Soft tissue biomechanics

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Pula, 22/06-08

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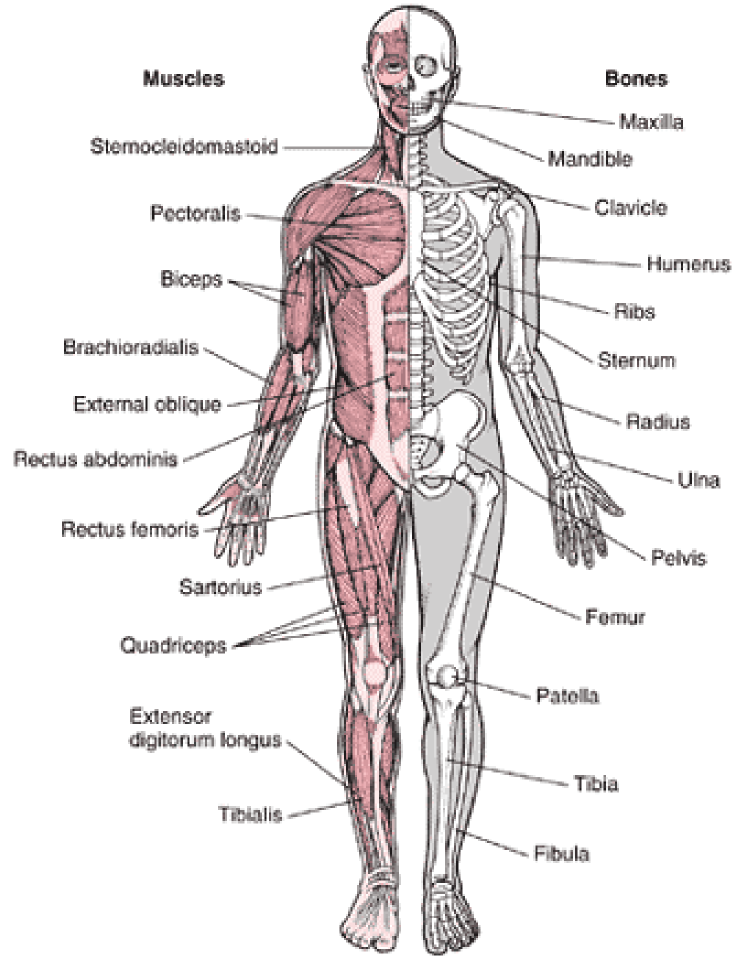
INTRODUCTION

The human body is composed of many different kinds of soft tissue:

- cartilages;
- epithelial tissues;
- menisci;
- inter-vertebral disks;
- muscles;
- nervous tissues;
- ligaments;
- adipose tissue;
- tendons, etc.



INTRODUCTION

Common properties of soft tissues:

- Negligible mineral content => low stiffness
- Large content of water (up to 90%)
- Organic components (collagen, elastin, proteoglycans) always present
- Mainly extra-cellular matrix
- Cellule: fibroblasts and fibrocytes (and derived cells)
- Visco-elastic behaviour is very pronounced

BUT, different functions and structures:

- support (articular cartilage, menisci);
- filling (elastic cartilage);
- storage of resources, thermal protection (adipose tissue);
- protection, absorption, diffusion (epithelial tissues);
- mechanical connection (ligaments, tendons and muscles).

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INTRODUCTION

Soft tissues that will not be dealt with in this lesson:

MUSCLE TISSUES

- Mechanical properties as defined so far are passive properties (elastic, plastic, visco-elastic)
- Mechanical response of muscles predominantly depends on their active function
- Difficult extract and conserve muscle tissue without degenerating its properties
- Muscles are not isolated bodies, there may be an interaction with one or several contiguous muscles

TENDONS AND LIGAMENTS

Tendons: connect a skeletal bone to a muscle: transmitting muscle force

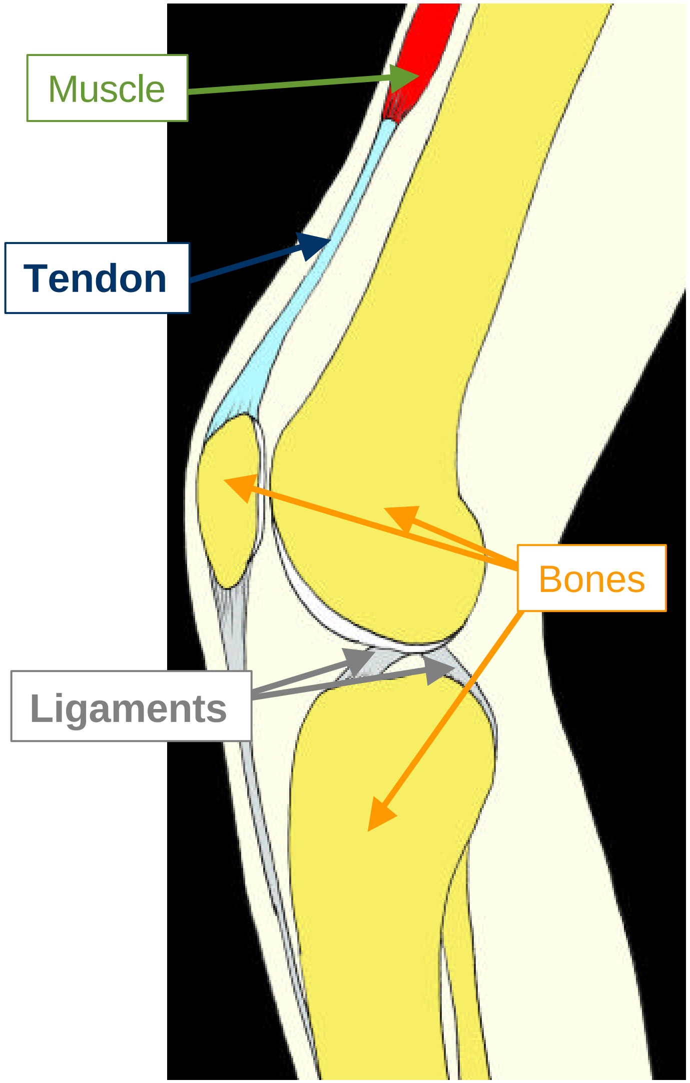
Ligaments: in joints, linking two bones

Ligaments & tendons are similar:

- Both transmit longitudinal loads
- Almost only tensile
- Wrapped in a layer of loose connective tissue (allow sliding with little friction)

Ligaments & tendons are different:

- Tendons act very often: transmit muscle forces (for motion, locomotion, etc.)
- Ligaments loaded heavily only occasionally: to avoid joint damage (dislocation, etc.)

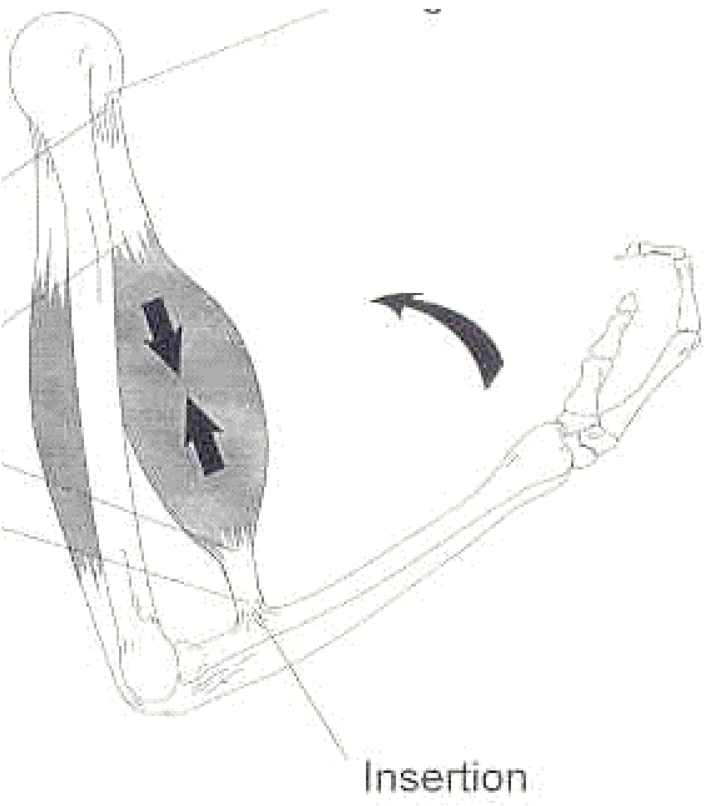


FUNCTION AND ANATOMY OF TENDONS

Each muscle has one, both or none extremity connected to a tendon

Long and with a quite constant section, different possible cross sections:

- Rounded cylindrical
- Flattened
- Severely loaded muscles (e.g. quadriceps) have short and thick tendons
- Muscles performing precise motion with light loads (e.g. flexors and extensors of hand have long, slender tendons



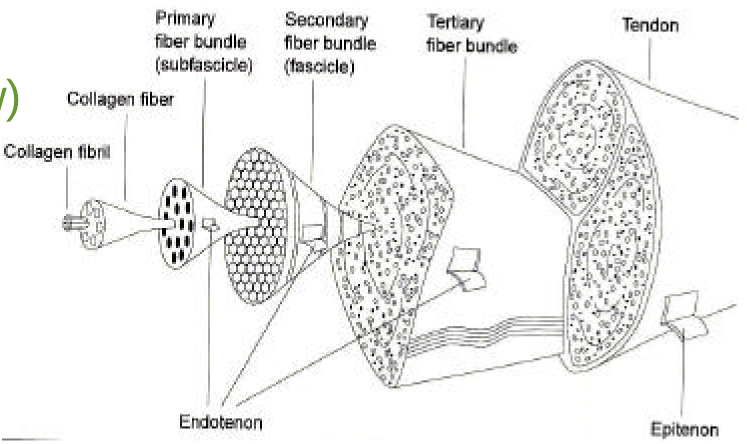
Biomechanical functions:

- Avoid excessive muscle length
- Localize muscles in areas where they do not interfere (e.g. hand)
- Absorb shocks and minimize impulsive load on muscles

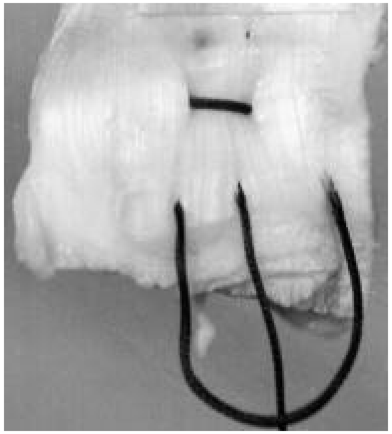
COMPOSITION OF TENDONS

Composite material

1=> Reinforcement:
- Bundles of collagen fibres (50-80% volume => yellow)
- Aligned with load (along tendon)
- Optimised for axial loading
- Little resistance to transverse loads



2=> Matrix:
- Proteoglycans (2-10%)
- Elastin (2-5%)
- Supports fibres and shares load between fibres
- Ties fibres together

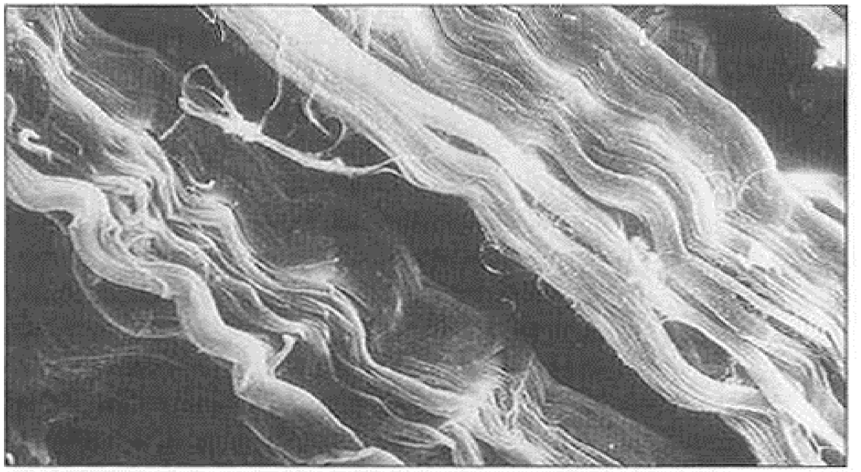


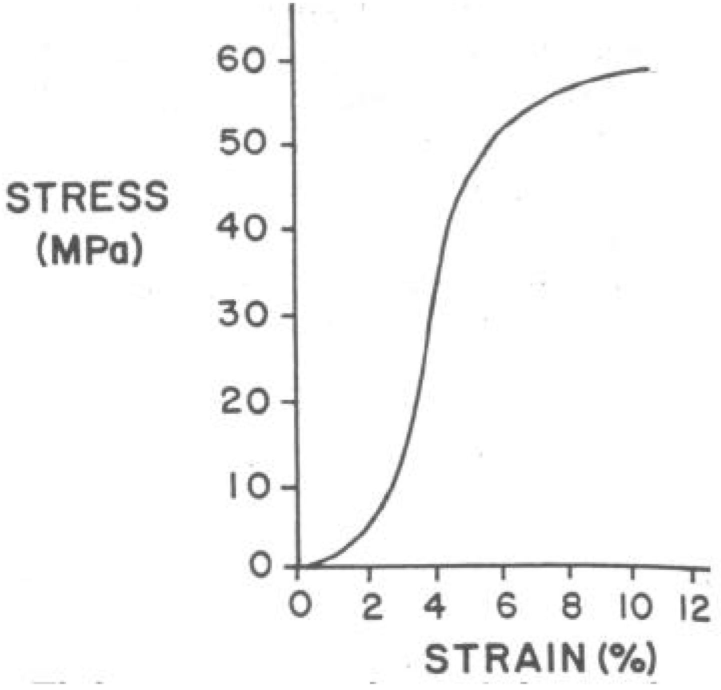
3=> Cellule:
- Tenoblasts: (similar to fibroblasts) build the matrix
- Tenocytes: derive from tenoblasts, inside tissue

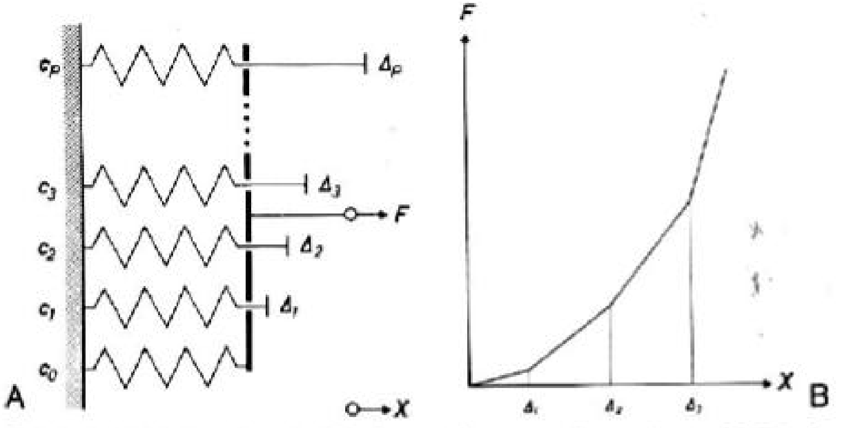
4=> Nerves, blood vessels, lymphatic

Most of load directly transmitted by collagen fibers

Fibers progressively stretched and recruited





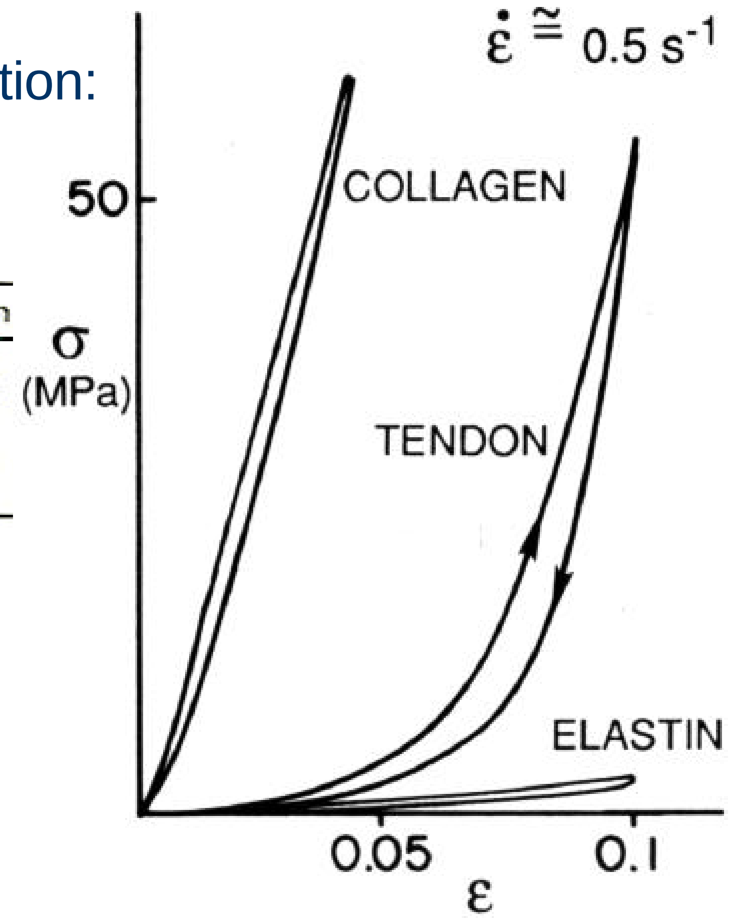


LIGAMENTS AND TENDONS:COMPOSITION

Tendons and ligaments have similar composition:

- Mainly made of collagen

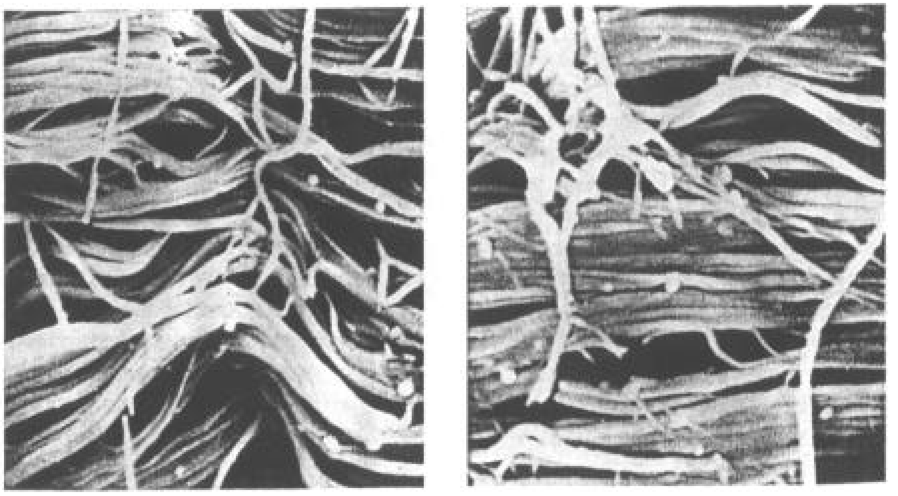
Component	Ligament	Tendon
Collagen (mostly as type I)	70–80	75–85
Elastin	10–15	<3
Proteoglycans	1–3	1–2



Different arrangement of the fibers

FUNCTION AND STRUCTURE OF LIGAMENTS

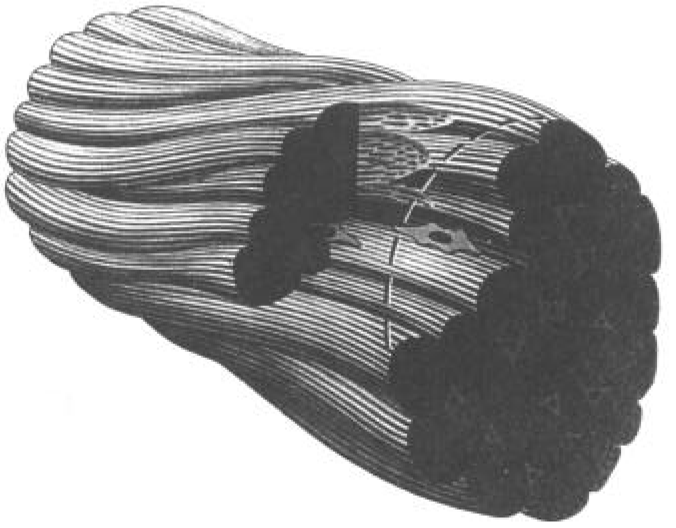
Similar composition to tendons

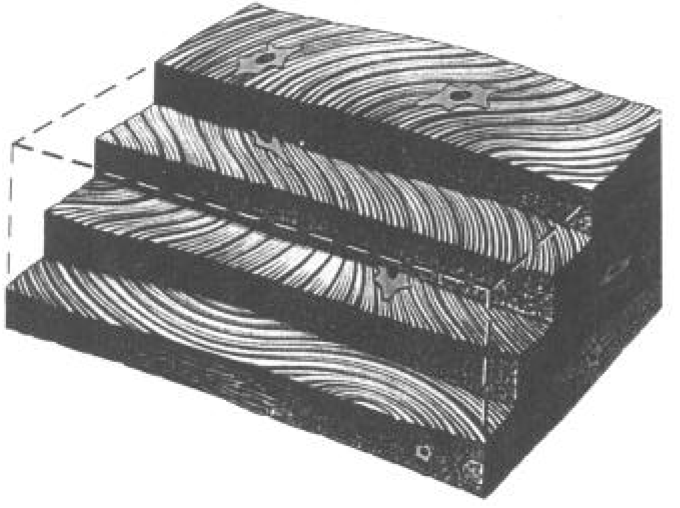


Different arrangement of collagen fibers:

- More wavy
- Arranged in layers

Initially compliant, then stiffening



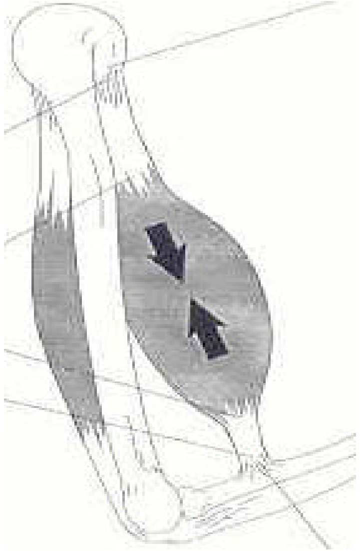


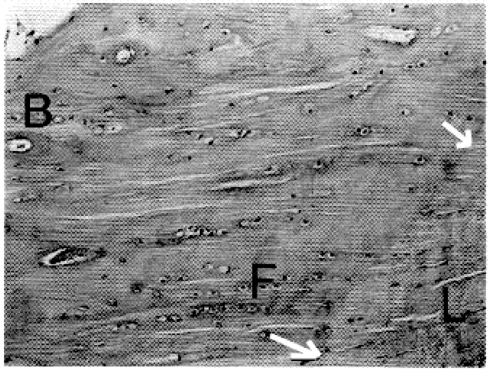
BONE INSERTIONS OF TENDONS & LIGAMENTS

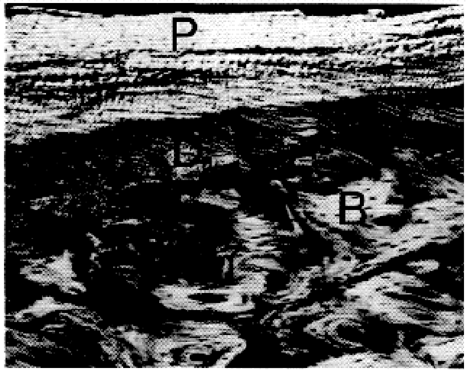
Collagen fibers (of both ligaments & tendons) extend below bone surface:

This fibrocartilage extends inside bone:

- In some cases transition to calcified tissue is sharp
- In other cases a gradient of mineralization is found along the collagen fibres:
  - Gradient of mechanical properties (stiffness increase with %mineral)
  - Transition minimizes stress concentration due to discontinuity

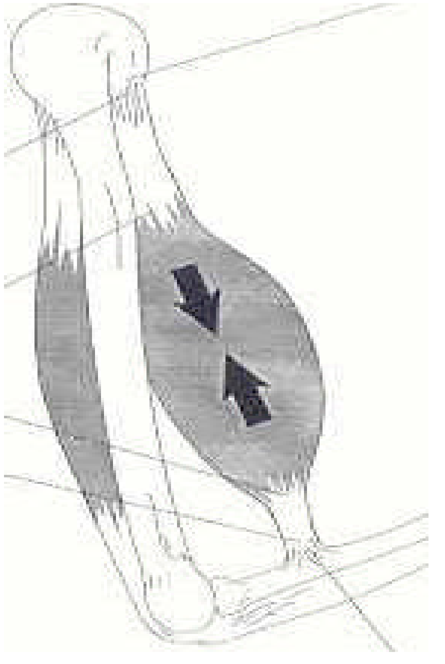






MUSCLE INSERTION OF TENDONS

Collagen fibres of tendon extend across the insertion into the muscle



Mechanical strength:

- Stress concentration is reduced
- Interface for transmission of force is one order of magnitude larger than cross section of tendon

Different specimen geometries can be tested:

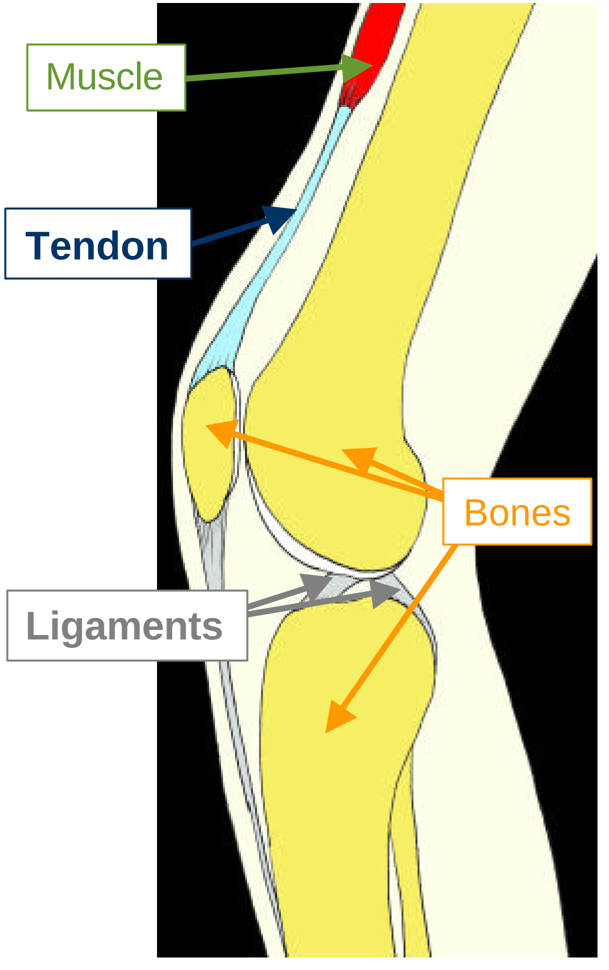
- whole complex (bone-tendon-muscle or bone-ligament-bone)
- single tendon or ligament
- single fascicles

Problems with not whole complex:

- Difficult to cut a specimen without damaging material texture
- Excised specimens difficult to clamp without causing stress concentrations (cutting failure)

Considering ligaments/tendons with surrounding structures:

- Failures in tendons may occur:
  - Bone-tendon interface
  - Muscle-tendon interface
  - In central part of tendon
- Possible failure sites in ligaments:
  - Bone-ligament interface (high speed)
  - Core of ligament (low speed)



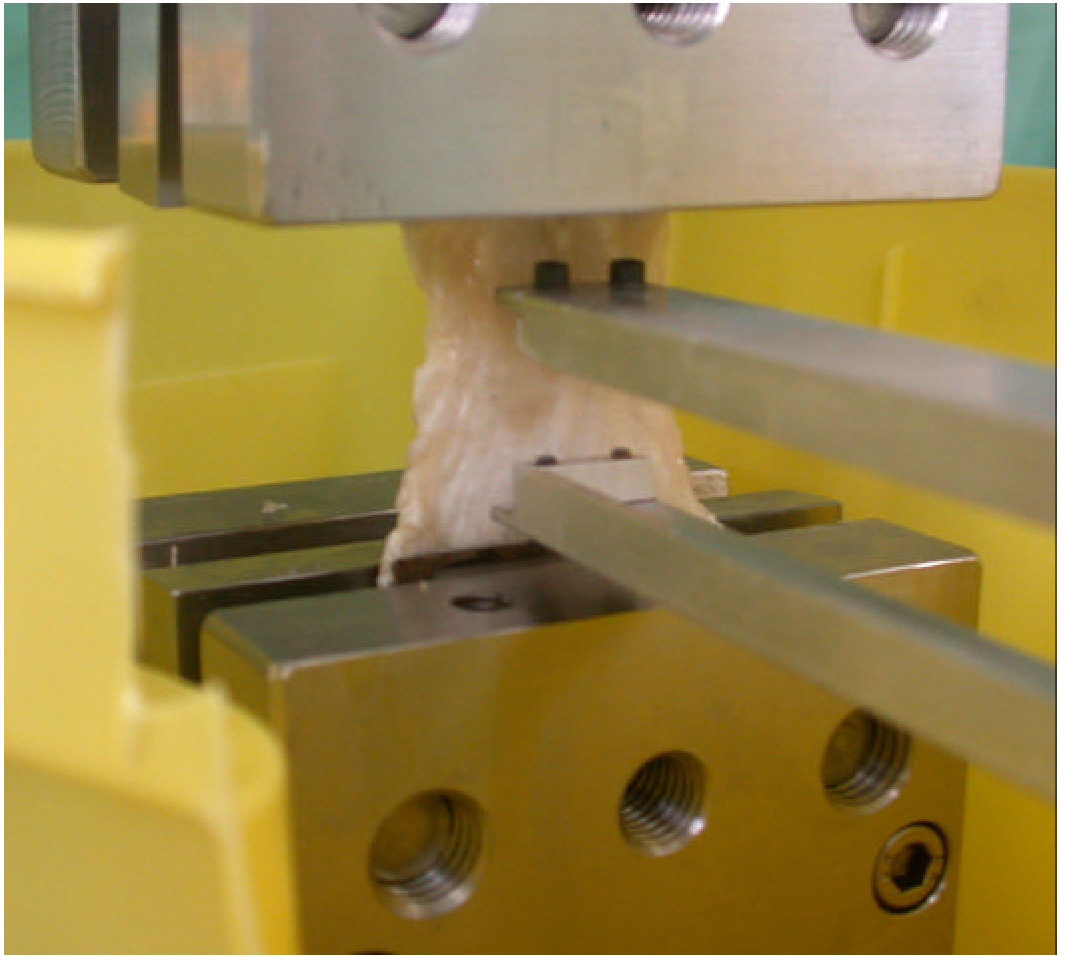
DEFINING AND MEASURING DIMENSIONS

Cross section needed to compute stress:

- Area & geometry of cross section are not constant along ligaments
- Difficult to assure precise measurements

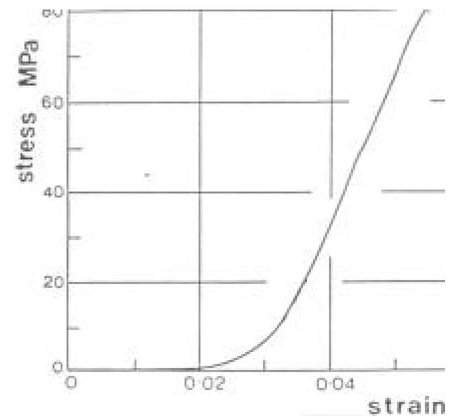
Length needed to compute strain:

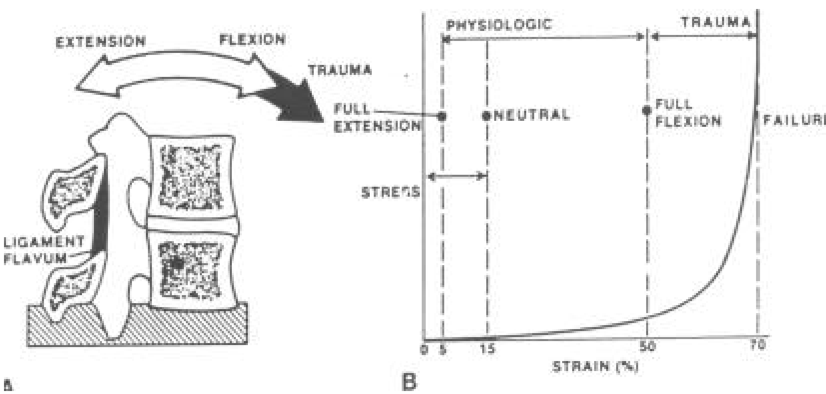
- Pre-tensioning of fibres are lost during dissection
- Preferable to measure deformation on the central portion

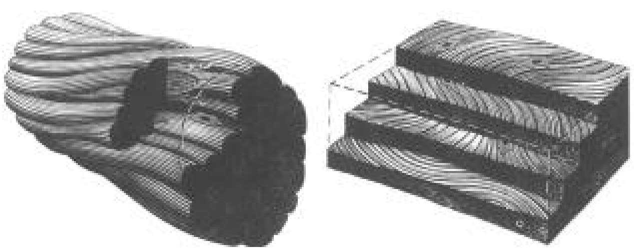


Under physiological stress:

- Tendons:
  - Transmit muscle loads
  - Minimal dissipation required for cyclic loads (e.g. walking)
- Ligaments:
  - Must be very compliant in physiological range (must not hinder motion) => no muscle work
  - Must become stiff if joint is close to dislocation



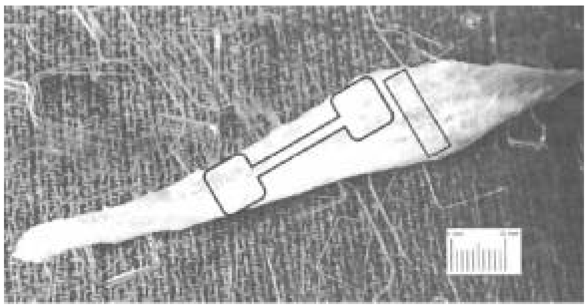


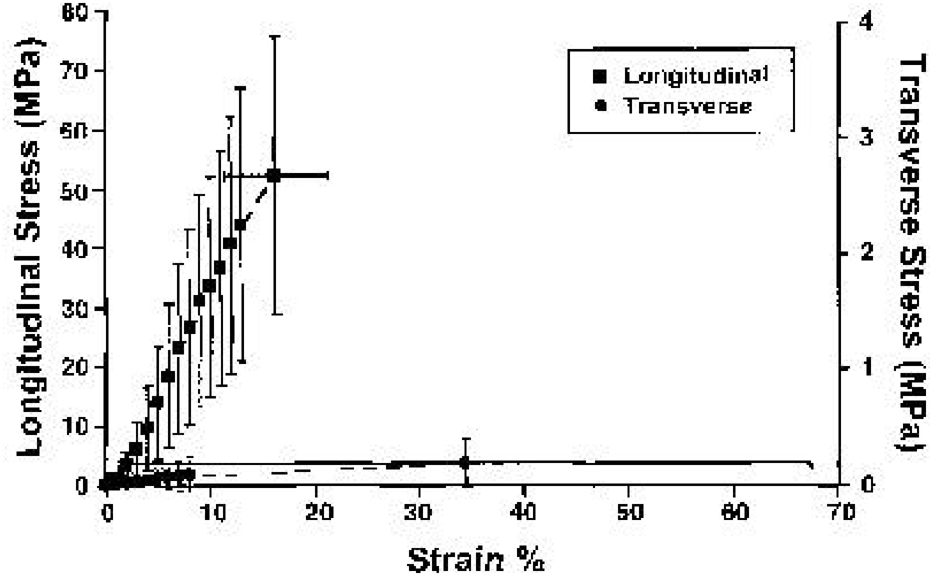


DIRECTION DEPENDENT

Longitudinal-transverse testing

Medial collateral ligament



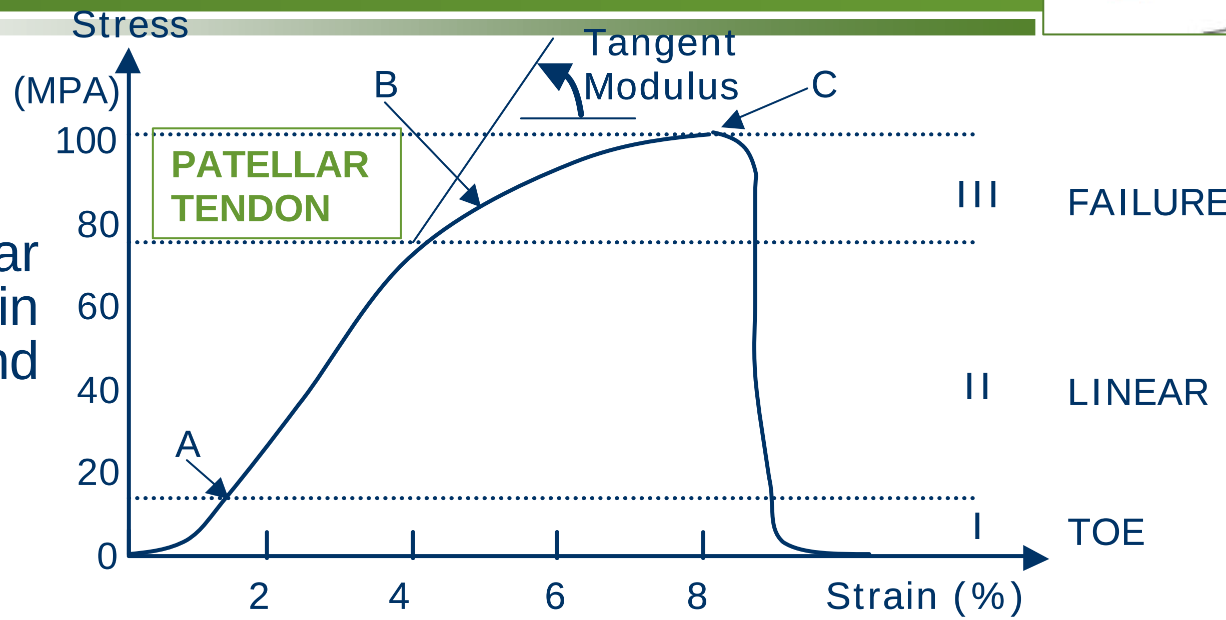


Tendons and ligaments have an anisotropic structure:

- work almost only in tension
- along axis of ligament/tendon

MECHANISM BEHIND STRESS-STRAIN CURVES

Qualitatively similar regions in stress-strain curve in tendons and ligaments:



0-A) First part has increasing slope (stiffening):

- Uncoiling and straightening collagen fibers
- Shear motion of the hydrophilic gel surrounding collagen fibres
- Tendons: up to 1.5-4% stretch
  - Muscle pre-tension sufficient to exceed this part to avoid slack
- Ligaments: stress <3MPa
  - No relevant muscle work

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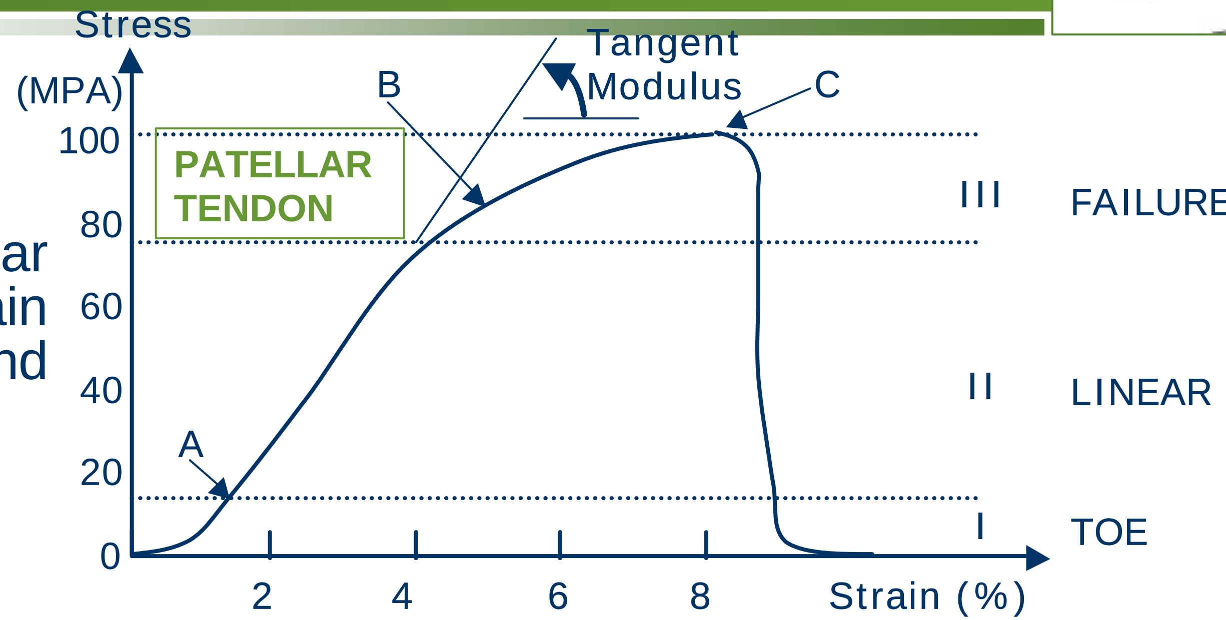

A-B) Almost-linear response for increasing stress

- Complete straightening of collagen fibers
- At the end of this region: small drop of stress: first collagen fibers get damaged
- Tendons: the region tendons are cycling during physiological activity
  - Linear, highly reversible: elastic energy accumulated is released when unloading
- Ligaments: the normal field of action for constraining motion in normal tasks
  - Ligament response becomes stiffer (=quicker) to avoid dislocation

MECHANISM BEHIND STRESS-STRAIN CURVES

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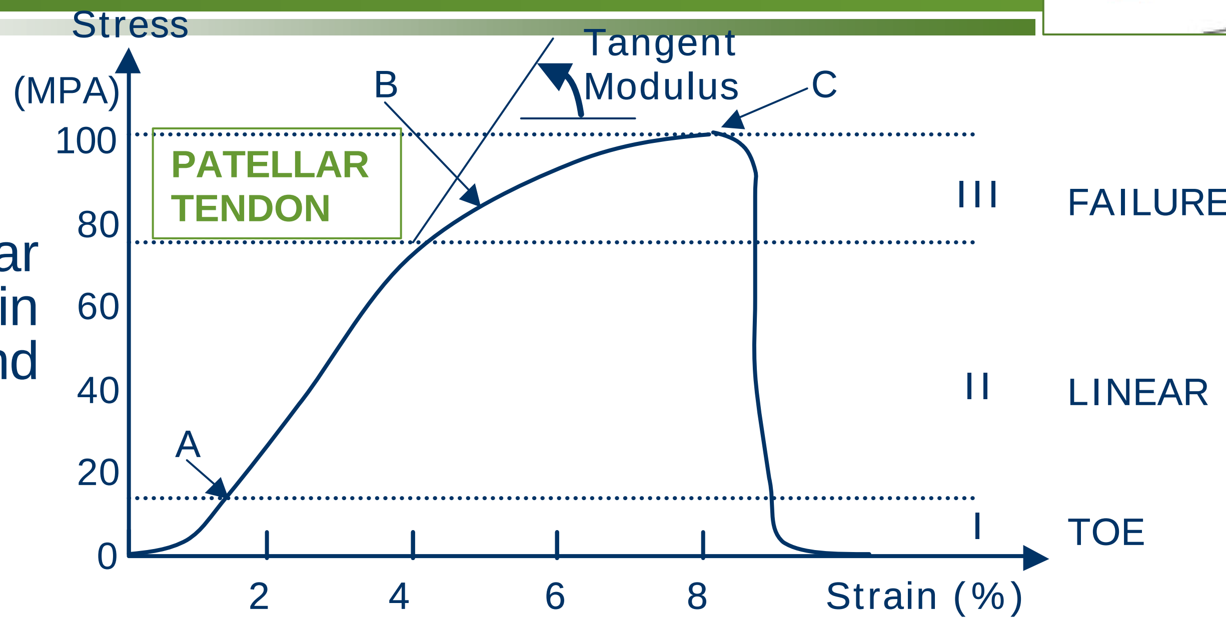


B-C) Progressive damage, up to failure

- This stress level is reached only in trauma conditions
- Tendons: stress = 50-120 MPa (10-15% strain)
- Ligaments: similar stress; larger strain, up to 70%
- In physiological conditions applied stress never exceed 1/3 - 1/4 of failure stress

DAMAGE & FAILURE

1 Reversible strain (physiological loading):

- Fibers progressively stretched and recruited
- Slope is increasing
- Tends to become linear

2 First fibers fail:

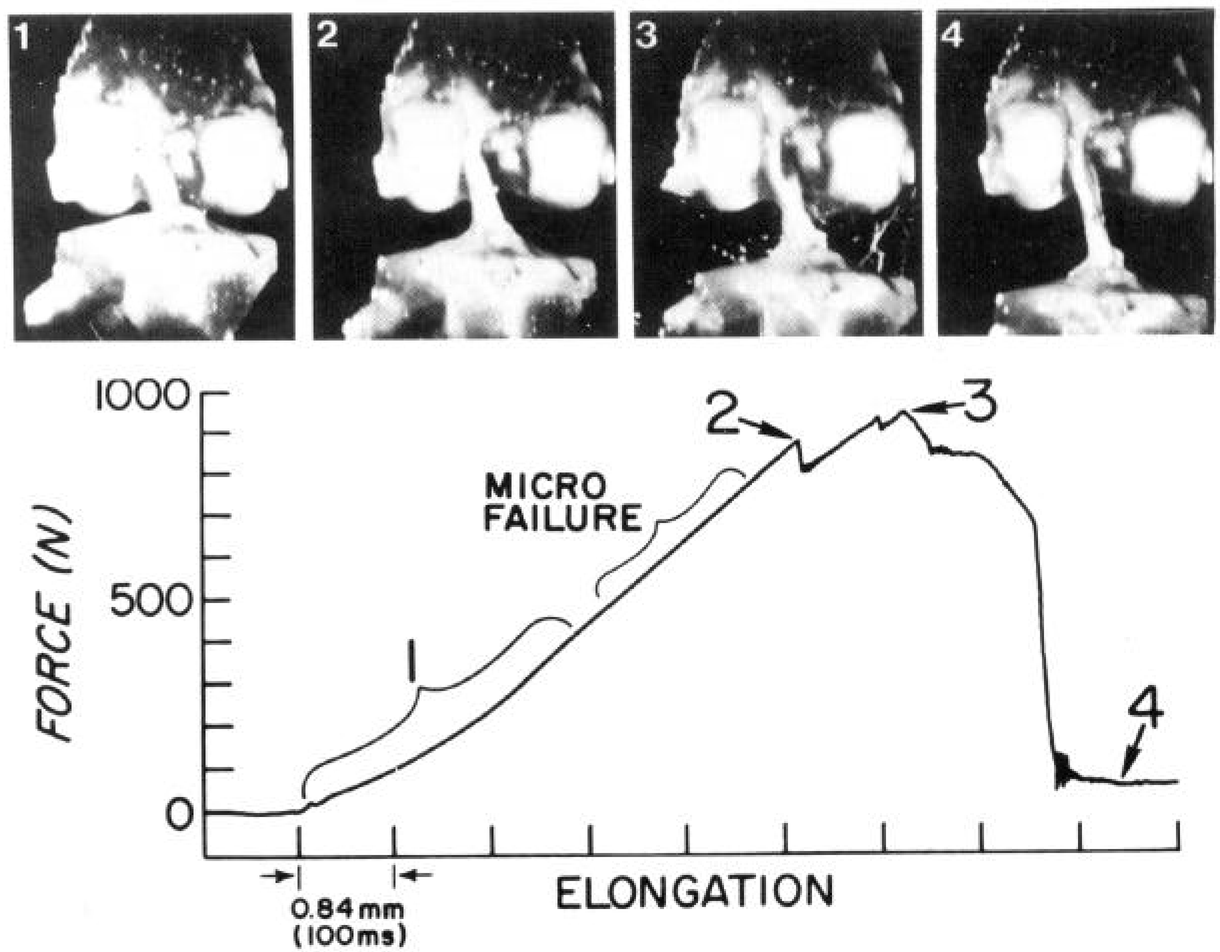
- First damage when curve still linear
- Load fluctuates

3 Peak load: most fibers stretched & ready to fail

4 Residual strength after damage:

- Ligament length is irreversibly increased (joint is loose)

POSTERIOR CRUCIATE LIGAMENT



VISCO-ELASTICITY

Both ligaments and tendons show visco-elastic behavior:

- Much more pronounced in ligaments (dissipative) than tendons (almost-reversible)

Visco-elastic tests:

- Hysteresis
- Asymptotic relaxation

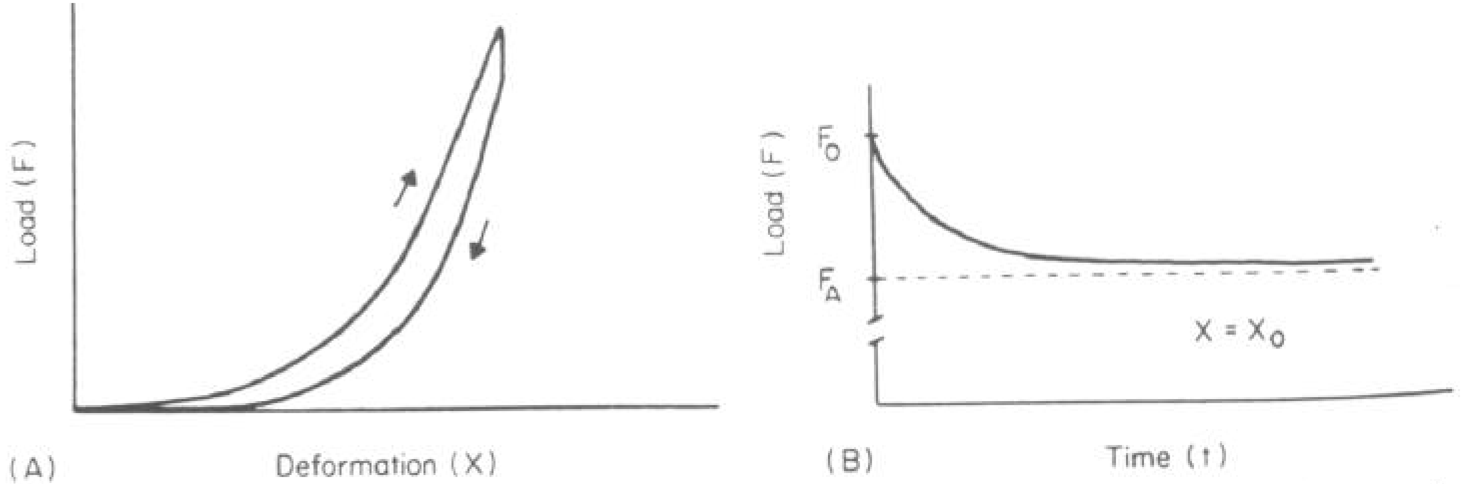


Figure 7.3:5 The load-elongation and relaxation curves of an anterior cruciate ligament specimen. In (A), the specimen was loaded to about one-third of its failure load and then unloaded at the same constant speed. In (B), the specimen was stretched at constant speed until the load reached F_0; then the stretching was stopped and the length was held constant. The load then relaxed. From Viidik (1973)

VISCO-ELASTICITY

Conditioning for cyclic loading:

- Drifting of stress-strain curves for the first 10-100 cycles
- Then stabilizing

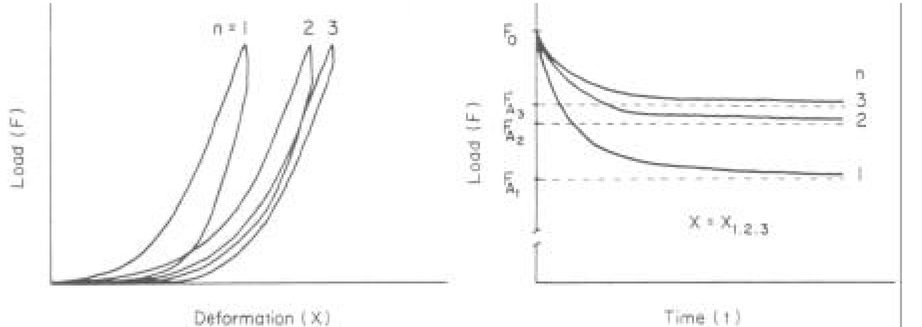
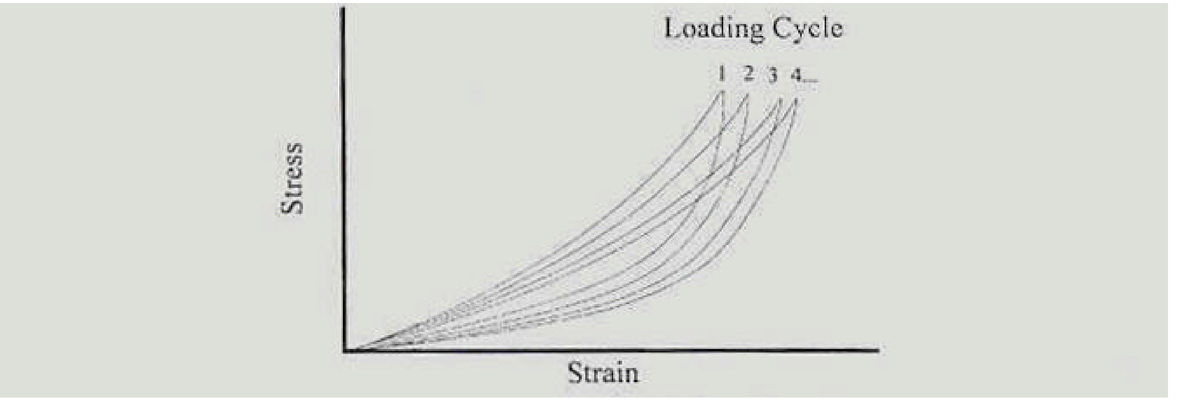


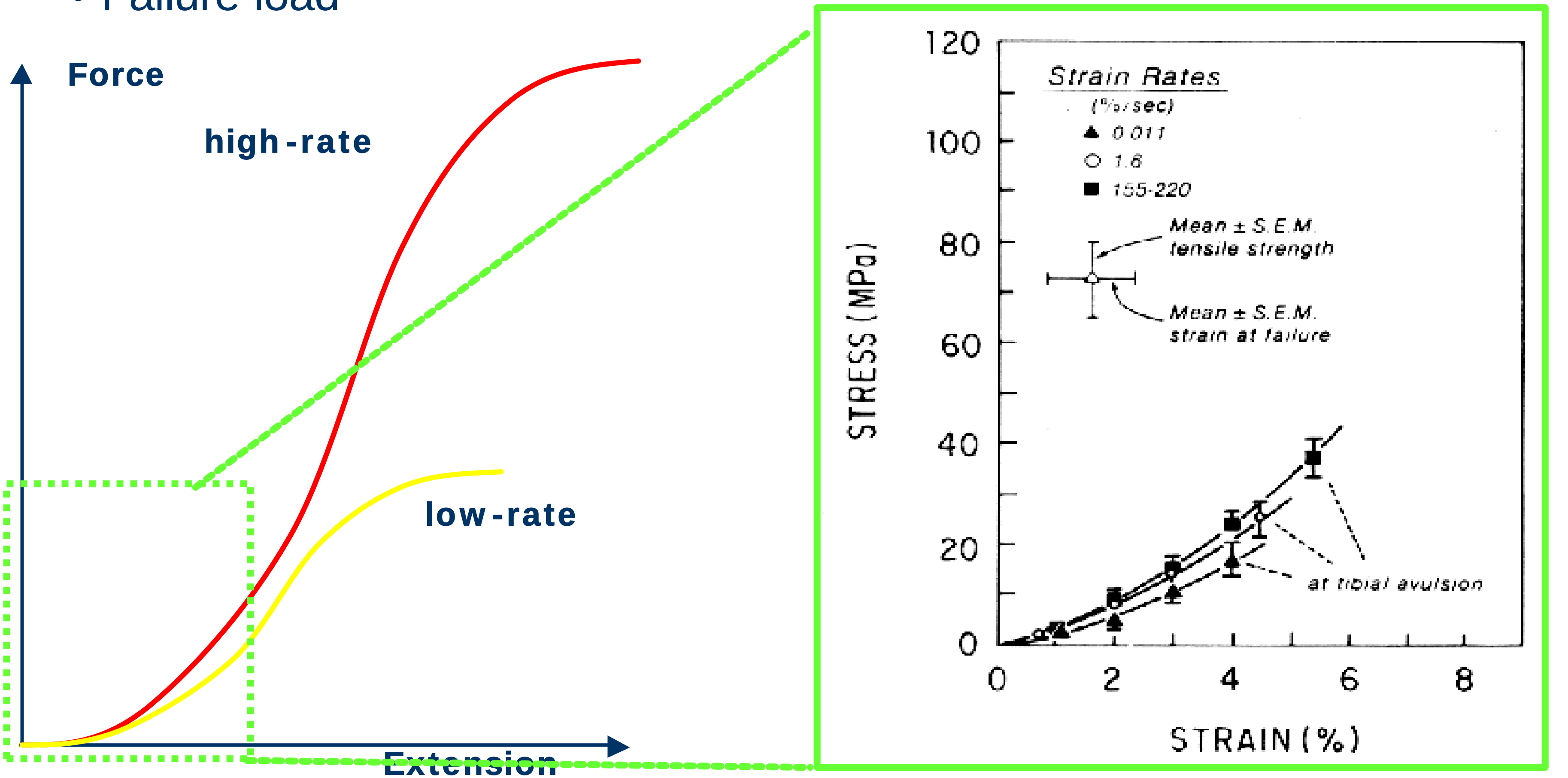
Figure 7.3:6 Preconditioning of an anterior cruciate ligament. The load-elongation and relaxation curves of the first three cycles are shown. From Viidik (1973)



VISCO-ELASTICITY

Strain rate affects:

- Slope of stress-strain curve (apparent stiffness)
- Failure load



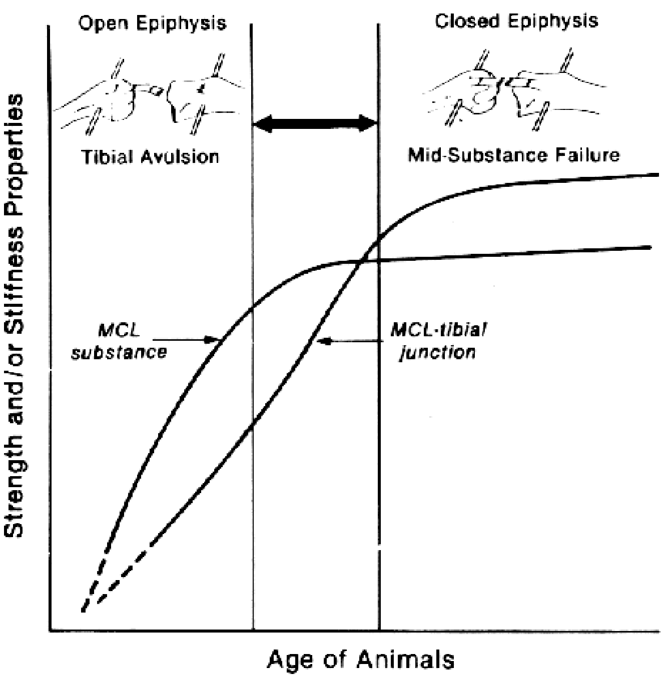
TENDONS & LIGAMENTS : CHANGES WITH AGE

Rapid change of mechanical properties adolescent/adult

Bone insertions are weaker initially (adolescent), then exceed the strength of ligament/tendon bulk part.

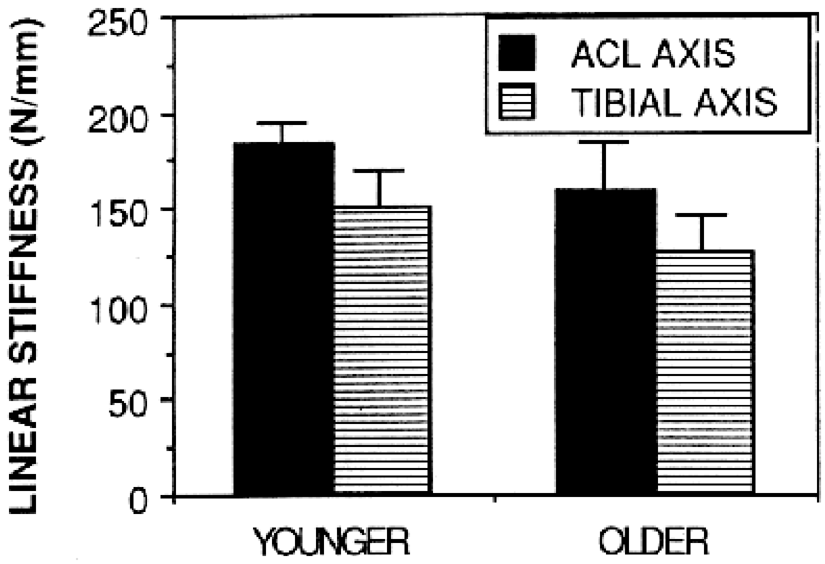
Failure mode tends to shift:

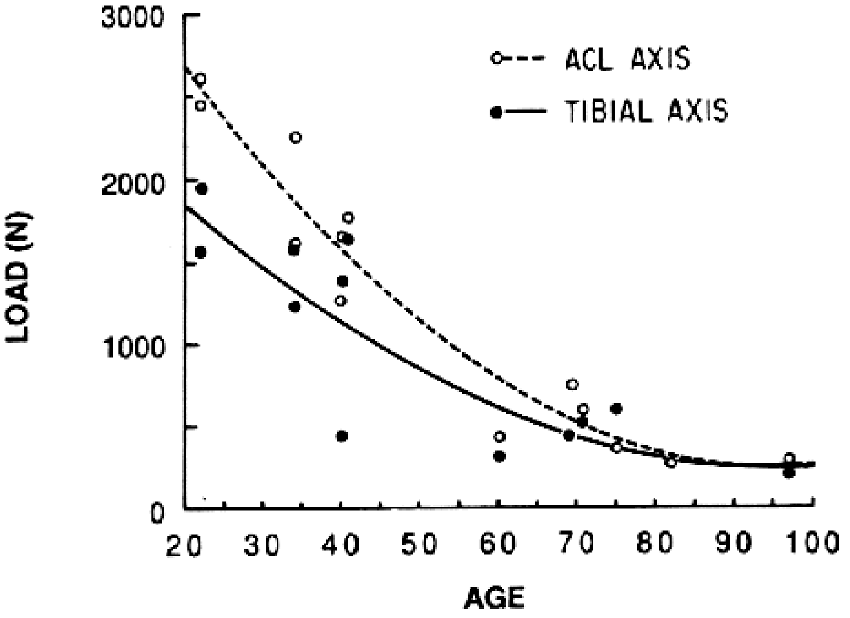
- Avulsion of insertion site (adolescent)
- Failure of mid-portion (adult)



Progressive change of mechanical properties with ageing in adult

- Size of collagen fibrils increase with age
- Stiffness and ultimate load decrease with age

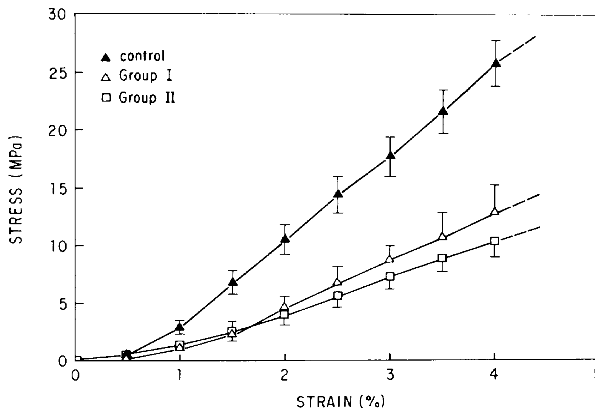


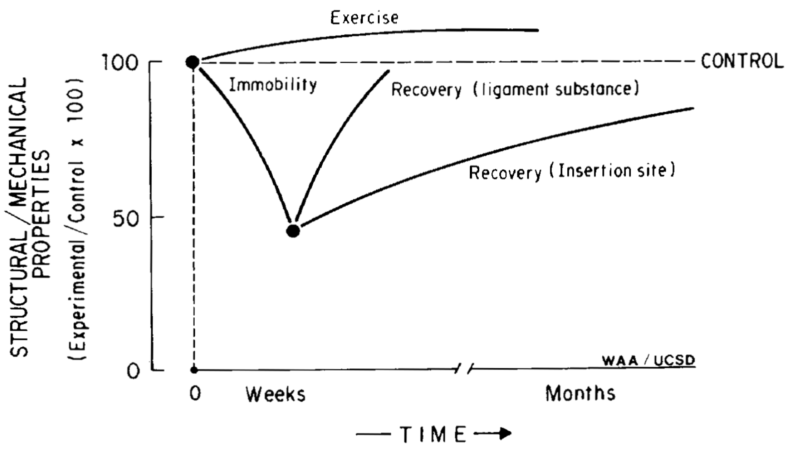


TENDONS & LIGAMENTS :
ADAPTATION TO MECHANICAL STRESS

Like all tissues:

- Increased material properties and cross-section in case of increased stress
- Decreased in case of immobilization
- Rapid resorption process (weeks-months)
- Healing and recovery slower
  - faster for ligament/tendon tissue, slower for bone insertion





Thank You