Physiotherapy Department

PT201: Biomechanics

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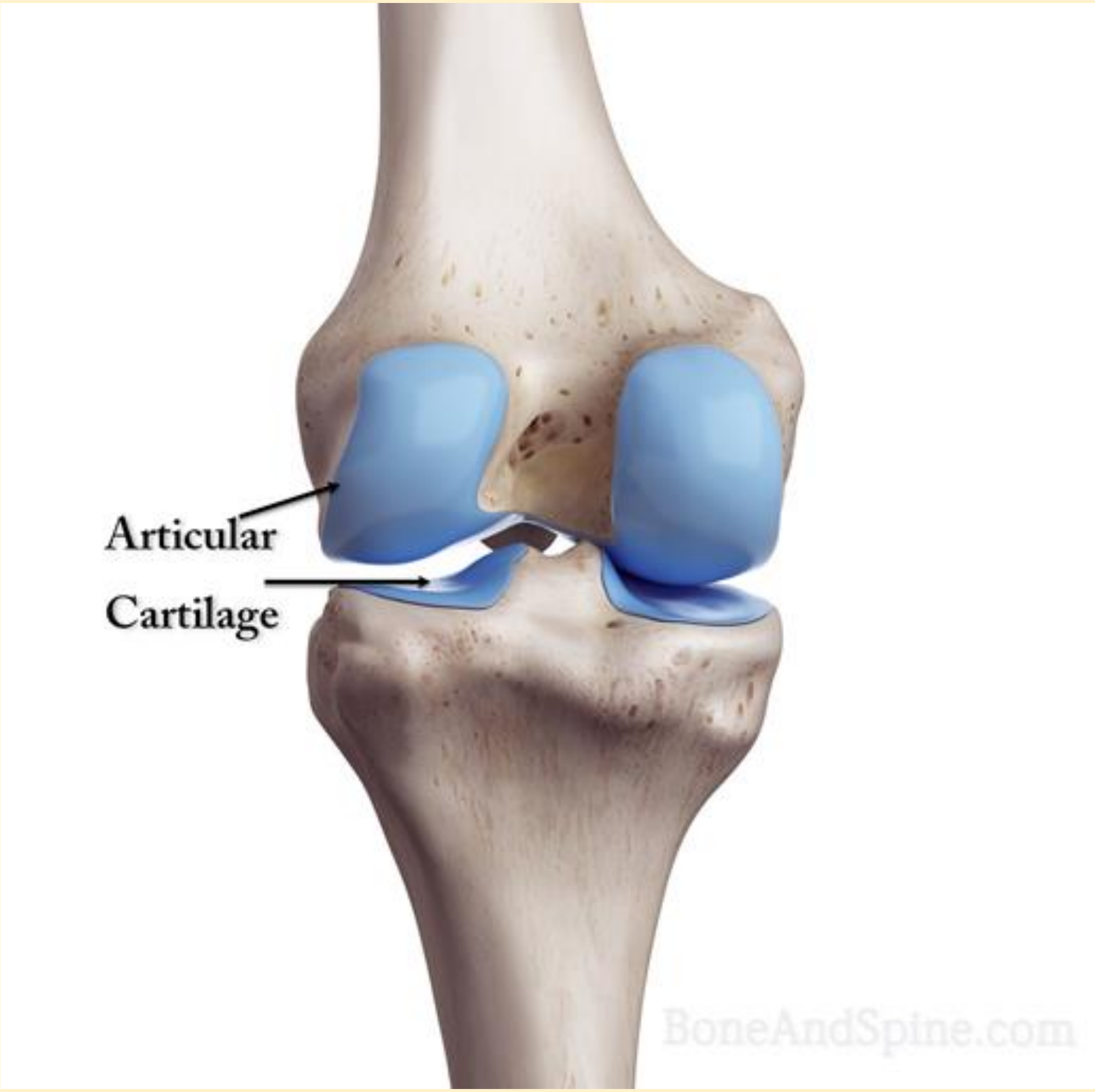
Biomechanics of Bone and Cartilage



Lecture 3

Biomechanics of Bone and Cartilage

17-10-2023

Synopsis

- Overview of bone
- Biomechanics of bone
- Overview of cartilage
- Biomechanics of cartilage

Objectives

- By the end of this lecture, students should understand and be able to describe the basic structure and biomechanical behaviors of the following:
  - ➢Bone
  - ➢Cartilage

Overview

- The skeletal system serves the following purposes
  - Protects internal organs
  - Provides kinematic links and muscle attachment sites
  - Facilitates muscle action and body movement

- Characteristically, the bone is:
  - Hardest tissue in the body
  - Highly vascularized
  - Self-repairing and adapting in response to changes in mechanical demand, e.g., changes in bone mineral density

Bone

Structure of bone

- Mechanical properties of bone are determined primarily by the structural components of bone

- Structurally, the bone is made up of organic and inorganic components

- The organic components consists of cells and organic extracellular matrix (fibers and ground substances, providing flexibility to the bone)

- The inorganic components comprises minerals that make the bone hard and rigid

Bone

- Cells: Osteoblast, Osteocytes, and Osteoclast
  - ➢Osteoblasts; Bone forming cells
  - ➢Osteocytes; Mature bone cells
  - ➢Osteoclasts; Bone resorption/breakdown cells

- Fibers: Type I collagen fibers
  - ➢90% of the Extracellular Matrix
  - ➢Tough and pliable i.e., resist stretching
  - ➢25-30% of dry weight
  - ➢Chief building block of the body

Bone

Types	Locations
Type I	Bone, skin, dentin, cornea, blood vessels, fibrocartilage and tendon
Type II	Cartilaginous tissues
Type III	Skin, ligaments, blood vessels and internal organs
Type IV	Basement membrane in various tissues
Type V	Blood vessel wall, synovium, corneal stoma, tendon, lung, bone, cartilage and skeletal muscle

Common types of collagen

Bone

- Ground substance:
  - 5% of Extracellular Matrix
  - Rich in glycosaminoglycan (GAGs)
  - GAGs serves as cementing substance between layers of collagen fibers

- Mineral: Hydroxyapatite (HA), a calcium phosphate–based mineral ($Ca_{10}(PO_4)_6(OH)_2$)
  - 60-70% of dry weight
  - Embedded in collagen fibers

- Water:
  - 25% total weight of the bone
  - 85% (in organic matrix) + 15% (in canals & cavities)
  - carry nutrients to bone tissues

Bone

Types of bone tissue

- There are two types of bone tissue
  - Compact
  - Spongy

- Compact and spongy bones differ in density and how tightly the tissue are packed together.

- Osteoblasts, osteocytes, and Osteoclasts contribute to bone homeostasis

- An equilibrium between osteoblasts and osteoclasts maintains bone tissue

Bone

Compact (Cortical) bone

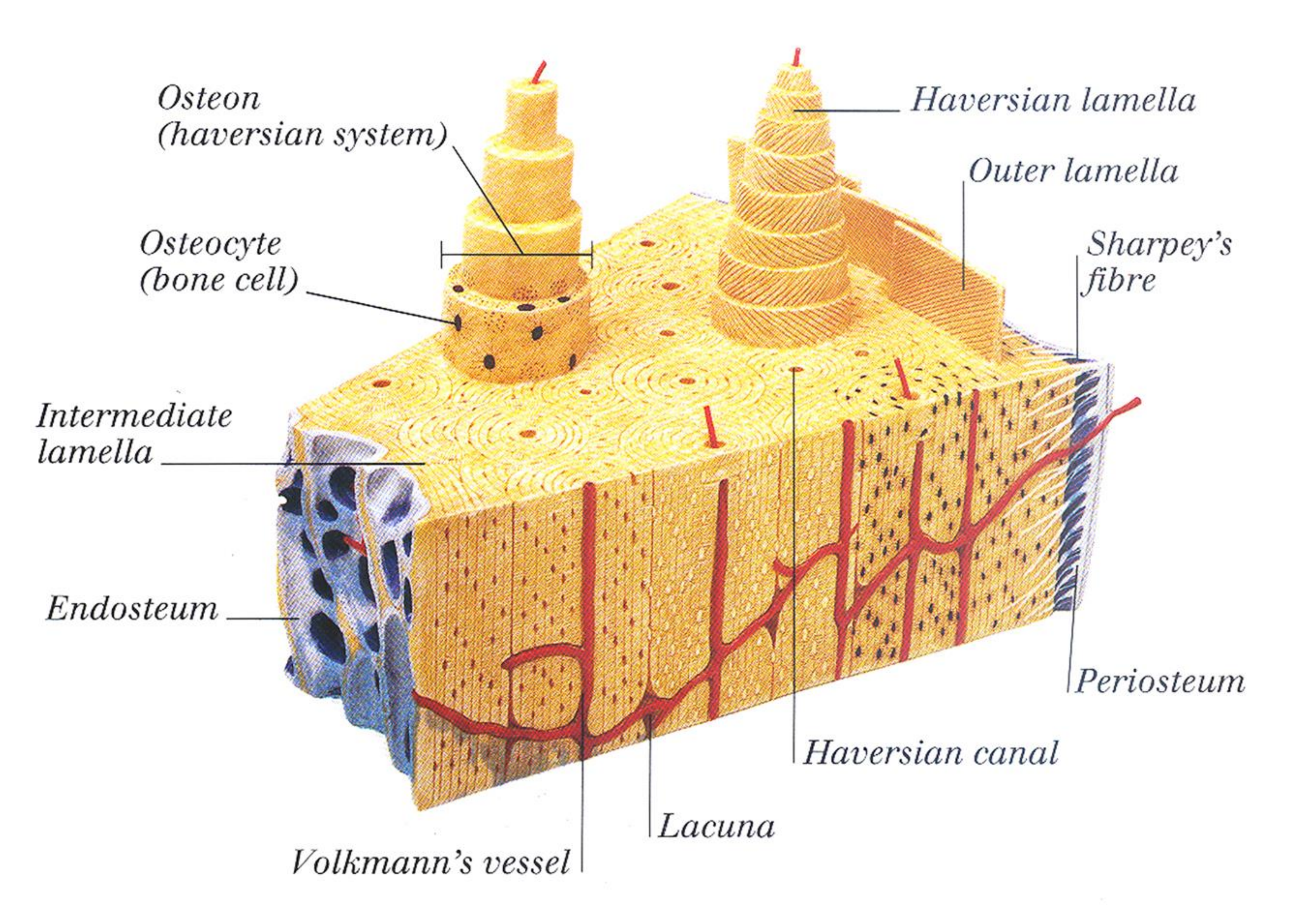
- Compact bone consists of closely packed osteons or haversian systems
- The osteon consists of a central canal called the osteonic (haversian) canal, which is surrounded by concentric rings (lamellae) of matrix
- Between the rings of matrix, the bone cells (osteocytes) are located in spaces called lacunae
- Small channels (canaliculi) radiate from the lacunae to the osteonic (haversian) canal to provide passageways through the hard matrix

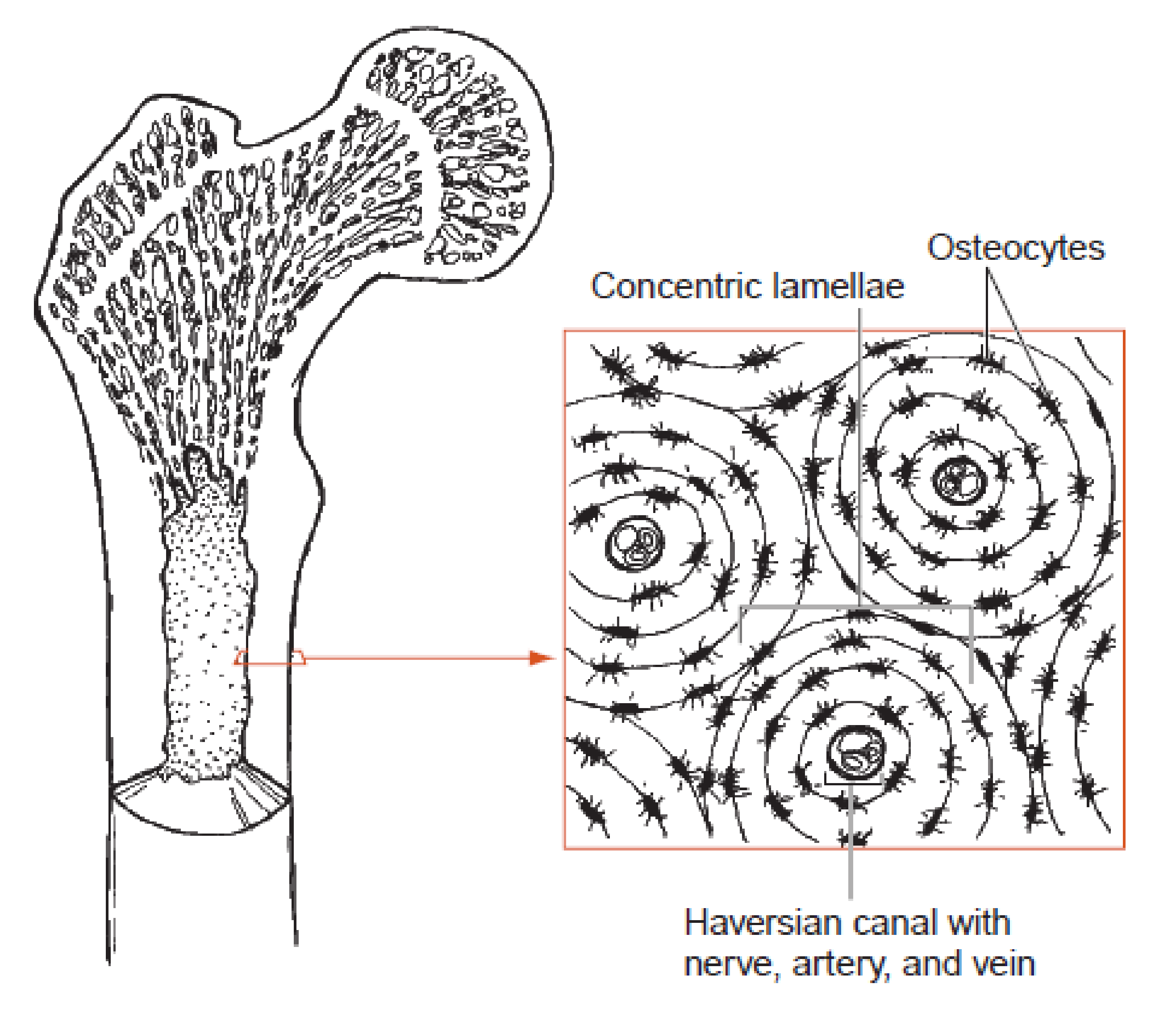
Bone

- In compact bone, the haversian systems are packed tightly together to form what appears to be a solid mass

- The osteonic canals contain blood vessels that are parallel to the long axis of the bone.

- The blood vessels interconnect, by way of perforating canals, with vessels on the surface of the bone


Osteon
(haversian system)
Haversian lamella
Outer lamella
Osteocyte
(bone cell)
Sharpey's
fibre
Intermediate
lamella
Endosteum
Periosteum
Haversian canal
Lacuna
Volkmann's vessel


Osteocytes
Concentric lamellae
Haversian canal with
nerve, artery, and vein

Bone

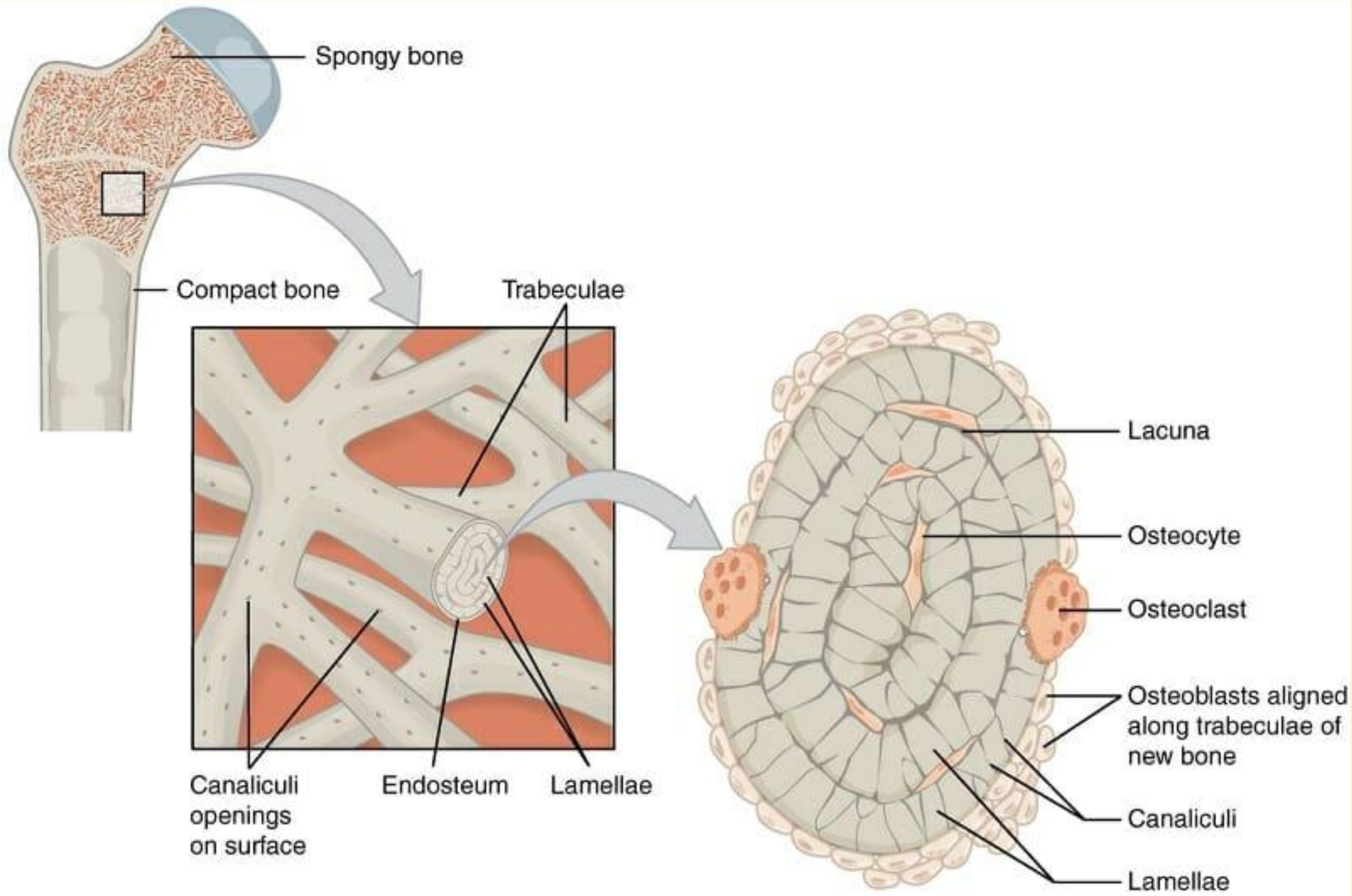
Spongy (Cancellous) bone

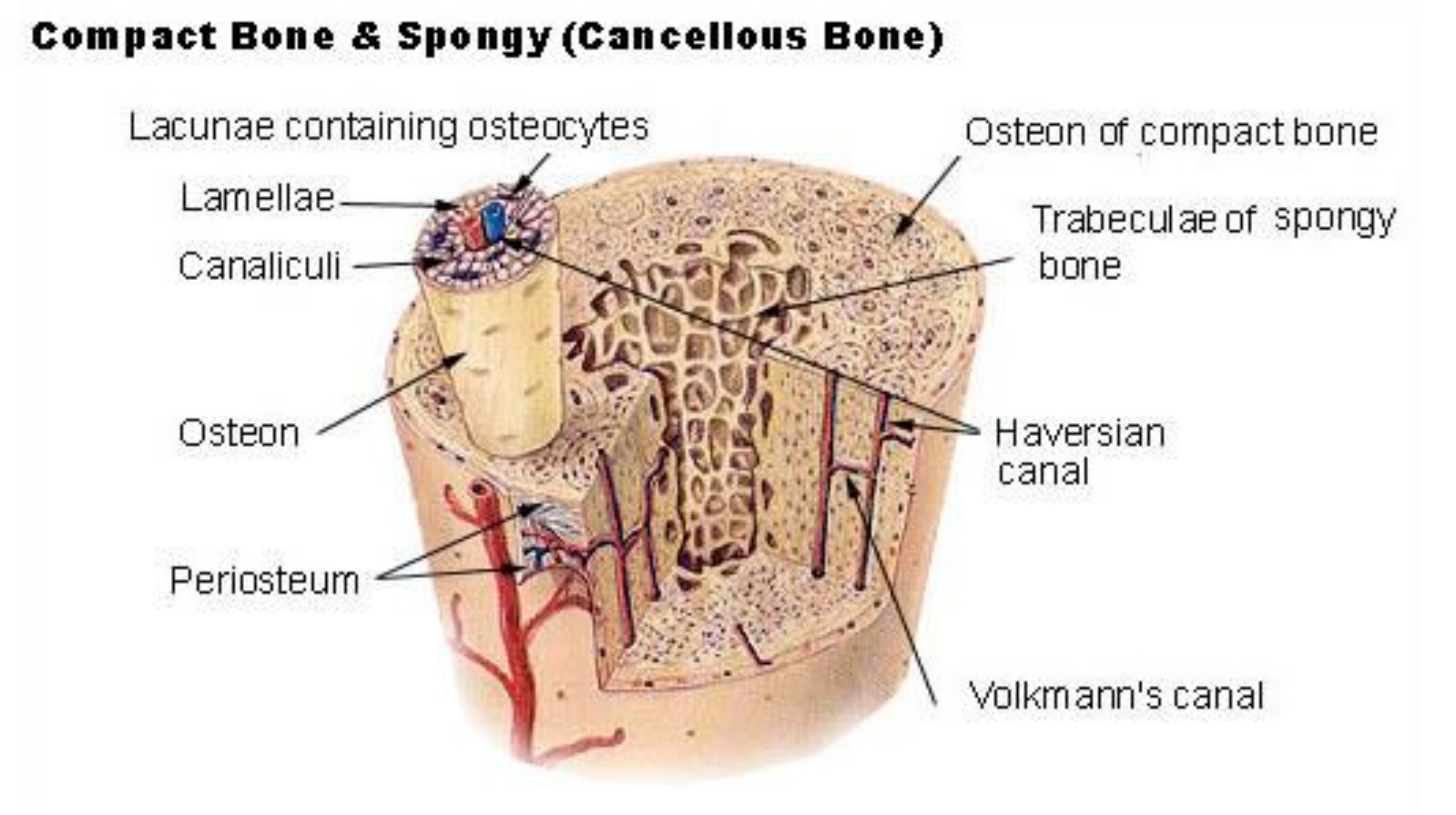
- Consists of plates (trabeculae) and bars of bone adjacent to small, irregular cavities that contain red bone marrow

- The canaliculi connect to the adjacent cavities, instead of a central haversian canal, to receive their blood supply.

- It may appear that the trabeculae are arranged in a haphazard manner, but they are organized to provide maximum strength similar to braces that are used to support a building.

- The trabeculae of spongy bone follow the lines of stress and can realign if the direction of stress changes.


Spongy bone
Compact bone
Trabeculae
Canaliculi openings on surface
Endosteum
Lamellae
Lacuna
Osteocyte
Osteoclast
Osteoblasts aligned along trabeculae of new bone
Canaliculi
Lamellae


Compact Bone & Spongy (Cancellous Bone)
Lacunae containing osteocytes
Lamellae
Canaliculi
Osteon
Periosteum
Osteon of compact bone
Trabeculae of spongy bone
Haversian canal
Volkmann's canal

Bone

Biomechanical properties of bone

- Mechanical properties of bone vary with both the type of bone (e.g., cancellous vs. cortical) and with the location of the bone (e.g., rib vs. femur)

- Bone is an anisotropic material; it has different mechanical properties in different directions

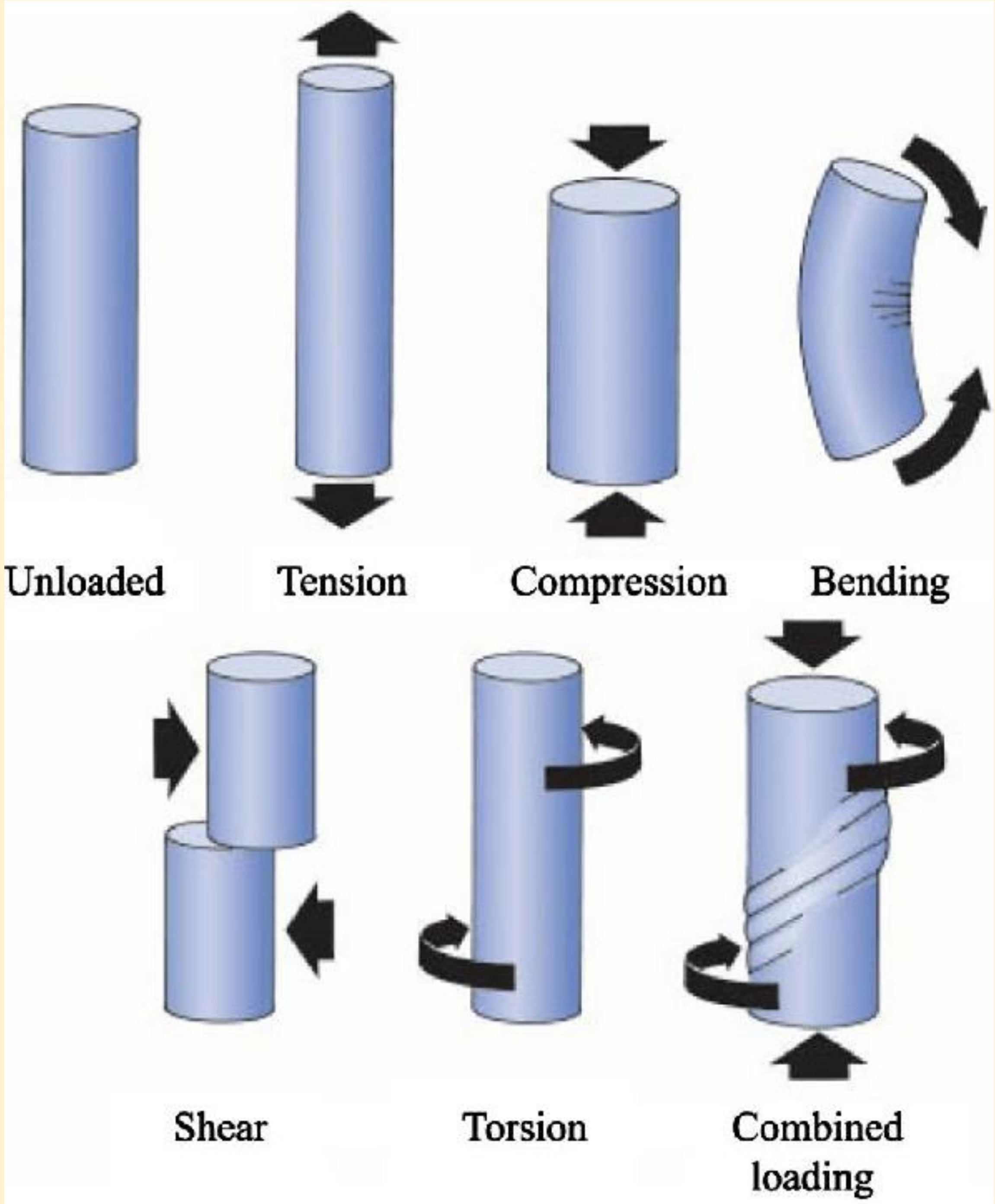
- The bone is strong to support loads in the longitudinal direction because it is used to receive loads in this direction

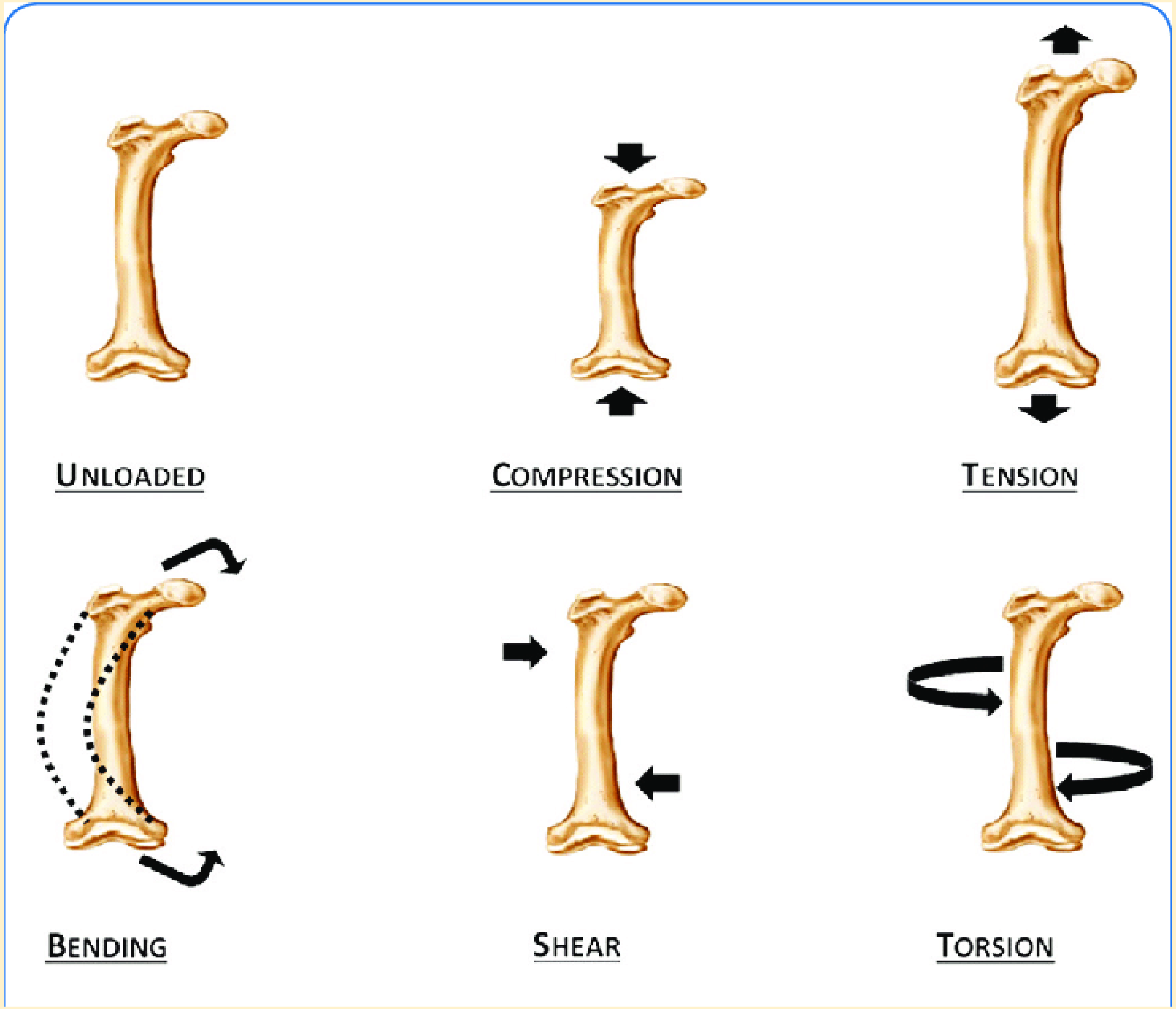
- Bone is also a composite material (consisting primarily of collagen and HA mineral) and behaves like a ceramic: it is stronger in compression than in tension, and it exhibits brittle fracture

Bone

- Bone is also viscoelastic: it responds differently depending on the speed to which load is applied and length of the load
- Bone collagen imparts viscoelastic behavior, as well as increase the tensile strength of the bone
- Bone is more ductile in young people and more brittle in older adults
- When bone is loaded or stressed, it tends to build up and becomes denser with use
- When activity decreases and the loads on the bone decrease, the bone loses mass through remodeling

Schematic representation of various loading modes





Schematic representation of various loading modes on bone

Bone

- Bones are subjected to different forms of loading and fail under different conditions
- Long bones (tibia and femur) sustain large compressive loads at the joint but commonly fail due to torsional forces, such as those applied to the tibia in a spiral fracture
- Vertebral fractures, on the other hand, are more commonly the result of compressive forces on the vertebral body
- Tensile forces produce avulsion fractures when ligaments or tendons are pulled away from their bony attachments

Cartilage

- Cartilage is a non-vascular type of supporting connective tissue that is found throughout the body
- Cartilage is a flexible connective tissue that differs from bone in several ways; it is avascular and its microarchitecture is less organized than bone
- Cartilage cells are scattered and lie firmly fixed in matrix supported by collagen and elastic fibers
- Cartilage is not innervated and therefore relies on diffusion to obtain nutrients. This causes it to heal very slowly

Cartilage

Types of Cartilage

- There are three types of cartilage:
  - Hyaline
  - Fibrous
  - Elastic

- Hyaline cartilage is the most typical and resembles glass. Embryonically, bone begins as hyaline cartilage and later ossifies

- Fibrous cartilage has many collagen fibers and is found in the intervertebral discs and pubic symphysis

- Elastic cartilage is springy, yellow, and elastic and is found in the internal support of the external ear and in the epiglottis

Type	Appearance	Location
Hyaline	Glassy, smooth	Covers long bones, growth plates
Fibro	Dense	Intervertebral disks, meniscus
Elastic	Yellow, opaque	Epiglottis, eustachian tube

Type and distribution of cartilage in the body

Cartilage

Structure of articular cartilage

- Articular cartilage is the highly specialized connective tissue of diarthrodial joints

- The principal function of articular cartilage is to:
  - Provide a smooth, lubricated surface for articulation
  - Facilitate the transmission of loads with a low frictional coefficient

- Articular cartilage (2-4mm thick) is composed of:
  - Dense extracellular matrix (98%)
  - Specialized cells called chondrocytes (2%)

Cartilage

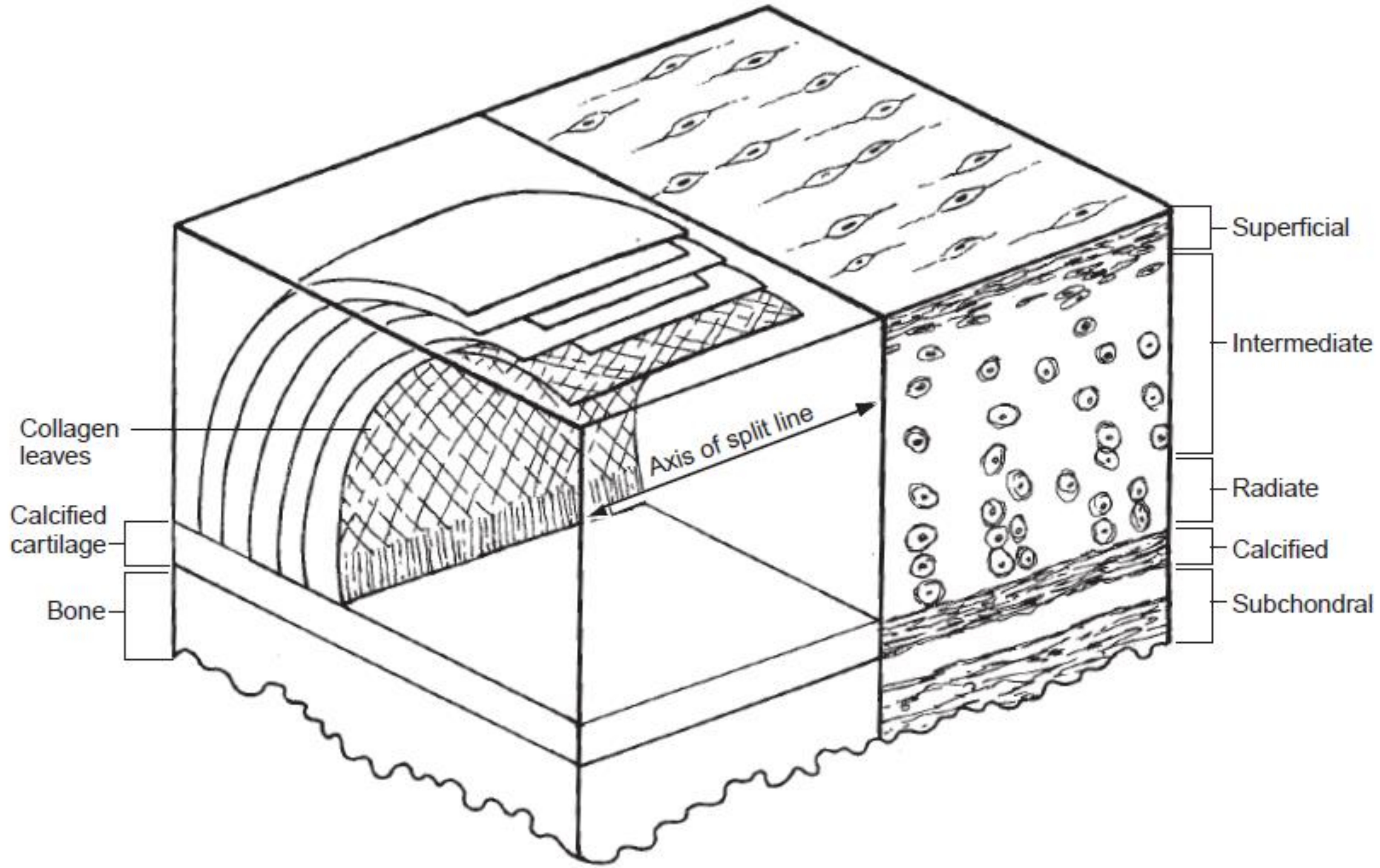
- Extracellular matrix (ECM) consists of:
  - Water (70%–85% of the whole weight)
  - Collagen (type II, makes up about 60% of the dry weight of cartilage)
  - Proteoglycans (10%–15% of the wet weight)
  - Noncollagenous proteins
  - Glycoproteins
- Components of the ECM help to retain water within the ECM, which is critical to maintaining its unique mechanical properties

Cartilage

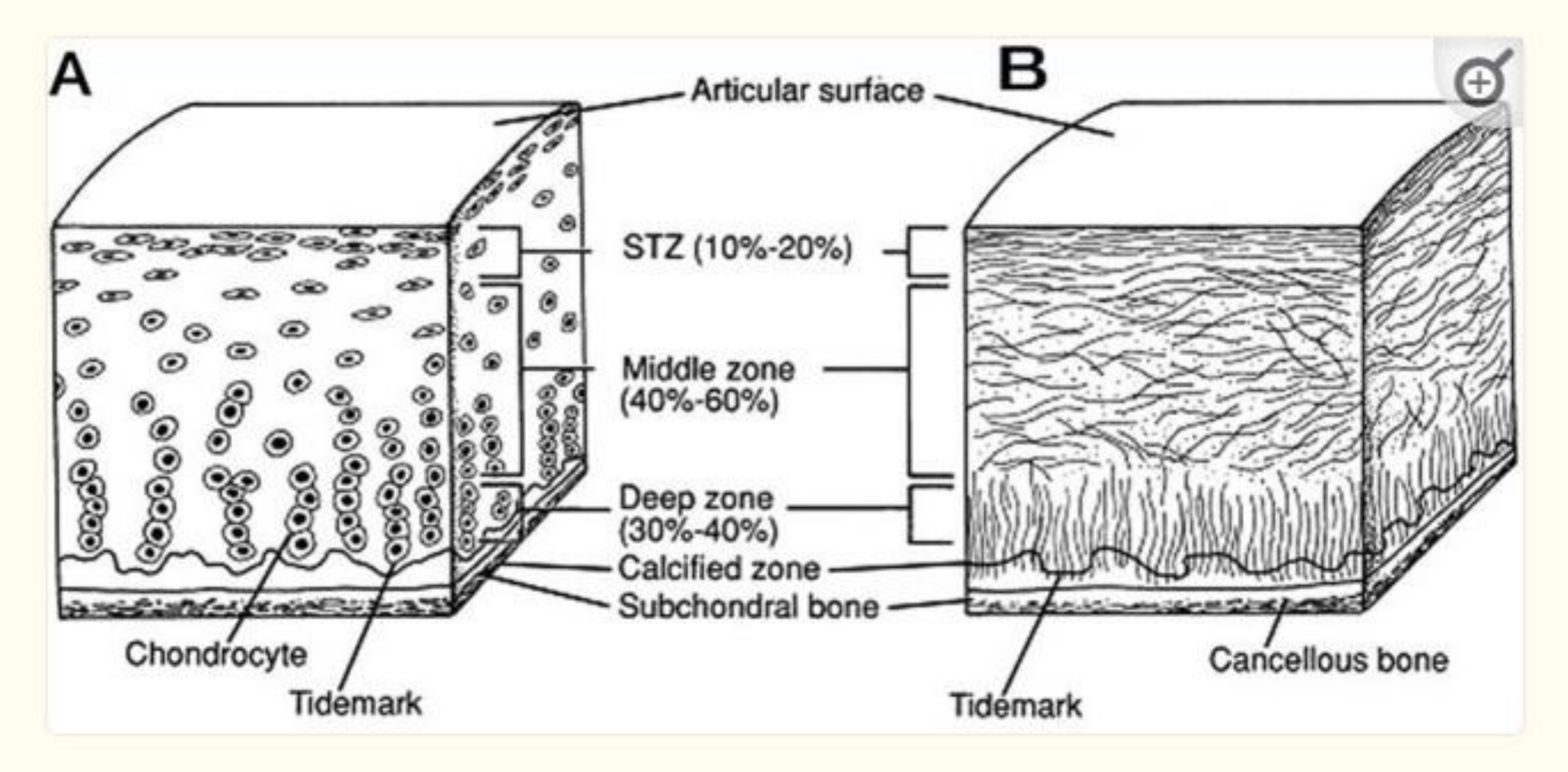
- Chondrocytes are highly specialized cells that synthesize, maintain, and degrade the extracellular matrix
- Chondrocytes originate from mesenchymal cells and vary in shape, number, and size, depending on the anatomical regions of the articular cartilage
- Chondrocytes have limited potential for replication, a factor that contributes to the limited intrinsic healing capacity of cartilage in response to injury
- Chondrocyte survival depends on an optimal chemical and mechanical environment

Cartilage

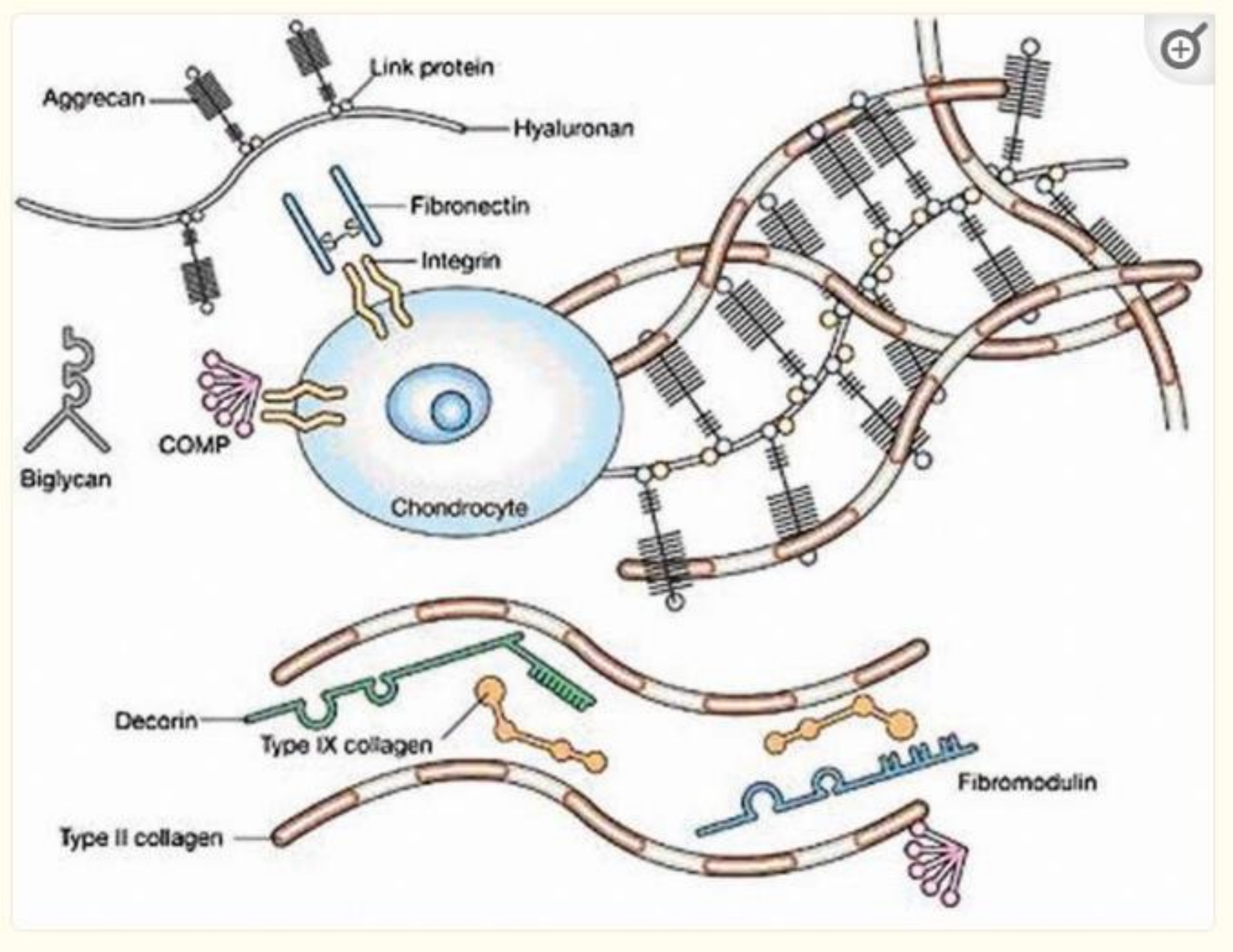
- Articular cartilage is often described in terms of 4 structural zones between the articular surface and the subchondral bone:
  - Surface or superficial tangential zone (STZ)
  - Intermediate or middle zone
  - Deep or radiate zone
  - Calcified zone
- Within each zone, there are 3 regions:
  - Pericellular region
  - Territorial region
  - Interterritorial region



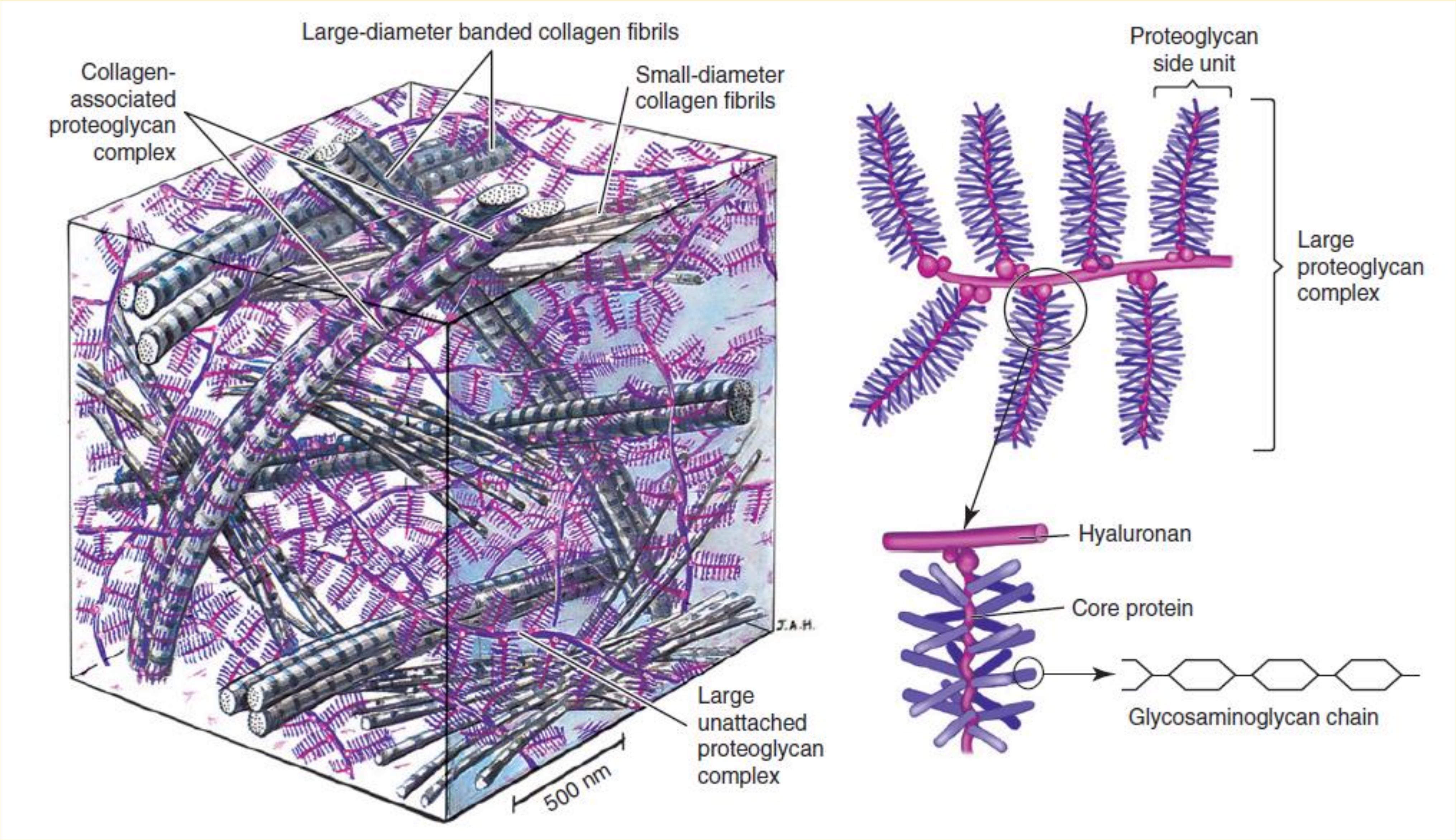
Cellular organization in the zones of articular cartilage



A. cellular organization in the zones of articular cartilage; B. collagen fiber architecture



Extracellular matrix of articular cartilage



Histologic organization of the ground substance of (hyaline) articular cartilage

Cartilage

Biomechanical properties

- The mechanical behavior of articular cartilage depends on the interaction of its fluid and solid components
- Articular cartilage is biphasic, consisting of fluid and solid phases, which provide compressive resilience to cartilage
- Articular cartilage exhibit unique viscoelastic properties
- Articular cartilage is unique in its ability to withstand high cyclic loads, demonstrating little or no evidence of damage or degenerative change

Cartilage

- Repeated tensile loading (fatigue) lowers the tensile strength of cartilage
- Repeated compressive loads applied to the cartilage surface in situ also cause a decrease in tensile strength
- Exercise has both beneficial and detrimental effects on cartilage
- It produces positive biochemical changes and reduces pain and increases function in people with arthritis

Cartilage

- Conversely, sports injuries are significant contributors to osteoarthritis

- Activities that involve torsional loading, fast acceleration and deceleration, repetitive high impact, and high levels of participation increase the risk of developing osteoarthritis

- Articular cartilage is devoid of blood vessels, lymphatics, and nerves and is subject to a harsh biomechanical environment

- Articular cartilage has a limited capacity for intrinsic healing and repair; thus, preservation and health of articular cartilage are paramount to joint health

Cartilage

- Injury to articular cartilage is recognized as a cause of significant musculoskeletal morbidity
- The unique and complex structure of articular cartilage makes treatment and repair or restoration of the defects challenging
- Preservation of articular cartilage is highly dependent on maintaining its organized architecture

Contributions and Questions

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