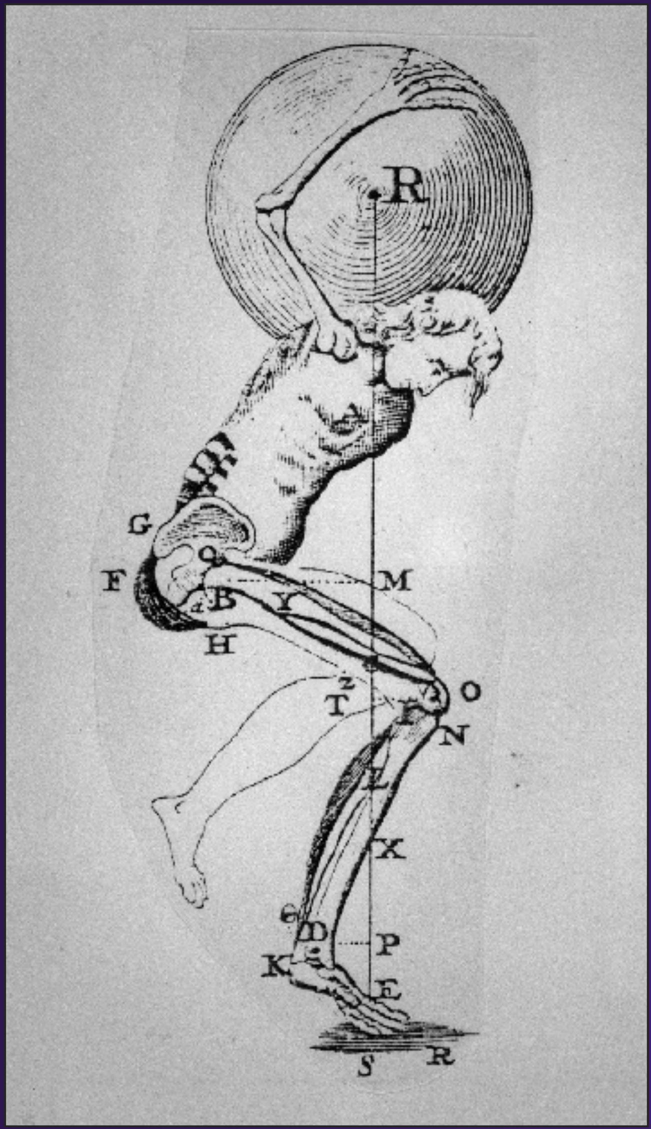


Musculoskeletal Biomechanics

BIOEN 520 | ME 527

Session 9B

Ligaments, Tendon and Cartilage

...Structure, Function, and Properties

Session 7A Review

- Computational modeling
- Define model and simulation
- Motivation - why develop models?
- Types of models
- Important modeling considerations
- Specific modeling examples

Session 9B Overview...

- Ligament
- Tendon
- Cartilage
- Injury survey

Structural Soft Tissues

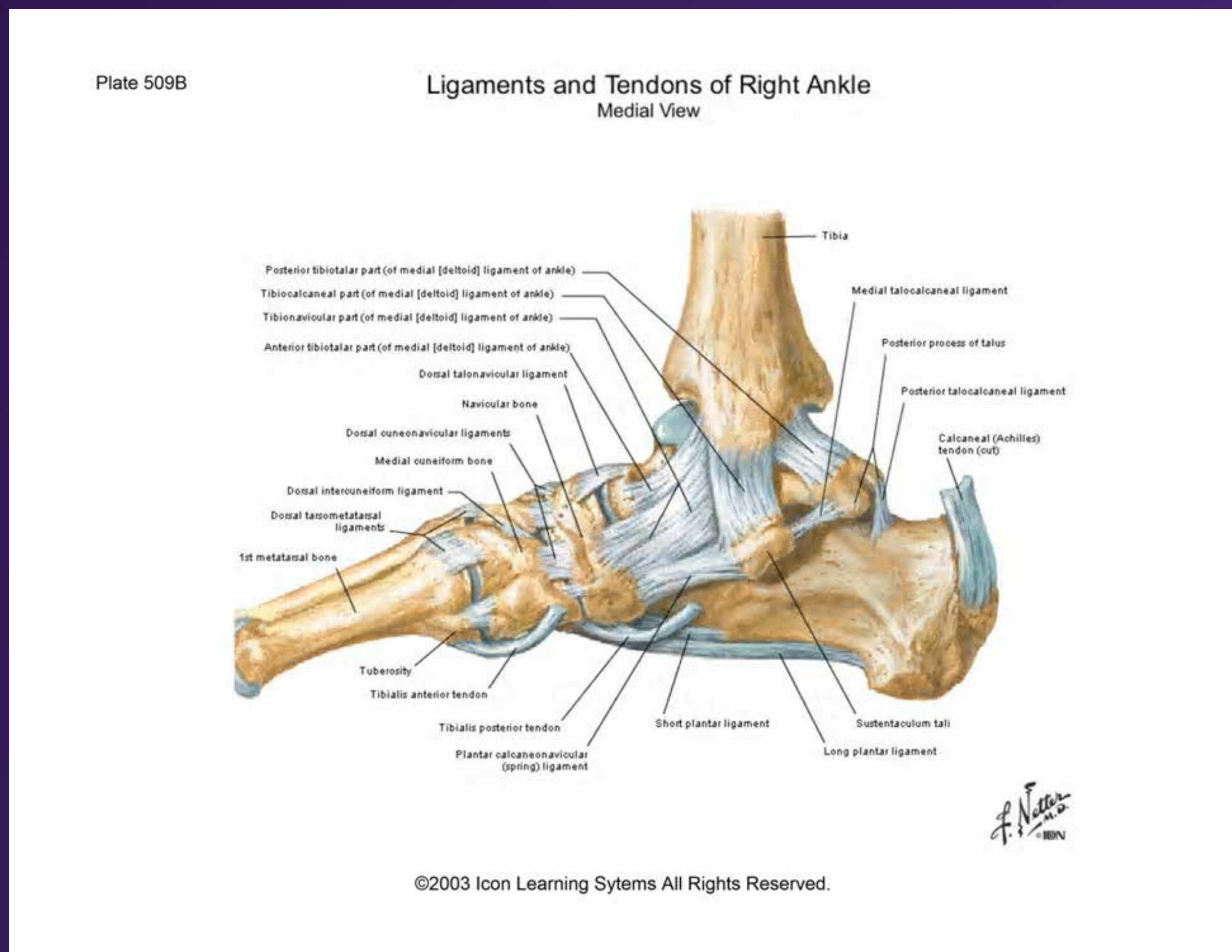
- ligament
- tendon
- cartilage (meniscus, labrum)
- muscle (all types)
- heel pad (plantar soft tissue)
- intervertebral discs

Structural Soft Tissues

- morphology and histology
- function
- mechanical properties
- additional information

Ligaments

- Fibrous, anisotropic tissue that connects bones



Ligaments

- Morphology - hierarchical structure

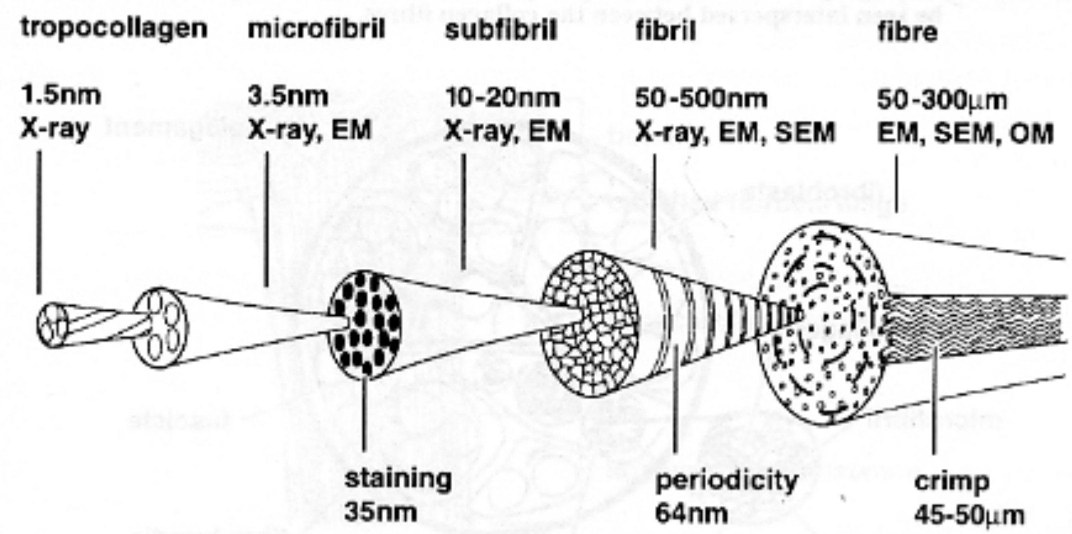


Figure 2.5.1 Schematic illustration depicting the hierarchical structure of collagen in ligament midsubstance. EM = electron microscope; SEM = scanning EM; OM = optical microscope (from Kastelic et al., 1978, with permission of Gordon and Breach, Science Publishers Ltd.).

Ligaments

- Steel belted radial tires
  - http://www.youtube.com/watch?v=9YZzYAYjw3I
- Suspension bridges

Ligaments

- Morphology - crimping
  - Undulating, 50 microns
  - Fibroblasts between fibers

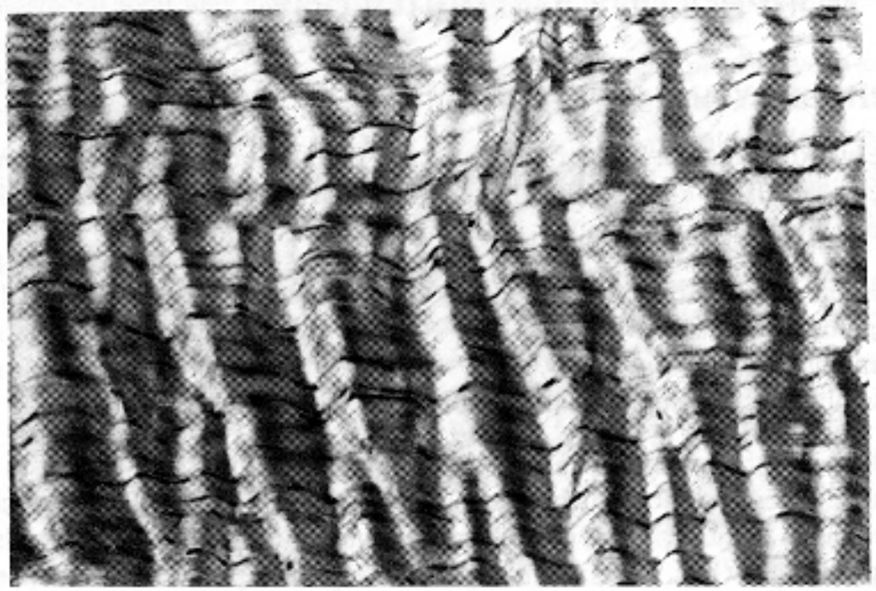


Figure 2.5.2 **Photograph illustrating crimped pattern of collagen in ligament. Fibroblasts may be seen interspersed between the collagen fibres.**

Ligaments

- Morphology - cross section
  - Epiligament – protect, support NV, control water

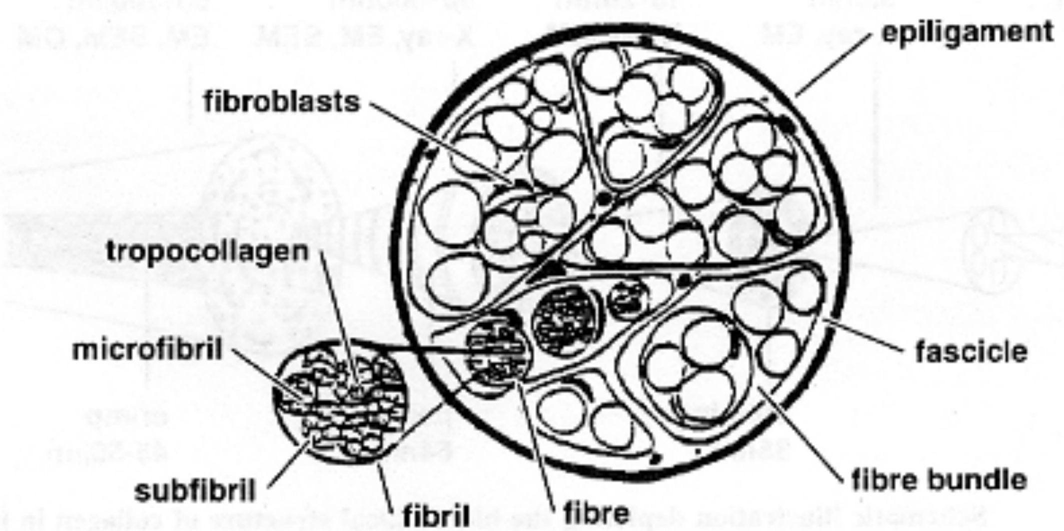
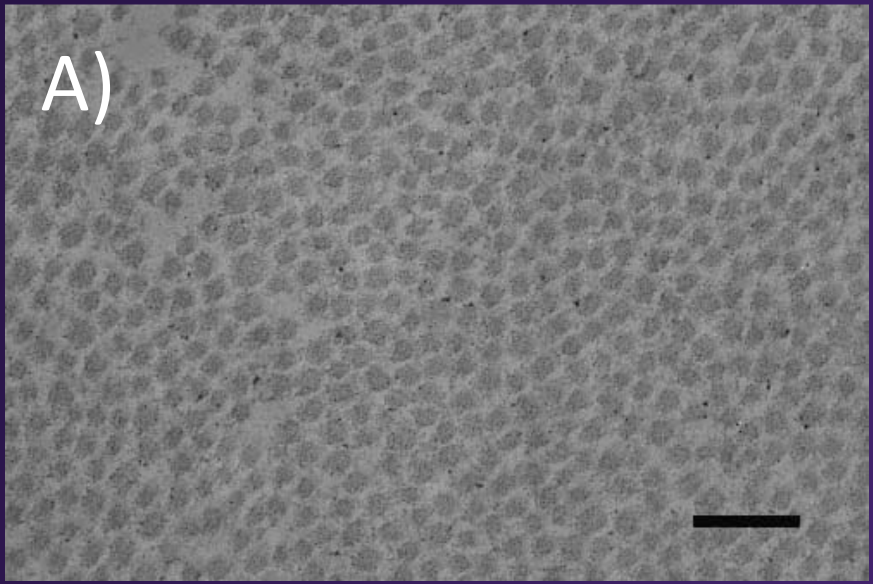


Figure 2.5.3 Schematic diagram of a ligament in cross-section.

Ligaments

- Morphology - cross section (EM, bar=200nm)



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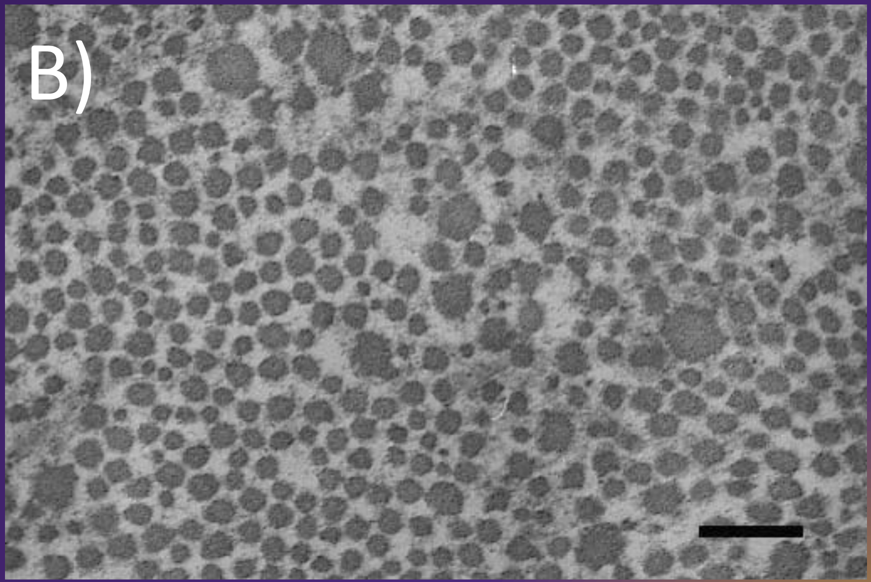

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Ligaments

- Morphology - hierarchical structure

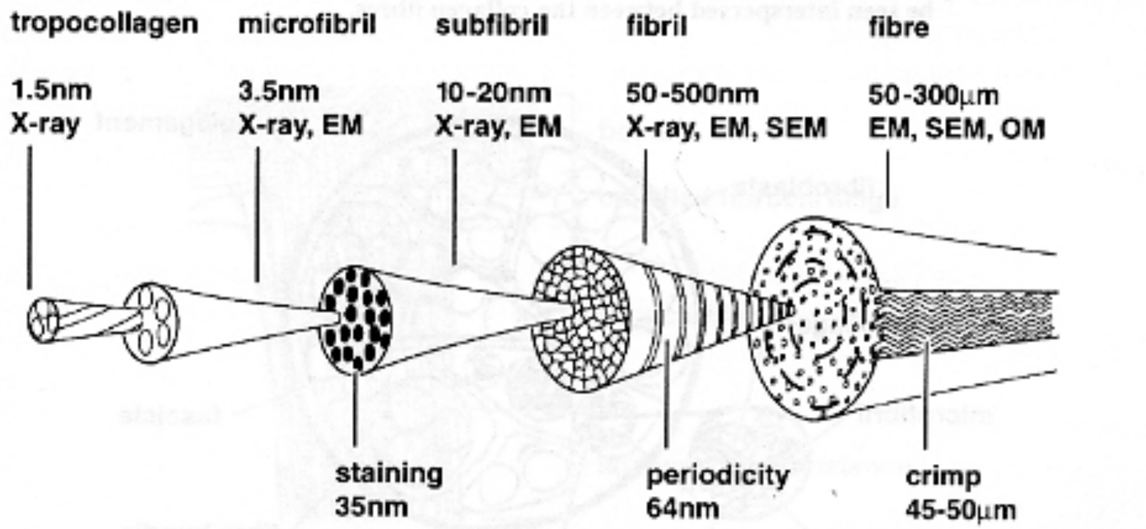


Figure 2.5.1 Schematic illustration depicting the hierarchical structure of collagen in ligament midsubstance. EM = electron microscope; SEM = scanning EM; OM = optical microscope (from Kastelic et al., 1978, with permission of Gordon and Breach, Science Publishers Ltd.).

Ligaments

- Morphology - direct insertion
  - 4 layers within 1 mm

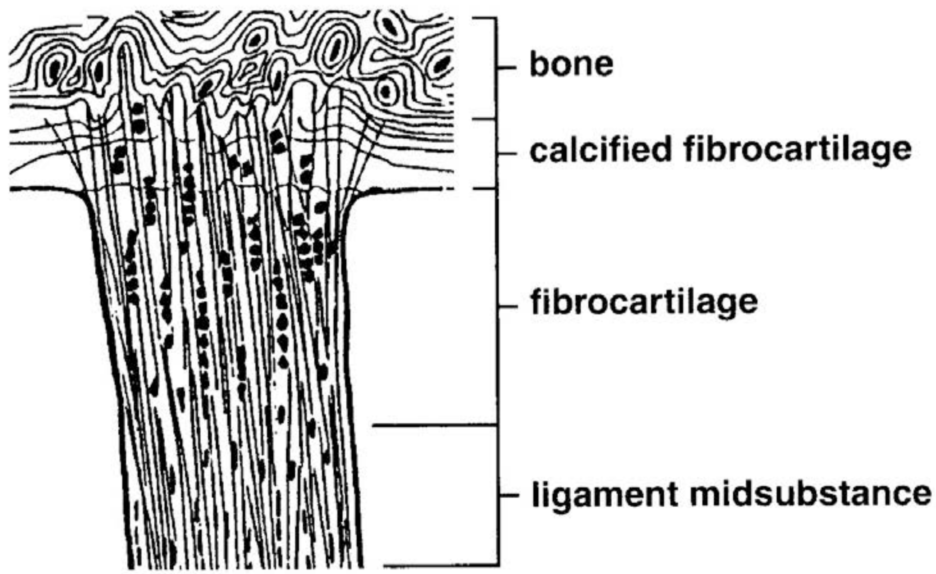
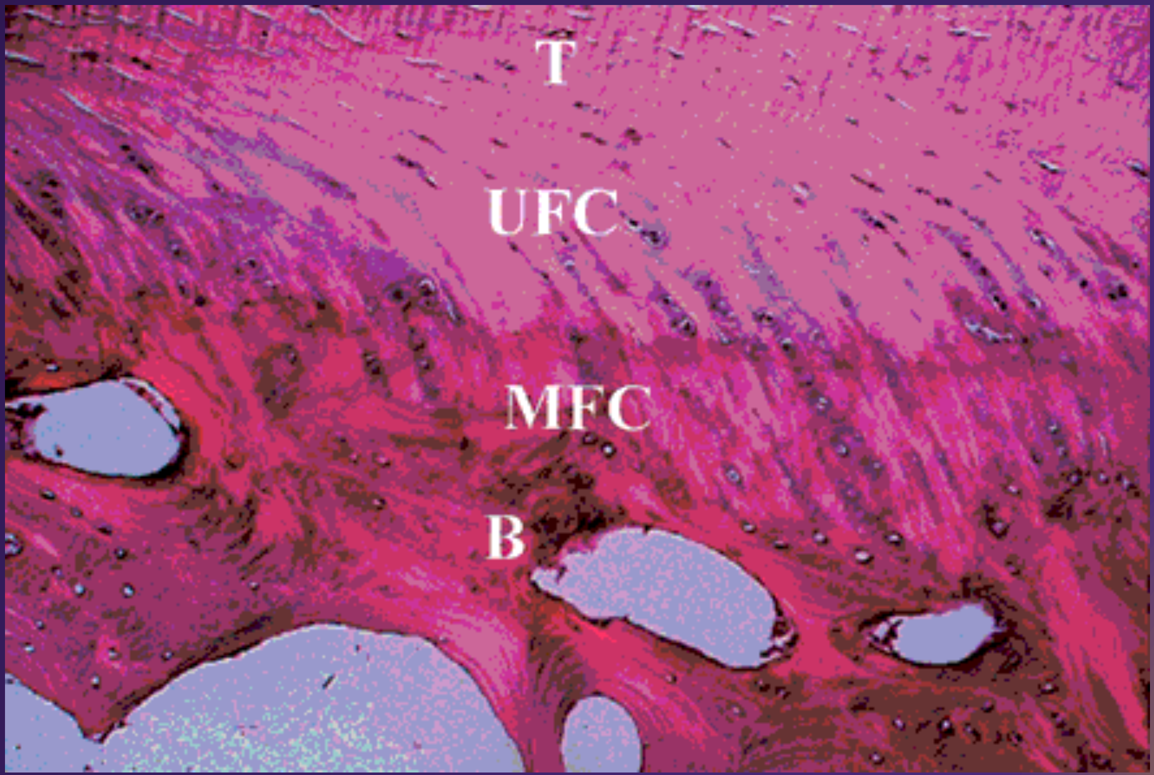


Figure 2.5.4 Schematic diagram of a zonal ligament insertion into bone. The bone is at the top of the diagram, the ligament at the bottom (from Matyas, 1985, with permission).

Ligaments

- Morphology - direct insertion
  - 4 layers within 1 mm



www.jbjs.org/Comments/c_p_rodeo.shtml

Ligaments

- Histology
  - Fibroblasts or fibrocytes = ligament cells
  - not homogenous - vary in size, shape, orientation and number
  - synthesize and degrade ligament matrix
  - repair microscopic damage

Ligaments

- Histology

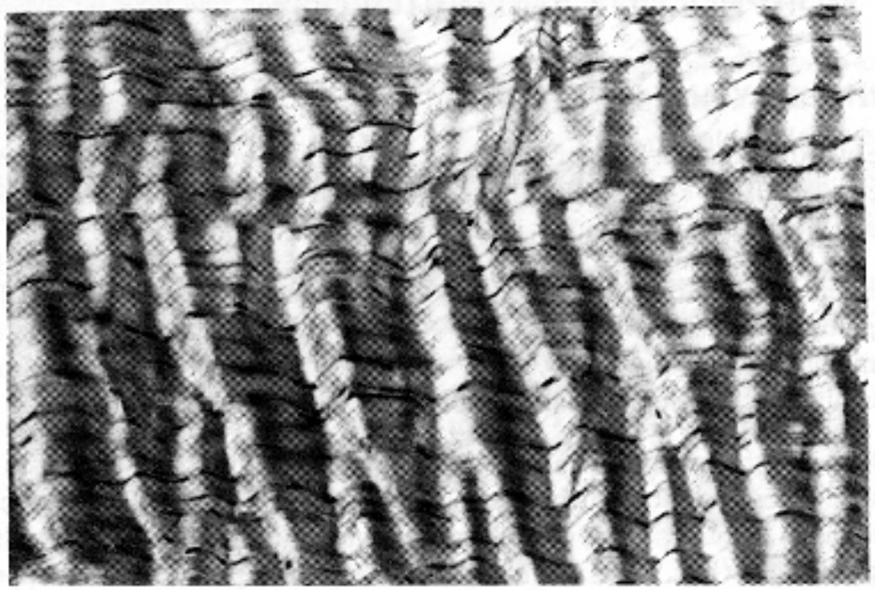
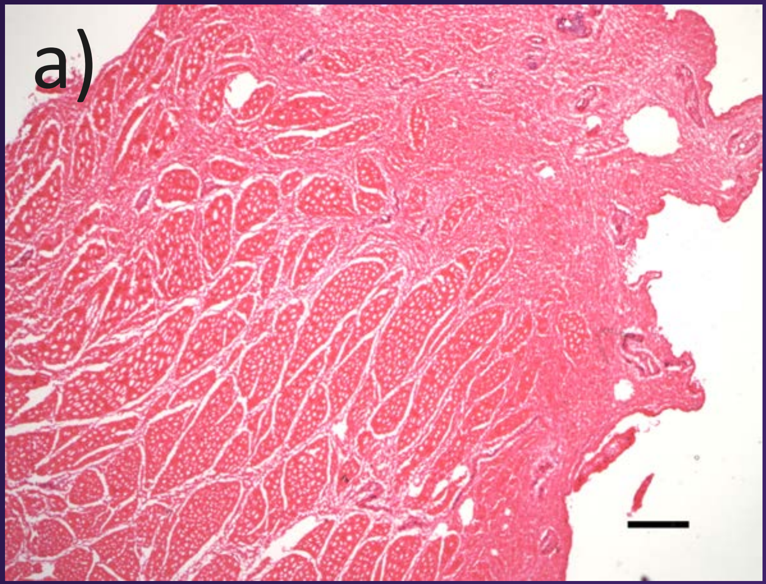


Figure 2.5.2 Photograph illustrating crimped pattern of collagen in ligament. Fibroblasts may be seen interspersed between the collagen fibres.

Ligaments

- Histology - hematoxylin and eosin or H&E staining, bar = 300μm



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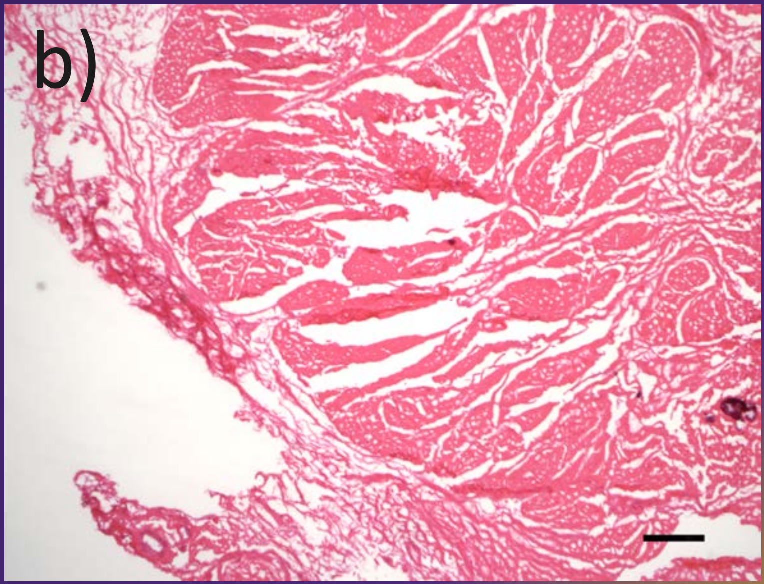

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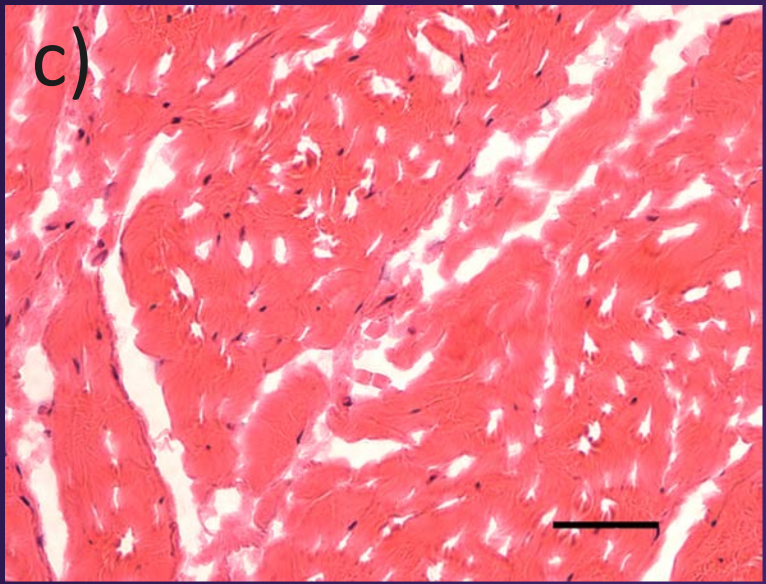
Ligaments

- Histology - hematoxylin and eosin or H&E staining, bar = 50μm



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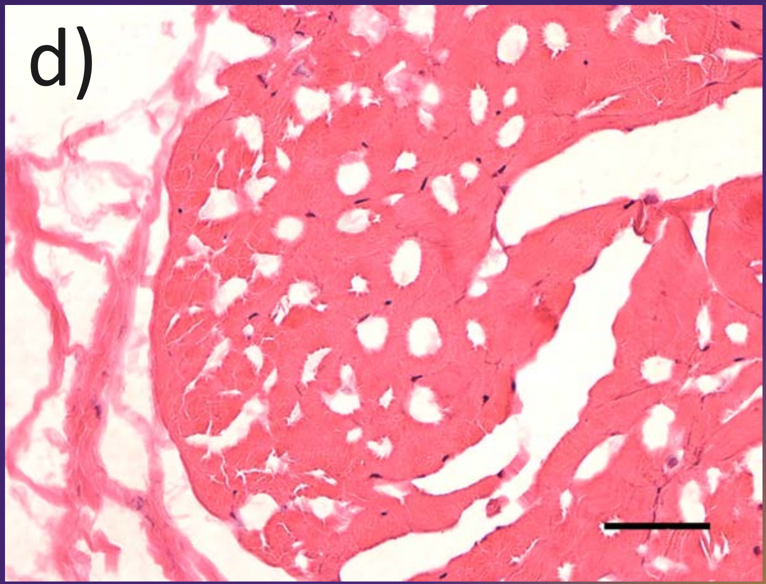

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Ligaments

- Histology - The matrix

Ligaments

- Histology - matrix: water
  - 60-70% of ligament wet weight
  - can structurally bond to other matrix components
  - interaction with ground substance (proteoglycans) influences viscoelasticity
  - lubrication
  - carries nutrients and removes waste

Ligaments

- Histology - matrix: collagen
  - constitutes 70-80% of dry weight
  - 90% Type I, with less than 10% type III, small quantities of Types V, VI, XI, XII and XIV
  - fiber size related to material strength
  - after exocytosis of collagen molecules from fibroblasts, crosslinks are formed
  - in mature ligament tissue, there is a balance between collagen synthesis and degradation

Ligaments

- Histology - matrix: water
  - 60-70% of ligament wet weight
- Histology - matrix: collagen
  - constitutes 70-80% of dry weight
  - 90% Type I

Ligaments

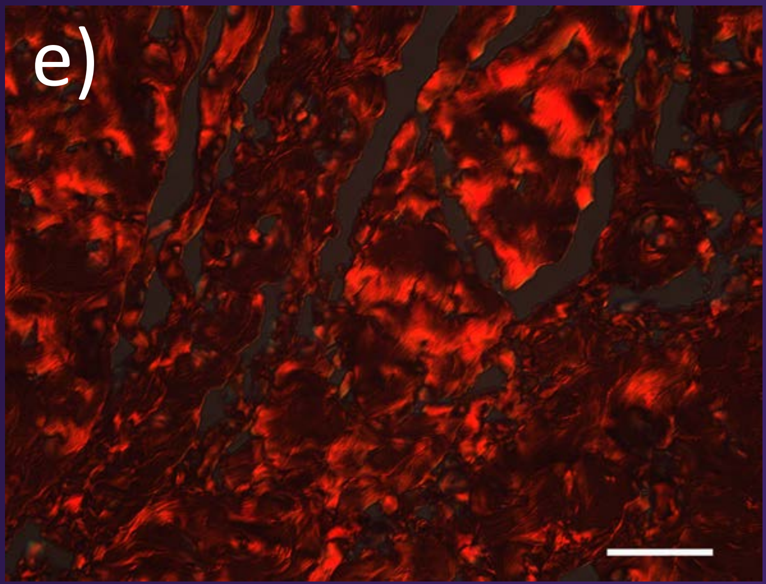
- Histology - matrix: water
  - most of ligament wet weight
- Histology - matrix: collagen
  - constitutes a lot of dry weight
  - almost all Type I

Ligaments

- What constitutes 90% of the dry weight of ligament?
- Type I collagen constitutes ____ % of the dry weight of ligament.
  - A) 80, B) 85, C) 90, D) 95
- Type I collagen constitutes ____ % of the dry weight of ligament.
  - A) 10, B) 25, C) 50, D) 90

Ligaments

- Histology - matrix: collagen, sirius red staining, bar = 50μm



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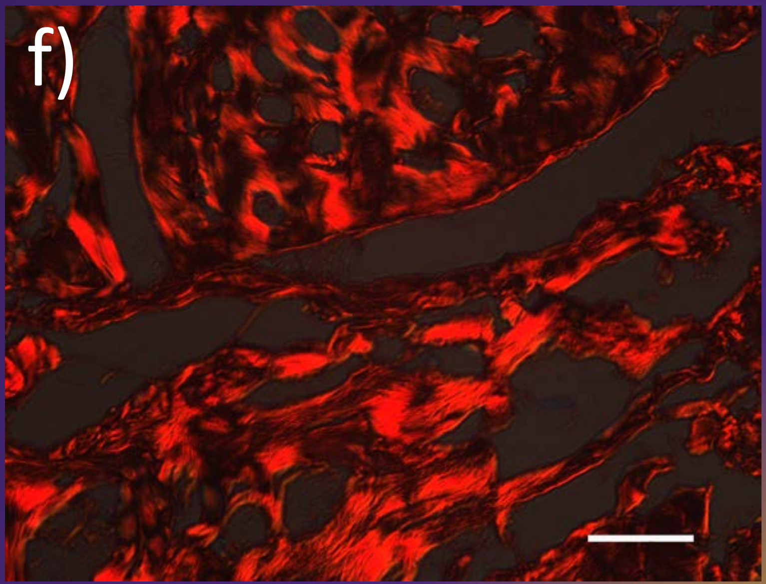

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Ligaments

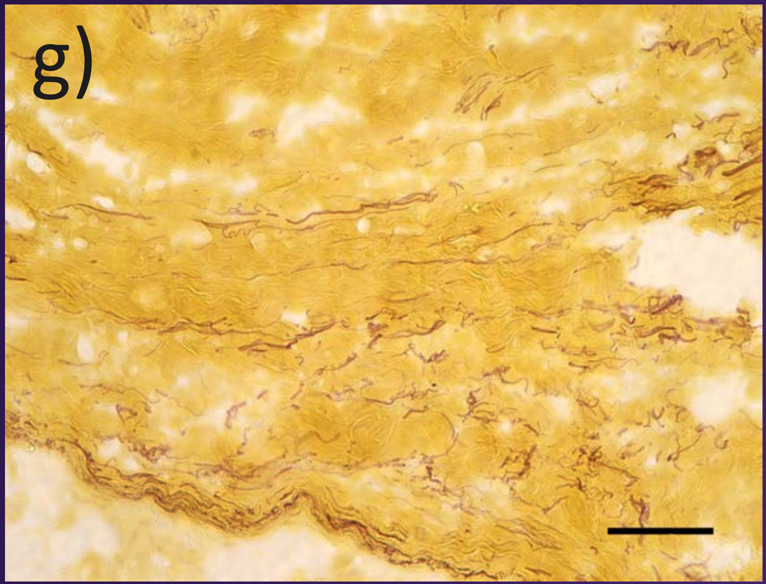
- Histology - matrix: proteoglycans
  - less than 1% of ligament dry weight (more than in tendons, but less than cartilage – 3 to 10%), but key to ligament function
  - do not provide cushioning as with cartilage
  - associate with water regulation (amount and movement), forming a gel-like extracellular matrix
  - influence the viscoelastic behavior of tissue

Ligaments

- Histology - matrix: elastin
  - occurs in small quantities (1.5%)
  - restoring ligament length after stress
  - protects collagen at low strains
- Histology – matrix: noncollagenous glycoproteins
  - fibronectin (matrix-cell feedback mechanism?)

Ligaments

- Histology - matrix: elastin, modified Hart's staining, bar = 50μm



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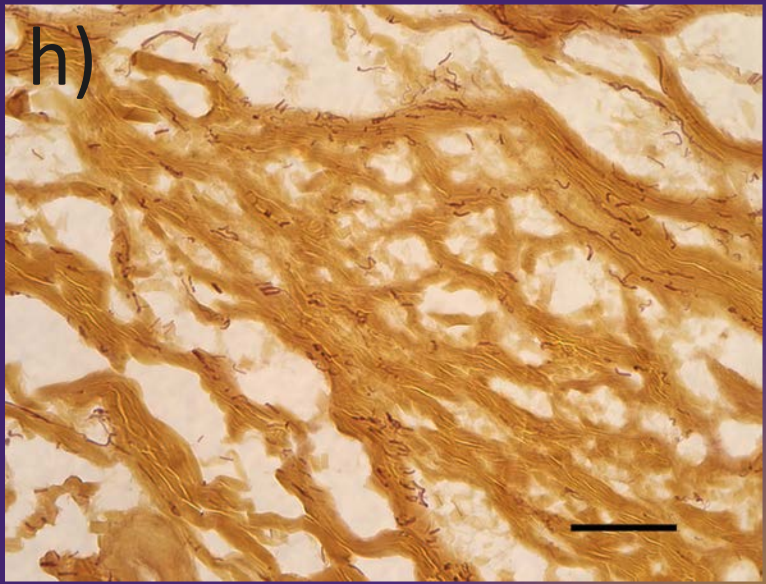

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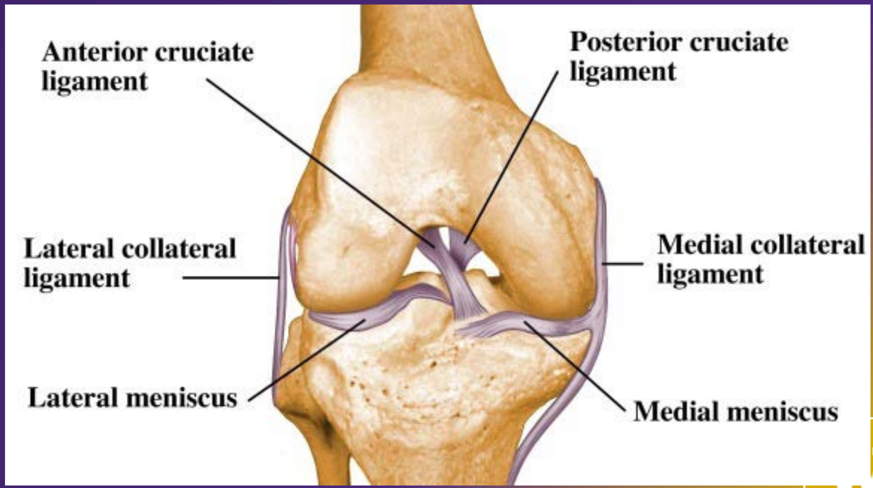
Ligaments

- Function
  - attach articulating bones to one another across a joint
  - guide joint movement
  - maintain joint congruency
  - possibly act as a positional bend or strain sensor for the joint (proprioception)
  - maintain joint capsule
    - capsular vs. extracapsular



Ligaments

- Mechanical properties - nonlinear force v. deformation curve

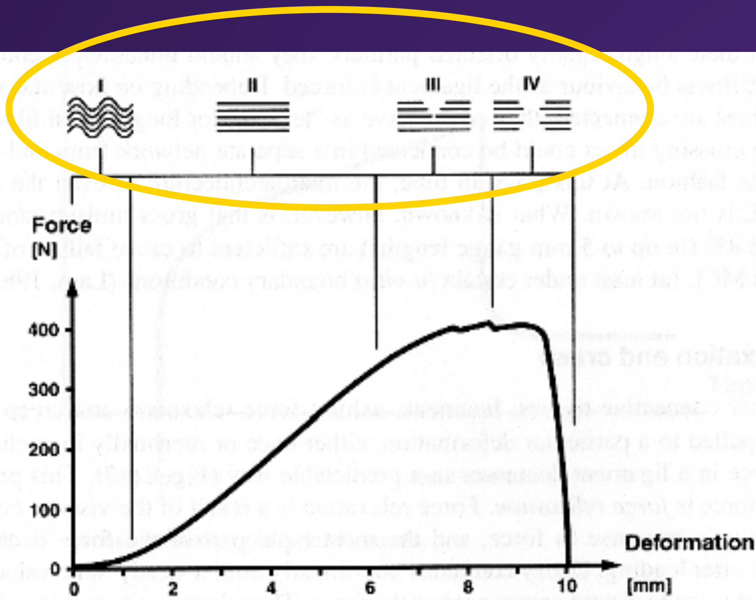


Figure 2.5.6 A typical force-deformation curve for a typical rabbit ligament under monotonic forcing. I = toe region; II = linear region; III = region of microfailure; IV = failure region. At top are schematic representations of fibres going from crimped (I) through recruitment (II) to progressive failure (III and IV).

Ligaments

- Mechanical properties
  - Stress (load) relaxation

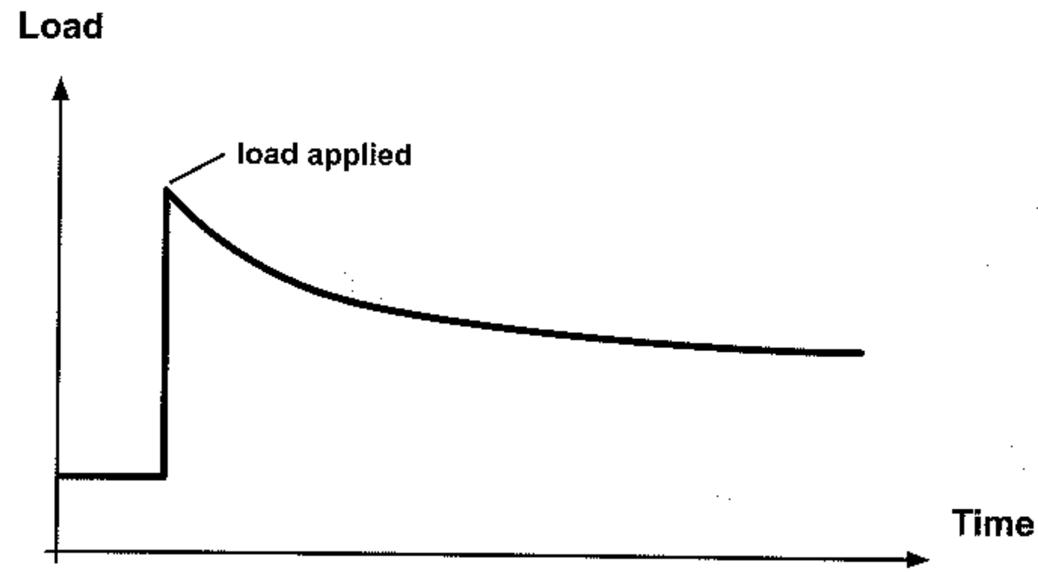


Figure 2.5.17 Schematic load-relaxation curve for ligament.

Ligaments

- Mechanical properties
  - Creep

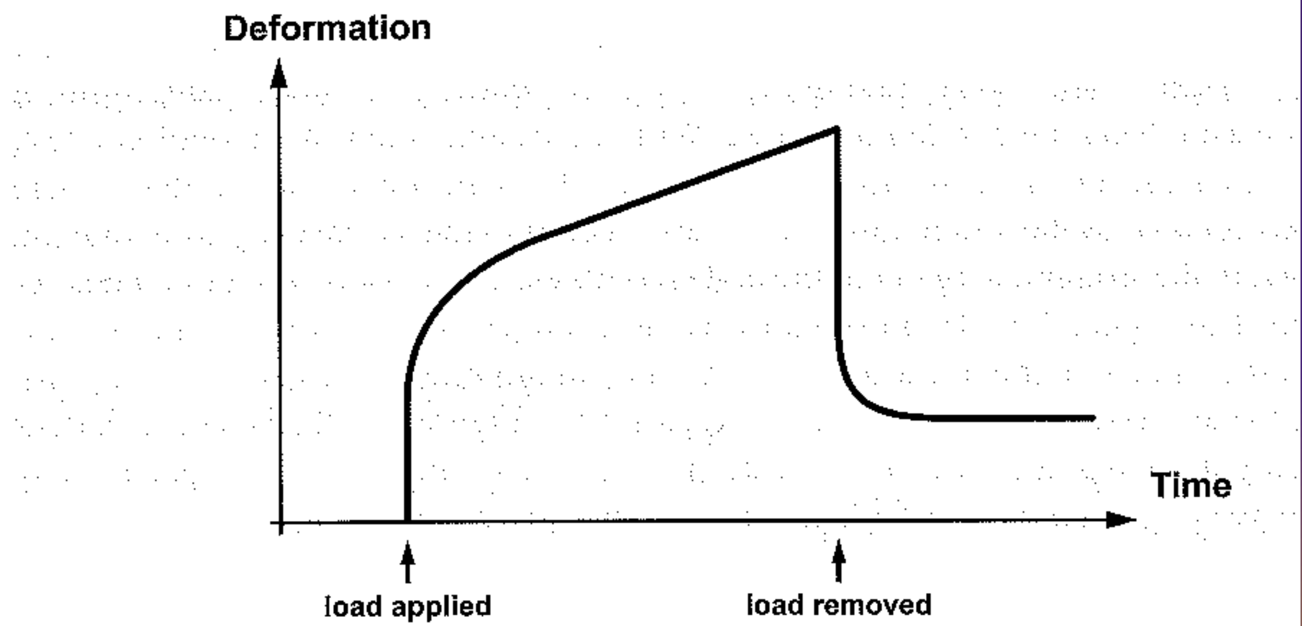


Figure 2.5.18 Schematic creep curve for ligament.

Ligaments

- Mechanical properties
  - Preconditioning (not described well in text)

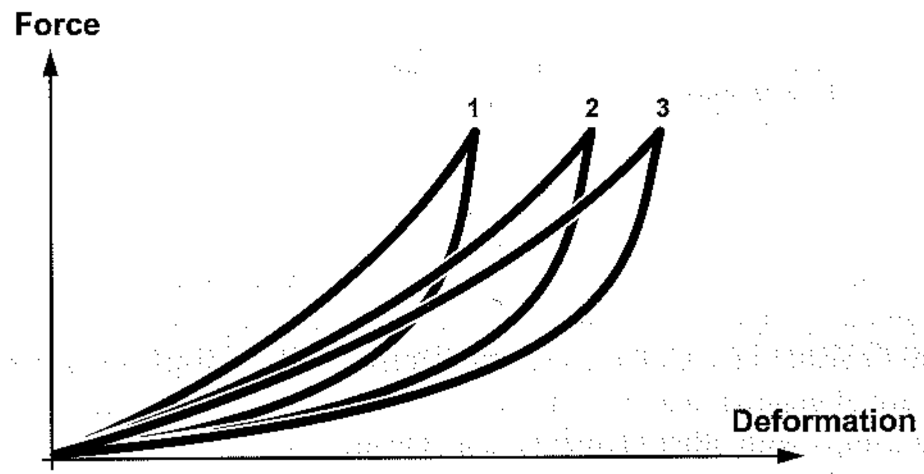


Figure 2.5.19 Schematic force-deformation graph showing three successive cycles in displacement control to an upper load limit and a lower displacement limit, illustrating the viscoelastic creep effect of cycling upon a ligament.

Ligaments

- Mechanical testing issues
  - Sources of tissue
  - Aspect ratios / securing tissue ends
  - Measurement of cross sectional area
  - Zero strain position

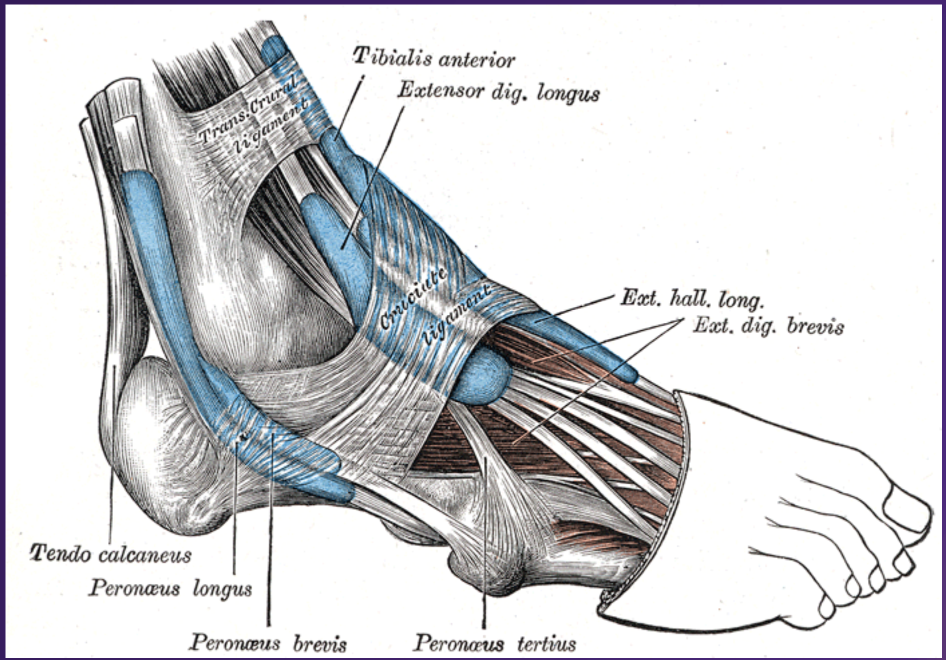
"The necessity for well-documented biomechanical testing has been demonstrated. All the factors mentioned above must be taken into consideration before conclusions about ligament behavior are drawn."

Injury survey

- Ligament
- Tendon
- Cartilage

Tendons

- Dense fibrous tissue that connects muscle to bone
- External vs internal tendon



Tendons

- Morphology - hierarchical structure

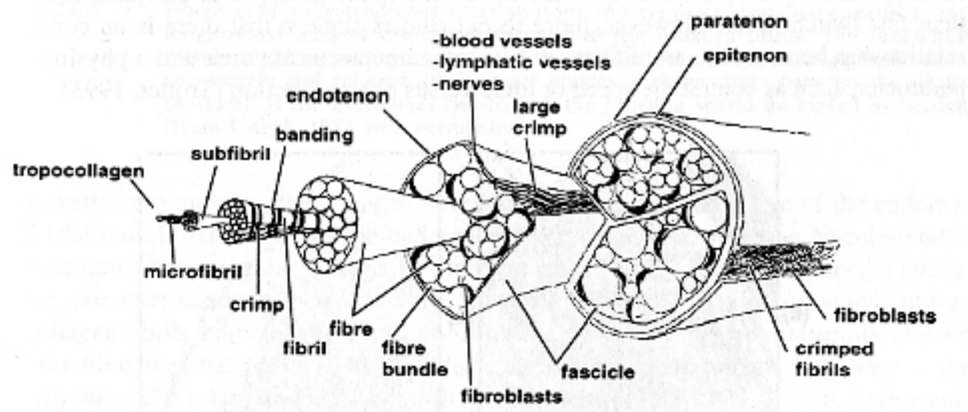
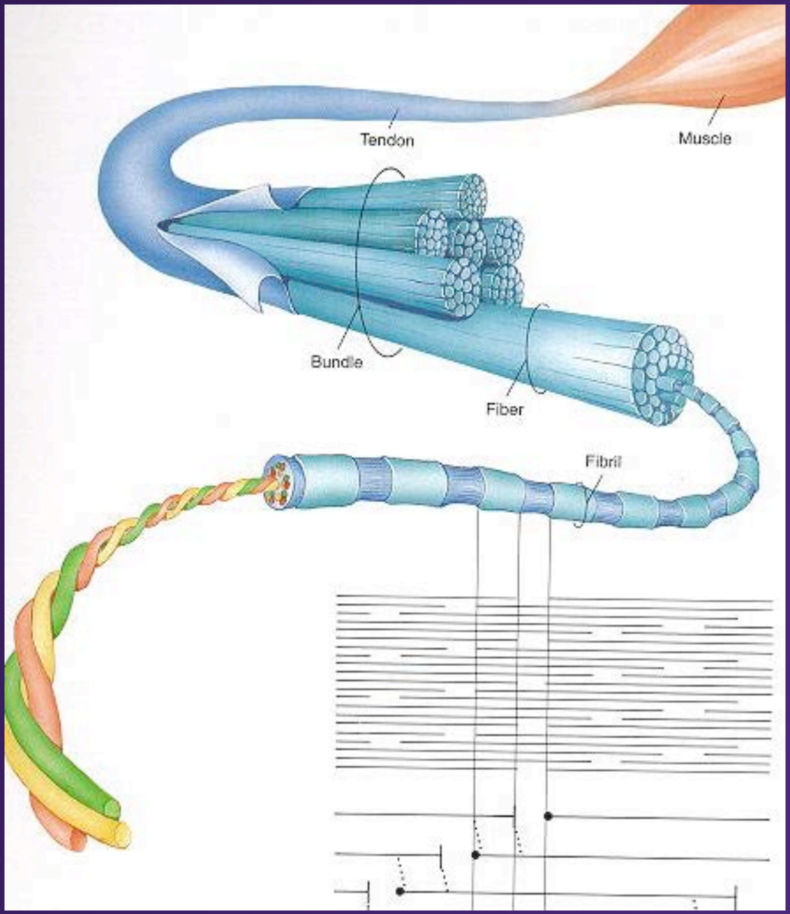


Figure 2.6.4 The structural hierarchy of a tendon, from the tropocollagen molecule to the entire tendon. Connective tissue layers or sheaths envelop the collagen fascicles (endotenon), bundles of fascicles (epitenon), and the entire tendon (paratenon). Note that blood and lymphatic vessels and nerves are cut in the cross-section within the endotenon (from Kastelic et al., 1978, with permission).

Tendons

- Morphology - hierarchical structure



Tendons

- Microscopic organization

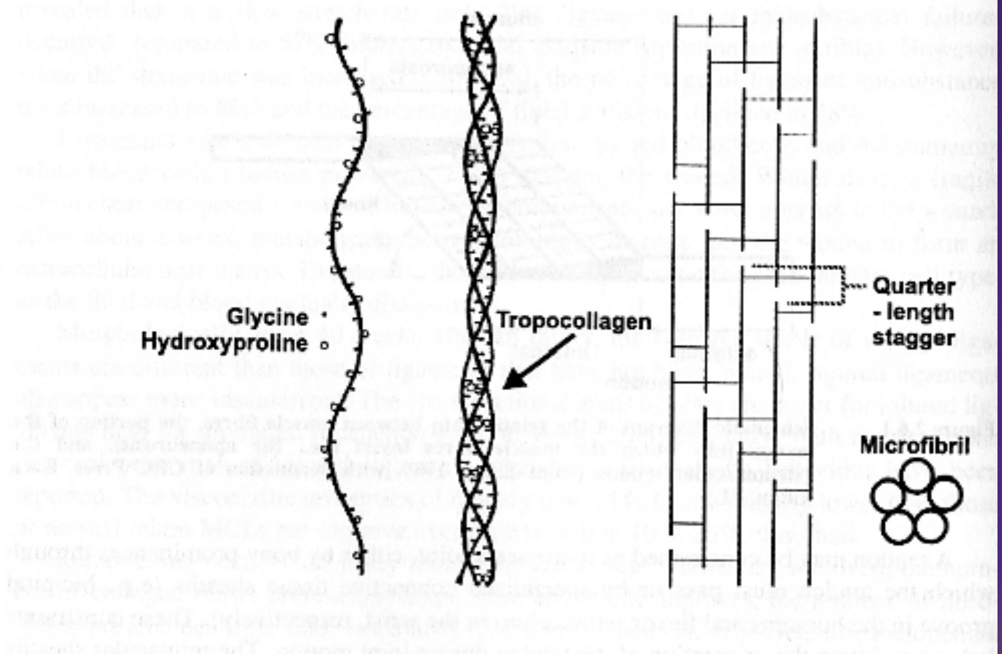


Figure 2.6.3 Schematic diagram of tropocollagen and microfibril assembly.

Tendons

- Macroscopic organization
  - musculo-tendonous junction or myotendonous junction
  - tendon proper
  - bone-tendon junction or osteotendinous junction

Tendons

- Myotendonous junction - occurs at origin and insertion ends
    - acute angle allows = force via shear

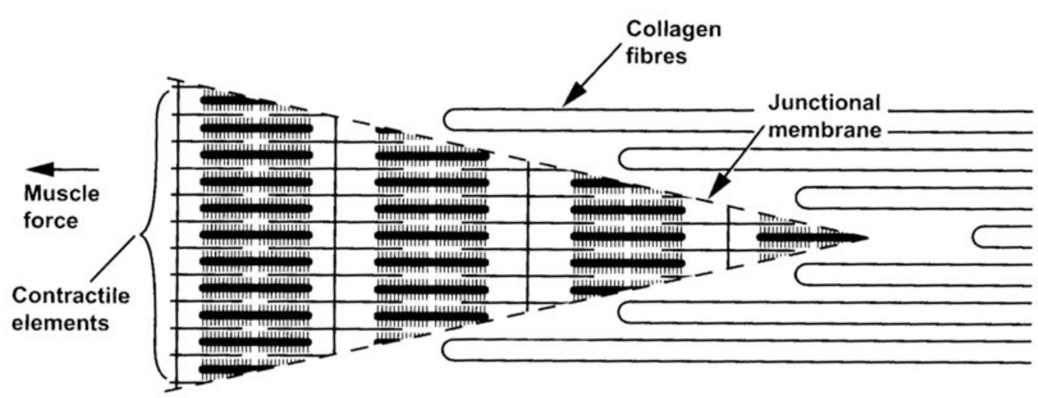
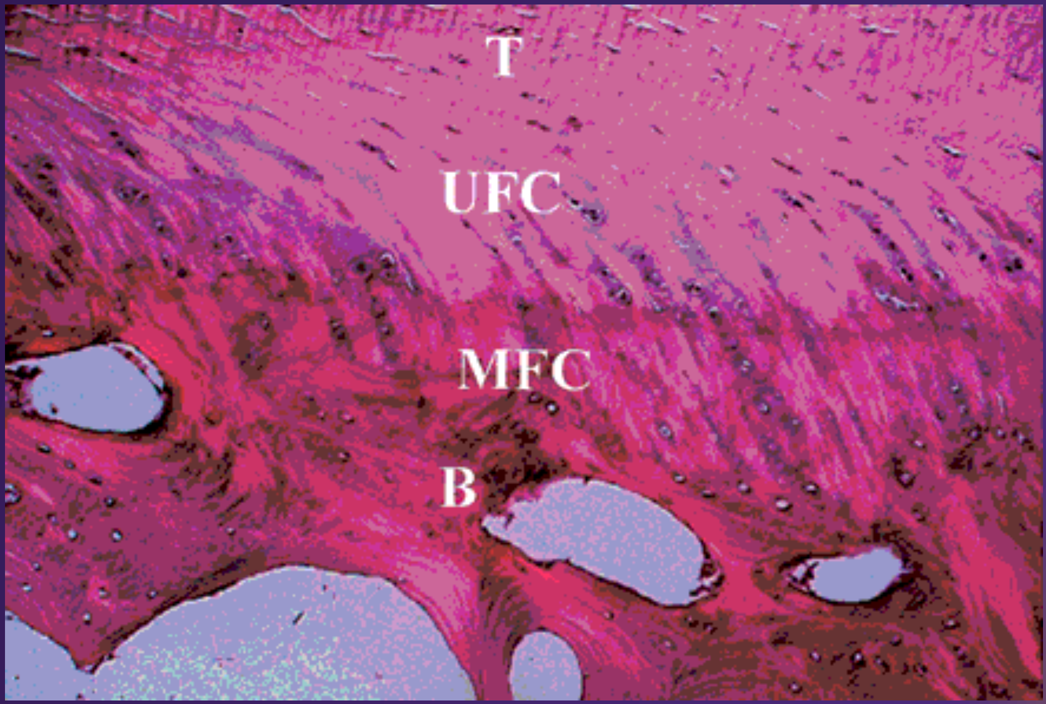


Figure 2.6.6 Diagram of a myotendinous junction. Muscle force is applied parallel to the longitudinal axes of the myofilaments and the collagen fibres. The junctional membrane lies at an angle relative to the myofilaments. The acute angle with which the muscle and collagen fibrils meet creates a shear stress between the fibrils. If the fibrils met end-to-end, the junction would be loaded in tension.

Tendons

- Direct fibro-cartilagenous insertion osteotendinous junction
  - Four-stage (like ligament)



www.jbjs.org/Comments/c_p_rodeo.shtml

Tendons

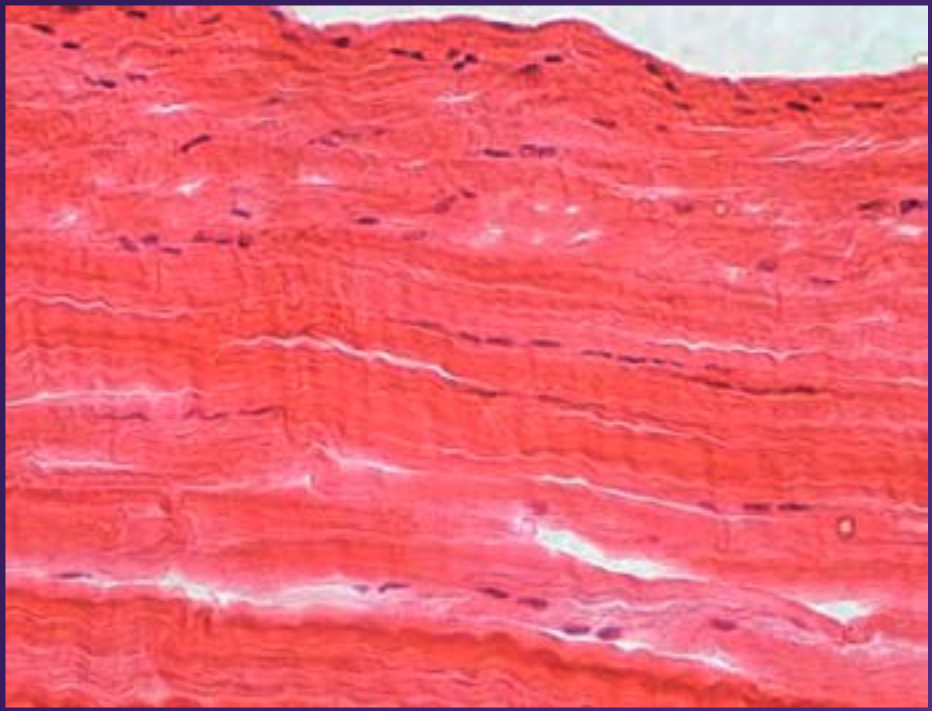
- Histology
  - Tenocytes (fibrocytes) and tenoblasts (fibroblasts) = tendon cells
  - Tenocytes are mature, anchored to collagen
  - Tenoblasts are spindle-shaped, immature cells – give rise to tenocytes; occur in clusters
  - Highly proliferative, synthesize collagen and other components of extracellular matrix

Tendons

- Major constituents of tendons
  - Type I collagen (~80% of dry weight)
  - water (65 to 70% of the wet weight)
  - elastin (<3% of dry weight)
  - proteoglycans (~1%).
- This composition is similar to ligaments.

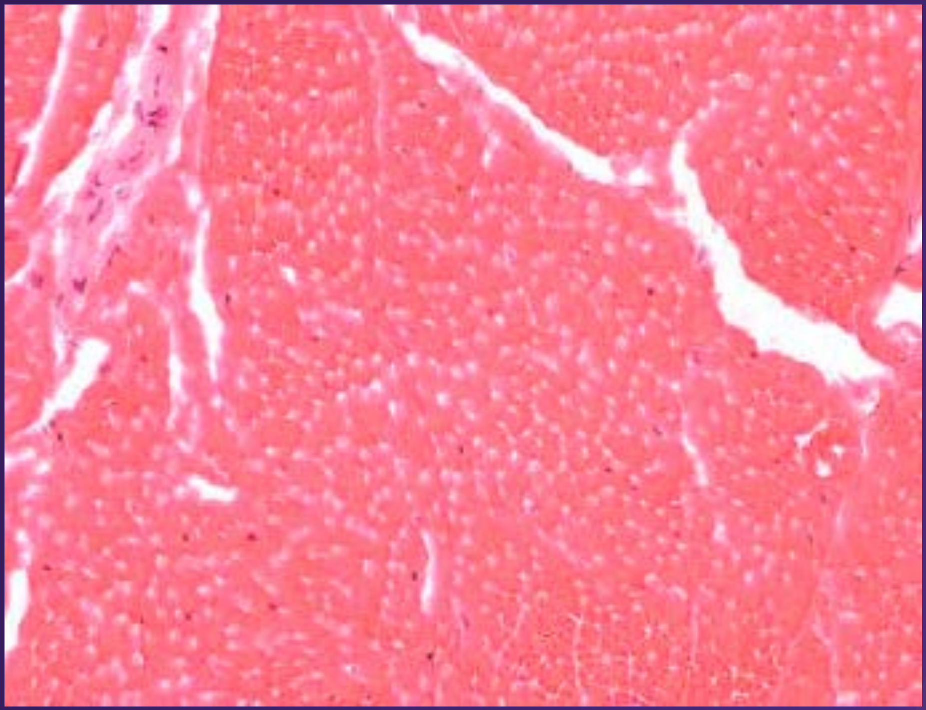
Tendons

- Histology - normal tendon, longitudinal section H&E 40x



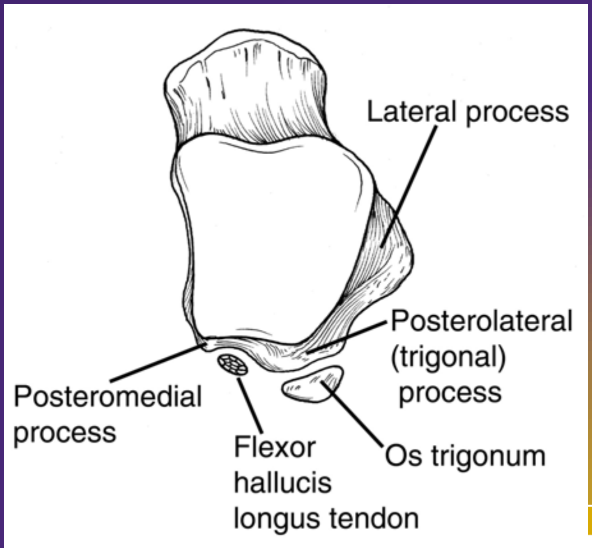
Tendons

- Histology - normal tendon, transverse section H&E 40x



Tendons

- Function
  - Transmit tensile loads to bones
  - Apply compressive forces to bones (flexor hallucis longus on talus)
  - Increase muscle moment arms
  - Sense force in muscles



Tendons

- Mechanical properties
  - Force v. deformation: toe, linear and yield regions

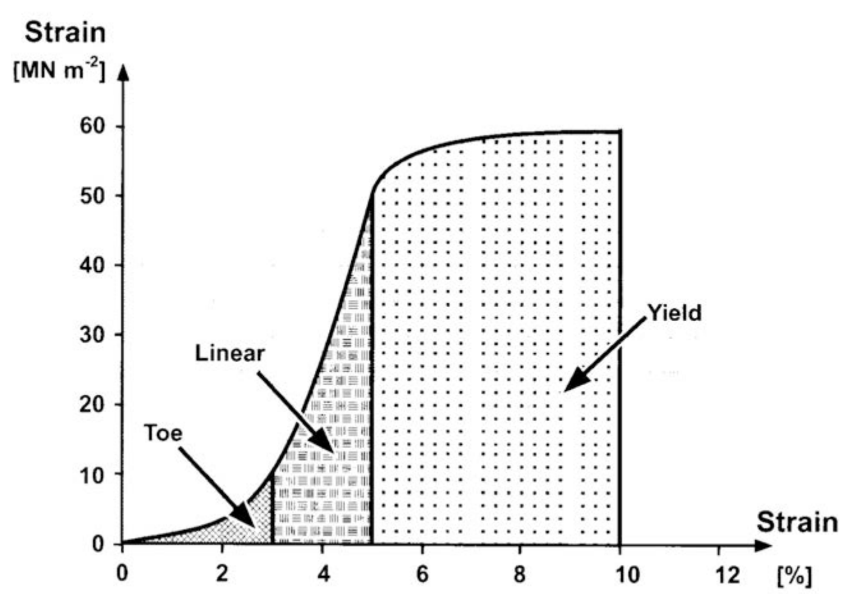


Figure 2.6.9 Typical tendon stress-strain curve for a tensile test to rupture.

Tendons

- Mechanical properties
  - Force v. deformation: hysteresis (6-11%)

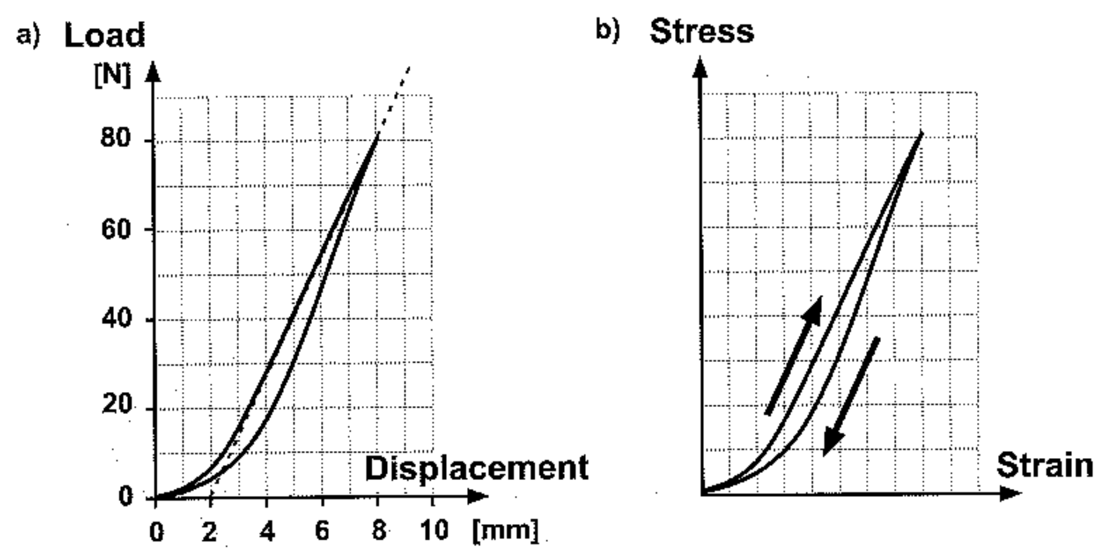
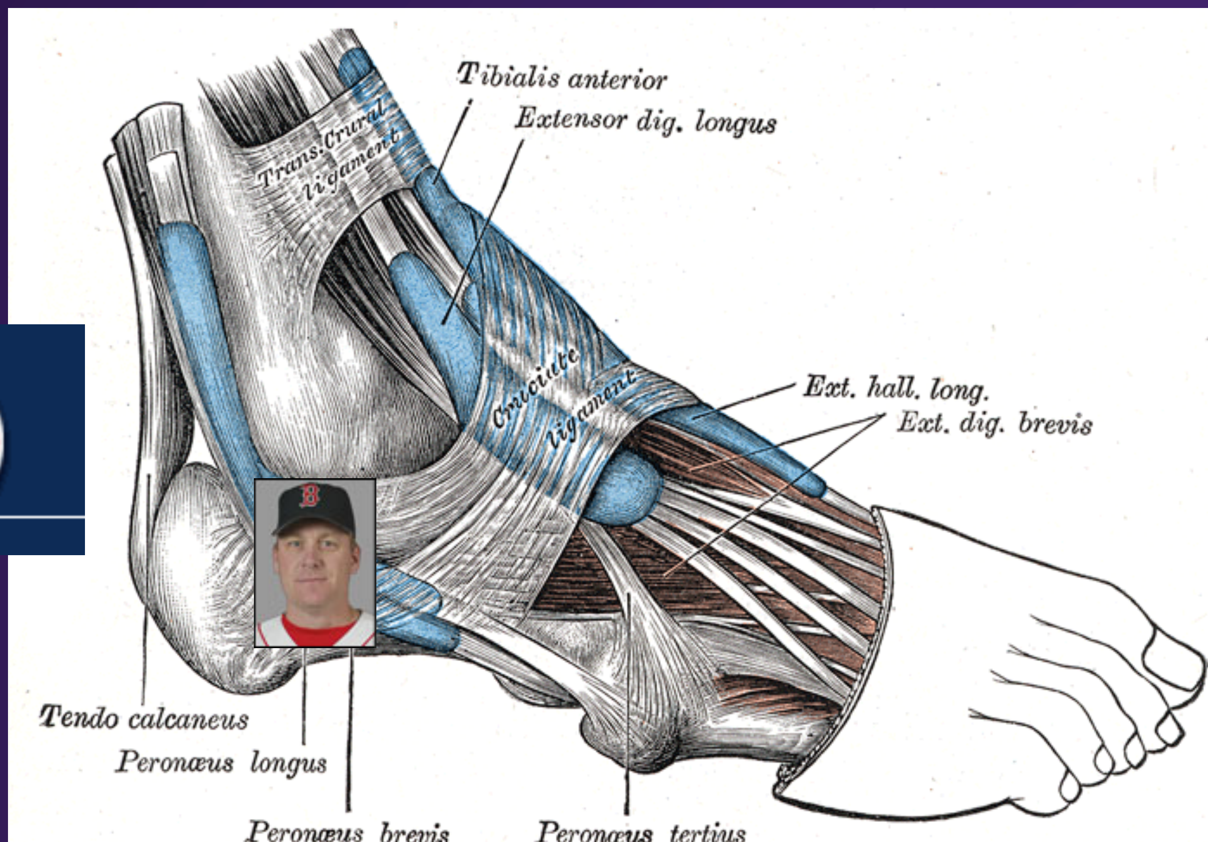


Figure 2.6.10 (a) Load-displacement curve for a wallaby tail tendon. The dashed line represents the tangent modulus. (b) Typical stress-strain curve for tendon showing loading, unloading, and hysteresis loop (see text for further explanation) (from Bennett et al., 1986, with permission).

Tendons

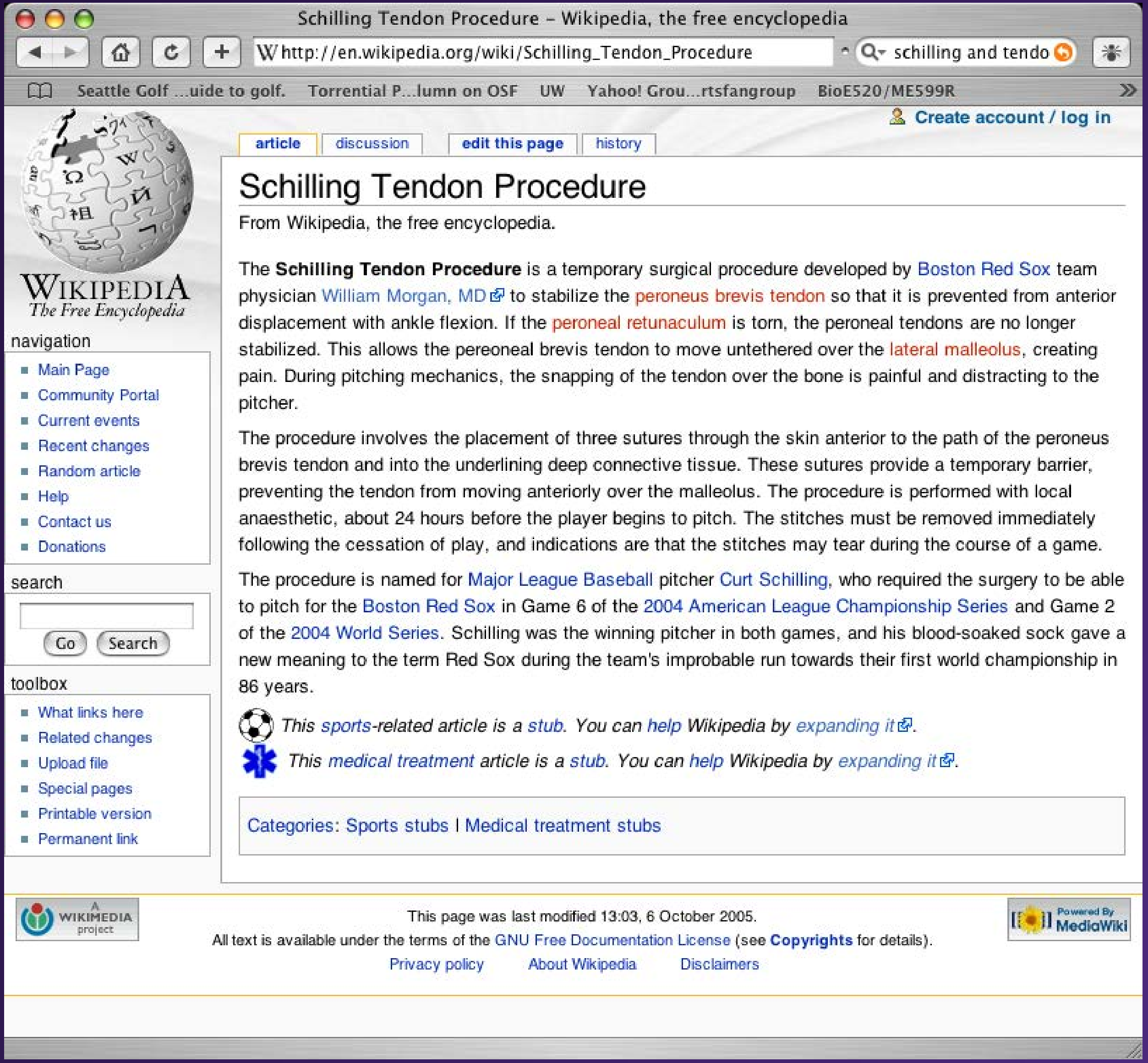
- Mechanical testing issues
  - Grip slippage
  - Bone-tendon-bone is not an option
  - Freeze clamps

Tendons



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

Tendons



Schilling Tendon Procedure – Wikipedia, the free encyclopedia

http://en.wikipedia.org/wiki/Schilling_Tendon_Procedure

schilling and tendo

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Schilling Tendon Procedure

From Wikipedia, the free encyclopedia.

The **Schilling Tendon Procedure** is a temporary surgical procedure developed by Boston Red Sox team physician William Morgan, MD to stabilize the peroneus brevis tendon so that it is prevented from anterior displacement with ankle flexion. If the peroneal retunaculum is torn, the peroneal tendons are no longer stabilized. This allows the pereoneal brevis tendon to move untethered over the lateral malleolus, creating pain. During pitching mechanics, the snapping of the tendon over the bone is painful and distracting to the pitcher.

The procedure involves the placement of three sutures through the skin anterior to the path of the peroneus brevis tendon and into the underlining deep connective tissue. These sutures provide a temporary barrier, preventing the tendon from moving anteriorly over the malleolus. The procedure is performed with local anaesthetic, about 24 hours before the player begins to pitch. The stitches must be removed immediately following the cessation of play, and indications are that the stitches may tear during the course of a game.

The procedure is named for Major League Baseball pitcher Curt Schilling, who required the surgery to be able to pitch for the Boston Red Sox in Game 6 of the 2004 American League Championship Series and Game 2 of the 2004 World Series. Schilling was the winning pitcher in both games, and his blood-soaked sock gave a new meaning to the term Red Sox during the team's improbable run towards their first world championship in 86 years.

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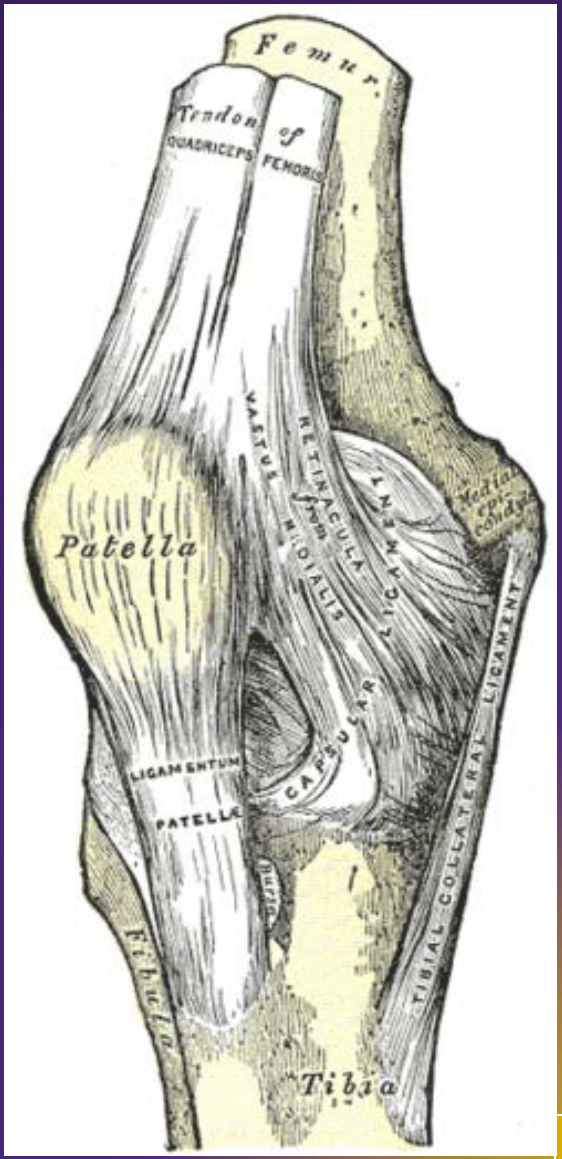
Tendons

- patellar tendon
- plantar aponeurosis



Ligaments vs. tendons

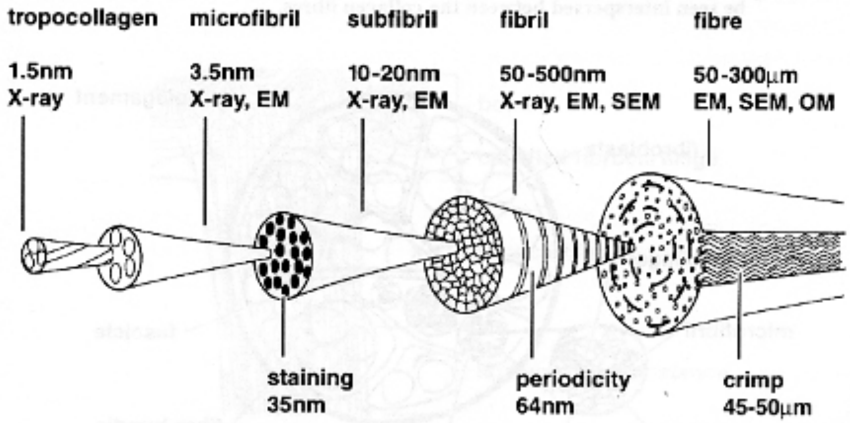


Figure 2.5.1 Schematic illustration depicting the hierarchical structure of collagen in ligament midsubstance. EM = electron microscope; SEM = scanning EM; OM = optical microscope (from Kastelic et al., 1978, with permission of Gordon and Breach, Science Publishers Ltd.).

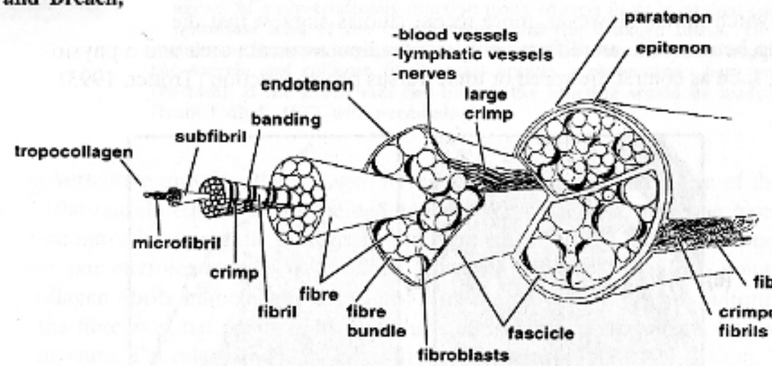


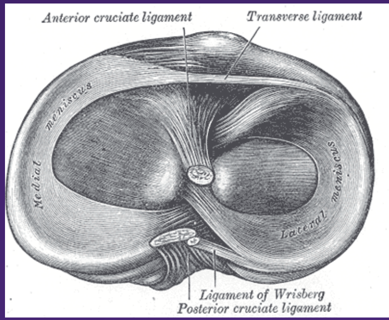
Figure 2.6.4 The structural hierarchy of a tendon, from the tropocollagen molecule to the entire tendon. Connective tissue layers or sheaths envelop the collagen fascicles (endotenon), bundles of fascicles (epitenon), and the entire tendon (paratenon). Note that blood and lymphatic vessels and nerves are cut in the cross-section within the endotenon (from Kastelic et al., 1978, with permission).

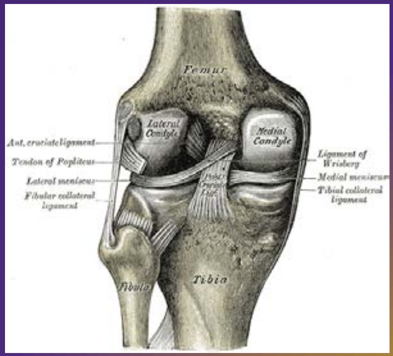
Ligaments vs. tendons

- Ligaments - short bands of tough but flexible fibrous connective tissue that bind bone to bone
- Tendons - similar to ligaments in structure and composition, but connect muscle to bone
- Suffice for the purposes of this class
- Ligament and tendon properties vary amongst themselves
  - Deltoid vs. spring; Achilles vs. tibialis anterior
  - Misnomers: plantar aponeurosis, patellar tendon

Cartilage

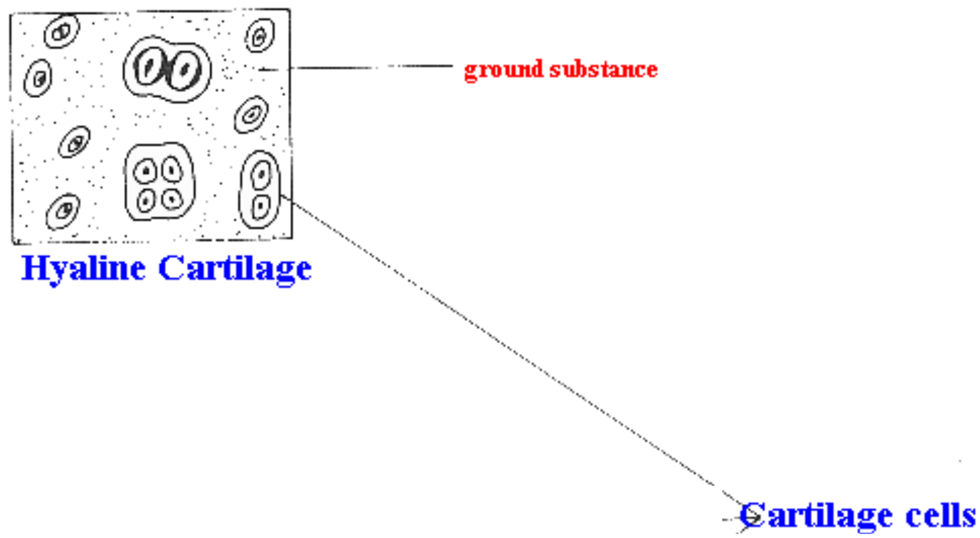
- Thin (1 - 6mm) layer of fibrous connective tissue
- biphasic
- 2 to 15% cells
- 85 to 98% intercellular matrix
    - 65 to 80% water
- virtually frictionless (0.002 to 0.05)





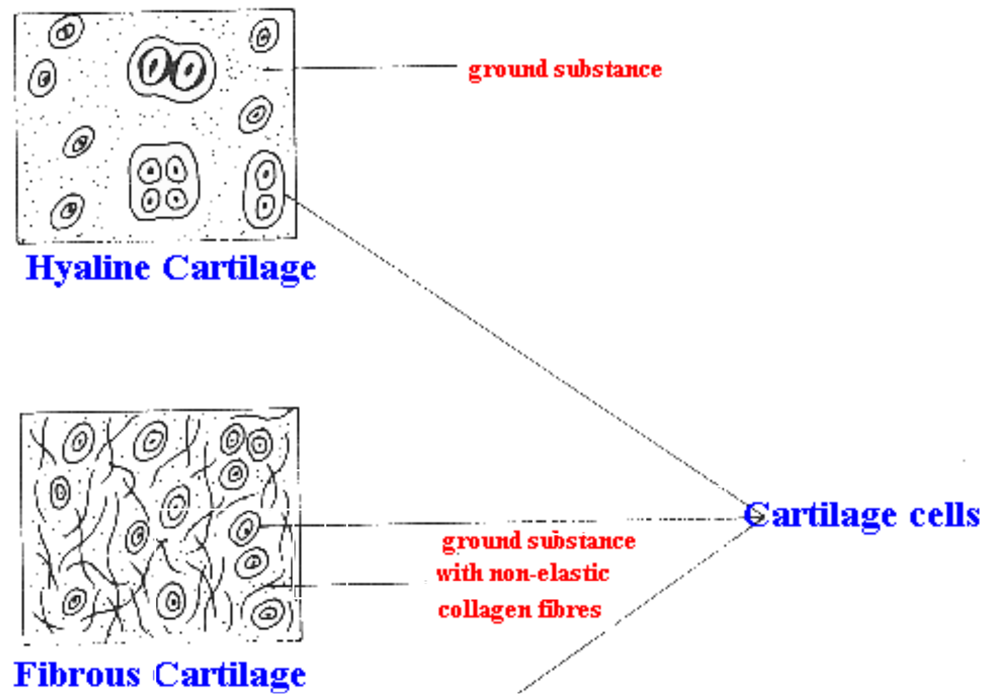
Cartilage

- Hyaline
- Bluish, semi-transparent
- Strong, but flex-ible and elastic
- Ends of bones, trachea, larynx, tip of nose
- Reduces friction



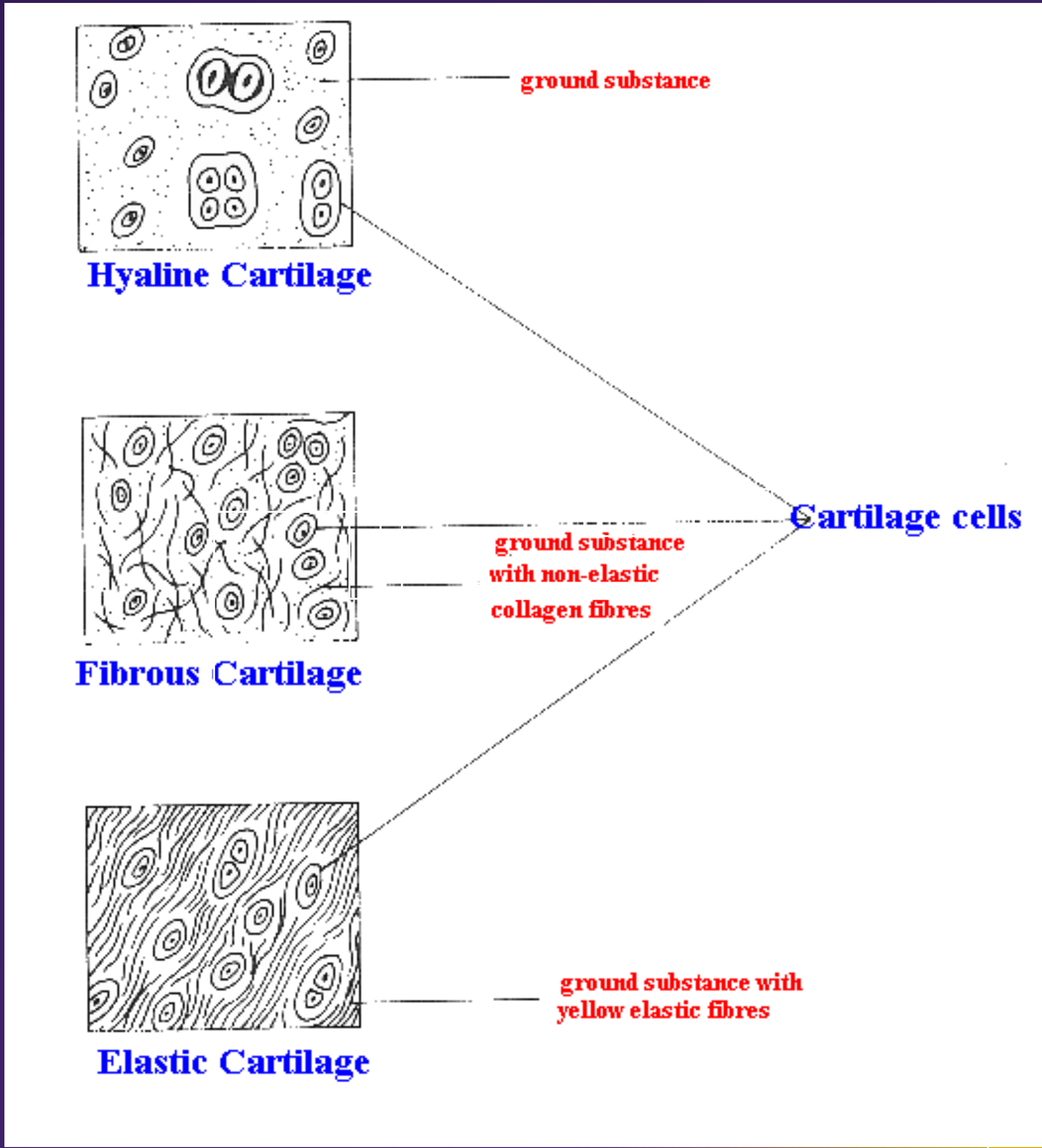
Cartilage

- Fibrocartilage
- White
- Extremely tough
- Discs, between pubic bones, edges of articular cavities (labrum), meniscus
- Shock absorption, provides sturdiness



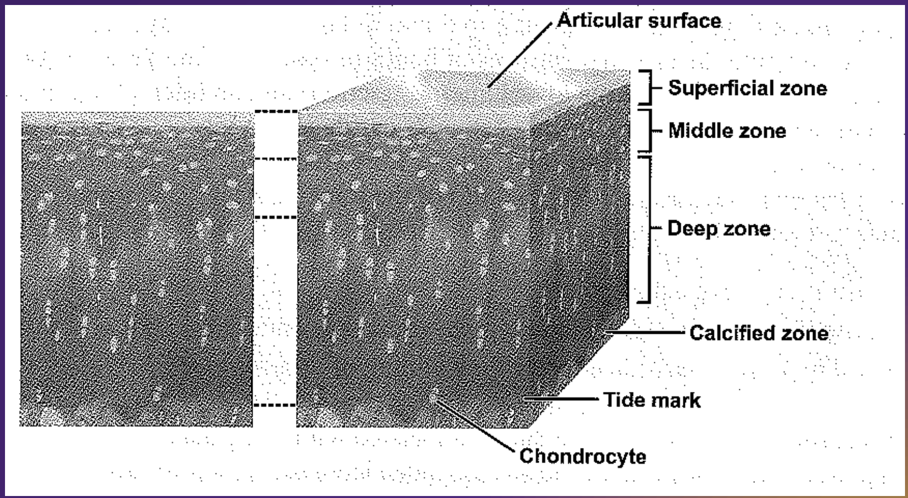
Cartilage

- Elastic
- Yellow
- Similar to hyaline, but with elastin
- Lobe of ear, epiglottis, parts of larynx
- Maintains shape, supports structures



Cartilage

- Morphology - structurally heterogeneous, properties change with depth
- superficial tangential (10-20%)
- middle (or transitional) (40-60%)
- deep (or radial) (30%)
- calcified



Cartilage

- Morphology - hierarchical structure

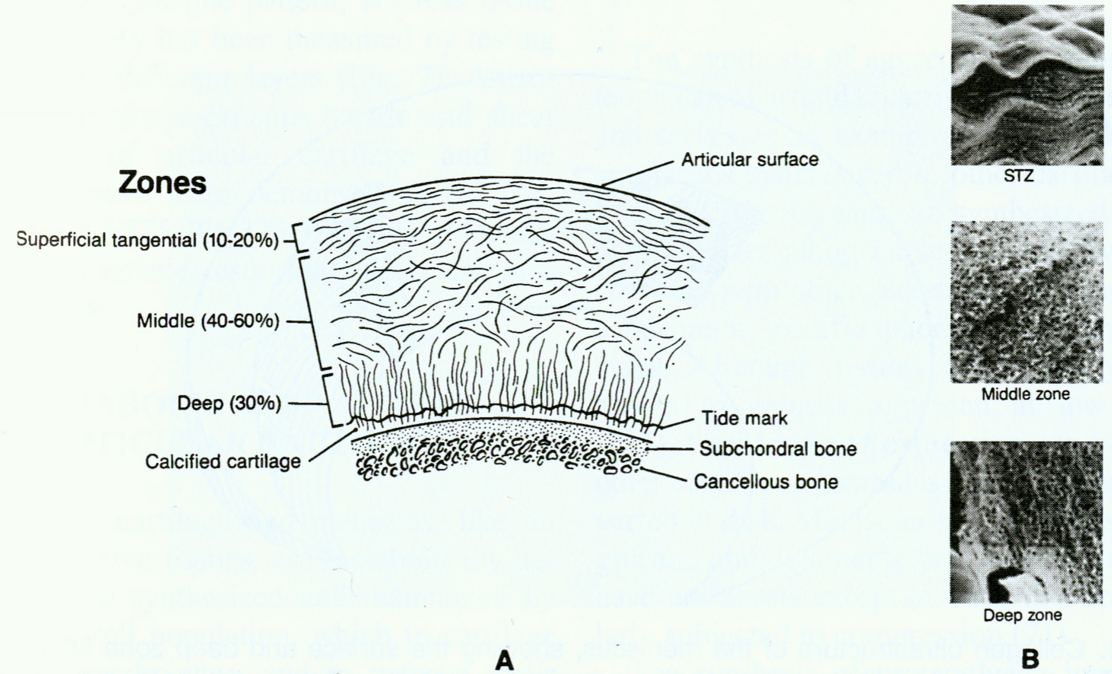


FIG. 7. **(A)** Layered structure of cartilage collagen network showing three distinct regions, and **(B)** corresponding SEM collagen fibrillar arrangement (SEMs are courtesy of Dr. T. Takei; 213).

Cartilage

- Morphology - hierarchical structure – other ideas

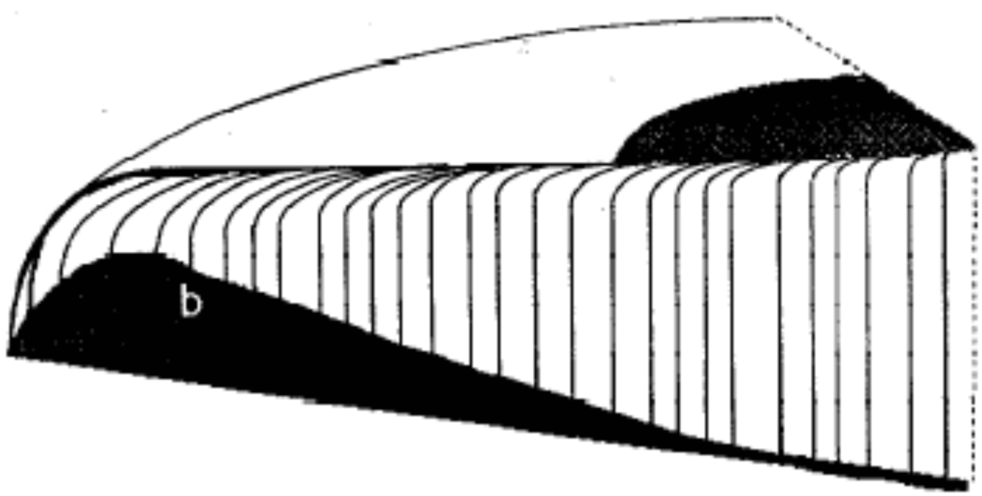
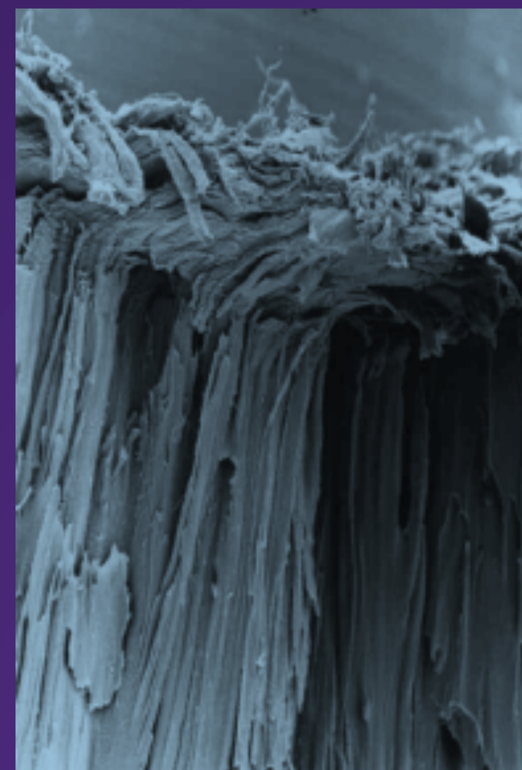


FIGURE 1: Diagrammatic representation of the collagen fiber anatomy in a tibial plateau. In the periphery, the radial collagen fibers run from the bone (b) to the surface where they turn and form the lamellae of the tangential layer. In the center (shaded) the radial fibers may arch somewhat but do not form lamellae. There, the surface is thin and softer than that of the periphery.

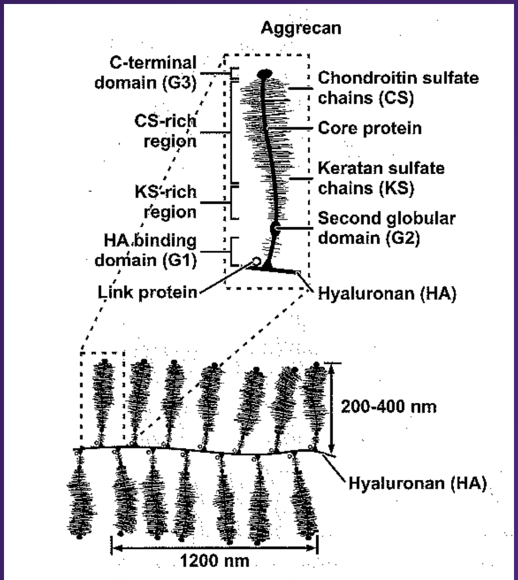


Cartilage

- Cells: chondrocytes and fibrocondrocytes
  - Synthesis of collagen type II and proteoglycans
- Matrix: structural macromolecules and fluid
  - Fluid = 65 to 80% of wet weight
  - Volumetric fraction decreases as you go deeper
  - Collagen = 50% dry weight
  - Proteoglycans = 30 to 35% dry weight
  - Non-collagenous proteins = 15 to 20%

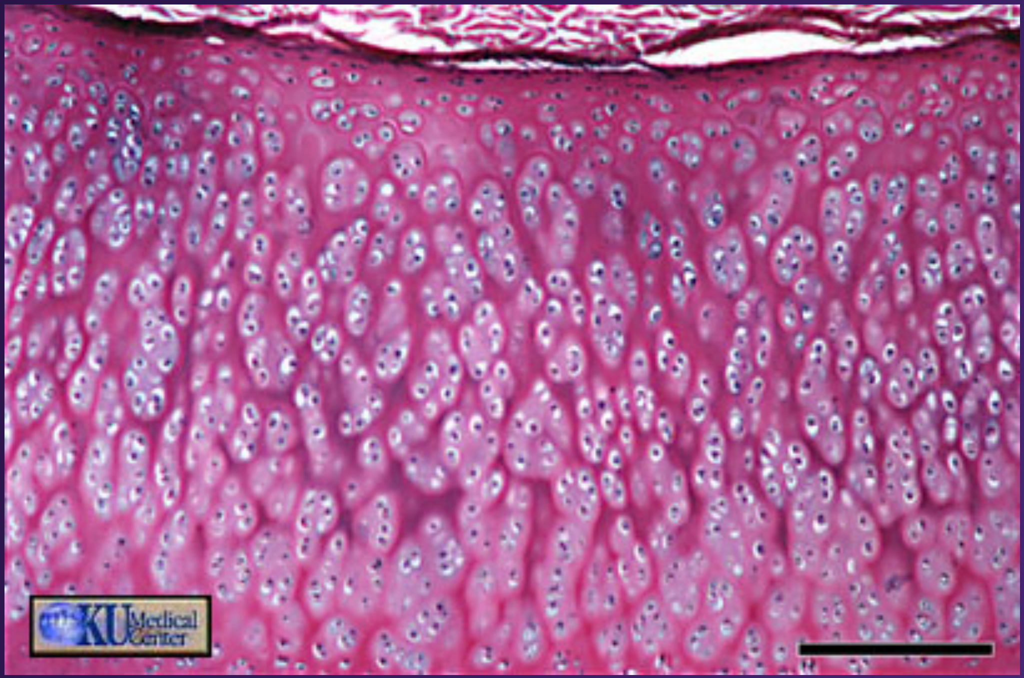
Cartilage

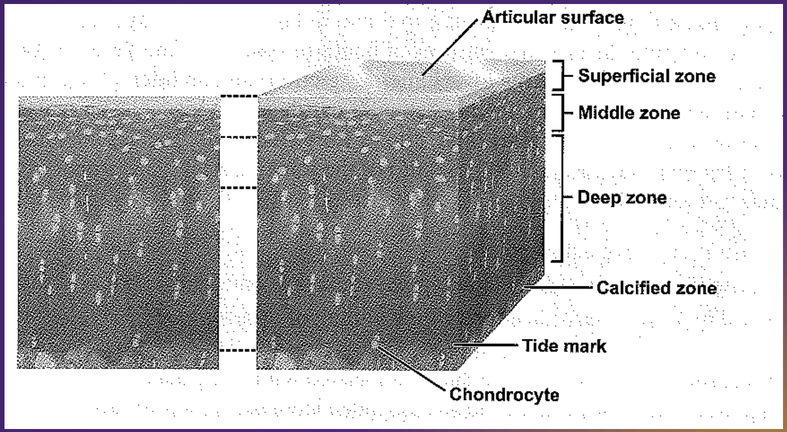
- Matrix proteins
  - collagen type II (80 to 85% of collagen)
  - collagen type V, VI, IX, X and XI
  - proteoglycans (aggrecan)
    - core = 10%, side chains = 90% (negatively charged)



Cartilage

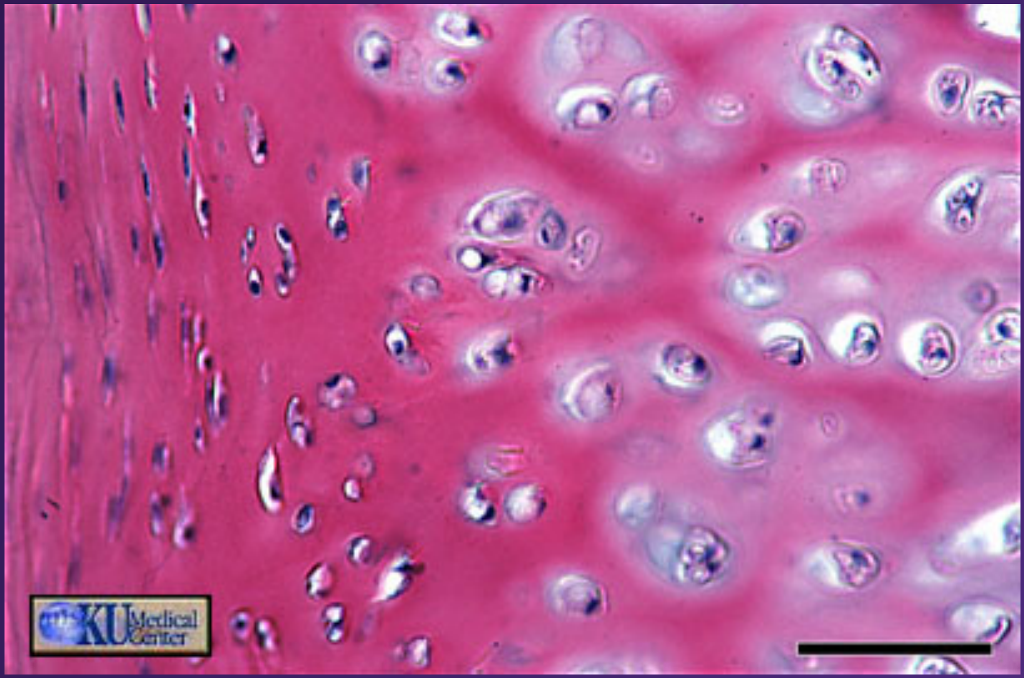
- Histology - hyaline cartilage, bar = 250 microns





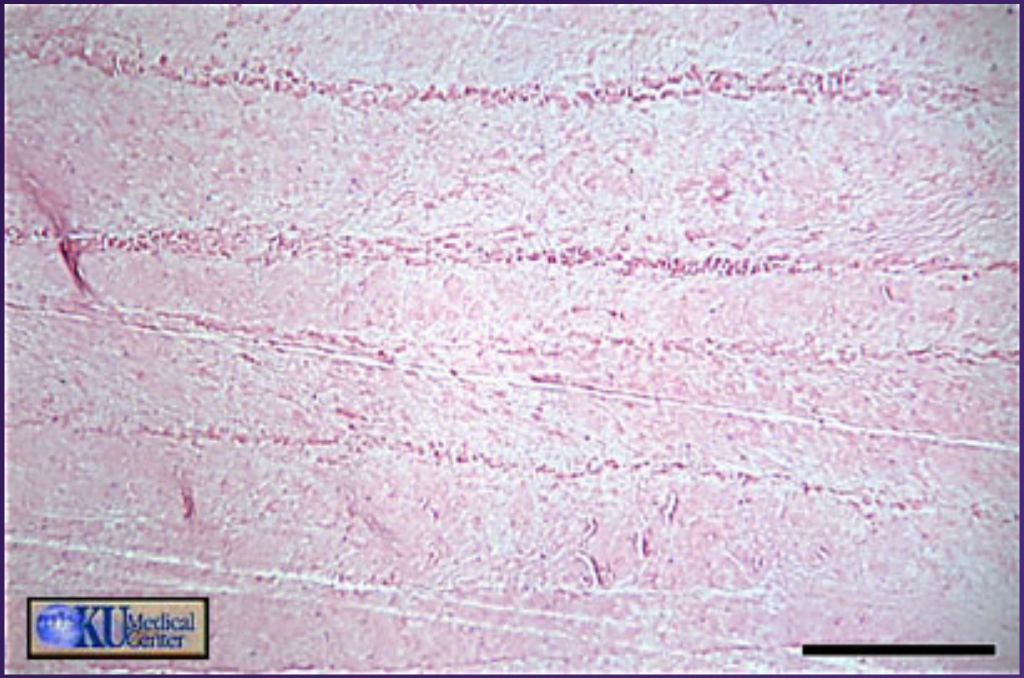
Cartilage

- Histology - hyaline cartilage, bar = 100 microns



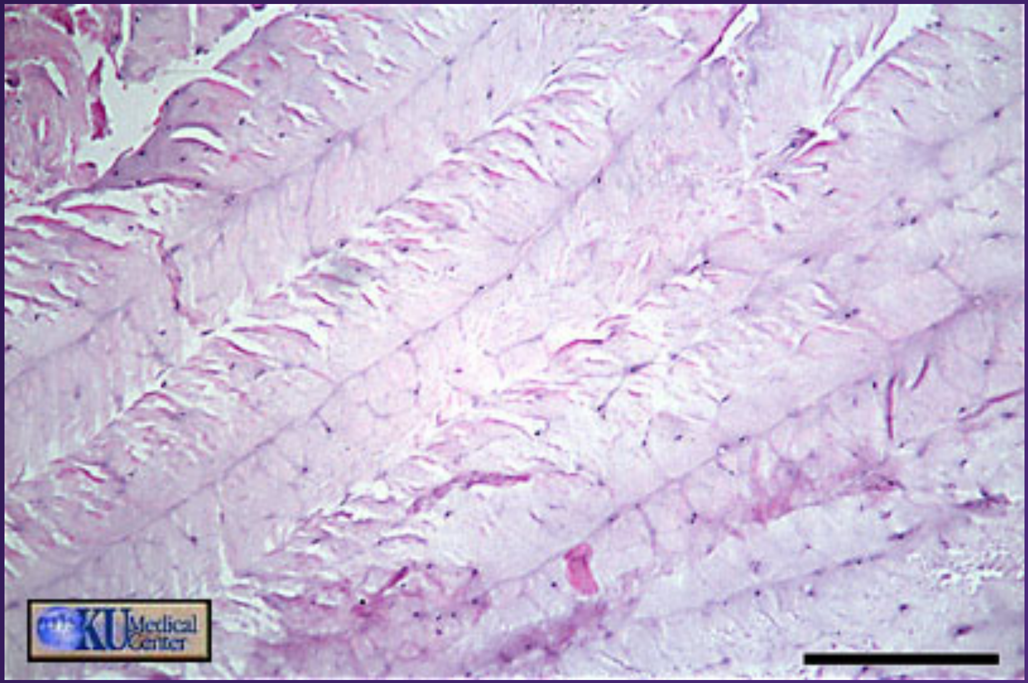
Cartilage

- Histology - fibrocartilage, bar = 250 microns



Cartilage

- Histology - fibrocartilage, bar = 100 microns



Cartilage

- Function
  - transmits forces across joints
  - cushion bones
    - load bearing and load distributor
  - low friction at joints
  - support structure (i.e., outside of joints - fibrocartilage or elastic cartilage)

Cartilage

- Mechanical properties

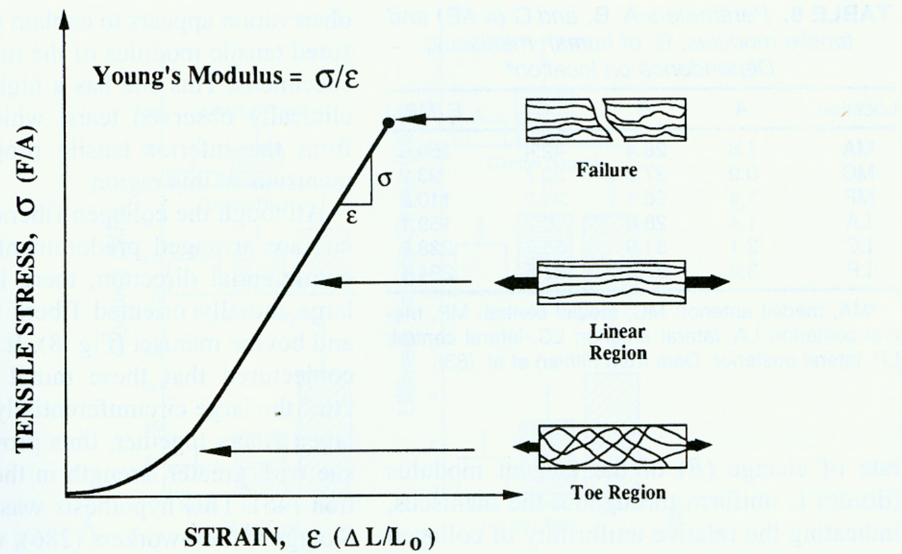
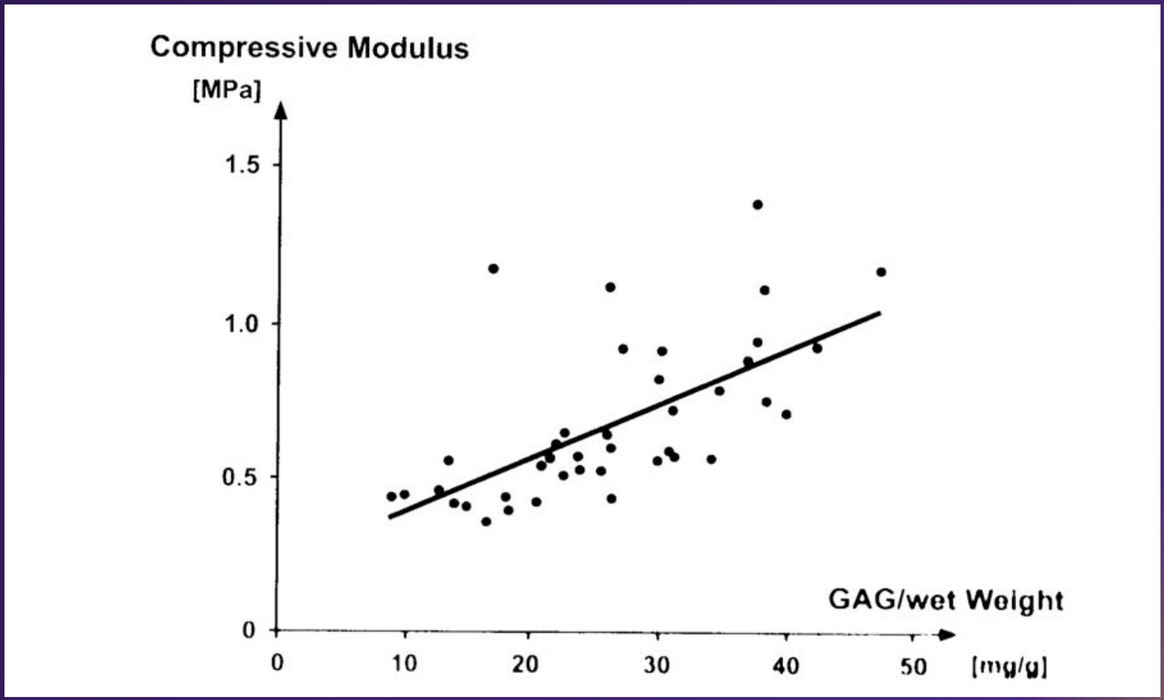


FIG. 13. Typical stress–strain curve for articular cartilage in a uniaxial and uniform strain rate experiment. The toe region is marked by an increasing slope, whereas the linear region appears to be a straight line with a slope of σ/ε (213).

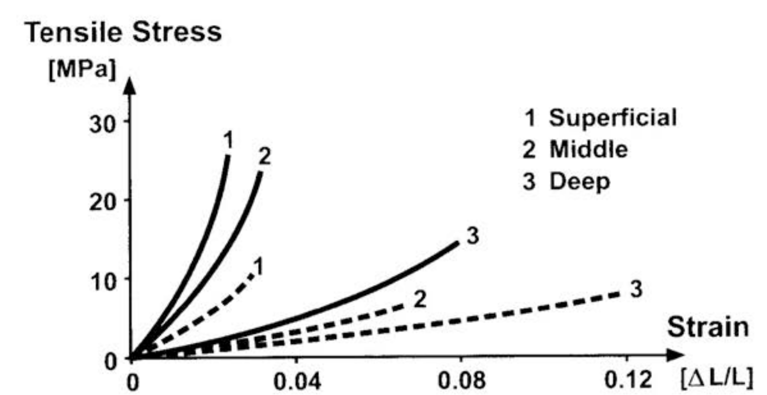
Cartilage

- Mechanical properties



Cartilage

- Mechanical properties



4.6 Stress-strain curves for tensile testing of articular cartilage specimens from the superficial (1), middle (2), and deep zone (3), and along the long axis of the collagen fibrils (solid lines) and perpendicular to the long axis of the collage fibrils (dashed lines). Tensile strength decreases continuously from the surface to the deep zone and is greater along the collagen fibril direction than perpendicular to it. Adapted from Kempson (1972), with permission.