

Advanced Biomechanics of Physical Activity

Biomechanics of Cartilage

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What do you know about
cartilage?

Types of Cartilage

- Hyaline
 - Synovial joints
 - Dense, translucent, connective tissue
- Fibrocartilage
 - Transitional cartilage found at the margins of some joint capsules
 - Joint capsules
 - Insertions of ligaments and tendons into bone
 - Menisci
 - Annulus fibrosus
- Elastic cartilage
 - External ear
 - Eustacian tube, epiglottis, and parts of the larynx

Hyaline Cartilage and Synovial (Diarthrodial) Joints

- Allows wide range of motion
- Articular surfaces covered with 1 to 6 mm of hyaline cartilage
 - Suited to withstand rigors of joint environment without failing during lifetime
 - Isolated tissue
 - Devoid of blood vessels, lymph channels, and neurological innervation
 - Cellular density less than any other tissue

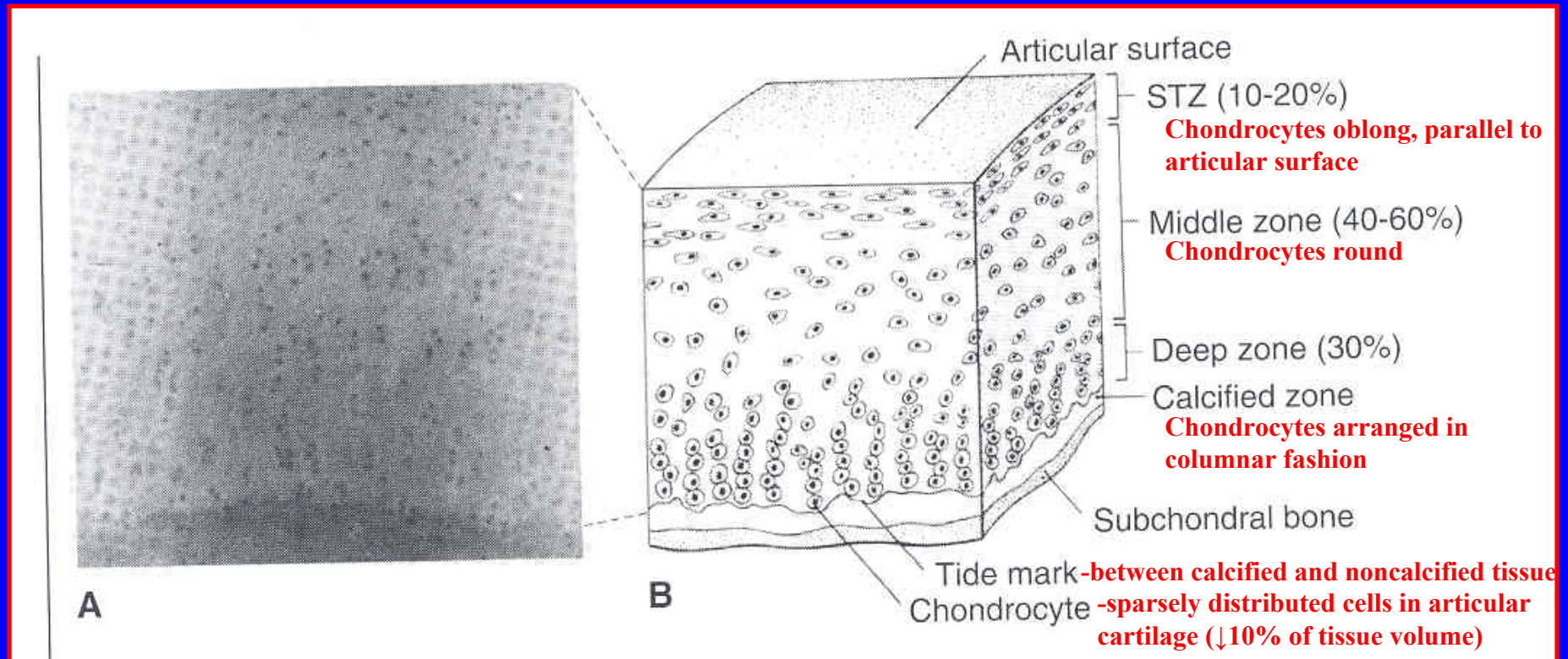
Primary Functions of Hyaline Cartilage

- Distribute joint loads over wide area to decrease stresses sustained by contacting joint surfaces
- Allow relative movement of opposing joint surfaces with minimal friction and wear

Composition and Structure of Articular Cartilage

- Chondrocytes
 - Sparsely distributed cells in articular cartilage
 - Less than 10% of tissue volume
 - Manufacture, secrete, and maintain organic component of extracellular matrix (ECM)
(see figure)

Chondrocyte Distribution in Articular Cartilage



Composition and Structure of Articular Cartilage (continued)

- Organic matrix
 - Composed of dense framework of type II collagen fibrils enmeshed in concentration of proteoglycans (PG)
 - Collagen content of cartilage 15-22% of wet weight
 - PG content of cartilage 4-7% of wet weight
 - 60-85% water content, inorganic salts, other proteins, glycoproteins, and lipids

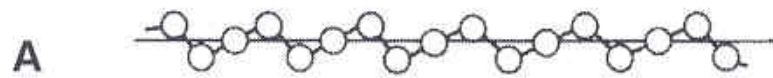
Composition and Structure of Articular Cartilage (continued)

- Collagen fibrils and PG's
 - Form structural components that support mechanical stresses applied to cartilage
 - Together with water determine biomechanical behavior of cartilage

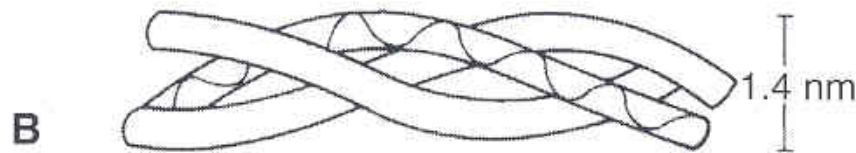
1. Collagen

- Most abundant protein in the body
- Provides fibrous ultrastructure in cartilage
- Tropocollagen is basic biological unit of collagen
 - Composed of 3 alpha chains coiled in left hand helices
 - Alpha chains coiled around each other in right hand triple helix
 - Form tropocollagen molecules
 - Cross links formed between tropocollagen molecules \Rightarrow high tensile strength(see figure)

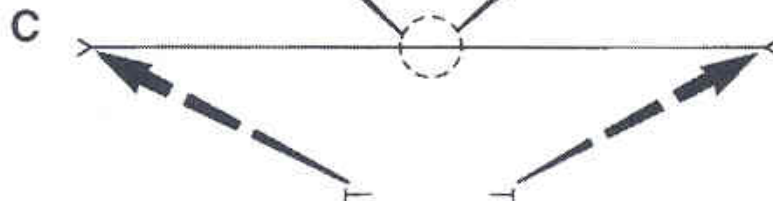
Collagen Structure



α chain



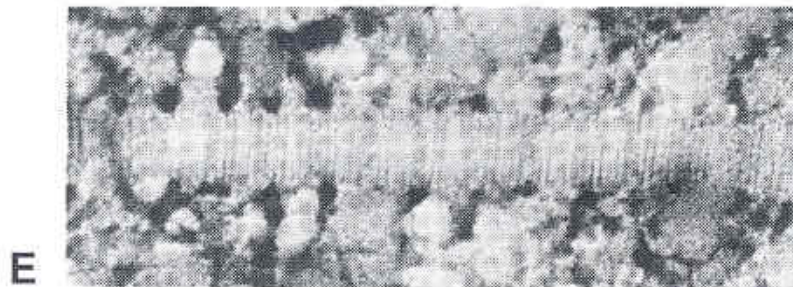
Triple helix



Tropocollagen molecule



Collagen fibril with quarter-stagger array of molecules

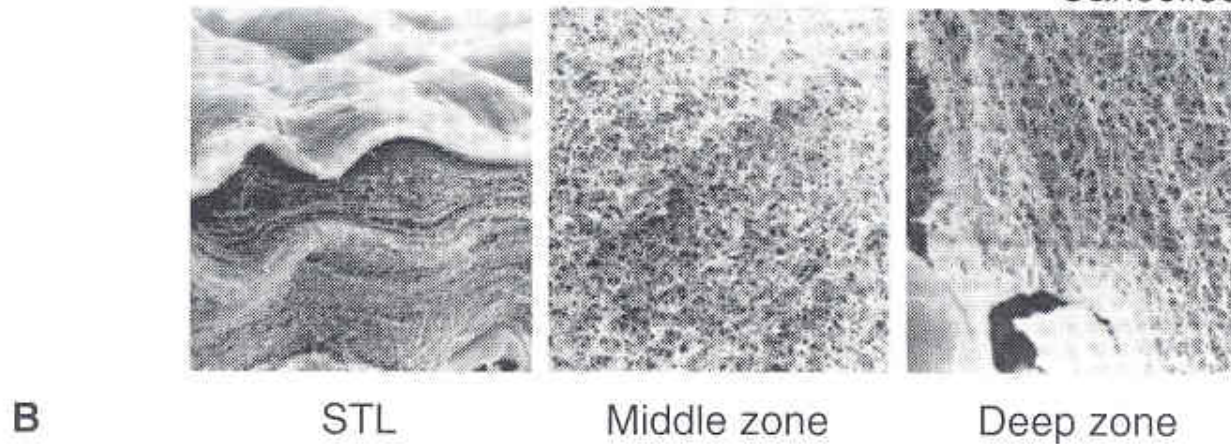
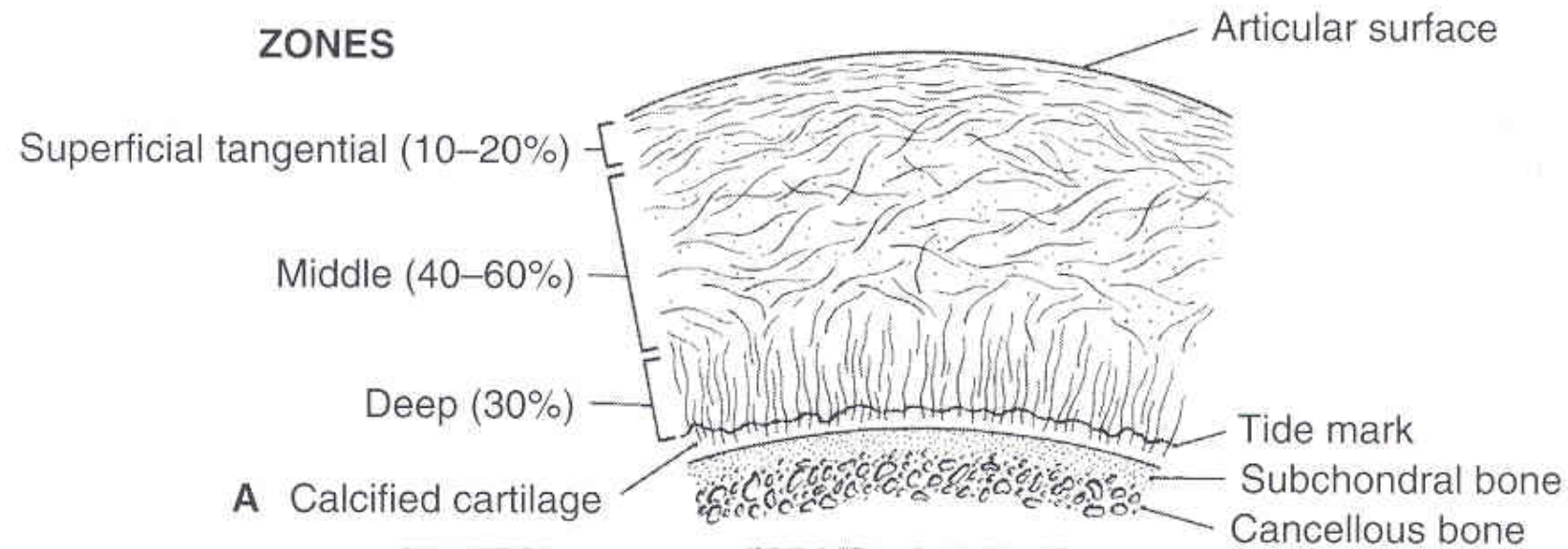


Fibril with repeated banding pattern seen under electron microscope

Structure of Collagen in Articular Cartilage (Zonal Arrangement)

- Inhomogeniously distributed (layered character)
- Three zones
 - Superficial tangential zone (STZ)
 - 10-20% of thickness
 - Fine densely packed collagen fibers randomly woven in planes parallel to articular surface
 - Zone with highest concentration of collagen
 - Middle zone
 - 40-60% of thickness
 - Collagen fibers randomly distributed and farther apart (see figure)

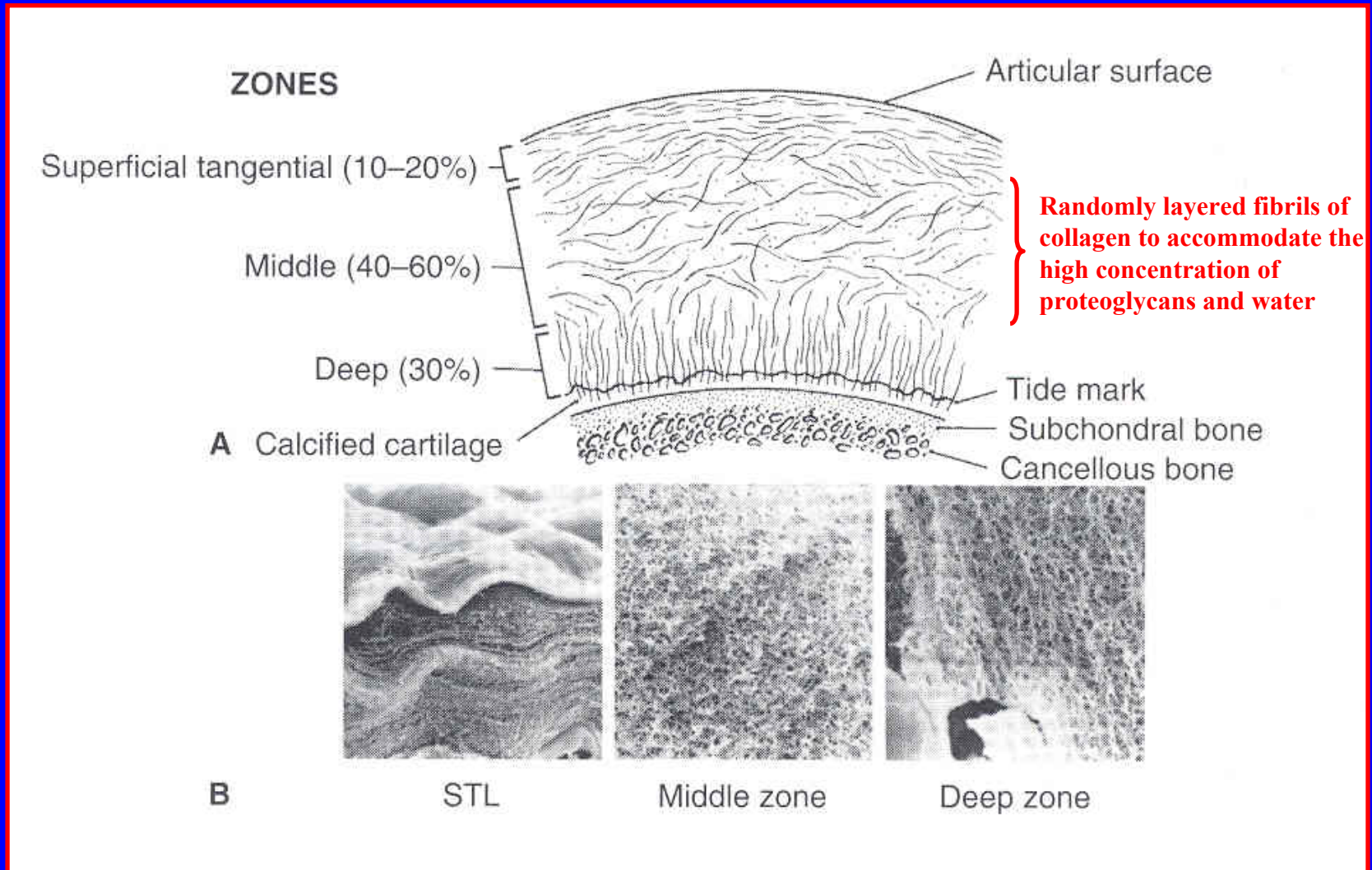
Arrangement of Collagen in Articular Cartilage



Structure of Collagen in Articular Cartilage (Zonal Arrangement)

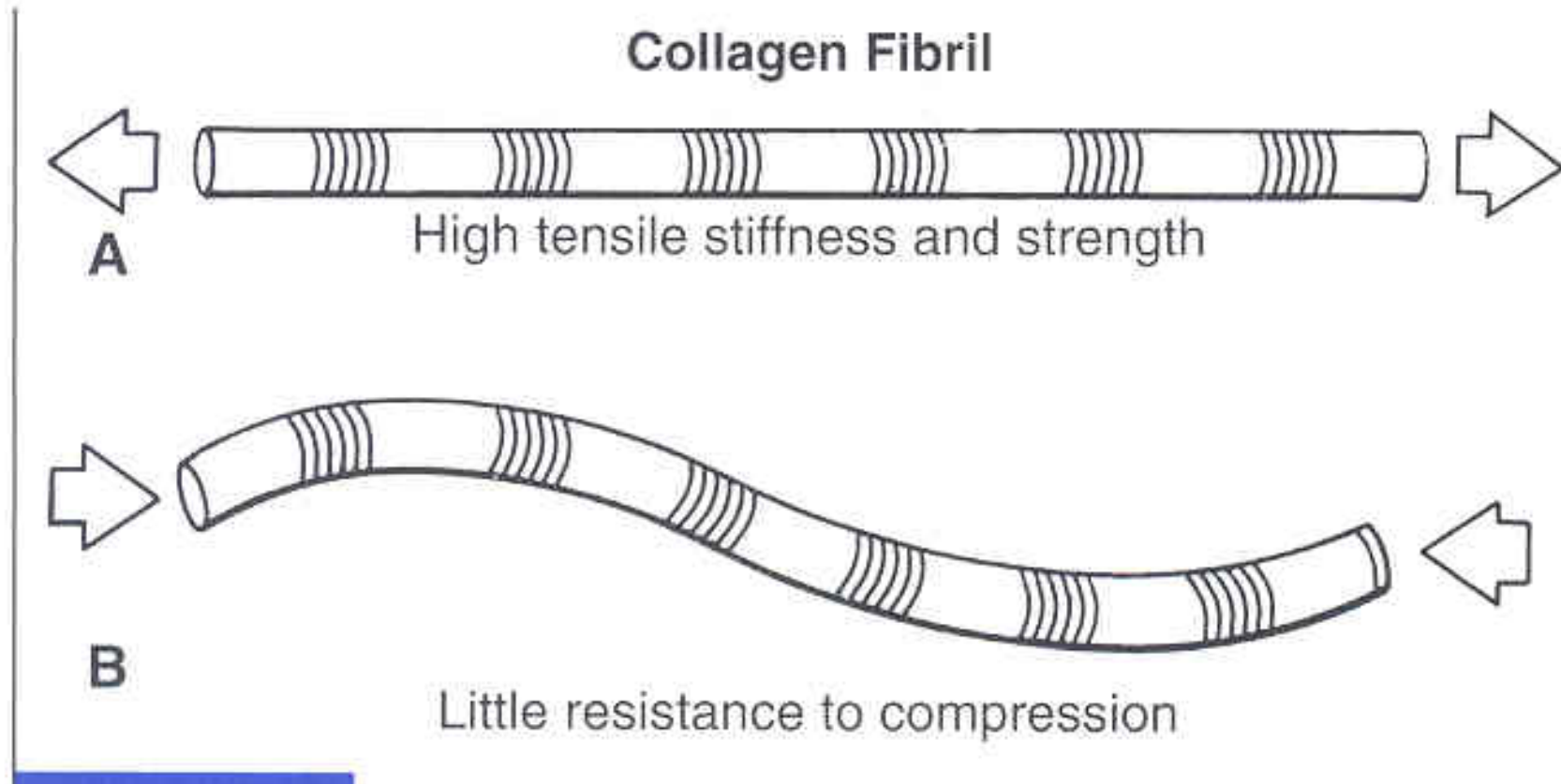
- Three zones (continued)
 - Deep zone
 - 30% of thickness
 - Radially oriented fiber bundles of collagen
 - Bundles cross tidemark (interface between articular cartilage and calcified cartilage)
 - Form interlocking root system to anchor cartilage to underlying bone
- Zonal arrangement provides for more even distribution of stress across loaded region of cartilage (see figure)

Arrangement of Collagen in Articular Cartilage



- Pattern of collagen fibril arrangement related to tensile stiffness and strength characteristics.
- Note correspondence between collagen and chondrocyte arrangement.

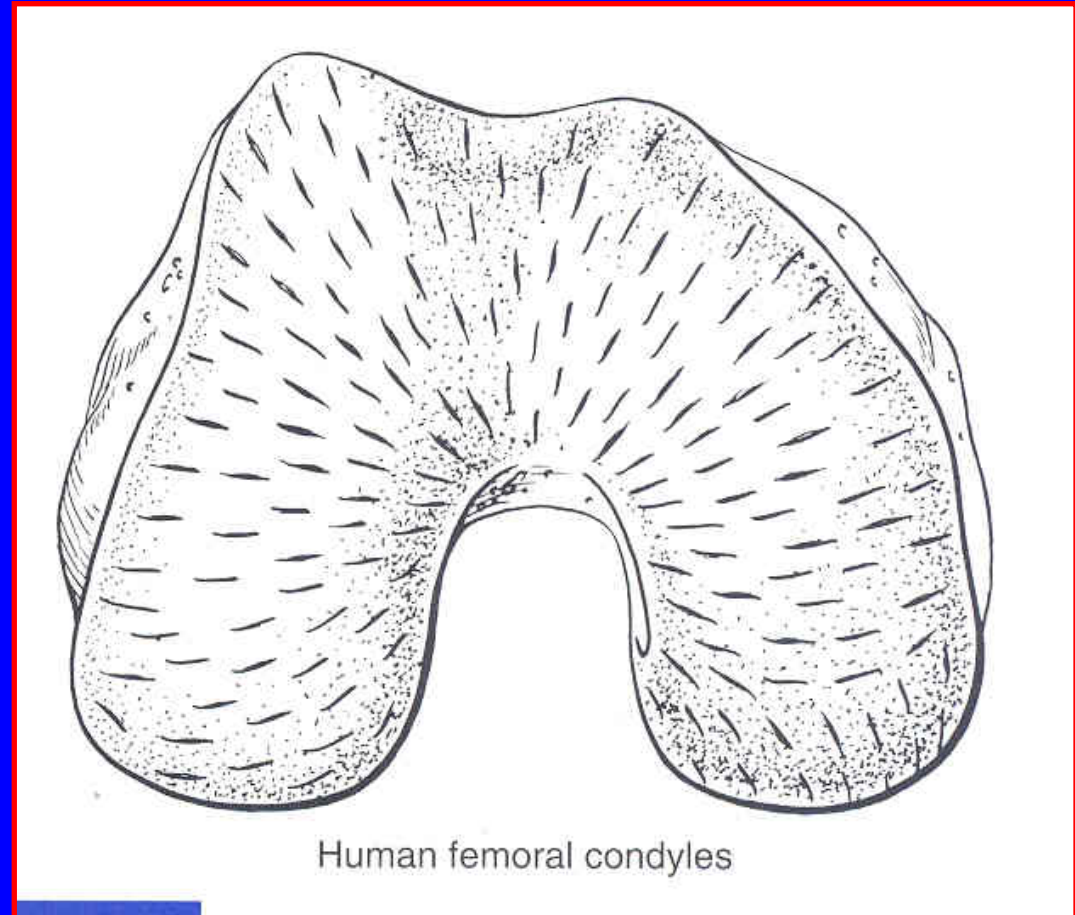
Strength of Collagen



- Strong in tension
- Weak in compression (high slenderness ratio: length/width)

Material Properties of Articular Cartilage

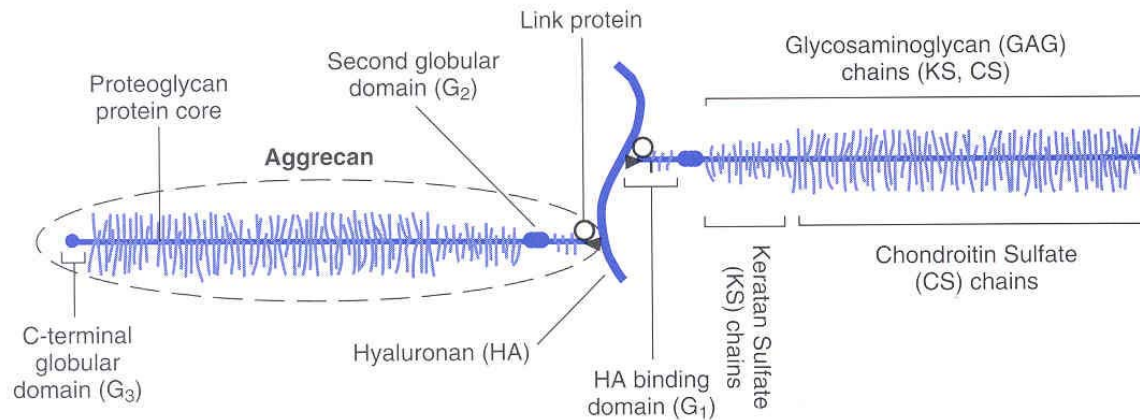
- Anisotropic – differ with direction of loading (may be associated with zonal arrangement of collagen)
- “Split lines” – surface collagen fiber pattern; functionally related to tensile strength



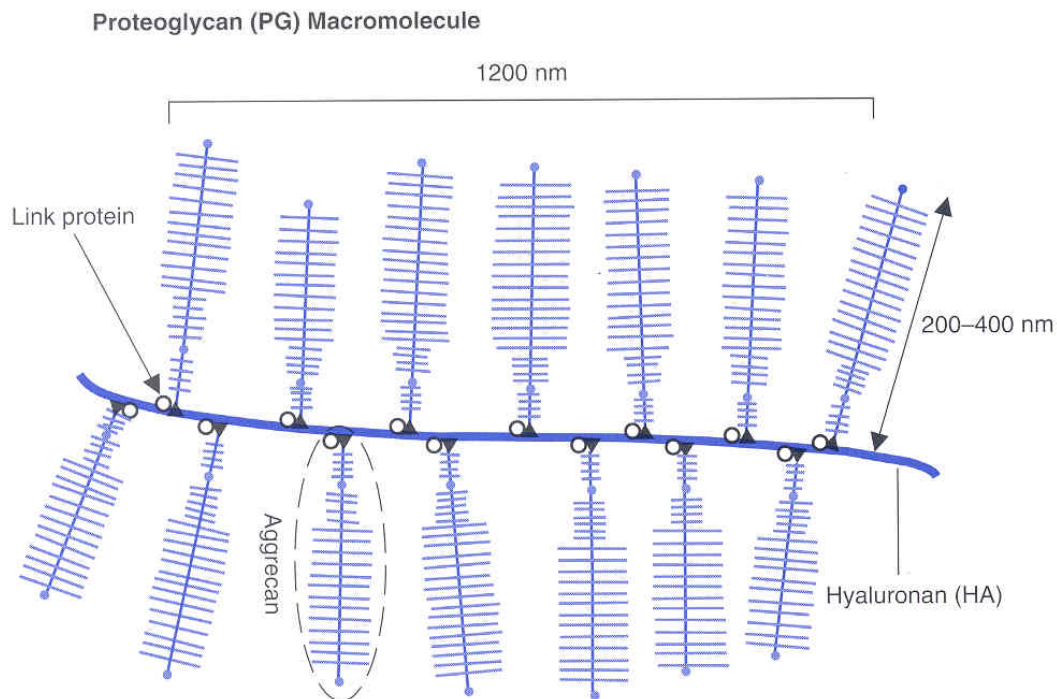
2. Proteoglycan (PG)

- Large protein-polysaccharide molecules that exist as either monomers or as aggregates
- PG aggregation promotes immobilization of the PG's within the collagen meshwork adding structural rigidity to the extracellular matrix of articular cartilage (see figure)

Proteoglycan Aggregate



A



B

- Many types of PG's found in cartilage

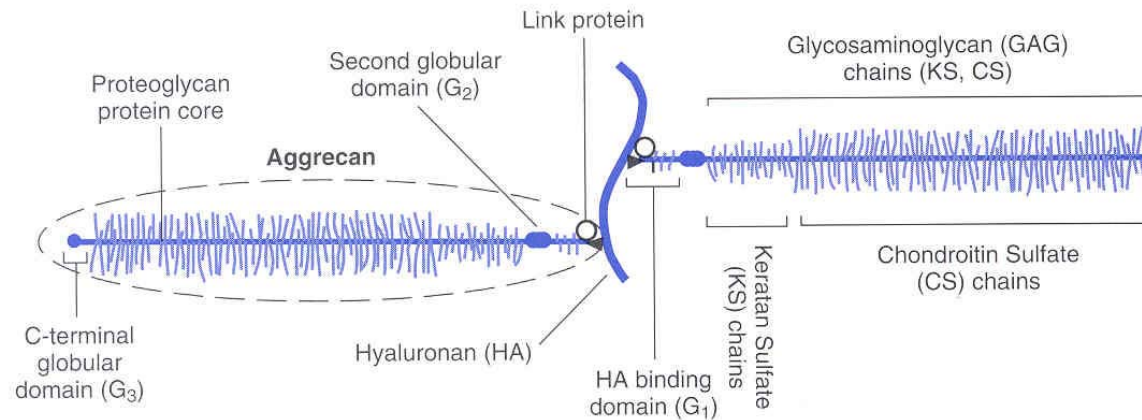
- PG's consist of protein core with one or more glucosaminoglycans (GAG's)

- Aggrecans molecules attach to hyaluronan molecule via HA-binding region (HABR)

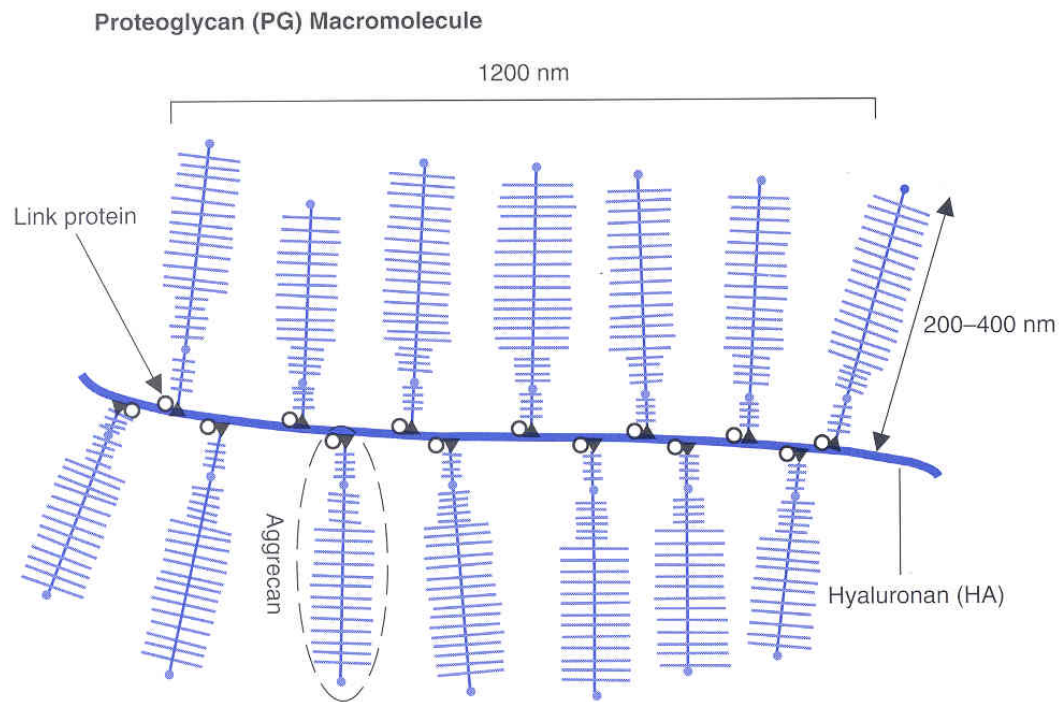
- Binding is stabilized by link protein (LP)

- Stabilization crucial to function of normal cartilage (without LP components of PG would escape from tissue)

Proteoglycan Aggregate (cont.)



A



B

- 2 types of GAG's –
condroitin sulfate (CS) and
keratan sulfate (KS)

- 3 globular regions

- PG aggregates has
major functional
significance – promotes
immobilization of PG's
within the fine collagen
meshwork, adding
functional stability and
rigidity to extracellular
matrix (ECM)

Aging of Articular Cartilage

- Decrease in water content
 - Decrease in carbohydrate/protein ratio
 - Decrease in chondroitin sulfate (CS)
 - Increase in keratin sulfate (KS)
-

Changes may relate to increased functional demand with aging

3. Water

- Most abundant component of articular cartilage
- 80% concentrated near articular surface
- Contains many mobile cations that greatly influence the mechanical and physiochemical behaviors of cartilage
- Essential to health of avascular cartilage (permits movement of gasses, nutrients, and waste products between chondrocytes and surrounding nutrient-rich synovial fluid)
- Small percent intracellular

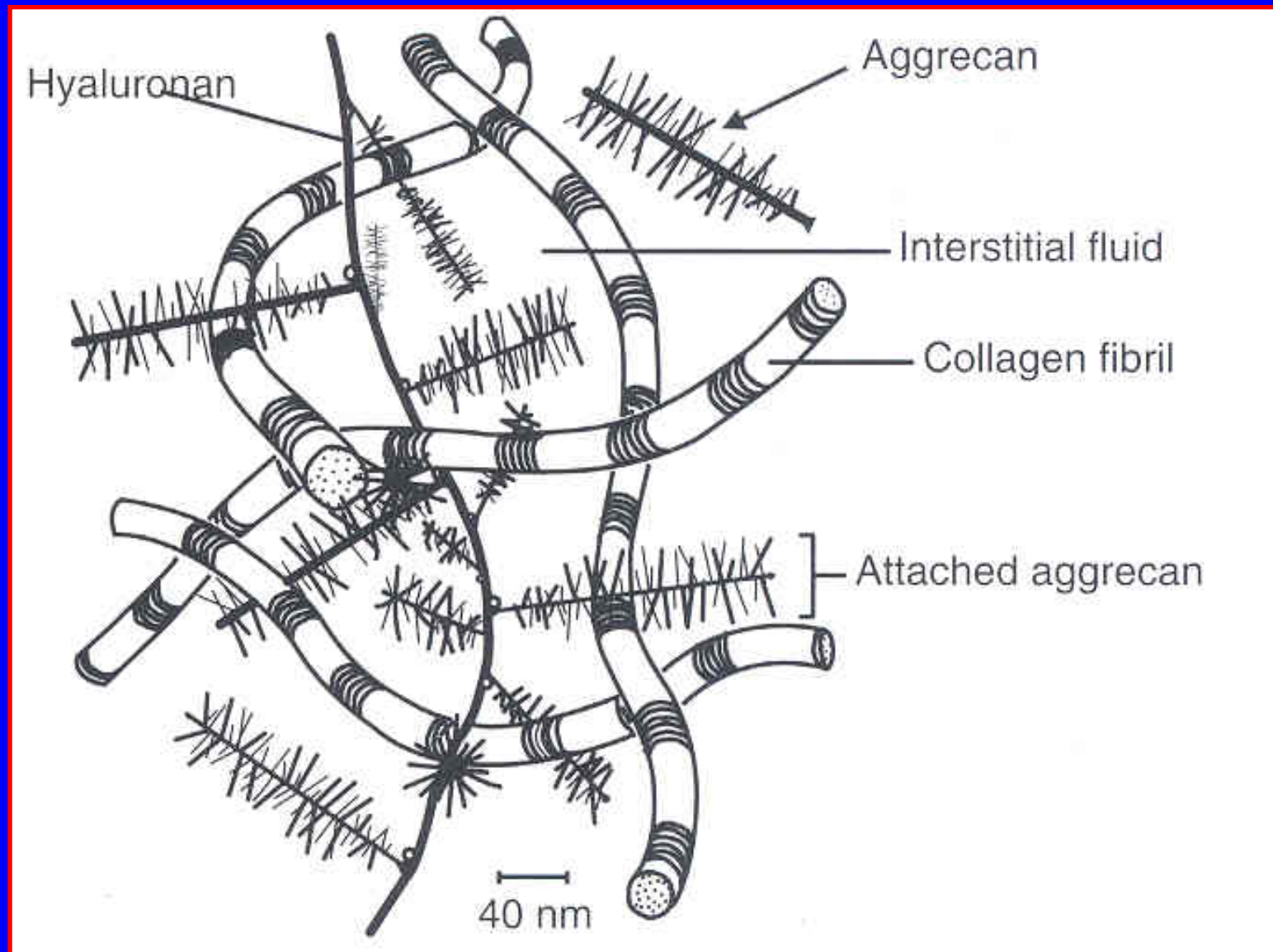
3. Water (cont.)

- 30% associated with collagen fibrils (important in structural organization of extracellular matrix)
- Most water occupies interfibrillar space
- Movement of water (up to 70% under load) important in
 - controlling cartilage mechanical behavior
 - joint lubrication

Interaction Among Cartilage Components

- Collagen and proteoglycans interact to form a porous composite fiber-reinforced organic solid matrix that is swollen with water
- Aggrecans bind covalently with hyaluronon (HA) to form large proteoglycan macromolecules
- Collagen-PG solid matrix and interstitial fluid protect against high levels of stress and strain developing in the ECM when articular cartilage subjected to external loads

Molecular Organization of Cartilage



Biomechanical Loading of Articular Cartilage

- Forces at joint surface vary from zero to several times body weight
- “Contact” area varies in a complex manner; typically only several square centimeters
- Potentially high pressure (force/unit area)

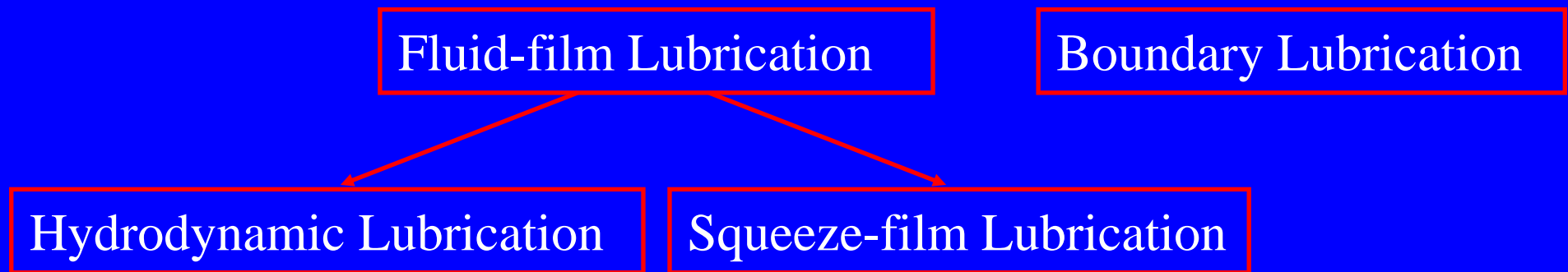
Lubrication of Articular Cartilage

- Synovial joints subjected to enormous range of loading conditions
 - Cartilage typically sustains little wear
-

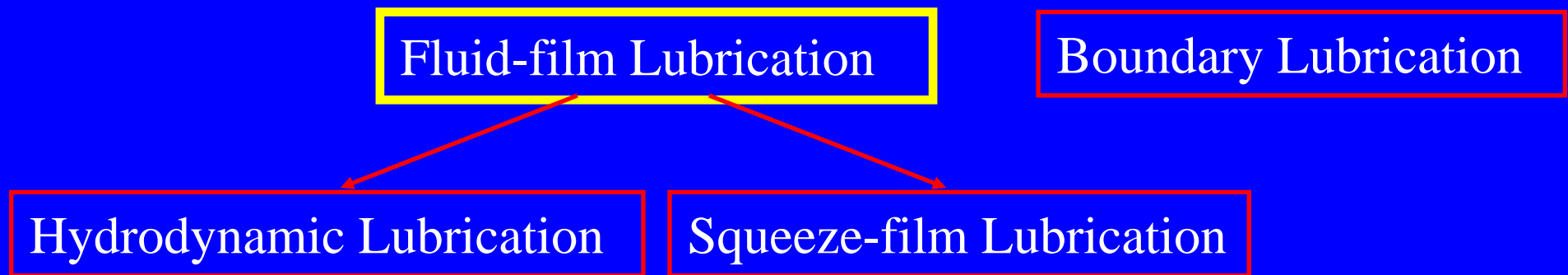
Implication:

Sophisticated lubrication process required

Lubrication Processes for Articular Cartilage



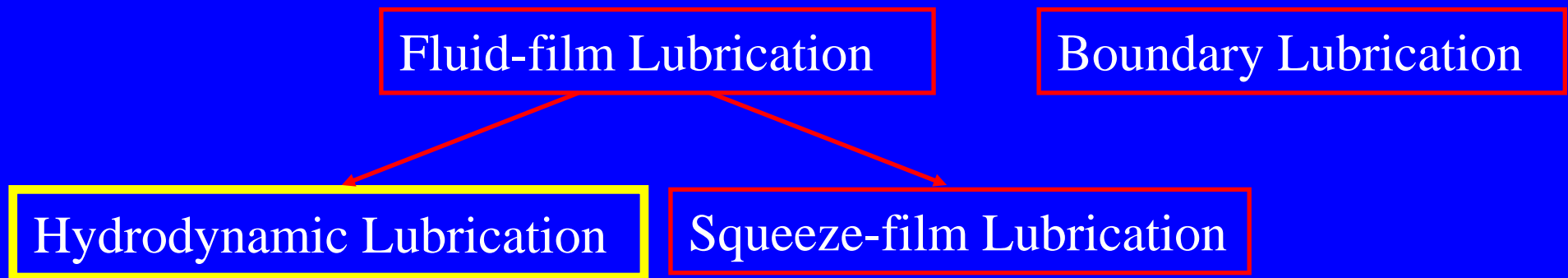
Lubrication Processes for Articular Cartilage



Fluid-film Lubrication

- Thin film of lubricant separates bearing surfaces
- Load on bearing surfaces supported by pressure developed in fluid-film
- Lubrication characteristics determined by lubricant's properties
 - Rheological properties
 - Viscosity and elasticity
 - Film geometry
 - Shape of gap between surfaces
 - Speed of relative motion of two surfaces

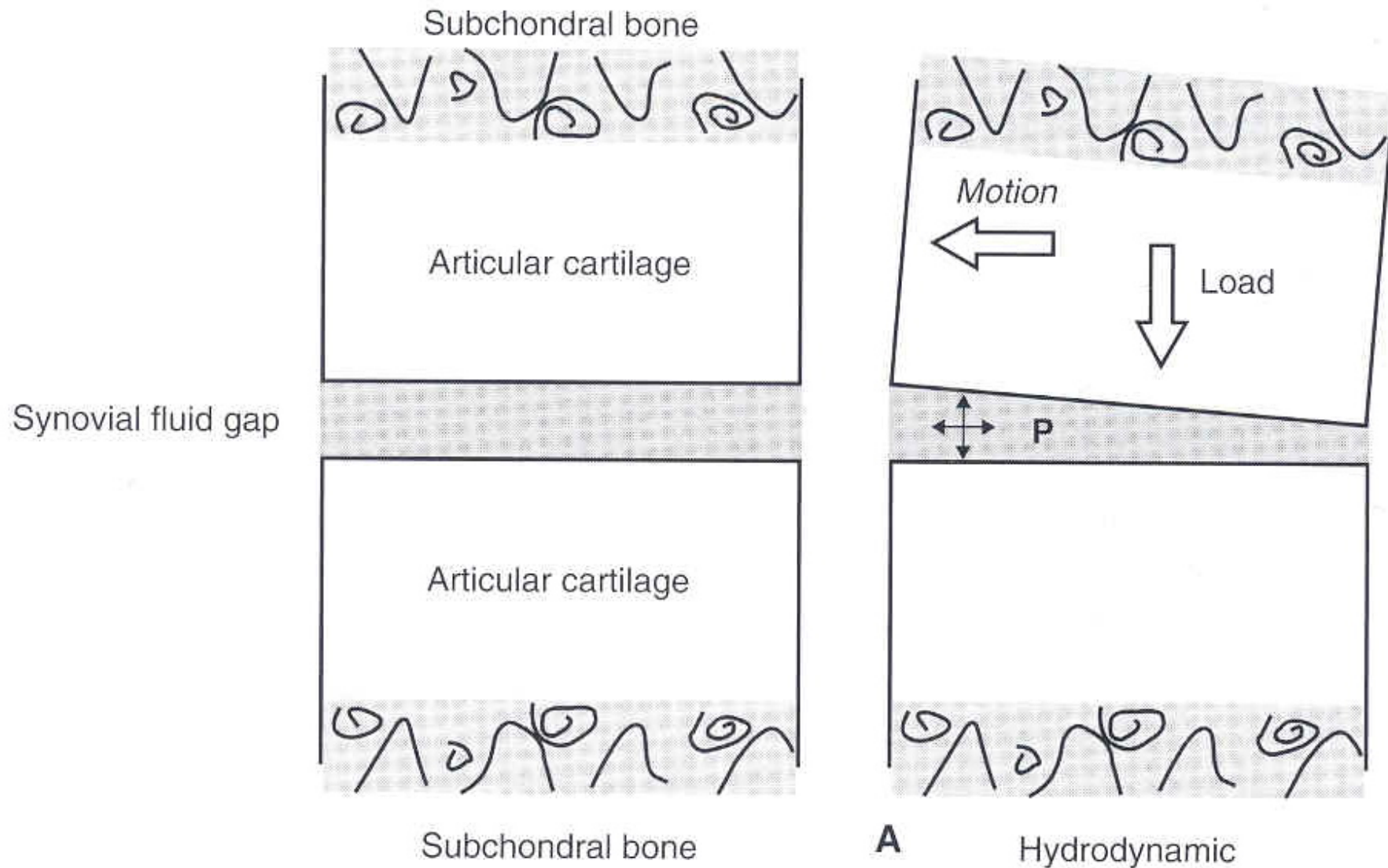
Lubrication Processes for Articular Cartilage



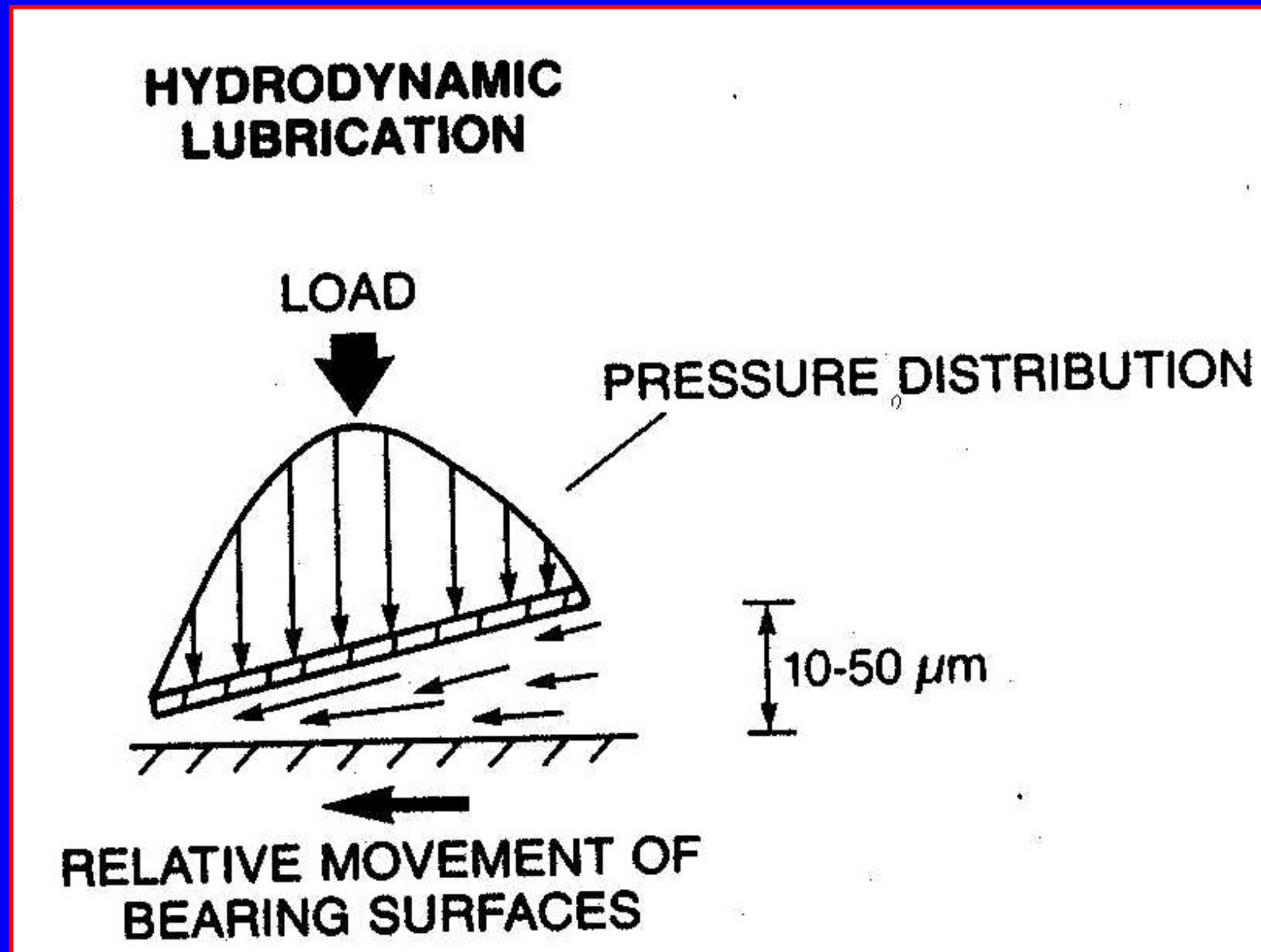
Hydrodynamic Lubrication

- Occurs when 2 nonparallel rigid bearing surfaces lubricated by a fluid-film that moves tangentially with respect to each other
- Wedge of converging fluid formed
- Lifting pressure generated in wedge by fluid viscosity as the bearing motion drags fluid into gap

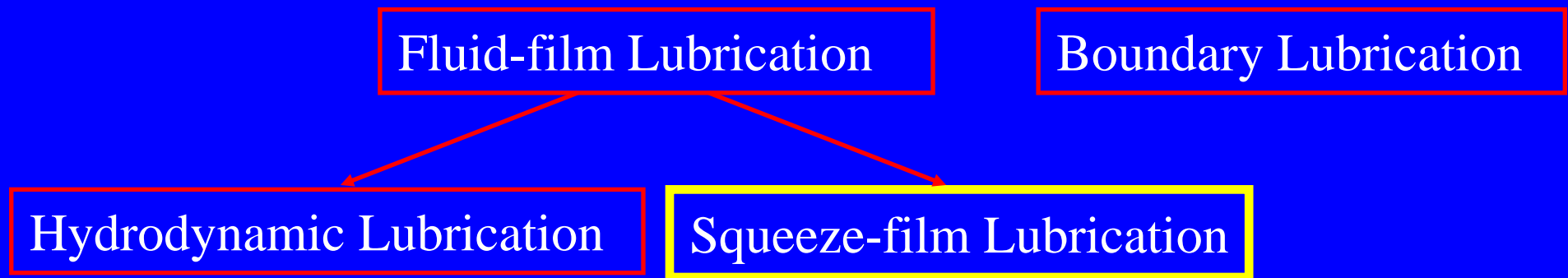
Schematic of Hydrodynamic Lubrication



Schematic of Hydrodynamic Lubrication



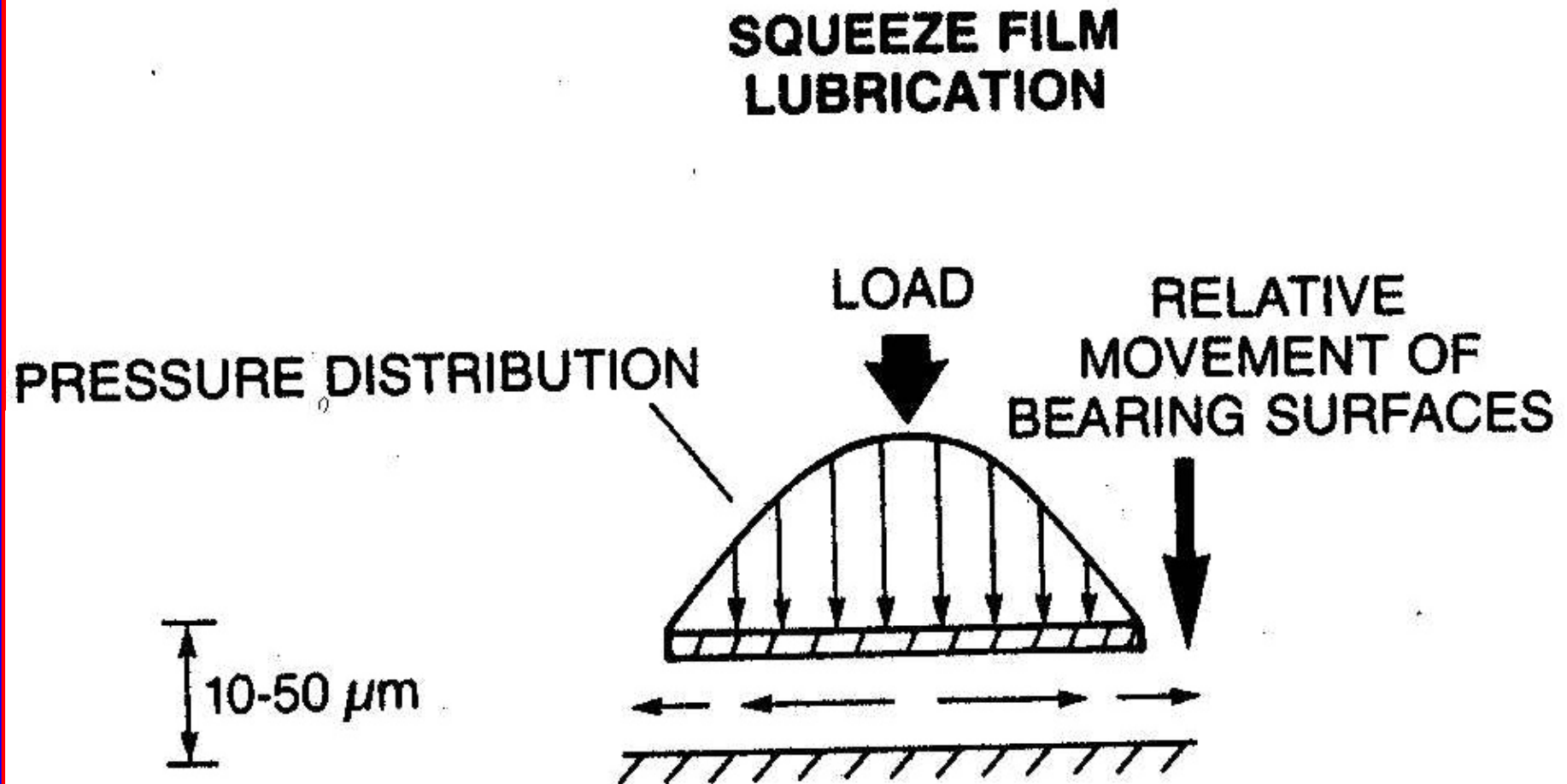
Lubrication Processes for Articular Cartilage



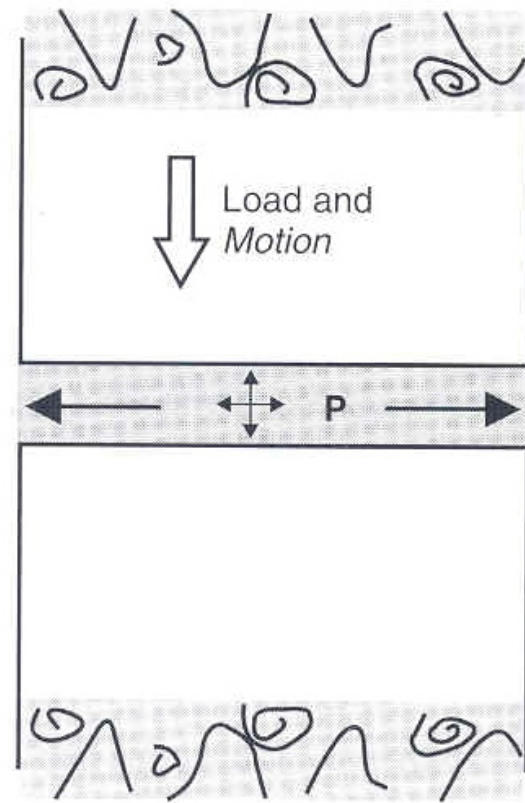
Squeeze-film Lubrication

- Occurs when weight bearing surfaces move perpendicularly toward each other
- Wedge of converging fluid formed
- Pressure in fluid-film result of viscous resistance of fluid that acts to impede its escape from the gap
- Sufficient to carry high loads for short durations (eventually contact between asperities in bearing surfaces)

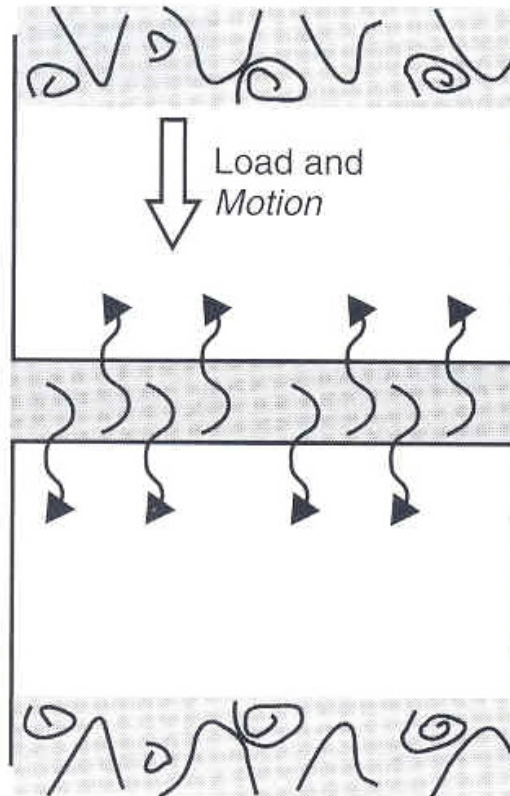
Schematic of Squeeze-film Lubrication



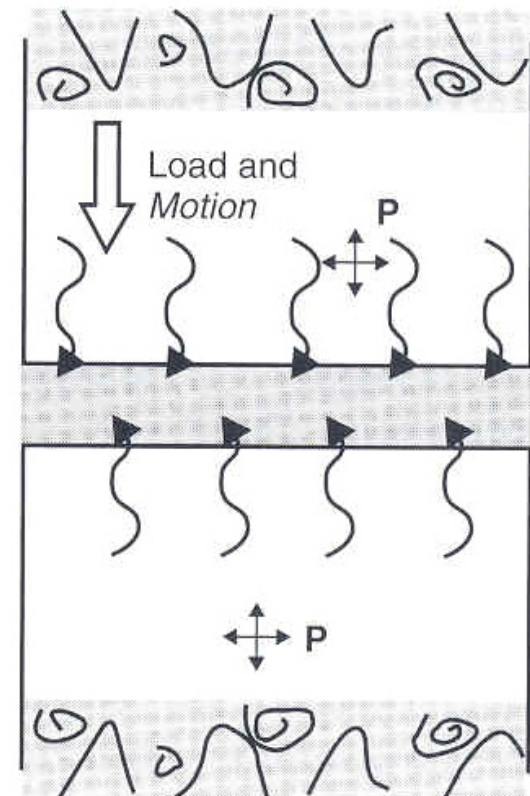
Schematic of Squeeze-film Lubrication



B Squeeze-Film

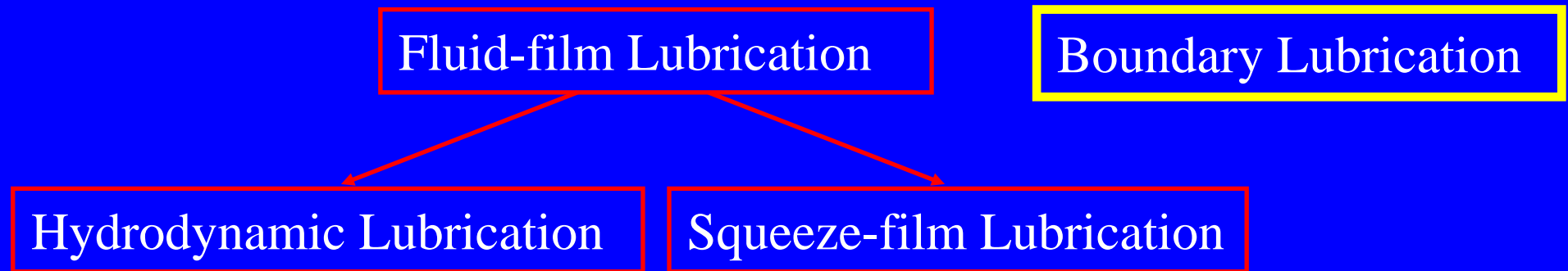


C Boosted



D Weeping

Lubrication Processes for Articular Cartilage



Boundary Lubrication

- Surfaces of cartilage protected by an adsorbed layer of boundary lubricant
 - Direct surface-to-surface contact is prevented
 - Most surface wear eliminated
 - Lubricin (glycoprotein) synovial fluid constituent responsible for boundary lubricant
 - Absorbed as monolayer to each articular surface
 - Able to carry loads (normal forces) and reduce friction
- Independent of physical properties of lubricant (e.g., viscosity) and bearing material (e.g., stiffness)
- Primarily depends on chemical properties of lubricant
- Functions under high loads at low relative velocities, preventing direct contact between surfaces

Articular Cartilage Asperities and Lubrication

- Articular cartilage not perfectly smooth; asperities
- Fluid film lubrication in regions of cartilage non-contact
- Boundary lubricant (lubricin) in areas of asperities
- Low rates of interfacial wear suggests that asperity contact rarely occurs in articular cartilage

Asperities in Articular Cartilage

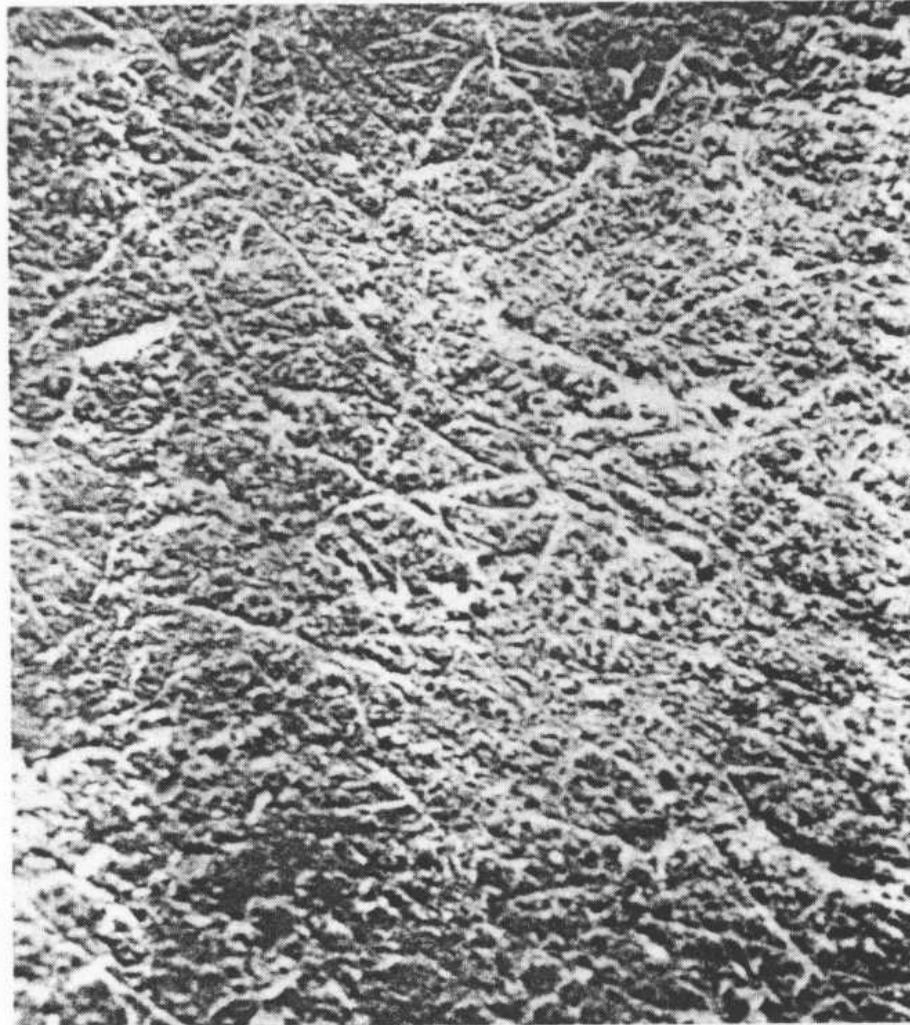
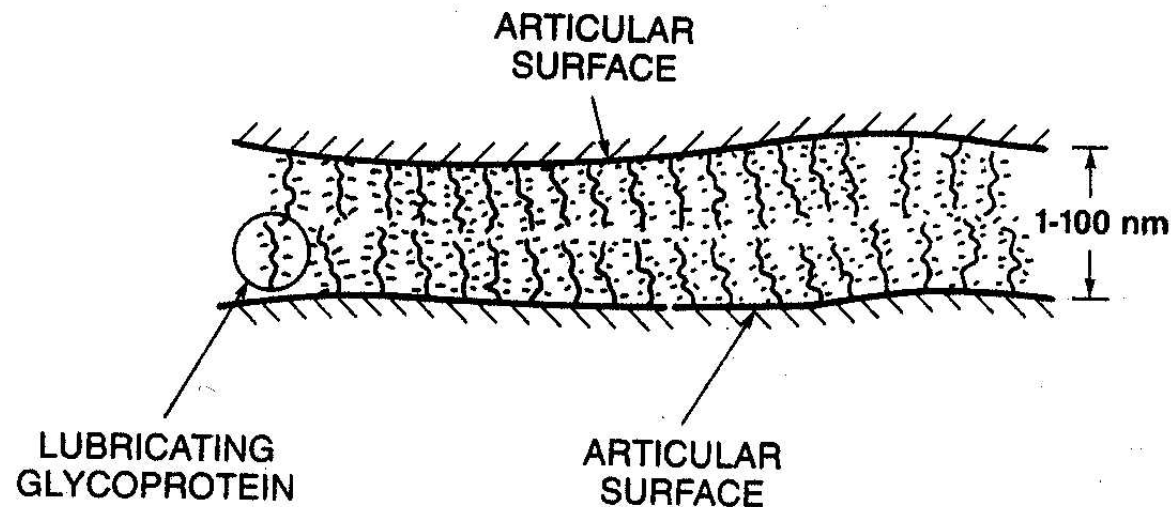


FIG. 2-21

Scanning electron micrograph of the surface of human articular cartilage from a normal young adult showing the typical irregularities characteristic of this tissue (3,000 \times). (Reprinted with permission from Armstrong and Mow, 1980.)

Schematic of Boundary Lubricant



Boundary lubrication of articular cartilage. The load is carried by a monolayer of the lubricating glycoprotein, which is adsorbed onto the articular surfaces. The monolayer effectively serves to reduce friction and helps to prevent cartilage wear. (Adapted from Armstrong and Mow, 1980.)

Synovial fluid constituent responsible for boundary lubrication

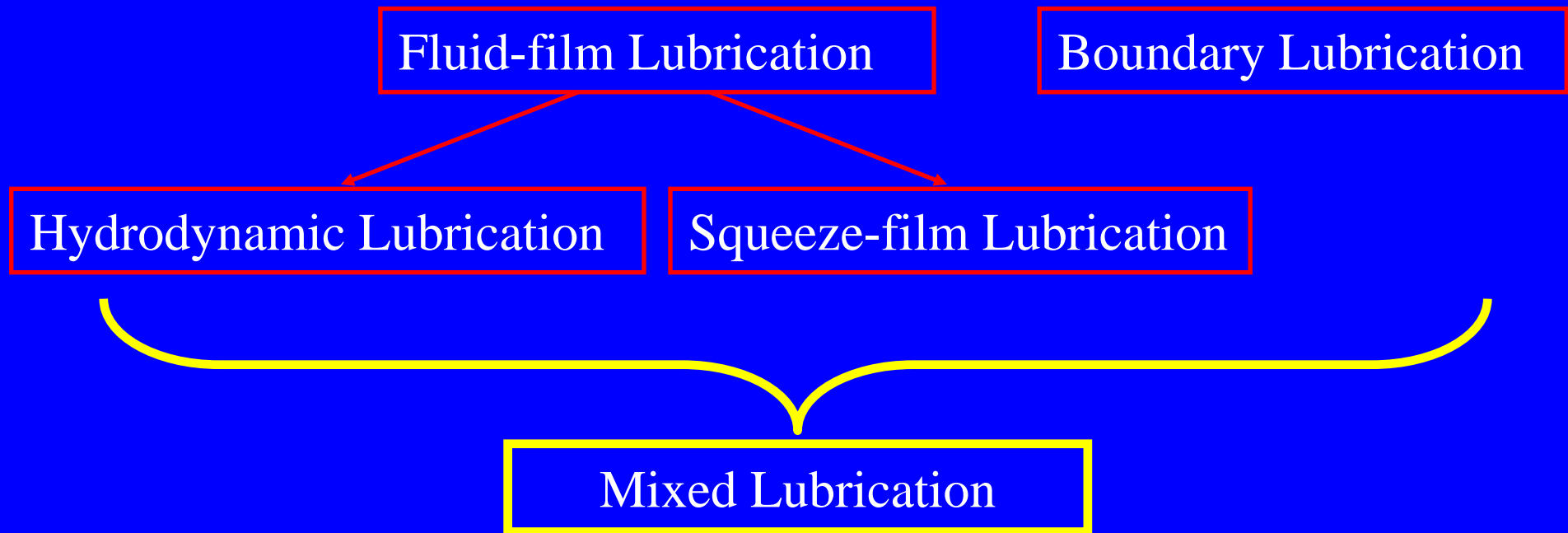
- glycoprotein – lubricin

or

- phospholipid –
dipalmitoyl

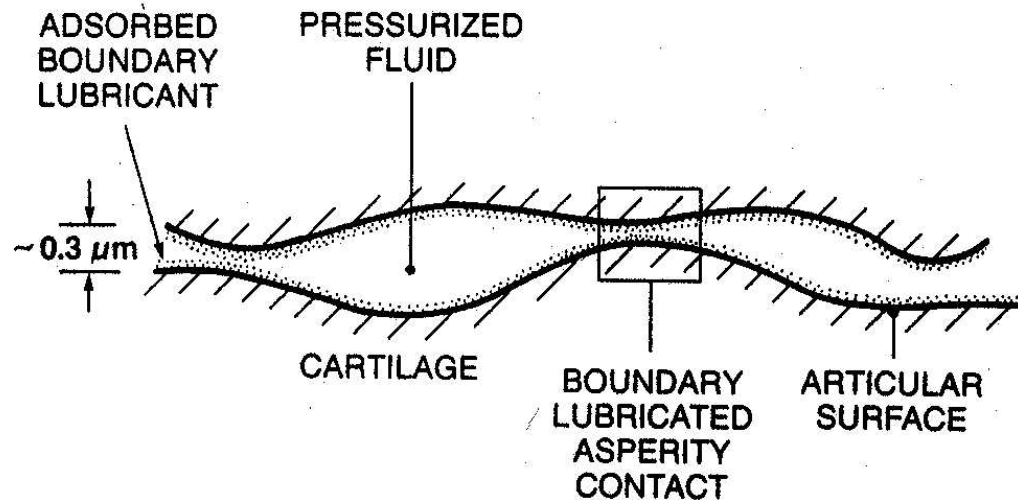
phosphatidylcholine ??

Lubrication Processes for Articular Cartilage



Modes of Mixed Lubrication

1. Combination of fluid-film and boundary lubrication
 - Temporal coexistence of fluid-film and boundary lubrication at spatially distinct locations
 - Joint surface load sustained by fluid-film and boundary lubrication
 - Most friction in boundary lubricated areas; most load supported by fluid-film

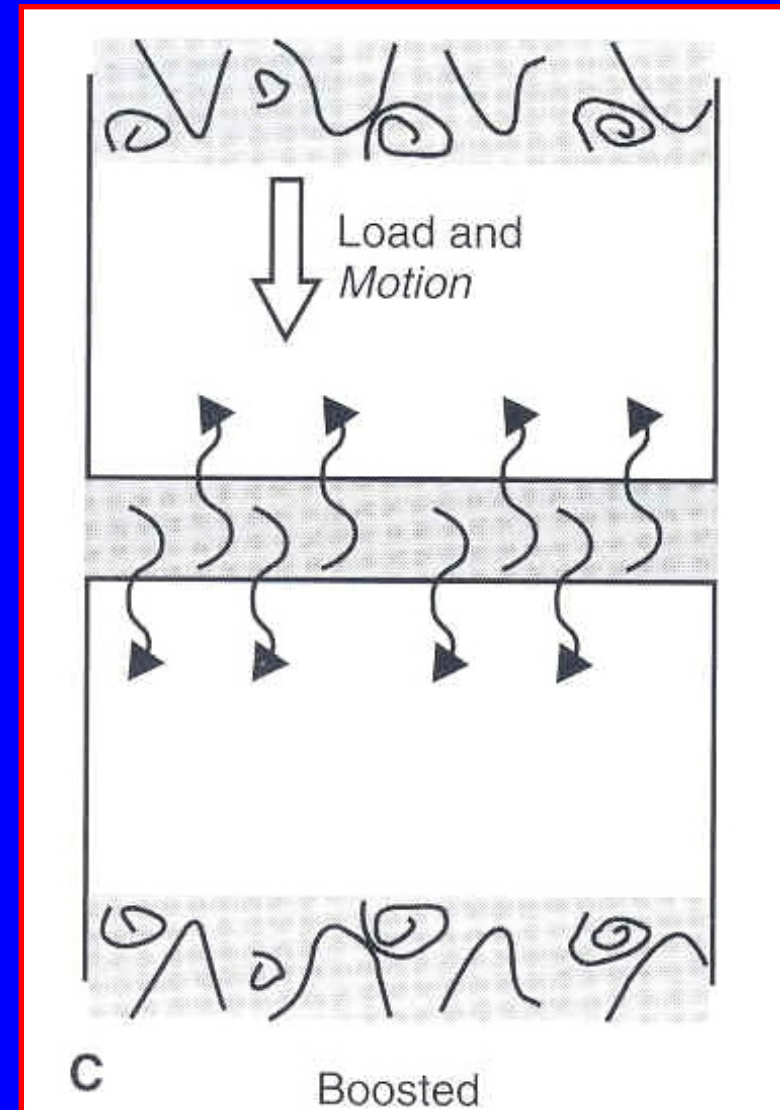


Schematic depiction of mixed lubrication operating in articular cartilage. Boundary lubrication occurs where the thickness of the fluid film is on the same order as the roughness of the bearing surfaces. Fluid film lubrication takes place in areas with more widely separated surfaces. (Adapted from Armstrong and Mow, 1980.)

Modes of Mixed Lubrication

2. Boosted lubrication

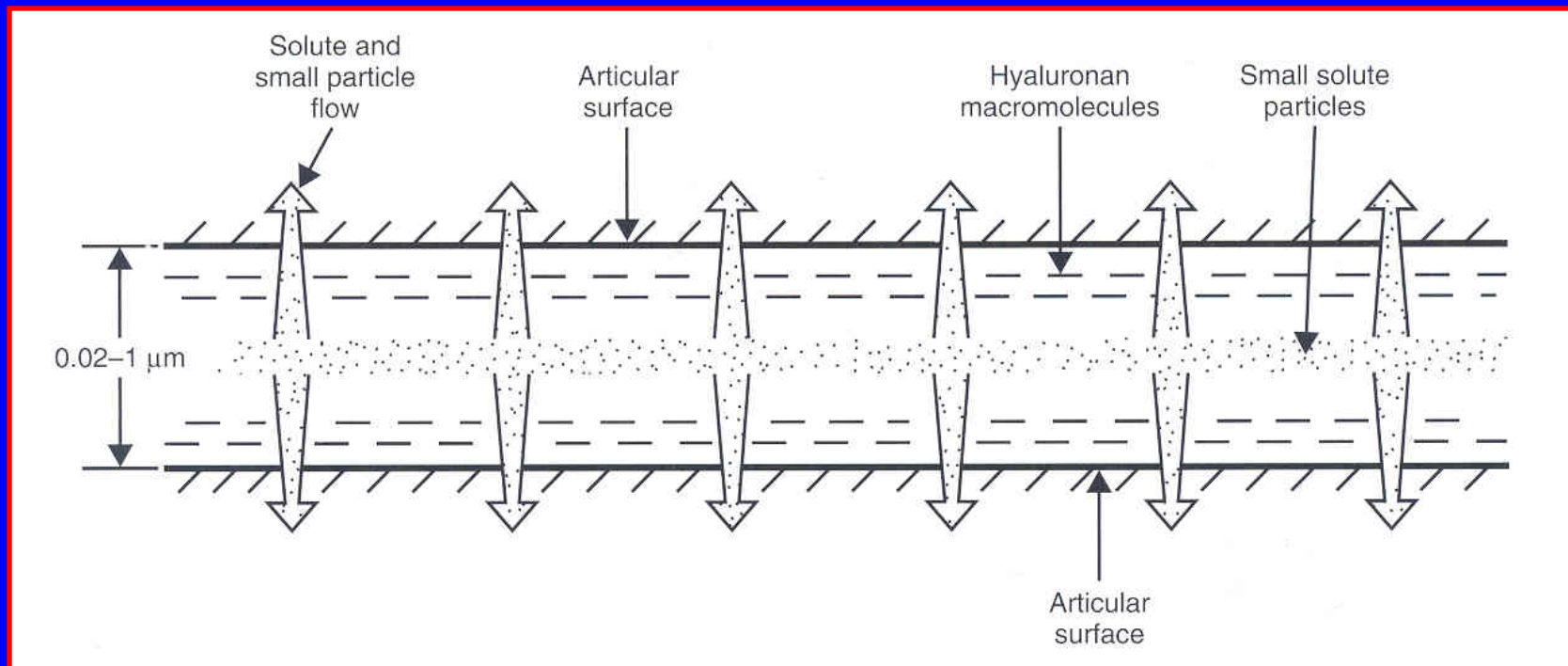
- Shift of fluid-film to boundary lubrication with time over the same location
- Articular surfaces protected during loading by ultrafiltration of synovial through the collagen-PG matrix



Modes of Mixed Lubrication

2. Boosted lubrication (continued)

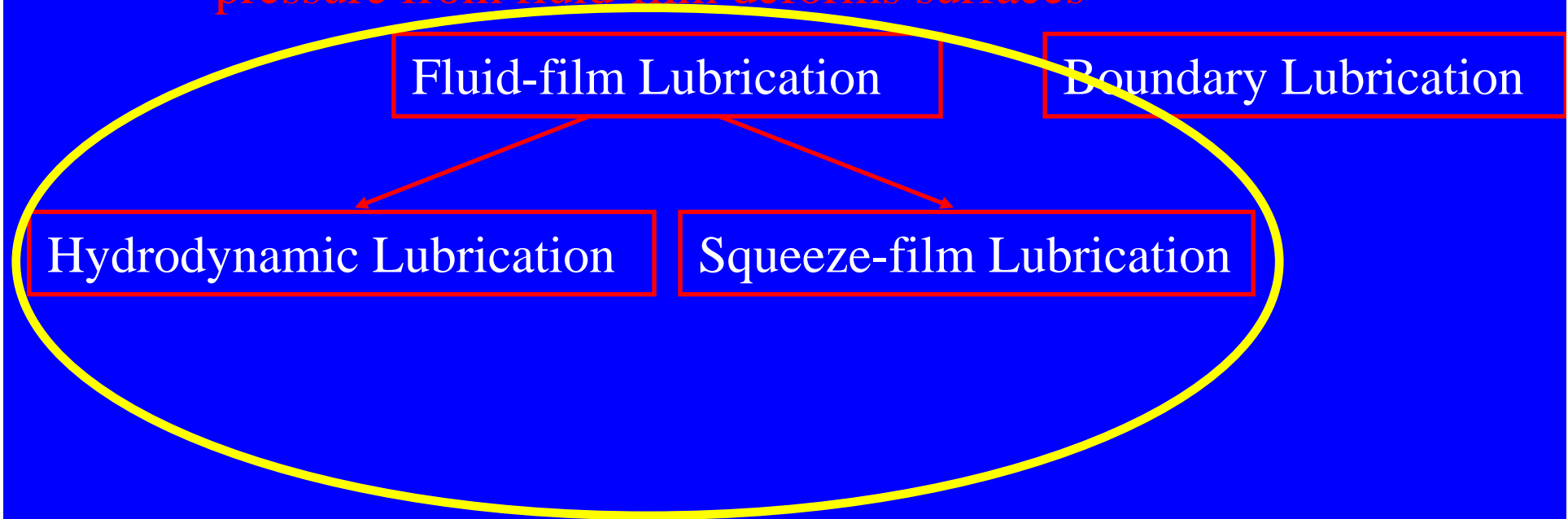
- Solvent component of synovial fluid passes into the articular cartilage during squeeze-film action yielding a concentrated gel of HA protein complex that coats and lubricates the surfaces
- As articular surfaces approach each other, difficult for HA macromolecules to escape from gap between surfaces



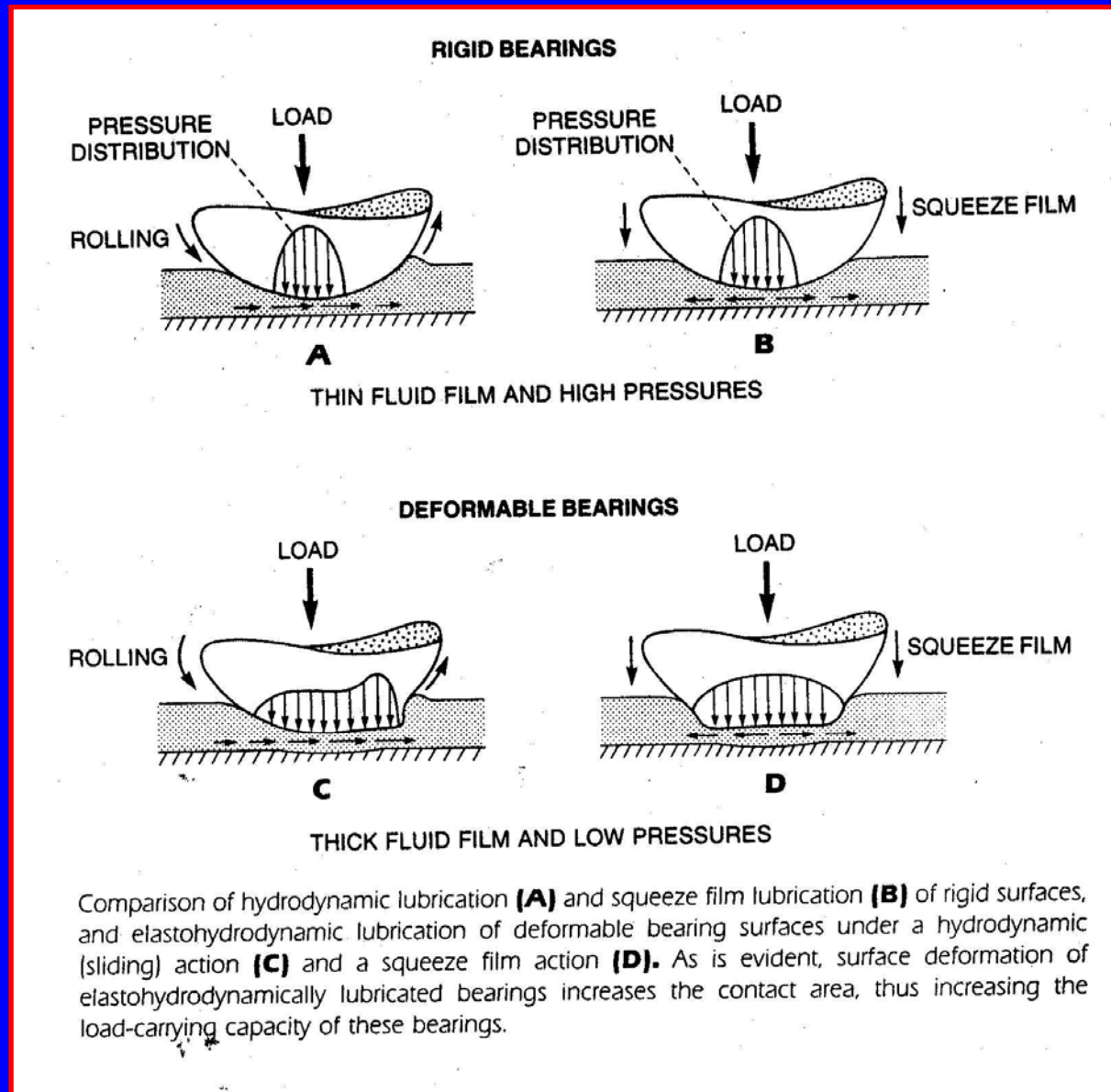
Variation of Lubrication Processes for Articular Cartilage

Elastohydrodynamic Lubrication

- associated with deformable articular cartilage
- pressure from fluid-film deforms surfaces



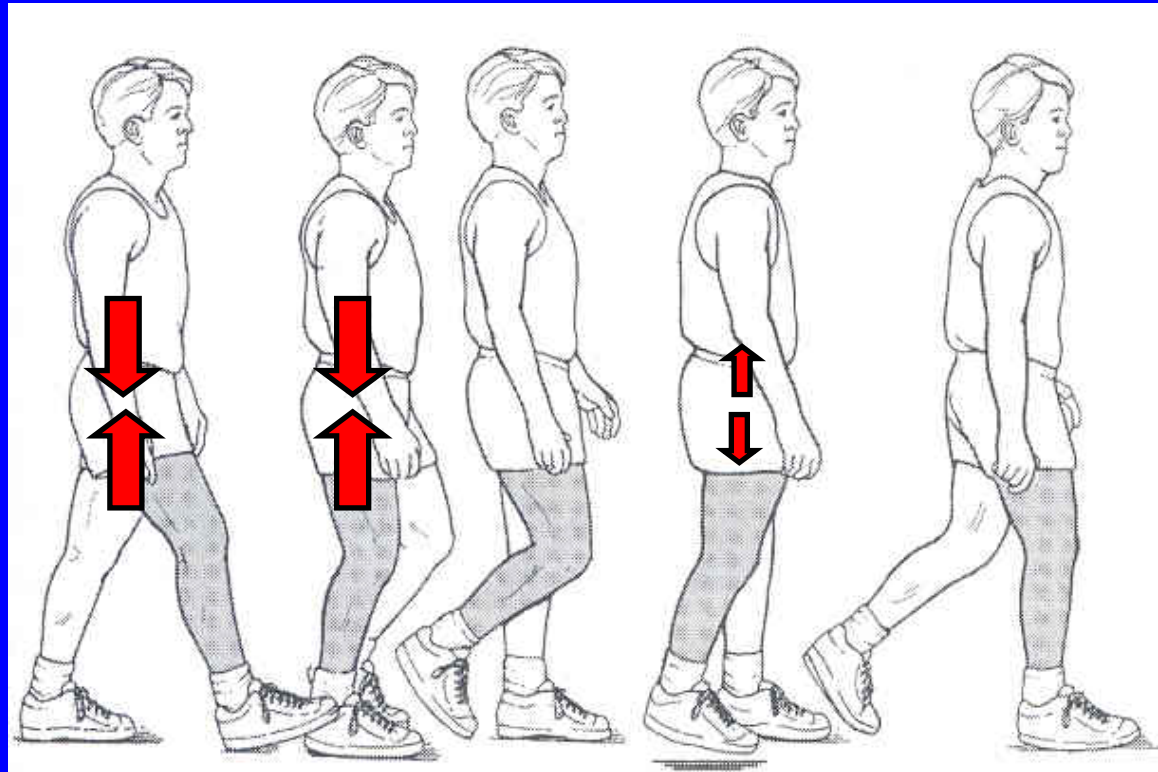
Comparison of Hydrodynamic and Squeeze-film Lubrication under Rigid and Elastodynamic Conditions



Elastohydrodynamic Lubrication

- Beneficial increase in surface areas
 - Lubricant escapes less rapidly from between the bearing surfaces
 - Longer lasting lubricant film generated
 - Stress of articulation lower and more sustainable
- Elastohydrodynamic lubrication greatly increases load bearing capacity

Dynamic Relationship between Vertical Load and Hip Joint Lubrication



Support phase

Swing phase

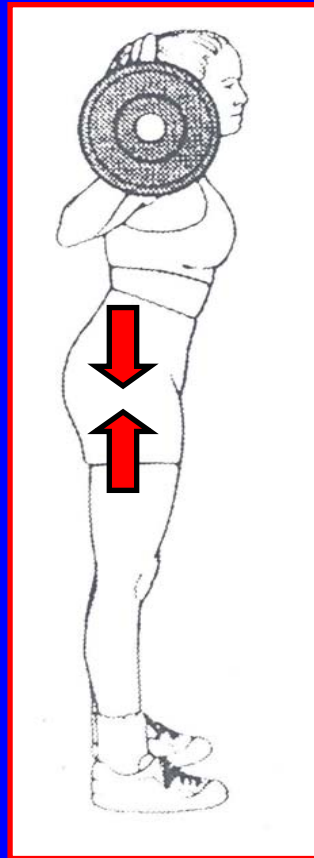
Support phase

- Initial load on hip at heel contact likely supported by hydrodynamic lubrication
- As load continues, fluid is squeezed between articular surfaces and is supported more by squeeze-film lubrication

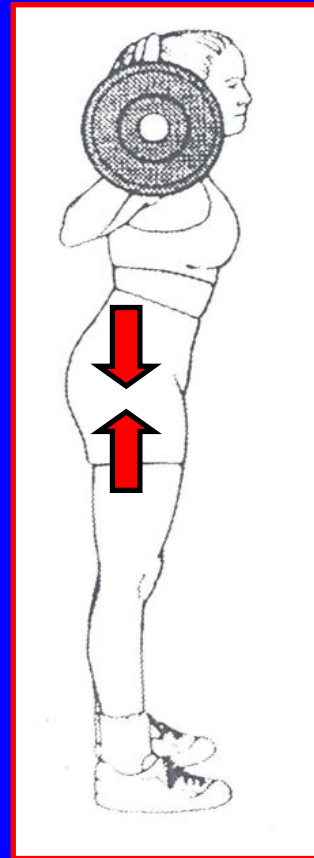
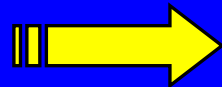
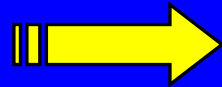
Swing phase

- Small vertical load on hip articular cartilage supported by hydrodynamic lubrication

Dynamic Relationship between Vertical Load and Hip Joint Lubrication



time = start



time = 3 minutes

Time = start

- Load on hip supported by squeeze-film lubrication

Time = 3 minutes

- Over time fluid-film may be eliminated and surface-to-surface contact may occur
- Surfaces protected by thin layer of ultrafiltrated synovial gel (boosted lubrication) or by the adsorbed lubricin monolayer (boundary lubrication)

Two Types of Wear of Articular Cartilage

- Interfacial – due to interaction between bearing surfaces
 - **Adhesion wear** – surface fragments from bearing surfaces in contact with each other adhere and are torn away
 - **Abrasion wear** – soft material is scraped by hard material (opposing surface or loose particles)

*Effective joint lubricating system makes interfacial wear unlikely under normal articular cartilage conditions

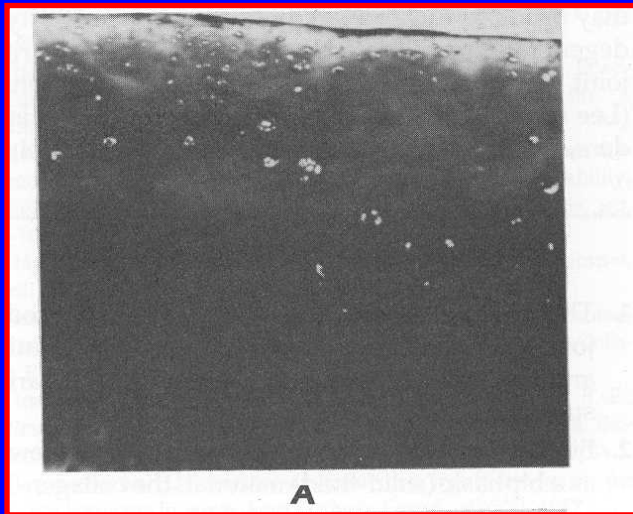
*Interfacial wear may take place in an impaired or degenerated synovial joint

- Fatigue wear
 - due to accumulation of microscopic damage within the bearing material under repetitive stress; not from surface-to-surface contact
 - Bearing surface failure from repeated application of high loads over short period of time or repetition of low loads over long period of time

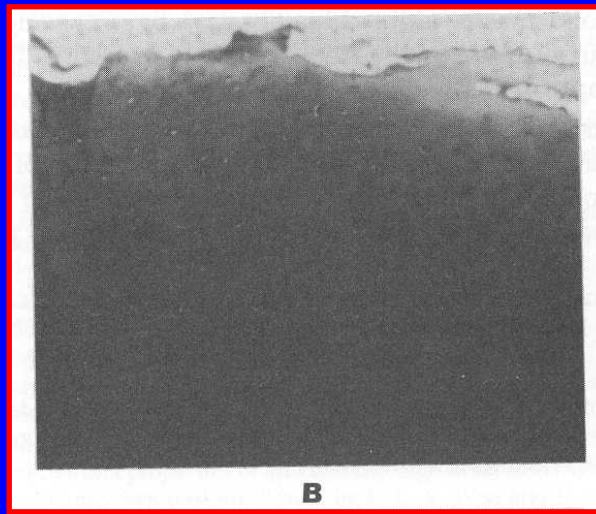
Potential Methods for Articular Cartilage Degeneration

- Magnitude of imposed stresses
- Total number of sustained stress peaks
- Change in the collagen-PG matrix
- Change in mechanical properties of the tissue

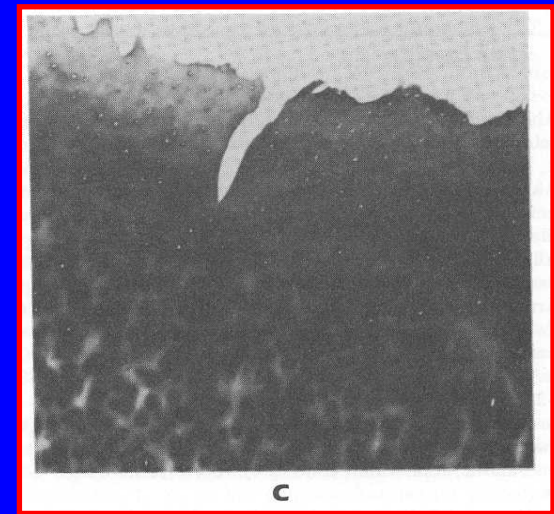
Articular Surface of Cartilage



**Normal intact
surface**



**Eroded articular
surface**



**Vertical split in
articular surface**