TL1

# Biomechanics of Tendons & Ligaments

(Parallel collagenous tissues)

Passive structures

**Tendons** what is a tendon & what is its function?

- connects ____ to ____
- Transmits muscle ____ to the ____

**Ligaments**

- connects ____ to bone
- provides joint ____
- guides smooth joint motion
- ____ range of motion.

**Composition of tendons & ligaments**

1. Cells (fibroblasts) — ___% of ~~total~~ volume
2. Extracellular material — ___% " " "
   a. Water ~ ___% of extracel. mat.
   b. solids ~ ___%
      1. collagen fibers ~ ___% of ~~total~~ solids (provides strength & stiffness) (___% in some tendons)
      2. elastin fibers ~ ___% (<1% in some tendons) (provides extensibility under load)
      3. ground substance ~ ___% (Proteoglycan gel) — may provide some lubrication between fibers

TL2

Outer structure of tendons & ligaments and insertion into bones

(see Fig 3-3 & 3-4 w/ accompanying notes)

see Fig 3-5, 3-6, 3-7. stress-strain curves for tendons & lig. flavum

How strong is collagen & elastin compared to bones?

Collagen relatively strong
can tolerate ~ ___ stress of cortical bone tested in tension.
No strength in compression or shear

Elastin ~ relatively weak (but very extensible) — can tolerate ~ ___ stress of cortical bone in tension — none in compression or shear.

Structural orientation

tendon: - higher proportion of collagen
- more parallel fibers

ligament: - lower proportion of collagen - less highly parallel fibers
(more stretch possible before limit is reached)

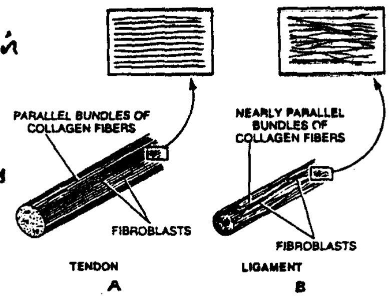


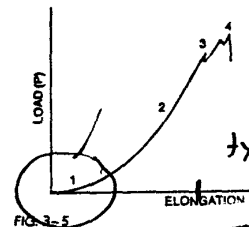

FIG. 3-3
Schematic diagram of the structural orientation of the fibers of tendon (A) and ligament (B); insets show longitudinal sections. In both structures the fibroblasts are elongated along an axis in the direction of function. (Adapted from Snell, 1984.)

Bone junction
4 zones:
1. parallel collagen fibers
2. unmineralized fibrocartilage
3. mineralized "
4. cortical bone

This transition provides a stronger bond to the bone - distributes the stresses between tendon (or ligament) and the bone.


FIG. 3-4
Electron micrograph of a patellar tendon insertion from a dog, showing four zones (25,000×). Zone 1, parallel collagen fibers; zone 2, unmineralized fibrocartilage; zone 3, mineralized fibrocartilage; zone 4, cortical bone. The ligament-bone junction (not pictured) has a similar appearance. (Reprinted with permission from Cooper, R. R., and Misol, S.: Tendon and ligament insertion. A light and electron microscopic study. J. Bone Joint Surg., 52A:1, 1970.)






typical tendon collagen in high proportion

FIG. 3-5
Load-elongation curve for rabbit tendon tested to failure in tension. The numbers indicate the four characteristic regions of the curve. (1) Primary, or "toe," region, in which the tissue elongated with a small increase in load as the wavy collagen fibers straightened out. (2) Secondary, or "linear," region, in which the fibers straightened out and the stiffness of the specimen increased rapidly. Deformation of the tissue began and had a more or less linear relationship with load. (3) End of secondary region. The load value at this point is designated as $P_{lin}$. Progressive failure of the collagen fibers took place after $P_{lin}$ was reached, and small force reductions (dips) occurred in the curve. (4) Maximum load ($P_{max}$), reflecting the ultimate tensile strength of the tissue. Complete failure occurred rapidly, and the specimen lost its ability to support loads. (Adapted from Carlstedt, 1987.)

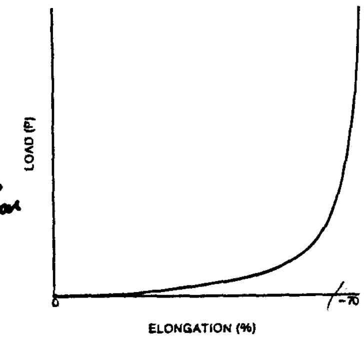



FIG. 3-7
Load-elongation curve for a human ligamentum flavum (60 to 70% elastic fibers) tested in tension to failure. At 70% elongation the ligament exhibited a great increase in stiffness with additional loading and failed abruptly without further deformation. (Adapted from Nachemson and Evans, 1968.)

proportion of elastin makes a big difference in the amount of strain possible
Elastin by itself can sustain ___ strain

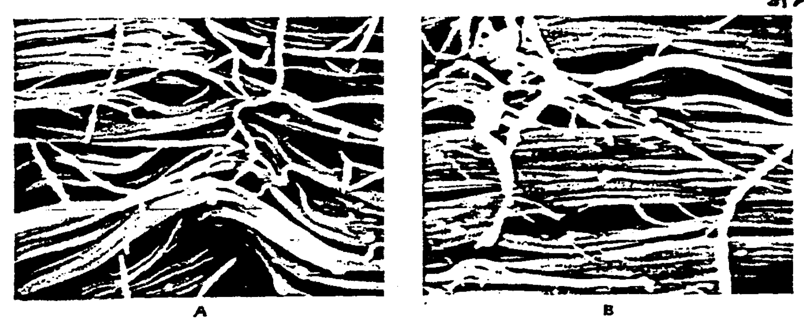



FIG. 3-6
Scanning electron micrographs of unloaded (relaxed) and loaded collagen fibers of human knee ligaments (10,000×). A. The unloaded collagen fibers have a wavy configuration. B. The collagen fibers have straightened out under load. (Reprinted with permission from Kennedy, J. C., et al.: Tension studies of human knee ligaments. Yield point, ultimate failure, and disruption of the cruciate and tibial collateral ligaments. J. Bone Joint Surg., 58A:350–355, 1976.)

How much stress & strain do our tendons & ligaments normally experience
  Normal peak stress < ___ % max (ultimate stress)
  Normal peak strain: ___ % strain,

## Viscoelastic behavior of tendons & ligaments

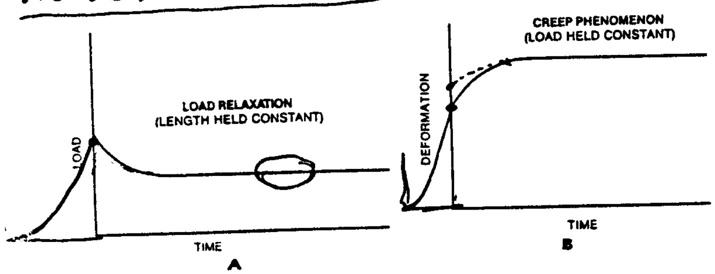



FIG. 3–10
The viscoelasticity (rate dependency, or time dependency) of ligaments and tendons can be demonstrated by two standard tests: the load-relaxation test and the creep test. A. Load relaxation is demonstrated when the loading of a specimen is halted safely below the linear region of the load-deformation curve and the specimen is maintained at a constant length over an extended period (i.e., the amount of elongation is constant). The load decreases rapidly at first (i.e., during the first 6 to 8 hours of loading) and then gradually more slowly, but the phenomenon may continue at a low rate for months. B. The creep response takes place when loading of a specimen is halted safely below the linear region of the load-deformation curve and the amount of load remains constant over an extended period. The deformation increases relatively quickly at first (within the first 6 to 8 hours of loading) but then progressively more slowly, continuing at a low rate for months.

## Effect of loading rate on tendons & ligaments

Slow vs Fast  Fast rate produces higher ultimate stress values and higher stiffness values

Loading rate effects on injury (Noyes & Grood)
ACL isolated 30 primates  bone-ligament-bone tested in tension
  loading rate (60 s to failure)
  compared to fast - strength ↓ % work done ↓ %
  stiffness about same as fast → weakest point was insertion points of ligament into bone
  loading rate (0.6 s to failure) ligament was stronger, required more work to failure.
  weak link — ligament itself  [As loading rate ↑ bone ↑ strength faster than ligament]

## Factors effecting strength of tendon & lig.

______ , ______ , ______

Tendon specifically:
  X-sectional area of tendon compared to X-sectional area of muscle
  (Tendons are generally stronger than the muscles to which they are attached)
  ~~Tendon~~ Max stress at failure is ~ ___ that of muscle.

## Tendon & ligament remodeling

similar to bone tendons & ligaments get ______ & ______ in response to loads placed upon them. (Like Wolfe's law for bone)
conversely lack of mechanical demand makes a tendon (ligament) weaker & less stiff.

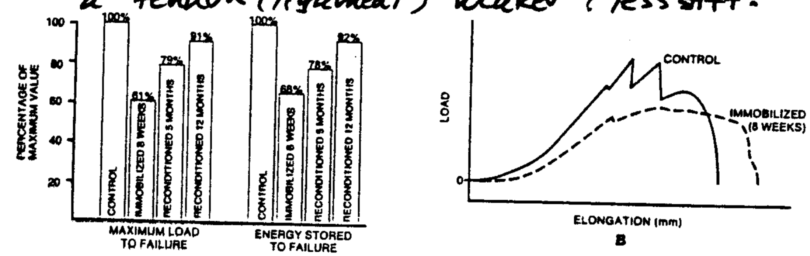



FIG. 3–11
A. Maximal load to failure and energy stored to failure for primate anterior cruciate ligaments tested in tension to failure. Values are shown as a percentage of control values for three groups of experimental animals: (1) those immobilized in body casts for 8 weeks; (2) those immobilized for 8 weeks and given a reconditioning program for 5 months; and (3) those immobilized for 8 weeks and given a reconditioning program for 12 months. B. Compared with controls, ligaments immobilized for 8 weeks were significantly less stiff (as indicated by the slope of the curve) and underwent greater elongation. (Adapted from Noyes, 1977.)

## Immobilization

**Aging** — with age tendons & ligaments tend to decrease in strength & stiffness

Example Ligament Most Commonly Studied —
Anterior Cruciate Ligament (ACL)

ACL

Location

Purpose

Clinical Tests

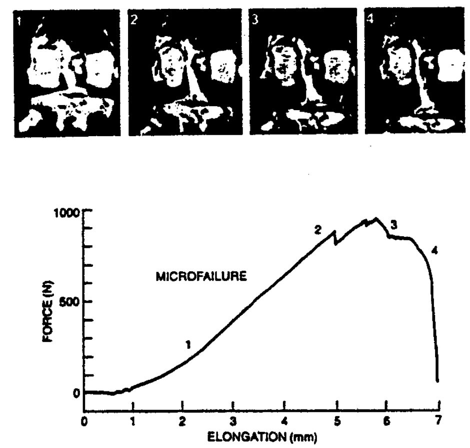



FIG. 3–8
Progressive failure of the anterior cruciate ligament from a cadaver knee tested in tension to failure at a physiologic strain rate (Noyes, 1977). The joint was displaced 7 mm before the ligament failed completely. The force-elongation curve generated during this experiment is correlated with various degrees of joint displacement recorded photographically; photos correspond to similarly numbered points on the curve. (Courtesy of Frank R. Noyes, M.D., and Edward S. Grood, Ph.D.)

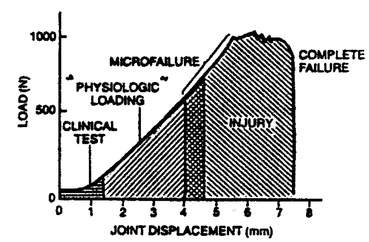



FIG. 3–9
The curve produced during tensile testing of a human anterior cruciate ligament in vitro (Noyes, 1977) (see Fig. 3–8) has been converted to a load-displacement curve and divided into three regions correlating with clinical findings: (1) the load imposed on the anterior cruciate ligament during the anterior drawer test; (2) that placed on the ligament during physiologic activity; and (3) that imposed on the ligament from partial injury to complete rupture. It should be noted that the divisions shown here represent a generalization. Microfailure is shown to begin toward the end of the physiologic loading region, but it may take place well before this point in any given ligament.

3 stages (categories) of ACL injury

1. some pain, no joint instability seen in clinical test — some microfailures
2. severe pain — some joint instability seen clinically — Test done under anesthesia to eliminate effects of muscle on joint stability — partial ligament rupture has occurred — strength & stiffness of ligament has decreased by 50% or more.
3. severe pain initially, then less pain later. Test done under anesthesia — completely unstable joint. Complete rupture. Cannot sustain load.