EXS – 321:
Applied Anatomy

Supplemental Reading

Included Documents:

1) Handout prepared by Course Instructor, Dr. Dutto.
2) Bone: Modlesky, C.M. and Lewis, R.D. (2002). Does exercise during growth have a long-term effect on bone? *Exerc. Sport Sci. Rev.*, 30(4), 171-176.
3) Muscle: Roberts, T.J., Marsh, R.L., Weyand, P.G., and Taylor, C.R. (1997). Muscular force in running turkeys: the economy of minimizing work. *Science,* 275, 113-115.
4) Upper limb: Pink, M., Perry, J., Browne, A., Scovazzo, M.L., and Kerrigan, J. (1990). The normal shoulder during freestyle swimming: an electromyographic and cinematographic analysis of twelve muscles. *Am. J. Sports Med.*, 19(6), 569-575.
5) Locomotion: Bramble, D.M. and Lieberman, D.E. (2004). Endurance running and the evolution of *Homo*. *Nature*, 432, 345-352.

The Skeletal System

In the context of kinesiology and the examination of human movement, the skeleton provides the solid structure that allows muscle to exert force and move individual body segments. You might imagine that without the skeleton, the human body would be a sack of skin, with fluid, muscles, and organs floating freely inside. This represents a rather horrific view of the human body – thus the skeleton is most important for not only allowing us to move, but also to maintain the general shape and structure of the body.

Primary functions of the skeletal system

There are five primary functions of the skeleton. Each is important in its own way.

1) Protect vital organs. Lets face it, with out a functioning brain, heart, lungs we would no longer be functioning living individuals. So the skeleton of the torso and head provides support and protect for these vital organs. The brain is encased in the skull. The ribs and spine surround and protect the heart and lungs. The pelvis and spine support and protect gastrointestinal and reproductive structures.
2) Mineral Storage. Bone is the primary storage site for calcium and phosphorus in the body. Magnesium, sodium, and other minerals are also stored in the skeleton in various amounts. When dietary intake of these minerals are low, they can be leeched from the bone to support physiological function. Calcium is the primary mineral of the bone, but is also important for muscle contraction and neuronal conduction. Phosphorus is a primary mineral of bone, but also a constituent of adenosine-triphosphate, the energy storing structure that powers all muscle activity in the body.
3) Hematopoiesis. This refers to the formation of red blood cells (RBCs) in the long bones of the skeletal system. Bone marrow contains hematopoietic cells that are responsible for the creation of RBCs. RBCs are important for carrying oxygen in the blood, an especially important function during exercise, but also necessary to maintain normal life functions.
4) Postural support. Our normal, upright posture is maintained via the upright spinal column. The spine has evolved such that it allows our head to be high off of the ground. Our head contains the primary sensory organs (eyes, vestibular, ears) that we rely on to navigate through the world. The skeleton also allows to maintain a general body structure and form.
5) Leverage. Levers are simple mechanisms the can magnify the force or speed of movement. The leverage provided by different bones (and the muscles that act on them) determine the form and speed of any motion that is produced. Levers will be described in more detail later.

In our discussions of human movement, the last two have the greatest import for our analyses. However, one can’t ignore the other functions of the skeletal system. Our body is an integrated system relying on the smooth interaction of all systems. What good would leverage be if no oxygen was available to the working muscles because of a deficiency of red blood cells? How would the skeleton move if there was no calcium available for contracting muscles? So I would ask that you remember the whole integrated being, not just the specific task of understanding the causes of movement.

Skeletal Microstructure

What is bone? It is specialized connective tissue! Bone falls under the same category of tendons, ligaments and cartilage. In fact, bone is the hardest of all connective tissue – it is simply calcified cartilage. So when we study bone, we are simply studying one aspect of connective tissue.

Bone tissue is highly dynamic. The architectural structure and density are constantly changing based upon daily changes in mechanical loads applied to the system, hormonal flux, and dietary and serum mineral levels. Think about what happens to astronauts who live for a long period of time on the space station. Significant amounts of bone are lost because they are no longer under the influence of Earth's gravity. In order to understand bone, we need to examine the skeleton at several different resolutions. We can examine bone as an organ, tissue, and at the cellular level.

Cells

As with all other active structures in our body, bones rely on the activity of cells to maintain function. There are three primary cells that are relevant for our discussion of bone. Two of these cells create and maintain bony tissue and the third dismantles bone. What exactly is bone made of?

Basic building block of bone is the protein collagen. Collagen is a long structural protein. It is highly resistant to tensile (stretching) loads placed upon it. It is very strong and found in all types of connective tissue. Between the collagen proteins are calcium and phosphate crystals, the inorganic element of bone. These mineral crystals are responsible for making bone hard. Collagen and minerals are held together by an organic glue called ground substance. During bone formation. ground substance is secreted by the cell. Ground substance is composed of collagen fibers and glycosaminoglycans (GAGs). These cells cause calcium and phosphorus to precipitate from the blood and bind to the ground substance causing mineralization. Thus cells that create bone essentially put these three elements (collagen, minerals, GAG) together, and the cell that dismantles bone takes these three elements apart.

The two cells that deposit bone are osteocytes and osteoblasts. Osteoblasts live on the surface of the bone. Osteocytes and osteoblasts are the same cell, except that an osteocyte is an osteoblast that has been trapped in the ground substance matrix. Since they are the same cell, they essentially do the same thing in the same way – build bone by putting together collagen, mineral and GAGs. Any addition to bony content by osteoblasts will generally widen the bone (or fill in the interior). Osteocytes live within the bony tissue and any addition to the bone will increase bone content within the bony structure.

Osteoclasts are responsible for absorbing bone material. Like osteoblasts, these cells live primarily on the outside of the bony structure. They are larger cells than osteoblasts.

Bone is undergoing constant remodeling. Even as you sit there reading this, some bone is being absorbed and new bone is being deposited. In a healthy, young individual this process stays relatively balanced – the amount of bone absorbed and deposited are the same. This process is called the bone remodeling cycle. Bone remodeling can be visualized as the classic balance scale, with absorption on one side and deposit on the other. Many factors can influence which way the scale tips.

Hormonal factors are one possible way to change activity of the bone cells. Both osteoblasts and osteoclasts have estrogen receptors. Estrogen increases the number of osteoblasts available for bone deposit. Estrogen inhibits osteoclast activity. Thus, pre-menopausal women actually have bone protection – the presence of estrogen favors bone deposit. Osteocytes are stimulated by calcitonin (a thyroid hormone) helping to increase bone material within the bone. There are other hormone regulators, but not important for this discussion.

Bony Structure

Of course, cells build bone tissue, but the tissue is layered in a specific way that gives bone the observable structure that we are familiar with. This structure will also be responsible for giving bone its strength. The fundamental structural unit of bone is an osteone (Fig. 1B). The osteone consists of concentric layers of mineralized bone matrix (which look like rings) called lamellae. In the center of the osteone is the Haversian canal, a central channel containing blood vessels and nerve fibers. Osteocytes are found in lacunae (small cavities) in the lamellae. Calaliculi are small channels that provide a channel for blood flow from the Haversian canal to the osteocyte.

Each osteone is separate from surrounding structures. However as seen in the cartoon in figure 1A, bone appears to be solid (especially in the wall of the bone). Osteones are round. Interstitial lamellae span the regions between osteones. Most often, interstitial lamellae are the remains of old osteones. Remember the bone remodeling cycle is continuous, so that osteones are constantly being made and dismantled. It is a slow process, so that remnants of old osteones are intermingled with new osteones. This provides the solid structure that we are familiar with.

Bone Growth

Remember that bony material begins as a collagen matrix that becomes mineralized, which causes the bone to harden. In a mature bone, this is how growth occurs. Osteoblasts and (to a lesser extent) osteocytes lay down ground substance causing bone to grow wider or denser. This is called architectural changes to the bone. This can result in a stronger bone. Growth lengthwise (particularly in the long bones) does not occur after a person has reached maturity.

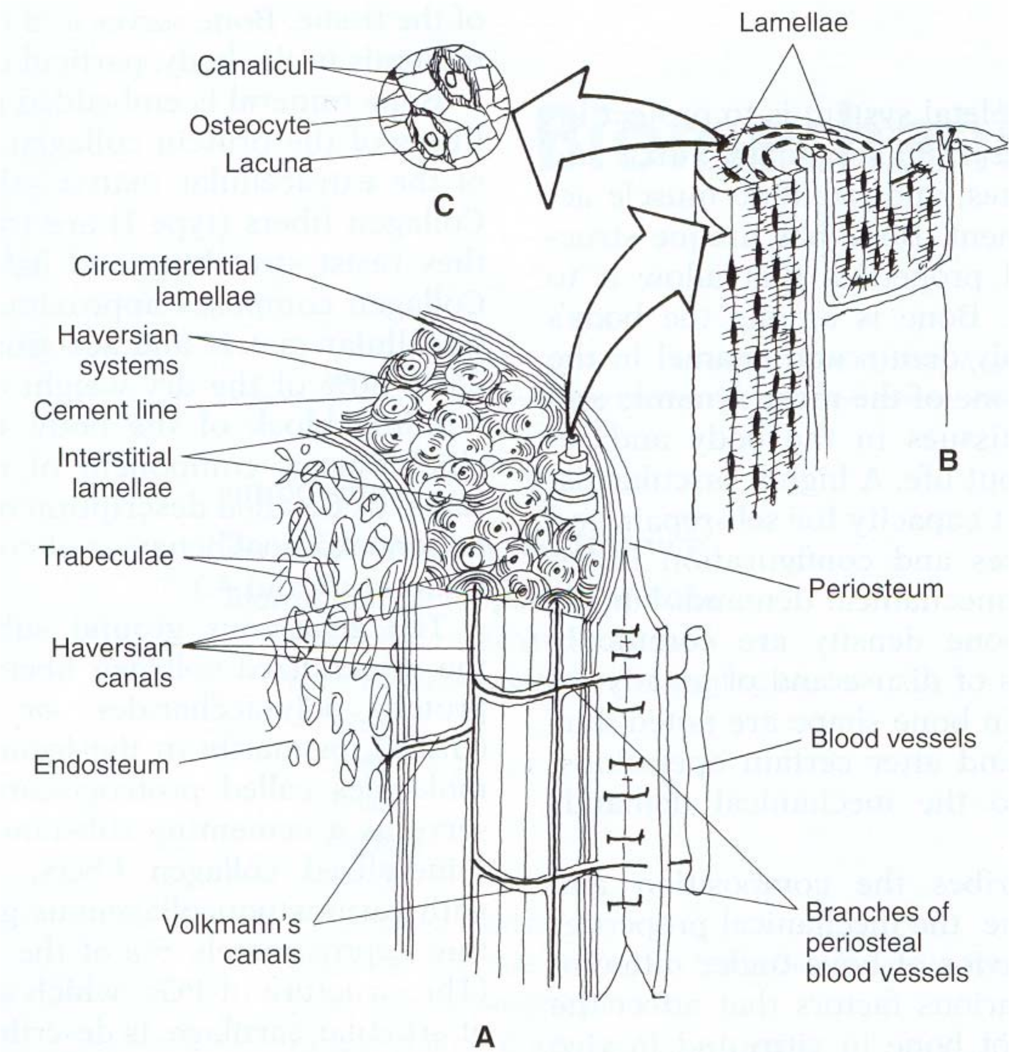


Figure 1. A) the solid structure of bone with osteones and interstitial lamellae. B) an osteone with Haversian canal and canaliculi, and C) osteocyte residing in a lacuna. (Figure from *Basic Biomechanics of the Musculoskeletal System 3rd edition*, Nordin and Frankel, Lippincott, Williams & Wilkins Publishing, 2001. Pg. 28, Fig.2-1)

During growth (childhood and adolescence) bone growth occurs in the epiphysial (or growth) plate (Fig. 2). The growth plate is at the end of the long bone, between the epiphysis (end of the long bone) and the diaphysis (the shaft of the bone). The transition from the epiphysis to the diaphysis is called the metaphysis. The are four layers in the epiphyseal plate that represent the different stages of bone growth.

In the reserve layer, cells that make cartilage (chondrocytes) live. Remember that bone is a specialized form of connective tissue, and so start out as cartilage one form of connective tissue. The reserve layer also acts as an anchor to the epiphysis to that the bone stays together. The layer below the reserve layer is the proliferation layer. In the proliferation layer, new cartilage is formed and there is an increased in the number of chondrocytes. It is this creation of new cartilage that is responsible for increasing the length of the bone. In the third layer, called the hypertrophic layer, the chondrocytes become arranged in columns and increase in size. In the final calcified layer, chondrocytes are replaced with calcified cartilage. This cartilage indiginates with the under lying bone to anchor the epiphyseal plate to the daiphysis.

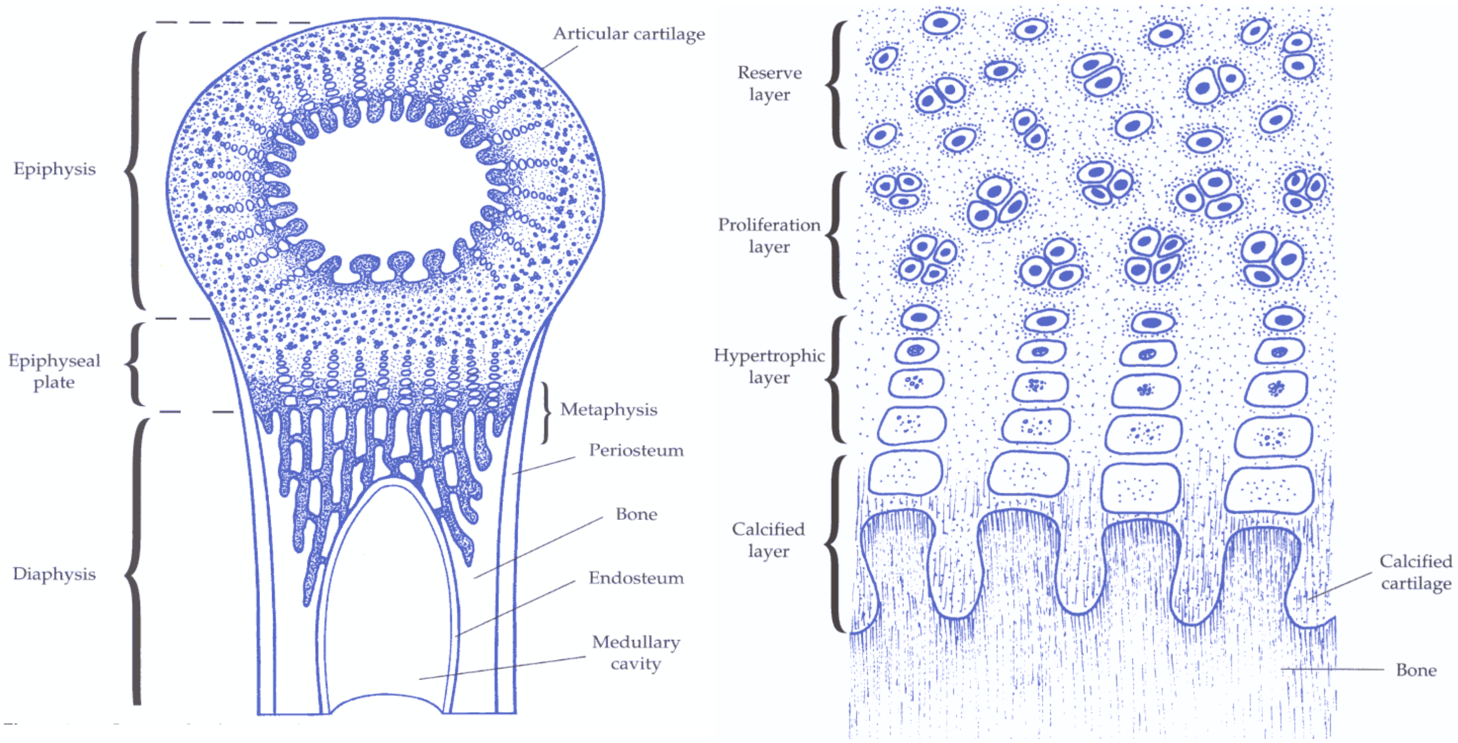


Figure 2. The left cartoon depicts the end of the long bone. The epiphysis is the end of the bone, the epiphyseal plate transitions to the diaphysis. The right cartoon is how growth of the bone occurs in the epiphyseal plate. There are four stages to bone growth. The first stage occurs in the reserve layer, and then flows downward in the plate. From *Biomechanics of musculoskeletal injury*, William C. Whiting and Ronald Zernicke, Human Kinetics, Champaign Illinois, 1998.

When bone grows at the epiphyseal plate, it lengthens away from the middle of the bone. The epiphysis is pushed upwards. When the bone has reached its mature length, the epiphyseal plate closes becoming bone material incapable of further long growth. The epiphyseal growth plate is susceptible to damage. A fracture of the bone at the epiphyseal plate can cause growth plate to close, preventing further longitudinal growth of the bone. When this occurs in a child, the bone will be shorter than its homolog on the contralateral limb. Not only is the bone damaged, but the articulations in which the bone participated are also affected.

Epiphyseal plates begin to close (bones have reached there mature length) at about 14 years of age. Typically they close in a proximal to distal pattern, with epiphyseal plates in the long bones closer to the torso closing first, then proceeding distally. Bone growth can occur to age 20 in women and 25 in men. One of the interesting aspects of skeletal growth is that skeletal age can be assessed by examining the closure of epiphyseal plates in the skeleton of adolescents. It may be that skeletal age does not match chronological age. Imagine that you have a 14 year old who is exceptional at their sport. Their skeletal age is 12 indicating that their physical development is lagging behind their chronological age. Perhaps this indicates that they have great potential due to the physical maturation that has yet to occur. In the case of a gymnast, it may be indicative of the training that keeps the athlete from gaining physical size, also a benefit to the sport.

Tissue

There are two types of bone tissue. Cortical bone has a dense structure characterized by densely packed osteones. It is the bone in the cortex or outer shell of the bone. The cartoon in figure1 shows the wall of the bone, which is cortical bone. The second type of bone tissue is cancellous (also called trabecular or spongy) bone. Canellous bone is characterized by loosely packed osteones that form trabeculae or thin plates that form a porous, lattice structure. There is open space in this structure that is typically filled with bone marrow. Cortical bone always surrounds cancellous bone.

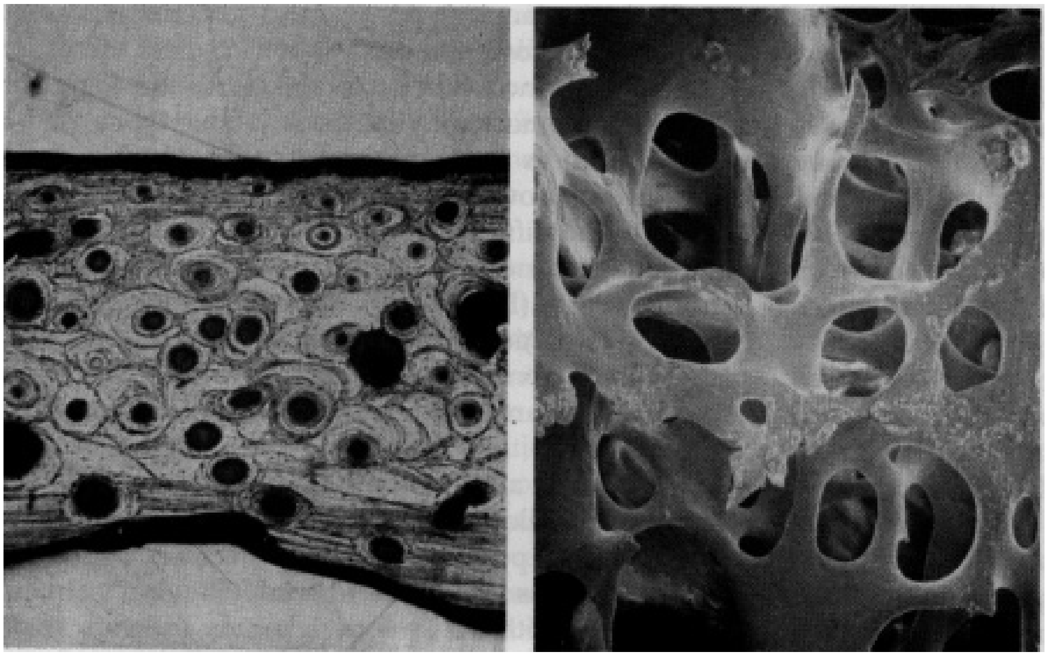


Figure 3. An enlarged image of cortical bone (left image) and cancellous bone (right image). From Carter, D.R. & Hayes W.C. (1977). Compact bone fatigue damage. A microscopic examination. Clin. Orthop., 127, 265.

Both types of bone have important roles in creating the strength and physical properties of the whole bone. Cortical bone creates the shell of the bone, while cancellous bone creates a mesh in the center (meduallary cavity) of the bone. Figure 4 shows a cross section of the proximal end of the femur. It is easy to see cortical bone on the outer edge and cancellous bone in the interior of the bone. It is also apparent that the bone tissue is not evenly distributed in the bone. On the medial side, the cortical bone is thicker than on the lateral side. Medial cortical bone thickness extends to the inferior aspect of the femoral neck. On the lateral side, it barely extends to the distal aspect of the trochanter. On the superior aspect of the femoral neck, the cancellous bone is thicker than anywhere else in the bone section. Why do these differences in bone distribution occur? Bone is distributed based upon the types of loads or demands that are placed upon it.

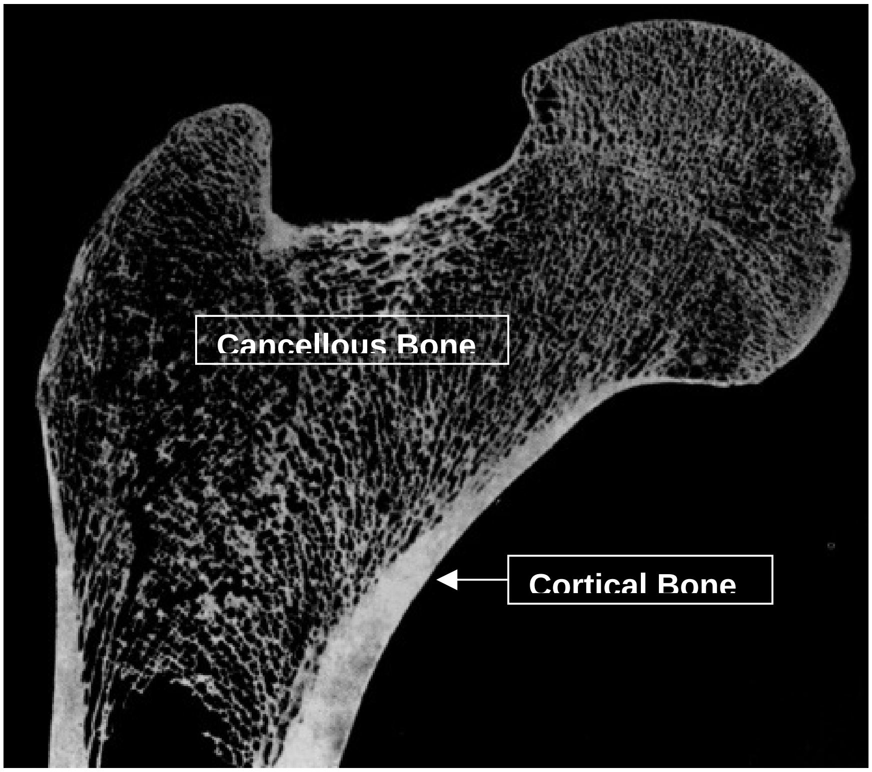
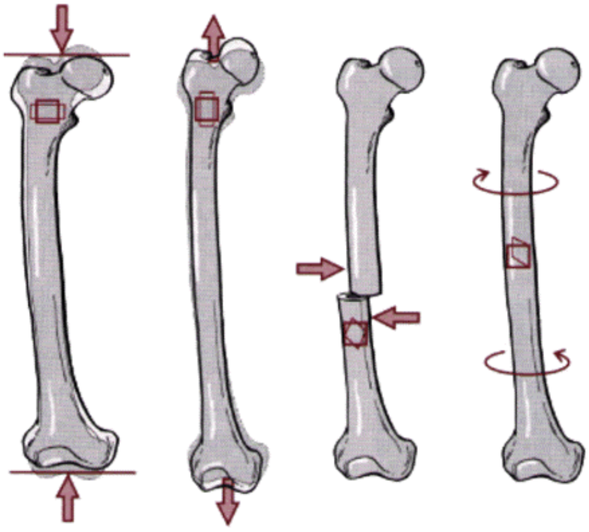


Figure 4. Cross section of the proximal femur, with cortical and cancellous bone clearly visible. (Figure from *Basic Biomechanics of the Musculoskeletal System 3rd edition*, Nordin and Frankel, Lippincott, Williams & Wilkins Publishing, 2001. Pg. 29, Fig.2-2)

Bone Loading

Loading refers to the types of mechanical loading that the bone undergoes. In order to understand why the bone has a certain distribution pattern of cortical and cancellous bone, one must understand the types of loading that occurs. There are four basic ways to mechanical load the bone (Figure 5): compression, tension, shear, and torsion.

Compressive loads occur when the ends of the bone are pushed towards one another along the long axis of the bone. Tension involves the pulling of the ends of the bone away from the center along the long axis of the bone. If force is applied perpindicular to the surface of the bone it creates a shear load. Finally, twisting the bone along the long axis creates a torsion load. There is a fifth type of load, a bending load, that is a combination of compression and tension. During a bending load, one side of the bone undergoes compression and the other tension.



A. Compression B. Tension C. Shear D. Torsion

Figure 5. The four primary types of loading. From *Biomechanical Basis for Human Movement 1st edition*. Hamill, J. and Knutzen, K.M. Williams & Wilkins, 1995. Pg. 47, Fig. 2-12.

Cortical bone is best able to resist compressive and shear loads. Tension loads are somewhat resisted by both cancellous and cortical bone. Both types of bone are not very resistant to torsion loads. Bone tissue that regularly undergoes compressive loading will develop more cortical bone. Bone that regularly undergoes tensile loads will have denser cancellous bone. This phenomenon is readily observed in the cross section of the femur in figure 4. The femoral neck is at an angle compared to the diaphysis of the femur. The weight of the torso is on the head of the femur. This causes a bending load on the neck of the femur. The bottom of the neck is compressed and the top is under tension. That is why there is thicker cortical bone on the inferior aspect of the femoral neck and denser cancellous bone of the superior aspect.

Can bones continue to grow?

Bones can be made to grow lengthwise after the epiphyseal growth plate has closed. How? Well, thank turkeys! The humerus (upper arm) of one wing of mature turkeys was affixed to an external rigid frame. The frame had a rod that could be lengthened with a turn of a screw. A little bit at a time, the rod was lengthened or many days. This put a constant tensile load on the bone of the wing. The bone could adapt to the load by lengthening, which reduced the tensile forces it experienced. The bone could be made to grow almost twice as long using this method, through the normal remodeling process of the bone. This process is now used on children or adolescents that need to have a bone lengthened. An external frame is attached to the bone that needs to be lengthened. A constant tensile load is placed on the bone for many months. This causes the bone to lengthen, proving the remarkable adaptability of the skeletal system.

Skeletal Macrostructure

The skeleton can be divided into two general functional areas. The axial skeleton represents the spine, ribs, pelvis, and skull. The appendecular skeleton is the arms and legs. The axial skeleton provides the central core and base for all movement, as well as housing all of the primary vital organs and structures to maintain life. Appendages are responsible for allow us to interact in the environment. Their length and mobility are responsible for allowing the body freedom of movement.

Types of bones

There are 5 classifications of bone.

1) long bones – bones that are much longer than they are wide. (Example – femur)

2) Flat bones – characterized by large curved surfaces and typically consists of two layers of cortical bone sandwiching cancellous bone. (Example – ilium)

3) Short bones – small, block-like bones that have cortical bone shell and filled with cancellous bone. (Example – navicular)

4) Irregular bones – bones with a specialized shape depending upon function. (Example – scapula)

5) Sesamoid bone – small bone embedded within a tendon or joint. (Example – patella)

Long bones

Most of the elements of long bones have been introduced previously. The ends of the long bone are the epiphyses, just adjacent to each epiphysis is a metaphysis, and the shaft of the long bone is the diaphysis. The central area devoid of bone is called the medullary cavity. The medullary cavity contains bone marrow and is the site of hematopoiesis. The ends of the bone are covered with articular cartilage (something that will be discussed further in the next section on articulations). The primary difference between the different long bones of the body is in the shape of the articulating surfaces at each end of the bone. Articulating surface is shaped based upon the articulation with the adjacent bone.

All bone (long bones or otherwise) is covered with a thin membrane called the periosteum. The periosteum is the outer protective covering of the bone. Osteoblasts and osteoclasts live in the space between the bone surface and the periosteum. Tendons from muscles attach to the bone through the periosteum.

“Form Follows Function”

One of the primary tenets governing the shape of a bone is Wolffe’s Law which states that “form follows function”. Thus, each bones unique shape is governed by the function that bone has.

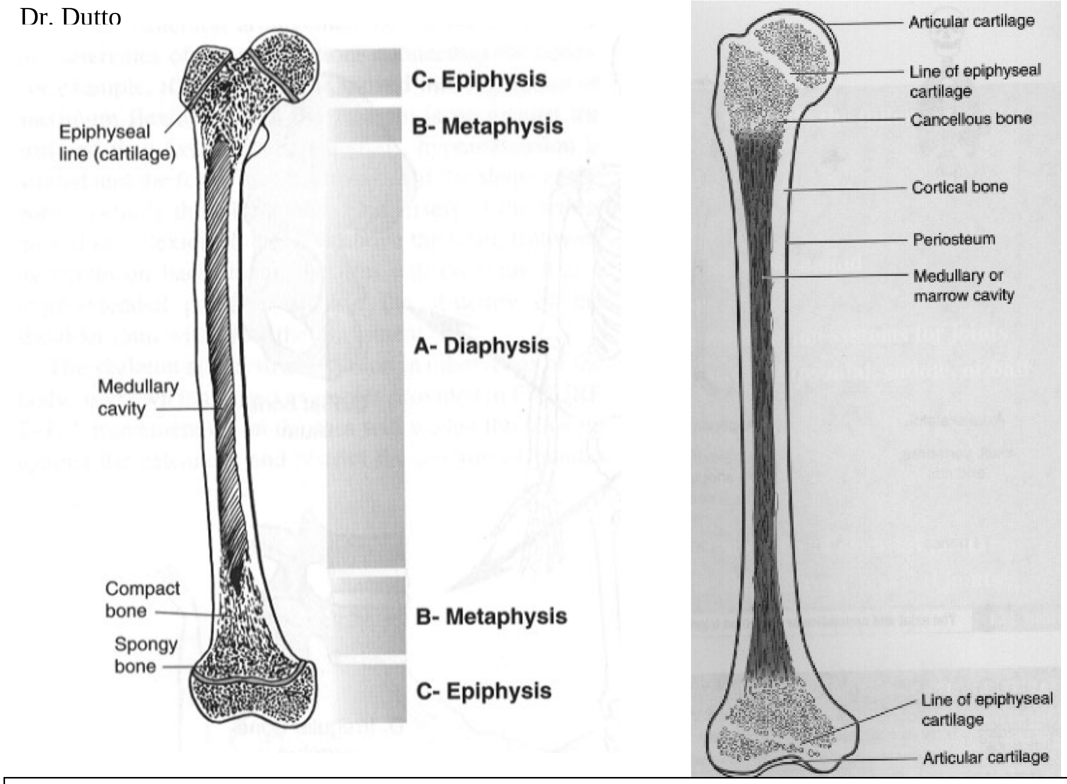


Figure 6. Relevant structures of the long bone. From *Biomechanical Basis for Human Movement 1st edition*. Hamill, J. and Knutzen, K.M. Williams & Wilkins, 1995. Pg. 40, Fig. 2-3.

Thus, whatever shape a bone has it has that particular shape from the forces and stresses applied to it. Like the turkey wing example from above, if you apply an abnormal force to the bone, the bone will grow and adapt to that force. Many of the bony landmarks used to identify structures in the body arise from stresses applied to a bone. One example is the tibial tuberosity. A tuberosity is a raised prominence on the surface of the bone. The patellar ligament attaches the patella (a sesamoid bone on the anterior aspect of the knee) to the superior, anterior surface of the tibia. The patellar ligament transmit the force generated by the quadriceps musculature to the tibia. The four quadriceps muscles (rectus femoris, vastus lateralis, vastus intermedius, and vastus medialis) act to extend the knee by rotating the tibia anteriorly about the knee. They can generate a tremendous amount of force and we use these muscles all of the time – to stand, walk, run, jump, etc. Since the patellar ligament pulls on the tibia, it creates tension loading to the bone. The tibia remodels by adding bone tissue to the attachment site to strengthen the bone and the attachment of the ligament. A small bony protuberance develops which one can palpate on the anterior tibia.

Osteoporosis is a condition resulting from the loss of bone material. Osteoporosis means porous bones. Individuals with osteoporosis suffer from increased fracture risk because they have less bone material to withstand forces applied to them. If you compare the two lumbar vertebrae, one normal and one osteoporotic, in figure 7 it is easy to see the effects of osteoporosis. One vertebra on the right is osteoporotic and typical for individuals that have the disease. Osteoporosis costs several 100 million dollars in direct medical cost every year. However, if we load our bones regularly with exercise, osteoporosis can be delayed or prevented reducing medical costs.

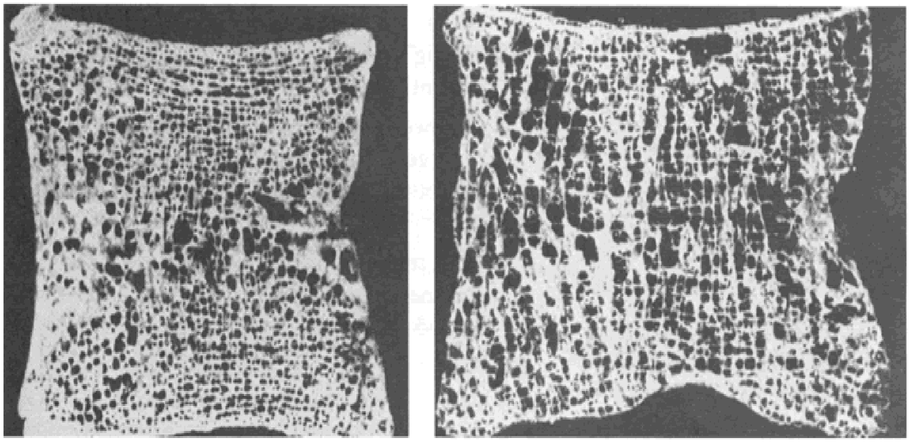


Figure 7. The left picture of a normal lumbar vertebra and the right from a a lumbar vertebra with osteoporosis. (Figure from *Basic Biomechanics of the Musculoskeletal System 3rd edition*, Nordin and Frankel, Lippincott, Williams & Wilkins Publishing, 2001. Pg. 53, Fig. 2-50)

Mechanostat Model of Bone Formation

There is a simple model that can be used to illustrate the adaptation of bone to applied loads. This model is the mechanstat model of bone development. Bones have an ability to detect changes in load (strain detection mechanism) that can be used to determine if the applied load is abnormal or not. It then can use the signal to determine whether or not to increase bone formation or bone absorption.

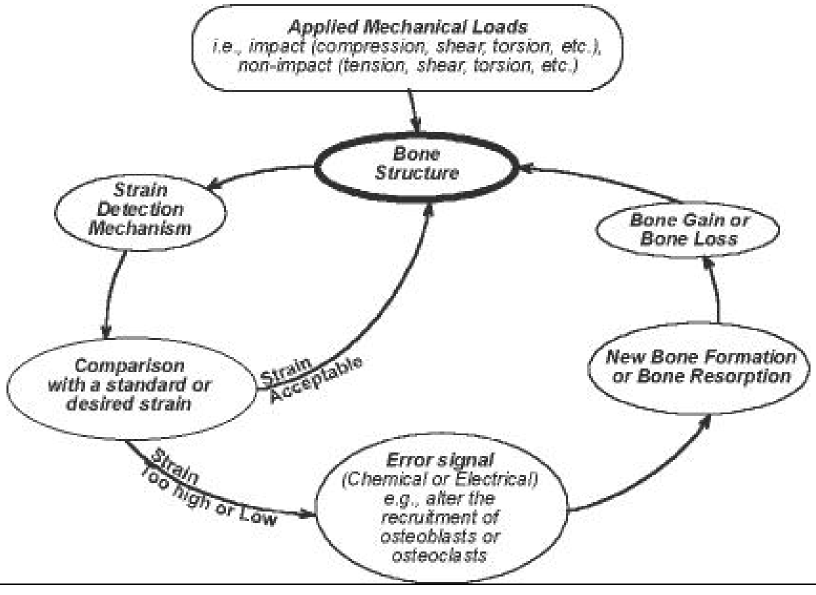
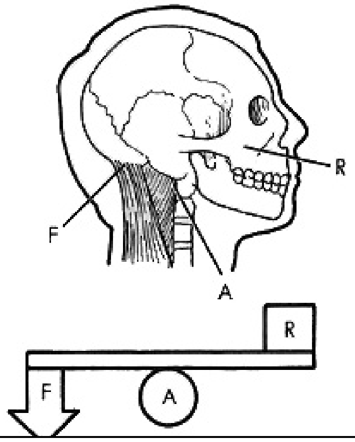


Figure 8. Mechanostat model for bone formation and absorption. Adapted from Parfitt, A.M. The two faces of growth: Benefits and risks to bone integrity. (1994). Osteoporosis International, 4(6), 382-398.

Bones as Levers

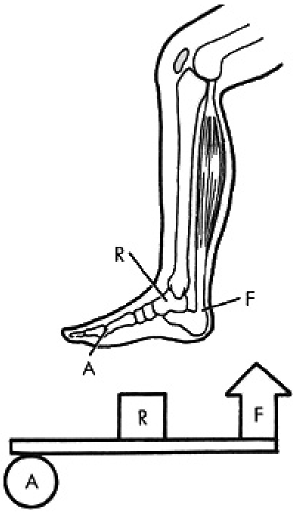
“Give me a lever long enough and I can move the world.” - Archimedes

Levers are basic mechanical devices that can be used to amplify force or range of motion. The bones of the skeleton and the ways in which they articulate create a system of levers. This system can be used to amplify the force from a muscle or muscle group, or to increase the range of motion of limb relative to the amount of muscle shortening that occurs.



1st class lever: A lever in which the axis of rotation of the segment is between the resistive and motive forces. This is considered to be a stabilizing lever. For example, in the cartoon to the right, the head (or skull) is behaving as a 1st class lever. The axis of rotation is the top of the spine. The resistive force is the weight of the skull (and brain, muscles, organs of the head), located primarily in front of the spine. Without a balancing force the head would tend to tip forward. The motive force comes from the muscles that attach to the back of the skull, counteracting the weight of the skull in front of the spine. Another situation in which the body has a first class lever is when you are standing on one leg. In this situation, the pelvis is the lever. The axis of rotation is the hip joint for the leg that is on the ground. The weight of the body is on one side of the hip. In the absence of a countering force on the other side of the hip, the weight of the body would cause a rotation about the hip. However, the hip abductors on the other side of the hip create a balancing force that prevents the weight of the body from causing a rotation.

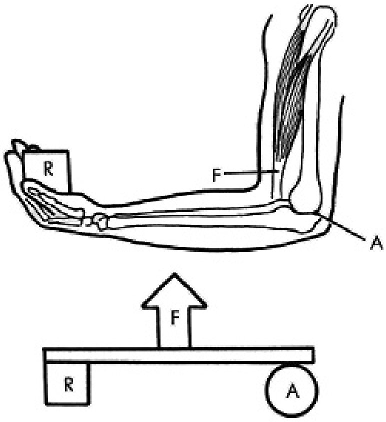
From Manual of Structural Kinesiology 15th Edition, Clem W. Thompson and R.T.Floyd, McGraw-Hill, 2004, pg 45, Fig. 3-2.



2nd class lever: This lever has an axis of rotation on one side of the segment, the resistive force in the middle and the motive force on the side opposite the axis of rotation. The 2nd class lever is designed to amplify force as it has a high mechanical advantage. That means that in order to counteract the resistive force, a lower motive force can be applied. Think of a wheelbarrow. You can load a lot of material in the bucket of the wheelbarrow and lift it at the handles much more easily than you could lift it directly. The trade-off is the loss of mobility and movement speed. 2nd class levers tend to have low range of motion. One example in the body is standing up on your toes. This involves ankle plantar flexion, where the motive force is supplied by the ankle plantarflexor muscles (calf muscles). The axis of rotation is the metatarsalphalangeal joint. The resistive force is the weight of the body acting through the ankle. The muscles of the ankle can generate a lower force than the weight of your body and raise you up onto your toes.

From Manual of Structural Kinesiology 15th Edition, Clem W. Thompson and R.T.Floyd, McGraw-Hill, 2004, pg 46, Fig. 3-3.

3rd class lever: This lever is similar to the second class lever except that the resistive and motive forces are switched. The resistive force is on the opposite side relative to the axis of rotation. The 3rd class lever is designed to amplify movement of the end of the segment, meaning that it has a low mechanical advantage. In order to counteract the resistive force, a much higher motive force must be applied. However, because the motive force is closer to the axis of rotation, the end of the segment away from the axis of rotation can move through a wide arc relative quickly. This is how many of the articulations of the long bodes operate. Elbow flexion is one example. Elbow flexors insert relative close to the elbow joint. Thus small shortening of these muscles allows the hand to swing through a wide arc. Unfortunately the trade-off is that the muscles have to generate relatively large forces to overcome any resistance at the end of the segment.



From Manual of Structural Kinesiology 15th Edition, Clem W. Thompson and R.T.Floyd, McGraw-Hill, 2004, pg 47, Fig. 3-4.

Joint Classification and Structure

The articulation system refers to the many joints that connect bones together is ways that provide stability or mobility. That is really one of the key pieces of information to take away – not all joints are designed for mobility. In fact, if some joints were mobile this would hinder movement of the body as opposed to being helpful. There are two general types of joints. One is fairly immovable and one is movable.

Synarthrotic Joints

Synarthroses are joints in which two bones are connected directly by connective tissue. The joint has a bone-connective tissue-bone configuration. These joints come in two forms: a fibrous joint and a cartilaginous joint. They are designed to be highly stable, fairly immovable joints. As you will see, almost all of these joints are present in the torso or skull where stability is a necessity.

Fibrous joints:

1) Suture syndesmoses – joints where two bones are joined by a dense layer of fibrous tissue. Typically the edges of the bones interlock or overlap. These joints are found between the bones of skull in children and adolescents. In adults the bones grow together to form synostosis.

2) Gomphosis – bony components that are adapted to each other like a “peg-in-hole” configuration. The two bones are connected to one another through fibrous tissue. Identifies the joint between a tooth and maxilla or mandible.

3) Membranous syndesnoses – two bones are joined directly by a ligament, cord, or aponeurotic membrane. This membrane is a thin sheet of fibrous material, and often visible in pictures of two bones by an interosseus membrane like the tibia and fibula or radius and ulna.

Cartilagenous joints: bones joined by either fibrocartilage or hyaline growth cartilage.

1) Symphysis – bones joined by fibrocartilage in the form of disks or plates. Examples are the symphysis pubis and intervetebral joints.

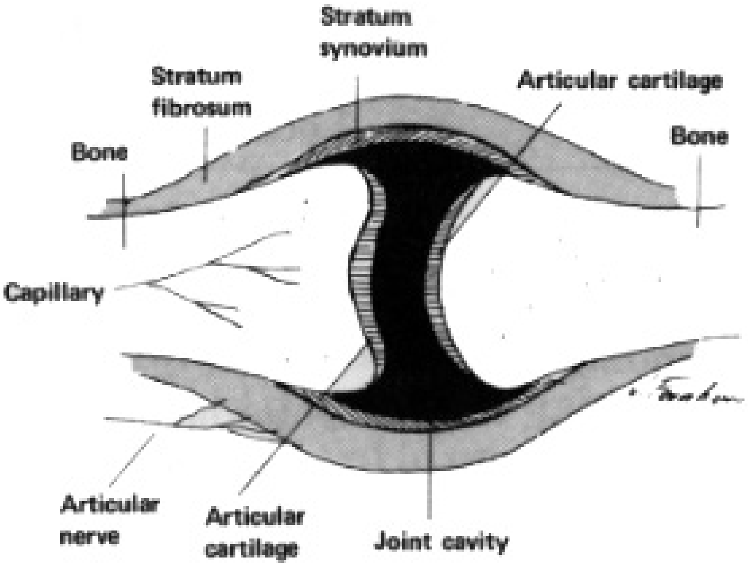
2) Synchondrosis – bones connected via hyaline growth cartilage. The temporary form of this type of joint is the epiphyseal growth plate present during childhood and adolescence. The permanent form of this joint is the costal cartilage that connects the ribs to the sternum.

Synovial Joints

All synovial joints are characterized by the presence of an articular cavity. The ends of the bone are not joined directly together as they are in the synarthrotic joints. Because of the articular cavity, these joints are freely movable. They are able to move with relatively large range of motion and often in more than one direction (depending upon the shape of the articular ends of the bones.

Characteristics

All synovial joints have the same general characteristics. Some of the structures will be slightly different across joints.



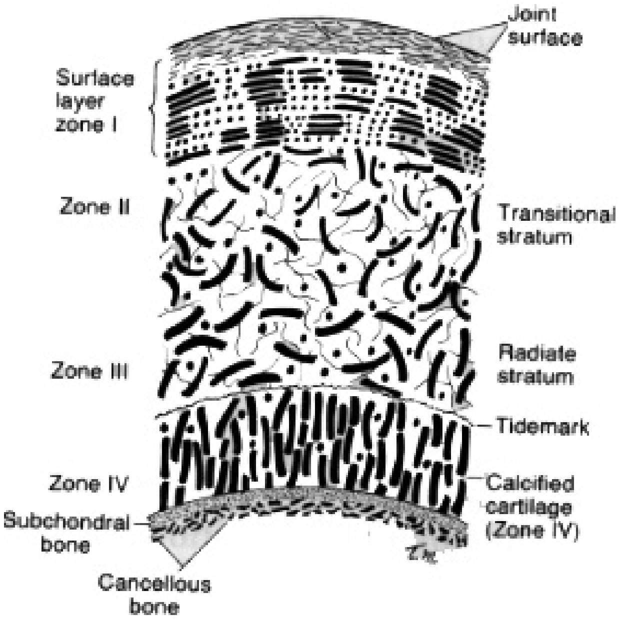
From *Joint Structure and Function: a Comprehensive Analysis 2nd edition,* C.C. Norkin and P.K. Levangie. F.A. Davis Company, Philadelphia, PA. Pg. 63, Fig. 2-5.

1) Presence of an articular cavity: the articular cavity is the space between the ends of the bones. The articular cavity is filled with synovial fluid. This fluid acts as a lubricant, reducing friction between the two bones. It also carries nutrients to and waste material from cells that live within the joint.

2) Fibrous capsule: The joint is encased in a fibrous capsule. The capsule is composed of two layers. The outer layer is the stratum fibrosum and inner layer is the stratum synovium. The stratum fibrosum is a relatively dense layer that is attached directly to the periosteum on the adjacent bones. It is reinforced by ligaments and tendons that also cross the joint. The stratum fibrosum is densely innervated with large sensory capabilities. The sensory organs are able to detect the rate and change of motion of the joint, whether compression or tension is occurring, vibration, and pain. This provides information about the status of the joint to the central nervous system. The central nervous system then coordinates muscle activity around the joint based partially on the information from the joint. The goal of the information is to protect the joint and associated structures, control movement of the joint, and provide a sinse of joint position in both static and dynamic situations. The stratum synovium is a thin inner layer of the joint capsule. It is highly vascularized. It is insensitive to pain, but is sensitive to changes in temperature. Synoviocytes are cells that live in the stratum synovium that create, maintain, and removed waste from synovial fluid.

3) Articular cartilage: the ends of the bones within the joint are covered with articular cartilage. Articular cartilage is called hyaline cartilage, and has a relatively smooth outer surface. The cartilage that covers the end of the bone is designed to protect the ends of the bone when they come in contact with one

another, and they also help to reduce friction so that the ends of the bone glide smoothly past one another. Hyaline cartilage is composed primarily of collagen (the dark fibers in the cartoon to the right) and some elastin (the thin fibers). The collagen fibers provide the strength in the cartilage. As you can see in the cartoon, collagen fibers are oriented differently in the “zones” of the cartilage. Collagen in Zone I are arranged parallel to the surface of joint. This provides resistance to tear as the two bones slide across one another during movement. Zone IV has collagen fibers that are perpendicular to the surface of the bone. These collagen fibers keep the hyaline cartilage attached to the underlying bone, preventing the cartilage from slipping off of the bone during movement. The middle two zones have both collagen and elastin in every direction. This helps the cartilage to resist applied loads from any direction.



From *Joint Structure and Function: a Comprehensive Analysis 2nd edition*, C.C. Norkin and P.K. Levangie. F.A. Davis Company, Philadelphia, PA. Pg. 77, Fig. 2-19.

4) Disks and menisci: There are other structures that may reside in the articular cavity including: fibrocartilagenous disks, menisci, labrums, and fat pads. These structures usually serve to protect the surfaces of the bone within the joint by providing cushioning, distributing force, and reducing friction. Fibrocartilagenous disks are small circular disks that have a relatively uniform width. They provide additional cushioning between the bones. A meniscus is also a fibrocartilage structure that provides additional cushioning. The menisci of the knee are irregularly shaped and are designed to distribute the force over a wider bony surface, preventing point trauma to the bone. Labrums are rings of fibercartilage that ring one of the bones in an articulation. Both the shoulder and the hip have labrums. Fat pads are simply masses of fatty tissue that provide cushioning or reduce friction in the joint.

5) Tendons and ligaments: Ligaments are non-contractile links between bones. They can be in the joint cavity or part of the joint capsule. Their structure will be discussed more fully below. Tendons provide mechanical links between muscle tissue and the bone. Both ligaments and tendons prevent abnormal range of motion for a given joint.

Factors Affecting Synovial Joint Stability

Synovial joints are freely movable. This is both a benefit and a detriment. The more mobile a joint is, the less stable that joint will be. The lower the mobility the more stable the joint. There are four categories or factors that determine the stability of a synovial joint.

1) Structure of the joint: The bony articulations themselves will provide stability. This refers to the congruency between the bones. Congruency is the amount of overlap of the bones. The greater the congruency, the greater the stability. For example, the hip is a fairly mobile joint, but also is very congruent. The head of the femur is rounded and shaped somewhat like a sphere and the acetabulum on the pelvis is concave, fitting around the head of the femur (although you will see later, that the congruency of the hip varies). The shoulder has a very low congruency since the glenoid fossa is very shallow and the head of the humerus simply sits on the edge. Another factor is the joint capsule, in terms of both the thickness of the capsule and the degree to which it covers the joint. The thicker and larger the capsule, the more stability it will supply to the joint.

2) Tendons and ligaments: The more tendons and ligaments around the joint, the greater stability these structures will provide to the joint. Ligaments are passive and are usually situated in places that are most susceptible to injury (bones subluxing or dislocating). Tendons provide structural control, but tension in tendons can be varied depending upon the contractile state of the muscle attached to the tendon.

3) Gravity: Gravity can both hurt and hinder joint stability. In the lower limb gravity usually increases stability. The weight of the upper body pushes down on the joints of the lower limb (and spine), increasing congruence and stability. The upper limb hangs at the side, so gravity pulls the arm down causing a dislocating force at the shoulder, elbow and wrist. Therefore gravity does not increase stability of the upper limb.

4) Pressure: Most articular cavities have a negative pressure relative to the atmosphere. This vacuum acts as a suction keeping the bones in the joint. It can be quite strong. The vacuum present in the hip joint is sufficient to resist the weight of the leg by itself. Observe an orthopedic surgery that has to rupture the joint capsule and the hiss of air entering the articular cavity can be heard. Remember, the stratum synovium has temperature sensors. The temperature of the articular cavity will change when the joint is ruptured. The receptors in the stratum synovium sense and send messages to the central nervous system that all is not right in the joint.

Some combination of these four factors affects the stability of every synovial joint. Probably the most stable joint in the body is the hip. All four factors are strongly present. There is good congruency between the bones; strong ligaments, large muscles, and thick tendons cross the joint; weight of the upper body presses the pelvis onto the femur; and there is a strong vacuum in the articular cavity. The shoulder is a highly unstable joint. There is poor congruency between the bones; there are a number of small muscles, tendons and ligaments crossing the joint; gravity is acting to pull the humerus out of the joint; there is a vacuum holding the arm, although not as strong as in the hip.

Joint stability also affects the flexibility about a particular joint. Flexibility is the range of motion of the joint in the directions considered to be normal for the joint. Flexibility at a joint is determined by the shape of the articular surfaces, the amount of tension in the joint capsule and ligaments, the amount of soft tissue bulk, and the extensibility of the muscle crossing the joint. Muscle extensibility depends upon the length of the muscle-tendon unit of all tendons that cross the joint. Typically this the primary limiting factor to flexibility, i.e. when a muscle-tendon unit becomes stiff. Hyper-flexibility is movement beyond the joints normal range of motion. A person can be hyperflexible relative to normal range of motion values of all people for a particular joint, however their range of motion might be normal for them. Are they hyper-flexible or not? I would argue that someone who can normally move a joint more than the average person is not hyperflexible. Instead think of hyperflexion is the movement of a joint beyond its normal range of motion and approaching the area where injury might occur.

Degrees of Freedom

Degrees of freedom (DOF) refer to the number of possible movements present in any joint. The greatest number of DOF possible is six. There are a maximum of three translational (linear) movements and three rotational movements possible at any joint. Due to congruency and other factors, some joints have fewer than six DOF. The three linear movements are anterior-posterior (forwards and backwards), medial-lateral (side to side), and inferior-superior (up and down). The three rotational movements are flexion/extension (rotation forward/backward around a mediolateral axis), ab/adduction (rotation to the side around an anterioposterior axis), and internal/external rotation (a twist around a vertical or longitudinal axis). Unless otherwise stated, we are concerned primarily with the rotational movements, thus we will identify the number of DOF possible at a joint from one to three.

The number of degrees of freedom total for a movement depends upon the number of joints involved in the task. The more complex the movement, the more joints that become involved, then there are a greater the number of DOF that must be accounted for. One can determine the total number of DOF for any movement by summing the DOF for each individual, involved joint. For example, when you are sitting and eating dinner, the DOF of the upper limb and torso must be accounted for, but those of the lower limb can be ignore (with regards to any movement occurring). However, in something like a free throw, both the upper and lower limbs are involved, so the total number of DOF possible is much greater.

Joint Classification

Joints are classified by the number of rotational DOF possible at the joint. There are three categories of joint classification (which should make sense to you).

1) Uniaxial joints: one DOF of movement is possible at the joint. There are two types of uniaxial joints:

    a. Ginglymus (hinge) – Typically, the surface of one bone is spool-like and rounded and the other bone has a concave articulating surface. The bone with spool-like surface first into the concave surface of the second bone. This configuration permits rotation around one axis, in one plane. The elbow and interphalangeal joints are ginglymus joints allowing only flexion and extension.

    b. Trochoid (screw; pivot) – The trochoid joint is characterized by the presence of a pivot on one of the bones surfaces. This pivot allows one bone to roll around the second bone about a longitudinal axis. The radio-ulnar joint is a trochoid joint allowing pronation and supination.

2) Biaxial joints: two DOF of movement are possible at the joint. There are two types of biaxial joints:

    a. Condyloid (ovoid; ellipsoidal) – One bone has an oval or egg shaped surface that fits into the concave surface of the second bone. Movement is possible about two axis, in two planes. The metacarophalangeal joints (base of the fingers) are condyloid joints allowing flexion/extension and abduction/adduction.

    b. Sellar (saddle) – The end of one bone is concave in one plane and convex in the other (looks like a horse saddle). The end of the other bone has the same shape. The two ends then fit together. The 1st carpometacarpal joint (where the thumb articulates with the wrist) is a sellar joint allowing flexion/extension and ab/adduction.

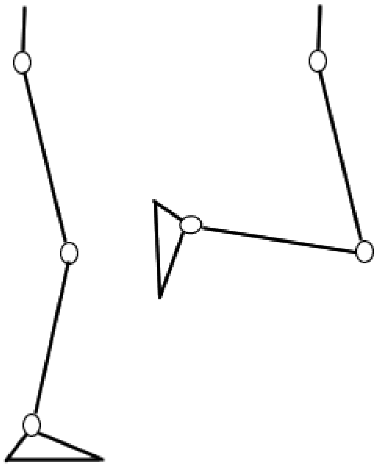
3) Triaxial joints: three DOF of movement are possible at the joint. There two types of biaxial joints.

    a. Enarthrodial (ball-and-socket) – ball like surface of one bone fits into the concave surface of the second bone. Allows rotation about all three axis, in all three planes. Both the hip and shoulder are enarthodial joints.

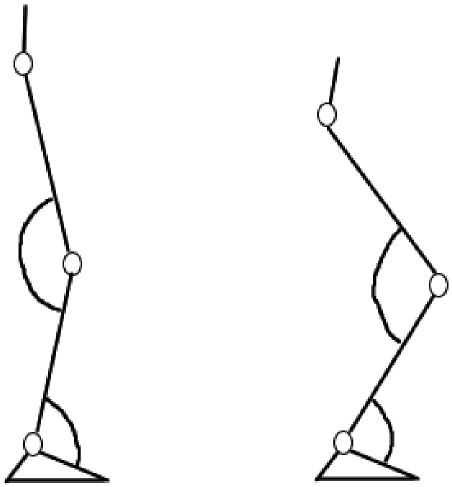
    b. Arthrodial (plane) – Both bones have flat surfaces. Gliding is permitted between the surfaces, and rotation about the longitudinal axis. The carpal and tarsal joints (articulations between the carpal bones of the wrist and those between the tarsal bones of the feet) are all arthrodial.

Kinematic Chains

A series of joints linked together via rigid segments form a kinematic chain. We can model a limb as a kinematic chain. Thinking of a limb as a kinematic chain will help us to understand the sequence of joint movements that have to occur in order to produce a particular movement.



An open kinematic chain occurs when one end of the kinematic chain is fixed (that is there is very little movement that occurs). The other end of the chain is allowed to freely move. In an open kinematic chain, if the angle at one joint changes, it does not affect the joints around it. The figure to the right shows stick figures of the leg. If the leg is held off of the floor and the knee flexes, the foot swings upwards. The ankle and the hip stay in the same angular position as they were in before the angle of the knee changed. The arm often acts like an open kinematic chain. The shoulder is the "fixed end" (although the scapula might move) and the hand is the freely movable end of the chain. Therefore, movement of the wrist, elbow, or shoulder does not necessarily affect the adjacent joints.



A closed kinematic chain consists of linked segments that have fixed ends. In this case both ends of the chain are not allowed to move. If the angle of one joint in the chain changes, then there will be angular changes in adjacent joints of the chain. The example at the right shows a squat down. In this case, the foot remains fixed. The upper body does move downward, but the movement is limited due to the requirement of stability. Thus, when the knee flexes, both the ankle and the hip also flex. There is no way to flex the knee and not flex the ankle and hip. At least, you can't do this without falling over as the torso will have to move, causing the person to become unbalanced. The squat is a fairly good example of a closed kinematic chain, the upper arm during a push-up is a similar example.

Joints are interdependent. There is a great deal of compensation possible. If the structure and function of one joint is compromised, adjacent joints can alter their function to compensate. For example, when you injure your knee you might be forced to where a knee brace that allows limited knee flexion. Your knee has to flex during the swing through (recovery) in order to walk with a normal pattern. However, if you can't flex your knee and try to swing your straight leg forward, you will hit the ground (try it if you don't believe me). You can compensate by raising your hip during the swing through.

Connective tissue

There are several different types of connective tissue. The role of these different structures are to maintain the integrity of the skeletal system. In most cases, connective tissue acts to: keep bones from moving in abnormal patterns from one another and transmit forces from bone to bone or from muscle to bone.

General Structure

All connective tissue has the same basic ingredients. How these ingredients are put together and in what proportion varies between the different tissues. The basic building block is the protein collagen. As seen in figure 9, the cell that creates connective tissue is the fibroblast. Collagen is created in the cell and extracellularly they are bound to together as microfibrils. Microfibrils are then bound into fibrils, which are bound into fibers, and finally into a bundle. The bundles are then encapsulated in endotenon and eventually the larger structure (e.g. tendon or ligament) is created.

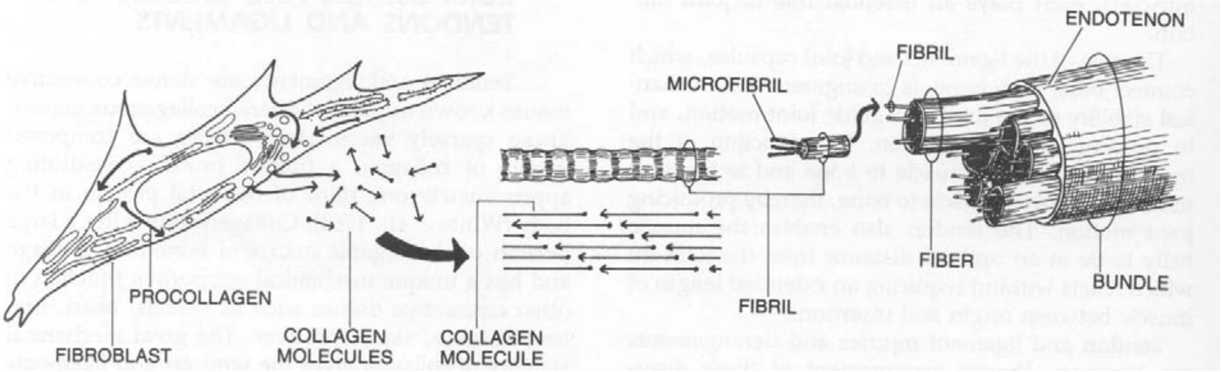


Figure 9. Formation of a bundle of connective tissue. (Figure from *Basic Biomechanics of the Musculoskeletal System 3rd edition*, Nordin and Frankel, Lippincott, Williams & Wilkins Publishing, 2001. Pg. 104, Fig. 4-1)

The protein elastin can also be bound together into the microfibrils. Elastin, as its name implies is elastic, meaning that it can be stretched and deformed, but then return to its original shape when the deforming force is removed. Elastin helps to give connective tissue is resiliency, which its ability to retain its shape and structure. The third substance in the microfibrils is a ground substance (glycoproteins and proteoglycans) which form the glue to hold everything together.

These bundles of collagen fibers are parallel or nearly parallel depending upon the type of connective tissue. In tendons, these bundles are parallel, and in ligaments they are nearly parallel. Why are they arranged slightly different in tendons and ligaments? In tendons, force is transmitted longitudinally through the tendon. The muscle pulls on one end of the tendon and the other end is fixed. This means that the tendon is loaded in one direction only. In the ligament, most of the time forces act longitudinally along the ligament, however, some forces may act obliquely do to the changing orientation of bones during movement. Because forces do not always pull in one direction of the ligament, collagen bundles are arranged in different directions to always be able to resist the applied forces.

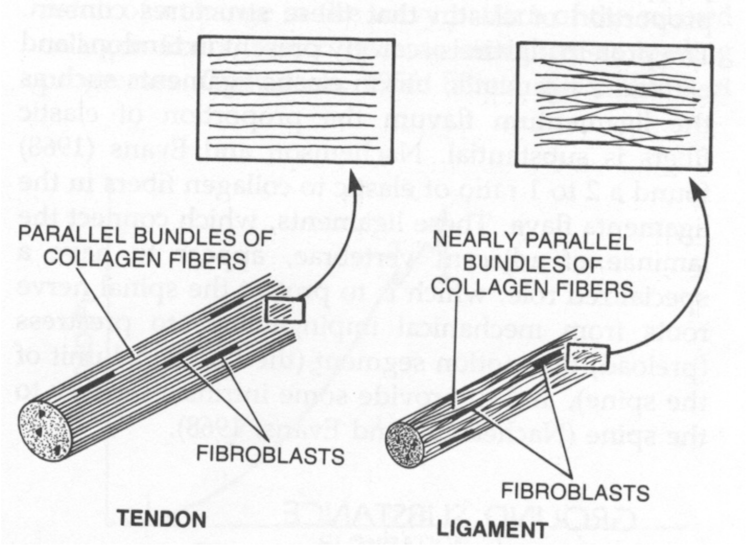


Figure 10. Collagen bundles are parallel in the tendon and nearly parallel in the ligament. (Figure from *Basic Biomechanics of the Musculoskeletal System 3rd edition*, Nordin and Frankel, Lippincott, Williams & Wilkins Publishing, 2001. Pg. 106, Fig. 4-4)

Properties of Connective Tissue

All connective tissue is fairly pliant and flexible until it becomes loaded. In an unloaded state, the bundles of collagen are relaxed. When tension is initially applied to the tissue, the bundles elongate slightly until they are no longer relaxed. When the bundles elongate slightly and become taught, then they resist further lengthening.

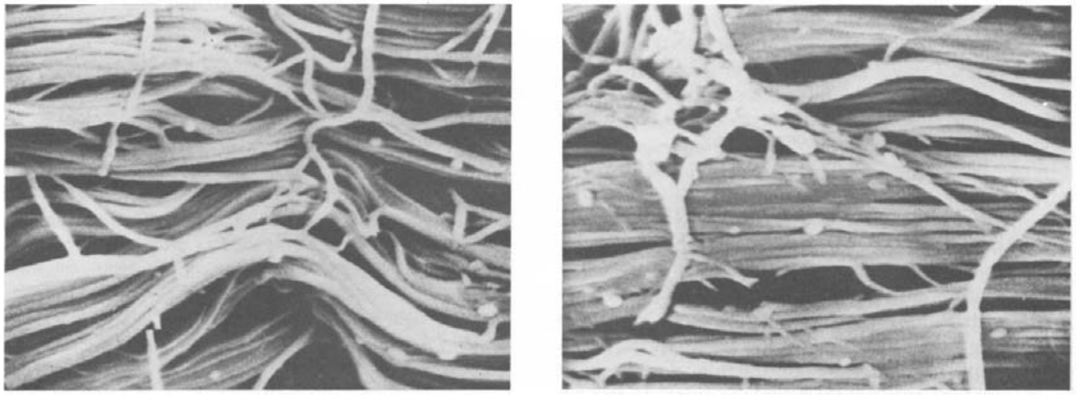


Figure 11. Collagen bundles from a knee ligament that are relaxed (left) and under tension (right). (Figure from Kennedy, J.C., Hawkins, R.J., Willis, R.B. and Danylchuck, K.D. (1976). Tension studies of human knee ligaments. Yield point, ultimate failure, and disruption of the cruciate and tibial collateral ligaments. The Journal of Bone and Joint Surgery, 58(3), 350-355.

Both tendons and ligaments can withstand a fair amount of stretch before failure (they rupture). The anterior cruciate ligament (ACL) of the knee can stretch 5 millimeters before substantial damage is done (although the ligament may not immediately tear). Once the ligament sustains damage its ability to resist additional loads is severely reduced. Even lower loads may damage the ligament. Once the ligament has been stretched too far and has been damaged, it will not be able to retain its original length when the tension is removed.

An example of taking a ligament or tendon to failure is seen in figure 12. The ACL ligament is being consistently loaded with an increasing force. As the force in creases, elongation of the ligament occurs. You can see initially that the ligament elongates with very little force placed upon it. This is when the bundles are straightened as seen in figure 11. The ligament can withstand much force without damage (until it has reached 4 or 5 mm of strain). Once it has surpassed 2 on the curve, permanent serious damage has occurred to the ligament. In a person, reaching this much strain is typically associated with ligament failure (ACL tear that must be surgically repaired).

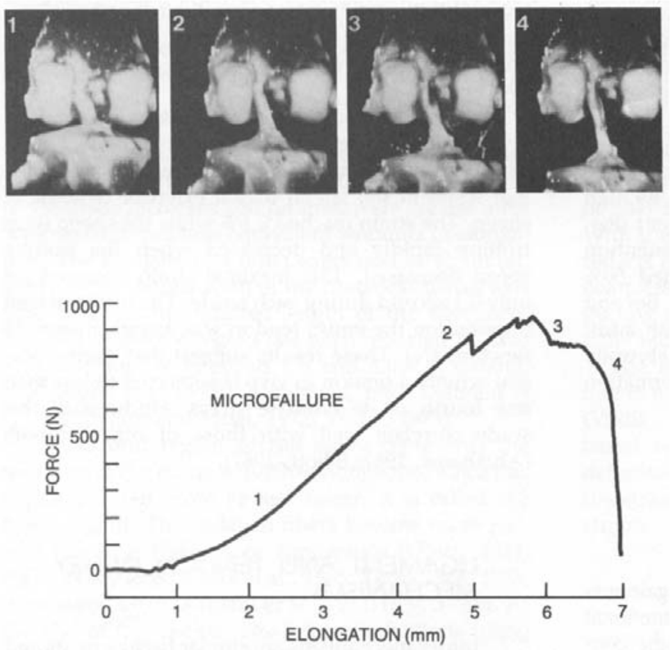


Figure 12. ACL ligament being loaded to failure. Once the force reaches 2 on the curve, injury and micro-tears would occur. The ligament would never retain its original length or condition. (Figure from Noyes, F.R. and Grood, E.S. (1976). The strength of the anterior cruciate ligament in humans and Rhesus monkeys. Age-related and species-related changes. The Journal of Bone and Joint Surgery, 58(8), 1074-1082)

One of the factors that will affect the damage that occurs to a connective tissue is not only the magnitude of force applied, but also the rate at which the force is applied. If you think about when most ACL injuries occur, they typically happen during sudden explosive movements or during sudden external blows to the knee. In these instances the forces are large but they are applied very quickly, increasing the likelihood of injury. The other instances in which ACL injuries occur are during planting and twisting movements. The twist loads the ligament in a non-uniform manner, again increasing the likelihood of injury.

The strength of connective tissue decreases with disuse. Like many of the structures in our body, one must “use it or lose it”. Eight weeks of immobilization of a limb so that muscles can’t act are enough to reduce the strength of tendons by 40%. It can take over a year with active conditioning to restore the tendon to 90% of its pre-injury strength. With continued conditioning, the tendon will achieve nearly 100% of its original strength. The same is true for ligaments and any other connective tissue.

Types of Connective Tissue

There are several different types of connective tissue. Two of them have already been discussed in a fair amount of detail – ligaments and tendons. Aponeuroses are similar to tendons in that they provide a link from muscle contractile tissue to bone. Tendons are bundles that resemble a rope or cord. Aponeuroses are broad sheets of connective tissue. Latissimus dorsi has an aponeuroses as part of its tendon structure because it is such a large muscle. The final type of connective tissue is retinacula. These are sheets of collagenous connective tissue that maintain the position and assist with the movement of tendons. Retinacula are present in the wrists to enable the wrist (and finger) flexors to work more efficiently.

Muscle Anatomy and Function

Muscle provides the motor for all human movement and life. This contractile element of the muscle tendon unit allows us to perform al of the movements for which we might be interested in developing a complete understanding. Muscle as we think about consists of two elements the contractile and noncontractile elements. Noncontractile elements consist of the tendon and connective tissue around the muscle fibers. The contractile elements are the muscle fibers themselves.

Muscle – Contractile and Non-contractile Elements

The muscle fiber is the structural unit of the muscle. A muscle fiber is a long cylindrical cell with hundreds of nuclei. Thickness of different muscle fibers vary from 10 to 100 micrometers and from 1 to 30 cm in length in human muscle. Muscles in large animals can have muscle fibers over 50 cm in length! Each muscle fiber consists of many myofibrils. Myofibrils, in turn, are made of sarcomeres. Sarcomeres are the functional unit of the muscle.

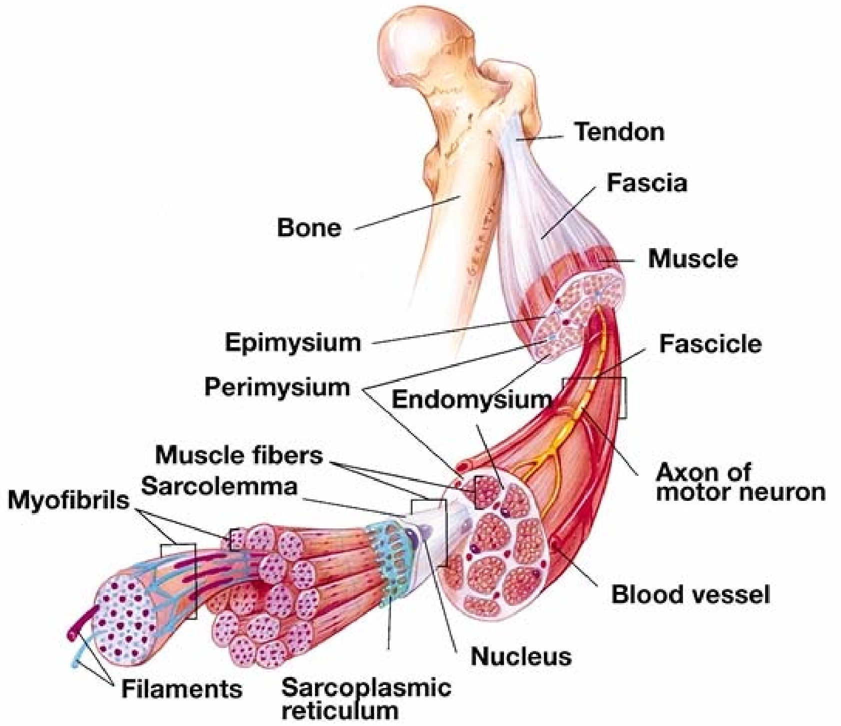


Figure 13. Macro- to micro-structure of muscle. (Figure from *Exercise Physiology: Theory and Application to Fitness and Performance.* Scott K. Powers and Edward T. Howley, McGraw-Hill Publishers, 2004, pg. 138, Fig. 8.1)

Sarcomeres are made of several proteins that can interact with each other in such a manner to cause the sarcomere to shorten. The exact mechanisms of the process are beyond the scope of this course, but will be discussed more completely in a physiology course. The short story is that a thick protein, myosin, attaches to a thin protein, actin, at specific sites. Once myosin attaches it bends causing the sarcomere to shorten slightly. Then the myosin releases and prepares to repeat the process. Another protein, titin, is an elastic protein that helps to transit force during shortening and prevent damage to the sarcomere during lengthening.

Each muscle fiber is encompassed by endomysium, a loose sheath of connective tissue. This connective tissue is continuous with the muscle fibers. It also helps to bundle the muscle fibers into fascicles. Fascicles are encapsulated by perimysium. All of the fascicles in the muscles are bundled together by epimysium, the out layer of connective tissue. All three levels of connective tissue –epimysium, perimysium, and endumysium – are continuous with one another and with the muscle tendon. This allows force that is developed by the contractile tissue to be smoothly delivered to the bone.

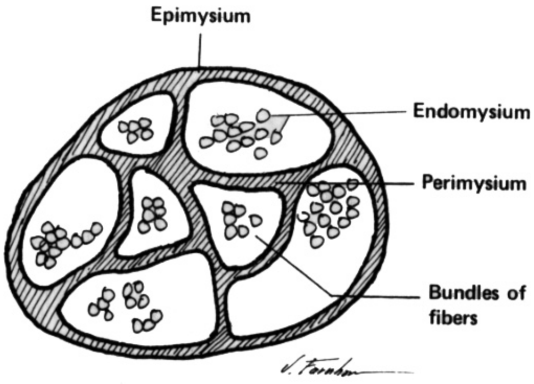


Figure 14. From *Joint Structure and Function: a Comprehensive Analysis 2nd edition*, C.C. Norkin and P.K. Levangie. F.A. Davis Company, Philadelphia, PA. Pg. 103, Fig. 3-10.

The connective tissue associated with the muscle, from the protein titin to the epimysium and tendon, has several highly important roles in the muscle. This tissue tends to keep the muscle in readiness for contraction and assure that muscle tension is produced and transmitted smoothly during contraction. Connective tissue, due to its elasticity, returns the contractile elements to resting position when the contraction is finished. These structures allow for the rapid adjustment of tension with out engaging the contractile elements which is important for preventing overstretch of the contractile elements when they are relaxed, reducing the danger of muscle injury. Finally, these structures help to absorb and dissipate energy (by releasing heat).

Muscle Tension

Muscle tension refers to the force developed by the both the contractile and non-contractile elements. There are several ways in which the muscle develops tension.

Active Tension

Active tension is the force developed by the contractile elements. The ultimate source of this force is from the crossbridges formed between actin and myosin in the sarcomere. One way to alter tension is to change the number of crossbridges formed. The more crossbridges formed, the greater the tension that can be developed. The length of the sarcomere affects the amount of tension that can be developed. There is an optimal relationship between force production and sarcomere length. Figure 15 shows the relationship between tension and sarcomere length. If the sarcomere is too short or long, then fewer crossbridges can be formed, so less tension can be developed. This translates to the larger muscle. If the muscle is short (like when the elbow is completely flexed), then active insufficiency occurs, resulting in reduced tension. If the muscle is too long (like when the elbow is fully extended) then lower tension is developed by the muscle. So the optimal position to develop force is the middle of the range of motion for most joints because that is when muscles are at their optimal length.

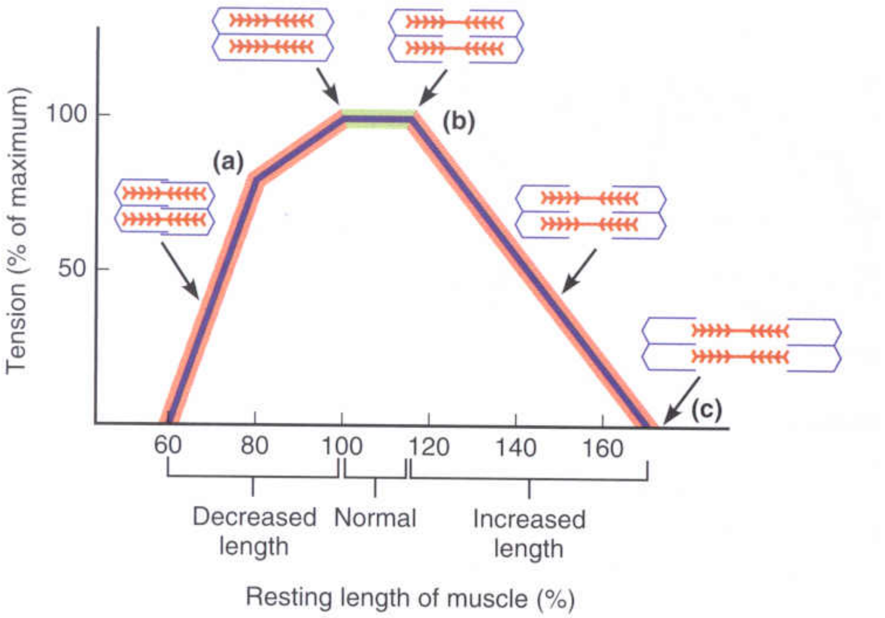
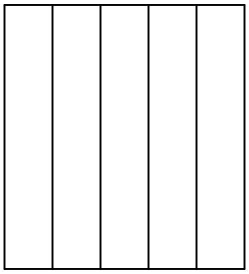
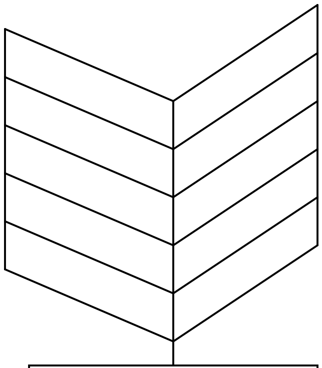


Figure 15. Length tension relationship. (Figure from *Physiology of Sport and Exercise 3rd Edition,* David Costill and Jack Wilmore, Human Kinetics, 2004)

The length of the muscle at any given time will determine the amount of force that can be developed. The total length of the muscle fibers will also determine the amount of force developed. Some muscles have very long muscle fibers and some muscle have very short muscle fibers. Typically, muscle with short muscle fibers are able to develop more force, but have a short range of motion and muscles with long fibers develop lower force but with greater shortening (or movement) capacity. Another factor that determines that amount of force is the physiological cross-sectional area (PCSA) of the muscle. The PCSA is the total length of the muscle fibers when measured as the perpendicular distance across all muscle fibers. Typically short fibers muscles have a large PCSA and muscle with long fibers have a smaller PCSA.



Fusiform Muscle



Pinnate Muscle

Long muscle fibers are usually arranged in a fusiform arrangement. This is when the fibers are arranged parallel to one another along the long axis of the muscle. Typically, fusiform muscles are long, have long muscle fibers, can produce lower forces, and larger amounts of shortening. In a pinnate muscle, fibers are shorter and arranged at an angle to the long axis of the muscle. Muscle fibers in a pinnate muscle are shorter, can produce greater forces, and have a lower capacity to shorten. Fusiform muscles have a lower PCSA and pinnate muscles have a larger PCSA.

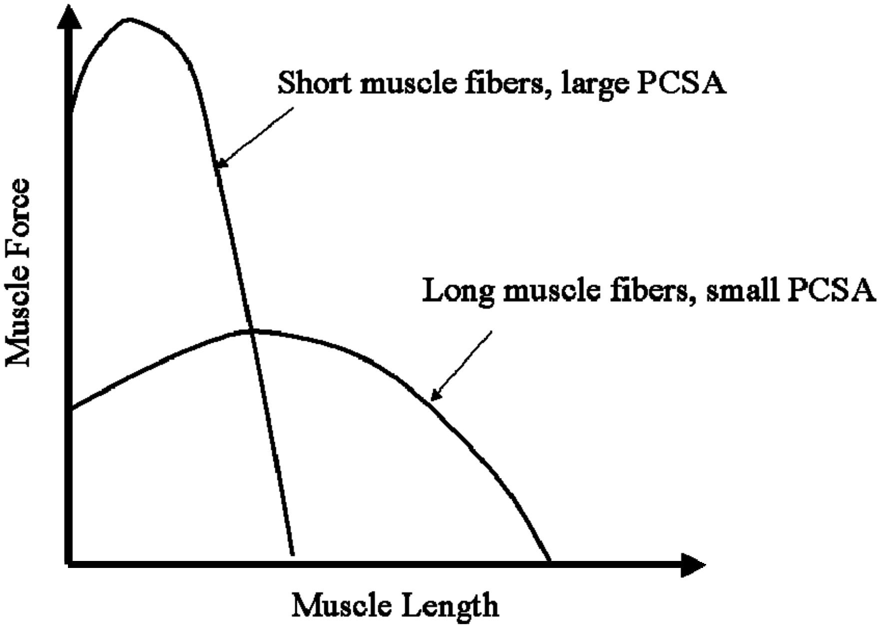


Figure 16. The relationship between muscle force and muscle length for muscles of different muscle fiber length and PCSA.

Passive Tension

Passive tension refers to the force that is created in the connective tissue around the muscle. Remember that the contractile tissue is surrounded by connective tissue (including the protein titin in the sarcomere) and attaches to the bone via a tendon. These connective tissue elements can behave as elastic elements. Think of a rubber band. When it is relaxed it is fairly easy to manipulate. However, the more you stretch it, the more it resists being stretched. The tendon and other connective tissue act the same way – the more they are stretched the more they resist being stretched, creating force. If you look back at the length-tension curve in Figure 15 when the contractile tissue starts to get too long, the amount of tension that the sarcomeres can develop decreases. However, as the contractile elements get too long, they stretch and begin to resist being stretched. Thus the **total** tension developed by the contractile and connective tissue actually *<u>increases</u>*.

When does passive tension play a significant role during movement? If you think about it, it can only assist movement after connective tissue has been stretched. Think about the rubber band once again. Stretch a rubber band and then release it while still holding it. It snaps back causing a painful impact against your skin. That pain is from the force being released from the rubber band. The same thing happens with the connective tissue around the muscle. Stretch it and energy is stored just waiting to be released – just like the snap of the rubber band! In order to understand how we use the elasticity of the connective tissue, we need to define the different types of muscle actions.

Concentric, Isometric, and Eccentric Muscle Actions

When we discuss muscle action, we have to include the entire muscle-tendon unit. Concentric muscle actions are when the origin and insertion of the muscle-tendon unit get closer together. An isometric muscle action is when the distance between the origin and insertion remains the same. Finally, an eccentric muscle action is when the distance between the origin and insertion of the muscle tendon unit increases. In no instance is the word contraction used. Contraction is when two objects draw closer together – which is our definition of concentric muscle action. So to say "concentric contraction" is repeating the same thing twice. To say an "eccentric contraction" is the opposite (one means lengthening and the other shortening). It is better to refer to any muscle movement as a "muscle action".

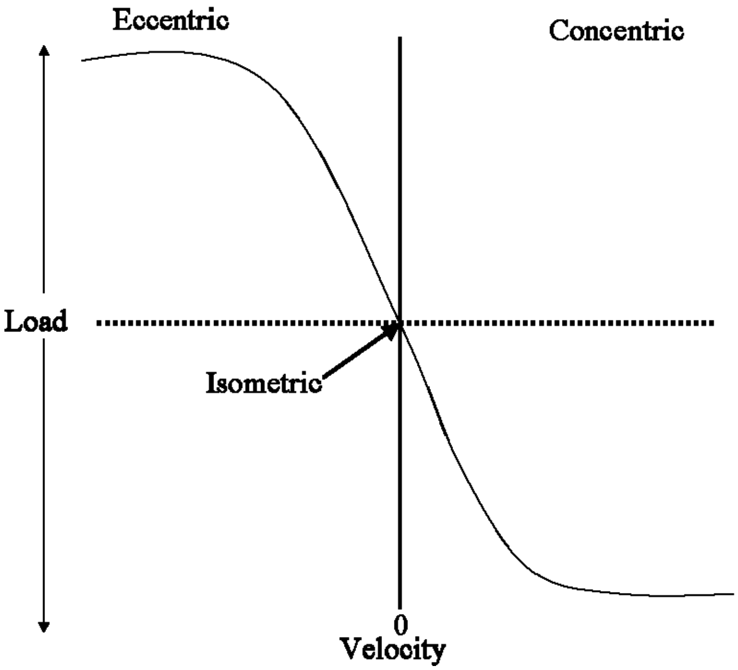


Figure 17. The relationship between muscle velocity and force. The muscle velocity is 0 during an isometric muscle action. To the left of the zero line, the muscle is lengthening (and lengthening at a greater rate the farther from the axis you go). To the right the muscle is shortening (at greater rates the farther to the right you go). So concentric muscle force is lower than isometric force and eccentric muscle force is greater than isometric muscle force (isometric force is the horizontal dotted line in the middle of the plot).

Concentric action causes a shortening of the muscle tendon unit due to the shortening of the muscle fiber (through normal crossbridge cycling in the sarcomere). Eccentric muscle action is an active lengthening of the muscle, in which the crossbridges are forming but they are attempting to prevent the muscle from lengthening. Which of these actions is capable of developing more force? Eccentric muscle action is correct! From the explanation of passive tension from above you should be able to arrive at this conclusion as well. Figure 17 also illustrates this phenomenon. Musculotendon force is greater during an eccentric muscle action than during a concentric muscle action. In fact, during a concentric muscle action, the faster the muscle shortens, the lower the force that muscle can produce.

Stretch-Shortening Cycle

If you want to throw a ball farther, you bring the arm farther back more quickly prior to moving it forward. If you want to kick a ball so that it travels faster, you bring the leg back farther behind you before swinging it forward. If you want to jump higher, you use a counter-movement where you squat first and then explode upward. In all of these situations you are *pre-loading* the muscle. To pre-load the muscle, it rapidly stretched prior to being shortened. This stretches the connective tissue, so that when the muscle shortens the force released from the connective tissue and the force developed by the contractile tissue is combined.

Repetitive pre-loading is called the stretch-shortening cycle (SSC). When the foot is contact with the ground during running, the muscles of the leg are initially pre-loaded and then released. So to a certain degree, your leg behaves *elastically* during running. Continuous hopping also is a SSC exercise. This allows for increased efficiency of movement. However, the anatomical mechanisms present in our legs are no where near as efficient as other animals. Wallabies can hop at fast speeds using almost no more energy than it takes to walk slowly!

Role of Muscles During Movement

One of the most important tasks that you have when dealing with physical movement is to identify the muscles that produce a certain movement. You do not truly know a movement unless you know the role that each muscle plays in producing that movement. A teacher or coach deficient in this knowledge is more likely to use inappropriate training methods that increase the likelihood of injury. Unfortunately, determining the muscles involved for a movement is not easy and requires that you have a very good knowledge of anatomy. One of the tricky things to remember is that many muscles have multiple actions at one joint or at more than one joint.

What will a muscle do at a joint? Remember that the muscle can do nothing except turn on and generate force along its long axis. The muscle doesn’t think about things and decide to produce flexion one time and abduction another. It simply tries to shorten. So what a muscle does at a joint will depend upon the position of the joint that it acts upon when the muscle is turned on. The initial length of the muscle and the number of motor units activated (more motor units = more force) will also be a factor. The amount of force generated by other muscles that cross the joint will also determine the movement produced. All of these factors must be accounted for when determining the role a particular muscle has at a joint.

Roles That Muscle Can Play

There are several roles that muscles can have at a joint during a movement. These roles are:

1) Agonist: Agonist muscles are the prime movers. The joint movement is produced (or controlled) directly by the muscle(s).

2) Antagonist: These are muscles that oppose the agonists. If activated they would tend to oppose or prevent the desired motion.

3) Synergist: Muscles that assist the agonist(s) produce the desired action are synergists. Generally the movement is not the synergist muscle(s) primary action, thus they are not primarily responsible for the movement. Often synergistic action of muscles is required for smooth joint movement. For example, to abduct the shoulder (raise the arm to the side), the rotator cuff muscles infraspinatus, teres minor, and subscapularis have to concentrically act in order to elevate the arm from the side, even though these muscles can’t abduct the arm (more on this when we discuss the shoulder later).

4) Stabilizers: These are muscles that surround a joint or body part and act to fixate or stabilize the area. This often establishes a firm base for the more distal joints to work from. Try heel-ups (standing on your toes) when your knees can flex as well, doesn’t work as well.

Multi-articular Muscles

Many muscles cross more than one joint. The multi-articular muscle can produce actions at all of the joints that it crosses. The muscles of the hamstrings are good examples of bi-articular muscles as they cross both the hip and the knee and can extend the hip and flex the knee. These muscles play important roles in the ability to produce movement efficiently. However, one must examine movements that involve multi-articular muscles cautiously. Multi-articular muscles may be producing an action at a joint that is not entirely obvious without careful consideration of the movement. Again the action of the hamstrings during the upward movement of a squat provides a good example. When one stands up from a squat, both the hip and the knee extend. The hamstrings extend the hip, but *flex* the knee, counter to what actually occurs. So, do hamstrings help with the squat? If so, can you think of how? I will tell you now, that the hamstrings are important for the squat, but not in the way that you are accustomed to thinking of them. The hamstings act isometrically (or nearly isometrically) during the squat. This helps to transfer muscle force from the knee extensors to the hip and ankle during the squat. We will discuss this in further detail when we detail the anatomy and function of the leg.