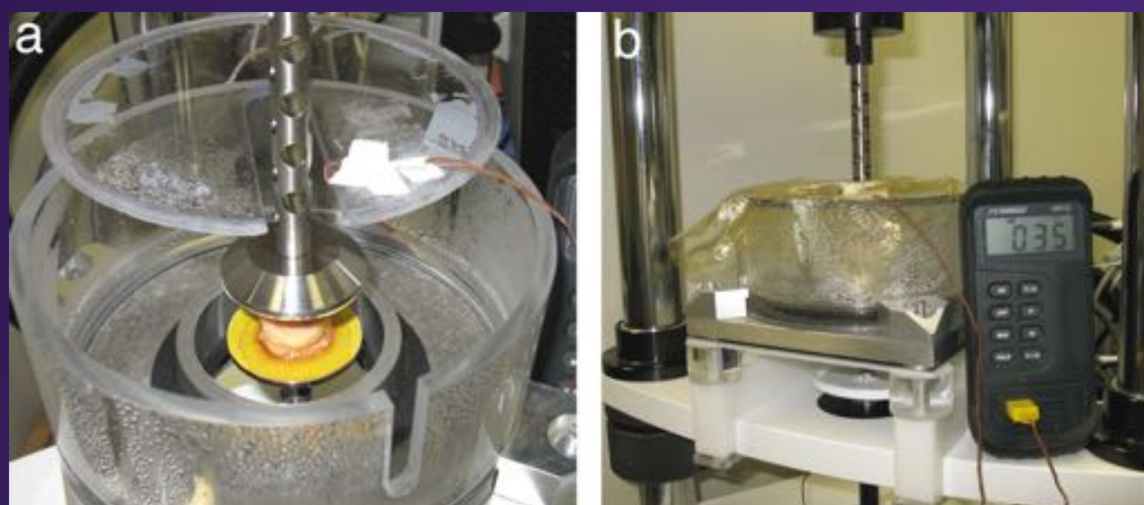
plantar soft tissue



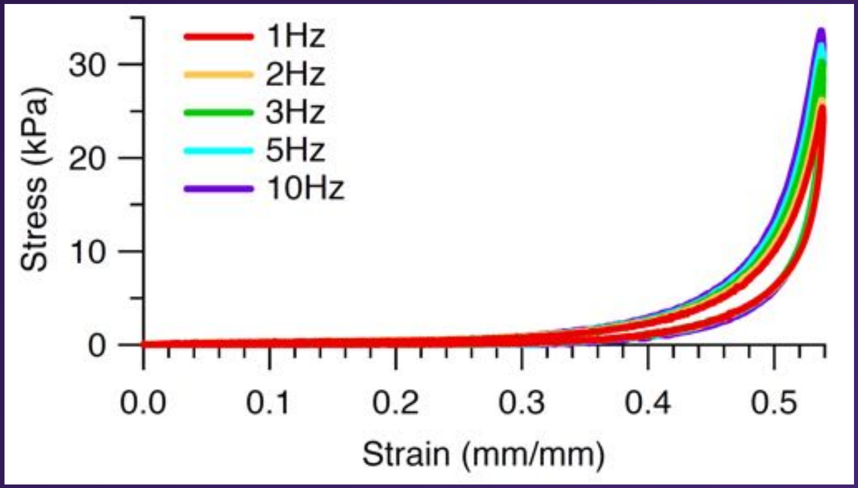

Diabetes-induced changes in the plantar soft tissue
Mechanical
Cellular / Matrix
Compression
Shear
Histology
Biochemistry
Stress (kPa)
Strain (mm/mm)
Normalized Force (N)
1.0
0.8
0.6
0.4
0.2
0
100
200
300
Time (s)
Diabetic
Non-diabetic

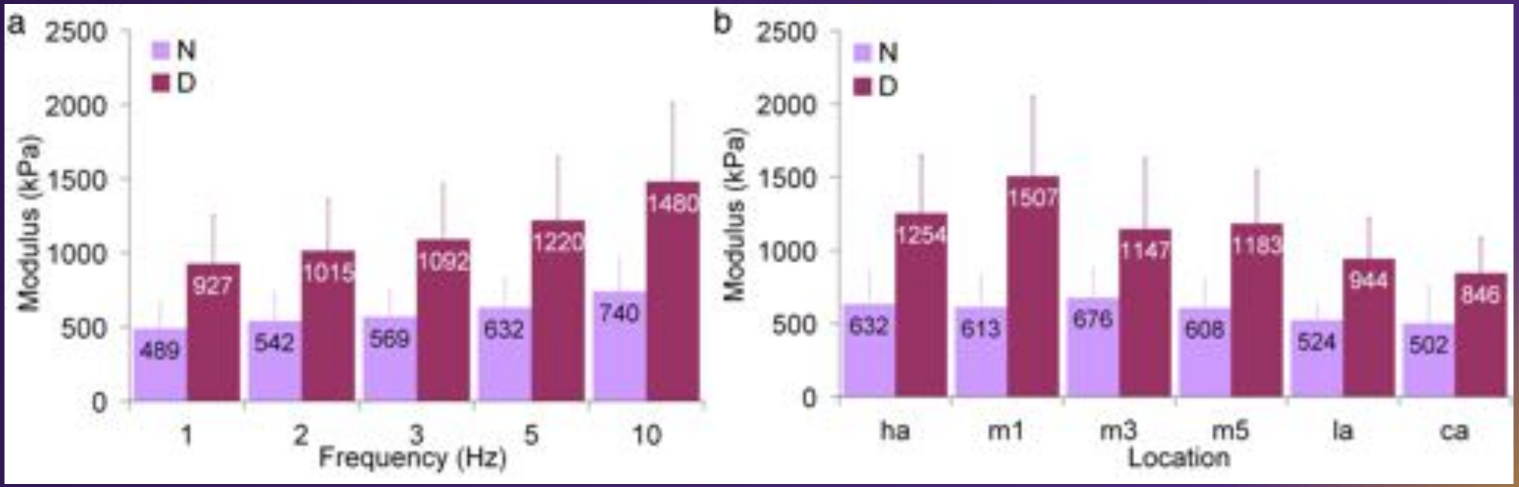
Compression testing





Compression testing



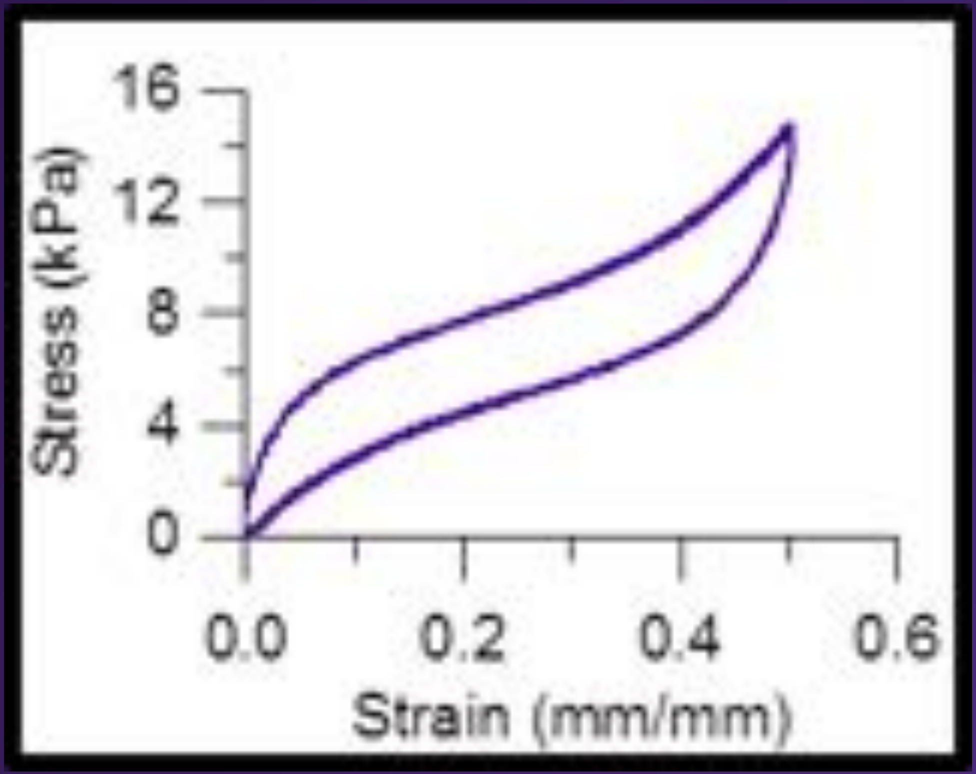


Pai and Ledoux, J Biomechanics, 2010

Shear testing

Pai and Ledoux, J Biomechanics, 2012

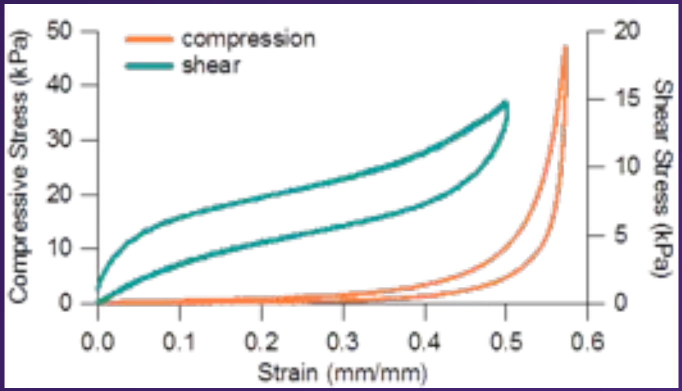
Shear testing

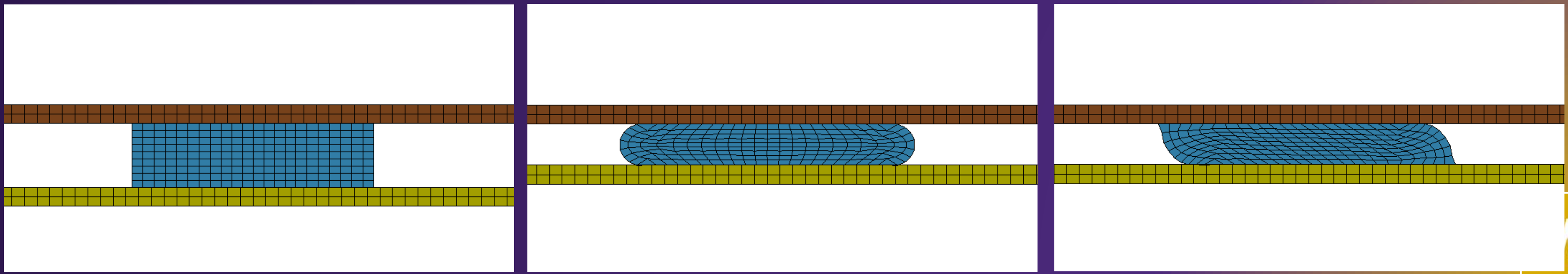


Pai and Ledoux, J Biomechanics, 2012

Compressive vs. Shear Properties

- J- vs. S-shaped curves
- Final modulus of 1147 vs. 60kPa for diabetic specimens and 593 vs. 41kPa for non-diabetic specimens



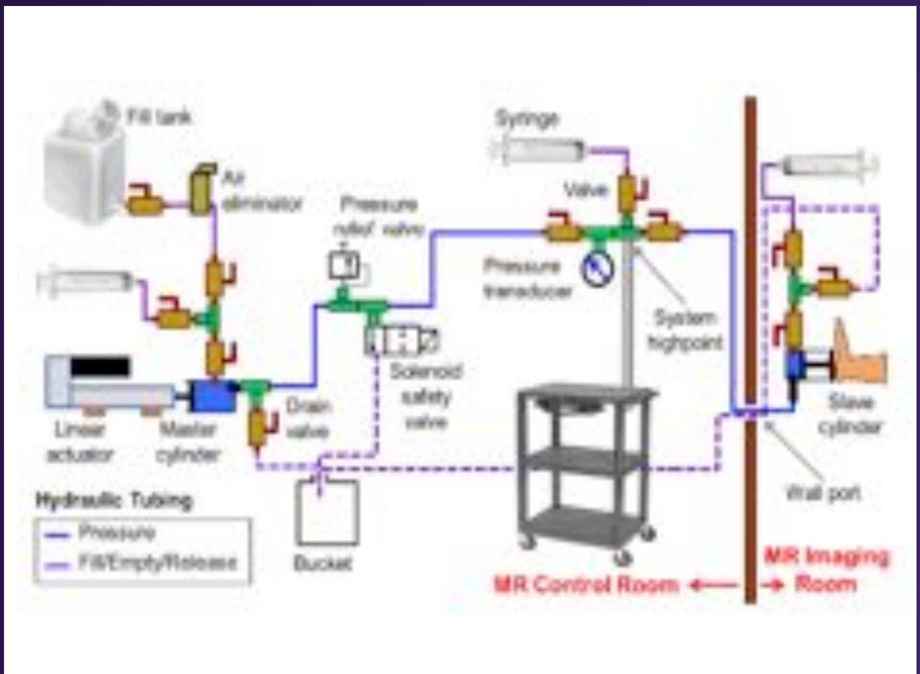


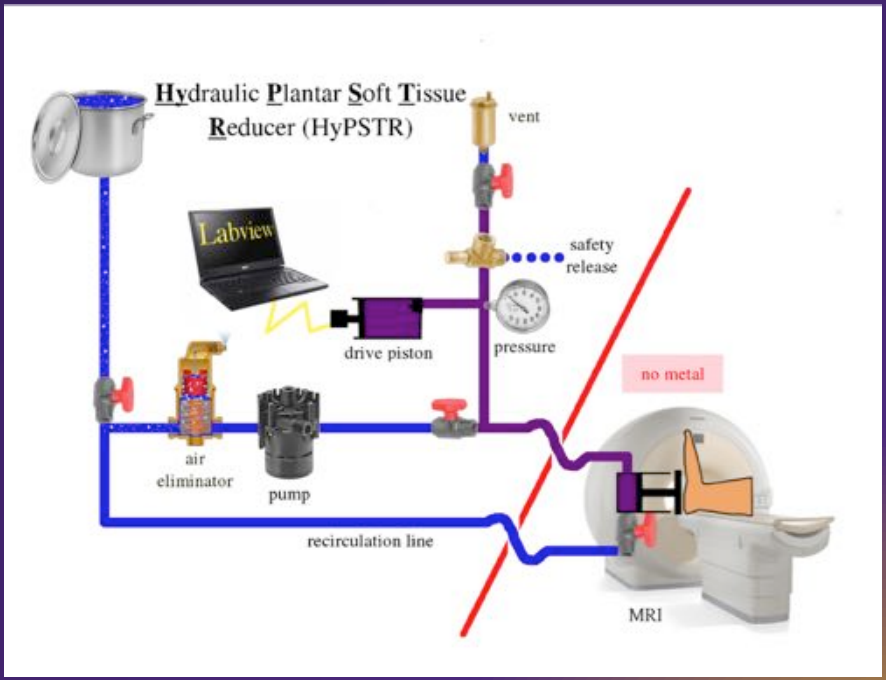
Session 16A Overview...

- Foot and ankle
- Anatomy
- General function
- Pathology
  - Flat foot reconstruction
  - Diabetic plantar soft tissue
  - Patient specific material properties

Hydraulic plantar soft tissue reducer

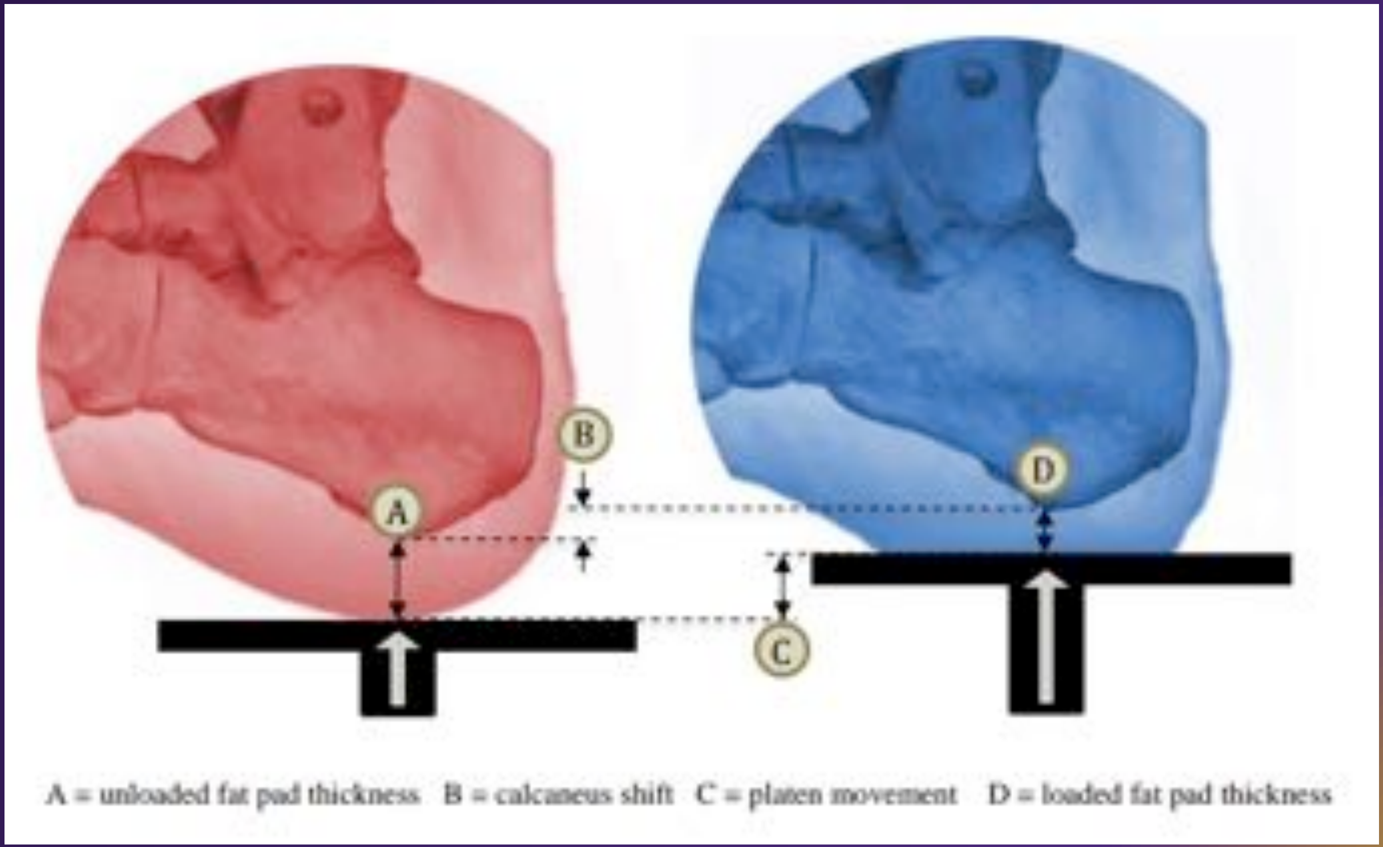
- HyPSTR





Hydraulic plantar soft tissue reducer

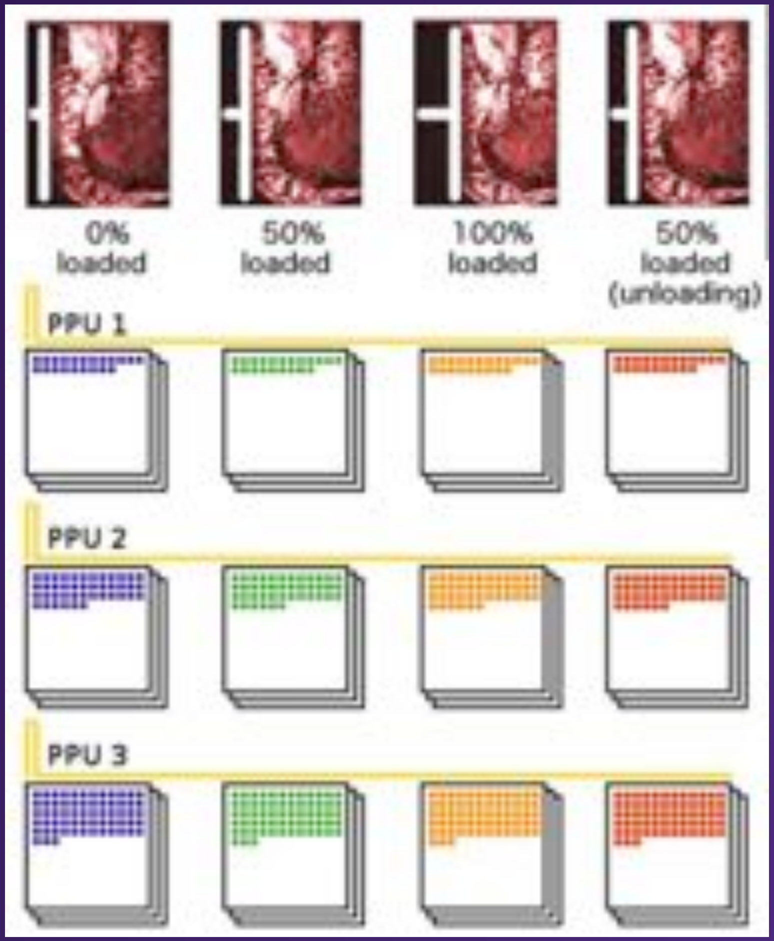
- HyPSTR



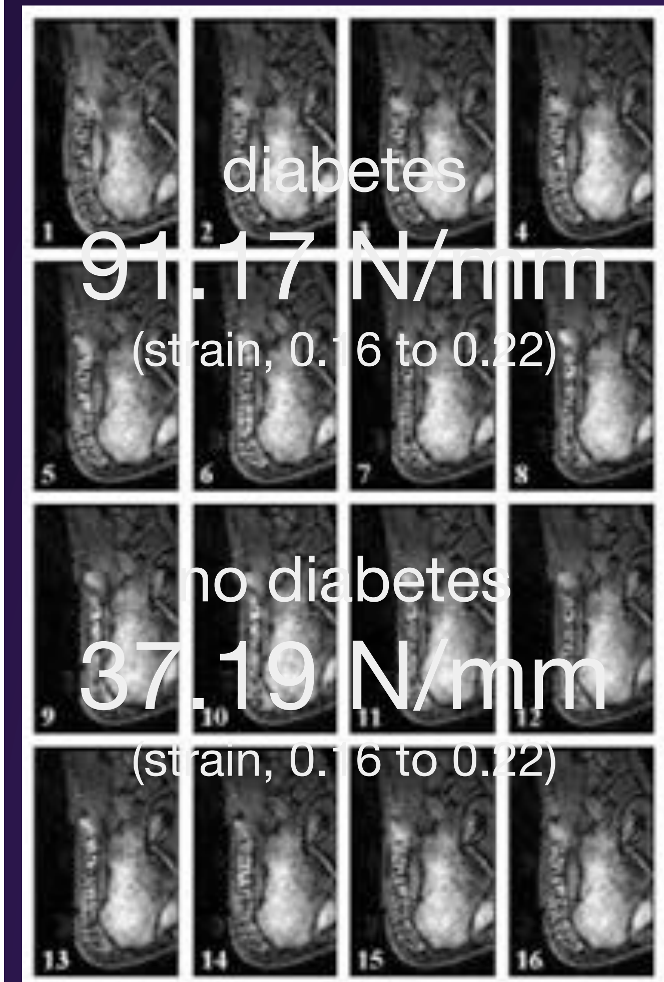
Ultrasound validation

Hydraulic plantar soft tissue reducer

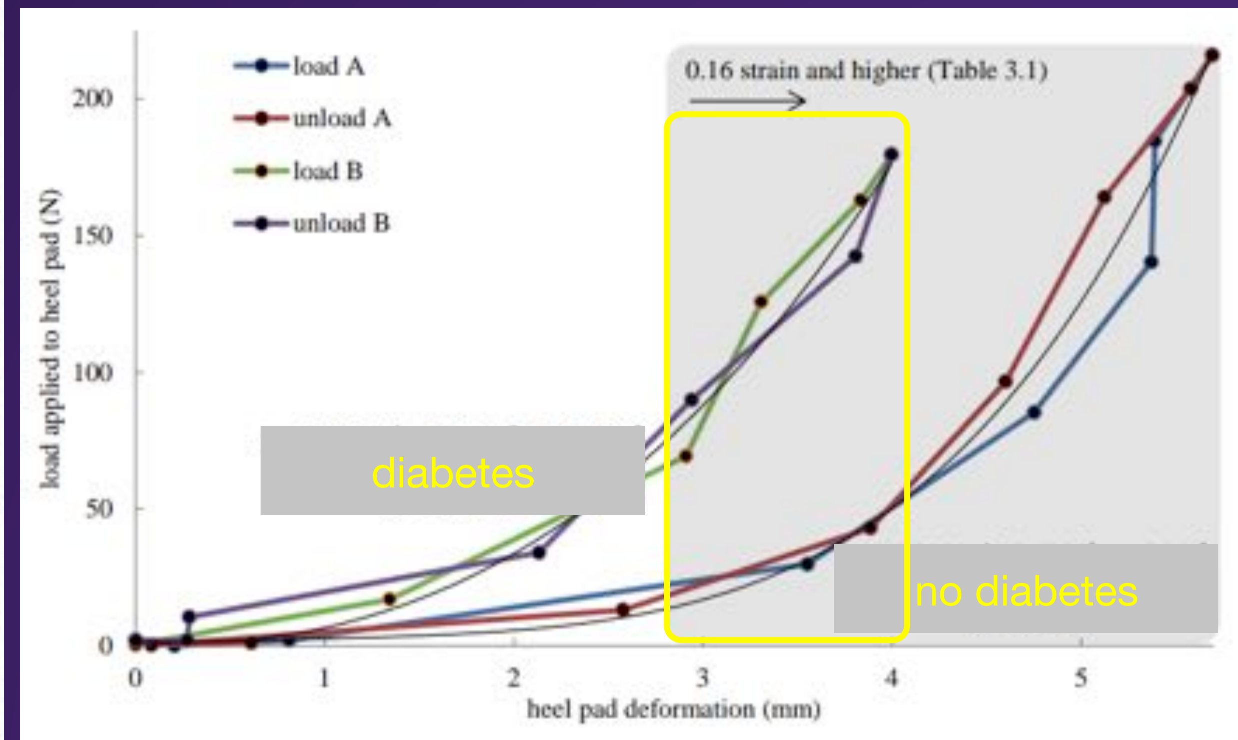
- HyPSTR



Hydraulic plantar soft tissue reducer

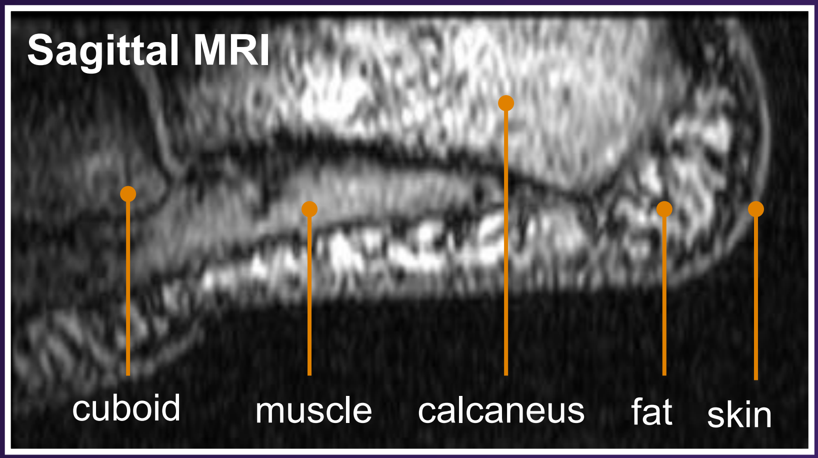


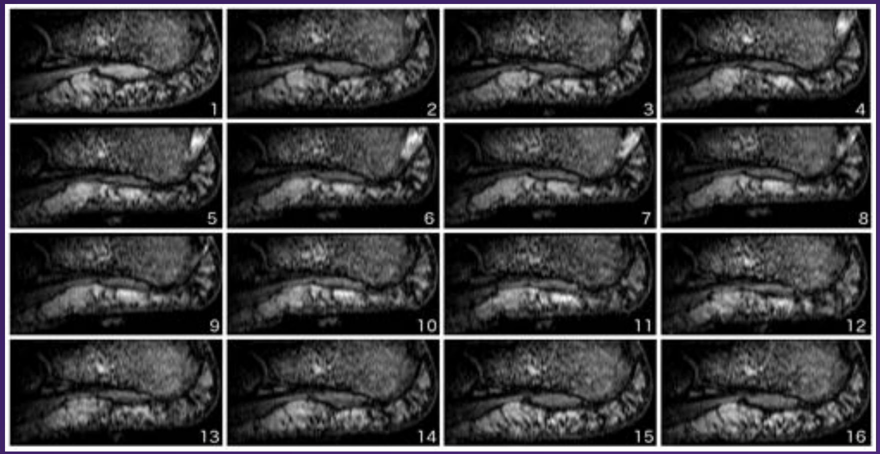
Subject A (no diabetes) and Subject B (diabetes) stiffness curves



Inverse finite element modeling

- Gated MRI (16 phases per cycle)

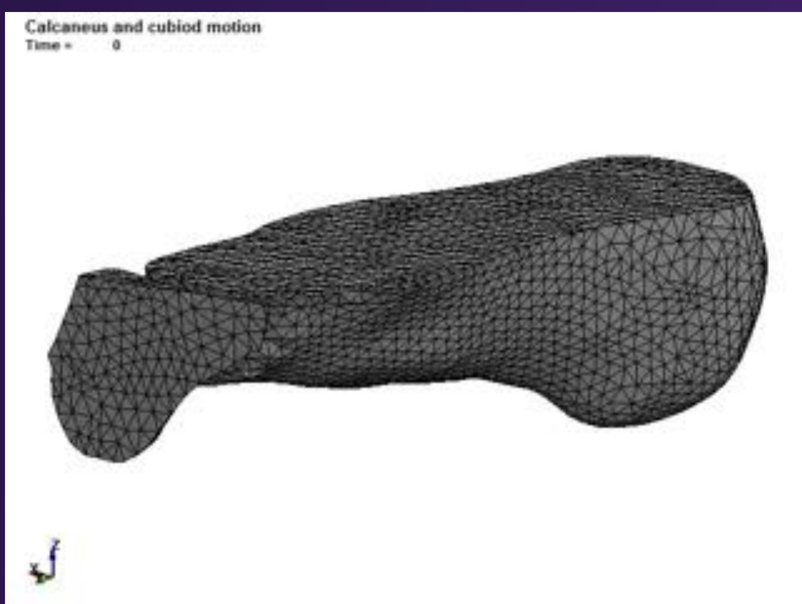




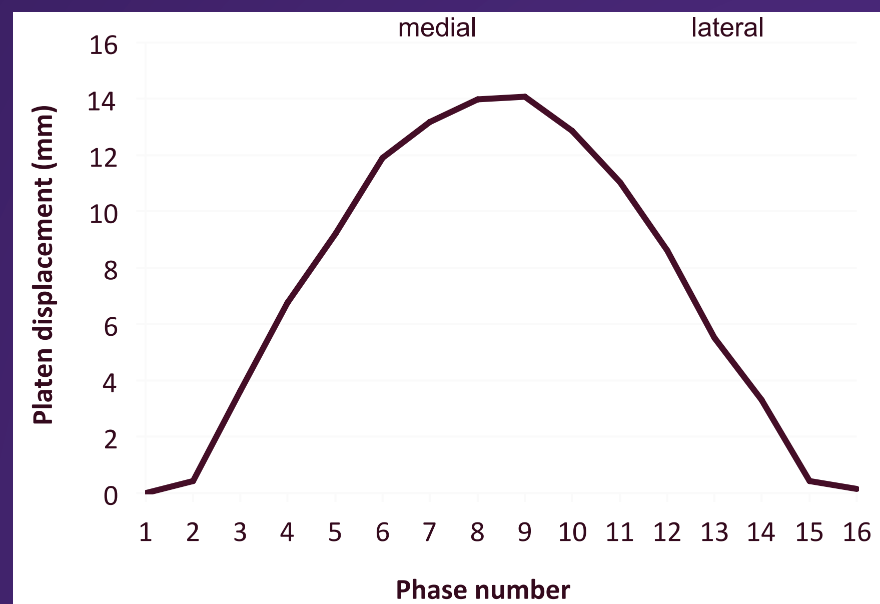
Inverse finite element modeling

- Extract force, deformation and kinematic data
  - Calcaneus and platen motions (FE model input)

Calcaneus motion

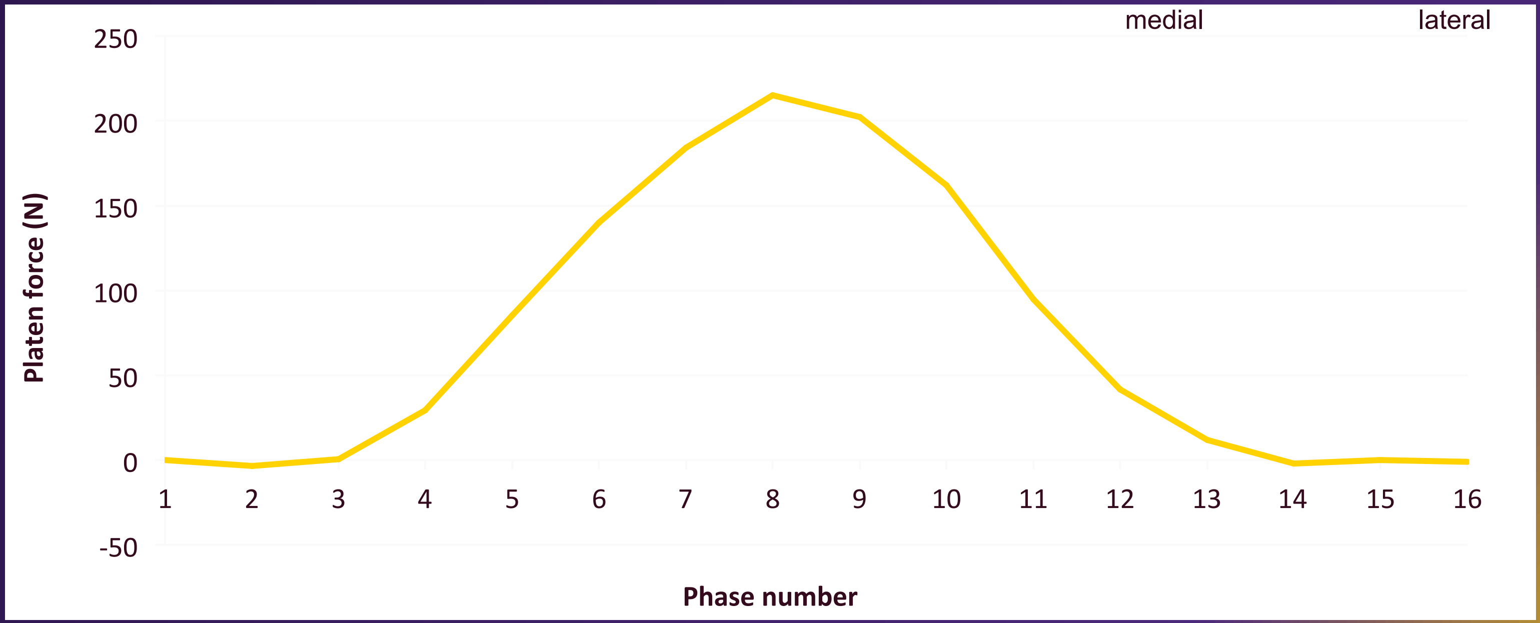


Platen motion



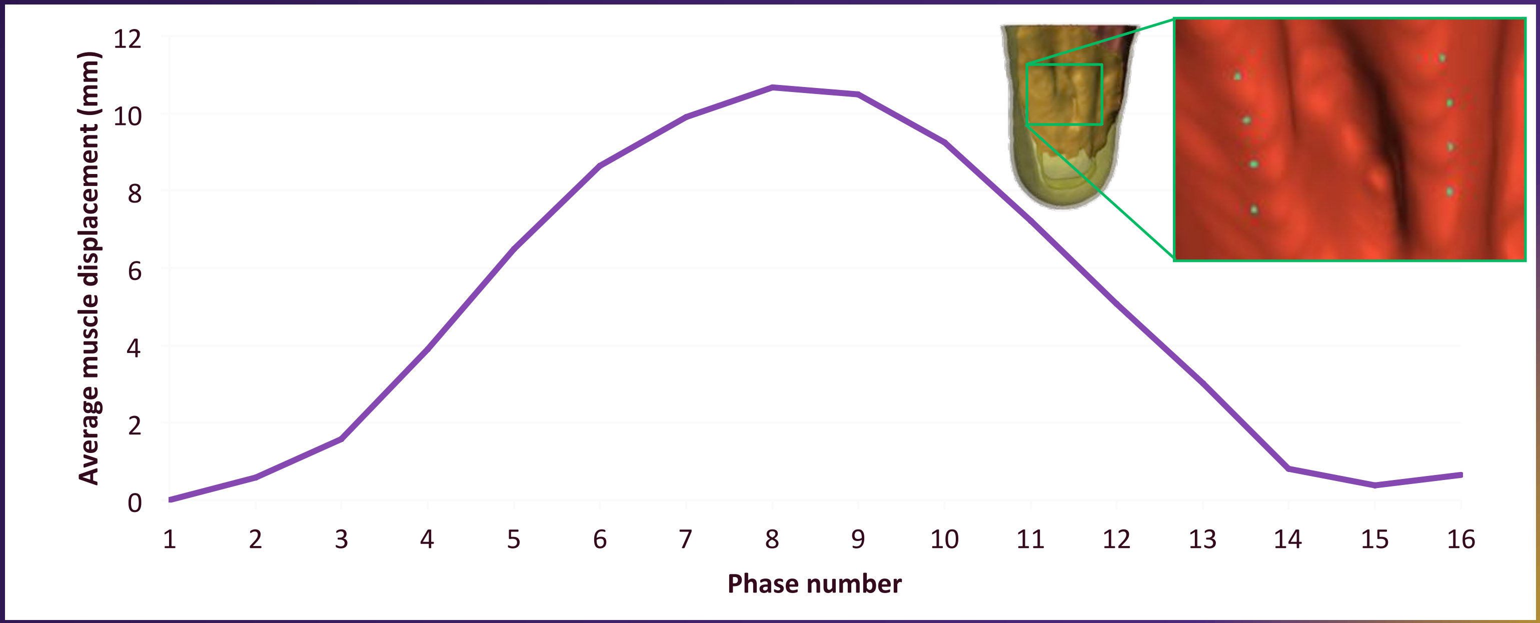
Inverse finite element modeling

- Extract force, deformation and kinematic data
  - Calcaneus and platen motions (FE model input)
  - Platen force (target optimization data)



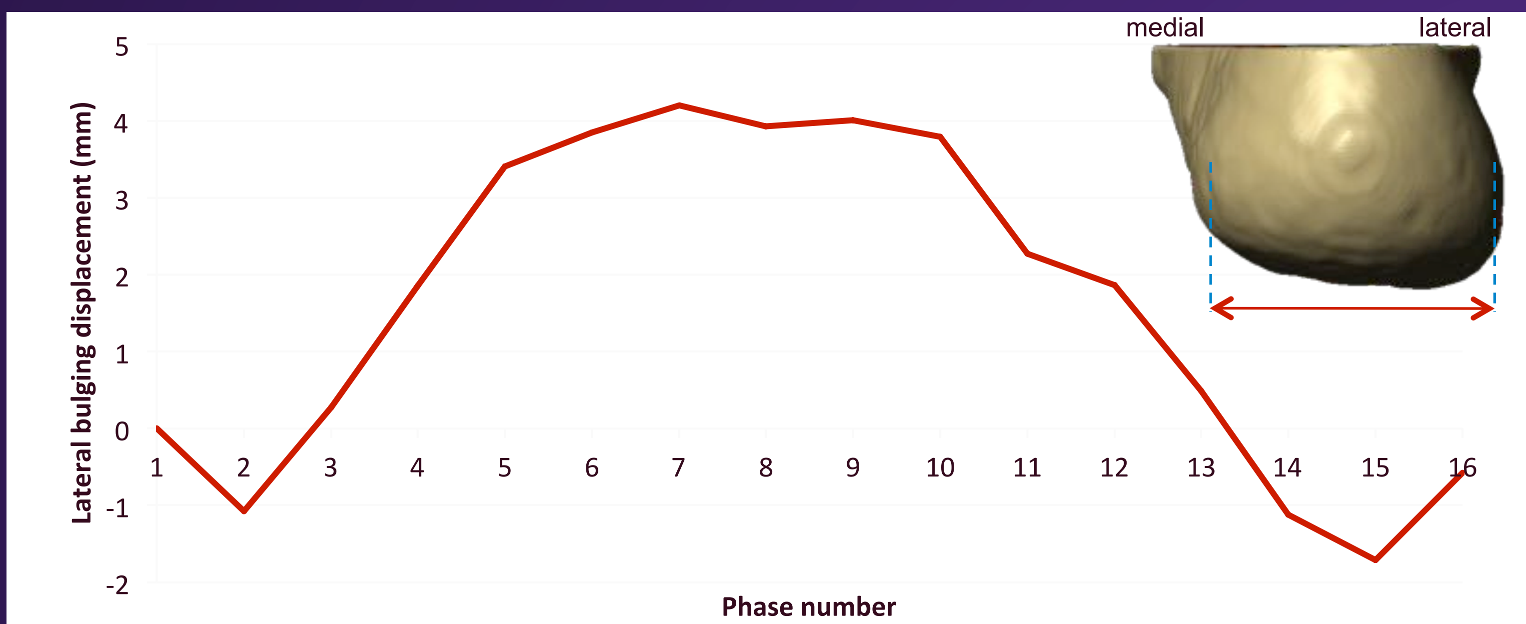
Inverse finite element modeling

- Extract force, deformation and kinematic data
  - Calcaneus and platen motions (FE model input)
  - Platen force (target optimization data)
  - Vertical muscle displacement (target optimization data)



Inverse finite element modeling

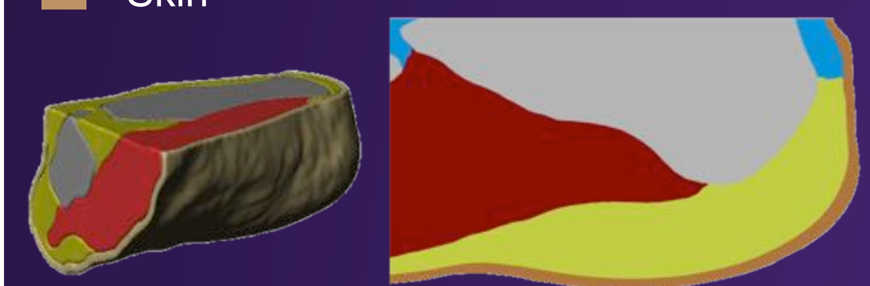
- Extract force, deformation and kinematic data
  - Calcaneus and platen motions (FE model input)
  - Platen force (target optimization data)
  - Vertical muscle displacement (target optimization data)
  - Mediolateral skin bulging (target optimization data)



Inverse finite element modeling

- Soft tissue anatomy from phase1 MRI (unloaded)
- Bone anatomy from CT scan
- Linear tetrahedral elements (LS-Dyna elform13)
- Mass and time scaling

Bone
Generic soft tissue
Muscle
Fat
Skin



Inverse finite element modeling

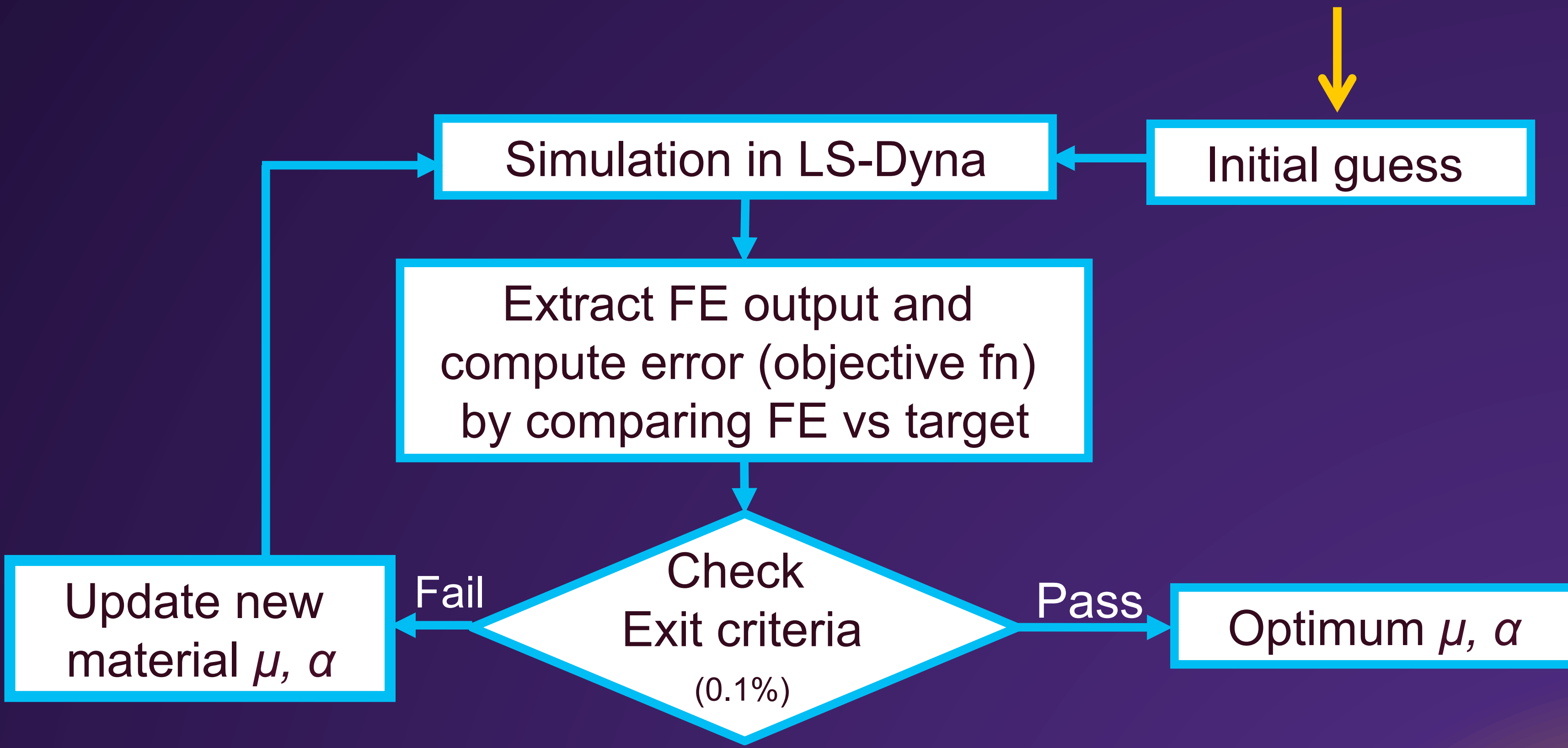
- Rigid bone, Ogden hyperelastic soft tissue

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

  - *(μ_S, α_S), (μ_F, α_F)* and *(μ_M, α_M)* are skin, fat and muscle material properties (inverse FE variables)
  - Also optimize lumped tissue (generic soft tissue) *(μ_G, α_G)*

- Use the platen reaction force, muscle displacement and skin bulging targets for computing inverse FE objective function

  (Only use force target for generic soft tissue optimization)



- Objective function is the sum of 3 normalized mean square errors (force, muscle displacement and skin bulging)
- 4 initial guesses per subject

Inverse finite element modeling

- Normal subject
  - Skin: μ_S = 0.156 kPa, α_S = 185.20
  - Fat: μ_F = 1.874 kPa, α_F = 8.29
  - Muscle: μ_M = 0.161 kPa, α_M = 31.95
  - Generic soft tissue: μ_G = 0.790 kPa, α_G = 21.08

- Stiffness: Skin > Muscle > Generic soft tissue > Fat

Session 16A Overview...

- Foot and ankle
- Anatomy
- General function
- Pathology
  - Flat foot reconstruction
  - Diabetic plantar soft tissue
  - Patient specific material properties
  - Finite element foot modeling (supplemental slides)