Ligaments

- hard to study due to size, but advances have been made

Introduction

- ligaments constrain movement of joints
+ viscoelastic too
- account for 50% of sports related injuries
- repeated trauma can lead to chronic pain ie plantar fasciopathy

Ligament Anatomy

- 28 bones, numerous articulations
- most bone-to-bone articulations have joint capsules with ligaments for reinforcements
+ depending on joint, thick and cord-like or thin & membrane-like

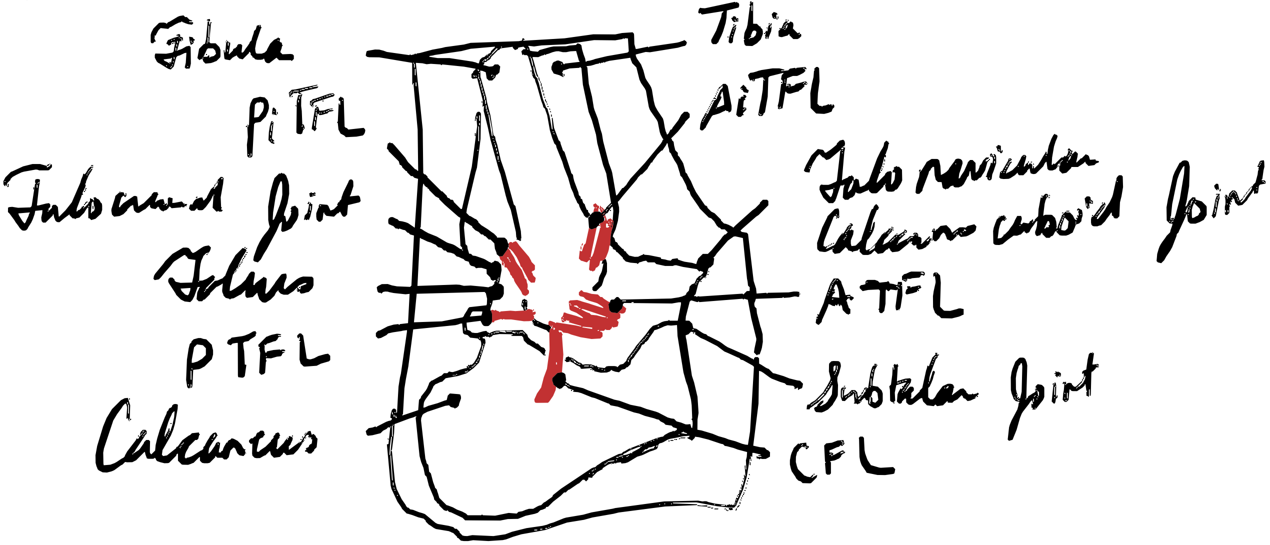
- 100+ ligaments in foot, hard to study them all
+ focus on mid, hind, forefoot, and ankle joint
* medial & lateral complexes
* subtalar
* plantar fascia + dorsal interosseous
* deep transverse metatarsal

Mechanical Properties

- size, shape, insertion, loading requirement all differ
- ligaments calcify near bony insertion
- failure occurs between insertion sites, at the insertion, or ligament with bony anchor come off (avulse)
- no engineering exact equation, high study variability

Ankle Joint

- LCL
+ from lat. malleolus; insert near tibia, talus, calcaneus



+ ATFL, disorganized, distal fibula across talar body
+ CFL, organized, cord like, distal fibula to posterior lat. calcaneus

+PTFL, opposite of ATFL, distal fib to very posterior talus

Stiffness (kN/m)

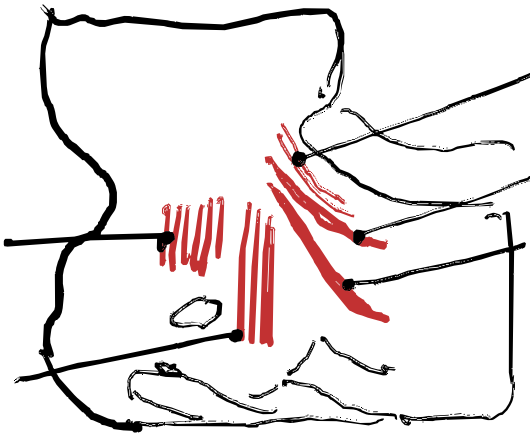
Study	ATFL	CFL	PTFL
Attarian	35.99 ± 8.54	7.05 ± 0.69	3.98 ± 1.38
Siegler	141.8 ± 79.3	126.6 ± 42.9	124.3 ± 55.5
Rochelle	44.7 ± 16.6	45.8 ± 19	59.0 ± 10.7

Ultimate Load (N)

Study	ATFL	CFL	PTFL
Attarian	138.9 ± 23.5	345.7 ± 55.2	261.2 ± 32.4
Siegler	231 ± 129	307 ± 90.2	418 ± 151
Rochelle	263.6 ± 164.3	367.8 ± 79.8	351.4 ± 10.7
	LOWEST!! → injury		

-MCL

+ deltoid ligament



+ limits ankle eversion
+ tibionavicular lig: broad, fan-like from anterolateral tibia to navicular

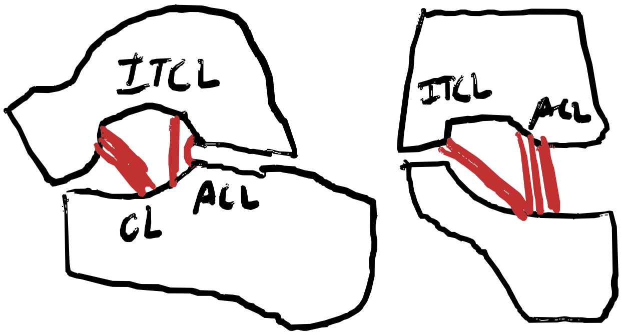
* lowest measured strength, ultimate load 120N

+ posterior tibiotalar lig: thick, highly organized, from distal tib to medial & posterior talus

* high elastic stiffness, yield load, ultimate load.

* contribute most to talus stability
+ & anterior tibiotalar & tibiocalcaneal (tibiospring portion)

Sagittal plane



Coronal Plane

Schematic of Subtalar ligaments

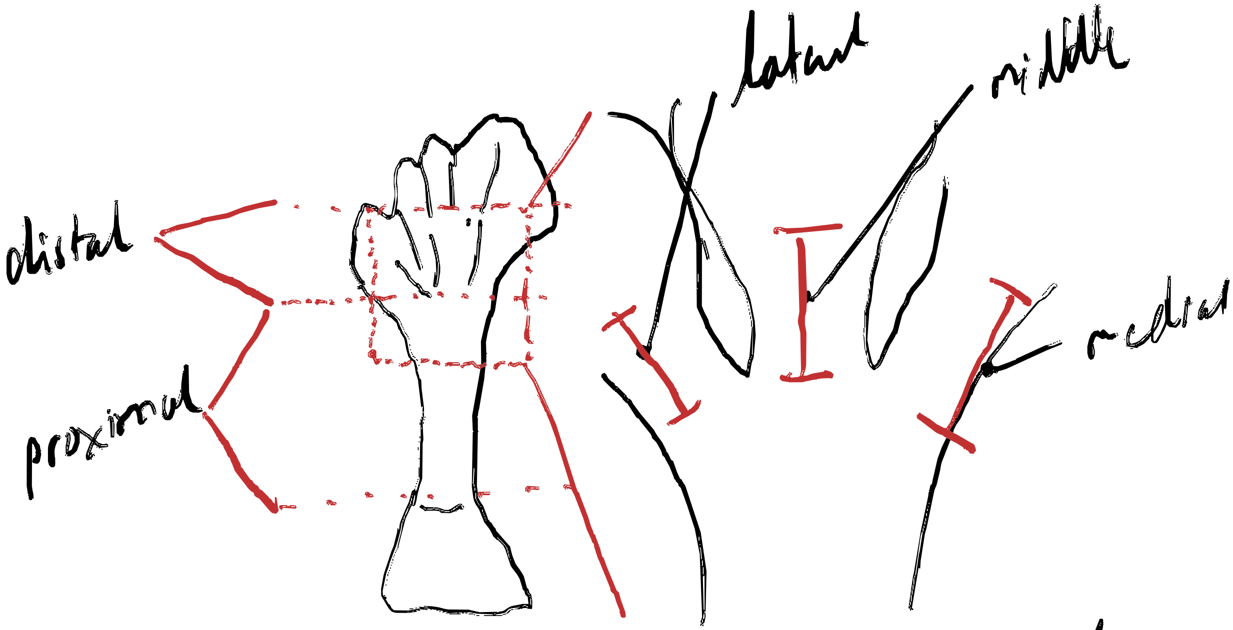
Hindfoot Ligaments

- Subtalar joint
  + accomodate coronal plane movement (uneven ground)
  + anterior capsular ligament (ACL) + interosseous talocalcaneal ligament (ITCL) stiffer than cervical lig. (CL)
  + CL narrow but extends deep
  + stiffness characteristics enable lower stability for gait
- Talonavicular joint
  + Spring Lig. supports medial arch
  + superomedial, medioplantar oblique, inferomedial bundles (not always identifiable!)

Midfoot Ligaments

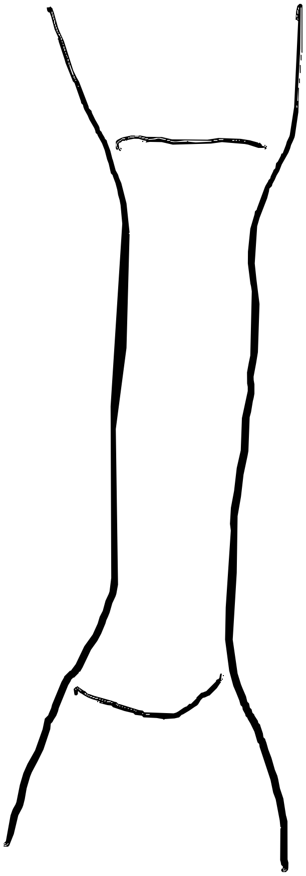
- Plantar Fascia
  + little strain dependence regardless of loading rate
  * however, tested as diff. regions, middle & lateral lower modulus compared to proximal distal
- Metatarsal Base ligaments
  + complex to study
  + dorsal cuneometatarsal lig. connecting 1st cuneiform to 2nd metatarsal weaker than interosseus lig. (Lisfranc) & plantar tarsometatarsal lig

(connecting 1st cuneiform to 2/3 metatarsals



bone - plantar fascia - bone

lateral view from right foot



medial & lateral bands resected

+ interosseus lig sig stronger & stiffer than plantar tarsometatarsal

+ injury to it probably more destabilizing

Refer to textbook for mechanical properties of plantar fascia & midfoot ligaments

Forefoot

- transverse metatarsal ligament
  + band between 1st & 2nd MTP resists dorsiflexion & dorsal dislocations

Variations in Mechanical Properties

- Changes in activity level
  + endurance exercises (in animal ligaments) increase strength & stiffness
  + lack of stress for 6 weeks or more decreases mechanical strength
- Foot comorbidity
  + hallux valgus = lower max force, stress, & strain
  + collagen negatively affected by diabetes, plays large role in achieving optimal strength & stiffness

- Age effects
  + obviously less physically active, degeneration
  * more frail at mid substance rather than insertion
- Influence of anthropomorphic effects
  + males larger CSA, higher yield + ultimate strength to females
  + higher BMI = higher ultimate load

Ligament Sprains

- greatest risk of ankle sprain is history of one
- LCL complex often hurt in inversion sprain + external leg rotation
- high ankle sprain of anterior + posterior inferior tibiofibular ligament.
- nonconservative if chronic instability:
  + anatomic: use normal anatomy
  + nonanatomic: use graft

Overcoming Limitations

- 80% of ligaments are Type I collagen organized nonuniformly, making testing difficult.
- use testing protocols outlin by ASTM for repeatability
- due to stress-relaxation of viscoelastic materials, testing must occur across multiple strain rates

- however, ligaments' response seem strain rate independent, so tests preload cyclically to stabilize hysteresis for a time independent response

+ $\boxed{\text{hysteresis}}$: phenomenon where a system's state is dependent on its history

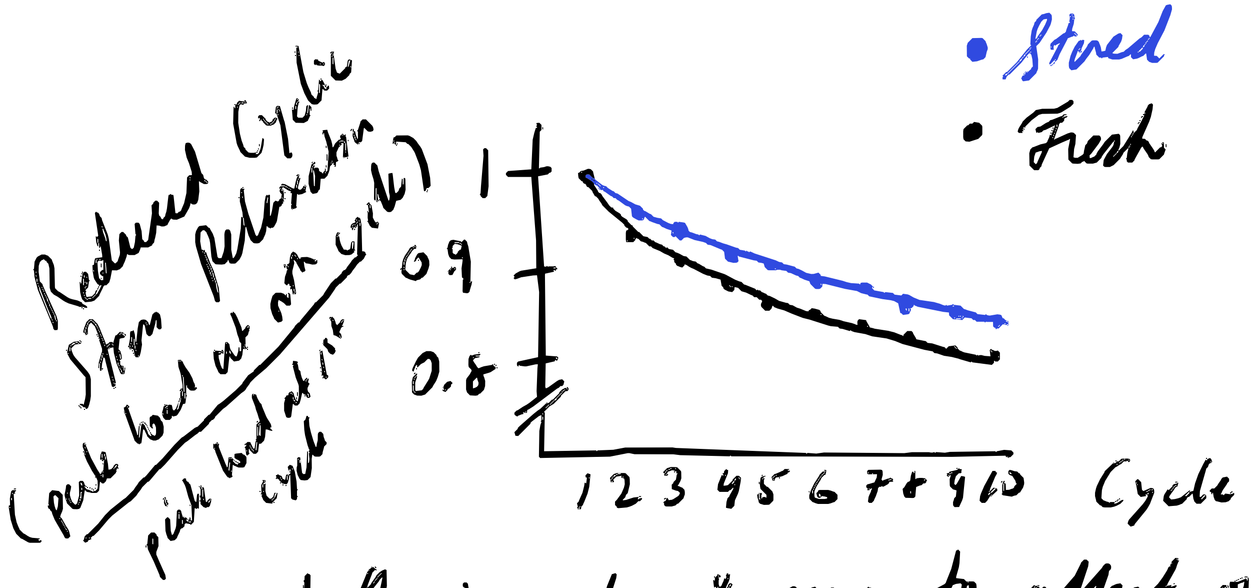
- testing must also maintain integrity of ligament

+ requires consistently good hydration

* protocols / setups differ e.g. 10% saline solution sprayed, encased in 100% humidity + temperature controlled, etc.

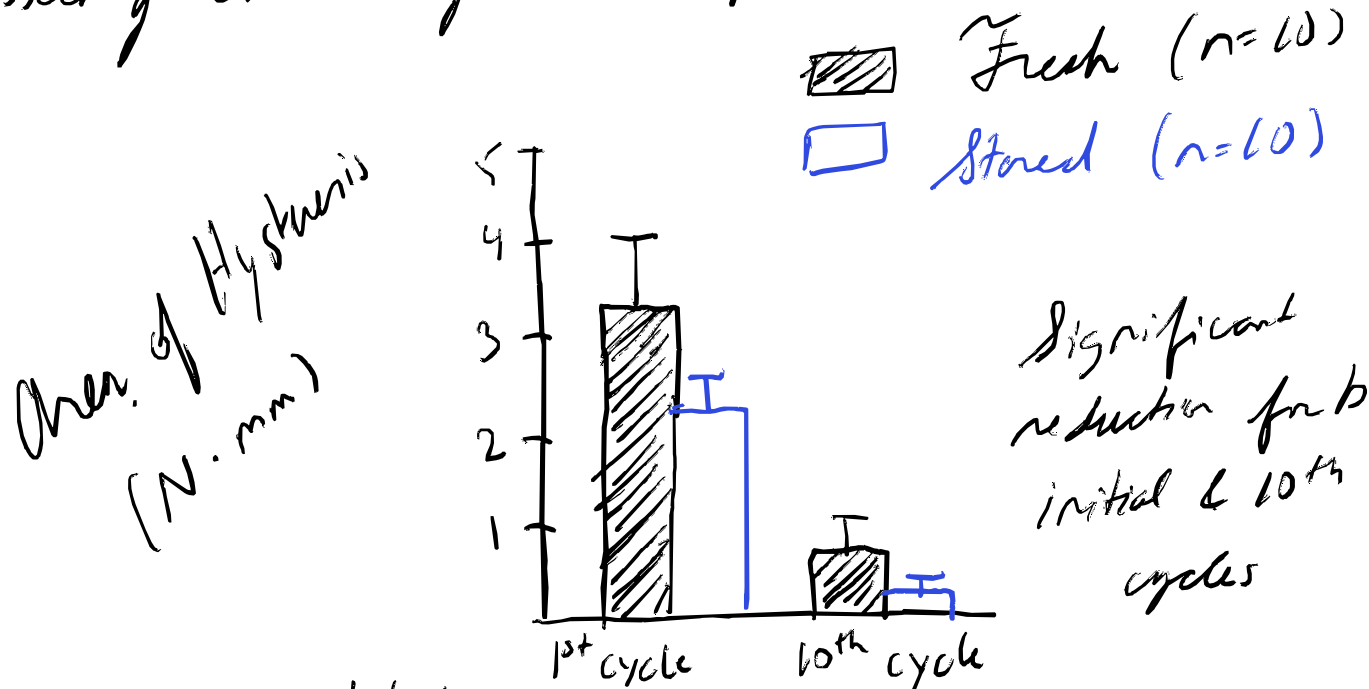
Refer to text for structural properties of femur-medial collateral ligament tibia complex before & after freezing

Same for mech mechanical properties before and after freezing medial collateral ligament.



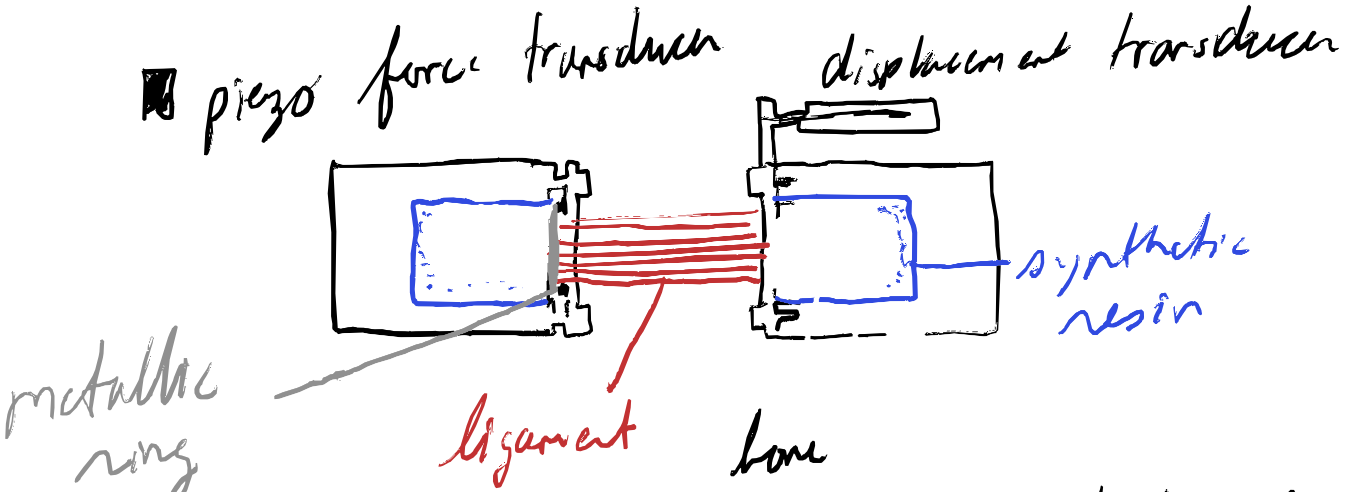
- freezing and thawing doesn't seem to affect overall peak stress
+ however, peak stress higher in initial 10 cycles, reduced hysteresis
- challenging to secure ligaments w/o damage due to short length + complex morphology
+ potting bony attachment in resin; mounting bone to test fixture;

dissecting and using custom fixture



Significant reduction for both initial & 10th cycles

paired t-test $p < 0.05$ $p > 0.1$



ligament bony attachments potted in plastic resin

- measuring true stress response, CSA must be measured, but irregular morphology makes it difficult

+ 3D scanning advancements mimic expensive high-accuracy tools

- molding techniques used to some success,

+ Liquid polyurethane & reusable silicone molds accurately captures ligament surface geometry.

Refer to textbook for pictures of tool usage to examine ligaments

- ligaments that wrap bony features before terminal insertions are complicated to measure

+ recent study mounted cadaver leg into rig, measured load & displacement at time of rupture

* use acoustic sensors, strain gauges, force & moment measurements, 3D bone kinematics

+ difficult to ascertain ground truth, no non invasive verification technique exits

* ligament strain elastography validation using cadaveric in situ specimens under physiologic loading conditions is an active research area

Future Areas of Research

- extensive understanding of ligament properties is hard
- ultrasound sonography is promising
- Standard procedures don't exist, novel innovation needed
- fully characterizing ligament behavior is essential towards validation computational simulations of joint biomechanics