BME/ME 456 Biomechanics

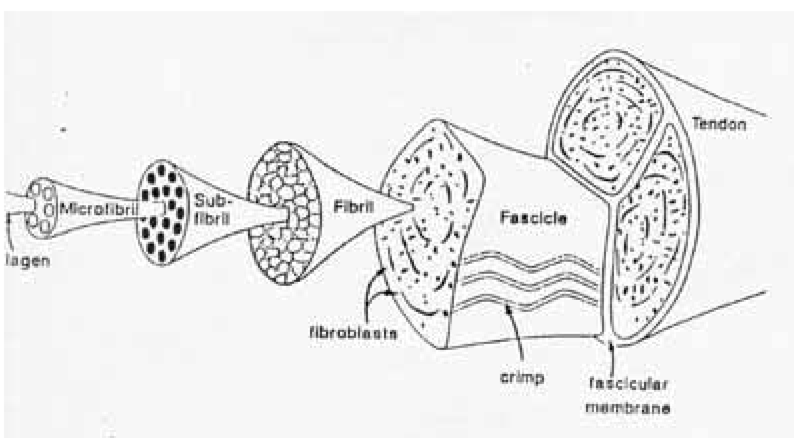
Structure and Function of Ligaments and Tendons

I. Overview

Ligaments and tendons are soft collagenous tissues. Ligaments connect bone to bone and tendons connect muscles to bone. Ligaments and tendons play a significant role in musculoskeletal biomechanics. They represent an important area of orthopaedic treatment for which many challenges for repair remain. A good deal of these challenges have to do with restoring the normal mechanical function of these tissues. Again, as with all biological tissues, ligaments and tendons have a hierarchical structure that affects their mechanical behavior. In addition, ligaments and tendons can adapt to changes in their mechanical environment due to injury, disease or excerise. Thus, ligaments and tendons are another example of the structure-function concept and the mechanically mediated adaptation concept that permeate this biomechanics course. In this section, we will review aspects of ligament and tendon structure, function and adaptation. These notes follow very closely Chapter 6 on Structure and Function of Tendons and Ligaments from your text.

II. Hierarchical Ligament and Tendon Structure

We start out again emphasizing that ligaments and tendons have a hierarchical structure. One schematic of this hierarchical structure is taken from your text, and is a very famous schematic from Kasterlic:



The largest structure in the above schematic is the tendon (shown) or the ligament itselt. The ligament or tendon then is split into smaller entities called fascicles. The fascicle contains the basic fibril of the ligament or tendon, and the fibroblasts, which are the biological cells that produce the ligament or tendon. There is a structural characteristic at this level that plays a significant role in the mechanics of ligaments and tendons: the crimp of the fibril. The crimp is the waviness of the fibril; we will see that this contributes significantly to the nonlinear stress strain relationship for ligaments and tendons and indeed for bascially all soft collagenous tissues.

The above schematic shows the basic common structures for ligaments and tendons. In terms of specific attributes for tendons:

<u>TENDONS</u>

Anatomy:

1. Tendons contain collagen fibrils (Type I)
2. Tendons contain a proteoglycan matrix
3. Tendons contain fibroblasts (biological cells) that are arranged in parallel rows

Basic Functions

1. Tendons carry tensile forces from muscle to bone
2. They carry compressive forces when wrapped around bone like a pulley

Type I Collagen:

1. ~86% of tendon dry weight
2. Glycine (~33%)
3. Proline (~15%)
4. Hydroxyproline (~15%, almost unique to collagen, often used to identify)

Blood Supply:

1. Vessels in perimysium (covering of tendon)
2. Periosteal insertion
3. surrounding tissues

LIGAMENTS

Anatomy

1. Similar to tendon in hierarchical structure
2. Collagen fibrils are slightly less in volume fraction and organization than tendon
3. Higher percentage of proteoglycan matrix than tendon
4. Fibroblasts

Blood Supply

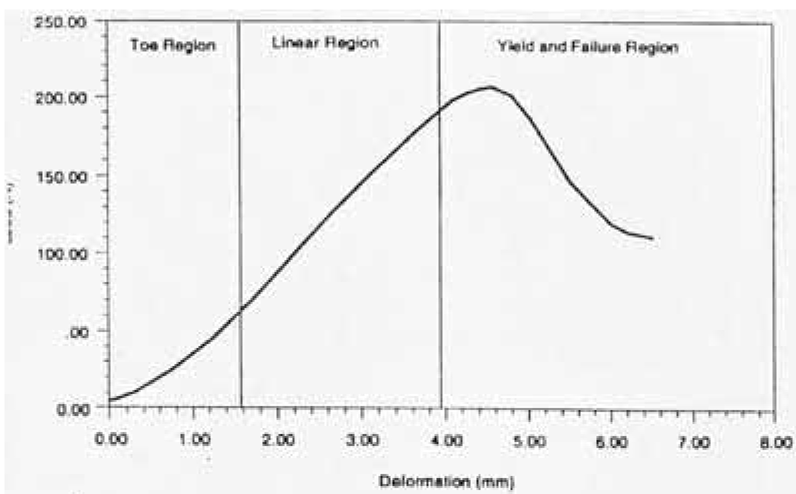
1. Microvascularity from insetion sites
2. Nutrition for cell population; necessary for matrix synthesis and repair

III. General overview of ligament and tendon mechanics

As with all biological tissues, the hierarchical structure of ligaments and tendons has a signficant influence on their mechanical behavior. Unlike bone, however, not nearly as much quantiative structure function relationships, either experiment/statistical or analytical, have been derived for ligaments and tendons. This is for two reasons: 1) the hierarchical structure of ligaments and tendons is much more difficult to quantify than bone, and 2) ligaments and tendons exhibit both nonlinear and viscoelastic behavior even under physiologic loading, which is more difficult to analyze than the linear behavior of bone.

Nonlinear Elasticity

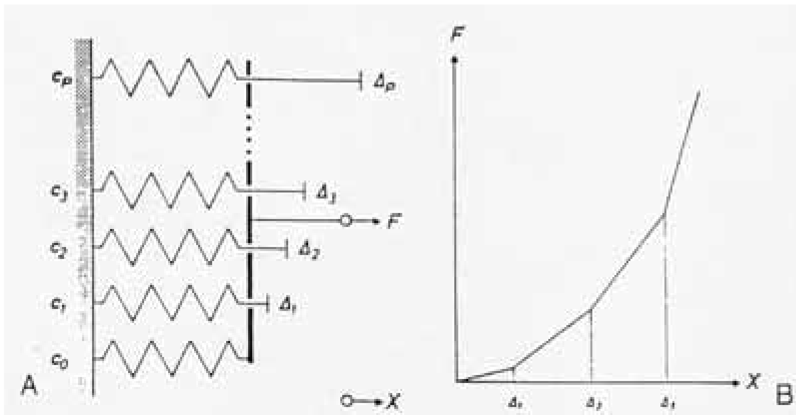
If one neglects viscoelastic behaviour, a typical stress strain curve for ligaments and tendons can be drawn as:



There are three major regions of the stress strain curve: 1) the toe or toe-in region, 2) the linear region and 3) the yield and failure region. In physiologic activity, most ligaments and tendons exist in the toe and somewhat in the linear region. These constitute a nonlinear stress strain curve, since the slope of the toe-in region is different from that of the linear region.

In terms of structure function relationships, the toe-in region represents "un-crimping" of the crimp in the collagen fibrils. Since it is easier to stretch out the crimp of the collagen fibrils, this part of the stress strain curve shows a relatively low stiffness. As the collagen fibrils become uncrimped, then we see that the collagen fibril backbone itself is being stretched, which gives rise to a stiffer material. As individual fibrils within the ligament or tendon begin to fail damage accumulates, stiffness is reduced and the ligament/tendons begins to fail. Thus a key concept is that the overall behavior of ligaments and tendons depends on the individual crimp structure and failure of the collagen fibrils.

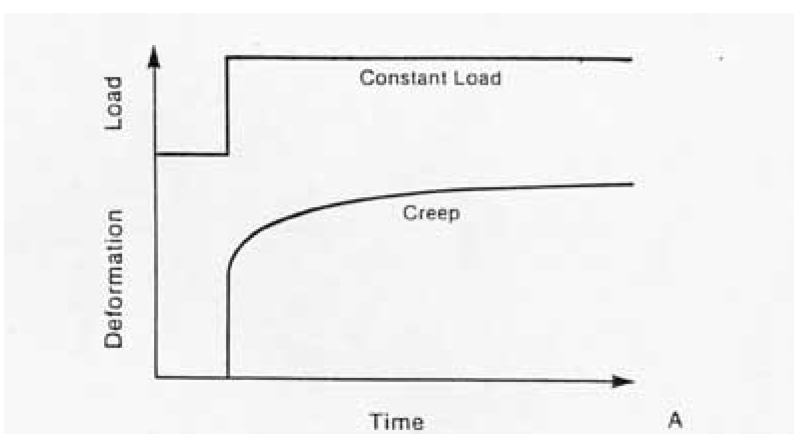
A simple model illustrating the dependence of ligament/tendon nonlinear stress/strain relationships is shown below:



In this case, as a spring is stretched to its limit its stiffness increases. This can easily be seen if the effective ligament stiffness is modeled using the Voight model, with each fibril contributing a small part to the overall stiffness. As a fibril becomes uncrimped, its stiffness increases, increasing the overall ligament/tendon stiffness.

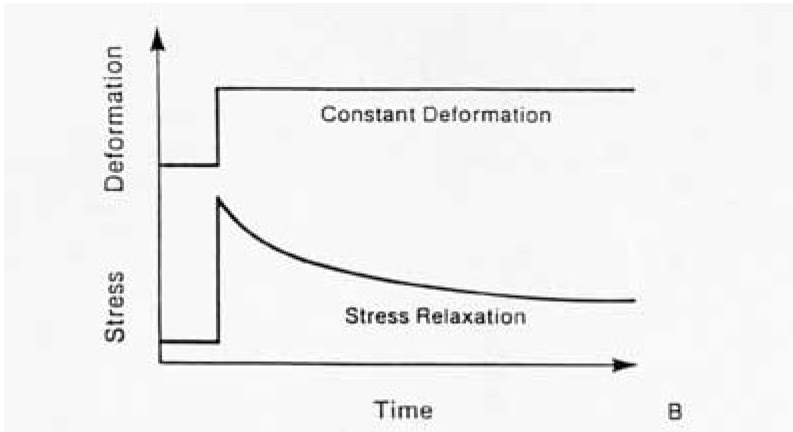
<u>Viscoelasticity</u>

Another important aspect of ligament/tendon behavior is viscoelasticity. Viscoelasticity indicates time dependent mechanical behavior. Thus, the relationship between stress and strain is not constant but depends on the time of displacement or load. There are two major types of behavior characteristic of viscoelasticity. The first is creep. Creep is increasing deformation under constant load. This contrasts with an elastic material which does not exhibit increase deformation no matter how long the load is applied. Creep is illustrated schematically below:



From: Hollister

The second significant behavior is stress relaxation. This means that the stress will be reduced or will relax under a constant deformation. This behavior is illustrated below:



The other major characteristic of a viscoelastic material is hysteresis or energy dissipation. This means that if a viscoelastic material is loaded and unloaded, the unloading curve will not follow the loading curve. The difference between the two curves represents the amount of energy that is dissipated or lost during loading. An example of hysteresis is shown below:

From: Hollister

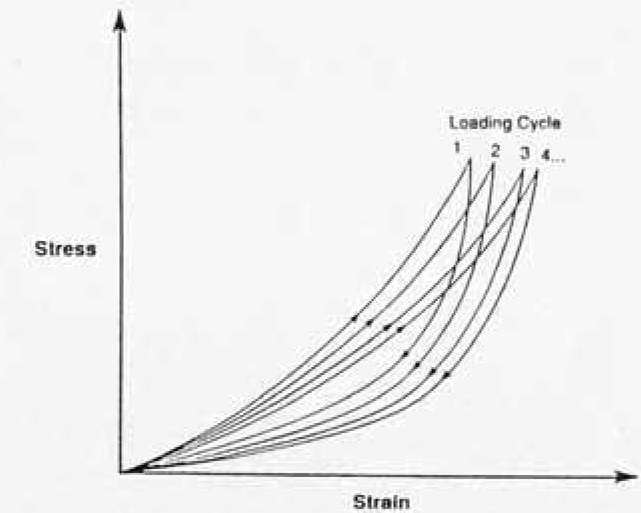
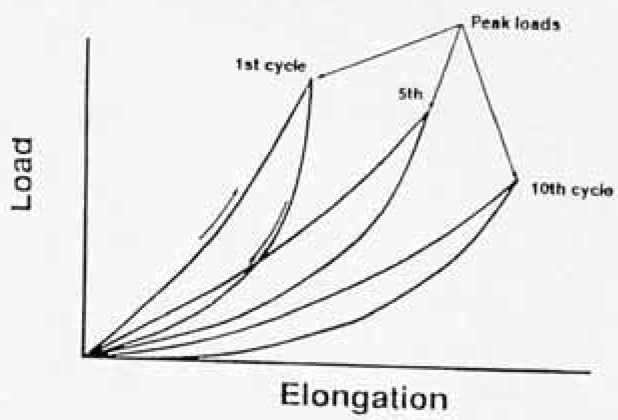


Figure 14
During cyclic loading of tendon, the stress-strain curve gradually shifts to the right. Usually, after 10 cycles, the curves become quite repeatable and steady.



The two figures above show that the amount of hysteresis under cyclic loading is reduced and eventually the stress-strain curve becomes reproducible. This gives rise to the use of pseudo-elasticity to represent the nonlinearity of ligament/tendon stress strain behavior.

Finally, in this overview of ligament/tendon mechanics we discuss briefly experimental considerations in testing ligaments and tendons. Directly measuring ligament or tendon behavior by directly griping the specimen can lead to erroneous measurements. This is because ligaments and tendons are extremely difficulty grip firmly and often slide in the grips leading to errors in displacement measurements. A way around this difficulty is to leave the ligament attached to the bone and use optical methods and markers to measure the strain. A schematic of such a test setup from the text is shown below: