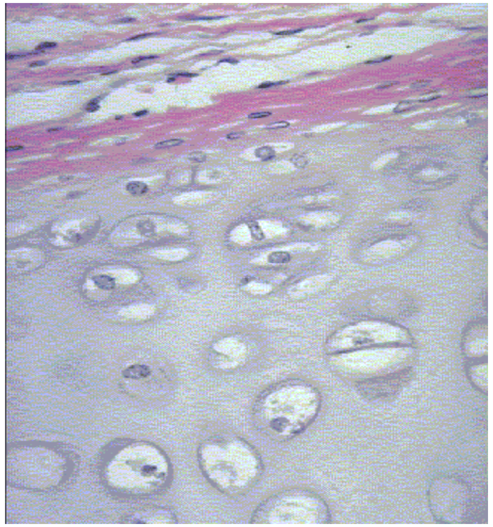
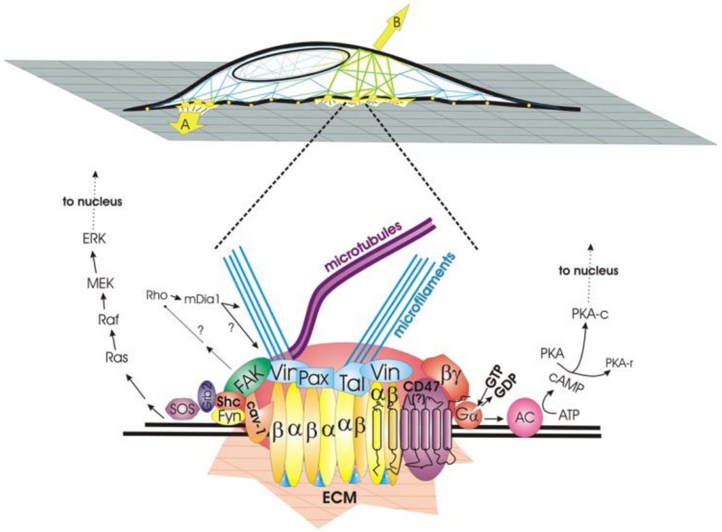
Structure, composition & biomechanics of articular cartilage





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Cartilage functions

Tissue with special **biomechanical** and **biochemical** characteristics

1. Distributes joint loads over a wide area, decreasing the stresses sustained by the contacting joint surfaces

2. Allows relative movement of the opposing joint surfaces with minimal friction and wear

3. Minimizes peak stresses on subchondral bone

4. Provides a friction-reducing, weight-bearing surface with a friction coefficient of 0.0025

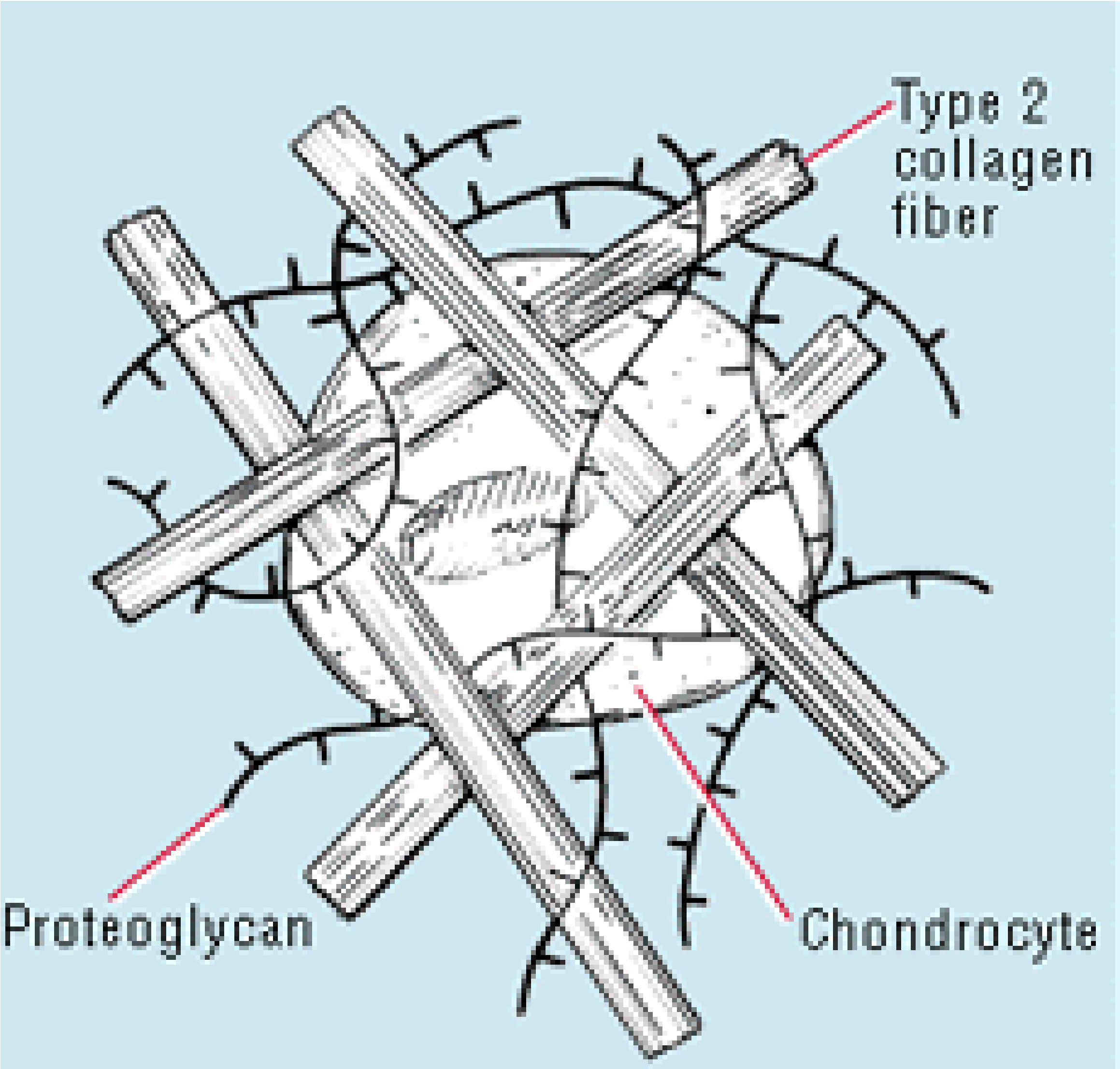
5. Functions within a contact pressure range of 2-11 MPa

Cartilage components

- Chondrocytes (<10%)
- Collagen (10-30%) (Type II)
- Proteoglycans — monomer & aggregates (3-10%)
- Water + ions (60-87 %)

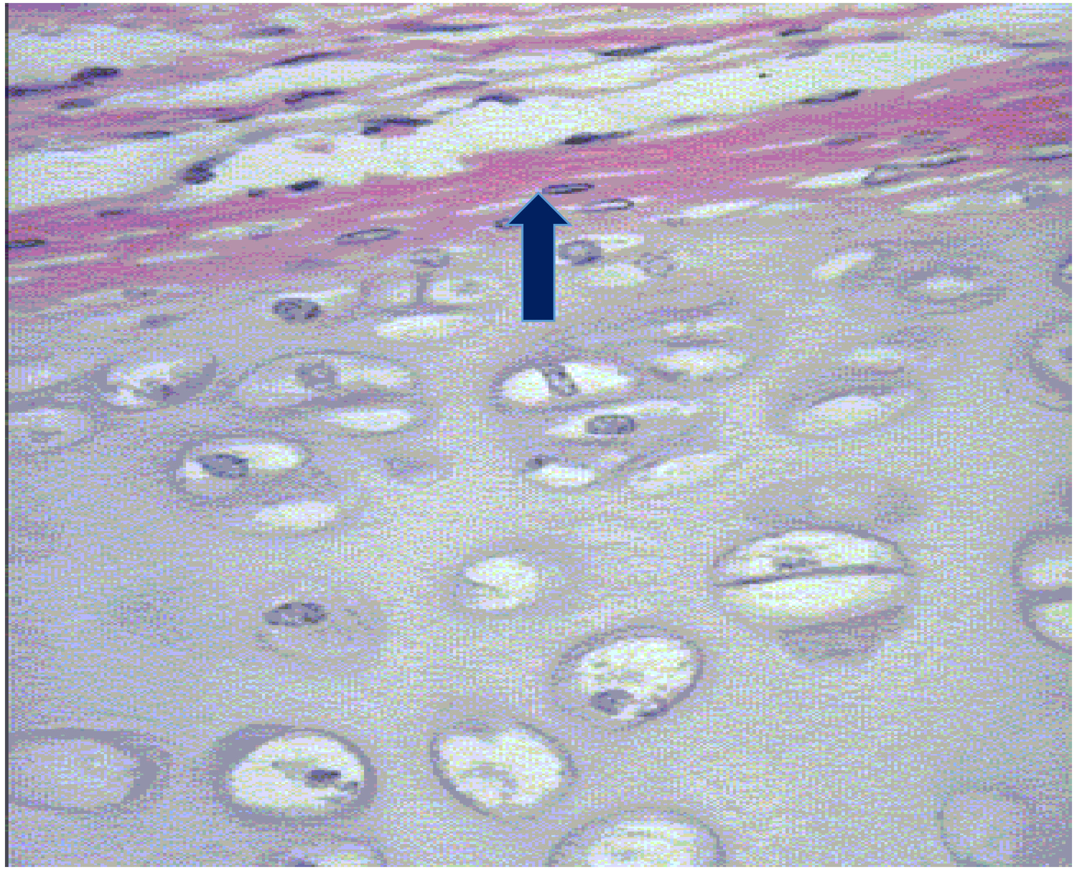
Cartilage components

Components are arranged in a way that is maximally adapted for biomechanical functions



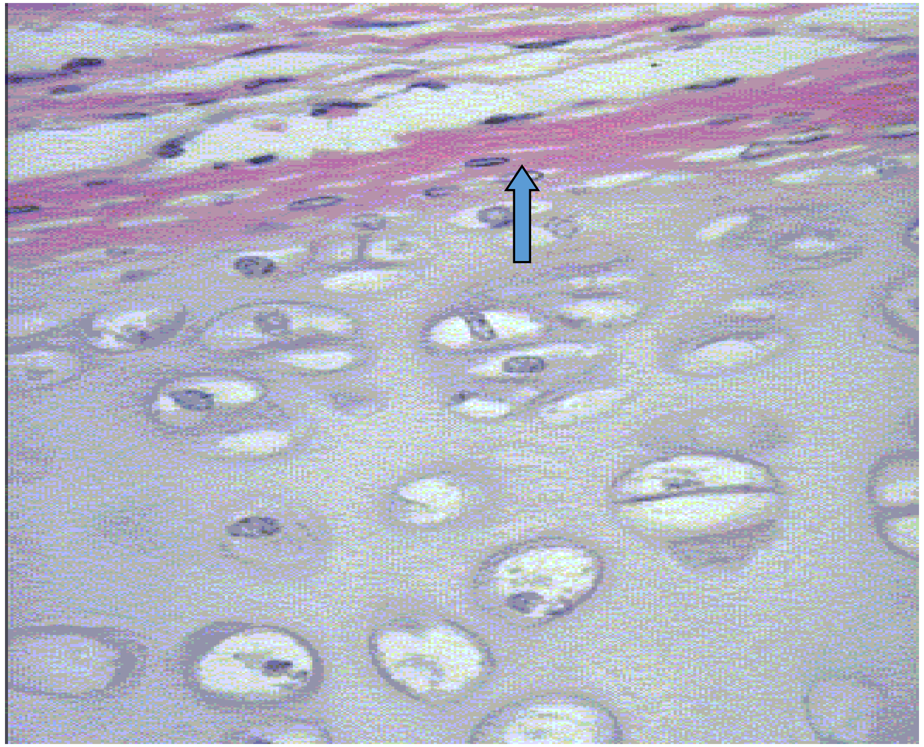
Perichondrium

- Dense irregularly arranged connective tissue (type I collagen)
- Ensheaths the cartilage
- Houses the blood vessels that nourish chondrocytes



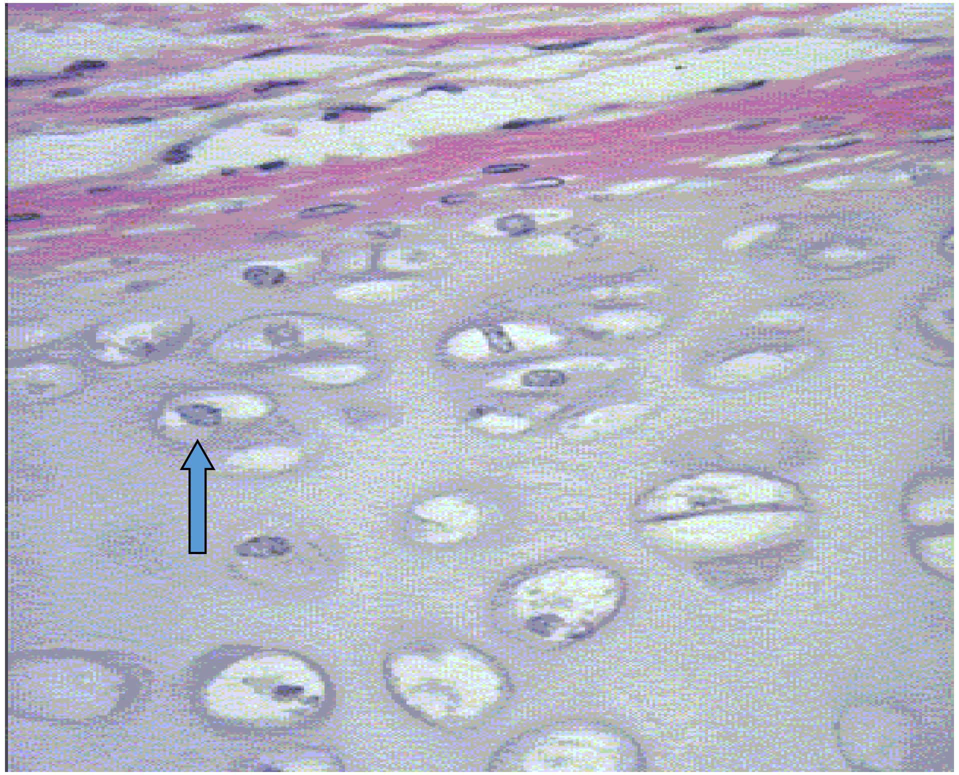
Chondroblast

- Progenitor of chondrocytes
- Lines border between perichondrium and matrix
- Secretes type II collagen and other extracellular matrix components



Chondrocyte

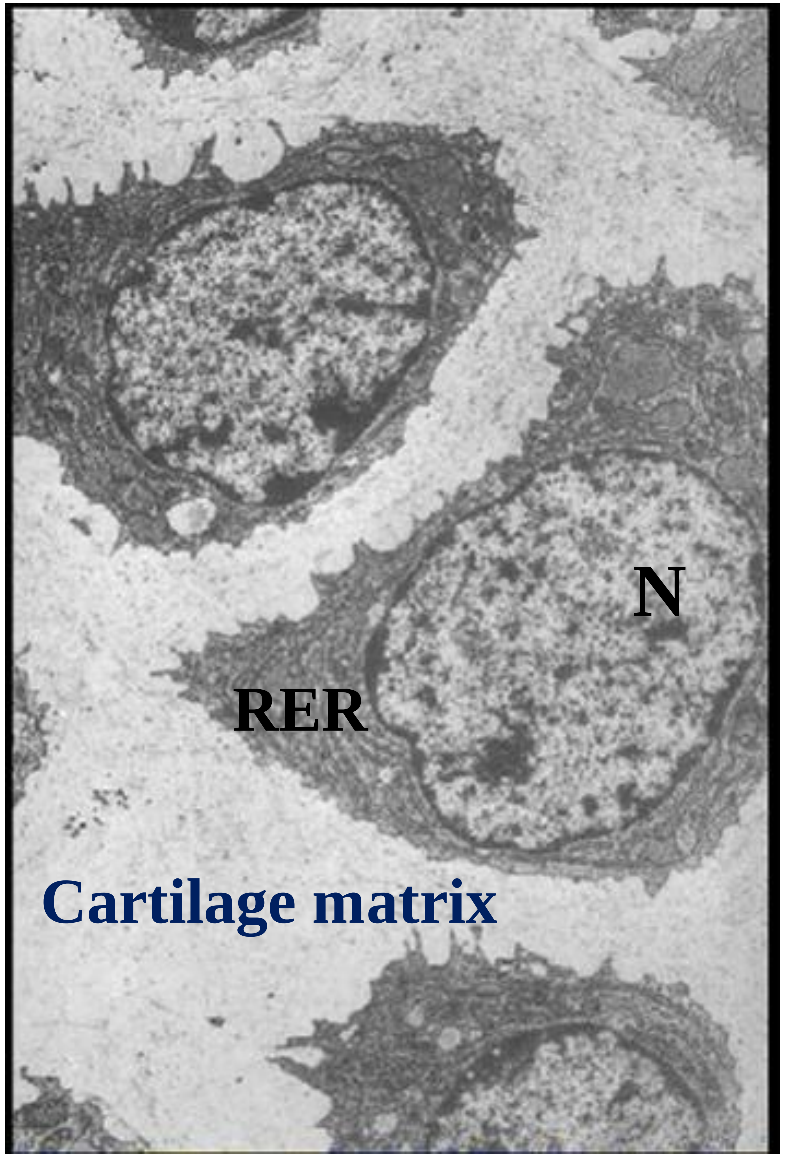
- highly specialized, active cell
- reside in a space called the **lacuna**
- limited potential for replication
- respond to a variety of **stimuli,** including growth factors, mechanical loads, piezoelectric forces, and hydrostatic pressures



Chondrocyte

- Each chondrocyte establishes a specialized microenvironment and is responsible for the turnover of the ECM in its immediate vicinity

- This microenvironment essentially traps the chondrocyte within its own matrix and so prevents any migration to adjacent areas of cartilage

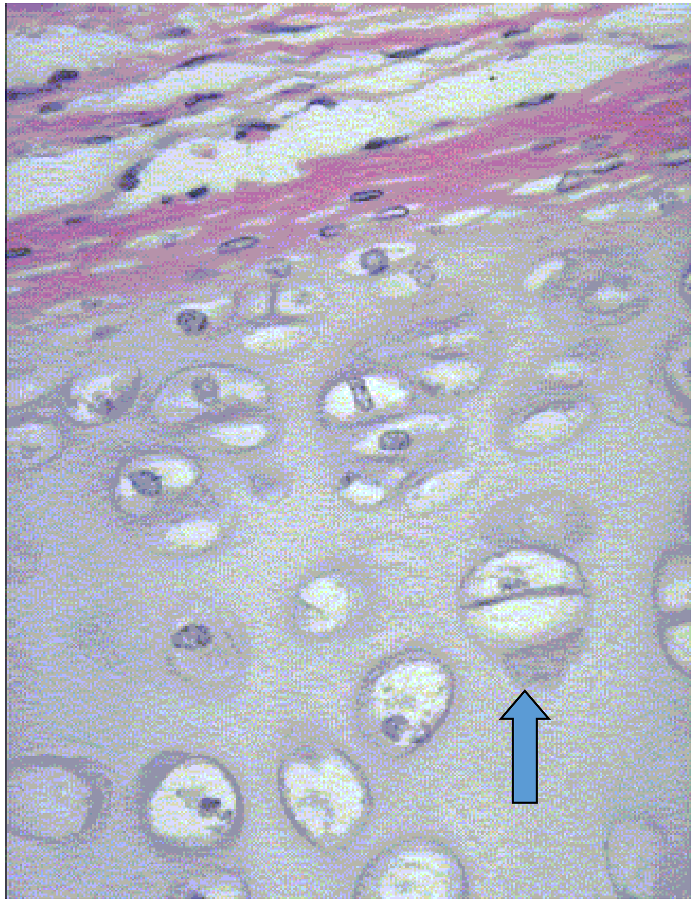


Extracellular matrix

- Provides the rigidity, elasticity, & resilience

- FIBERS
  - **Collagenous and elastic**

- GROUND SUBSTANCE
  - Glycosaminoglycans (chondroitin sulfates, keratin sulfate, hyaluronic acid)
  - Proteoglycans: GAGs + core protein
  - Water



Collagen

Creates a framework that houses the other components of cartilage

Majority is Type II collagen (90-95%)

Minor collagens (I, IV, V, VI, IX, and XI) help to form and stabilize the type II collagen fibril network.

Provides cartilage with its tensile strength

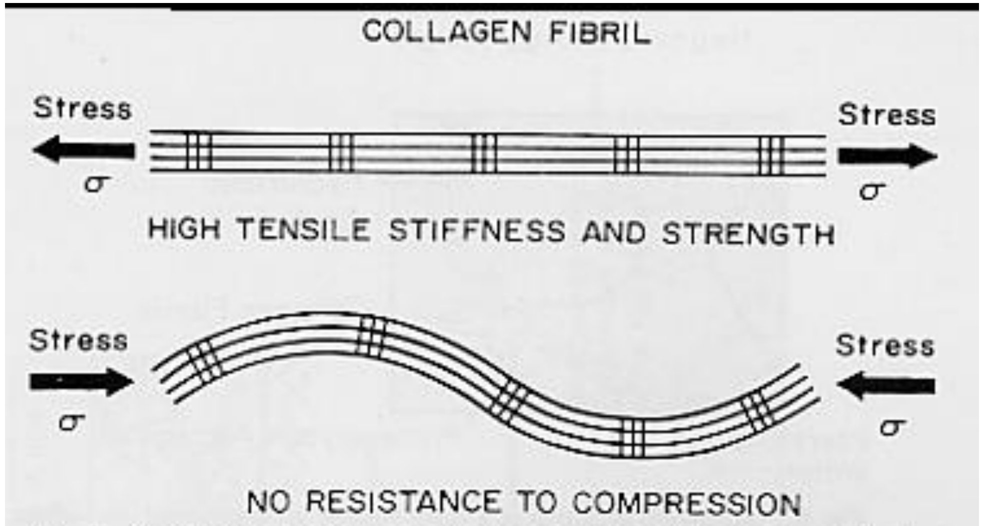
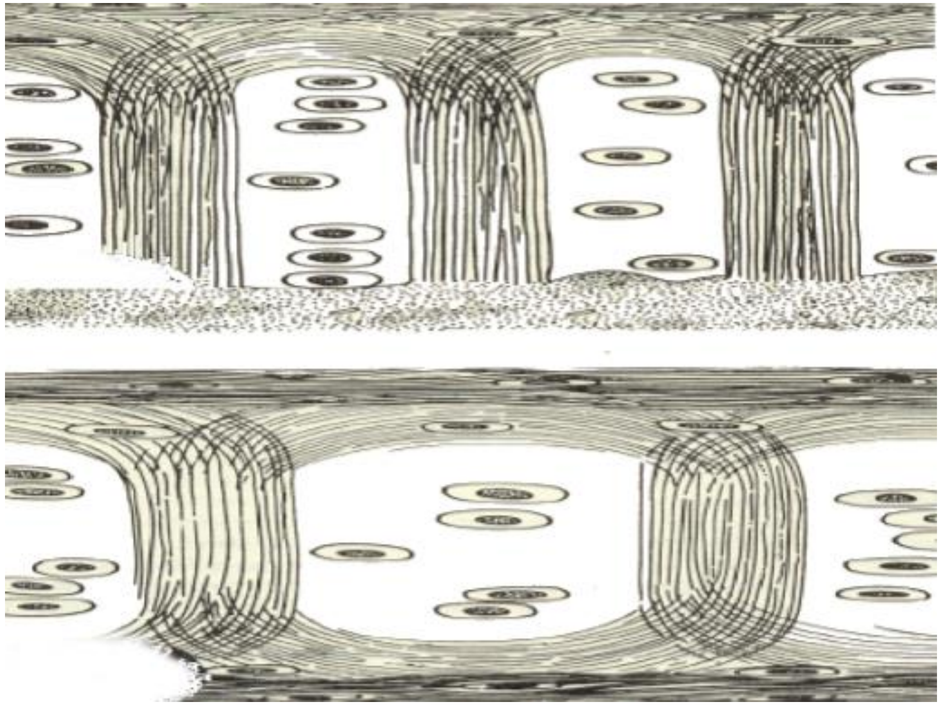
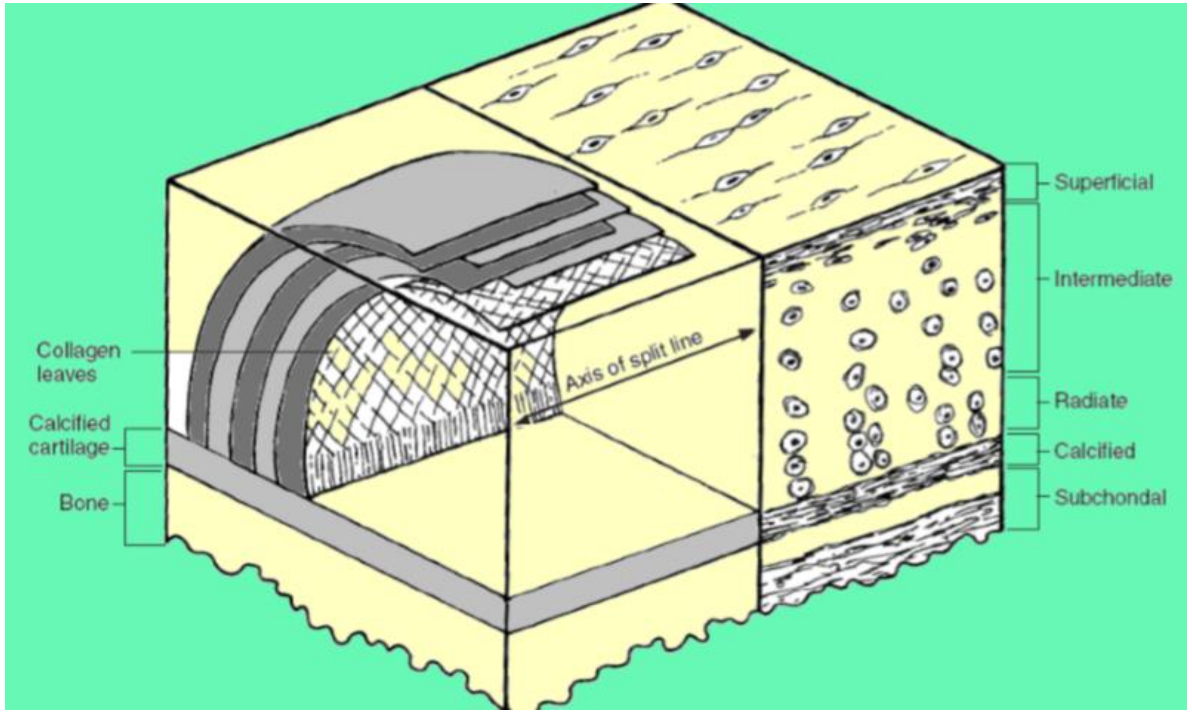


Fig. 8. Schematic representation of collagen fibrils, stiff and strong in tension but weak in compression.

Collagen

Collagen fiber arrangement



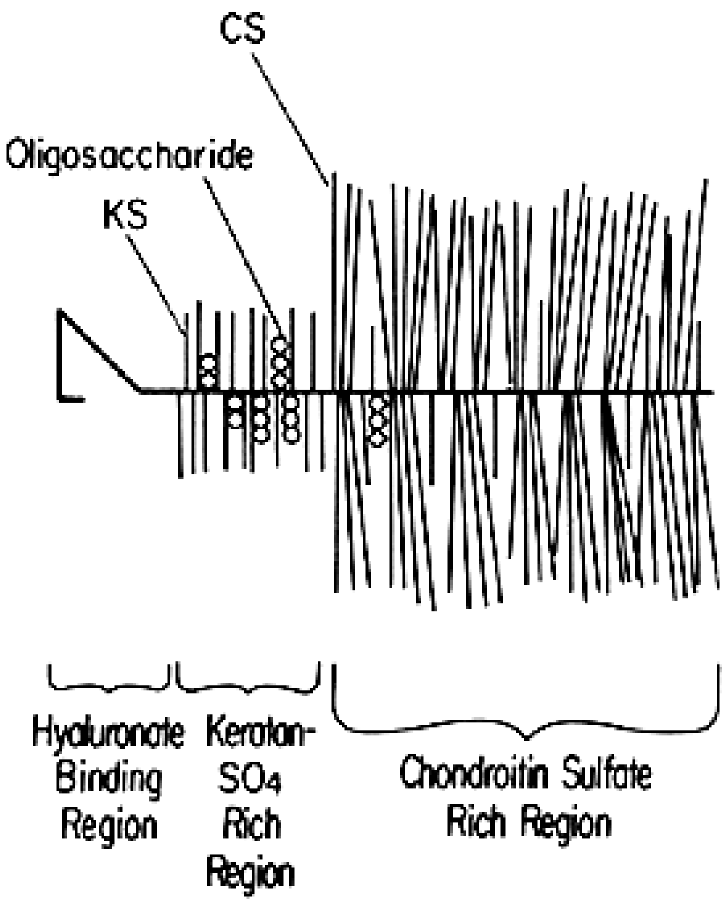


Proteoglycans

heavily glycosolated protein monomers

aggrecan, decorin, biglycan, and fibromodulin

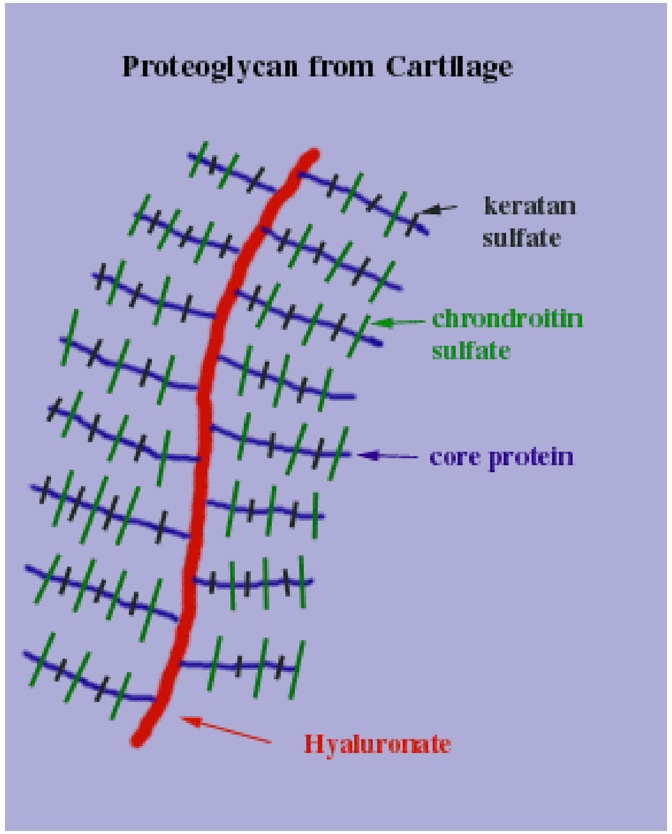
Each subunit consists of a combination of protein and sugar:
Long protein chain
Sugars units attached densely in parallel

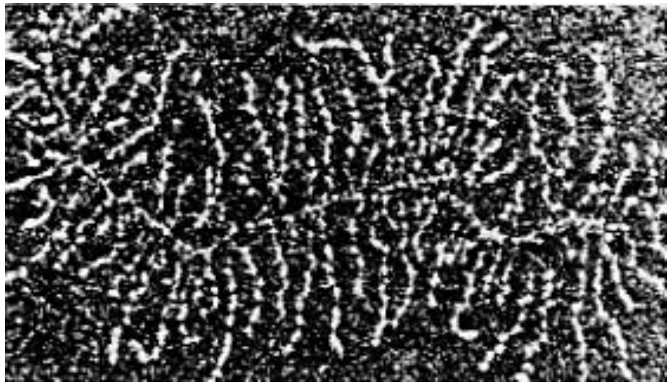


Aggrecanes

Aggrecan is characterized by its ability to interact with hyaluronan (HA) to form large proteoglycan aggregates via link proteins

Aggrecan occupies the interfibrillar space of the cartilage ECM and provides cartilage with its **osmotic properties**, which are critical to its ability to resist compressive loads.





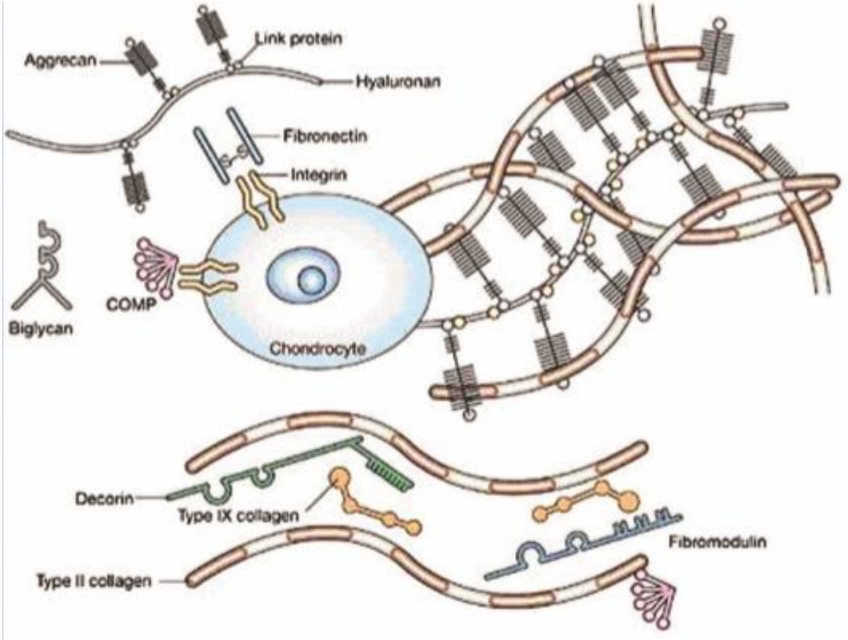
Non-aggregating proteoglycans

- interact with collagen.

- differ in glycosaminoglycan composition and function

- Decorin and fibromodulin interact with type II collagen fibrils in the matrix and play a role in fibrillogenesis and interfibril interactions

- Biglycan is mainly found in the immediate surrounding of the chondrocytes, where they may interact with collagen VI



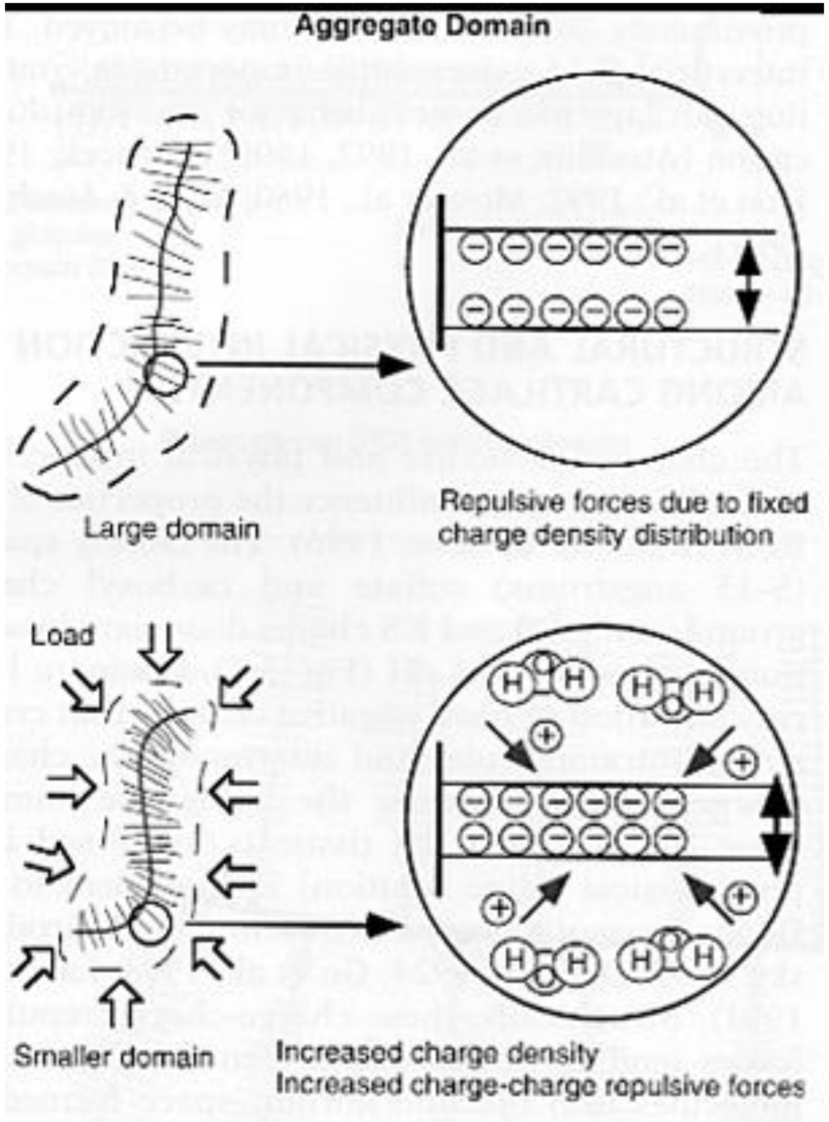
Proteoglycans

Each sugar has one or two negative charges, so collectively there is an enormous repulsive force within each subunit and between neighboring subunits
This causes the molecule to **extend stiffly** out in space

This gives articular cartilage its resiliency to compression

The negative charges make the molecules extremely hydrophilic and cause water to be trapped within. It is used during biomechanical or lubricant activity.

This water functions acts are "shock absorbers“, lubricates and nourishes the cartilage



Cartilage zones

- (10-20%) CF packed tightly & aligned parallel.

  High number of flattened chondrocytes

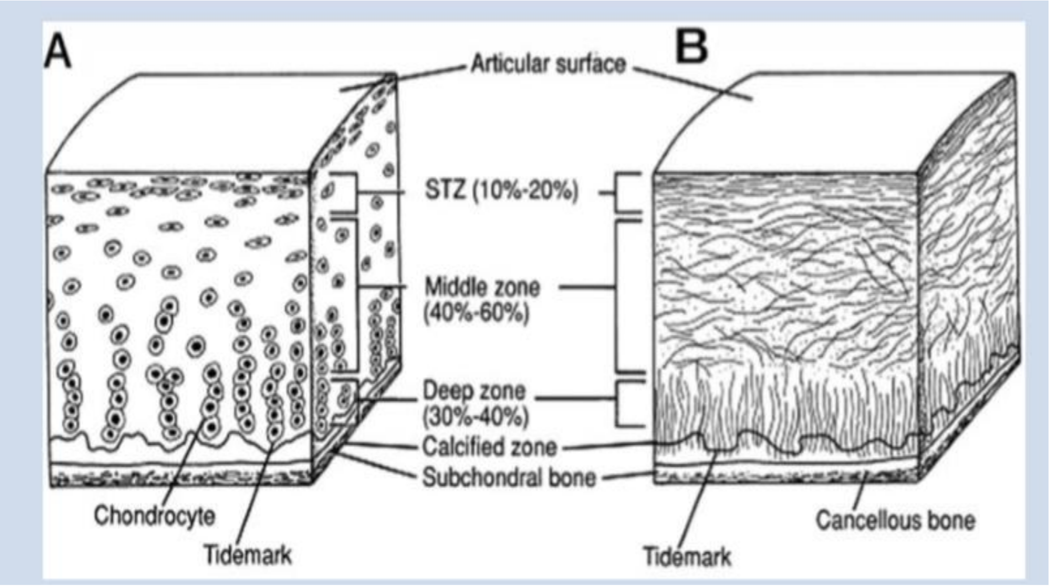
- (40%-60%) thicker CF organized obliquely.

  The chondrocytes are spherical and at low density

- (30%) CF in a radial disposition.

  Chondrocytes in columnar orientation

- The calcified layer secures the cartilage to bone

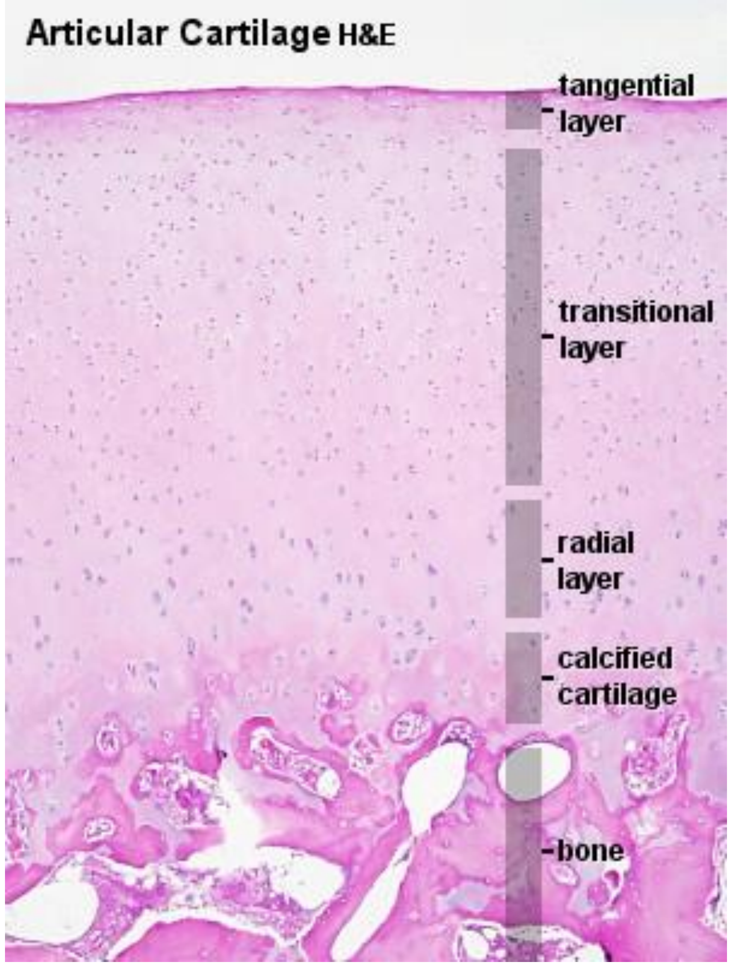


Cartilage zones - biomechanics

Tangential: most of the tensile properties of cartilage, which enable it to resist the sheer, tensile, and compressive forces imposed by articulation

Transitional: is the first line of resistance to compressive forces

Deep zone: providing the greatest resistance to compressive forces, given that collagen fibrils are arranged perpendicular to the articular surface



Regions of pericellular matrix

Pericellular matrix: mainly proteoglycans, glycoproteins & other noncollagenous proteins

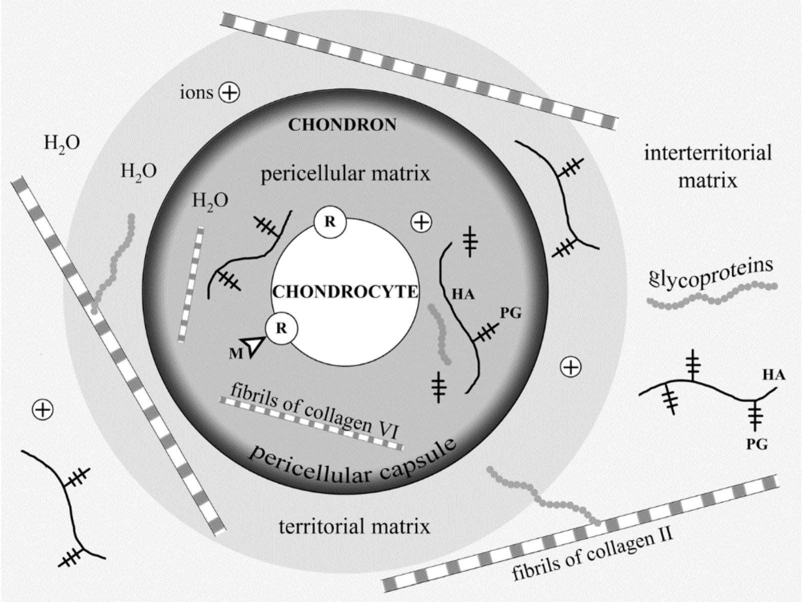
- initiate **signal transduction** within cartilage with load bearing

Territorial matrix: mostly fine collagen fibrils, forming a basketlike network.

- may protect the cartilage cells against mechanical stresses and may contribute to its ability to withstand substantial loads.

Interterritorial matrix: is the largest with randomly oriented bundles of large collagen fibrils.

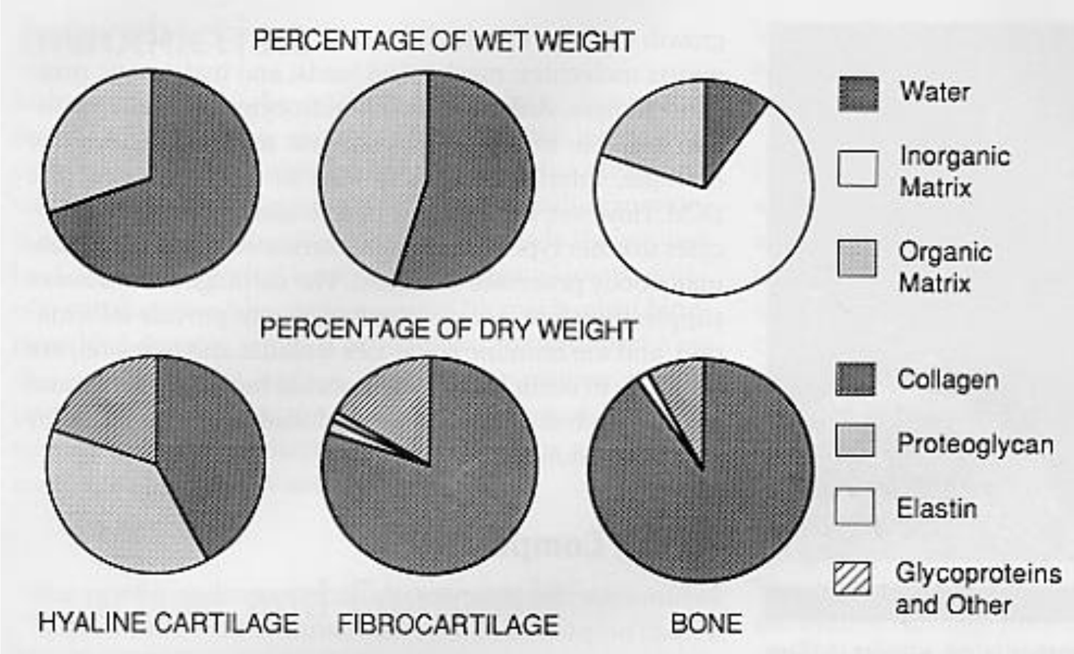
- contributes most to the biomechanical properties of articular cartilage



Water proportion

Note that articular (hyaline) cartilage has the highest proportion of water and also the highest proteoglycan content

It is the combination of the frictional resistance to water flow and the pressurization of water within the matrix that forms the 2 basic mechanisms by which articular cartilage derives its ability to withstand significant loads

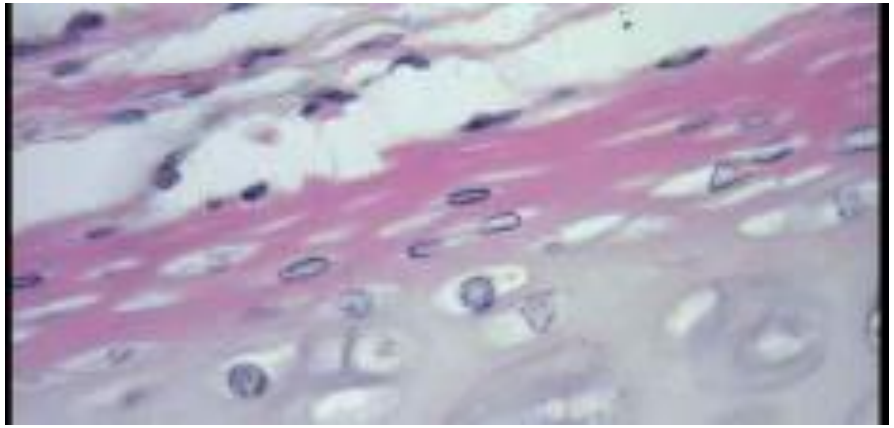


Cartilage growth

Appositional

Increasing in **width**

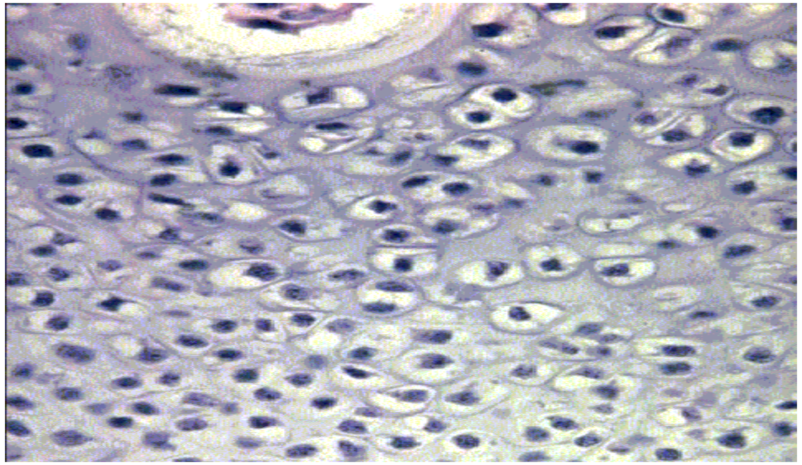
chondroblasts deposit matrix on surface of pre-existing cartilage



Interstitial

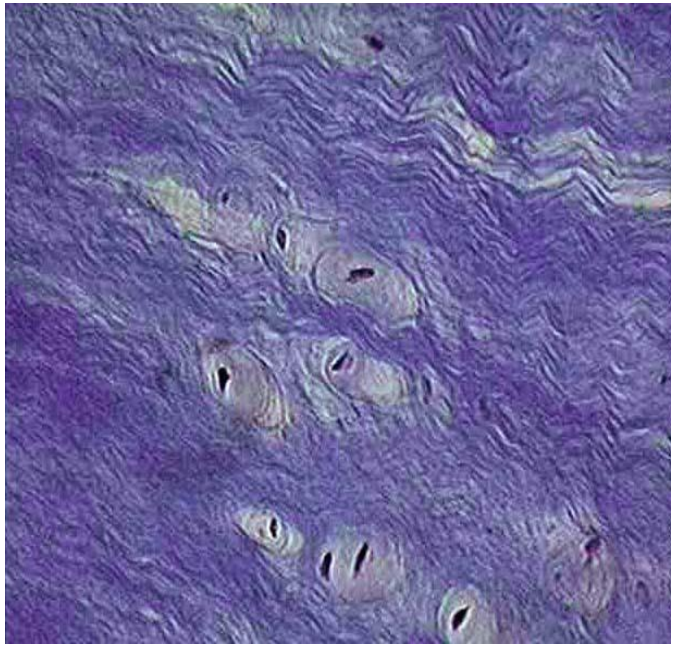
Increasing in **length**

chondrocytes divide and secrete matrix from w/in lacunae

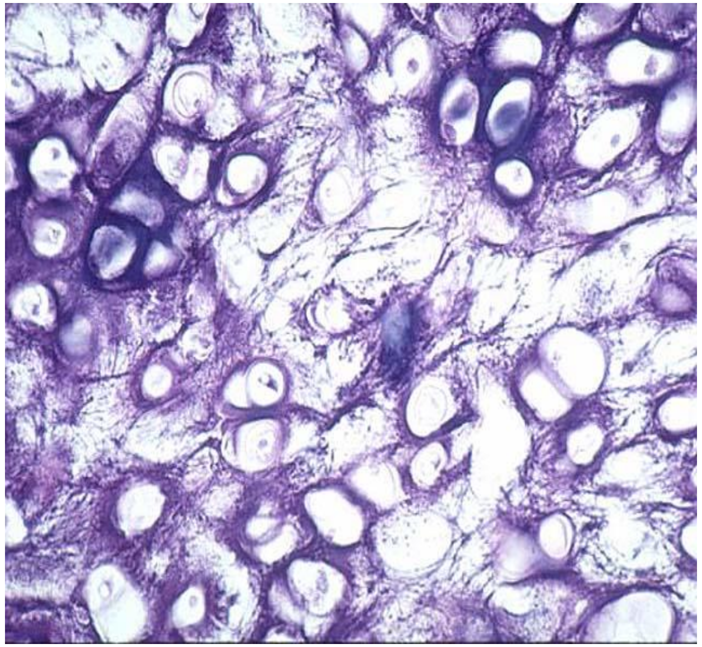


Types of cartilage

Hyaloid

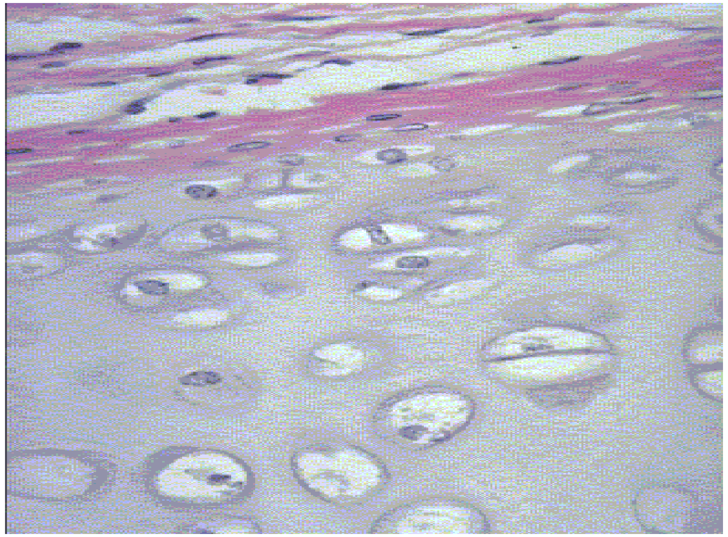


Elastic

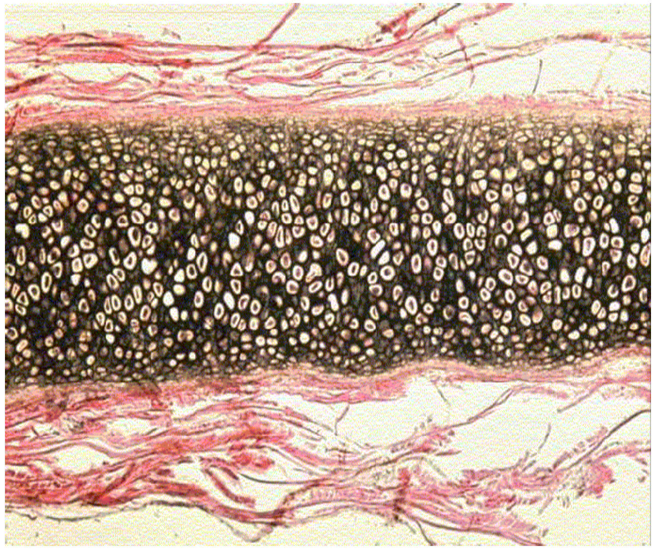


Fibrous

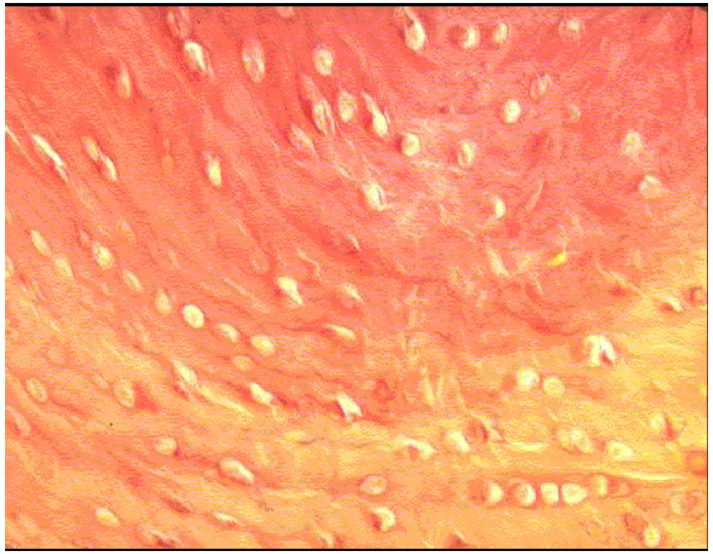
Types of cartilage



Hyaloid



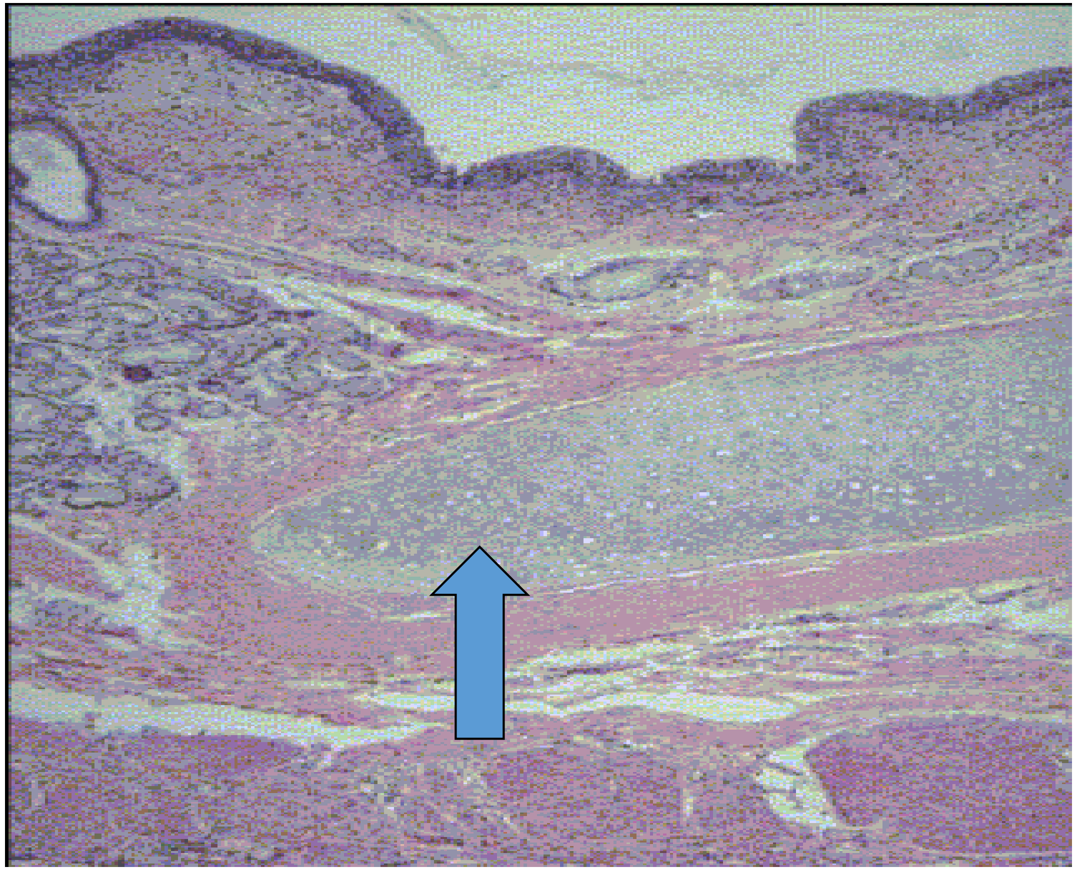
Elastic



Fibrous

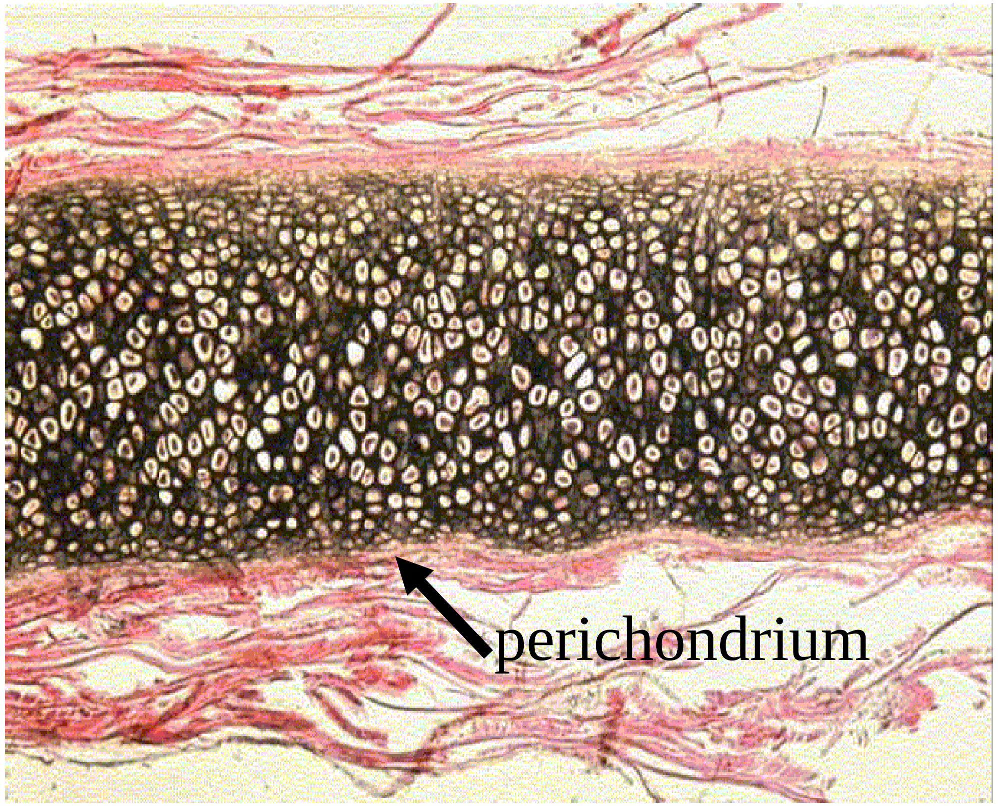
Hyaline cartilage

- FUNCTION
  - Support tissue and organs
  - Model for bone development
- MATRIX
  - **Type II collagen** (thin fibrils)
  - Chondroitin sulfate, keratin sulfate, hyaluronic acid
  - Water
- LOCATION
  - Tracheal rings, nasal septum, larynx, articular surfaces of joints



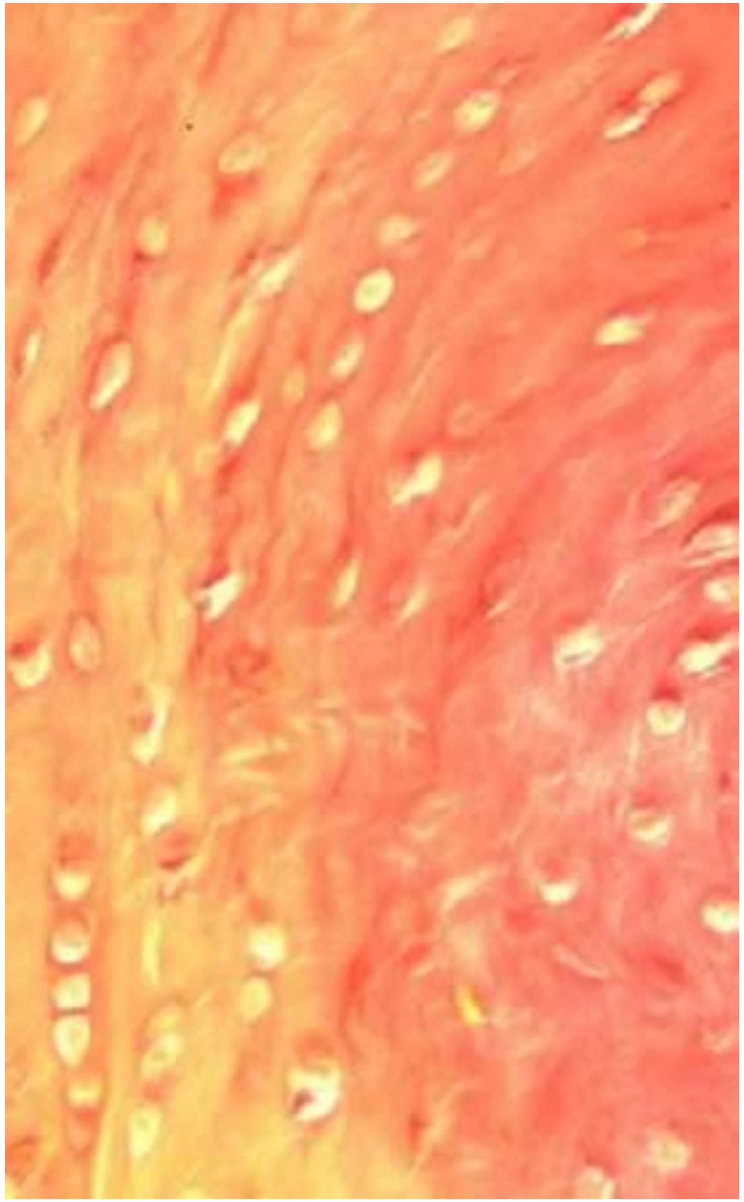
Elastic cartilage

- FUNCTION
  - Support with **flexibility**
- MATRIX
  - Normal components of hyaline matrix plus **elastic** fibers
- LOCATION
  - External ear, external auditory canal, epiglottis



Fibrous cartilage

- FUNCTION
  - Support with great tensile strength
- MATRIX
  - **Type I collagen** - Oriented parallel to stress plane
- LOCATION
  - Intervertebral disks, pubic symphysis



Basic biomechanics of cartilage

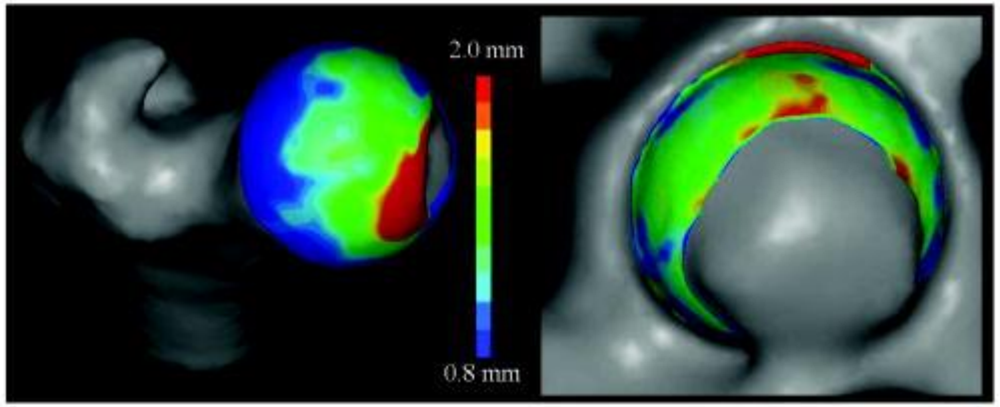
Biomechanical **definition**: porous, viscoelastic material with 2 principal phases:
- solid phase: collagen (mainly type II)
- fluid phase: water, normally G 80% by wet weight)
  (ion phase: Na+, Ca++, Clj, (1% by wet weight))

Functions

wear resistance,

load bearing,

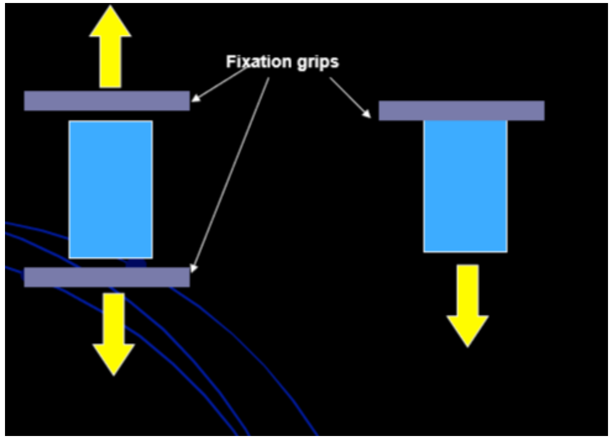
shock absorption



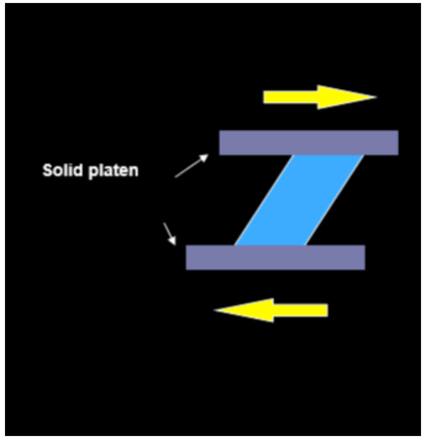
compressive stresses are as high as 20 MPa in the hip, which is approximately 3000 lb per square inch

Basic biomechanics of cartilage

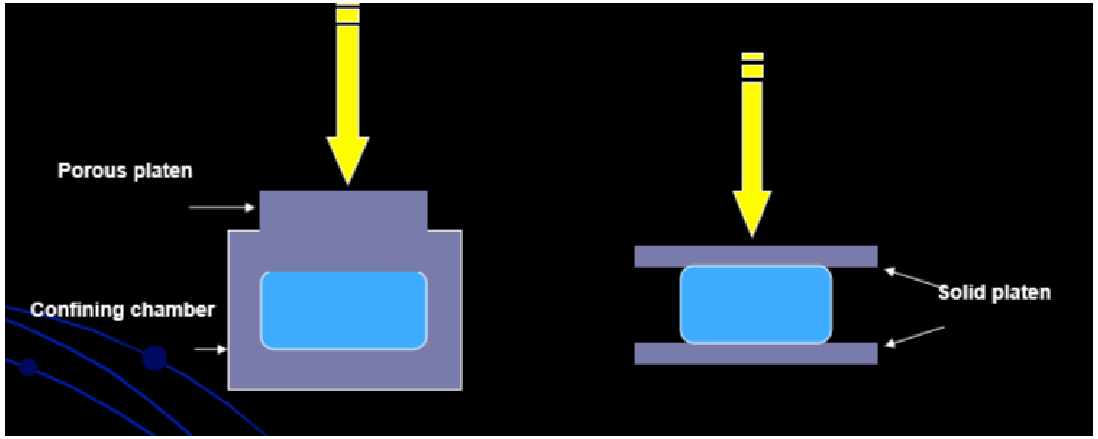
Tension



Shear



Compression



Viscoelastic, nonlinear, inhomogeneous, anisotropic

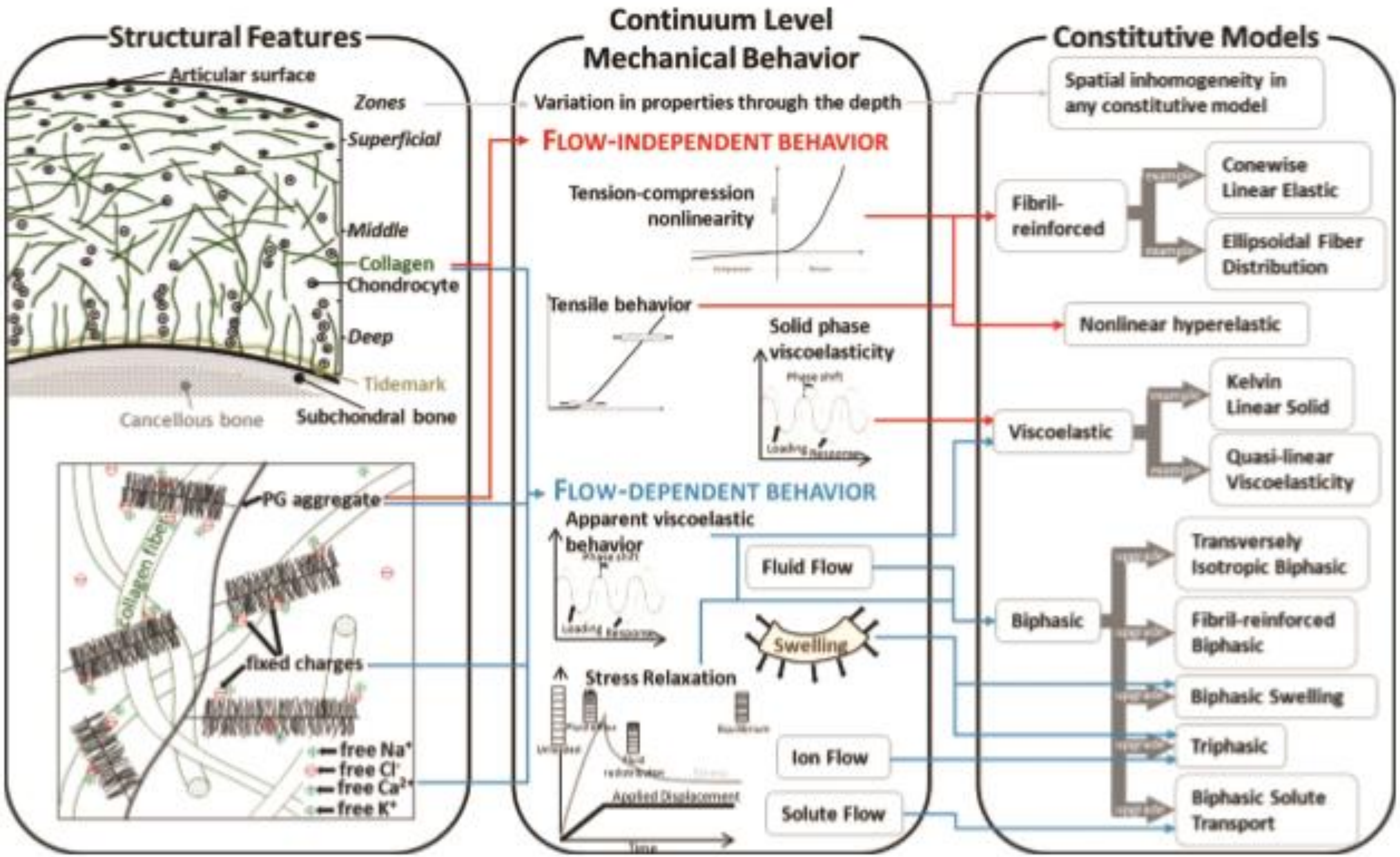
Problems in cartilage models

Complex material behavior

Structure and composition vary with depth

Material properties also vary with depth

Material behavior varies within the same joint,
and spatially within each joint within each part



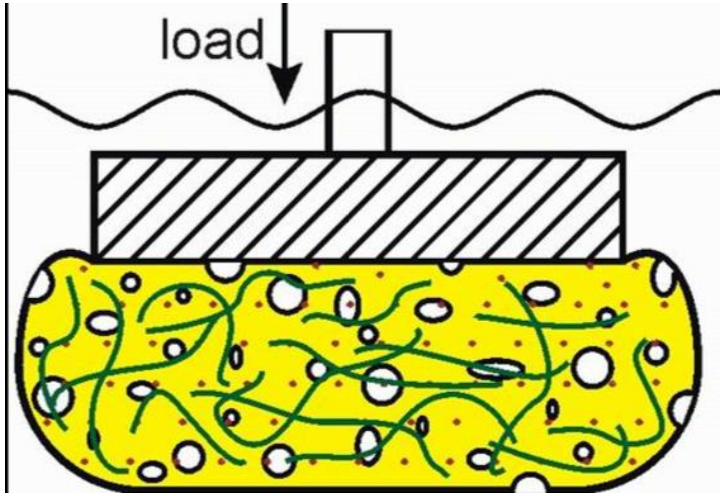
Structural Features
Articular surface
Zones
Superficial
Middle
Collagen
Chondrocyte
Deep
Tidemark
Cancellous bone
Subchondral bone
Collagen fiber
PG aggregate
fixed charges
free Na+
free Cl-
free Ca2+
free K+
Continuum Level Mechanical Behavior
Variation in properties through the depth
FLOW-INDEPENDENT BEHAVIOR
Tension-compression nonlinearity
Tensile behavior
Solid phase viscoelasticity
Phase shift
Loading
Response
FLOW-DEPENDENT BEHAVIOR
Apparent viscoelastic behavior
Phase shift
Loading
Response
Fluid Flow
Swelling
Stress Relaxation
Applied Displacement
Time
Ion Flow
Solute Flow
Constitutive Models
Spatial inhomogeneity in any constitutive model
Fibril-reinforced
Conewise Linear Elastic
Ellipsoidal Fiber Distribution
Nonlinear hyperelastic
Viscoelastic
Kelvin Linear Solid
Quasi-linear Viscoelasticity
Biphasic
Transversely Isotropic Biphasic
Fibril-reinforced Biphasic
Biphasic Swelling
Triphasic
Biphasic Solute Transport

Viscoelasticity

Time-dependent behavior when subjected to a constant load or deformation. Two types of mechanisms are responsible for viscoelasticity:

flow dependent (biphasic): the frictional drag force of interstitial fluid flow through the porous solid matrix (water is forces out of the tissue like a sponge = volume changes)

flow independent: is caused by macromolecular motion— specifically, the intrinsic viscoelastic behavior of the collagen-proteoglycan matrix As a result, the fluid pressure provides a significant component of total load support (No volume changes)



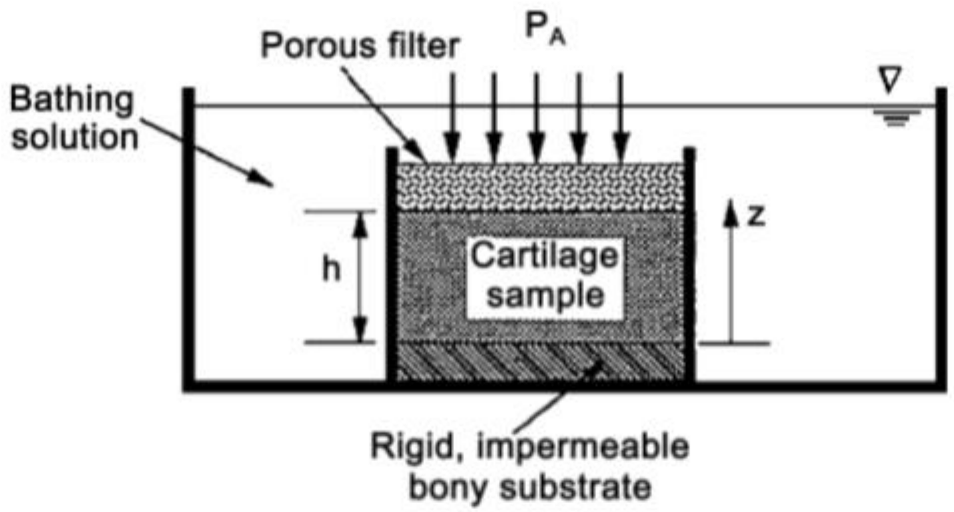
Fluid flow and biphasic theory

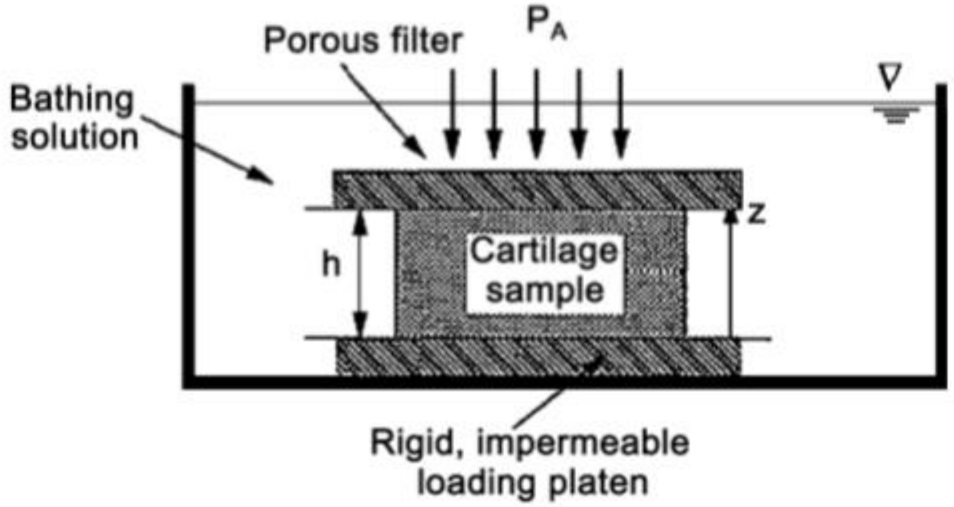
Volumetric change under compression

Flow or **extrusion** of the interstitial fluid

The fluid passing through the porous solid matrix generates very high frictional resistance

The low permeability of articular cartilage prevents fluid from being quickly squeezed out of the matrix

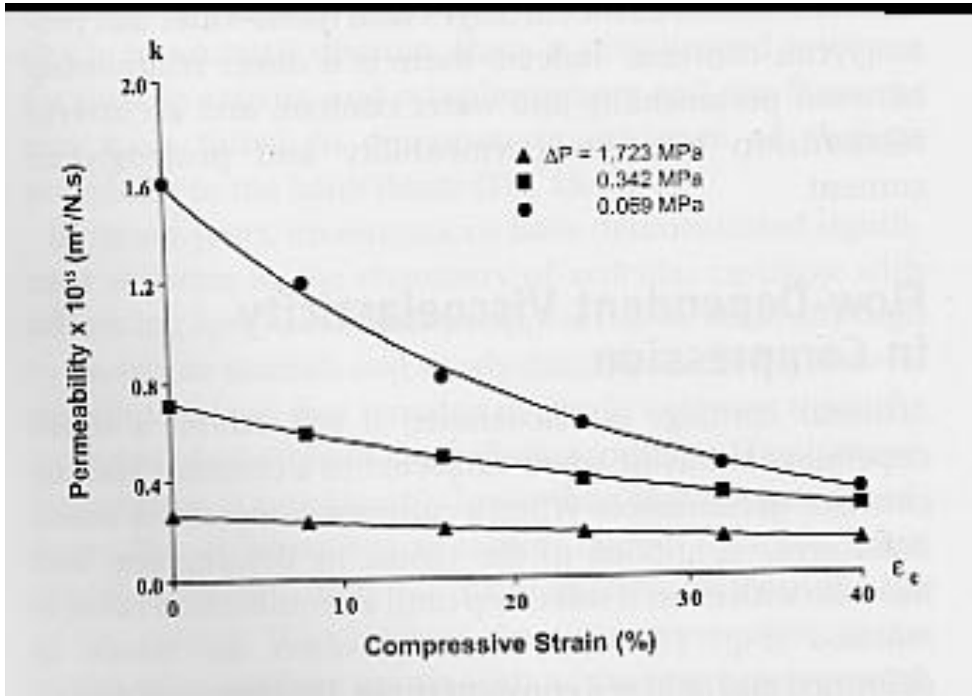




Permeability

Articular cartilage shows nonlinear strain dependence and pressure dependence

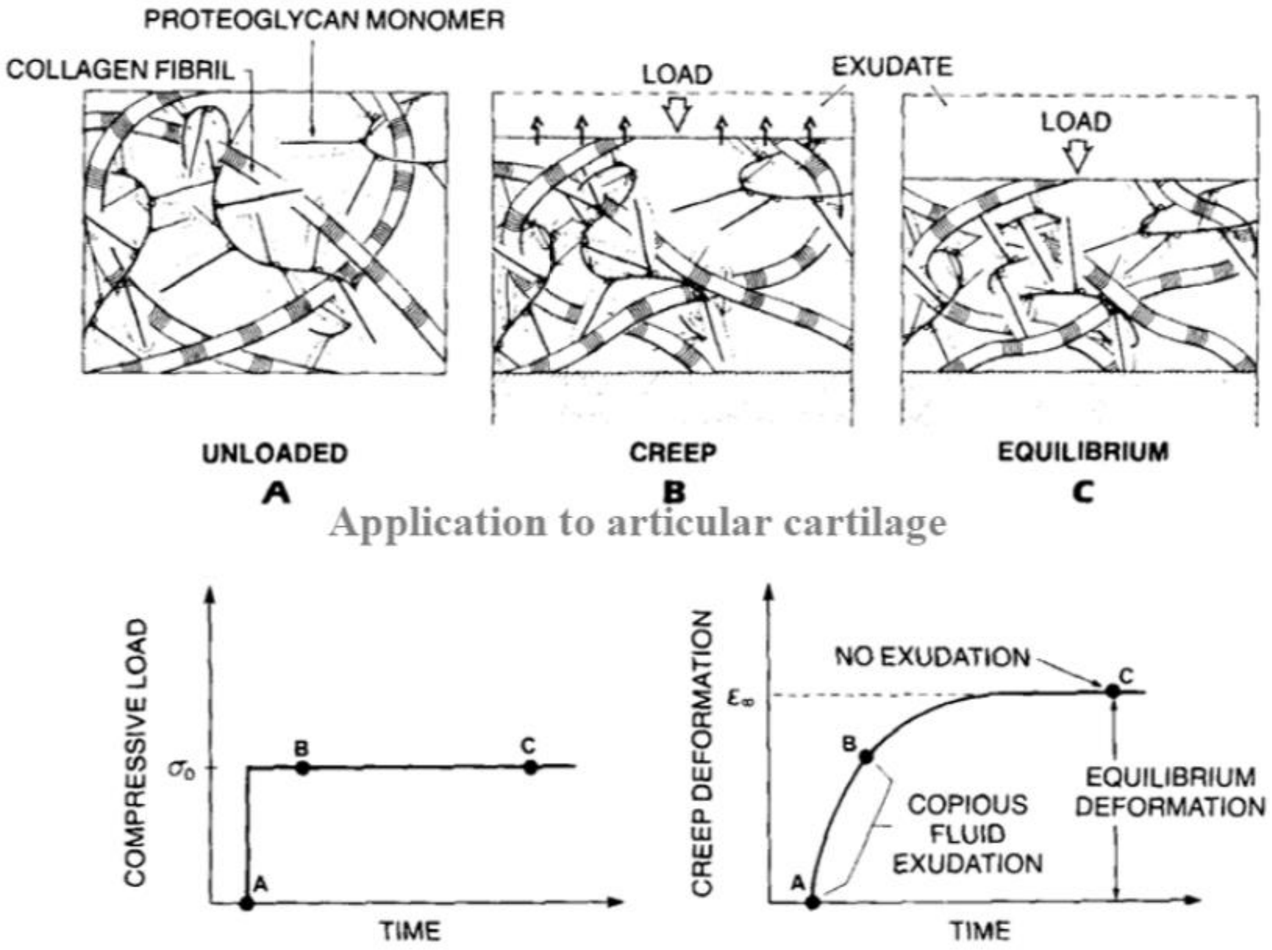
The decrease of permeability with compression acts to **retard rapid loss** of interstitial fluid during high joint loadings



Compression force

Confined compression test

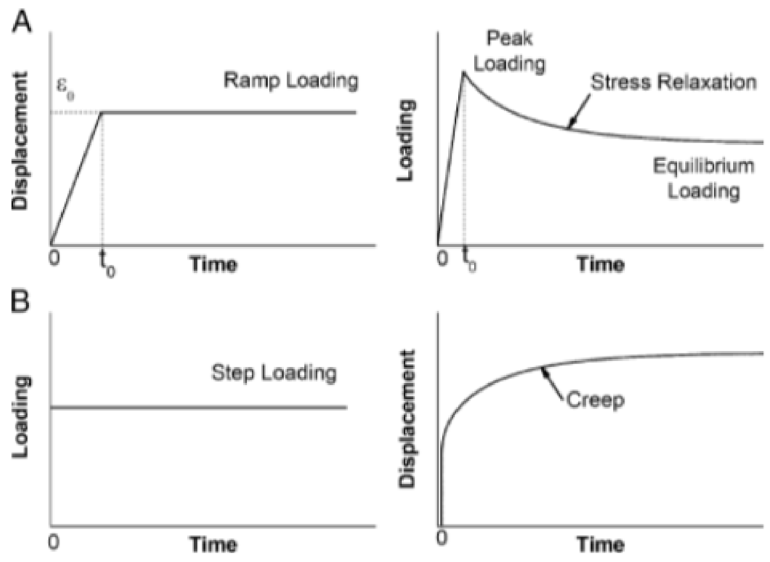
Copious exudation of fluid at start but the rate of exudation decreases over time from points A to B to C



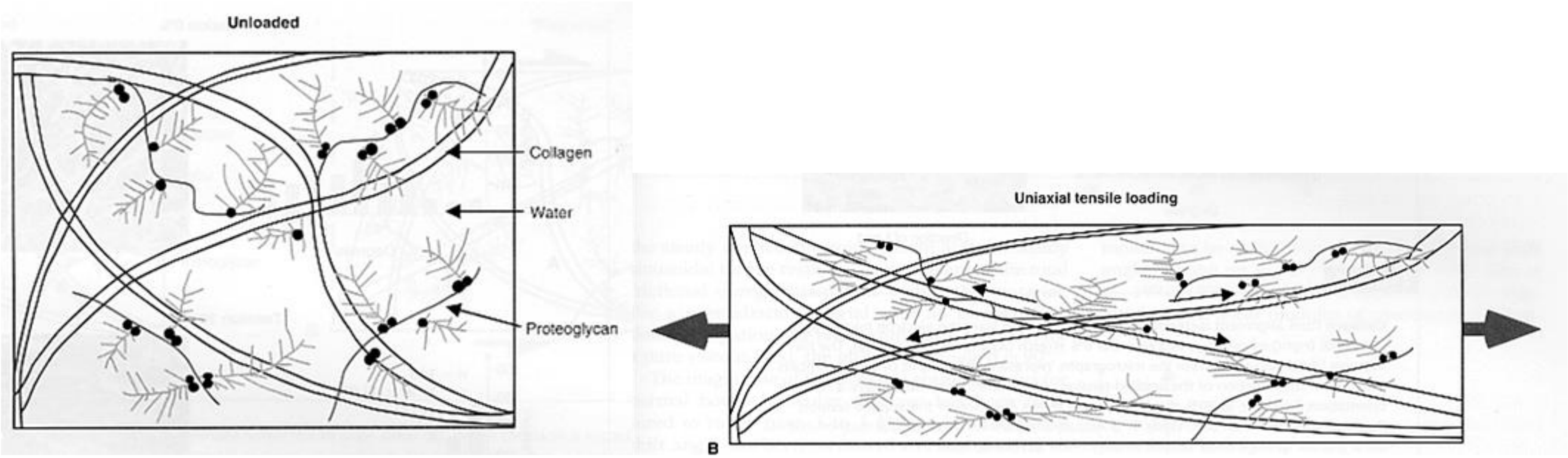
Creep behavior & stress-relaxation

In a stress-relaxation test, a displacement is applied on the tissue at a constant rate until a desired level of compression is reached. This displacement results in a force rise followed by a period of stress relaxation until an equilibrium force value is reached.

B, In a creep test, a step force is suddenly applied (stepwise) onto cartilage results in a transient increase in deformation (i.e., creep).



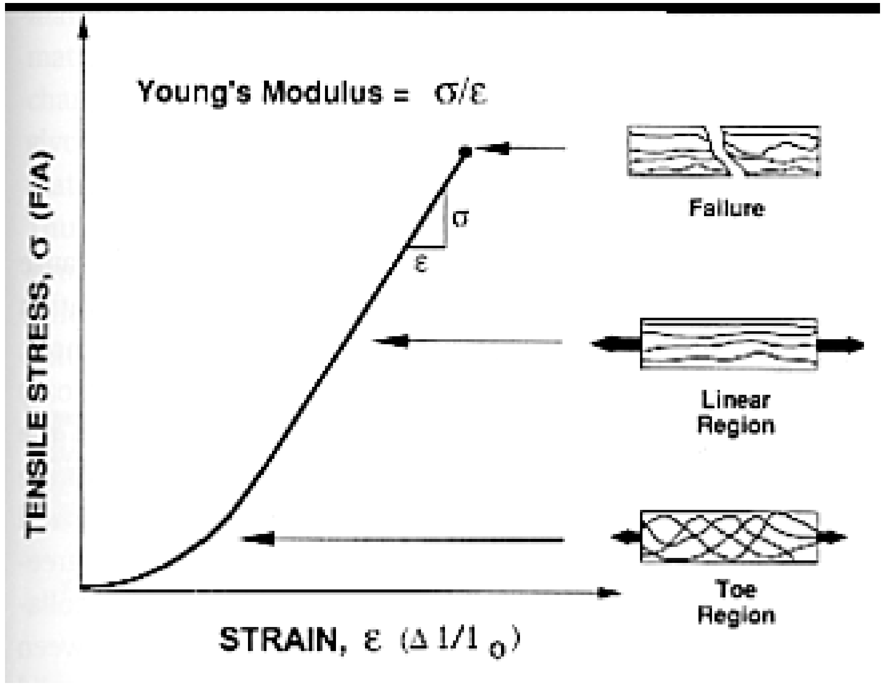
Tensile Force



- Toe region: collagen fibrils straighten out and un- “crimp”

- Linear region that parallels the tensile strength of collagen fibrils: collagen aligns with axis of tension

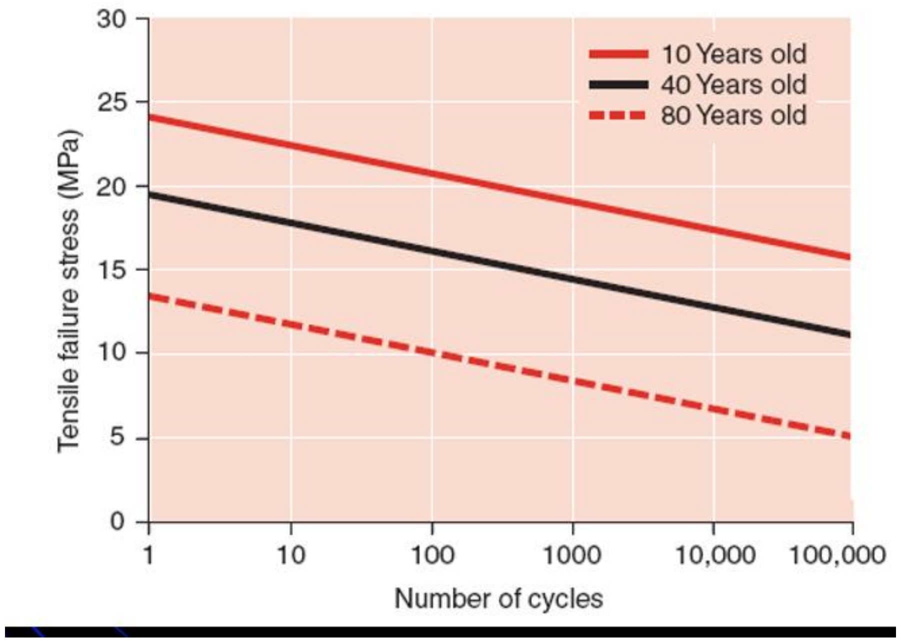
- Failure region



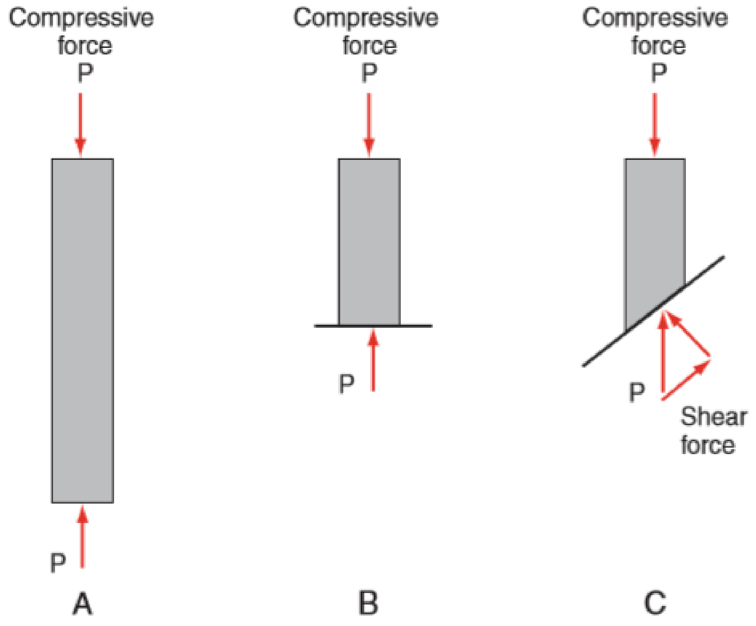
Tensile strength of cartilage

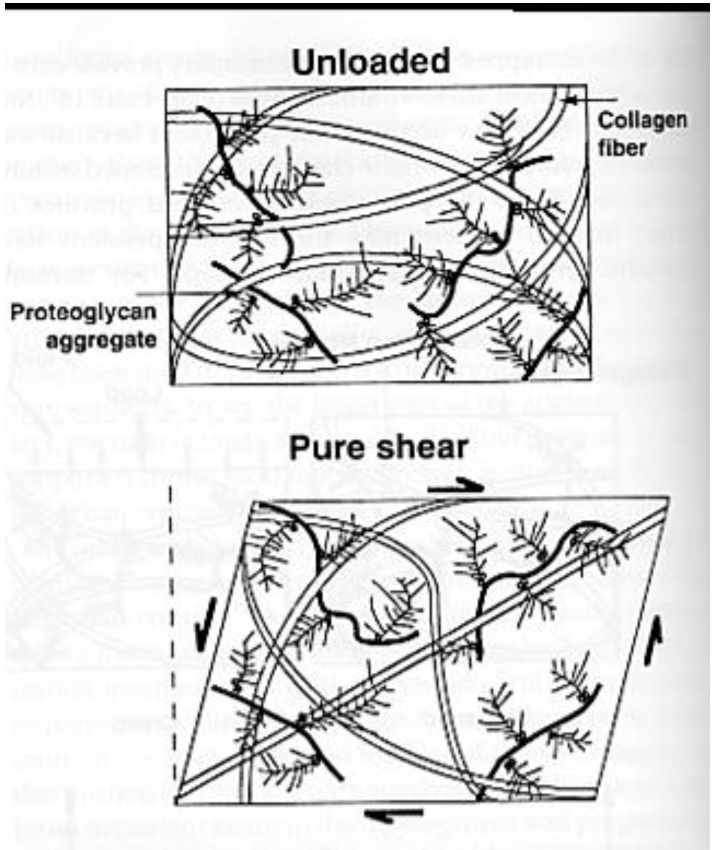
As the tensile loading stress increases, fewer cycles of loading are needed to cause failure.

Cartilage from older individuals fails at a lower stress than that from younger people.



Shear Force



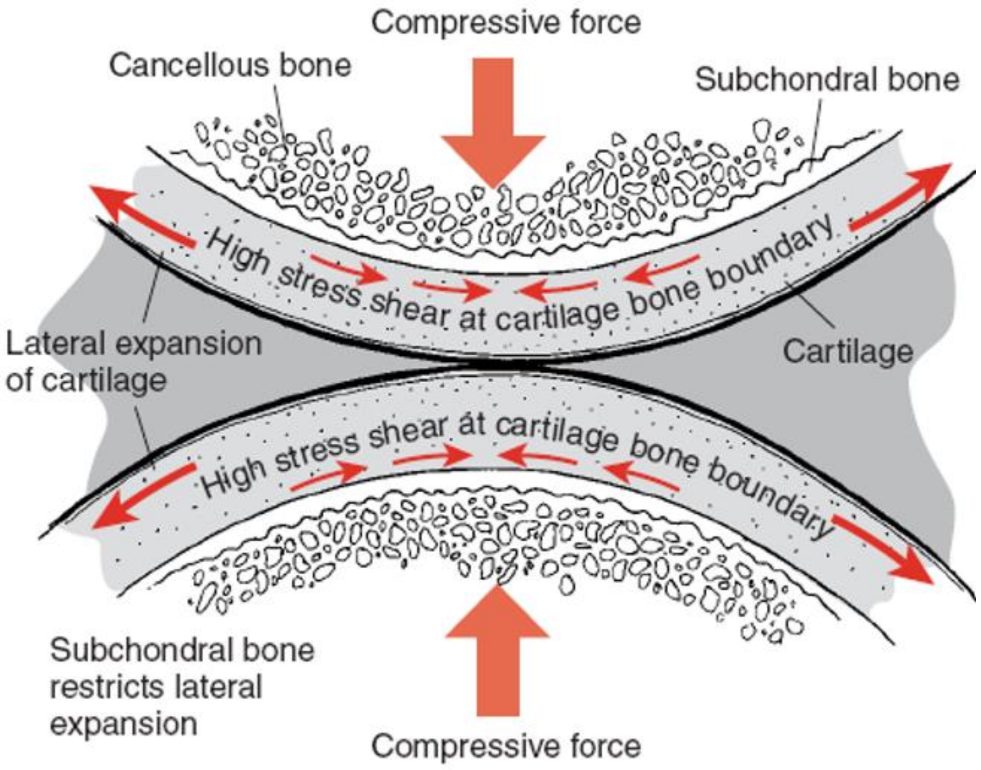


The component parallel to the cut is a shear force that gives rise to a shear stress on the inclined surface.

Shear Force

Under impulsive compressive loads, the cartilage experiences a relatively large lateral displacement due to its high Poisson's ratio.

This expansion is restrained by the much stiffer subchondral bone, causing a high shear stress at the cartilage bone interface.



Conclusions

Articular cartilage provides an efficient load- bearing surface for synovial joints

The mechanical behavior of this tissue depends on the interaction of its fluid and solid components.

Each phase (the charged solid matrix, water and ions) of the cartilage contributes to its compressive, tensile and transport behaviors

The biphasic mixture theory has been successfully used to describe the flow-dependent and flow-independent viscoe-lastic behavior

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Multiscale Mechanics of Articular Cartilage: Potentials and Challenges of Coupling Musculoskeletal, Joint, and Microscale Computational Models

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