BIOLOGICAL FRAMEWORKS FOR ENGINEERS

Session #19 [cm: Connective tissues]

General Objectives:

- ✓ Connective tissues are a group of tissues which bind structures together and provide a framework of support for organs and the body
- ✓ Diverse population of tissues whose hallmark is the extracellular matrix
- ✓ Mechanics of connective tissues and systems

Central Framework:

- ✓ Connective tissues provide the mechanical framework for our body and enable motion as adaptable composite materials / tissues.

Session Outline:

What is a connective tissue?

Connective tissues are characterized by an abundance of extracellular matrix with relatively few cells that make the matrix of this composite tissue.

The more specialized connective tissues are cartilage, bone, adipose (fat) tissue and blood. Numerous cell types are found in connective tissue. Three of the most common are the fibroblast, macrophage, and mast cell.

Roles of Connective Tissues:

Constituents of Connective Tissues

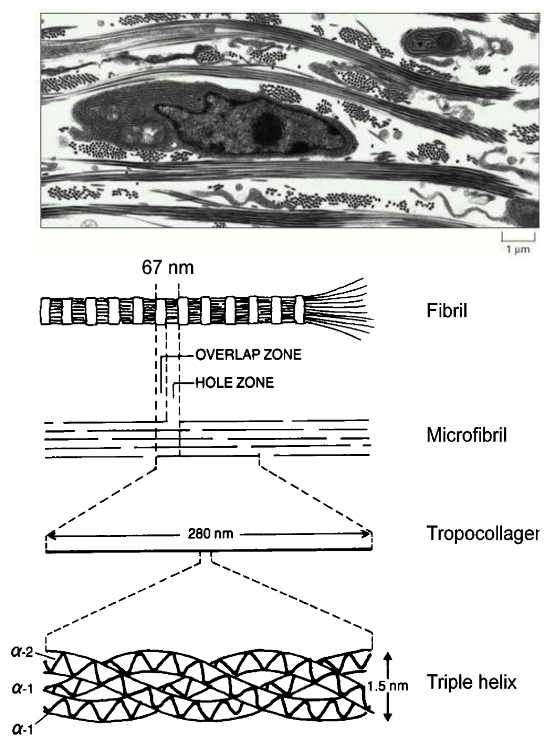
Tissue	% of dry weight			Weight % water in wet sample
	Collagen	Elastin	Proteoglycans	
Tendon	75–85	<3	1–2	65–70
Ligament (extremity)	75–80	<5	1–3	55–65
Articular Cartilage	50–75	Trace	20–30	60–80
Fibrocartilage	65–75	Trace	1–3	60–70

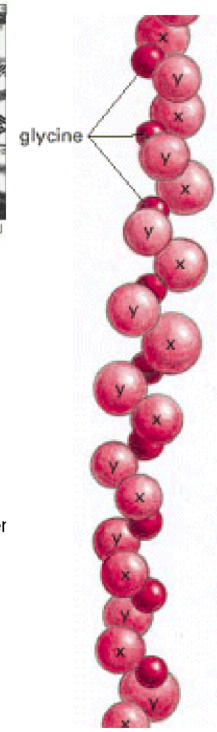
Collagen

Collagen is a truly ubiquitous fibrous protein (~25% of body's proteins) that participates in the construction of extracellular aggregates functioning primarily as supporting elements. It is a major protein constituent of all vertebrates and provides mechanical integrity and strength to the body as the basic structural element for soft and hard tissues. It is present in practically every tissue and organ with a half-life of 300 to 500 days. There are many isoforms of collagen identified and these each have different characteristic morphology, distribution, and functional properties.

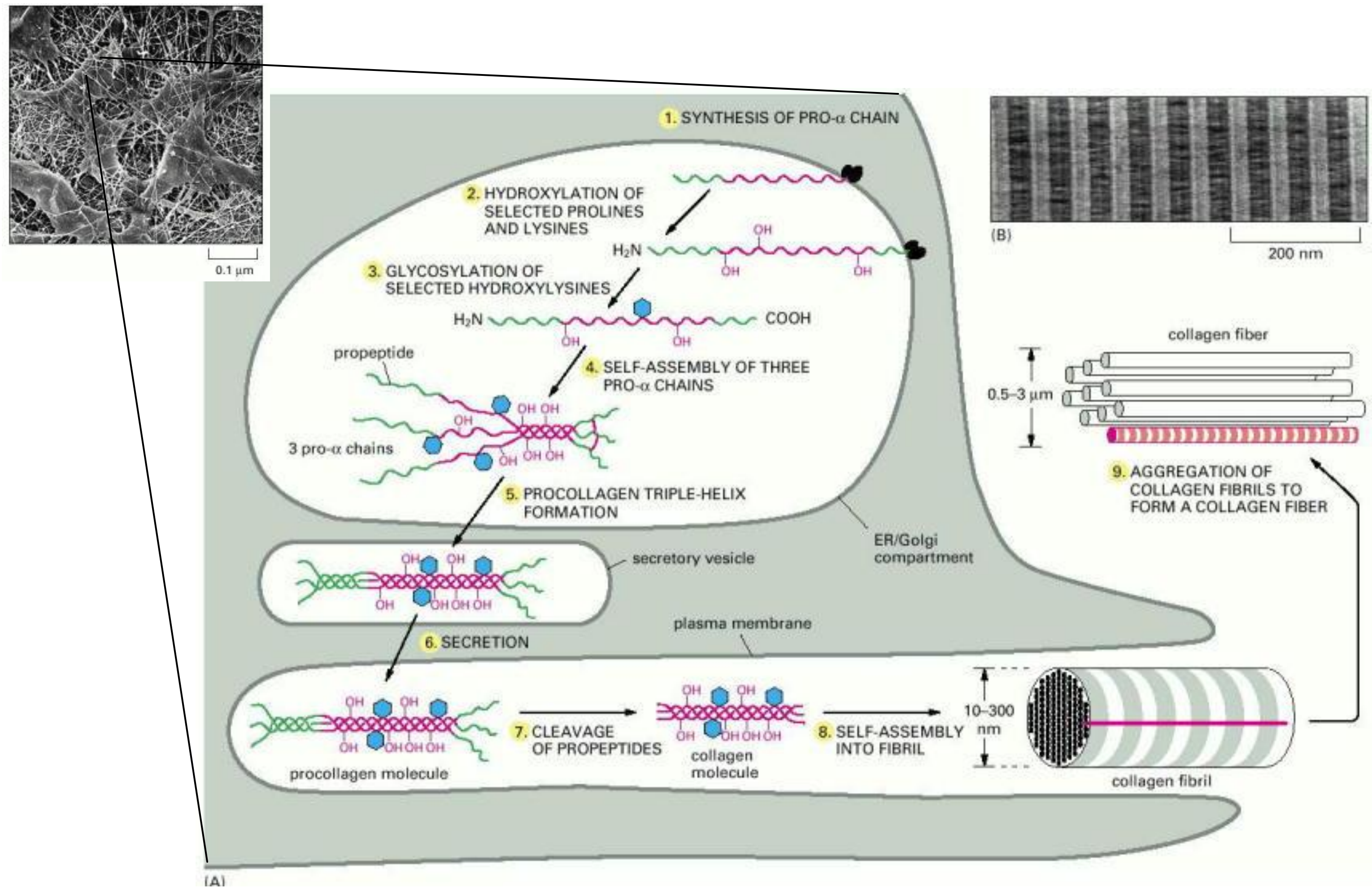
Structure of Collagen

- ✓ Fibers-
- ✓ Fibrils-
- ✓ Microfibrils-
- ✓ Tropocollagen-
- ✓ Alpha chains-





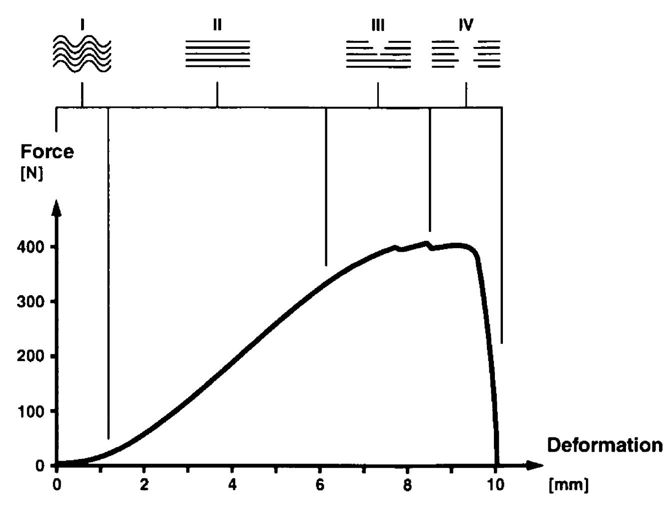
Biosynthesis of Collagen



Biomechanics of Collagen

- ✓ Load-displacement curve of all collagen-based tissues have characteristic upward concave shape with stiffness varying nonlinearly.

- ✓ General Characteristics
  - I. Initial region (toe region)
  - II. Linear region
  - III. Microfailure region
  - IV. Complete failure region



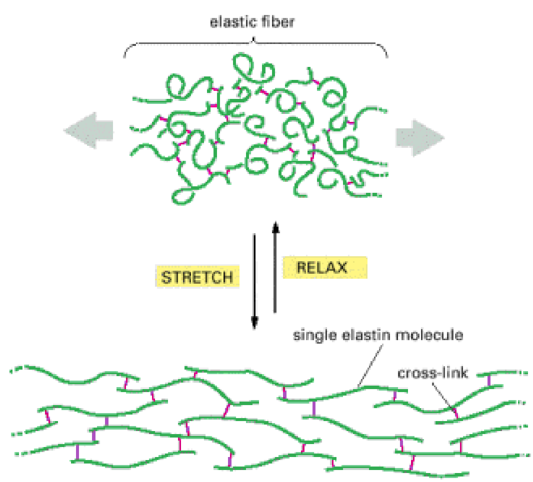
✓ Factors Affecting Mechanical Response

a. Collagen Crimp

b. Spatial orientation of fibers

Elastin

Elastin is an extracellular matrix protein containing a linear elastic biomechanical response. It exhibits a high degree of reversible stretching including the ability to deform to large extensions with small forces. Elastin is the primary constituent of elastic fibers found in soft tissues and is chemically inert, hydrophobic, and stable under physiologic conditions such that it may last for the life of the organism.

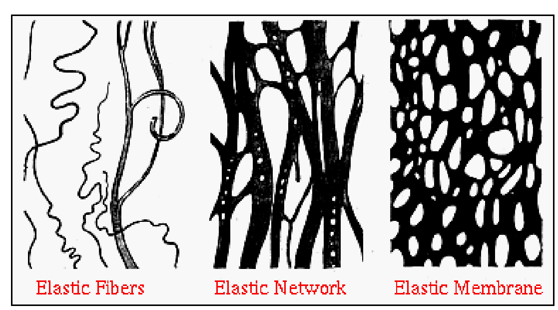


Structure of Elastin

✓ Tropoelastin-

✓ Elastin Fibers-

✓ Fiber Networks-

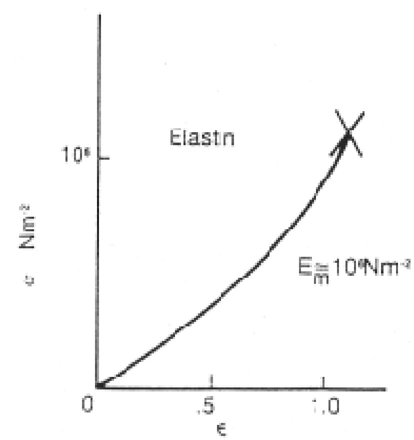


Biosynthesis of Elastin

- ✓ Synthesis of tropoelastin on the rough endoplasmic reticulum of fibroblasts
- ✓ Secretion of tropoelastin initiates the extracellular enzymatic cross linking by lysyl oxidase catalysts and condensation
- ✓ Once cross linked, very stable
- ✓ Fibrillogenesis occurs close to the cell membrane surface and involves the coalescence of the central core
- ✓ These reactions result in a highly insoluble polymer with frequent interchain links
- ✓ Fiber development continues as the central core gains a progressively larger microfibril outer aspect
- ✓ The mature fiber is large and irregular in shape and has a variable diameter and length

Biomechanics of Elastin

- ✓ Shallow load deformation curve shows large extension with small forces and a complete return to its original dimensions. Efficient storage of elastic energy allows an elastic recoil with little energy dissipation
- ✓ General Characteristics
    - o Modulus of elasticity ≈ 0.6×10^6 N/m^2.
    - o Tensile stress at failure ≈ 1×10^6 N/m^2.
    - o Tensile strain at failure ≈ 100 ±25 %
    - o Dynamic Properties
        - ▪ Above 10-Hz, the resilience (energy recovered / energy put in) of elastin begins to drop off



Stress-strain relationship of elastin.

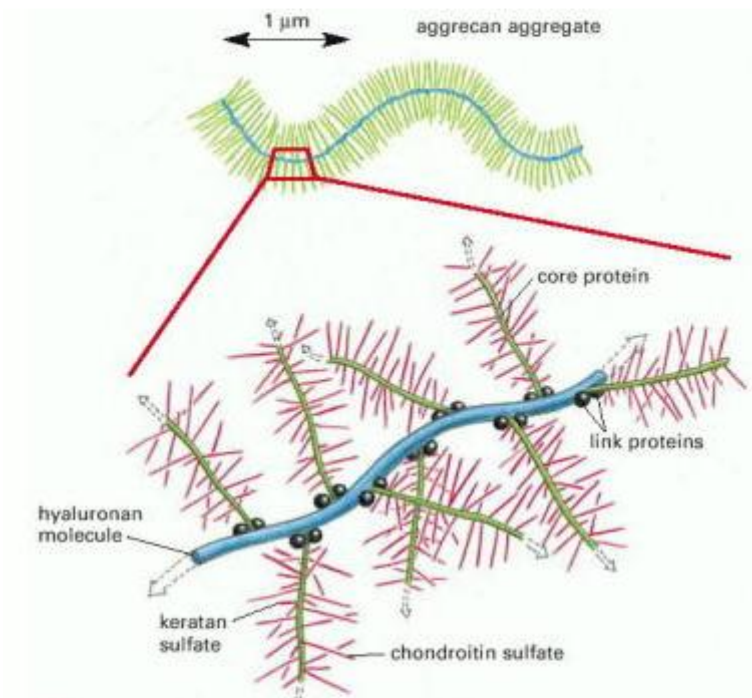
- ✓ Modeling the Mechanical Response
    - o Entropy model
    - o Hydrophobic model

Glycosaminoglyans (GAGS)

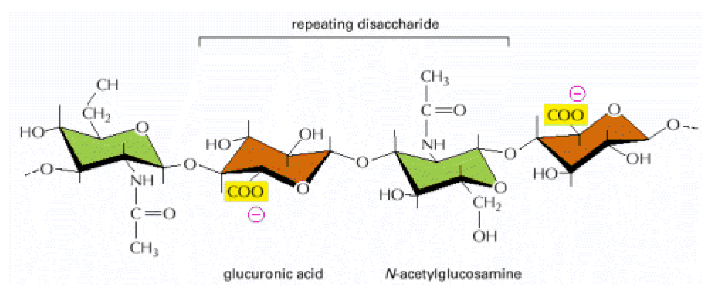
GAGs are carbohydrate (polysaccharide) molecules that may or may not be covalently linked to a core protein. They form a highly hydrated, gel-like "ground substance" that retains water and comprises most of the extracellular space. They function as space fillers, physical binders forming the matrix, and supply compressive resistance to tissues.

<u>Structure</u>

- ✓ GAGs



- ✓ Proteoglycans



- ✓ Polymeric Complexes

- ✓ Genesis is molecule specific and most are produced in fibroblasts and mesenchymal cells

Biomechanics

- ✓ Hydrophilic nature causes gel-like properties
- ✓ Lubricants, space fillers, and shock absorbers (compressive strength)

Connective Tissues:

Ligaments

Ligaments connect bone to bone and function to stabilize, guide, and limit the motion of joints. Ligaments have a collagen fibril orientation that is variable but generally parallel and also contain elastin fibers. In joint capsules, ligaments are maximally elongated and taut in the close packed position of a joint. Ligaments are generally shorter than tendons and often appear as thickenings of joint capsules. Further, they are typically well vascularized and innervated.

Biomechanics

Ligaments are pliant and flexible, allowing natural movement of the bones to which they attach, while also are strong and inextensible so as to offer suitable resistance to applied forces.

[Anterior Cruciate Ligament]

- ✓ Physiologic strain range is 10-20%
- ✓ Ultimate tensile strain is about 30%
- ✓ Physiologic stress range is 2-7 Mpa
- ✓ Ultimate tensile stress is approximately 50 Mpa

Tendons

Tendons connect muscle to bone and function as a force transmission member in the musculoskeletal system. These connective tissues are very orderly with parallel collagen fibrils. They can be very short (*Achilles T.*) or long distance acting (*Flexor Digitorum Profundus T.*). Tendons typically have a good vascular supply from their surroundings and contain special mechanoreceptors called Golgi tendon organs that supply neural input (afferent fibers) as to the position of the tendon.

Biomechanics

Tendons are strong structures sustaining high tensile forces from muscle contraction during joint motion, but are flexible enough to deform around bony surfaces and retinacula to direct muscular action.

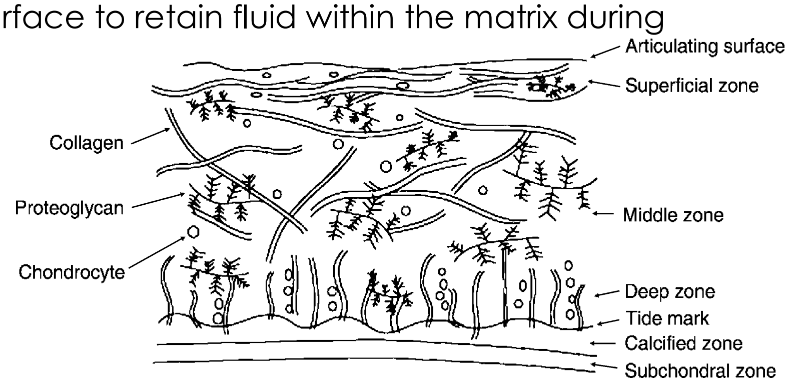
- ✓ Physiologic strain range is 2-5% *[Flexor Digitorum Tendon]*
- ✓ Ultimate tensile strain is about 10%
- ✓ Physiologic stress range is 5-10 MPa
- ✓ Ultimate tensile stress is approximately 100 MPa *[Loren & Lieber, 1994]*
- ✓ Its ultimate tensile strength is about 4-times the isometric tension generated by muscle and is greater than steel when weight adjusted.

Cartilage

A dense connective tissue that is composed for three main types which differ in their proportions of collage, elastin, and proteoglycans. *Elastic cartilage* has high elastin content is found in the ear and larynx. *Fibrocartilage* has layers of dense collagen fibers for flexibility and toughness and is found between intervertebral discs, the knee, and at transition regions between bone and ligaments/tendons. *Hyaline cartilage* is the most abundant and is commonly known as "gristle". At joint regions, this type is called *articular cartilage*. *Synovial fluid* is a clear viscous fluid between opposing cartilage layers and acts as a lubriant to reduce friction. *Chondrocytes*, derived from the fibroblast family, live in cartilage and produce the appropriate matrix constituents.

Biomechanics

Articular cartilage is an anisotropic material with zones of different composition. Near the articulating surface, the collagen is arranged in dense fibrils that run in a parallel fashion. They help to resist shear forces generate by joint movement and to resist fluid flow through the surface to retain fluid within the matrix during compression. In the middle zone, the collage content is reduced and fibrils organized in a random fashion. The water content is lower than the articulating surface but the proportion of proteoglycans is higher and provide the compressive stiffness of cartilage.



- ✓ Compressive moduli: 0.1 – 2 MPa
- ✓ Ultimate modulus: 18 MPa *[hip socket]*
- ✓ Friction coefficient of 0.005 – 0.05 (c.f. ice: 0.04, steel, 0.05)