Anatomy and Physiology of the Knee

by Richard B. Souza and Ryan Doan

Preview

This chapter details the normal anatomy and physiology of the knee. The focus of this chapter centers on those anatomical structures that are involved in osteoarthritis (OA). The chapter begins with MRI images of the healthy knee in all three cardinal planes (Figs. 1 to 3). These images will serve as a source of healthy tissue that can be referred back to in later chapters when discussing pathology within the knee joint.

The knee joint, once described as a simple hinge joint, is in fact a much more complex structure. There are three articulations: one between each femoral condyle and its associated tibial condyle, and one between the patella and the femur. This joint is a common location for pathology, with OA being one of the most common conditions affecting the knee. The three bones that form the knee joint (femur, tibia, and patella) are covered in thick articular cartilage and supported by several ligaments both inside and outside the joint capsule. Furthermore, the knee joint is supported by muscles on the anterior, medial and posterior aspects of the joint. The lateral joint is supported by dense connective tissue. Inside the joint, two fibrocartilagenous crescent-shaped menisci provide cushioning and improve joint congruity. Additional supportive anatomy includes several bursae and fat pads located throughout the knee joint. From the architecture and physiology of bone to the integrity of the menisci, the knee requires an orchestra of events to protect the articular cartilage from the degenerative process of OA.
Fig. 1. Axial $T_2$-weighted magnetic resonance images of the knee and surrounding structures.
Fig. 1. (Continued)
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Fig. 2. Coronal $T_2$-weighted magnetic resonance images of the knee and surrounding structures.
Fig. 2. (Continued)
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Fig. 3. Sagittal T₂-weighted magnetic resonance images of the knee and surrounding structures.
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Bone

Bone Structure

Bone is organized into compact bone and cancellous or trabecular bone. The cortex, or compact bone, consists of dense bone tissue. It forms the outer shell of the bone as well as much of the diaphysis, the shaft-like portion of long bones. In contrast, cancellous bone is relatively porous with bony spicules called trabeculae spanning pores. Cancellous bone is found within the epiphysis, the area at the ends of the long bones.

Other tissues found in close proximity to bone include periosteum, endosteum, blood vessels, nerves, and bone marrow. Periosteum is a fibrous layer that surrounds the outer surface of the bone. It includes fibroblasts, collagen, nerves and a pool of osteoprogenitor cells. These osteoprogenitor cells can differentiate into osteoblasts and play important roles in fracture healing. Endosteum is also a fibrous layer and it lines the inner surfaces of bones, which include the inner surface of cortical bone and the surface of the trabeculae. The composition of endosteum is similar to that of periosteum, but it is usually thinner. Osteoprogenitor cells in the endosteum contribute to bone remodeling, as will be discussed later. Bone marrow tissue fills the pores in trabecular bone. It is composed of adipocytes, hematopoietic stem cells, and mesenchymal stem cells. Hematopoietic stem cells are precursor cells that can differentiate to form leukocytes, erythrocytes, platelets, and osteoclasts. Mesenchymal stem cells are also found in the bone marrow, adherent to the surface of the trabeculae. These cells can differentiate to form chondrocytes, myocytes, adipocytes, and osteoblasts.

Bone tissue itself consists of two major components: bone matrix and cells. Bone matrix is made up of type 1 collagen, proteoglycans, glycoproteins, hydroxyapatite \((\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2)\), and various growth and regulatory factors. The matrix provides the actual structure for bone, provides much of the mechanical properties for bone, and supports the growth of bone cells. The cellular component of bone includes osteoblasts, osteoclasts, and osteocytes. These cells are responsible for formation, resorption, and maintenance of the bone matrix.

Bone matrix is structured as a series of lamellae. Each lamella is a layer of mineralized extracellular matrix that contains collagen fibers oriented parallel to each other, in a helical course. Furthermore, in cortical bone,
adjacent lamellae have collagen fiber orientations that are approximately perpendicular to each other. In trabeculae, the collagen fibers in the lamellae are oriented parallel to the long axis of the bony spicule. This anisotropy is responsible for the unique mechanical properties of bone. Osteocytes are housed in lacunae between lamellae. These cells extend processes into the lamellae through canaliculi, giving osteocytes the ability to communicate with each other and receive signals from the extracellular matrix. Blood vessels penetrate bone in canals called Volkmann’s canals, providing the tissue with important nutrients.

**Bone Remodeling**

Bone is constantly undergoing remodeling in response to mechanical stresses as well as metabolic factors. During remodeling, old bone is broken down and replaced with new bone. The first step of this process is resorption of old bone by osteoclasts, phagocytic cells derived from hematopoietic stem cells. Osteoclasts bind to the surface of the bone through adhesion molecules in the bone matrix, then form a seal around the area that will be resorbed. They will then release acid and metalloproteinases to break down the bone matrix. During this breakdown, growth factors and collagenases impregnated in the matrix are released, providing further stimulus for bone remodeling. Following resorption, osteoblasts lay down new unmineralized bone matrix in the lamellar arrangement described earlier. Osteoblasts that become trapped in the matrix during this process will eventually become osteocytes. Mineralization of bone matrix follows within 12 to 15 days as calcium and phosphate diffuse into the area and crystallize.

Osteoblasts and osteoclasts work together in a system called the basic multicellular unit. Osteoblasts have receptors for vitamin D, parathyroid hormone, and estrogen. Presence of these hormones stimulates osteoblasts through these receptors, enabling osteoblasts to produce a hormone called Receptor Activator of NF-kappaB Ligand (RANKL). RANKL binds Receptor Activator of NF-kappaB (RANK) receptors on osteoclasts, stimulating bone resorption. As bone resorption progresses, growth factors released from the matrix such as Transforming Growth Factor-Beta (TGF-β), Bone Morphogenic Protein (BMP), and Platelet Derived Growth Factor (PDGF) stimulate the differentiation and activation of osteoblasts to matrix-producing cells.
Fracture Healing

Upon injury, mesenchymal stem cells will be recruited to the site of fracture. These pluripotent stem cells will initially condense, forming cellular aggregates joined by adhesion molecules such as Neural Cell Adhesion Molecule (NCAM) and N-cadherin. After aggregation, these mesenchymal stem cells will begin to differentiate into chondrocytes. These proliferating chondrocytes express collagen-2 and Indian hedgehog protein (Ihh). Collagen 2 is incorporated into the extracellular matrix. Ihh expression may stimulate the proliferation of prehypertrophic chondrocytes through production of Parathyroid Hormone Related Protein (PTH-RP). Bone morphogenetic protein-7 (BMP7) also stimulates proliferation of these chondrocytes while Fibroblast Growth Factor-3 (FGF3) inhibits proliferation. Runx2 stimulates these proliferative chondrocytes to become hypertrophic. The chondrocytes separate, enlarge in size and begin secretion of type X collagen and Vascular Endothelial Growth Factor (VEGF). VEGF stimulates angiogenesis; osteoprogenitors derived from mesenchymal stem cells arrive with the invasion of new blood vessels. Osteoprogenitors differentiate into osteoblasts under the control of Runx2, Ihh and BMPs. Differentiated osteoblasts secrete osteoid over the cartilage matrix. Hypertrophic chondrocytes die as the surrounding matrix is calcified. Osteoblasts trapped in the matrix differentiate into osteocytes. Invading osteoclasts, differentiated from a monocyte lineage, initiate remodeling. These break down matrix using cathepsin K, metalloproteinases and hydrochloric acid. These osteoclasts are followed by differentiated osteoblasts, which will fill in bone. The combined action of osteoblasts and osteoclasts help the bone achieve its final form.

Anatomical Structures of Knee

The knee includes the distal end of the femur, the proximal end of the tibia, and the patella. The distal end of the femur is composed of two condyles, which articulate with the proximal tibia. The anterior portion of the condyle is relatively flat compared with the posterior portion. This flattened area serves as the weight-bearing portion of the condyle. The anterior condyles are separated by a groove called the trochlea or patellofemoral groove. The posterior aspect of the condyles are rounded.
and separated by the intercondylar notch. The posterior intercondylar region provides attachment points for the anterior and posterior cruciate ligaments.

The proximal end of the tibia is also composed of two condyles, also called plateaus, that articulate with the femoral condyles. The medial plateau is slightly larger and flatter than the lateral plateau. The plateaus are separated by the intercondylar region, which provides attachment sites for the medial meniscus, lateral meniscus, anterior cruciate ligament, and posterior cruciate ligament. The tibial tuberosity is also located between the plateaus, on the anterior surface of the tibia. It serves as the attachment point for the patellar tendon.

The patella is a sesamoid bone that is roughly triangular in shape. Its proximal edge is wider than the distal edge, providing a broad attachment for the quadriceps femoris tendon. The narrow distal edge provides an attachment for the patellar ligament, which connects the patella to the tibial tuberosity. The posterior aspect of the patella has a medial and lateral facet, which articulate with the medial and lateral condyles of the femur, respectively. The lateral facet is larger than the medial facet.

**Cartilage**

**Cartilage Structure**

Cartilage is found in the human body in one of three different forms: hyaline cartilage, elastic cartilage, and fibrocartilage. Hyaline cartilage is the most common form, found in joint (articular) surfaces, nose, larynx, trachea, and bronchi. Fibrocartilage, a type of cartilage that is more dense, fibrous and resistant to tensile loading, serves as a key component in intervertebral discs, menisci of the knee, tendon insertions, sternoclavicular joints, mandibular joints, and the pubic symphysis. Elastic cartilage, as its name suggests, is the most flexible form of cartilage and helps form the external ear, the epiglottis, and part of the larynx.

The three types of cartilage all share a basic structure composed of chondrocytes and extracellular matrix, but differ in the components of their extracellular matrix. Chondrocytes, the cellular component of cartilage, are responsible for production and maintenance of the extracellular matrix. Hyaline cartilage contains an extracellular matrix (ECM) primarily made up
of hyaluronic acid, proteoglycans, type II collagen, and water. The ECM of fibrocartilage is more fibrous and dense because of the abundance of type I collagen and the relative scarcity of water and proteoglycans. Elastic cartilage ECM has all of the same components of the hyaline cartilage ECM, with the addition of elastic fibers that provide it with its unique flexibility.

Interactions between the components of the ECM in articular cartilage form the basis for much of the mechanical properties of cartilage. Proteoglycans are molecules that consist of glycosaminoglycans attached to a protein. In articular cartilage, the most abundant proteoglycan is aggrecan. The aggrecan molecule is composed of chains of two types of glycosaminoglycans, chondroitin sulfate and keratan sulfate, attached to a central protein core. The structure has often been compared to a “bottle brush,” with the protein representing the metal core and the glycosaminoglycan chains representing the brush bristles. Hundreds of aggrecan molecules may noncovalently bind to a hyaluronate molecule, resulting in fixation of aggrecan. Thus, these aggrecan molecules are unable to move within the cartilage matrix. These fixed aggrecan molecules attract water with the negative charges on their glycosaminoglycan chains and trap water between molecules, resulting in swelling of the extracellular matrix. This hydrostatic swelling is balanced by tension in type II collagen fibers. The negative charges on these glycosaminoglycans also repel each other when the cartilage matrix is compressed, providing cartilage with resiliency.

When viewed in cross-section, articular cartilage is organized into four zones based on depth from the surface. The most superficial layer of articular cartilage, zone 1 or tangential zone, primarily consists of collagen fibers that are parallel to the joint surface. This layer is under tension and resists swelling from the deeper layers. The layer deep to the superficial zone is zone 2, or the transitional zone. In zone 2, collagen fibers are arranged in random orientations. Zone 3 is characterized by collagen fibers that are oriented radially from the deepest layer of the cartilage to the surface. Lastly, zone 4 mainly consists of calcified cartilage and serves as the attachment of cartilage to underlying subchondral bone.

In the knee joint, hyaline cartilage covers the articulating surfaces of the femur, tibia, and patella. Hyaline cartilage, also known as articular cartilage, facilitates the sliding motion of the joint. Fibrocartilage can also be found in
the knee joint, especially following injury. A mixture of fibrocartilage-like cartilage and hyaline-like cartilage makes up the meniscus.

**Histology of Cartilage**

A variety of histological techniques have been employed to stain articular cartilage. Hematoxylin and eosin is a commonly used staining combination that has been applied to all tissues of the body. It is a nonspecific stain that colors nuclei blue and cytoplasm pink. It can be used to evaluate general morphological features of articular cartilage tissue. However, in the study of articular cartilage, it is often helpful to employ stains that are specifically directed against proteoglycans and collagen. Proteoglycan staining can be achieved by the use of safranin O or toluidine blue. The intensity of staining has been correlated with proteoglycan content for both of these stains. However, safranin O provides a superior correlation. For this reason, safranin O is the most widely used cartilage staining technique. It is often used in combination with fast green FCF and hematoxylin, which stain protein and nuclei, respectively. The safranin O/fast green FCF/hematoxylin combination stains the extracellular matrix red, the subchondral bone gray, and nuclei blue. Alcian blue is another stain for proteoglycans that has been used in the past. However, the intensity of staining is not correlated to proteoglycan content. Thus, it is not often used in histological analysis because it provides no information on proteoglycan changes that are often seen in osteoarthritis. Lastly, sirius red F3BA is a stain for collagen that has been used in the past. However, it is difficult to obtain quantitative correlation of staining intensity to collagen content, so this method is not a popular method of histological cartilage characterization.

**Joint Capsule and Ligaments**

**Capsule**

A strong fibrous capsule surrounds the knee joint. It attaches proximally at the femur just superior to the femoral condyles. Distally, it attaches to the articular margin of the tibia. Laterally the articular capsule is deficient, allowing the popliteus tendon to exit the knee joint before attaching on the tibia. However, the capsule is reinforced extracapsularly by the iliotibial tract that originates at the proximal femur and inserts at the
lateral tibial condyle (Gerde’s tubercle). In addition, the lateral capsule is supported by the lateral collateral ligament (LCL) and the medial capsule by the medial collateral ligament (MCL). The oblique popliteal ligament arises from the semimembranosus tendon and supports the posterior joint capsule as it passes from the medial tibial condyle to the posterior femur. Additionally, the posterior capsule is supported by the arcuate popliteal ligament.

**Ligaments**

The LCL is round and cord-like, extending from the lateral epicondyle of the femur to the head of the fibula. The MCL is a broad, flat ligament that attaches from the medial epicondyle of the femur to the proximal medial tibia. The deep fibers of the MCL penetrate the joint capsule and attach firmly to the medial meniscus. The LCL prevents tibial adduction (varus) and the MCL prevents tibial abduction (valgus). The MCL is weaker than the LCL and more susceptible to injury. Its direct attachment to the medial meniscus often results in the concomitant injury of the MCL and medial meniscus together. Intracapsularly, the knee joint is supported by the anterior cruciate ligament (ACL) and the posterior cruciate ligament (PCL). The ACL is a two-bundle ligament consisting of an anteromedial and posterolateral band. Together these bands prevent anterior tibial translation and knee joint hyperextension. The PCL is the stronger of the two cruciate ligaments and attaches from the central aspect of the tibia posteriorly and passes anteriorly to the lateral aspect of the medial femoral condyle. The PCL prevents anterior femur translation.

**Menisci**

The crescent-shaped menisci of the knee consist of fibrocartilage arranged in concentric plates in the medial and lateral knee joint. They function to deepen the joint surface, increasing the congruity at the tibiofemoral joint, as well as serve as shock absorbers. The circumference of each crescent is thick, convex and attached to the joint capsule as well as the tibial plateaus via coronary ligaments. Conversely, the inner borders of the menisci are thin, concave and free, making them prone to tears. Superiorly, they are concave to provide congruent articulation for the round femoral condyles.
The roots of the menisci attach mesially near the tibial spines. Just as the lateral root is becoming anchored to the tibial plateau, a meniscofemoral ligament arises and attaches to the lateral femoral condyle. Anteriorly, the transverse ligament connects the medial and lateral menisci.

The blood supply to the menisci is often described by dividing each meniscus into thirds: the outer third, the middle third and the inner third. The outer third, sometimes referred to as the “red zone” has a rich blood supply and capable of healing in cases of injury. The inner third, called the “white zone” is devoid of circulating blood and incapable of healing when torn. The middle third, the “pink zone” is a transition between the inner and outer thirds with limited capacity to heal. It is becoming increasingly apparent that injuries to the meniscus are highly detrimental to articular cartilage health.

Molecularly, the medial and lateral menisci consist primarily of type I collagen. The matrix of the meniscus is not unlike articular cartilage discussed previously; however, the concentration of chondrocytes and proteoglycan molecules is much lower.

Muscles

The knee joint is supported by several muscle groups that surround the knee joint. The quadriceps is the primary muscle group located anterior to the knee joint. It functions to generate knee extensor torque and attaches to the tibial tuberosity via the patellar tendon. The four muscles that comprise the quadriceps group are the vastus medialis, vastus intermedius, vastus lateralis and the rectus femoris. The vastus medialis is located on the medial aspect of the anterior thigh and originates from the medial border of the linea aspera on the posterior femur. Its fibers wrap around medially and anteriorly, inserting into the superior medial patella via the broad quadriceps tendon. The vastus intermedius lies on the anterior aspect of the femur, deep to the rectus femoris. It originates from the anterior and lateral aspects of the femoral shaft and inserts into the superior margin of the patella via the quadriceps tendon. The vastus lateralis is the largest of the quadriceps muscles and originates from the lateral border of the linea aspera. Its fibers wrap around the femur laterally and anteriorly, inserting into the superior lateral patella via the quadriceps tendon. The rectus femoris, the only of the
four quadriceps muscles to cross the hip joint, lies on the anterior aspect of the femur, superficial to the vastus intermedius. It originates from the anterior inferior iliac spine and inserts into the superior margin of the patella via the quadriceps tendon. The strong fibrous quadriceps tendon envelopes the patella and continues inferiorly via the patellar tendon before inserting on the tibial tuberosity.

Posteriorly, the hamstrings are the primary knee flexor group. Four muscle heads comprise the hamstrings; two laterally and two medially. The biceps femoris is the two-headed lateral hamstring. This long head of the biceps femoris originates from the ischial tuberosity while the short head originates along the linea aspera. The two heads join at the distal femur and attach to the head of the fibula and lateral tibia. While the long head crosses the hip joint to provide hip extension torque, both heads act together to generate knee flexion torque. The two medial hamstrings are the semimembranosus and semitendinosus. Both muscles originate from the ischial tuberosity along with the long head of the biceps. They extend distally and medially together and insert on the posterior medial tibia. After inserting on the tibia, the tendon of the semimembranosus reflects superiorly and laterally to form the oblique popliteal ligament which helps support the posterior joint capsule.

Additional knee flexors include the gastrocnemius, the plantaris and the popliteus muscles. The gastrocnemius forms part of the calf muscle and originates at the femoral condyles. The medial and lateral heads of the gastrocnemius extend distally from each of the femoral condyles, respectively. They fuse together to insert on the Achilles tendon which ultimately is attached to the posterior calcaneus. The gastrocnemius helps support the posterior knee joint and provides flexion torque upon contraction. The small belly of the plantaris muscle originates from the posterior femur above the lateral condyle and has a long slender tendon that inserts along with the Achilles tendon to the posterior calcaneus. The thin triangular-shaped popliteus originates from the lateral femoral condyle and inserts along the proximal medial tibia. While it assists with knee flexion, its primary function is to internally rotate the tibia, a movement necessary to unlock the knee joint in extension.

The medial aspect of the knee joint is supported by the pes anserine muscle group. This group consists of the sartorius muscle, the gracilis muscle,
and the aforementioned semitendinosus muscle. The sartorius muscle originates from the anterior superior iliac spine of the pelvis and courses obliquely across the anterior thigh before inserting at the medial surface of the tibia. While a knee flexor, it also generates hip flexion, and hip external rotation torque. The gracilis is a long strap-like muscle that is part of the hip adductors group as well. It originates from the inferior ramus of the pubis and ischium and inserts along with the sartorius and semitendinosus into the medial aspect of the proximal tibia.

**Bursae and Fat Pads**

**Bursae**

Structures of the knee joint may become inflamed in the absence or in combination with osteoarthritis. One such structure that is a common site for inflammation is the bursae of the knee joint. Several bursae are found around the knee joint. These are the suprapatellar (quadriceps) bursa, popliteal bursa, anserine bursa, gastrocnemius bursa, semimembranosus bursa, prepatellar bursa, and subcutaneous and deep infrapatellar bursae. The bursae are typically located between tendons and bones and function to decrease friction. They consist of a pouch of synovial membrane with small amounts of synovial fluid that acts as a lubricant. However, with excessive loads, the bursa can become inflamed and the synovial walls can become thickened and swell. This typically presents as a large focal deformity at the site of the bursa.

The suprapatellar bursa is located between the femur and the quadriceps tendon and is a direct extension from the superior joint capsule of the knee. The popliteal bursa lies between the tendon of the popliteus and the lateral condyle of the tibia and travels into the joint capsule under the lateral meniscus. The anserine bursa in located between the tendons of the pes anserine (sartorius, gracilis, semitendinosus) and the medial tibial condyle. The gastrocnemius bursa is found deep in the medial head of the gastrocnemius, over the posterior medial femoral and tibial condyles. The semimembranosus bursa is located between the medial head of the gastrocnemius and the tendon of the semimembranosus. The prepatellar bursa lies superior to the anterior patella, just beneath the skin overlying the patella. It allows for the skin to move freely over the anterior patellar
surface during knee flexion and extension. The two infrapatellar bursae are located just superficial and deep to the patellar tendon, and function to withstand pressures during kneeling.

**Fat Pads**

Three fat pads occupy the anterior knee: the quadriceps, prefemoral, and infrapatellar fat pads. The largest fat pad of the knee joint is the infrapatellar fat pad or Hoffa’s fat pad. It has been extensively studied due to its proposed role in various pathologies. Located just inferior to the inferior patellar pole, the infrapatellar fat pad occupies much of the space between the patella and the tibia. It extends inferiorly to the deep infrapatellar bursa located at the insertion of the patellar ligament into the tibial tuberosity. The infrapatellar fat pad attaches to several structures including the intercondylar notch via the ligamentum mucosum, the patellar tendon, the inferior pole of the patella and the anterior horns of the menisci.

The two smaller fat pads are the quadriceps and the prefemoral fat pads. The quadriceps fat pad, also known as the anterior suprapatellar fat pad, lies superior to the suprapatellar pole between the distal quadriceps tendon anteriorly, and the suprapatellar recess posteriorly. Just deep (posterior) to the suprapatellar recess and the suprapatellar bursa is the prefemoral fat pad, which lies on the anterior femoral shaft, superior to the trochlear groove.

Fat pads of the knee are highly vascularized and highly innervated. Terminal extensions of the genicular arteries anastomose in the fat pads richly supplying them and their synovial coverings. Substance P immunoreactive pain fibers have been found to be widespread and equally distributed throughout the fat pads, retinaculum, and synovium.

Several functions of the fat pads have been proposed including synovial fluid secretion, dead space occupiers, and joint stability. Current research concludes that the infrapatellar fat pad appears to play a role in biomechanical support and neurovascular supply to the adjacent structures.

**Nociceptors**

Histochemical and anatomical studies have investigated the prevalence of substance P in the structures surrounding the knee. Substance P is
a neurotransmitter found in afferent nerve fibers. It is believed that this neurotransmitter is associated with the cascade of events that result in the perception of pain. These events include activation of afferent nerve fibers that enter the dorsal horn of the spinal cord at the appropriate segmental level. The impulses are propagated to the contralateral side at that level and ascend the spinal cord in the spinothalamic tract, entering the brainstem as the spinal lemniscus, before arriving to the thalamus and continuing to the primary sensory cortex on the post central gyrus. It is there where pain is perceived and then further understood through secondary sensory processing. These substance P fibers have been found in tissues surrounding the knee joint including the medial and lateral retinaculum, the infrapatellar and suprapatellar fat pads, the synovial lining, periosteum and subchondral plate of the patella, femur and tibia.

Conclusion

This chapter has detailed the normal anatomy and physiology of the knee joint. Particular detail was provided for cartilage and bone anatomy. However, many of the supportive structures of knee, such as the menisci and the ligaments are also believed to be involved in OA. As you read later chapters and learn about the details of OA, refer back to this chapter for the normal anatomy and physiology of the knee.

References and Suggested Readings


