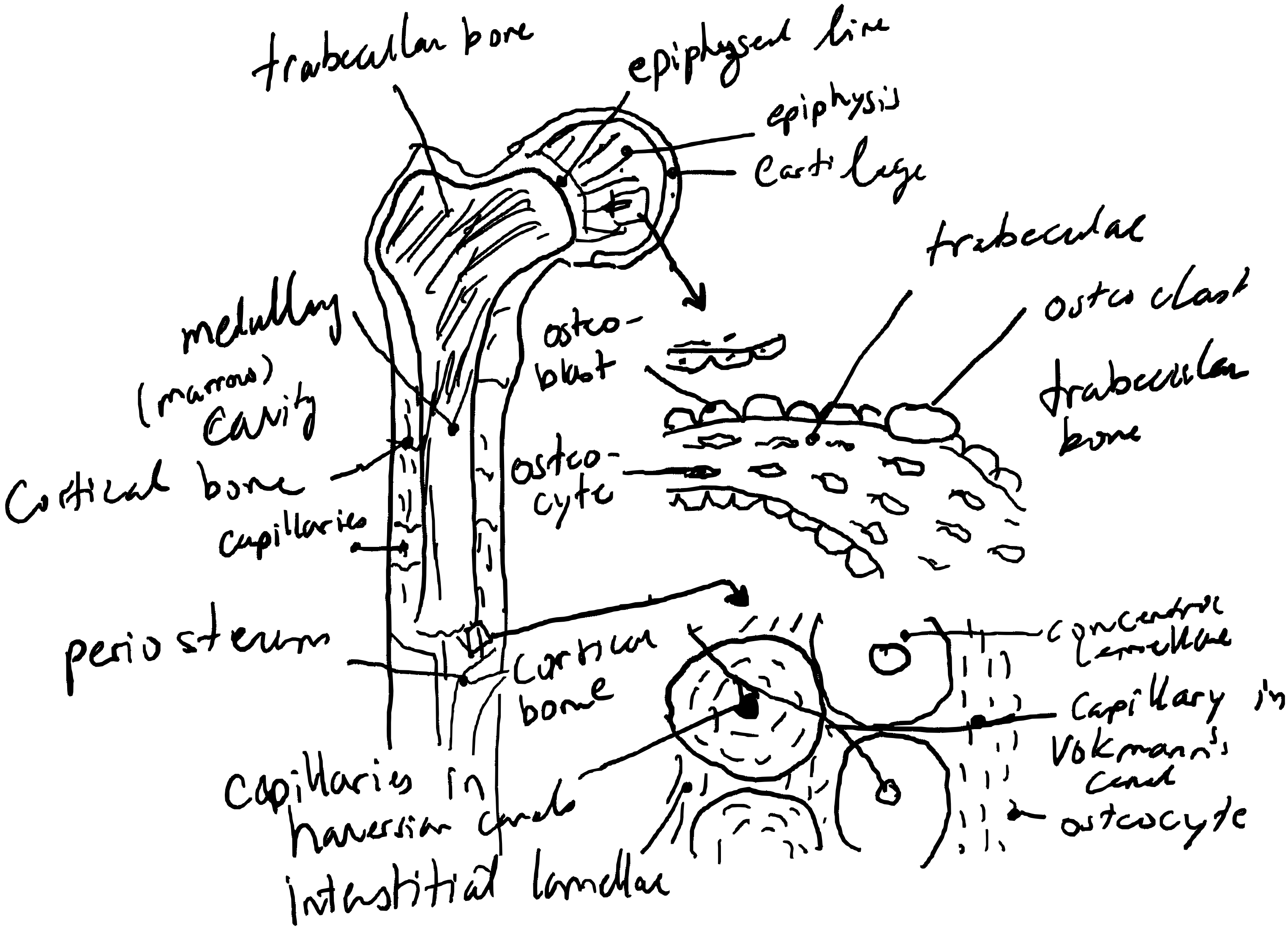
Bone, Cartilage, and Joint Function

Bone Components and Structure

- 28 skeletal bones, 40+ articulations
- bone: solid components hydrated by water
+ ECM largest portion by volume
* ECM makeup: Inorganic mineral hydroxyapatite (HA) (65-70% dry weight) and organic protein Type I collagen (25-30%)
+ HA = strength, but brittle. Collagen reinforces against it, giving bone toughness akin to other composite structures
+ 20% water in weight
- skeletal bone either: cortical or cancellous
+ cortical: tight osteons, structural units surround canal for blood supply and innervation
+ cancellous: porous, spongy, trabecular
+ foot has both, interior cancellous bones surrounded by dense cortical bone
- osteoclasts & blasts control ECM resorption, formation
+ synergistic repair, first with immature woven bone, then replaced by stronger lamellar bone

- repeated loading of certain kind causes modeling



- bone biomechanics: 2 concepts

1. cortical bone has parallel org. of lamellar bone. trabecular plate + rod also have orientation
   + anisotropic → material orientation affects properties
   + orthotropic → having properties symmetric about 2 or 3 perpendicular planes
   + within bones, alignment can change indicating diff properties
   + bone modeled as linearly elastic with viscoelastic behavior when hydrated, makes strain rate dependent on elastic mod. & ultimate strength

2. whole behavior > sum of its parts

\+ compact osteons in cortical are outer shell of tarsal bones, provide diaphysis (shaft) of metatarsals strength

\+ cancellous not as strong, aids in load transmission at joints + dampen sudden stress

\- quantify skeletal bone: bone volume fraction ($\frac{BV}{TV}$) + cortical & trabecular thickness for bone morphology, BMD + degree of anisotropy inform loading pattern of bone

\- account for 98% of bone elastic properties

\- $\frac{BV}{TV}$ = mineralized bone volume / total volume

\+ important for trabecular (latticework of bone with voids)

\- foot: BV/TV = lifestyle + personal traits to handle stressors esp. in calcaneus

\+ e.g. nonrunners: body weights explain 80% of BV/TV, trabecular thickness, trabecular density variation

\+ runners: age at onset of running matters most

\- DEXA: gold standard for BMD

\- BMD informs locations in bone that would best resist pullout of cortical screws

\+ e.g. medial cuneiform may provide best purchase

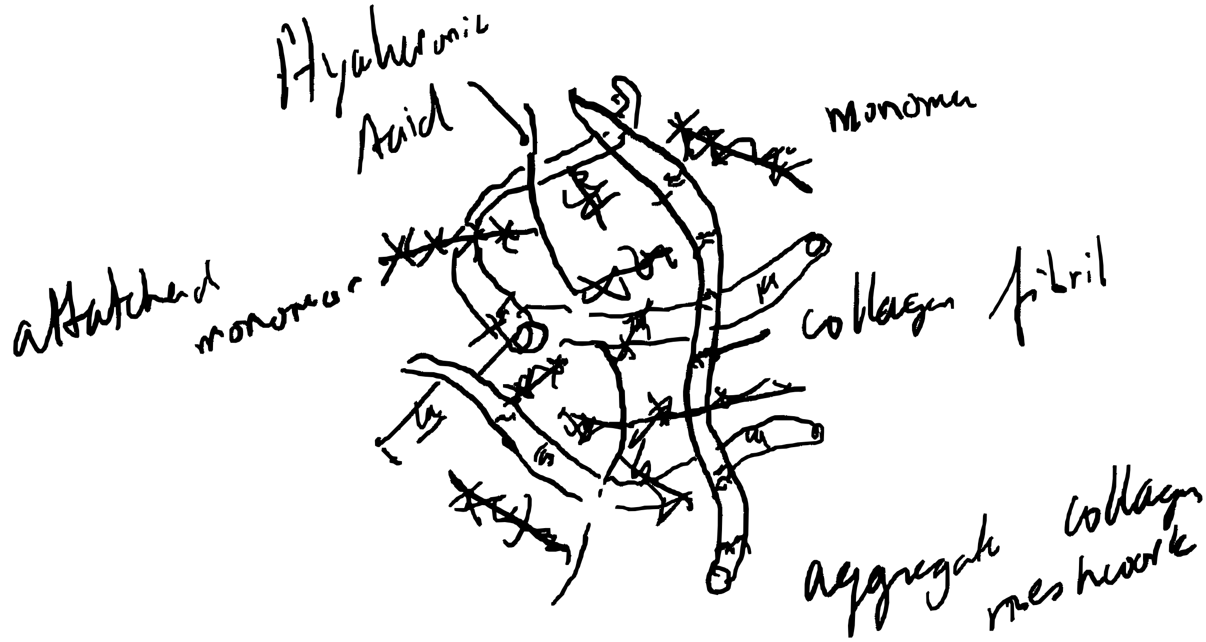
\- possibly use BMD to suggest injury probability curve for foot + ankle

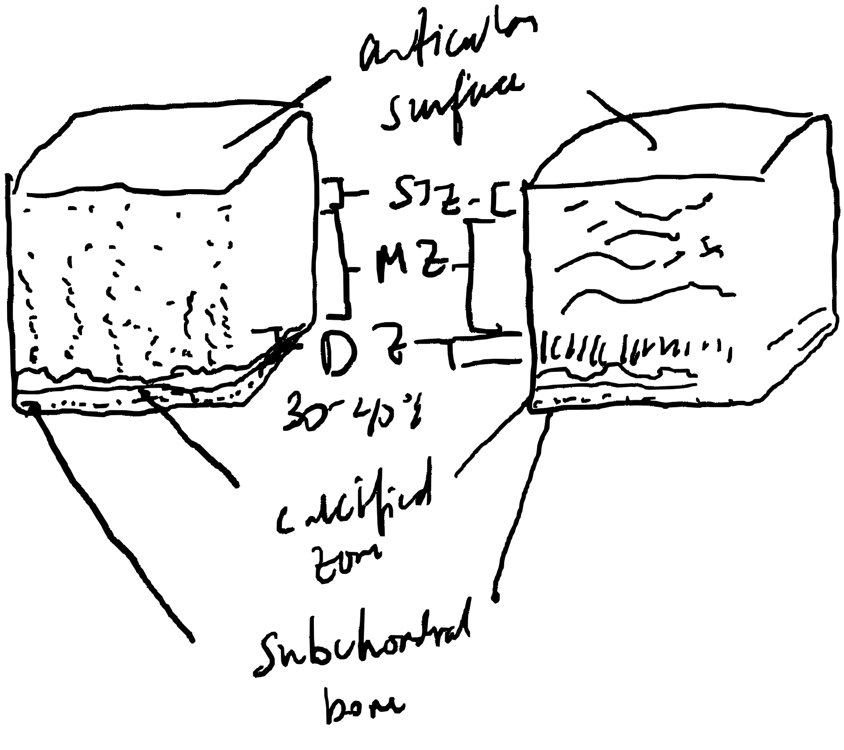
- characterize trabecular anisotropy for bone function
+ trabeculae in foot, like those in femoral head, orient along line of loading
+ posterior calcaneus (posterior talar articular surface to calcaneal tuberosity) shows high anisotropy, transmitting force to ground or midfoot
+ bipedal walkers have distinct trabecular alignment.
- another approach: trabecular thickness, number, separation represent levels of activity.
+ ultimate strength of cancellous bone highly correlates with ↑
+ hard to measure
- loss of activity = transient loss of BMD, can be recovered

Cartilage

- 70-85% weight by water, hydrophilic, majority ECM of proteoglycans and Type II collagen
- pressurization and porous nature result in withstanding cyclic load handling
- low blood supply, nerves, or lymph system
- 3 zones:

1. STZ: superficial tangential zone: organized collagen and elongated chondrocytes
2. middle zone: collagen + proteoglycans + spherical chondrocytes
3. deep: radially oriented collagen, few proteoglycans w/ columnar chondrocytes





- multiple equations/models for biomechanics and regen of cartilage

+ Biphasic Theory: linearly elastic ECM + viscous fluid
* predicts creep and stress relaxation
+ STZ: few proteoglycans, compacted, preventing fluid flow, pressurizing container

+ middle zone: high proteoglycans: handles hard compressive load
+ deep zone: radial fiber orientation for anchoring to bone
- biphasic good but misses tensile properties of ECM, specifically collagen, & if viscoelastic, not purely elastic
- new model considers ECM as network of collagen fibrils resisting tension, surrounded by hydrophilic gel of proteoglycans to resist compression
+ does not replicate heterogeneous nature
- triphasic model accounts for mobile ions interaction with negatively charged glycosaminoglycan chains.
+ explains more mechanical & chemical loading observed
+ other improvements: viscoelastic ECM, bilinear tension / compression of ECM
- foot bones have many articulating joints, so lots of articulating cartilage e.g: metatarsal head of MTP joint, talar dome @ talocrural joint.
- noticeable diff in ankle cartilage vs e.g. knee cartilage
+ higher proteoglycan & water composition
+ higher rate of proteoglycan breakdown + synthesis
+ diff healing. After lesion, chondrocytes in knee down regulate collagen & proteoglycan production. Ankle upregulates
- Ankle has less OA than knee.
+ Typical OA, subchondral bone density ↑ w/ cartilage degen
+ Ankle: subchondral bone density ↓, preventing OA

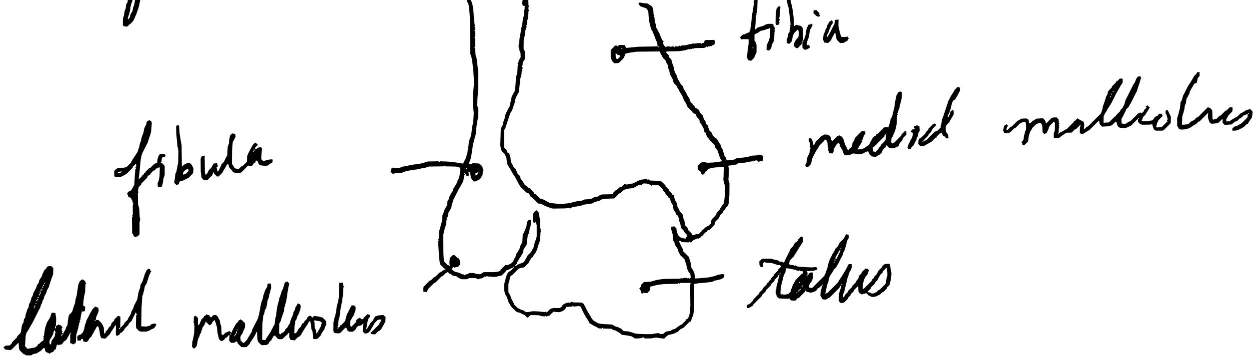
- OA happens with injury e.g. dislocations
+ ipsilateral foot after arthrodesis, perhaps accomodating for fused ankle walking limitation

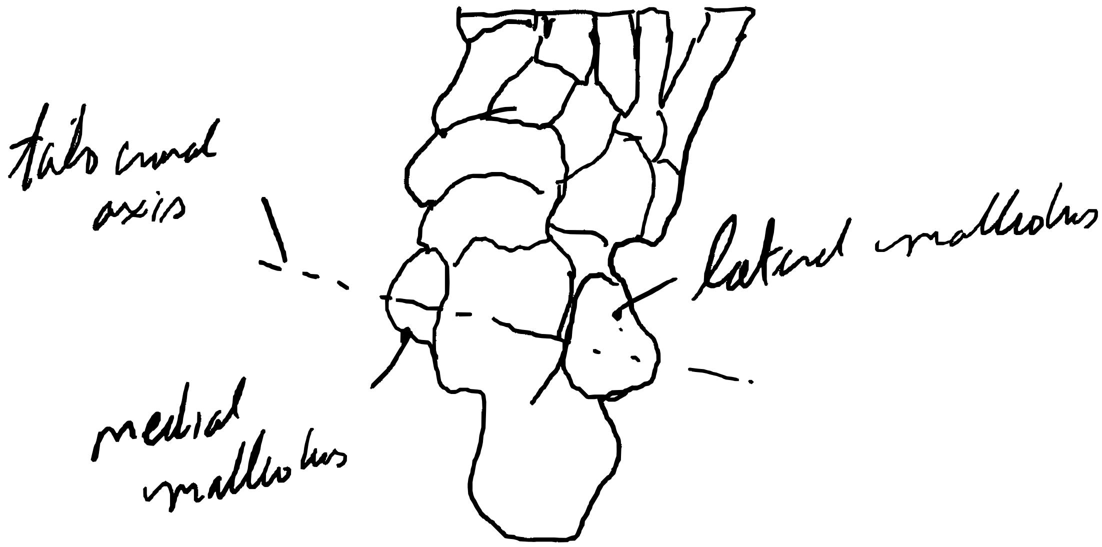
Joint Functions

- unique geometry of soft tissue contribute to DOF & kinematics of joint
- understand all motions, forces, injuries, points of failure

Talocrural Joint

- tibia / fibula sits on dome of talus
+ tibial plafond articulates with dome superiorly, malleolo medial & laterally.
* articular cartilage on majority of talar body
- functions mostly as hinge joint.
+ various degrees of inversion/eversion & lateral translation at degrees of flexion / dorsiflexion.
* limited by medial collateral & deltoid ligament
- axis of flexion around line from medial to lateral malleolo



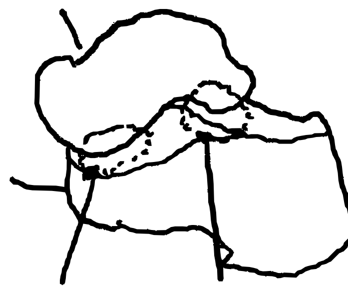


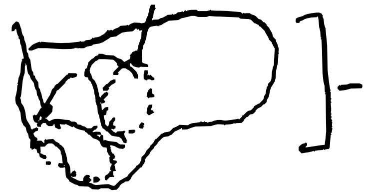
- talus expands in width posterior to anterior.
+ tighten in dorsiflexion, but more unstable in plantar flexion, relying on ligaments
* lateral collateral ligament strained throughout ROM
* deltoid ligament anterior band taught during plantar flexion, posterior ~ dorsiflexion
- common injury: excessive inversion/eversion when plantarflexed

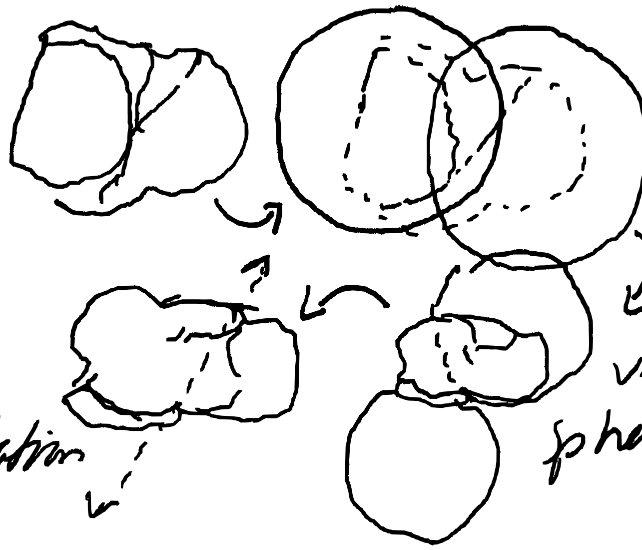
Talocalcaneal (subtalar) joint

- 2 articulating surfaces responsible for inversion / eversion
+ both have synovial capsules
- antero-medial to posterolateral axis, helix / screw-like
- approximate as two connected spheres.
- joint axis changes orientation as motion changes, not well represented
- deltoid & lateral ligament stabilize without connecting to talus, so from

calcaneus to tibia/fibula





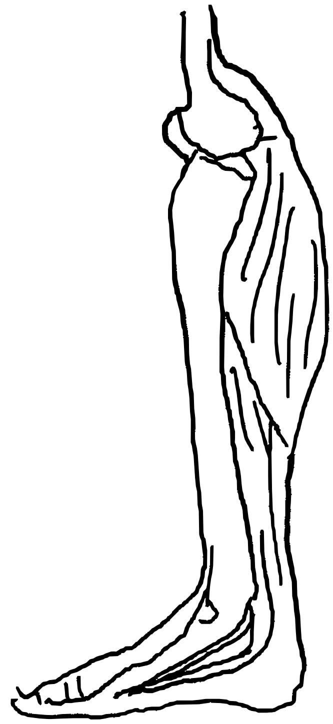


- also supported by tendons wrapping calcaneus & insert int plantar anterior region
+ peroneus longus + brevis, FHL, FDL, tib post.

Transverse Tarsal Joint (Chopart's Joint)

- talonavicular + calcaneocuboid joint
+ flexibility & rigid lever in push off phase
+ point of midtarsal amputation

- talonavicular is anterior talus with posterior navicular held by ligaments



medial view showing course of tendons

fibula

tibia

talus

calcaneus

- cartilage of talar head extends inferiorly to anterior aspect of subtalar joint
- talus- navicular articulation is "unstable" ball and socket held fast by bifurcate lig laterally, inferomedial + superomedial calcaneonavicular ligament & tib post & flexor tendons
- calcaneocuboid joint is saddle joint, small ROM
+ cuboid bony projection into fossa of calcaneus during inversion
- changes in subtalar → "midfoot locking" of transverse joint
- initial foot contact in gait = eversion at subtalar

+ talonavicular & calcaneocuboid axes move & align, unlocking midfoot

- stance to heel off, subtalar inverts, axes of transverse joints move out of alignment, midfoot locks into rigid lever

- injury/disease impact on midfoot locking

+ calcaneal fracture/hindfoot joint fusion prevents midfoot unlocking, increasing stress

+ tib post weakness, subtalar inversion fails, no locking

Tarsometatarsal (Lisfranc's joint)

- cuneiform/cuboid articulation with metatarsals

- intermediary cuneiform & 2nd metatarsal unique

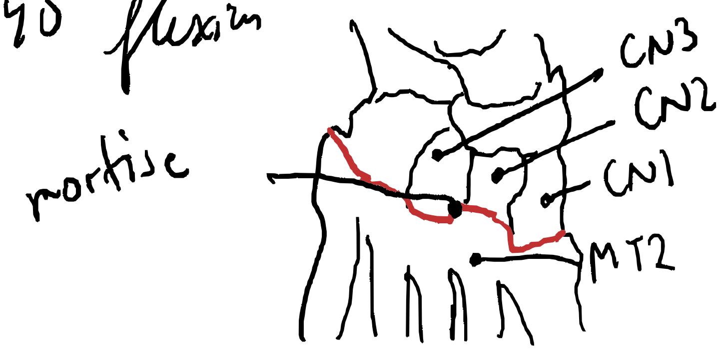
+ 2nd metatarsal sits in recessed mortise of intermediary cuneiform

+ only ligaments connect & prevent 1st & 2nd ray separation

- not well studied because of limited motion, leading to increased arthritis & poor surgical outcomes

Metatarsophalangeal joint

- fully covered in cartilage to allow for large articulation (75° extension, 40° flexion



- mostly hinge action

- long axis from metatarsal to phalange does not align
+ hallux normally < 15°
* hallux valgus > 15°, often called bunion

Areas of Future Research

- prevent arthrodesis at all costs
+ orthosis (braces) for "simulated" arthrodesis.
* no great understanding / relative comparison
+ Total Ankle Arthroplasty (TAA) for late stage OA
* current techniques do not suggest success, often more revisions needed
- relationship between intrinsic anatomy of bones & biomechanics using improved computational models to define movement as it truly is, rather than approximations like "hinge"
+ contributed greatly to understanding how stress and joint contact forces change after injury
* characterize material properties of healthy & diseased tissue
* improve estimates of loading conditions to research for specific activities
* incorporate patient specific anatomy