ME 482 Experimental Tissue Mechanics

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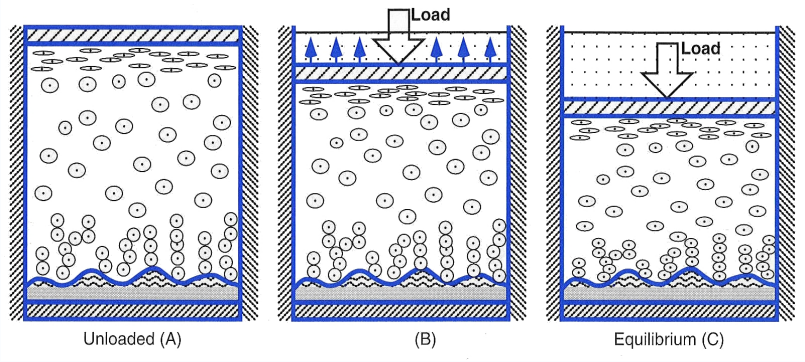
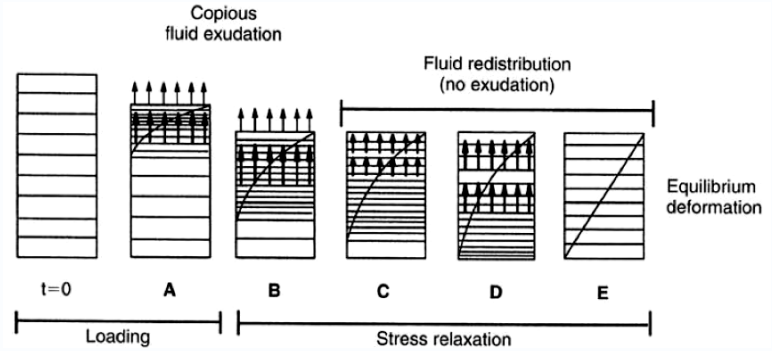
9/12/16 and 9/14/16

Contributions to mechanical behavior of cartilage

Note that a lot of work was done on the board for this lecture.

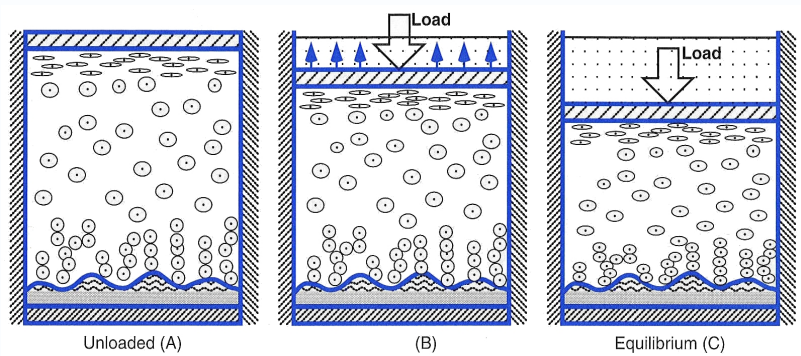




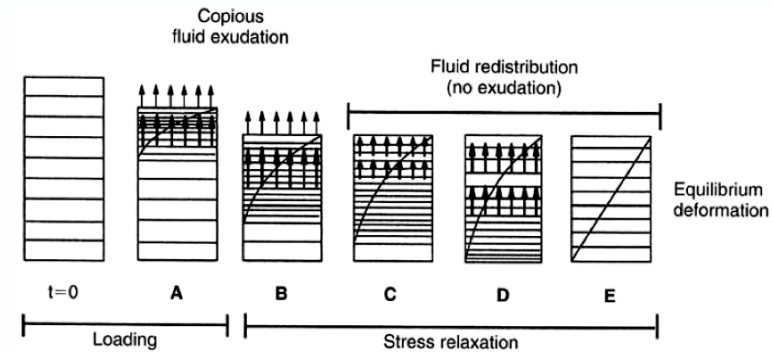
Nordin and frenkel

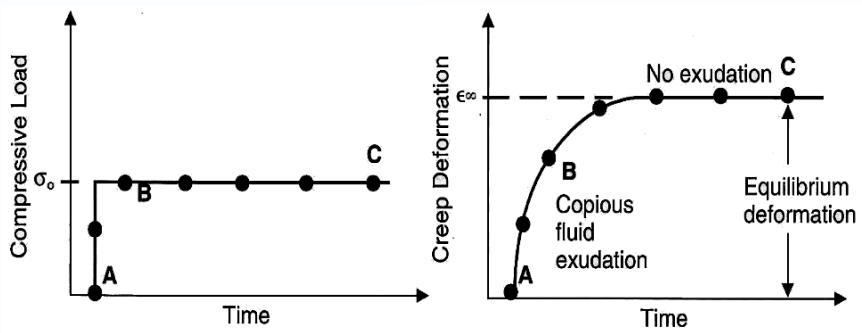
Compressive modulus of solid matrix, called the Aggregate modulus, H_A, can be determined 2 ways

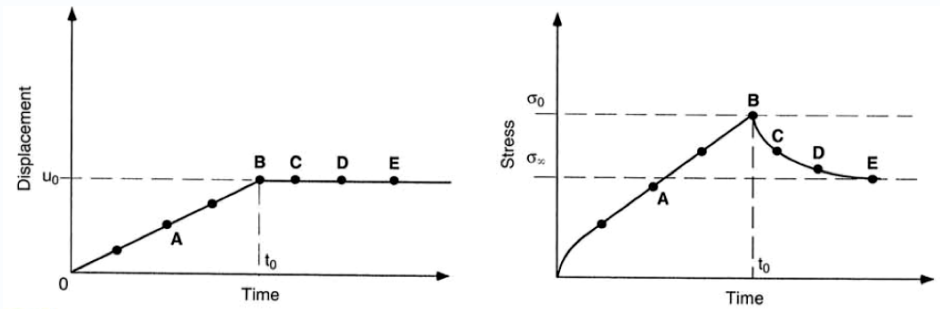
1. Creep experiments



2. Stress relaxation experiments







Nordin & Frenkel

Compressive properties of articular cartilage depend mostly on:

1. Fraction of solid and fluid phases (no need for explanation)
2. Characteristics of the solid phases
   a. Intrinsic stiffness of the solid phases (H_A~0.5-1MPa) – already discussed
   b. Fluid pressurization/osmotic pressure (~0.25 MPa), depends in part on charge density of PGs)
   c. Coll/PG interactions (i.e. ability of collagen to resist swelling of PGs)
   d. Permeability (resistance to fluid flow) – *all on board*

Interaction of PGs and water contribute to compressive load carrying capacity of cartilage by *fluid pressurization*

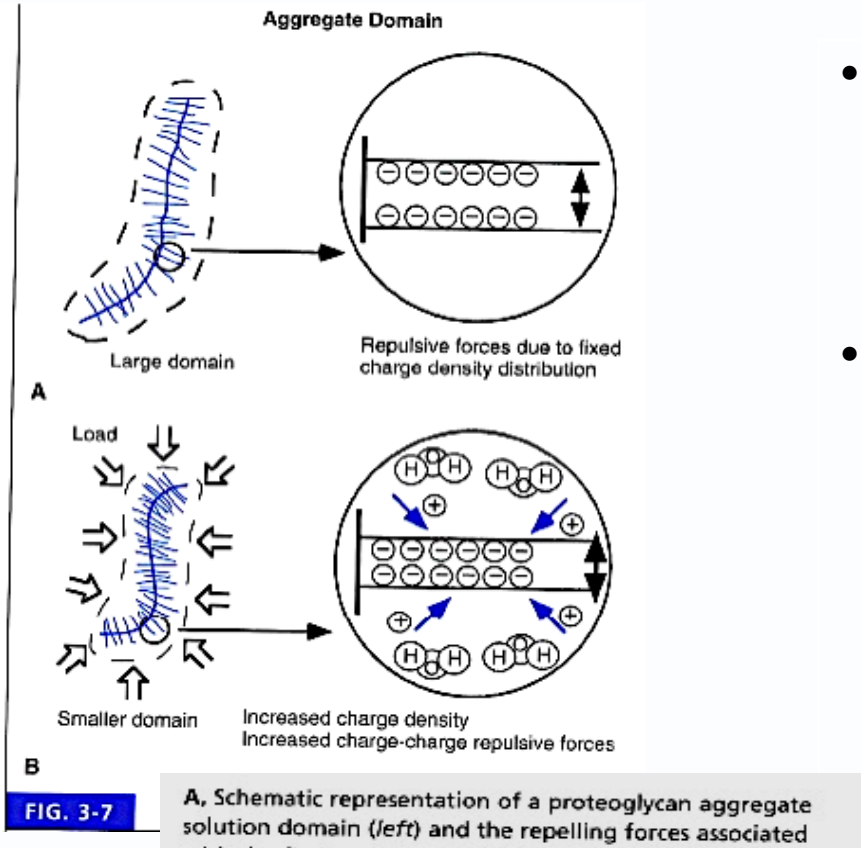
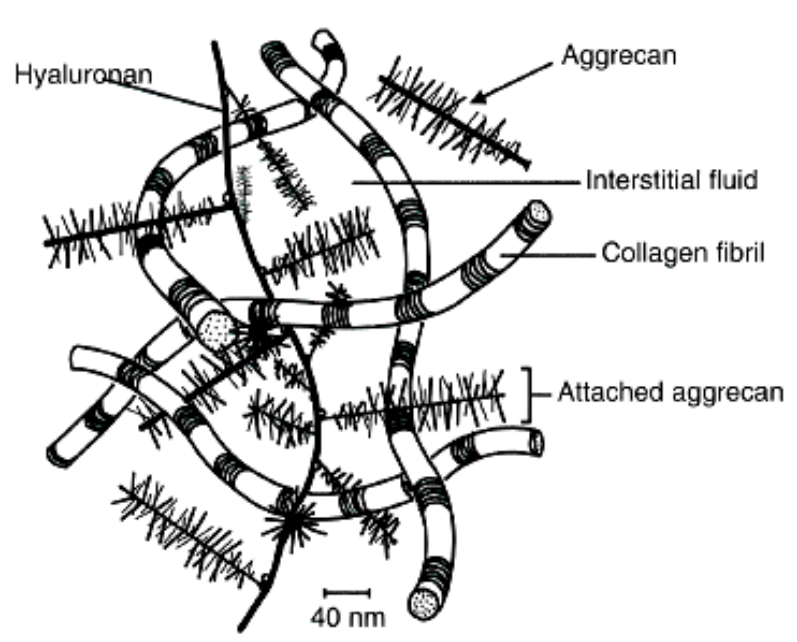


FIG. 3-7

A, Schematic representation of a proteoglycan aggregate solution domain (*left*) and the repelling forces associated with the fixed negative charge groups on the GAGs of aggrecan (*right*). These repulsive forces cause the aggregate to assume a stiffly extended conformation, occupying a large solution domain. B, Applied compressive stress decreases the aggregate solution domain (*left*), which in turn increases the charge density and thus the intermolecular charge repulsive forces (*right*).

- PGs have high negative charge density – high repulsive forces
  - Negative charge
  - Closely bound
- Contributes to an internal fluid pressure called the Donnan osmotic swelling pressure
  - To maintain electroneutrality, charge is balanced by positive ions and water (Na+, Ca2+)
  - The influx causes the PG to swell
  - Osmotic pressure ~0.25 MPa (compressive stiffness of ECM ~0.5-1MPa)

Osmotic swelling pressure is balanced by the tensile resistance from the collagen network (Coll/PG interactions)

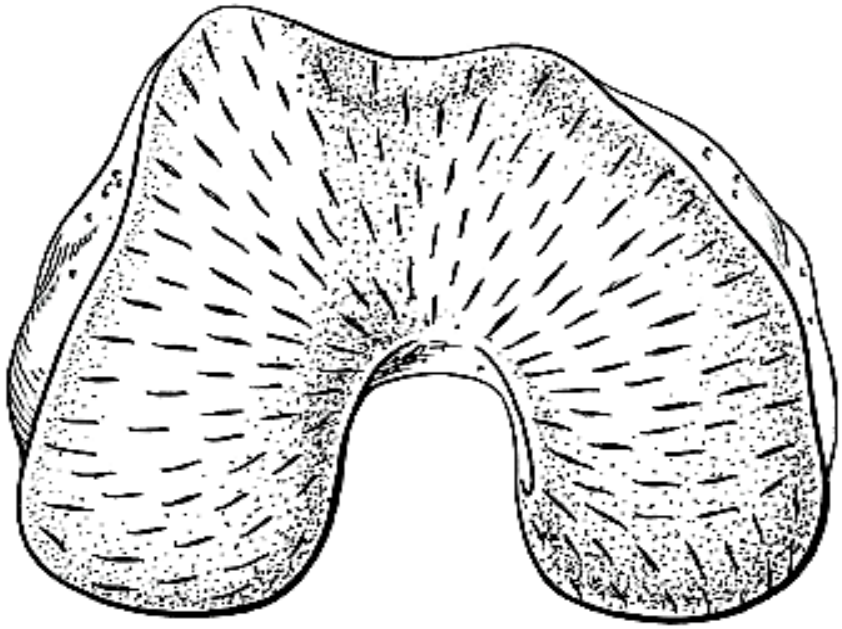


Schematic representation of the molecular organization of cartilage. The structural components of cartilage, collagen, and proteoglycans, interact to form a porous composite fiber-reinforced organic solid matrix that is swollen with water. Aggrecans bind covalently to HA to form large proteoglycan macromolecules.

Nordin and frenkel

- Osmotic swelling pressure balanced by tensile resistance from collagen
  - PGs can only swell 20% of maximum with the collagen present
  - Collagen network is 'pre-stressed' this is likened to a residual stress in an engineering material
  - Disruption of collagen allows PGs to swell

Tensile anisotropy of cartilage on surface and split lines



Human femoral condyles

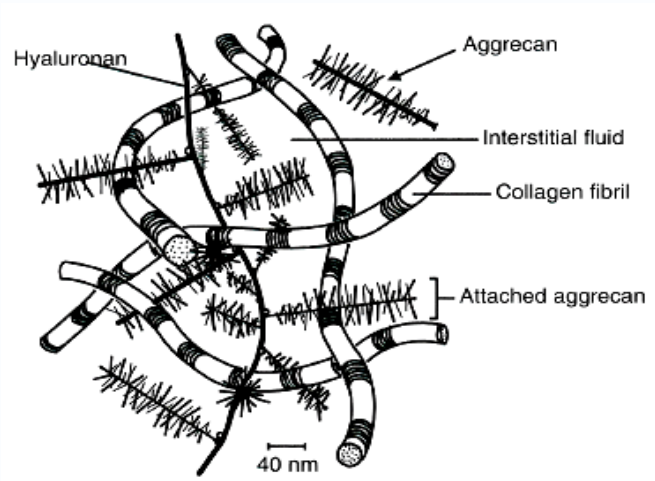
FIG. 3-5

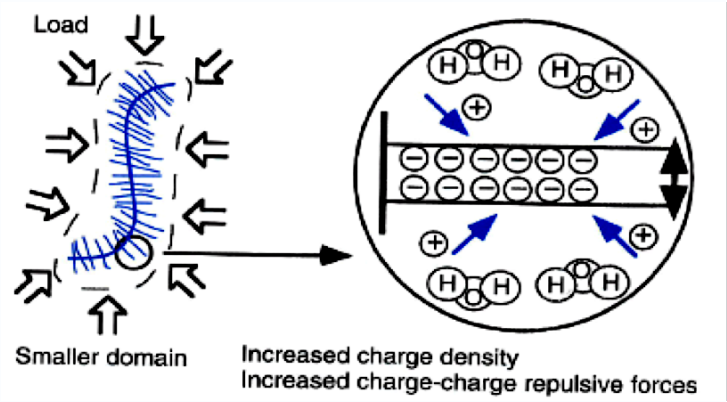
Based on what you know about the interaction between PGs and collagen, and the composition and structure on the surface of the cartilage:

- **<u>Why do split lines form???</u>**

Nordin and Frankel

Mechanism for mechanical function of cartilage and Coll/PG/fluid interactions

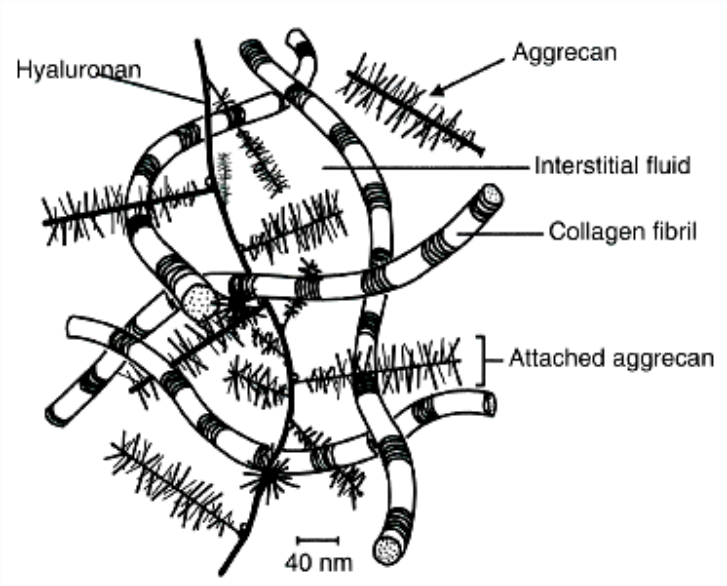




What happens when load is applied??

- Instantaneous deformation
- External load exceeds internal swelling pressure
  - fluid flow out,
  - negative charges closer together (higher PG concentration)
  - higher repulsive forces
- Repulsive forces increase until balanced with external applied compressive stress

Donnan osmotic pressure is balanced by the tensile resistance from the collagen network in vivo



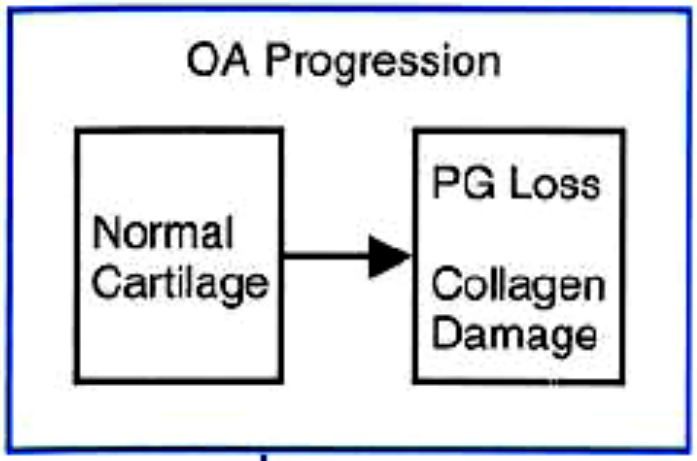
Schematic representation of the molecular organization of cartilage. The structural components of cartilage, collagen, and proteoglycans, interact to form a porous composite fiber-reinforced organic solid matrix that is swollen with water. Aggrecans bind covalently to HA to form large proteoglycan macromolecules.

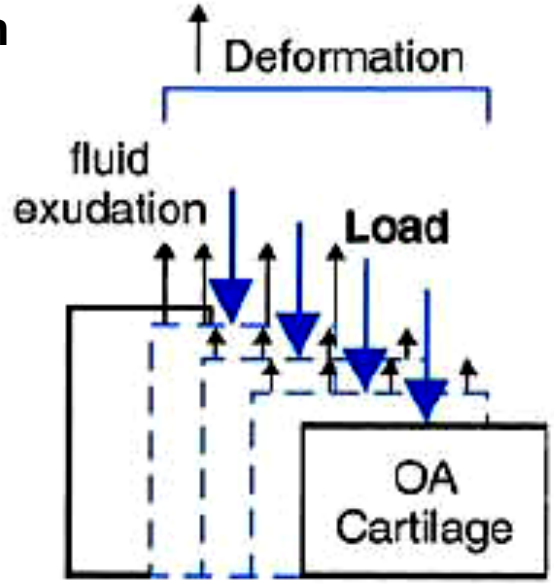
- The repulsive force is a swelling pressure called the Donnan osmotic pressure
- Osmotic pressure ~0.25 MPa (compressive stiffness of ECM ~0.5-1MPa)
- Swelling pressure balanced by tensile resistance from collagen
- The resistance prevents the PGs from swelling to the extent they would without collagen (so in vitro swelling is much more)
- Collagen network is 'pre-stressed' this is likened to a residual stress in an engineering material
- Compression forces cause fluid flow out, negative charges closer together, higher repulsive forces
- Repulsive forces increase until in balance with external applied compressive stress

What factors would be detrimental to mechanical properties and why?

1) Disruption of coll network. Why?
   - decreased resistance to fluid flow,
   - less ability to pressurize the fluid, less load carrying capacity of the fluid.
   - Decreased intrinsic properties of the ECM.
2) Increase in water.
   - Decrease in PG concentration,
   - As a result, decrease in repulsive forces associated with PG charge
   - and decrease in swelling pressure associated with influx of ions and water to maintain electroneutrality.
3) Increase in permeability
   - (less resistance to flow). see (1)
4) Decrease in charge (could be due to PG concentration).
   - Decrease in swelling pressure and resistance to load

Osteoarthritis (OA) Progression





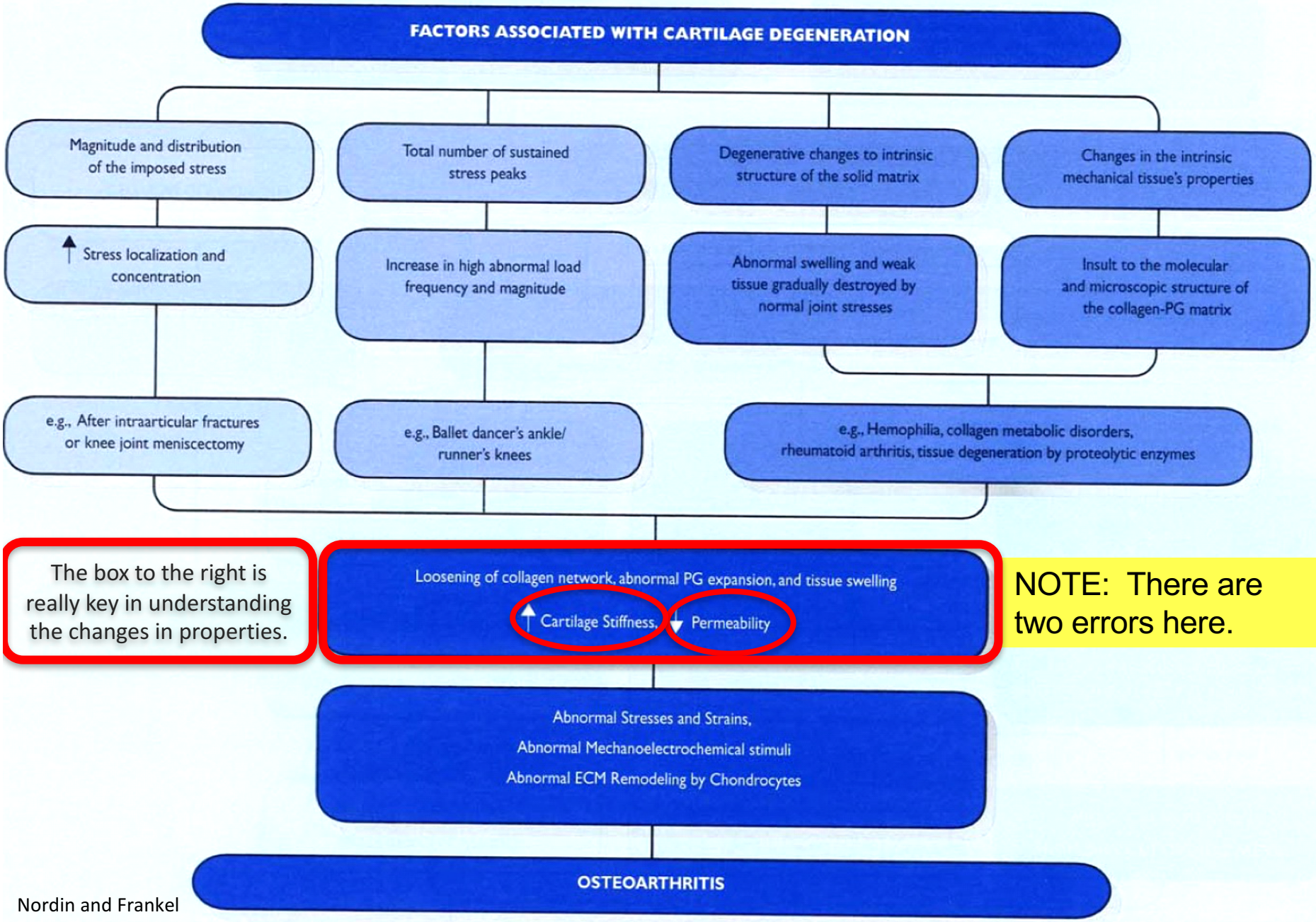
↓ Fixed Charge Density → ↓ Swelling Pressure

↓ Frictional Drag → ↑ Hydraulic Permeability

Increased Matrix Deformation
Increased Fluid Flow

Acts to diminish cartilage load-bearing properties.

FIG. 3-27 A figure illustrating how osteoarthritic changes to the collagen-PG network can compromise the ability of articular cartilage to maintain interstitial fluid pressurization, which underlies the tissue's load-bearing and joint lubrication capacity. Loss of PG and damage to the collagen fibers result in an increased hydraulic permeability (decreased resistance to fluid flow) and supra-normal loads and strains on the solid matrix (and chondrocyte).



The box to the right is really key in understanding the changes in properties.

NOTE: There are two errors here.

FLOW CHART 3-3 Factors associated with cartilage degeneration.* (*PG*, proteoglycan; *ECM*, extracellular matrix)

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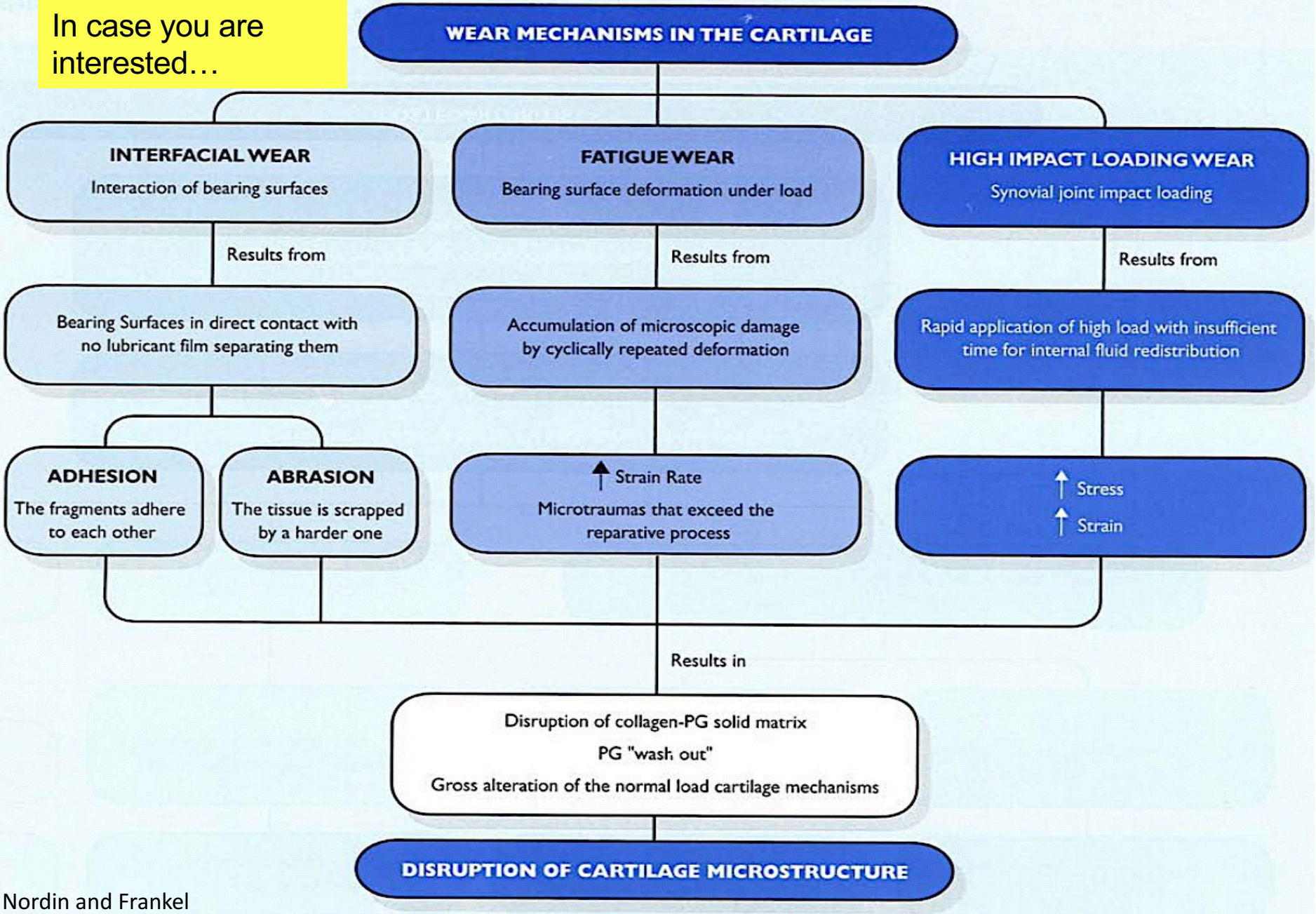
In case you are interested…



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