Muscle is one of the 4 primary types of tissue. There are 3 types of muscles:
- Skeletal muscle (striated voluntary)
- Cardiac muscle (striated involuntary)
- Smooth muscle (nonstriated, involuntary)
Voluntary muscle also referred to as somatic tissue, and involuntary muscle referred to as visceral tissue.

**Properties of Muscle Tissue**

- **Excitability** → the ability to respond to stimulation.
- **Contractility** → the ability to shorten actively and exert tension.
- **Extensibility** → the ability to contract after being stretched to various initial lengths.
- **Elasticity** → the ability to regain its initial length after contraction.
Skeletal Muscle

- Introduction & Functions.
- Anatomy.
  - Macroanatomy
  - Microanatomy
- Control of skeletal muscle activity
- The contraction cycle.
- Relaxation.
- Muscle mechanics.
- Energetics of muscular activity.
- Muscle performance.

Introduction and Functions

- Skeletal muscle composed of:
  - Skeletal muscle tissue.
  - Blood vessels.
  - Connective tissue.
  - Neural tissue.
- Approximately 700 different skeletal muscles in the human body.
- Functions:
  - Produce movement.
  - Maintain posture and body position.
  - Support soft tissues.
  - Guard entrances and exits.
  - Maintain body temperature.
Gross Anatomy

- Three layers of connective tissue are part of each muscle.
  - Outer epimysium.
  - Central perimysium.
  - Inner endomysium.
- At each end of the muscle, fibers in epimysium converge to form tendons.
- Tendons attach the muscle to bones.
- Epimysium.
  - Layer of collagen fibers that separates muscles from surrounding tissue.
- Perimysium.
  - Made up of connective tissue fibers (collagen and elastic).
  - Divide each muscle into separate compartments, each containing a bundle of muscle fibers (fascicle).
  - Also contains blood vessels and nerves.
- Endomysium.
  - Found within the perimysium.
  - Surrounds each muscle fiber (ie, each muscle cell) and ties fibers together.
  - Stem cells located within endomysium for renewal and repair.

How many muscle fascicles do you see?
How many muscle cells do you see in the enlarged fascicle?
What is the smallest unit of contraction pictured?
Microanatomy

- Muscle cells are called fibers due their long, stringy appearance.
- Individual muscle fiber can be very long: 30 – 40 cm.
- Each cell also contains several nuclei:
  - Genes within each nucleus participate in the production of enzymes and proteins associated with contraction.
  - Multiple copies of the genes allow parallel processing approach to the generation of proteins and enzymes.

Microanatomy

- Cell membrane of a muscle cell is called the sarcolemma.
- Internal cellular portion (cytoplasm) is called the sarcoplasm.
Microanatomy – T Tubules

- Openings on the surface of the sarcolemma lead to a network of narrow tubules (transverse tubules – T tubules).
- Inside of the T-tubules is still outside the cell.

T Tubules and the Sarcoplasmic Reticulum

- Contraction of individual myocyte occurs through electrical and chemical interactions.
- Electrical event at the sarcolemma trigger a contraction by “instantaneously” changing the chemical makeup within the cell.
- T-tubules extend to all parts of the cell.
  - Encircle myofibrils → cylindrical structures that are anchored to either end of the cell and produce contraction.
- Sarcoplasmic reticulum also encircles myofibrils.
  - SR is a specialized form of the endoplasmic reticulum.
- Ends of SR form chambers called cisternae.
- T-tubules are in contact with cisternae.
T-Tubules, SR, Myofibrils and Cisternae

- Cisternae are within the cell, but internal components are still separated by the SR membrane.
  - Lots of Ca\(^{2+}\) within cisternae, held by protein calsequestrin \(\rightarrow\) however, Ca\(^{2+}\) concentration within sarcoplasm is low.
  - Myofibrils contract when Ca\(^{2+}\) ions are released by cisternae.

Myofibrils

- Sarcoplasm contains 1000’s of myofibrils.
- Each myofibril diameter: 1 – 2\(\mu\) diameter; length: as long as the entire muscle fiber.
- Myofibril is attached to sarcolemma at either end \(\rightarrow\) as myofibril contracts, entire cell shortens.
- Glycogen granules and mitochondria are scattered between myofibrils \(\rightarrow\) provide energy for contraction.
Myofibrils, Myofilaments and Sarcomeres

- Each myofibril is made up of myofilaments organized in a bundle.
- Myofilaments are protein filaments, consisting primarily of the proteins actin and myosin.
- Myofilaments are organized into repeating structures known as sarcomeres.
- Myofilaments are made up of thick filaments (myosin) and thin filaments (actin).
- The sarcomere is the basic functional unit of the muscle fiber → smallest unit of muscle contraction.

Organization of the Sarcomere

- All myofibrils (and all sarcomeres) are oriented parallel to the long axis of the cell.
- Organization of thick and thin filaments produces a banded appearance.
- Each myofibril consists of a linear sequence of around 10,000 sarcomeres.
- Each sarcomere is around 2.6 μm length in relaxed state.
- Thick filaments lie at the center (lengthwise) of the sarcomere.
- Thin filaments are at either end (lengthwise).
- Connection line between sarcomeres is called the Z-line.
- M-line (middle-line) exists at center of the sarcomere and connects thick filaments together.
- A-band is the band containing the thick filaments (center of the sarcomere).
- I-band is the band between two successive A-bands (note that I-band contains the Z-line and is made up only of Actin).
Thin and Thick Filaments

- Thin filament composed of a twisted strand of actin molecules.
- Each actin molecule has an active site where interaction with the myosin molecules of the thick filament takes place.
- Tropomyosin strands cover active sites during resting state (held by troponin).
- Thick filament is composed of the molecule myosin.
- Each molecule has a tail and a head (golf-club shape).
- Head of myosin molecule is located away from M-line; heads face outward.
- Myosin head interacts with active site of actin to produce contraction.

Initiation of Muscle Contraction

- $\text{Ca}^{2+}$ is the key to unlocking the active sites so that muscle contraction can begin.
- $\text{Ca}^{2+}$ binds to troponin \(\rightarrow\) protein changes shape and moves tropomyosin strand away from the active site \(\rightarrow\) Myosin then binds to active site and contraction can begin.
- Cisternae of sarcoplasmic reticulum are the sources of $\text{Ca}^{2+}$. 
Sliding Filaments

- When muscle contracts, thin filaments move closer to M-line.
- This causes the Z-lines to move closer together.
- Myosin head forms cross-bridge with actin active site.
- When cross-bridge occurs, the head of the myosin molecule pivots towards the center.
- Myosin head detaches and attaches to the next active site further, thereby producing a ratcheting mechanism that brings the thin filaments toward center.
- Note that Z-lines come together, but length of actin and myosin molecules remains the same.

The Control of Muscle Fiber Contraction

- Each muscle fiber contains a connection to the nervous system.
- This connection point is known as the neuromuscular joint (NMJ).
The Neuromuscular Joint

- The axon of the nerve ends at a synaptic knob.
- Cytoplasm of nerve cell at the synaptic knob contains mitochondria and vesicles filled with acetylcholine (ACh).
  - ACh is a chemical released by a neuron to modulate activities of other cells (neurotransmitter).
  - Release of ACh causes changes in the sarcolemma that triggers contraction of the muscular fiber.
- The synaptic cleft separates the synaptic knob from the sarcolemma.
- Sarcolemma at this site contains receptors specific to ACh (the motor end plate).
- Enzyme acetylcholinesterase (AChE) found in the synaptic cleft and in the motor end plate breaks down ACh.

The Action Potential

- Neurons control muscle fibers by stimulating the production of an action potential (an electrical impulse) along the sarcolemma.
- Sequence of events:
  - Release of acetylcholine by vesicles in the neuron.
  - Binding of ACh at the motor end plate.
    - ACh diffuses across the synaptic cleft and attaches to the ACh receptors on the sarcolemma.
    - This changes the permeability of the sarcolemma to Na⁺.
    - Rush of Na⁺ into the sarcoplasm produces the action potential.
  - The action potential spreads down the sarcolemma and over all the surfaces of the T-tubules.
  - The passage of the action potential causes the cisternae to release the Ca²⁺ ions.
T-tubules help propagate action potential into various parts of the cell

Steps in the Contraction Cycle

- ATP $\leftrightarrow$ ADP + PO$_4^{3-}$
- Exposure of the active site to troponin following binding of calcium ions.
- Attachment of the myosin cross-bridge to the exposed active site on the actin filaments.
- The pivoting of the myosin head toward the center of the sarcomere and the release of ADP and PO$_4^{3-}$.
- The detachment of the myosin head when it binds another ATP molecule.
- Reactivation of the detached myosin molecule as it splits ATP and stores ADP, phosphate group + energy (potential energy produced by changing the myosin head configuration “cocking the gun.”)
- Cycle is broken when Ca$^{2+}$ concentrations return to normal through active transport across sarcolemma.
Rigor Mortis

- After death, circulation ceases → skeletal muscles are deprived of nutrients and O₂.
- Within few hours, skeletal muscles run out of existing ATP.
- Since active transport of Ca²⁺ out of sarcoplasm and back into sarcoplasmic reticulum requires ATP, sarcoplasm starts filling with Ca²⁺ (diffusion along concentration gradient).
- Movement of Ca²⁺ into sarcoplasm triggers contraction.
- Without ATP, myosin heads cannot detach from cross-bridges → muscle locks in contracted state.
- This happens to all skeletal muscles, leading to rigor mortis.
- Autolytic enzymes break down myofilaments 15 – 25 hours later.
Introduction to Muscle Mechanics

- Muscle mechanics deals with the working of an entire group of muscle fibers.
- Amount of tension produced by an individual muscle fiber depends only on number of activated cross-bridges.
- If a muscle fiber at a given resting length is stimulated to contract, it will always produce the same tension.
- This is the all or none principle → no variation in muscle tension produced by an individual muscle fiber.
- However, tension produced by an entire skeletal muscle can vary and is determined by:
  - Frequency of stimulation.
  - Number of muscle fibers activated.

Frequency of Muscle Stimulation

- Twitch: Single event composed of stimulus-contraction-relaxation within a muscle fiber.
- Time duration of twitch varies depending on type of muscle.
  - Eye muscles → 7.5 msec.
  - Calf muscles → 100 msec.
- Myogram: time course graph of a muscle twitch (tension vs time).
- Phases of a muscle fiber twitch:
  - Latent period: from stimulation to initiation of contraction (2 msec).
  - Contraction phase: initiation of contraction to peak tension.
  - Relaxation phase: fall of tension back to resting levels.
Incomplete and Complete Tetanus

- Arrival of a 2nd stimulus before the relaxation phase ends produces a summation in tension.
- Continual stimulation of the muscle without allowing it to relax produces incomplete tetanus.
- If stimulation frequency is increased to a point where the relaxation phase never occurs, the condition known as complete tetanus is produced → all normal muscular activity involve complete tetanus of the participating muscles.

Number of Muscle Fibers

- Control of muscle tension is a function of the muscle being in complete tetanus.
- Movements are smooth (not jerky).
- Total force exerted by muscle depends on total number of fibers that are activated for contraction.
- Typical skeletal muscle contains 1000’s of fibers.
- One motor neuron can control 100’s or 1000’s of fibers through multiple synaptic knobs.
- Motor Unit: All muscle fibers controlled by a single motor neuron.
- Size of motor unit indicates degree of control:
  - Motor neuron for eye muscles control 1 - 2 fibers.
  - Motor neuron for leg muscles control up to 2000 fibers.
Recruitment and Tetanic Contraction

- Specific motor neurons are stimulated when decision is made to initiate movement.
- Over time, number of activated motor units gradually increases over time.
- Increasing the tension by increasing active number of motor units is called recruitment.
- Peak tension occurs when all motor units are stimulating muscle in complete tetanus.
- Since peak tension cannot last for long (available reserves will be used up quickly), many movements involve tetanic contraction, where motor units are activated on a rotating basis.

Muscle Tone and Types of Contraction

- For certain muscle groups, some motor units are always active even though entire muscle is not contracting.
- This produces muscle tone (resting skeletal muscle tension).
- Atrophy (weakening and size decrease) can occur when muscle is not regularly stimulated.
- Muscle contraction can be classified as isotonic or isometric.
- Isotonic: Tension rises and is maintained until relaxation (walking, running); muscle length shortens.
- Isometric: Tension rises but muscle length remains same (heavy lifting, maintenance of posture).
**Muscle Relaxation**

- At peak tension, muscle is at contracted length.
- How does it “relax?”

- Combination of elastic “recoil” of surrounding structures and movements of opposing muscles.
- Elastic forces are set up in surrounding structures (ex: fibers of the endomysium).
  - Recoil of these structures causes re-establishment of original length.
- Faster means of returning to original length produced by movement of opposing muscles:
  - Ex: biceps brachii contract, relax faster when triceps brachii contract in opposition.

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**Muscle Energetics**

- Large amount of energy needed for skeletal muscle contractions.
  - Ex: Active muscle fiber may require > 600 X 10^{12} ATP molecules per second!
- Energy for muscle is provided by a combination of resources:
  - Available ATP provides immediately accessible energy.
  - Creatine Phosphate provides a “savings account” to replenish depleted ATP reserves.
**Muscle Metabolism**

1. Creatine Phosphate binds the high energy phosphate group ($\text{PO}_4^{3-}$).
2. CP provides this group to boost ADP to ATP.
3. CP concentration in muscle fiber is much greater than ATP concentration.
4. However, both reserves will be used up in about 30 seconds during active contraction.
5. For these circumstances, the muscle must rely on other sources to convert ADP $\rightarrow$ ATP.
Generation of ATP

- Cells produce ATP through aerobic (oxygen requiring) metabolism within the mitochondria.
- Mitochondria absorb O₂, ADP, etc, from surrounding cytoplasm, and release ATP, CO₂, etc.
- Rate limiting factor in ATP production is amount of O₂ available.
- For skeletal muscle, energy demands can increase X120 at peak periods of activity.
- However, mitochondrial energy producing capacity is much lower (X40).
- Remaining ATP is produced through the process of glycolysis.

Glycolysis

- Involves the breakdown of glucose to pyruvic acid within sarcoplasm.
- Process is anaerobic (does not require O₂).
- Process is inherently inefficient:
  - Produces 2 molecules of ATP + 2 molecules of pyruvic acid
    (breakdown of 2 pyruvic acid molecules in mitochondria would create 34 ATP molecules).
  - Still, glycolysis is the primary source of ATP during periods of peak activity.
- Glucose is obtained from glycogen reserves within the sarcoplasm.
- Problem with this method is that lots of pyruvic acid is produced (more than can be processed by mitochondria).
- Excess pyruvic acid is converted to lactic acid.
- Excess concentration of lactic acid is dangerous to the cell (changes pH).
Muscle Fatigue and Recovery

- After all energy reserves are exhausted (or due to too much lactic acid), muscle fatigues: ie, it does not contract despite neural stimulation.
- Intense and brief activity utilizes the glycolysis pathway to produce ATP.
- Longer, less intense activity utilizes the aerobic pathway (mitochondria).
- Recovery of muscle involves replacement of lost energy reserves and removal/conversion of lactic acid.
- Liver utilizes O₂ during recovery period to produce ATP, which in turn is used to return muscle back to original state.

Muscle Performance

- Muscle performance can be divided based on peak tension developed and duration of activity.
- Two factors affect performance:
  - Type of muscle fibers used.
  - Physical conditioning.
- Types of fibers:
  - Fast fibers:
    - Contract in less than 10 msec.
    - Large in diameter; lots of glycogen reserves; densely packed myofibrils; relatively few mitochondria.
    - Fatigue quickly.
  - Slow fibers:
    - Contract slower (> 30 msec).
    - Smaller in diameter; lots of vascularization; presence of myoglobin (O₂ reserves); lots of mitochondria
    - More resistant to fatigue.
Cardiac and Smooth Muscle Tissues

Different function → implies different structure

<table>
<thead>
<tr>
<th>Property</th>
<th>Skeletal Muscle Fiber</th>
<th>Cardiac Muscle Cell</th>
<th>Smooth Muscle Cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber dimensions (diameter × length)</td>
<td>100 μm × up to 30 cm</td>
<td>15 μm × 100 μm</td>
<td>5–10 μm × 30–200 μm</td>
</tr>
<tr>
<td>Nuclei</td>
<td>Multiples, near sarcolemma</td>
<td>Usually single, centrally located</td>
<td>Single, centrally located</td>
</tr>
<tr>
<td>Filament organization</td>
<td>Sarcomeres along myofilaments</td>
<td>Sarcomeres along myofilaments</td>
<td>Scattered throughout sarcoplasm</td>
</tr>
<tr>
<td>Control mechanism</td>
<td>Neuromuscular junction</td>
<td>Automaticity (pacemaker cells)</td>
<td>Automaticity (parasite cells), neural or hormonal control</td>
</tr>
<tr>
<td>Ca²⁺ source</td>
<td>Release from sarcoplasmic reticulum</td>
<td>Across sarcolemma and release from sarcoplasmic reticulum</td>
<td>Across sarcolemma</td>
</tr>
<tr>
<td>Contraction</td>
<td>Rapid onset, tetanus can occur, rapid fatigue</td>
<td>Slower onset, tetanus cannot occur, resistant to fatigue</td>
<td>Slow onset, tetanus can occur, resistant to fatigue</td>
</tr>
<tr>
<td>Energy source</td>
<td>Aerobic metabolism at moderate levels of activity, glycolysis (anaerobic) during peak activity</td>
<td>Aerobic metabolism, usually lipid or carbohydrate substrates</td>
<td>Primarily aerobic metabolism</td>
</tr>
</tbody>
</table>

Differences Between Skeletal and Cardiac Muscle Tissue

- Cardiac muscle tissue needs to function as a unified system.
- Cardiac muscle has its own conduction system (it does not rely on neural action potential to initiate contraction).
- Cardiac contractility (rate and force) controlled involuntarily.
- Cardiac muscle contractions last longer than skeletal muscle contractions (X10).
- Purely aerobic metabolic pathway (lots of mitochondria and myoglobin).
Differences Between Skeletal and Smooth Muscle Tissue

- Smooth muscle cells are similar in size to cardiac muscle cells.
- However, no myofibrils, sarcomeres or striations present in smooth muscles.
- Also no connection to skeletal system; instead smooth muscles are found in the walls of hollow organs -- no tendons.
- Thin filaments are present -- these are anchored to sarcolemma and to cytoplasm.
- Adjacent smooth muscle cells are bound together at these anchoring sites.
- Ca^{2+} triggers contraction through a different mechanism than for cardiac or smooth muscle cells (no troponin present).
- Contraction can occur over a larger range of lengths (no rigid organization of actin and myosin filaments).
- Many smooth muscles not controlled by neurons, or not voluntary control.

Anatomy of the Muscular System

- Muscular system includes all skeletal muscles that can be controlled voluntarily.
- Each muscle begins at an origin, ends at an insertion, and contracts to produce specific action.
- Origin remains stationary while insertion point moves.
- Origination and insertion occurs at skeletal system for nearly all muscles.
- Various movements (flexion, extension, etc.) produced by contraction.
- Muscles can be grouped by their primary actions:
  - Agonist (prime mover) is a muscle whose contraction is chiefly responsible for the movement.
  - Antagonists are muscles where primary movement opposes the movement of the agonist being studied.
  - Synergist assists prime mover in performing the action.
Names of Muscles

- Name of the muscle usually gives clues as to location and function.
- Examples:
  - Rectus Abdominus ("straight" along the abdomen).
  - Temporalis (at the temporal bones).
  - Biceps (two tendons of origin),
  - Triceps (three tendons of origin).
  - Externus or superficialis refers to muscle being visible at body surface, while internus or profundus refers to muscles lying beneath.
  - Names that indicate location usually appear in pairs: if there is an exterior, there is probably an interior; same with superior and inferior.
  - For many compound names, first part of the name indicates origin and second part indicates insertion point (sternohyoid: originates at sternum, inserts at hyoid bone).
- Association and repetition again key to learning.

Appendicular and Axial Muscles

- Axial muscles arise from the axial skeleton.
- Functions include:
  - Positioning of head and spinal column.
  - Move the rib cage.
  - Assist in breathing movements.
- Appendicular musculature arises on the appendicular skeleton.
  - Stabilizes and moves components of the appendicular skeleton.
**Axial Muscles of the Trunk**

- **External and internal intercostals:**
  - Origin at inferior (external) or superior (internal) border of each rib.
  - Insert at superior (external) or inferior (internal) border of next rib.
  - Action is to elevate (external) or depress (internal) ribs.

- **Diaphragm:**
  - Origin at xiphoid process, cartilages of ribs 4-10, and anterior surfaces of lumbar vertebrae.
  - Insertion into a large central tendinous sheath.
  - Action is to expand thoracic cavity and compress abdominopelvic cavity as a function of breathing.

**Muscles of the Upper Thorax**

- **Trapezius:**
  - Covers back and portions of the neck.
  - Originates in occipital bone and spinous processes of thoracic vertebrae.
  - Inserts into clavicle and scapula.
  - Various actions depending on other muscles and region of activation.
Muscles of the Upper Thorax

- **Rhomboideus (rhomboids):**
  - Found deeper within the body.
  - Origin at spinous processes of lower cervical and upper thoracic vertebrae.
  - Inserts into vertebral border of scapula.
  - Adducts and rotates scapula laterally.

- **Levator Scapulae:**
  - Also covered by trapezius.
  - Origin at posterior surfaces of 1st 4 cervical vertebrae.
  - Inserts into vertebral border of scapula.
  - Elevates scapula (as name implies).
Muscles of the Upper Thorax

- **Pectoralis minor:**
  - Originates at anterior surface of ribs 3-5.
  - Inserts at scapular process (coracoid).
  - Depresses and protracts shoulder; rotates scapula laterally; elevates ribs if scapula is stationary.

Muscles of the Upper Thorax

- **Pectoralis Major:**
  - Originates at cartilages of ribs 2-6, sternal body and clavicle.
  - Inserts at the humerus.
  - Flexion, adduction and medial rotation of the shoulder joint.
Muscles of the Upper Thorax

✿ Lattissimus Dorsi:
  ✿ Originate at spinous processes of lower thoracic vertebrae, ribs and lumbar vertebrae.
  ✿ Inserts at the humerus.
  ✿ Extension, adduction and medial rotation of the shoulder joint.

Muscles of the Upper Thorax

✿ Deltoid:
  ✿ Originates at clavicle and scapula.
  ✿ Inserts at the humerus.
  ✿ Abduction of the shoulder joint.
Muscles of the Upper Thorax

- **Biceps Brachii and Triceps Brachii:**
  - Originate at the scapula (biceps) and humerus and scapula (triceps).
  - Insert at the radius (biceps), and ulna (triceps).
  - Flexes elbow, supinates forearm (biceps); Extends elbow (triceps).

Muscles of the Lower Limbs

- **Gluteus Maximus:**
  - Originates at the ilium, sacrum and coccyx (iliac crest).
  - Inserts at the iliotibial tract (band of connective tissue) and proximal femur.
  - Extension and lateral rotation of the hip joint.
Muscles of the Lower Limbs

- The muscles of the “hamstrings”:
  - These are the biceps femoris, the semimembranosus, and the semitendinosus.
  - Originate at the inferior surface of the ischium.
  - Insert at the head of fibula (femoris), and tibia (all three muscles).
  - Flex knee, extend and adduct hip.

Muscles of the Lower Limbs

- The muscles of the “quadriceps”:
  - These include the three vastus muscles (lateralis, medialis, intermedus) and the rectus femoris.
  - Originate at the proximal and central portions of the femur (vastus), and at acetabulum (rectus femoris).
  - Insert at tibia via the patellar ligament.
  - Vastus muscles extend knee; rectus femoris also flexes hip.
Muscles of the Lower Limbs

The muscles of the knee:

- In addition to the quadriceps muscles, these include the popliteus, sartorius, and the gracilis.
- Popliteus originates at lateral condyle of femur; sartorius at the antero-superior spine of the ilium; gracilis at inferior surface of pubis and ischium.
- Popliteus inserts at posterior surface of proximal tibia; sartorius at medial surface of tibia; gracilis at anterior surface of tibia.
- Popliteus rotates tibia medially; sartorius flexes knee and hip; gracilis flexes knee and adducts hip.

The muscles of the calf:

- The gastrocnemius and the soleus.
- Gastrocnemius originates above distal condyles of femur.
- Soleus originates at the proximal head of the tibia.
- Gastrocnemius and soleus insert into the calcaneus via the calcanean tendon.
- Both muscles flex ankle, invert and adduct foot.