Muscle lectures
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Motion, as a reaction of multicellular organisms to changes in the internal and external environment, is mediated by muscle cells.

The basis for motion mediated by muscle cells is the conversion of chemical energy (ATP) into mechanical energy by the contractile apparatus of muscle cells. The proteins actin and myosin are part of the contractile apparatus.

The interaction of these two proteins mediates the contraction of muscle cells.

Actin and myosin form myofilaments arranged parallel to the direction of cellular contraction.

Muscle (from Latin *musculus* "little mouse") is contractile tissue of the body and is derived from the mesodermal layer of embryonic germ cells.

Its function is to produce force and cause motion, either locomotion or movement within internal organs.

Much of muscle contraction occurs without conscious thought and is necessary for survival, like the contraction of the heart, or peristalsis (which pushes food through the digestive system).

Voluntary muscle contraction is used to move the body, and can be finely controlled, like movements of the finger or gross movements like the quadriceps muscle of the thigh.

There are 2 types of muscle movement, slow twitch and fast twitch.

Slow twitch movements act for a long time but not very fast, whilst fast twitch movements act quickly, but not for a very long time.

MUSCLE TISSUE

- Capable of Contraction
- Composition = Muscle cells + CT (carries blood vessels and nerves, each muscle cell is supplied with capillaries and nerve fiber) - Muscle cells are elongate (therefore they are termed fibers) and lie in parallel arrays (with the longitudinal axis of the muscle).

- Muscle cells contain filaments of two kinds of proteins, **actin** and **myosin**, which slide past each other as the muscle contracts.
- After a muscle contracts, ATP (produced in the muscle cells' mitochondria) is needed to relax the muscle and return the actin and myosin filaments to their normal positions. When a person (or other animal) dies and the mitochondria are no longer producing ATP, the muscles cannot relax. This stiffening of the muscles is called **rigor mortis**.
- Muscle contraction is initiated when an electrical impulse from a nerve cell reaches its associated muscle cell(s), causing positively- and negatively-charged ions to switch places all along the muscle cell (fiber).
- Movement of Ca^{++} ions in/out of the muscle cell (fiber) is important in both contraction and relaxation of the muscle, so if a person doesn't ingest enough calcium, some could be taken out of the bones to supply the muscles with what they need to contract and relax.
- Any given muscle fiber reacts in an "all or none" response — it is either relaxed or contracted, and the

variability in contraction of the overall muscle is based on the *number* of fibers which contract.

A further specialisation of muscle cells is an excitable cell membrane which propagates the stimuli which initiate cellular contraction.

Three structurally and functionally distinct types of muscle are found in vertebrates:

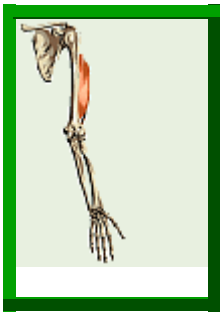
1. smooth muscle,
2. skeletal muscle and
3. cardiac muscle.

Function of Muscles
• Produce movement
• Maintain posture
• Stabilize joints
• Support soft tissue
• Guard openings to the internal body
• Generate heat

Skeletal muscles can be classified as one of several different types including:

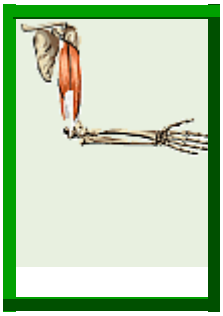
Flexor

A muscle which bends a joint (click to show animation)



Extensor

A muscle which straightens a joint (click to show animation)



Abductor

A muscle which moves a body part away from the midline of the body

Adductor

A muscle which moves a body part toward the midline of the body

Some definition to know:

Agonist
A muscle that causes motion.
Antagonist
A muscle that can move the joint opposite to the movement produced by the agonist.
Target
The primary muscle intended for exercise.

Synergist
A muscle that assists another muscle to accomplish a movement.
Stabilizer

A muscle that contracts with no significant movement

- **Origin** (b): muscle attatchment that moves least, generally more proximal.
- **Insertion** (a): muscle attatchment that moves most, generally more distal.
- **Abduction**: Lateral movement away from the midline of the body
- **Adduction**: Medial movement toward the midline of the body
- **Circumduction**: circular movement (combining flexion, extension, adduction, and abduction) with no shaft rotation
- **Extension**: Straightening the joint resulting in an increase of angle
- **Eversion**: Moving sole of foot away from medial plane
- **Flexion**: Bending the joint resulting in a decrease of angle
- **Hyperextension**: extending the joint beyond anatomical position
- **Inversion**: Moving sole of foot toward medial plane
- **Pronation**: Internal rotation resulting in appendage facing downward
- **Protrusion**: Moving anteriorly (eg: chin out)
- **Supination**: External rotation resulting in appendage facing upward
- **Retrusion**: Moving posteriorly (eg: chin in)
- **Rotation**: Rotary movement around the longitudinal axis of the bone

MUSCULAR MOVEMENT OF BONES

1. Skeleton Muscles generate Force and produce Movement only by CONTRACTING or PULLING on Body Parts.

2. Individual Muscles can only PULL; they CANNOT PUSH.

3. Skeleton Muscles are joined to bone by TOUGH CONNECTIVE TISSUE CALLED **TENDONS**.

4. **TENDONS** ATTACH MUSCLE TO BONE; THE **ORIGIN** IS THE MORE STATIONARY BONE, THE **INSERTION** IS THE MORE MOVABLE BONE.

5. Tendons are attached in such a way that they PULL on the Bones and make them work like **LEVERS**. The movements of the Muscles and Joints enable the Bones to act as LEVERS.

6. The Joint functions as a **FULCRUM** (The fixed point around which the lever moves) and the Muscles provide the FORCE to move the Lever.

7. Usually there several Muscles surrounding each Joint that PULL in DIFFERENT DIRECTIONS.

8. MOST SKELETAL MUSCLES WORK IN PAIRS.

9. When one Muscle or set of Muscles CONTRACTS, the other RELAXES.

10. The Muscles of the upper arm are a good example of this dual action: **ANTAGONISTIC MUSCLES**. (Figure 45-13) **FLEXOR**, A MUSCLE THAT BENDS A JOINT. **EXTENSOR**, A MUSCLE THAT STRAIGHTENS A JOINT.

A. When the BICEPS Muscle (on the front of the upper arm, FLEXOR) CONTRACTS, it BENDS OR FLEXES THE ELBOW JOINT.

B. When the TRICEPS Muscle (on the back of the upper arm, EXTENSOR) CONTRACTS, it opens, or extends, the elbow joint.

C. A controlled movement requires contraction by both muscles.

11. **ANTAGONISTIC MUSCLES** ARE OPPONENTS, MUSCLES WHICH HAVE OPPOSING OR OPPOSITE FUNCTIONS. A muscle pulls when it contracts, but exerts no force when it relaxes and CANNOT PUSH. When one muscle Pulls a bone in one direction, another muscle is needed to PULL the bone in the other direction.

12. **SYNERGISTIC MUSCLES** ARE THOSE WITH THE SAME FUNCTION, OR THOSE THAT WORK TOGETHER TO PERFORM A PARTICULAR FUNCTION. They also stabilize a joint to make a more precise movement possible.

13. A normal characteristic of all Skeleton Muscles is that they remain in a state of **PARTIAL CONTRACTION**.

14. At any given time, some Muscles are being Stimulated while other are not. This causes a TIGHTENED, or FIRMED, Muscle and is known as **MUSCLE TONE**.

15. Muscle Tone is responsible for keeping the back and legs straight and the head upright even when you are relaxed.

16. **EXERCISE** IS THE KEY TO MAINTAINING GOOD MUSCLE TONE WITHIN YOUR BODY.

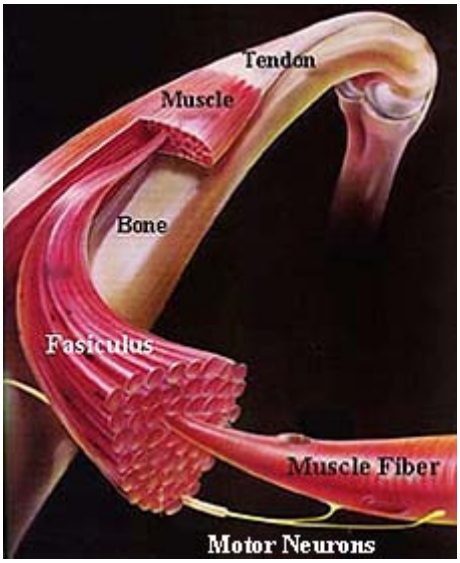
17. MUSCLES THAT ARE EXERCISED REGULARLY STAY FIRM AND INCREASE IN SIZE BY ADDING MORE MATERIALS TO THE INSIDE OF MUSCLE FIBERS.

18. **MUSCLE FATIGUE** is a Physiological Inability of a muscle to contract. Muscle fatigue is a result of a relative depletion of ATP. When ATP is absent, a state of continuous contraction occurs. This causes severe muscle cramps.

19. **OXYGEN DEBT** is a temporary Lack of Oxygen. When this occurs Muscles will switch from the normal Aerobic Respiration to a form of Anaerobic Respiration called Lactic Acid Fermentation. As the oxygen becomes Depleted, the muscle cells begin to switch. Oxygen debt leads to the accumulation of Metabolic Waste (Lactic Acid) in the muscle fibers, resulting in muscle fatigue, pain, and even cramps. Eventually, the lactic acid diffuses into the blood and is transported to the Liver. So if you ever experienced Soreness after prolong exercise, it may have been caused by Oxygen Debt - Your body could not provide your Muscles the Oxygen they needed to function properly.

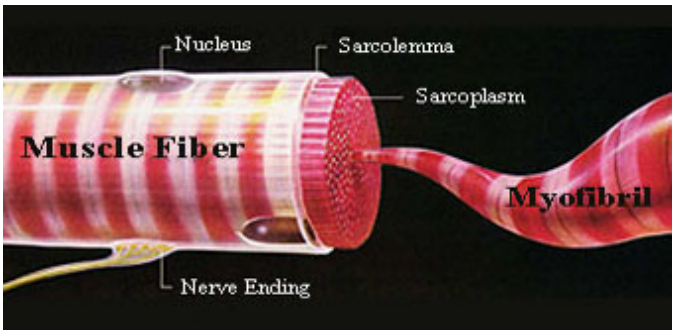
Types of Muscles
- **Skeletal muscle**
- **Cardiac muscle**
- **Smooth muscle**

Muscle Structure:



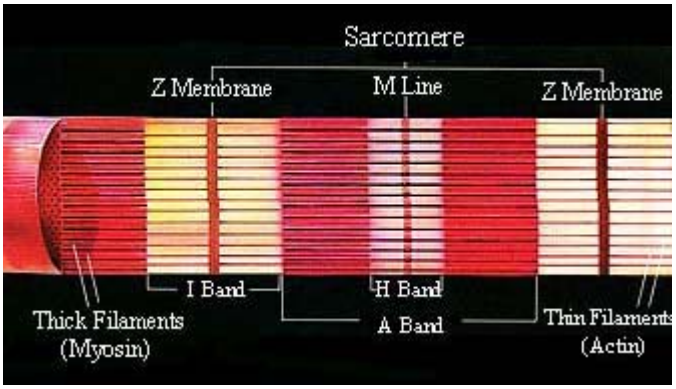
Muscle

A muscle consists of thousands of muscle fibers, the cellular units of muscle.



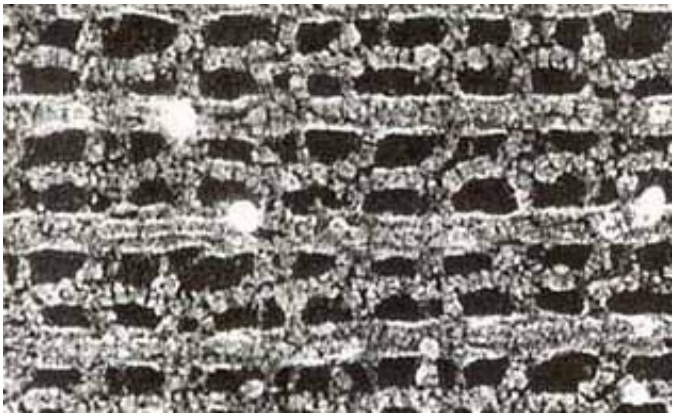
Muscle Fiber

Each muscle fiber is made up of thousands of myofibrils.



Myofibril

Myofibrils contain filaments of actin and myosin. The filaments form an ordered array and make up sarcomeres, the functional units of muscle.



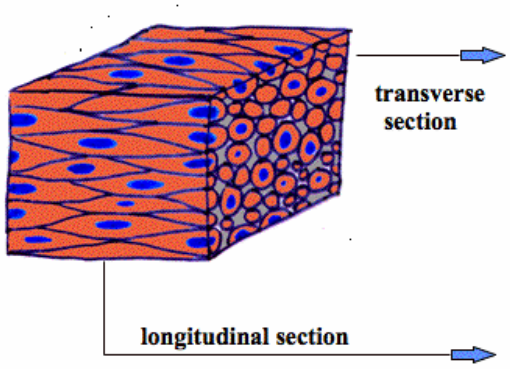
Actin and Myosin

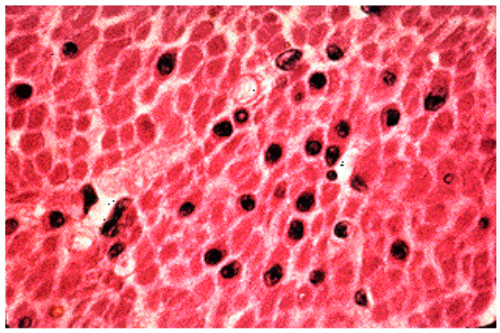
According to the sliding filament theory, myosin heads bind actin filaments and move them during contraction. The micrograph shows myosin bound to actin, supporting this theory.

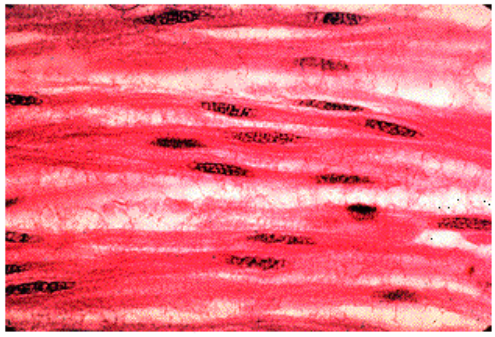
Smooth Muscle

SMOOTH MUSCLE

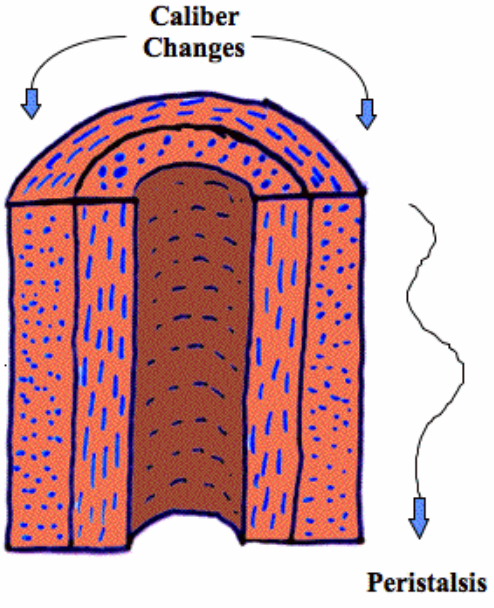
Smooth Muscle Fiber (Cell)- spindle shaped

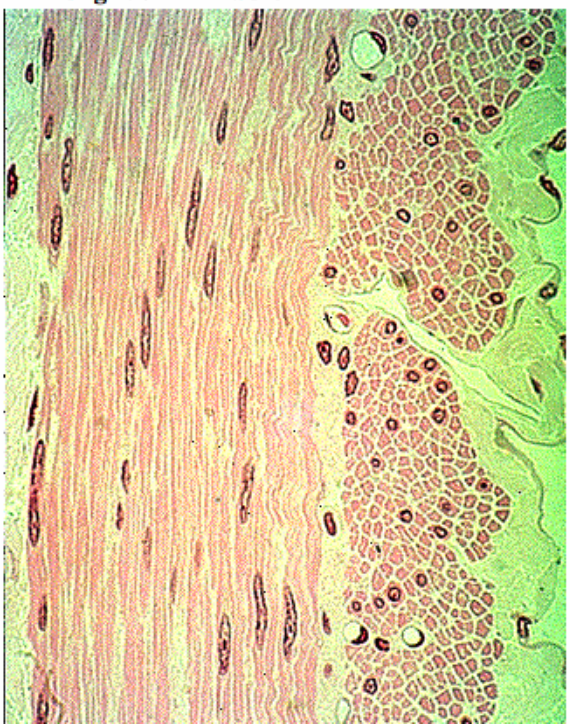






SMOOTH MUSCLE IN TUBES





- Smooth muscle consists of spindle shaped cells of variable size.
  The largest smooth muscle cells occur in the uterus during pregnancy (12x600 µm). The smallest are found around small arterioles (1x10 µm).
- Smooth muscle cells contain one centrally placed nucleus.
  The chromatin is finely granular and the nucleus contains 2-5 nucleoli.

- The innervation of smooth muscle is provided by the autonomic nervous system.
- Smooth muscle makes up the visceral or involuntary muscle.

Structure of smooth muscle

In the cytoplasm, we find longitudinally oriented bundles of the myofilaments actin and myosin. Actin filaments insert into attachment plaques located on the cytoplasmic surface of the plasma membrane. From here, they extend into the cytoplasm and interact with myosin filaments. The myosin filaments interact with a second set of actin filaments which insert into intracytoplasmatic dense bodies. From these dense bodies further actin filaments extend to interact with yet another set of myosin filaments. This sequence is repeated until the last actin filaments of the bundle again insert into attachment plaques.

In principle, this organisation of bundles of myofilaments, or myofibrils, into repeating units corresponds to that in other muscle types. The repeating units of different myofibrils are however not aligned with each other, and myofibrils do not run exactly longitudinally or parallel to each other through the smooth muscle cells. Striations, which reflect the alignment of myofibrils in other muscle types, are therefore not visible in smooth muscle.

Smooth endoplasmatic reticulum is found close to the cytoplasmatic surface of the plasma membrane. Most of the other organelles tend to accumulate in the cytoplasmic regions around the poles of the nucleus. The plasma membrane, cytoplasm and endoplasmatic reticulum of muscle cells are often referred to as sarcolemma, sarcoplasm, and sarcoplasmatic reticulum.

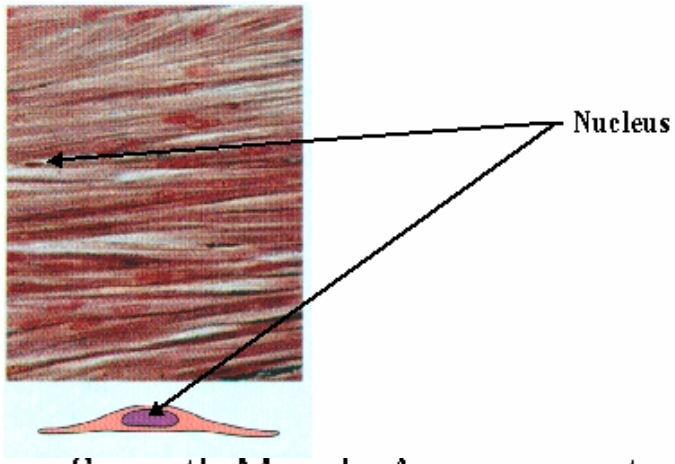
During contraction, the tensile force generated by individual muscle cells is conveyed to the surrounding connective tissue by the sheath of reticular fibres. These fibres are part of a basal lamina which surrounds muscle cells of all muscle types. Smooth muscle cells can remain in a state of contraction for long periods. Contraction is usually slow and may take minutes to develop.

Origin of smooth muscle

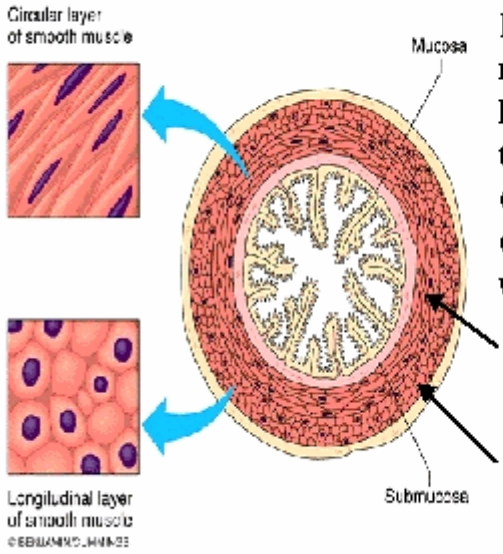
Smooth muscle cells arise from undifferentiated mesenchymal cells. These cells differentiate first into mitotically active cells, myoblasts, which contain a few myofilaments. Myoblasts give rise to the cells which will differentiate into mature smooth muscle cells.

Smooth Muscle Characteristics

Smooth muscle cells connect to form single-unit syncytia similar to cardiac muscle. But impulses and contractions occur much more slowly in smooth than in cardiac muscle.



Smooth Muscle Arrangement in the Gut



In the intestine smooth muscle forms two distinct layers, one running along, the other running around the organ. Together these layers cause wave-like peristalsis which propels the contents.

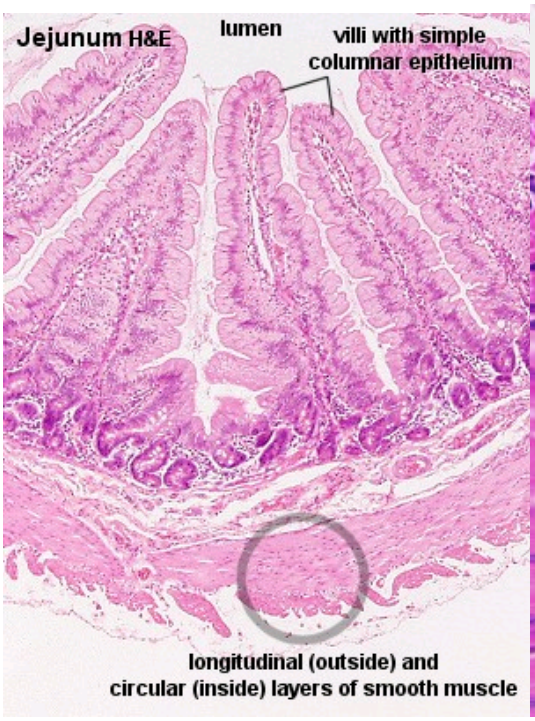
The circular layer runs around the intestine and its contraction causes segmentation

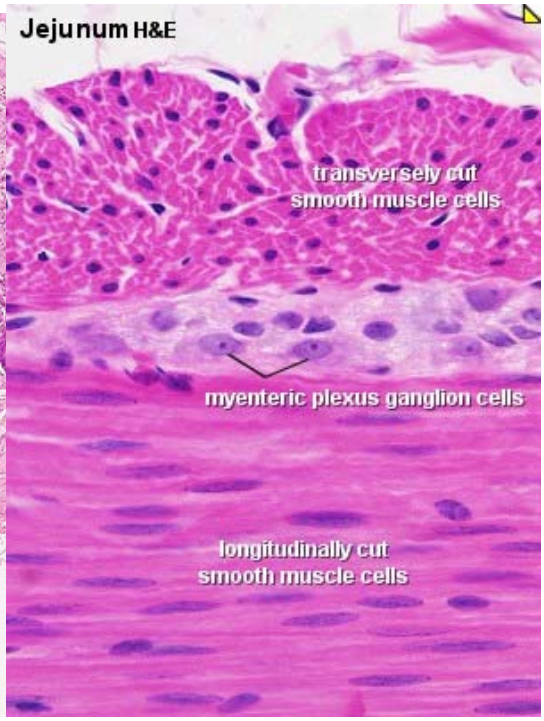
The longitudinal layer runs along the intestine; it causes wave-like contractions.

Types of smooth muscle

Two broad types of smooth muscle can be distinguished on the basis of the type of stimulus which results in contraction and the specificity with which individual smooth muscle cells react to the stimulus:

1. The multiunit type represents functionally independent smooth muscle cells which are often innervated by a single nerve terminal and which never contract spontaneously (e.g. smooth muscle in the walls of blood vessels).
2. The visceral type represents bundles of smooth muscle cells connected by GAP junctions, which contract spontaneously if stretched beyond a certain limit (e.g. smooth muscle in the walls of the intestines).





The only tissues which perhaps could be confused with smooth muscle are dense regular connective tissues and peripheral nerves. Both the number of nuclei and their shapes clearly distinguish smooth muscle from dense regular connective tissues. Nuclei are much more frequent and larger in smooth muscle, and they are very elongated if cut longitudinally. Peripheral nerves will be surrounded by a capsule of cells and connective tissue - the perineurium. The thickness of longitudinally cut nerve fibres is constant while smooth muscle cells are spindle shaped. Also, axon and nodes of Ranvier should be visible in peripheral nerves

SMOOTH MUSCLE - present in walls of tubes (e.g., digestive tract, circulatory system, etc.); contraction is slow process, fibers capable of sustaining partial contraction indefinitely (= tonus)

I. CELLS (Fibers)

1) Elongate and tapering (40-200 micrometers long)
2) Uninucleate, centrally located, in longitudinal section assume "snake-like" appearance when contracted
3) no striations

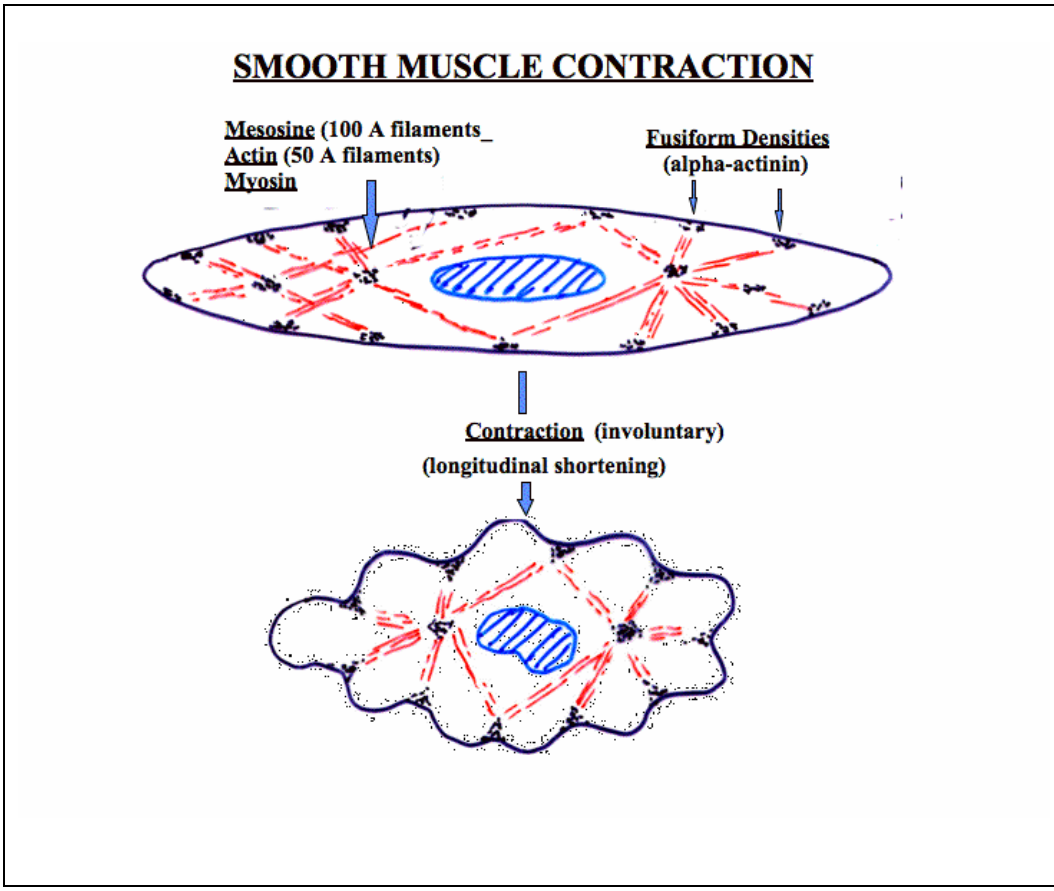
II. ULTRASTRUCTURE

1) No myofilament arrangement into sarcomeres
2) Arrangement of Contractile Elements:
   a) Intermediate Filaments (tonofilaments) attached to dense bodies distributed throughout sarcoplasm
   b) Bundles of intermediate filaments stretch from one dense body to the next, assumes cable-like system
   c) Sliding of thin filaments over thick filaments harnessed by "cables" so that dense bodies are pulled together = contraction

III. ARRANGEMENT OF FIBERS

- Smooth Muscle cells arranged shingle-like in longitudinal-section, held together with elastic + reticular fibers and some collagen

- In cross-section, look for "a light smattering of nuclei in a field of cells"; this appearance is characteristic of smooth muscle



Muscle Similarities

- ***Skeletal and smooth muscle cells are elongated and are called muscle fibers***
- ***Muscle contraction depends on two kinds of myofilaments – actin and myosin***
- ***Muscle terminology is similar***
  - **Sarcolemma – muscle plasma membrane**
  - **Sarcoplasm – cytoplasm of a muscle cell**
  - **Prefixes – myo, mys, and sarco all refer to muscle**

Skeletal Muscle Tissue

- ***Packaged in skeletal muscles that attach to and cover the bony skeleton***
- ***Has obvious stripes called striations***
- ***Is controlled voluntarily (i.e., by conscious control)***
- ***Contracts rapidly but tires easily***
- ***Is responsible for overall body motility***
- ***Is extremely adaptable and can exert forces ranging from a fraction of an ounce to over 70 pounds***

Cardiac Muscle Tissue

- ***Occurs only in the heart***
- ***Is striated like skeletal muscle but is not voluntary***
- ***Contracts at a fairly steady rate set by the heart's pacemaker***
- ***Neural controls allow the heart to respond to changes in bodily needs***

Smooth Muscle Tissue

- ***Found in the walls of hollow visceral organs, such as the stomach, urinary bladder, and respiratory passages***
- ***Forces food and other substances through internal body channels***
- ***It is not striated and is involuntary***

Functional Characteristics of Muscle Tissue

- ***Excitability, or irritability – the ability to receive and respond to stimuli***
- ***Contractility – the ability to shorten forcibly***
- ***Extensibility – the ability to be stretched or extended***
- ***Elasticity – the ability to recoil and resume the original resting length***

Muscle Function

- ***Skeletal muscles are responsible for all locomotion***
- ***Cardiac muscle is responsible for coursing the blood through the body***
- ***Smooth muscle helps maintain blood pressure, and squeezes or propels substances (i.e., food, feces) through organs***

Muscles also maintain posture, stabilize joints, and generate heat

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Skeletal Muscle

Skeletal muscle is made up of thousands of cylindrical muscle **fibers** often running all the way from origin to insertion. The fibers are bound together by connective tissue through which run blood vessels and nerves.

Each muscle fibers contains:

- an array of **myofibrils** that are stacked lengthwise and run the entire length of the fiber.
- **mitochondria**
- an extensive **smooth endoplasmic reticulum (SER)**
- **many nuclei**.

The multiple nuclei arise from the fact that each muscle fiber develops from the fusion of many cells (called **myoblasts**).

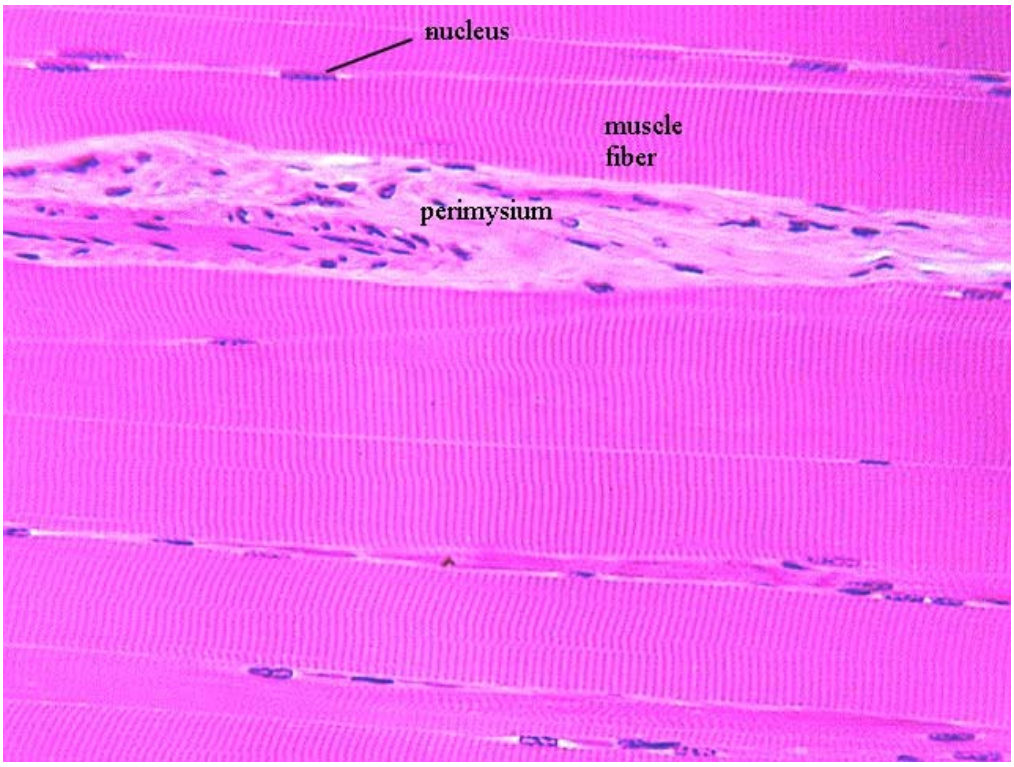
The number of fibers is probably fixed early in life. This is regulated by **myostatin**, a cytokine that is synthesized in muscle cells (and circulates as a hormone later in life). Myostatin **suppresses** skeletal muscle development. Cattle and mice with inactivating mutations in their myostatin genes develop much larger muscles. Some athletes and other remarkably strong people have been found to carry one mutant myostatin gene. These discoveries have already led to the growth of an illicit market in drugs supposedly able to suppress myostatin.

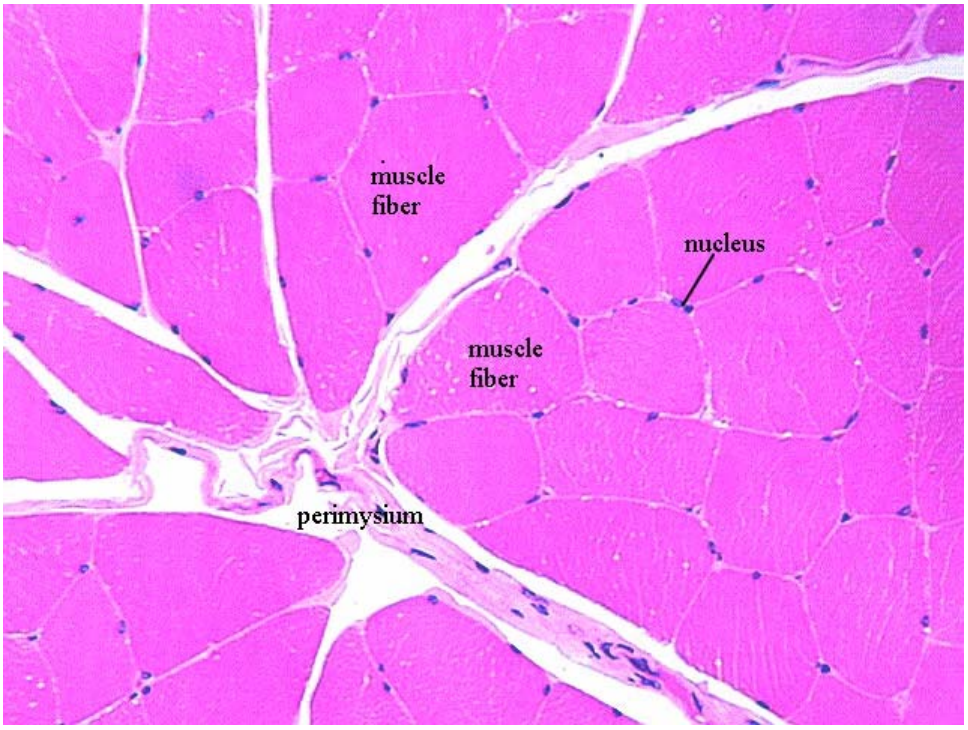
In adults, increased strength and muscle mass comes about through an increase in the thickness of the individual fibers and increase in the amount of connective tissue. In the mouse, at least, fibers increase in size by attracting more myoblasts to fuse with them. The fibers attract more myoblasts by releasing the cytokine interleukin 4 (IL-4). Anything that lowers the level of myostatin also leads to an increase in fiber size.

Because a muscle fiber is not a single cell, its parts are often given special names such as

- **sarcolemma** for plasma membrane
- **sarcoplasmic reticulum** for endoplasmic reticulum
- **sarcosome** for mitochondrion
- **sarcoplasm** for cytoplasm

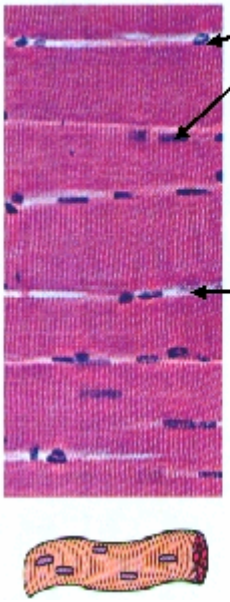
although this tends to obscure the essential similarity in structure and function of these structures and those found in other cells

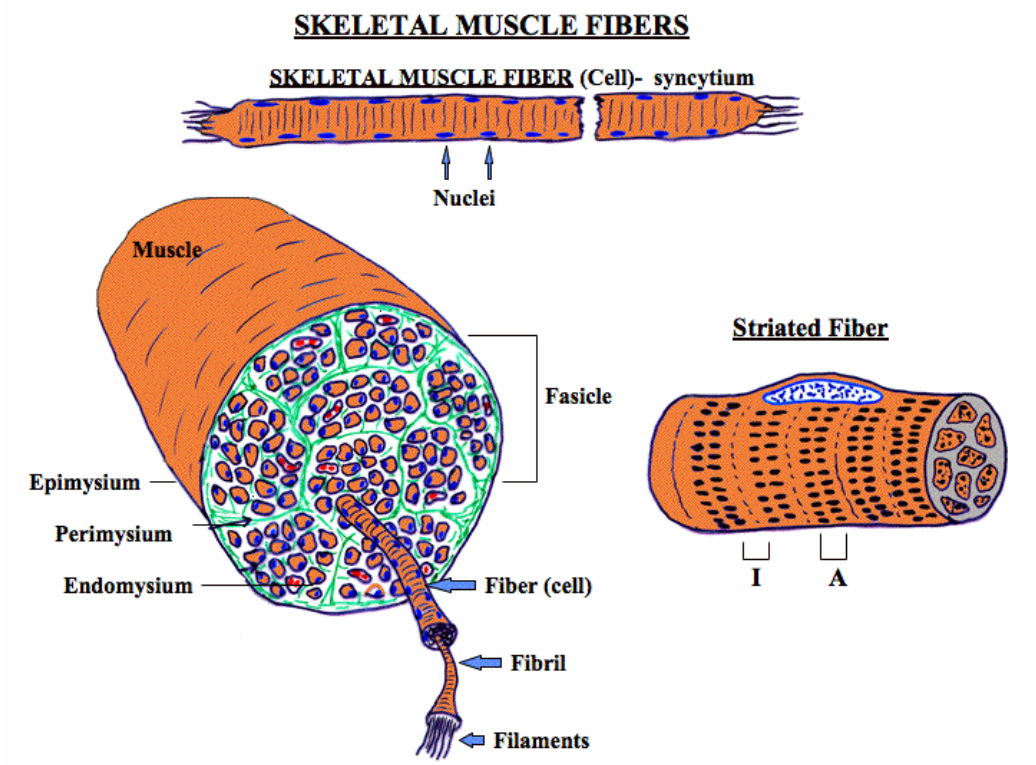




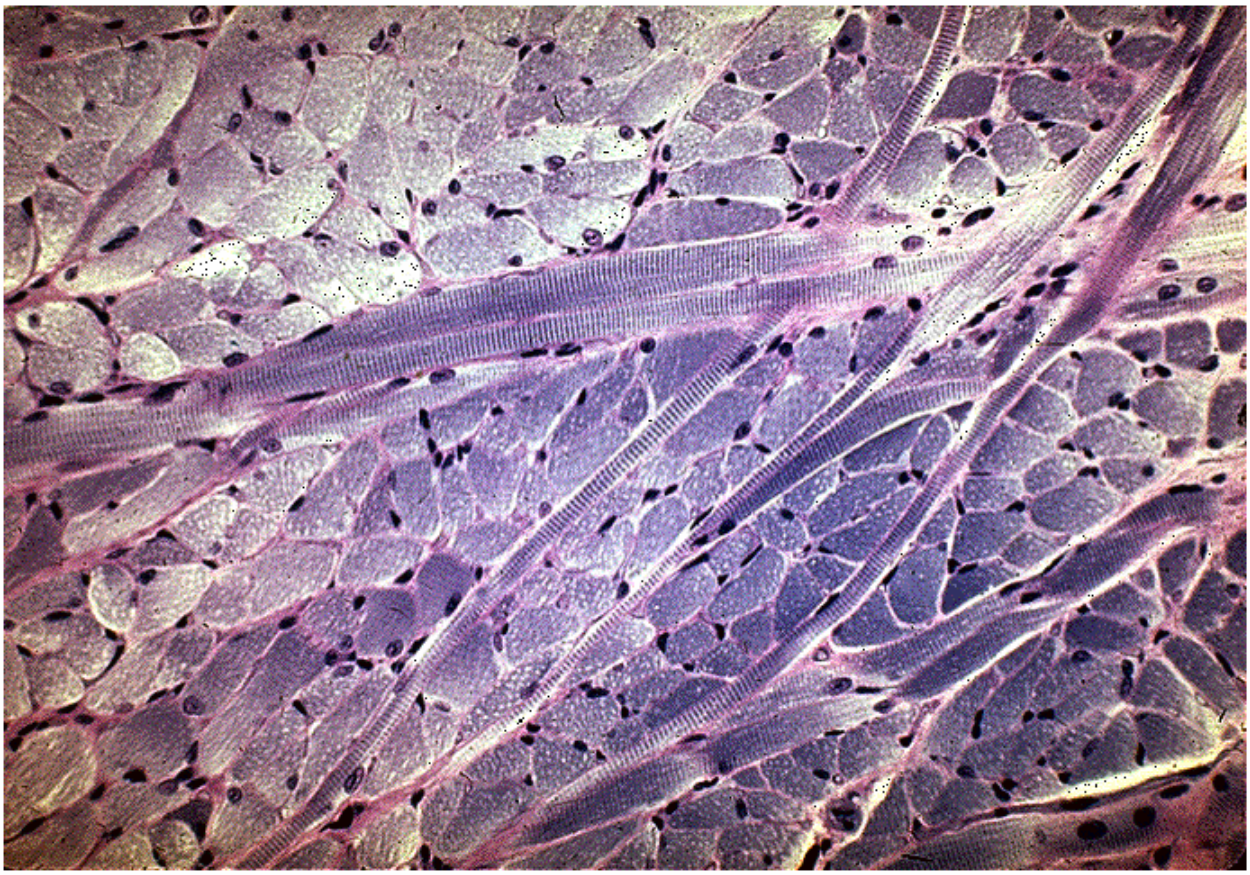
Skeletal Muscle

Skeletal muscle cells are long multi-nucleated cylinders, separated by connective tissue. Each independent cell is stimulated by a branch from a motor neuron





STRIATED MUSCLE FIBERS- Long. and Transverse Sections



- Skeletal muscle consists of very long tubular cells (also called muscle fibres).
  The average length of skeletal muscle cells in humans is about 3 cm (sartorius muscle up to 30 cm, stapedius muscle only about 1 mm). Their diameters vary from 10 to 100 µm.

- Skeletal muscle fibres contain many peripherally placed nuclei.
  Up to several hundred rather small nuclei with 1 or 2 nucleoli are located just beneath the plasma membrane.
- Skeletal muscle fibres show in many preparations characteristic cross-striations. It is therefore also called striated muscle.
- Skeletal muscle is innervated by the somatic nervous system.
- Skeletal muscle makes up the voluntary muscle.

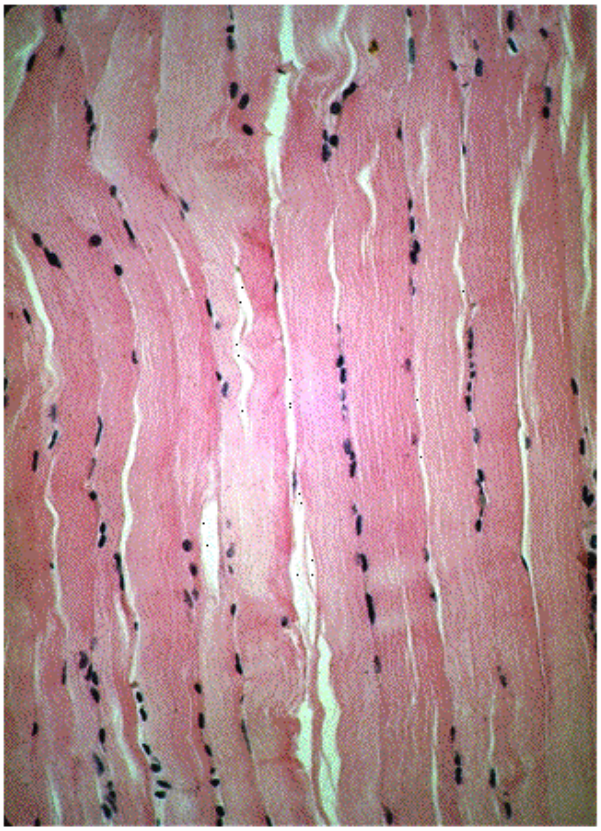
SKELETAL MUSCLE

I. CELLS (FIBERS)

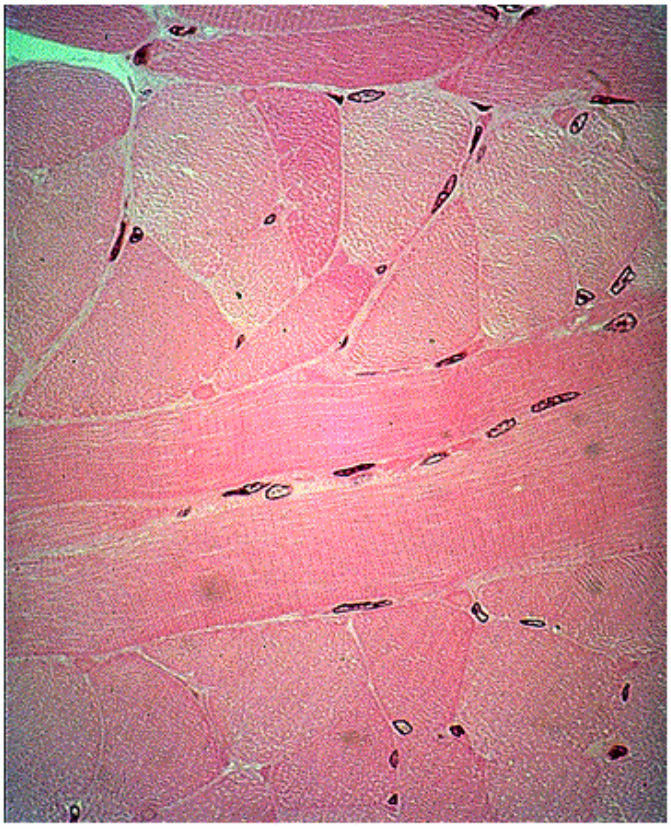
1) Very long compared with most other cells, up to several cm long, 10-100 micrometers in diameter
2) Multinucleate, nuclei are located peripherally
3) Development:
Mesenchymal cell ---> Myoblast (proliferative) ---> Myotubule ---> Muscle Cell

II. ARRANGEMENT OF FIBERS - similar to tendon arrangement
- Blood vessels, lymph vessels, and nerves penetrate muscle with perimysium
- Endomysium contains capillaries and nerve fibers

Striated Muscle Fibers-Long. Section



Striated Muscle Fibers- Long. & Trans. Sects.



III. STRIATION ULTRASTRUCTURE (Fibers ---> Myofibrils ---> Myofilaments)
- Proteins are *actin* (thin filaments) and myosin (thick filaments), also tropomyosin and troponin are associated with thin filaments

Sarcomere = the smallest contractile unit of skeletal muscle, bounded by Z-lines, 2-3 micrometers long.

Z-line = disc-like structures to which actin filaments attach on both sides; composed of alpha-actinin and a dense

amorphous matrix

A-band = "anisotropic" band: birefringent in polarized light (as light source rotated 360 degrees becomes light-dark-light-dark); signifies greater than 1 molecular species present (in this case, myosin & actin filaments)

I-band = "isotropic" band: maintains darkness in polarized light; signifies a singular molecular species is present (actin filaments)

H-zone = pale central region in A-band; due to absence of thin filaments; outer portions of A-band with both filaments

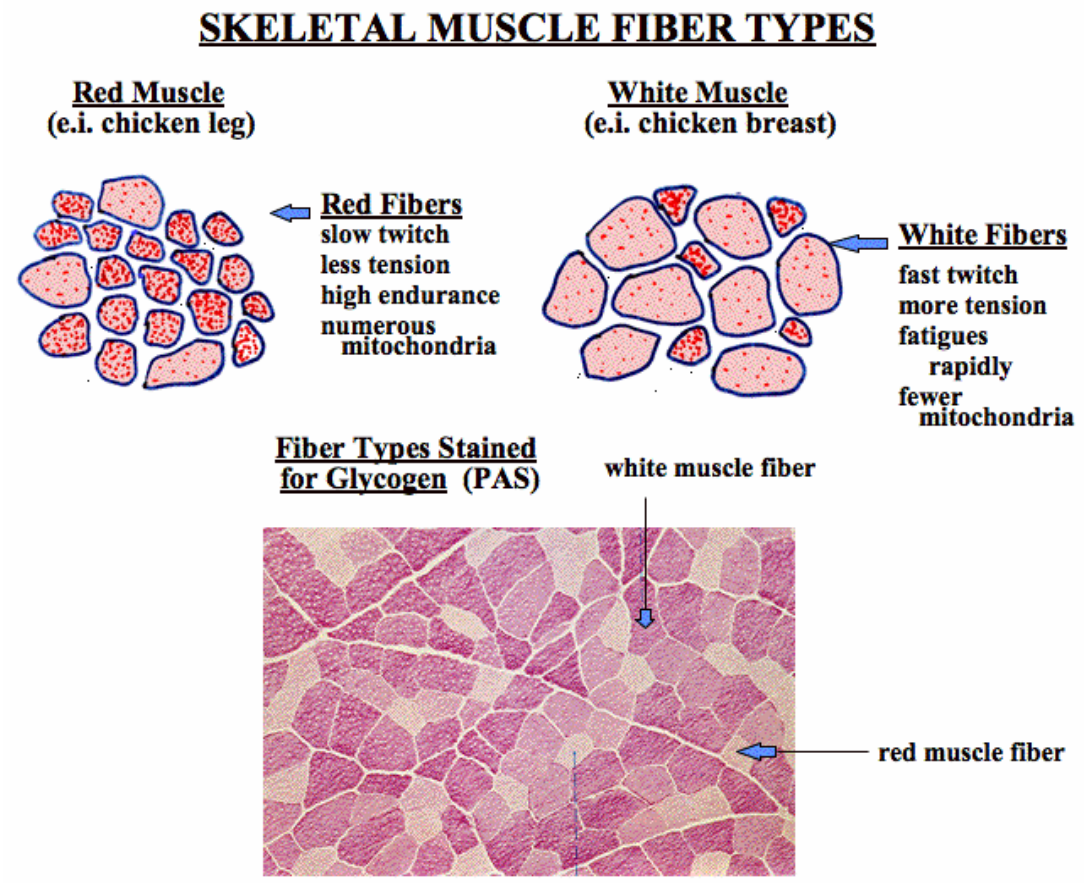
M-line = thick filaments interconnected by cross-linking fine radial filaments, acts to maintain regular spacing and arrangement of thick filaments

During contraction, A-band width remains unchanged, I-band width decreases, H-zone also decreases, Sarcomere shortens.

MYOFILAMENTS
1) Thin = composed mainly of F-actin (polymer of globularG-actin subunits) in two-stranded double helix (1 micrometers in length); associated with actin double helix is a long slender filament of tropomyosin that lies in the groove between the

2 F-actin strands; Troponin (globular protein) is attached to tropomyosin at regular intervals.

2) Thick = composed of myosin (1.5 micrometers long) arranged in bundle; Structurally has smooth central region with projections at each end; each myosin molecule is shaped like a golf club with a shaft and head



Structure of skeletal muscle

- Muscle fibres in skeletal muscle occur in bundles, fascicles, which make up the muscle.
- The muscle is surrounded by a layer of connective tissue, the epimysium, which is continuous with the muscle fascia.
- Connective tissue from the epimysium extends into the muscle to surround individual fascicles (perimysium) from which a delicate network of reticular fibres surrounds each individual muscle fibre (endomysium).
- The connective tissue transduces the force generated by the muscle fibres to the tendons.
- The insertion into the tendon of the connective tissue fibres surrounding the muscle fibres, i.e. the muscle-tendon junction, is shown in one of the

HISTOPHYSIOLOGICAL TYPES OF SKELETAL MUSCLE

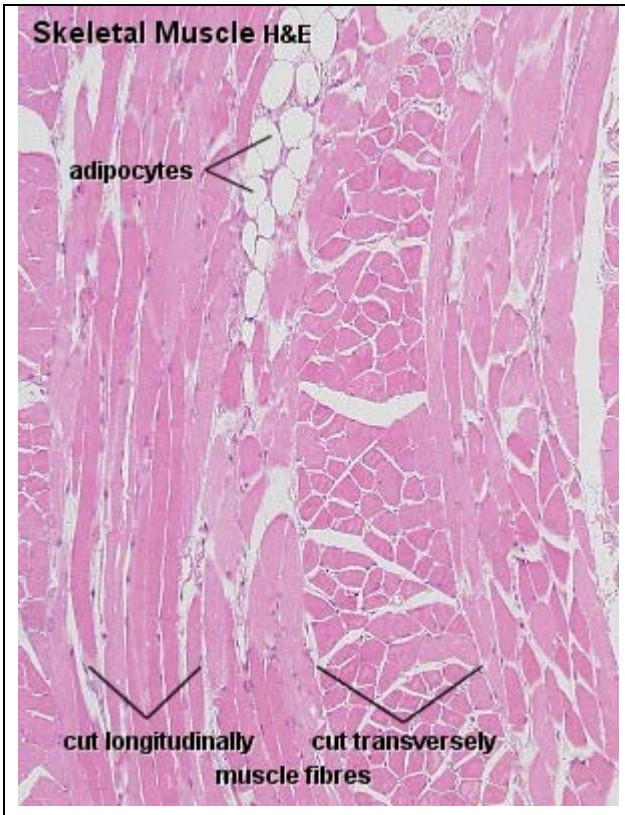
1) Red Fibers = High concentration of myoglobin (involved in oxygen uptake from the blood), high numbers of mitochondria, aerobic, slow-twitch, fatigue-resistant

2) White Fibers = Lower myoglobin concentration and lower numbers of mitochondria, glycolytic, fast-twitch, fatigue-rapidly

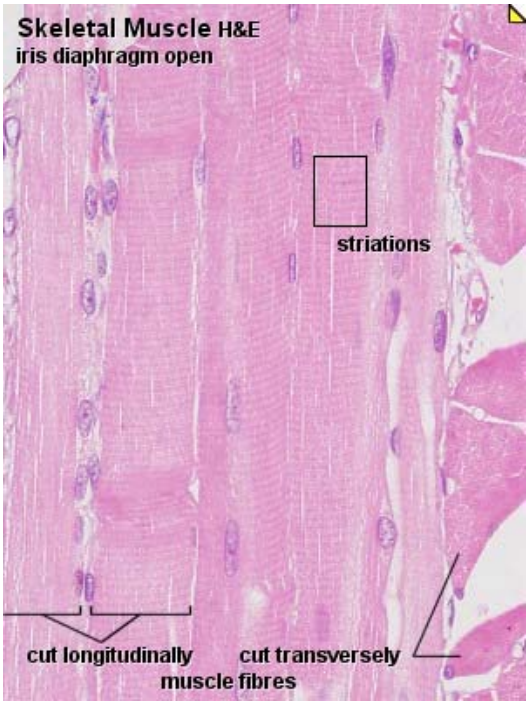
3) Intermediate Fibers = intermediate myoglobin concentration and relatively high numbers of mitochondria, fast-twitch, oxidative-glycolytic, fatigue-resistan

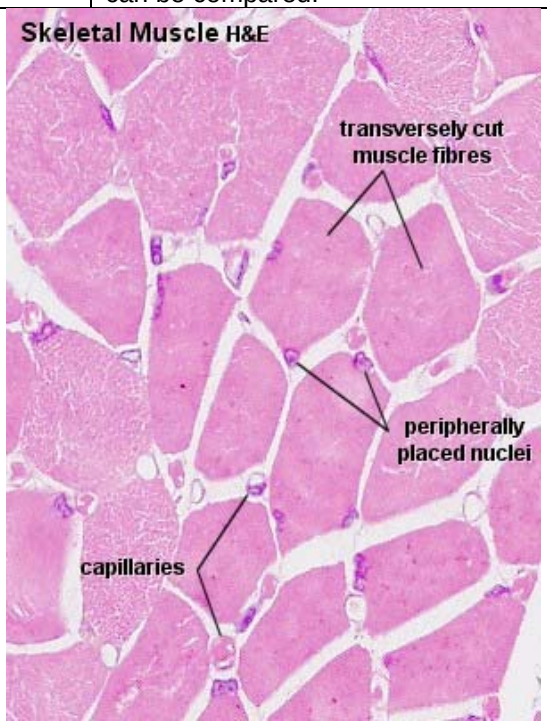
Origin of skeletal muscle

- The myoblasts of all skeletal muscle fibres originate from the paraxial mesoderm. Myoblasts undergo frequent divisions and coalesce with the formation of a multinucleated, syncytial muscle fibre or myotube. The nuclei of the myotube are still located centrally in the muscle fibre. In the course of the synthesis of the myofilaments/myofibrils, the nuclei are gradually displaced to the periphery of the cell.
- Satellite cells are small cells which are closely apposed to muscle fibres within the basal lamina which surrounds the muscle fibre. Their nuclei are slightly darker than those of the muscle fibre. Satellite cells are believed to represent persistent myoblasts. They may regenerate muscle fibres in case of damage.



Tongue, Skeletal Muscle, human - H&E
Skeletal muscle in the tongue is arranged in bundles which typically run at right angles to each other. Both longitudinally and transversely cut skeletal muscle fibres are present. In both section planes you can see that the nuclei are located in the periphery of the muscle fibre. Striations are visible in longitudinally cut fibres. They stand out more clearly if you close the iris diaphragm of the microscope. Remember to open the diaphragm after you have seen the striations clearly ! In well-preserved tissue it is possible to identify Z-lines and H-bands in addition to A-bands and I-bands. Numerous capillaries between the muscle fibres supply the muscle with oxygen and nutrients.
Draw a small section of longitudinal and transversely cut skeletal muscle at high magnification.
The muscle surrounding the upper one-third of the oesophagus is skeletal muscle. Smooth muscle surrounds its lower one-third. In section of the middle of the esophagus it is usually possible to identify both muscle types and their appearances can be compared.





MUSCLE CONTRACTION – [see more in muscle physiology]
Sliding Filament Theory (applies to other muscle types as well)

1) Myosin ATPase splits ATP to ADP + P_i providing energy for "cocking" of myosin head

2) Stimulation causes release of Ca^{2+} from Sarcoplasmic Reticulum (muscle ER)

3) Ca^{2+} binds to troponin (C subunit)

4) Structural change in troponin removes tropomyosin from actin-myosin binding site

5) Myosin head contacts actin molecule

6) Upon contact, inorganic phosphate released concurrent with release of stored energy in myosin head causing "backward rowing" motion of mysoin head and sliding of acting along myosin

7) Another ATP molecule becomes bound to myosin causing release from actin, splitting of ATP causes return of head to "cocked" state, and reattachment to actin (if Ca^{2+} present)

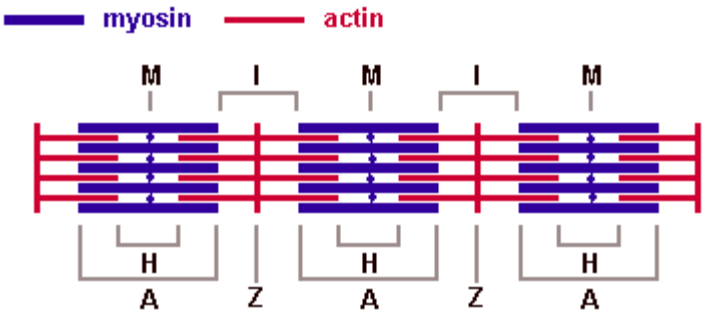
8) Repeat process until contraction attained

The Contractile Apparatus of Skeletal Muscle

The spatial relation between the filaments that make up the myofibrils within skeletal muscle fibres is highly regular. This regular organisation of the myofibrils gives rise to the cross-striation, which characterises skeletal and cardiac muscle. Sets of individual "stria" within a myofibril correspond to the smallest contractile units of skeletal muscle, the sarcomeres.

Depending on the distribution and interconnection of myofilaments a number of "bands" and "lines" can be distinguished in the sarcomeres

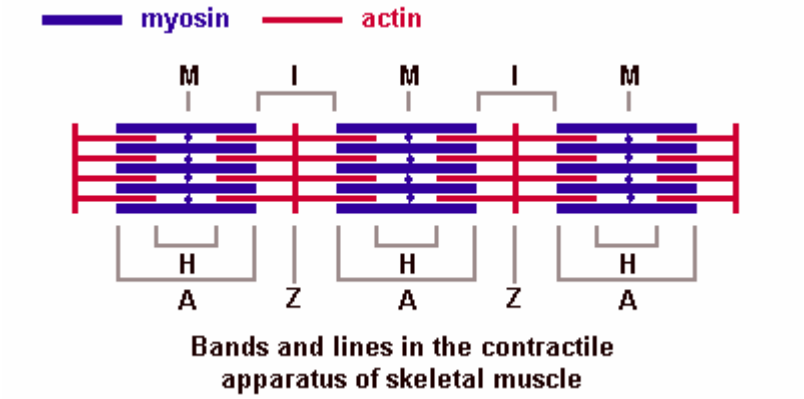
I-band - actin filaments,
A-band - myosin filaments which may overlap with actin filaments,
H-band - zone of myosin filaments only (no overlap with actin filaments) within the A-band,
Z-line - zone of apposition of actin filaments belonging to two neighbouring sarcomeres (mediated by a protein called alpha-actinin),
M-line - band of connections between myosin filaments (mediated by proteins, e.g. myomesin, M-protein).



Bands and lines in the contractile apparatus of skeletal muscle

The average length of a sarcomere is about 2.5 µm (contracted ~1.5 µm, stretched ~3 µm).

The protein titin extends from the Z-line to the M-line. It is attached to the Z-line and the myosin filaments. Titin has an elastic part which is located between the Z-line and the border between the I- and A-bands. Titin contributes to keeping the filaments of the contractile apparatus in alignment and to the passive stretch resistance of muscle fibres. Other cytoskeletal proteins interconnect the Z-lines of neighbouring myofibrils. Cytoskeletal proteins also connect the Z-lines of the peripheral myofibrils to the sarcolemma



Bands and lines in the contractile apparatus of skeletal muscle

INNERVATION OF SKELETAL MUSCLE

1) Every muscle fiber is supplied with a motor neuron
2) Generally, one motor neuron innervates several muscle fibers (Motor Unit = all muscle fibers innervated by a single neuron)
3) Each motor unit has a different stimulus threshold, when the threshold stimulus is attained get all-or-none contraction of all fibers within motor unit
4) Graded contraction possible by activating different numbers of motor units

Motor End Plates = synapse of motor neuron on sarcolemma

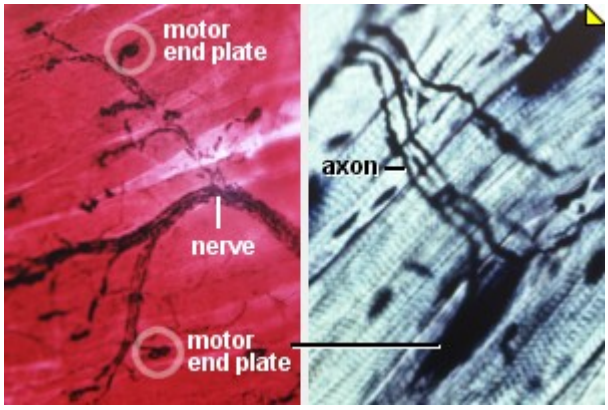
STIMULUS CONDUCTION AND TRANSFORMATION WITHIN MUSCLE CELLS

Transverse Tubules = tubular invaginations of sarcolemma extending deep into muscle fiber. In humans, enters at A-I junction; in amphibians at Z-line. Function is to conduct stimulus into entire fiber.

Sarcoplasmic Reticulum = muscle cell equivalent of smooth ER. Forms collar-like complex around each myofibril, consisting of connecting tubules and flattened terminal cisternae. A pair of terminal cisternae, in association with a single T-tubule, occur at each A-I junction. SR function = regulation of Ca2+ concentration in myofibrils.

Excitation and Contraction of Skeletal Muscle

The area of contact between the end of a motor nerve and a skeletal muscle cell is called the motor end plate. Small branches of the motor nerve form contacts (boutons) with the muscle cell in a roughly eliptical area. The excitatory transmitter at the motor end plate is acetylcholine. The space between the boutons and the muscle fibre is called primary synaptic cleft. Numerous infoldings of the sarcolemma in the area of the motor end plate form secondary synaptic clefts. Motor end plates typically concentrate in a narrow zone close to the middle of the belly of a muscle. The excitable sarcolemma of skeletal muscle cells will allow the stimulus to spread, from this zone, over the entire muscle cell.



The spread of excitation over the sarcolemma is mediated by voltage-gated ion channels.

Invaginations of the sarcolemma form the T-tubule system which "leads" the excitation into the muscle fibre, close to the border between the A- and I-bands of the myofibrils. Here, the T-tubules are in close apposition with cisternae formed by the sarcoplasmatic reticulum. This association is called a triad. The narrow gap between the T-tubule and the cisternae of the sarcoplasmatic reticulum is spanned by proteins which mediate the excitation-contraction coupling.

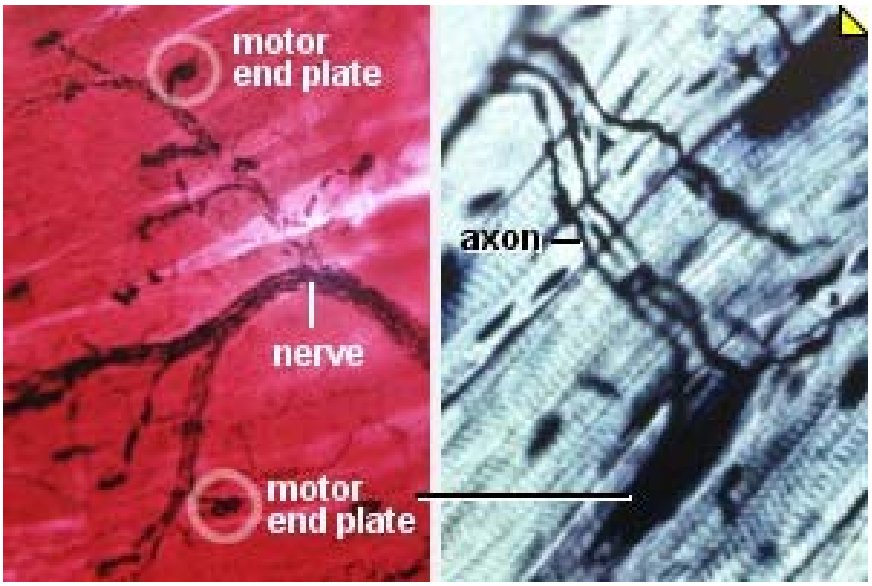
Proteins in the sarcolemma which forms the wall of the T-tubule (dihydropyridine (DHP) receptors) change conformation, i.e. they change their shape, in response to the excitation travelling over the sarcolemma. These proteins are in touch with calcium channels (ryanodine receptors) which are embedded in the membrane of the cisternae of the sarcoplasmatic reticulum. The change in the shape of the proteins belonging to the T-tubule opens the calcium channels of the sarcoplasmatic reticulum. Calcium can now move from stores in the sarcoplasmatic reticulum into the cytoplasm surrounding the myofilaments.

Sites of interaction between actin and myosin are in resting muscle cells "hidden" by tropomyosin. Tropomyosin is kept in place by a complex of proteins collectively called troponin. The binding of calcium to troponin-C induces a conformational change in the troponin-tropomyosin complex which permits the interaction between myosin and actin and, as a consequence of this interaction, contraction.

ATP-dependent calcium pumps in the membrane of the sarcoplasmatic reticulum typically restore the concentration of Ca to resting levels within 30 milliseconds after the activation of the muscle fibre.

Types of Skeletal Muscle

Skeletal muscle cells respond to stimulation with a brief maximal contraction - they are of the twitch type. Individual muscles fibres cannot maintain their contraction over longer periods. The sustained contraction of a muscle depends on the "averaged" activity of often many muscles fibres, which individually only contract for a brief period of time.
The force generated by the muscle fibre does depend on its state of contraction at the time of excitation. Excitation frequency and the mechanical summation of the force generated is one way to graduate the force generated by the entire muscle. Another way is the regulation of the number of muscle fibres which contract in the muscle. Additional motor units, i.e. groups of muscle fibres innervated by one motor neurone and its branches, are recruited if their force is required. The functional properties of the muscle can be "fine-tuned" further to the tasks the muscle performs by blending functionally different types of muscle fibres:

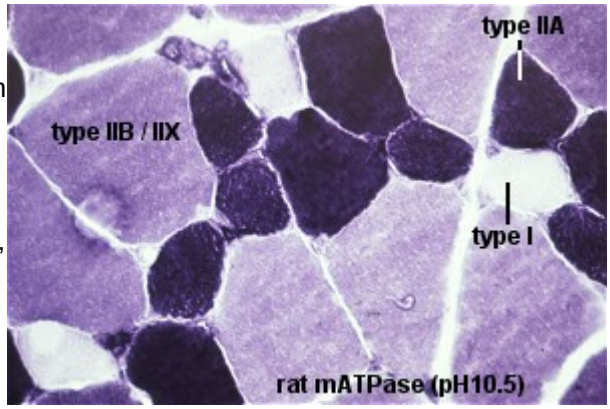


Type I fibres (red fibres)

> Red muscles contain predominantly (but not exclusively) red muscle cells. Red muscle fibres are comparatively thin and contain large amounts of myoglobin and mitochondria. Red fibres contain an isoform of myosin with low ATPase activity, i.e. the speed with which myosin is able to use up ATP. Contraction is therefore slow. Red muscles are used when sustained production of force is necessary, e.g. in the control of posture.

Type II fibres

White muscle cells, which are predominantly found in white muscles, are thicker and contain less myoglobin. ATPase activity of the myosin isoform in white fibres is high, and contraction is fast. Type IIA fibres (red) contain many mitochondria and are available for both sustained activity and short-lasting, intense contractions. Type IIB/IIX fibres (white) contain only few mitochondria. They are recruited in the case of rapid accelerations and short lasting maximal contraction. Type IIB/IIX fibres rely on anaerobic glycolysis to generate the ATP needed for contraction.



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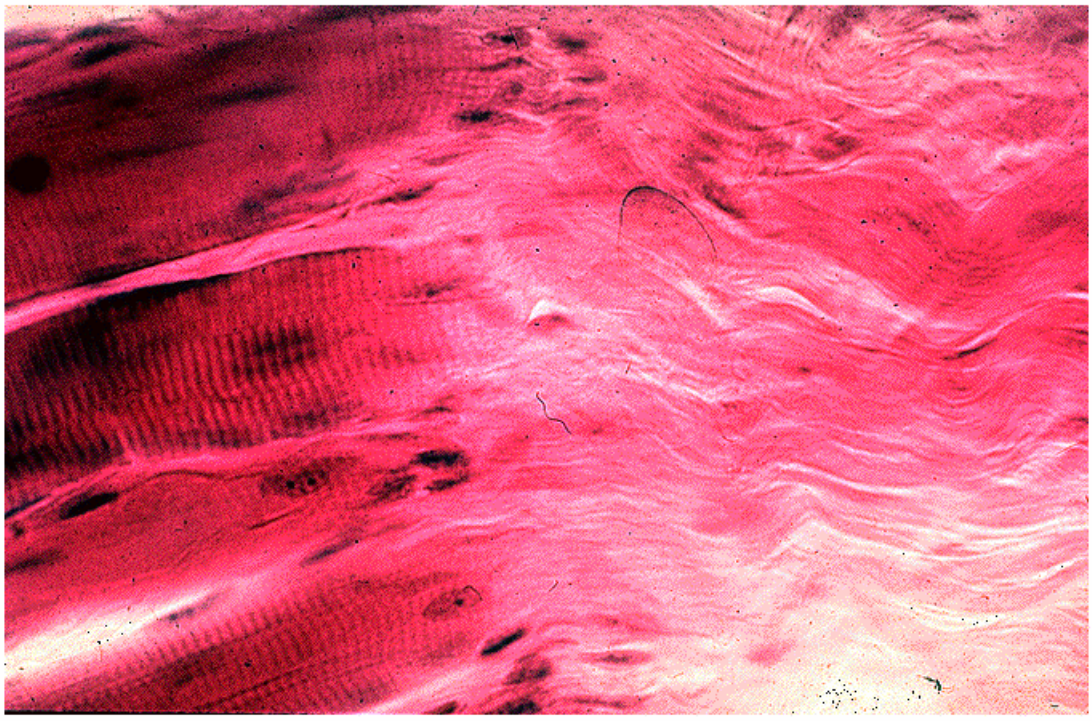
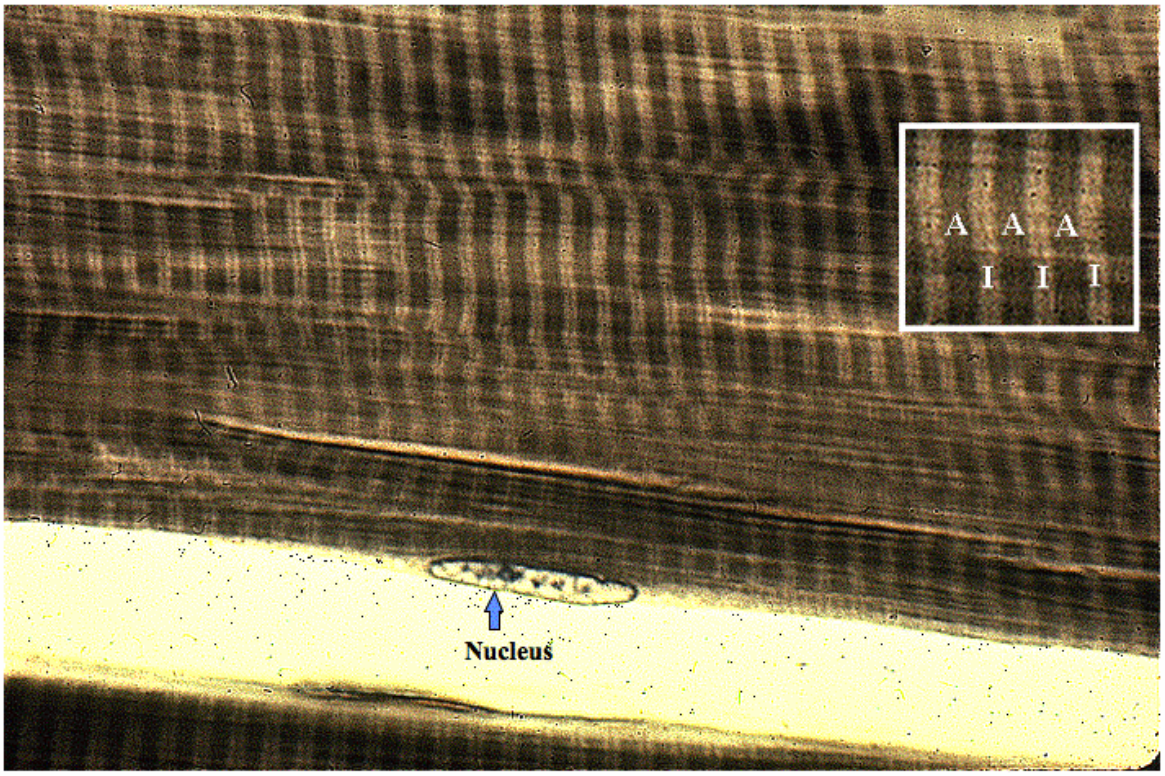
Skeletal muscle fibres do not contract spontaneously. Skeletal muscle fibres are not interconnected via GAP junctions but depend on nervous stimulation for contraction. All muscle fibres of a motor unit are of the same type.

Fibre type is determined by the pattern of stimulation of the fibre, which, in turn, is determined by the type of neuron which innervates the muscle. If the stimulation pattern is changed experimentally, fibre type will change accordingly. This is of some clinical / pathological importance. Nerve fibres have the capacity to form new branches, i.e. to "sprout", and to re-innervate muscle fibres, which may have lost their innervation as a consequence of an acute lesion to the nerve or a neurodegenerative disorder. The type of the muscle fibre will change if the type of stimulation provided by the sprouting nerve fibre does not match with the type of muscle. The process of reinnervation and type adjustment may result in fibre type grouping within the muscle, i.e. large areas of the muscle are populated by muscle fibres of one type.

MYOTENDONOUS JUNCTION

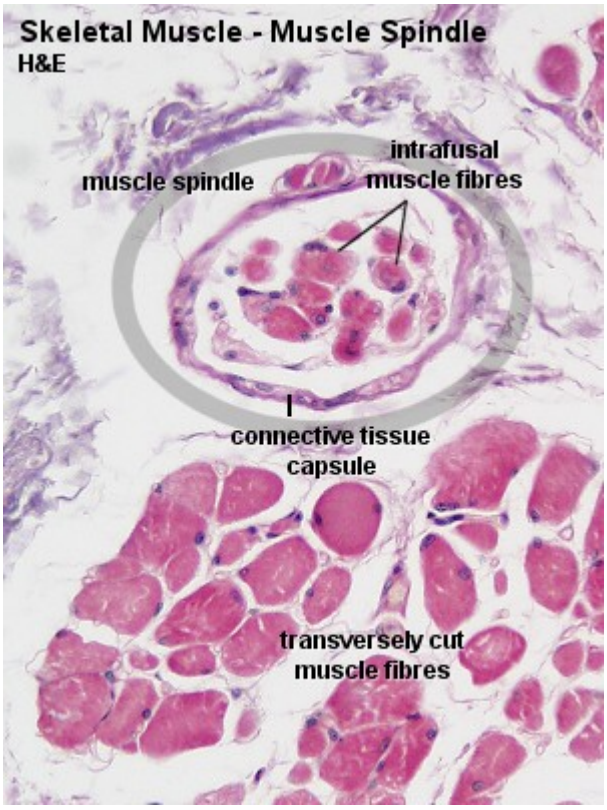


STRIATIONS IN SKELETAL MUSCLE FIBERS



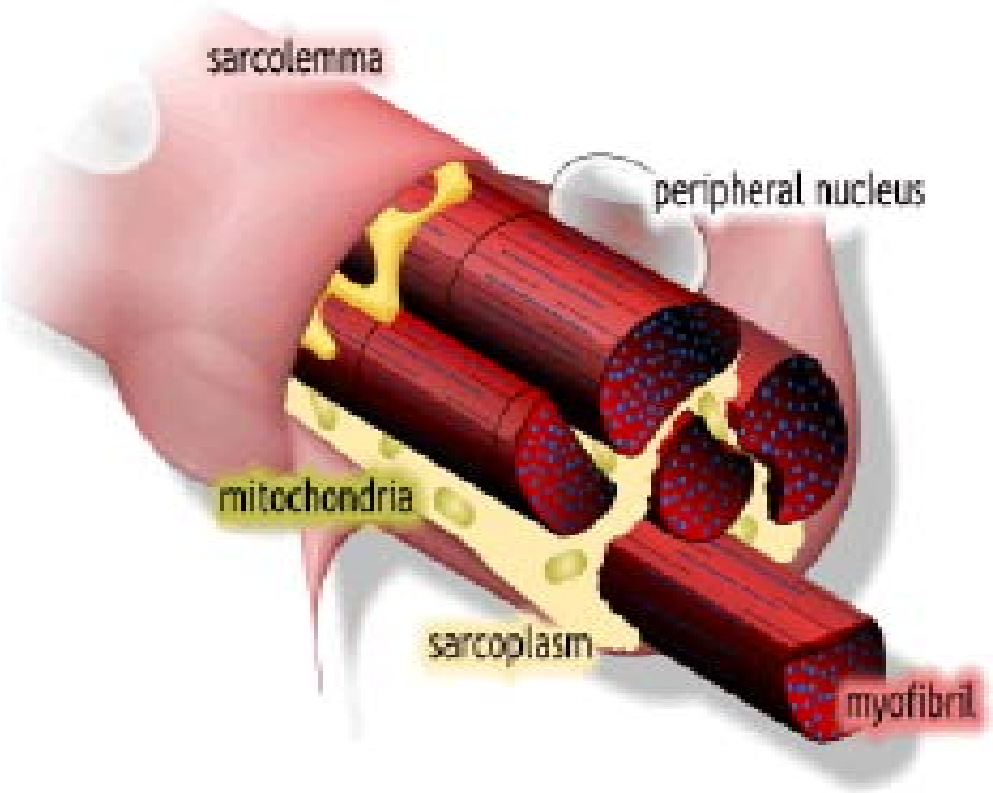
Muscle Spindles

Muscle spindles are sensory specialization of the muscular tissue. A number of small specialised intrafusal muscle fibres (nuclear bag fibres and nuclear chain fibres) are surrounded by a capsule of connective tissue. The intrafusal fibres are innervated by efferent motor nerve fibres. Afferent sensory nerve fibres surround the intrafusal muscle fibres. If the muscle is stretched, the muscle fibres in the muscle spindle are stretched, sensory nerves are stimulated, and a change in contraction of the muscle is perceived. Different types of intrafusal fibres and nerve endings allow the perception of position, velocity and acceleration of the contraction of the muscle.
The contraction of the intrafusal fibres, after stimulation by the efferent nerve fibres, may counteract or magnify the changes imposed on the muscle spindle by the surrounding muscle. The intrafusal fibres and the efferent nerves can in this way set the sensitivity for the sensory nerve ending in the muscle spindle.



Skeletal Muscle

- ***Each muscle is a discrete organ composed of muscle tissue, blood vessels, nerve fibers, and connective tissue***
- ***The three connective tissue sheaths are:***
  - **Endomysium – fine sheath of connective tissue composed of reticular fibers surrounding each muscle fiber**
  - **Perimysium – fibrous connective tissue that surrounds groups of muscle fibers called fascicles**
  - **Epimysium – an overcoat of dense regular connective tissue that surrounds the entire muscle**



Skeletal Muscle: Nerve and Blood Supply

- ***Each muscle is served by one nerve, an artery, and one or more veins***
- ***Each skeletal muscle fiber is supplied with a nerve ending that controls contraction***
- ***Contracting fibers require continuous delivery of oxygen and nutrients via arteries***
- ***Wastes must be removed via veins***

Skeletal Muscle: Attachments

- ***Most skeletal muscles span joints and are attached to bone in at least two places***
- ***When muscles contract the movable bone, the muscle's insertion moves toward the immovable bone, the muscle's origin***
- ***Muscles attach:***
  - **Directly – epimysium of the muscle is fused to the periosteum of a bone**
  - **Indirectly – connective tissue wrappings extend beyond the muscle as a tendon or aponeurosis**

Microscopic Anatomy of a Skeletal Muscle Fiber

- ***Each fiber is a long, cylindrical cell with multiple nuclei just beneath the sarcolemma***
- ***Fibers are 10 to 100 μm in diameter, and up to hundreds of centimeters long***
- ***Each cell is a syncytium produced by fusion of embryonic cells***
- ***Sarcoplasm has numerous glycosomes and a unique oxygen-binding protein called myoglobin***
- ***Fibers contain the usual organelles, myofibrils, sarcoplasmic reticulum, and T tubules***

Myofibrils

- ***Myofibrils are densely packed, rodlike contractile elements***
- ***They make up most of the muscle volume***
- ***The arrangement of myofibrils within a fiber is such that a perfectly aligned repeating series of dark A bands and light I bands is evident***

Sarcomeres

- ***The smallest contractile unit of a muscle***
- ***The region of a myofibril between two successive Z discs***
- ***Composed of myofilaments made up of contractile proteins***
  - **Myofilaments are of two types – thick and thin**

Myofilaments: Banding Pattern

- ***Thick filaments – extend the entire length of an A band***
- ***Thin filaments – extend across the I band and partway into the A band***
- ***Z-disc – coin-shaped sheet of proteins (connectins) that anchors the thin filaments and connects myofibrils to one another***
- ***Thin filaments do not overlap thick filaments in the lighter H zone***
- ***M lines appear darker due to the presence of the protein desmin***

Ultrastructure of Myofilaments: Thick Filaments

- ***Thick filaments are composed of the protein myosin***
- ***Each myosin molecule has a rod-like tail and two globular heads***
  - **Tails – two interwoven, heavy polypeptide chains**
  - **Heads – two smaller, light polypeptide chains called cross bridges**

Ultrastructure of Myofilaments: Thin Filaments

- ***Thin filaments are chiefly composed of the protein actin***
- ***Each actin molecule is a helical polymer of globular subunits called G actin***
- ***The subunits contain the active sites to which myosin heads attach during contraction***
- ***Tropomyosin and troponin are regulatory subunits bound to actin***

Arrangement of the Filaments in a Sarcomere

- ***Longitudinal section within one sarcomere***

Sarcoplasmic Reticulum (SR)

- ***SR is an elaborate, smooth endoplasmic reticulum that mostly runs longitudinally and surrounds each myofibril***
- ***Paired terminal cisternae form perpendicular cross channels***
- ***Functions in the regulation of intracellular calcium levels***
- ***Elongated tubes called T tubules penetrate into the cell's interior at each A band–I band junction***
- ***T tubules associate with the paired terminal cisternae to form triads***

T Tubules

- ***T tubules are continuous with the sarcolemma***
- ***They conduct impulses to the deepest regions of the muscle***
- ***These impulses signal for the release of Ca^{2+} from adjacent terminal cisternae***

Triad Relationships

- ***T tubules and SR provide tightly linked signals for muscle contraction***
- ***A double zipper of integral membrane proteins protrudes into the intermembrane space***
- ***T tubule proteins act as voltage sensors***
- ***SR foot proteins are receptors that regulate Ca^{2+} release from the SR cisternae***

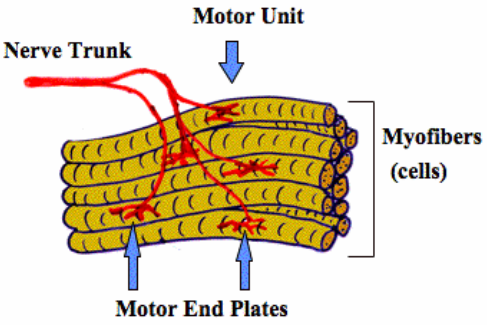
Sliding Filament Model of Contraction

- ***Thin filaments slide past the thick ones so that the actin and myosin filaments overlap to a greater degree***
- ***In the relaxed state, thin and thick filaments overlap only slightly***
- ***Upon stimulation, myosin heads bind to actin and sliding begins***
- ***Each myosin head binds and detaches several times during contraction, acting like a ratchet to generate***

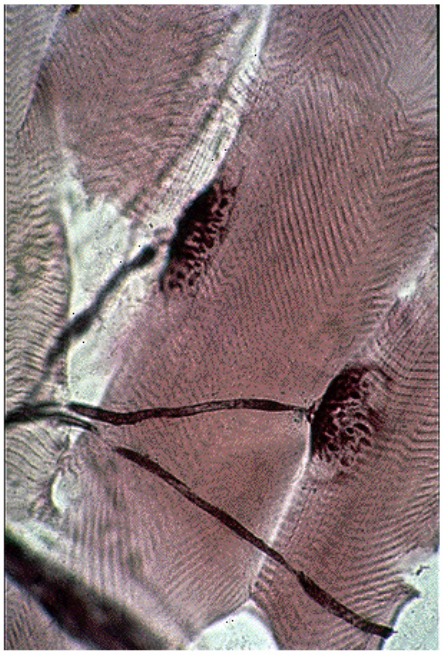
tension and propel the thin filaments to the center of the sarcomere

- *As this event occurs throughout the sarcomeres, the muscle shortens*

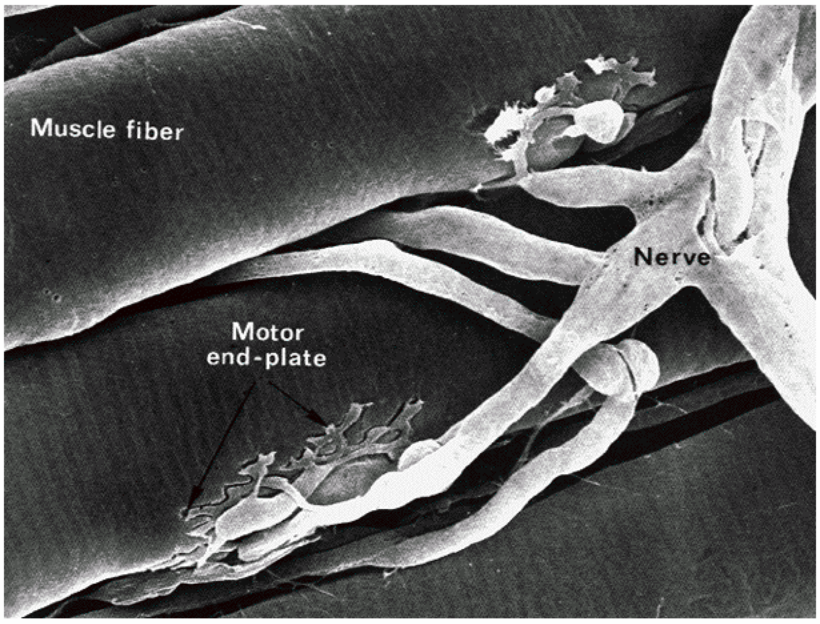
MOTOR END PLATES

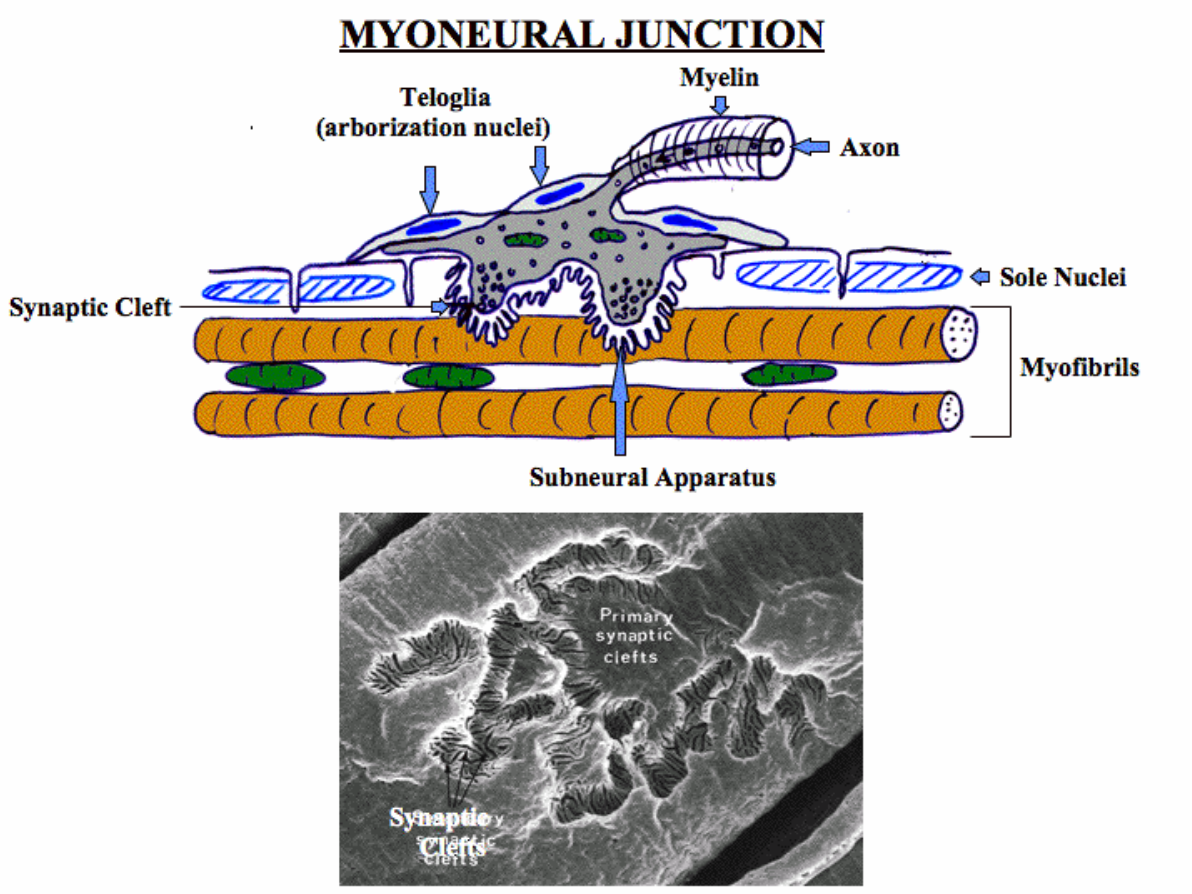


Motor End Plates



SEM OF MOTOR END PLATES





Skeletal Muscle Contraction

- ***In order to contract, a skeletal muscle must:***
  - **Be stimulated by a nerve ending**
  - **Propagate an electrical current, or action potential, along its sarcolemma**
  - **Have a rise in intracellular Ca^{2+} levels, the final trigger for contraction**
- ***Linking the electrical signal to the contraction is excitation-contraction coupling***

Nerve Stimulus of Skeletal Muscle

- ***Skeletal muscles are stimulated by motor neurons of the somatic nervous system***
- ***Axons of these neurons travel in nerves to muscle cells***
- ***Axons of motor neurons branch profusely as they enter muscles***
- ***Each axonal branch forms a neuromuscular junction with a single muscle fiber***

Neuromuscular Junction

- ***The neuromuscular junction is formed from:***
  - **Axonal endings, which have small membranous sacs (synaptic vesicles) that contain the neurotransmitter acetylcholine (ACh)**
  - **The motor end plate of a muscle, which is a specific part of the sarcolemma that contains ACh receptors and helps form the neuromuscular junction**
- ***Though exceedingly close, axonal ends and muscle fibers are always separated by a space called the synaptic cleft***
- ***When a nerve impulse reaches the end of an axon at the neuromuscular junction:***
  - **Voltage-regulated calcium channels open and allow Ca^{2+} to enter the axon**
  - **Ca^{2+} inside the axon terminal causes axonal vesicles to fuse with the axonal membrane**

Neuromuscular Junction

- **This fusion releases ACh into the synaptic cleft via exocytosis**
- **ACh diffuses across the synaptic cleft to ACh receptors on the sarcolemma**
- **Binding of ACh to its receptors initiates an action potential in the muscle**

Destruction of Acetylcholine

- ***ACh bound to ACh receptors is quickly destroyed by the enzyme acetylcholinesterase***
- ***This destruction prevents continued muscle fiber contraction in the absence of additional stimuli***

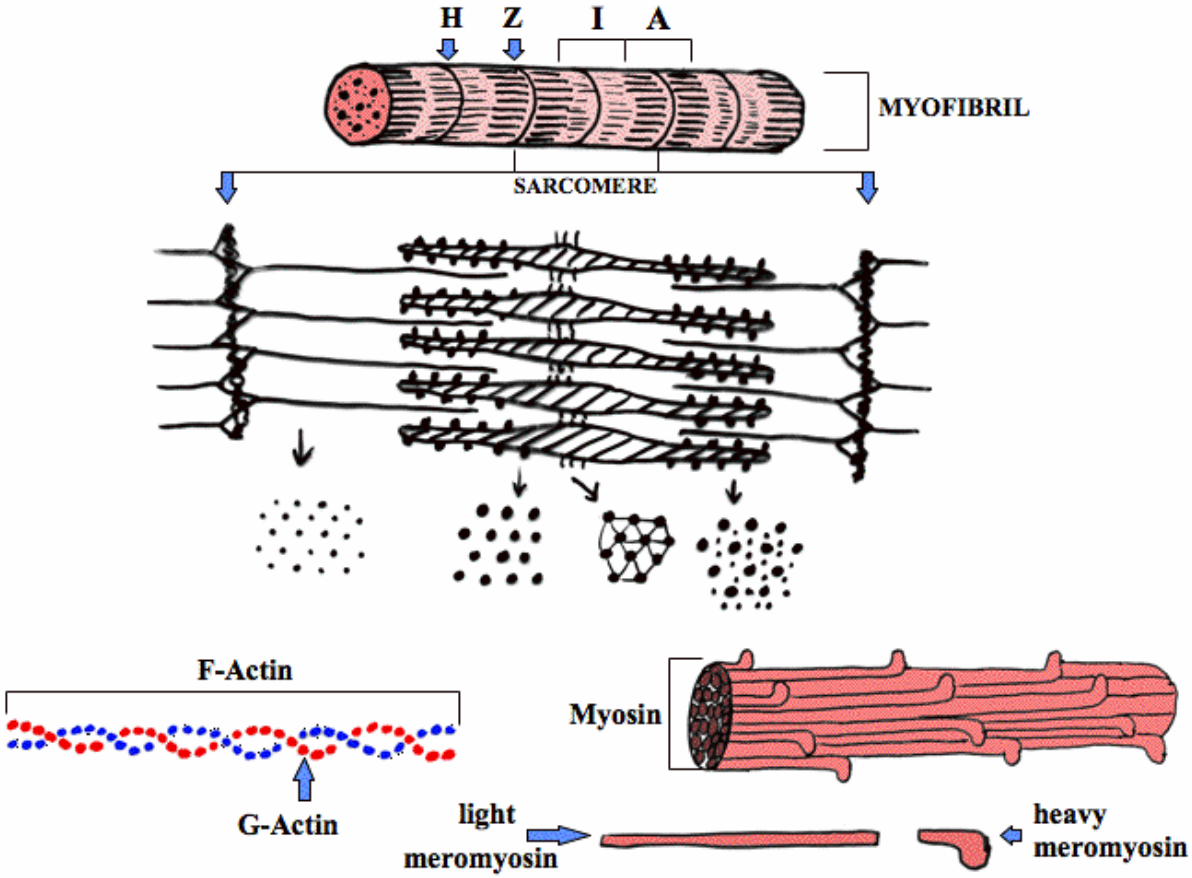
Action Potential

- ***A transient depolarization event that includes polarity reversal of a sarcolemma (or nerve cell membrane) and the propagation of an action potential along the membrane***

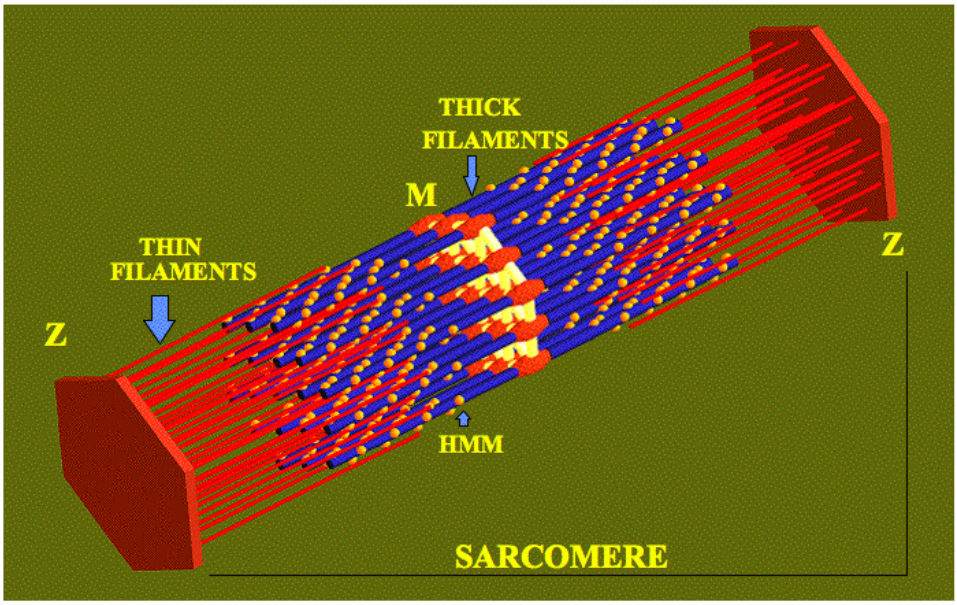
Role of Acetylcholine (Ach)

- ***ACh binds its receptors at the motor end plate***
- ***Binding opens chemically (ligand) gated channels***
- ***Na^+ and K^+ diffuse out and the interior of the sarcolemma becomes less negative***
- ***This event is called depolarization***

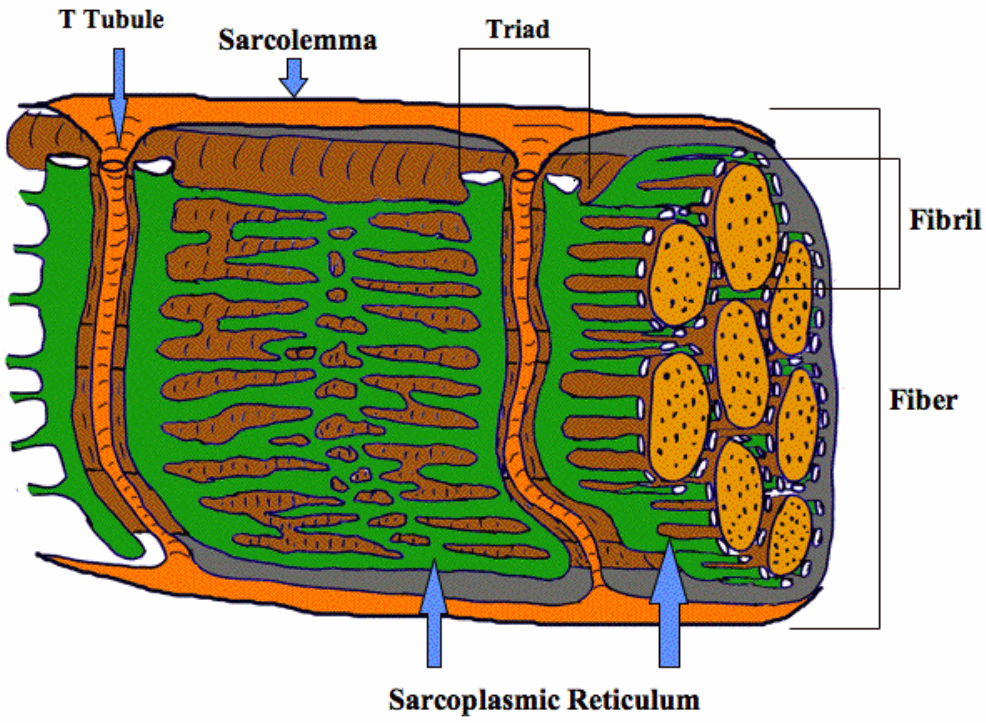
STRUCTURAL HIERARCHY OF STRIATED MUSCLE



SLIDING FILAMENT MODEL OF STRIATED MUSCLE CONTRACTION



SARCOPLASMIC RETICULUM



Major Skeletal Muscles

A. Muscles are named according to any of the following criteria: size, shape, location, action, number of attachments, or direction of its fibers.

B. Muscles of Facial Expression

1. Muscles of facial expression attach to underlying bones and overlying connective tissue of skin, and are responsible for the variety of facial expressions possible in the human face.

2. Major muscles include epicranius, orbicularis oculi, orbicularis oris, buccinator, zygomatigus, and platysma.

C. Muscles of Mastication

1. Chewing movements include up and down as well as side-to-side grinding motions of muscles attached to the skull and lower jaw.

2. Chewing muscles include: masseter and temporalis.

D. Muscles that Move the Head

1. Paired muscles in the neck and back flex, extend, and turn the head.

2. Major muscles include: sternocleidomastoid, splenius capitis, and semispinalis capitis.

E. Muscles that Move the Pectoral Girdle

1. The chest and shoulder muscles move the scapula.

2. Major muscles include: trapezius, rhomboideus major, levator scapulae, serratus anterior, and pectoralis minor.

F. Muscles that Move the Arm

1. Muscles connect the arm to the pectoral girdle, ribs, and vertebral column, making the arm freely movable.

2. Flexors include the coracobrachialis and pectoralis major.

3. Extensors include the teres major and latissimus dorsi.

4. Abductors include the supraspinatus and the deltoid.

5. Rotators are the subscapularis, infraspinatus, and teres minor.

G. Muscles that Move the Forearm

1. These muscles arise from the humerus or pectoral girdle and connect to the ulna and radius.

2. Flexors are the biceps brachii, brachialis, and brachioradialis.

3. An extensor is the triceps brachii muscle.

4. Rotators include the supinator, pronator teres, and pronator quadratus.

H. Muscle that Move the Wrist, Hand, and Fingers

1. Movements of the hand are caused by muscles originating from the distal humerus, and the radius and ulna.

2. Flexors include the flexor carpi radialis, flexor carpi ulnaris, palmaris longus, and flexor digitorum profundus.

3. Extensors include the extensor carpi radialis longus, extensor carpi radialis brevis, extensor carpi ulnaris, and extensor digitorum.

I. Muscles of the Abdominal Wall

1. This group of muscles connects the rib cage and vertebral column to the pelvic girdle.

a. A band of tough connective tissue, the linea alba, extending from the xiphoid process to the symphysis pubis, serves as an attachment for certain abdominal wall muscles.

2. These four muscles include: external oblique, internal oblique, transverse abdominis, and rectus abdominis.

J. Muscles of the Pelvic Outlet

1. The superficial urogenital diaphragm fills the space within the pubic arch, and the deeper pelvic diaphragm forms the floor of the pelvic cavity.

2. Pelvic diaphragm includes the levator ani.

3. Urogenital diaphragm includes the superficial transversus perinei, bulbospongiosus, and ischiocavernosus.

K. Muscles that Move the Thigh

1. The muscles that move the thigh are attached to the femur and to the pelvic girdle.

2. Anterior group includes the psoas major and iliacus.

3. Posterior group is made up of the gluteus maximus, gluteus medius, gluteus minimus, and tensor fasciae latae.

4. Thigh adductors include the adductor longus, adductor magnus, and gracilis.

L. Muscles that Move the Leg

1. This group connects the tibia or fibula to the femur or pelvic girdle.

2. Flexors are the biceps femoris, semitendinosus, semimembranosus, and sartorius.

3. An extensor is the quadriceps femoris group made up of four parts: rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius.

M. Muscles that Move the Ankle, Foot, and Toes

1. Muscles that move the foot are attached to the femur, fibula, or tibia, and move the foot upward, downward, or in a turning motion.

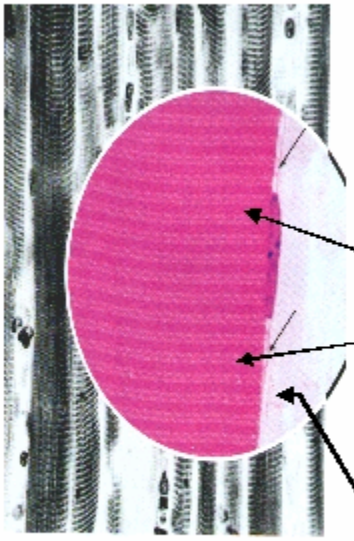
2. Dorsal flexors include the tibialis anterior, peroneus tertius, and extensor digitorum longus.

3. Plantar flexors are the gastrocnemius, soleus, and flexor digitorum longus.

4. An invertor is the tibialis posterior.

5. An evertor is the peroneus longus.

Striations



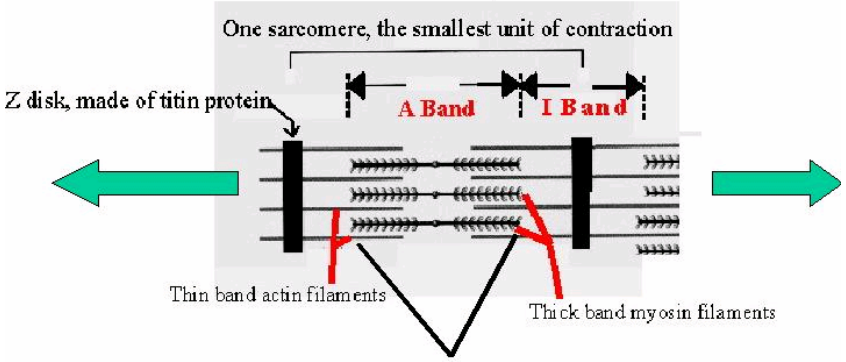
Striations reflect the arrangement of protein myofilaments within the cell. The dark bands are called A-bands, the light areas between are the I-bands. Z lines (Z disks) run through the middle of each I-band. The unit from one Z line to the next is a sarcomere.

The sarcolemma is the cell membrane

The Sarcomere

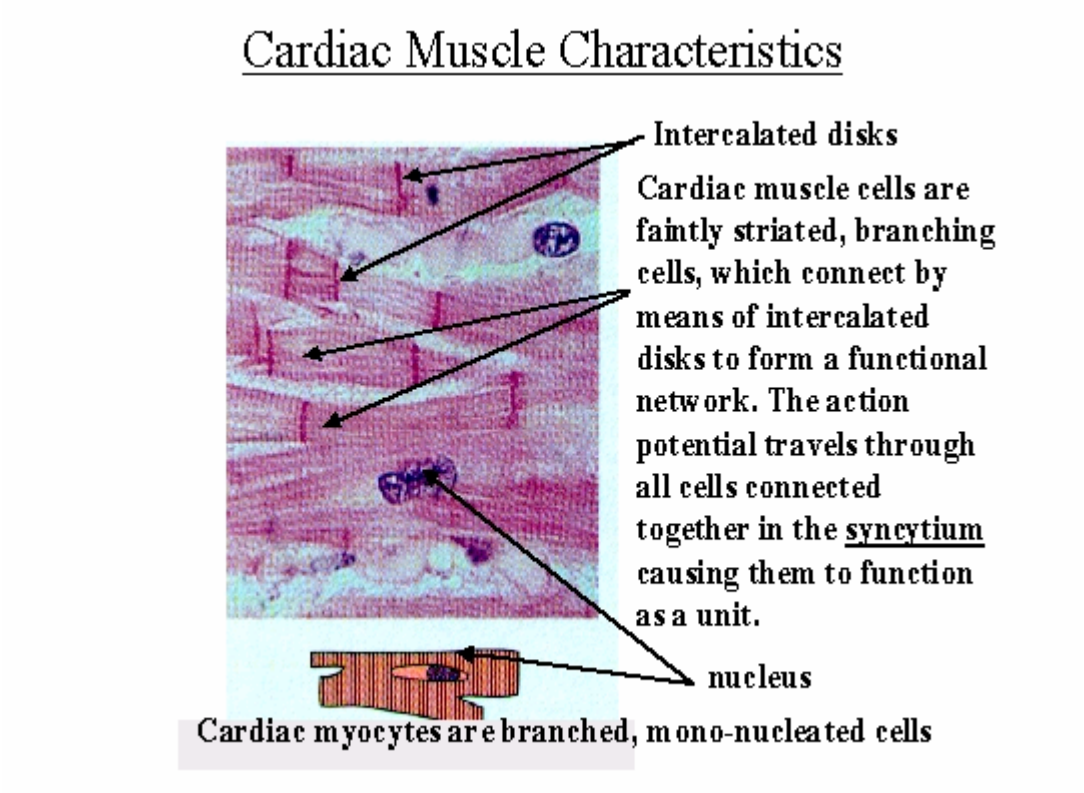
Arrangement of Myofilaments

Arrows indicate the direction of the myofibril and muscle cell.

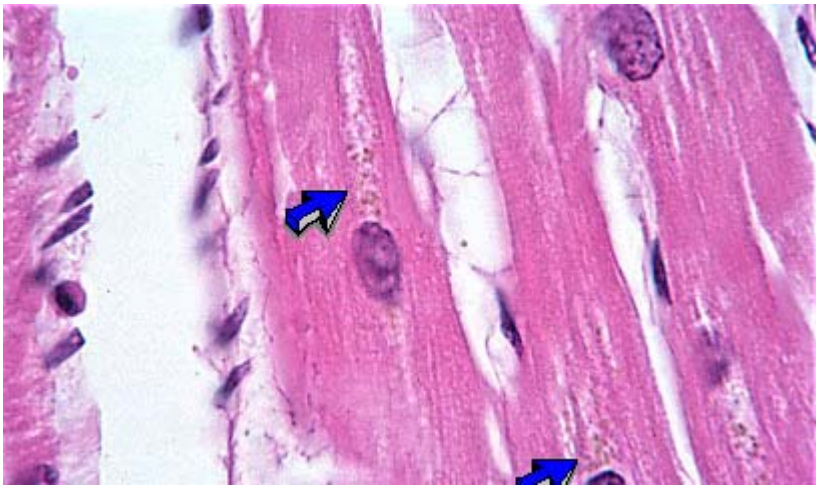


These filaments form the dark bands, called A bands, which are seen as striations,

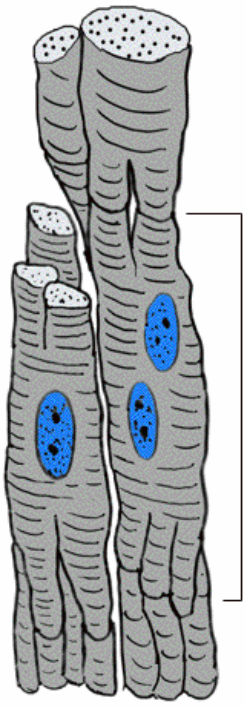
CARDIAC MUSCLE –

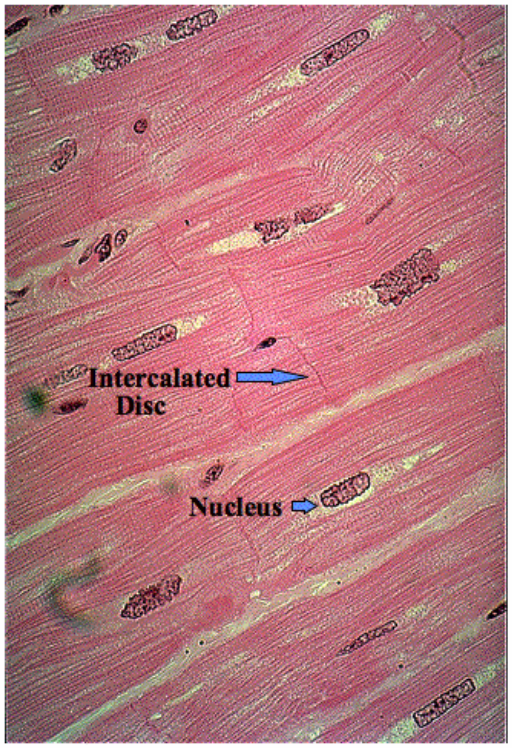


present in heart and walls of aorta as it leaves the heart

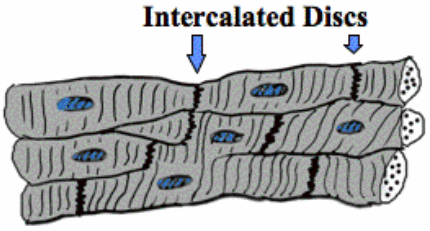


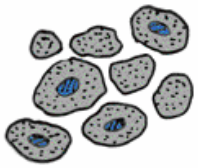
CARDIAC MUSCLE



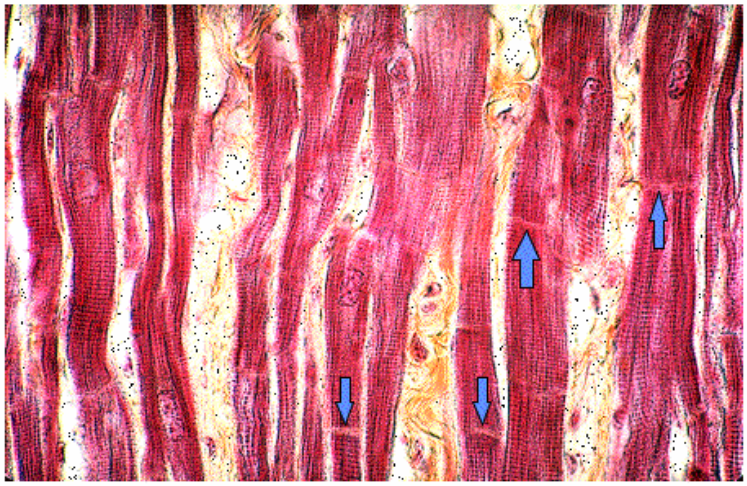


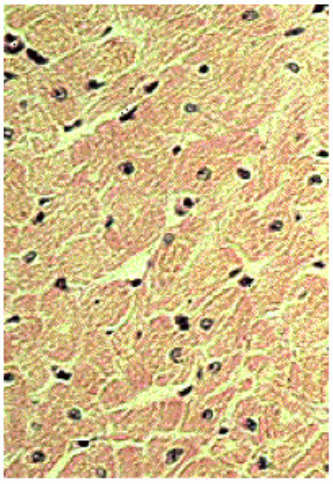
INTERCALATED DISCS





Cardiac Muscle Fibers
(transverse section)





I. CELLS (Fibers)

1) elongate and cylindrical (80 micrometers long, 15 micrometers wide)

2) may be branched

3) single central nucleus

4) striations - same as in skeletal

5) Intercalated Discs = appear at junction betw. adjacent cells of muscle. Represent points of cohesion between cells; composed of sarcolemma and cell junctions. Occur at Z-lines.

6) Development: Mesenchymal cell ---> Myoblast ---> Cardiac muscle cell

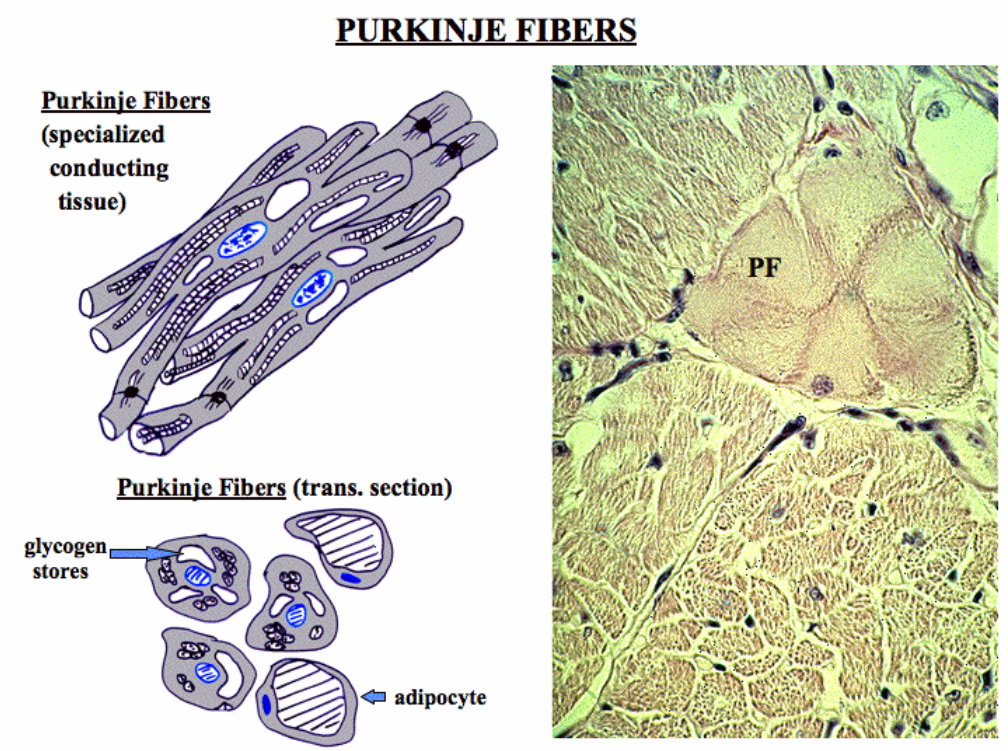
I. ULTRASTRUCTURE

1) myofibrils branch, anastomose, and are of variable width; not discrete cylinders as in skeletal muscle

2) T-tubules less well-developed (wider and fewer) and enter at Z-lines

3) SR smaller and less complex, more dependent on extracellular Ca2+

4) Only endomysium present - no perimysium or epimysium and no fascicles present



II. **CARDIAC MUSCLE INNERVATION/IMPULSE CONDUCTION**

1) Heart is Myogenic = demonstrates inherent spontaneous rhythmic activity

2) Sinoatrial Node = located near junction of vena cava with right atrium; consists of specialized mass of cardiac muscle fibers innervated by Autonomic NS; functions as pacemaker, each wave of excitation spreading over heart begins here -- spreads via gap junctions between cardiac muscle cells

3) Atrioventricular Node = located near junction of right atrium and ventricle; specialized cardiac muscle fibers innervated by Autonomic NS; as excitation wave spreads over atria, it is momentarily delayed here before transmission to ventricles

4) A-V Bundle = Bundle of Histawara = bundle of specialized conducting cardiac muscle fibers; function = passes impulse rapidly from AV node to ventricles

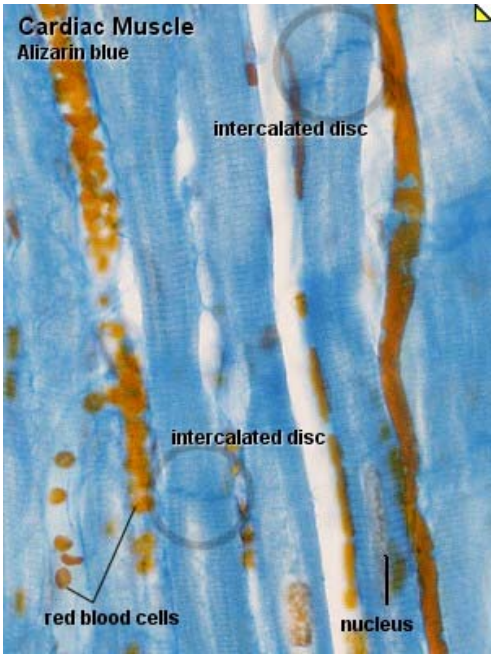
5) Purkinge Fibers = specialized cardiac muscle fibers extending from A-V septum and lateral ventricle walls to supply ventricular muscle (base supplied after apex, What does this order say about the spread of contraction?)
- Purkinge Fibers are larger than normal cardiac muscle cells; stain more lightly and are swollen in nuclear region where no myofibrils or striations are present

Cardiac Muscle

- Cardiac muscle consists of muscle cells with one centrally placed nucleus.
  Nuclei are oval, rather pale and located centrally in the muscle cell which is 10 - 15 µm wide.
- Cardiac muscle is innervated by the autonomic nervous system.
- Cardiac muscle exhibits cross-striations.
- Cardiac muscle is for these reasons also called involuntary striated muscle.

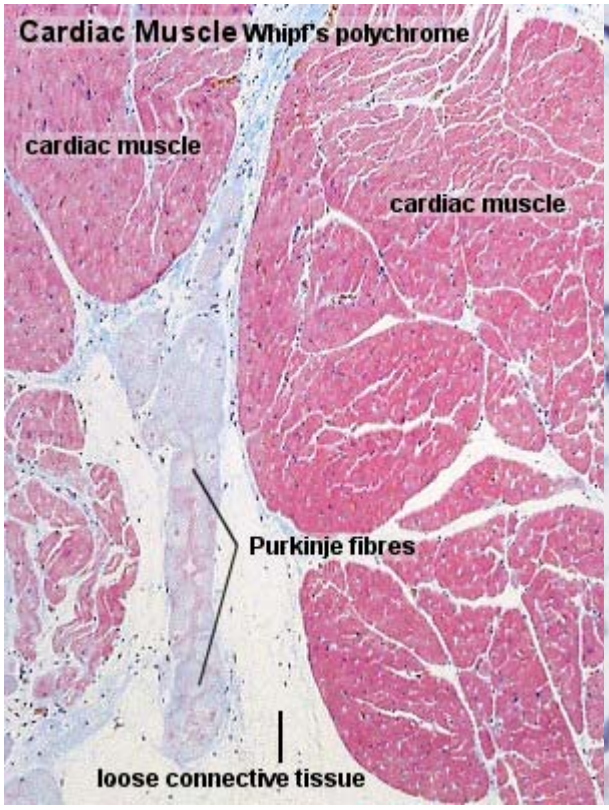
Structure of cardiac muscle

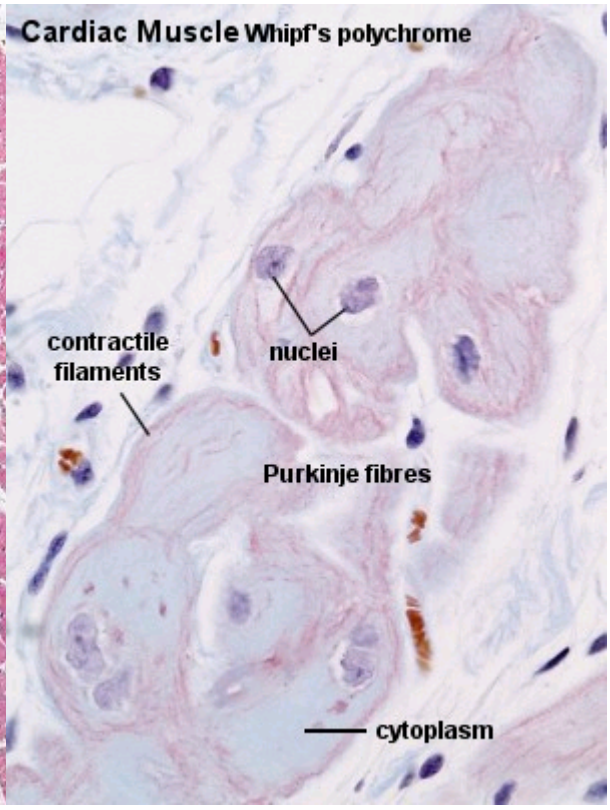
- The ultrastructure of the contractile apparatus and the mechanism of contraction largely correspond to that seen in skeletal muscle cells. Although equal in ultrastructure to skeletal muscle, the cross-striations in cardiac muscle are less distinct, in part because rows of mitochondria and many lipid and glycogen droplets are found between myofibrils.
- In contrast to skeletal muscle cells, cardiac muscle cells often branch at acute angles and are connected to each other by specialisations of the cell membrane in the region of the intercalated discs. Intercalated discs invariably occur at the ends of cardiac muscle cells in a region corresponding to the Z-line of the myofibrils (the last Z-line of the myofibril within the cell is "replaced" by the intercalated disk of the cell membrane). In the longitudinal part of the cell membrane, between the "steps" typically formed by the intercalated disk, we find extensive GAP junctions.
- T-tubules are typically wider than in skeletal muscle, but there is only one T-tubule set for each sarcomere, which is located close to the Z-line. The associated sarcoplasmatic reticulum is organised somewhat simpler than in skeletal muscle. It does not form continuous cisternae but instead an irregular tubular network around the sarcomere with only small isolated dilations in association with the T-tubules.
- Cardiac muscle does not contain cells equivalent to the satellite cells of skeletal muscle. Therefore cardiac muscle cannot regenerate.



Excitation in cardiac muscle

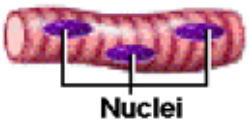
- In theory, a stimulus can be propagated throughout the muscular tissue by way of the GAP junctions between individual muscle cells.
- A further system of modified cardiac muscle cells, Purkinje fibres, has developed, which conduct stimuli faster than ordinary cardiac muscle cells (2-3 m/s vs. 0.6 m/s), and which ensure that the contraction of the atria and ventricles takes place in the order that is most appropriate to the pumping function of the heart.
- Purkinje fibres contain fewer myofibrils than ordinary cardiac muscle cells. Myofibrils are mainly located in the periphery of the cell.
- Purkinje fibres are also thicker than ordinary cardiac muscle cells.
- Modified muscle cells in nodal tissue (nodal muscle cells or P cells; P ~ pacemaker or pale-staining) of the heart exert the pacemaker function that drives the Purkinje cells.
- The rhythm generated by the nodal muscle cells can be modified by the autonomic nervous system, which innervates the nodal tissue and accelerates (sympathetic) or decelerates (parasympathetic) heart rate.



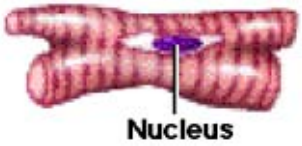


Comparison of Skeletal, Cardiac and Smooth Muscle Cells

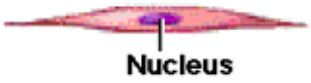
Skeletal Muscle Cell:
Elongated Cells
Multiple Peripheral Nuclei
Visible Striations
Voluntary



Cardiac Muscle:
Branching Cells
Single Central Nucleus
Visible Striations
Involuntary



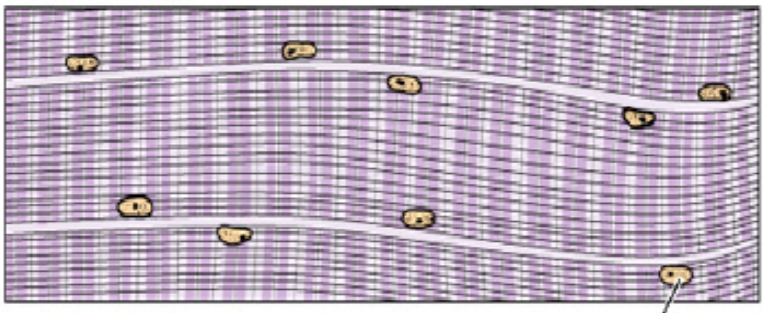
Smooth Muscle Cell:
Spindle-Shaped Cell
Single Central Nucleus
Lack Visible Striations
Involuntary

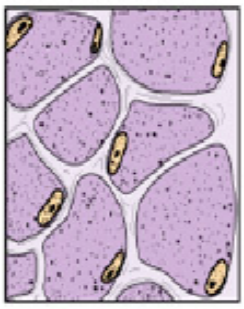


Muscle types **Activity**

Skeletal muscle

Cross sections

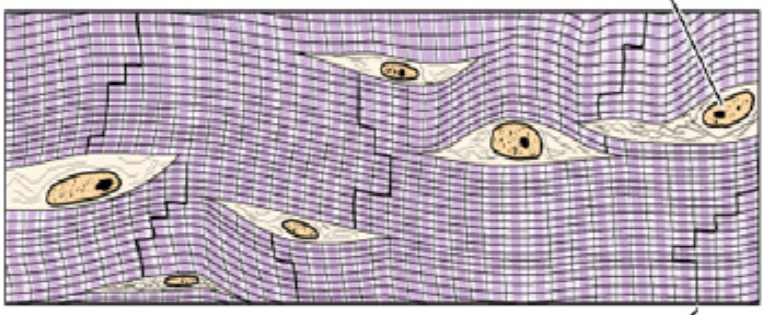


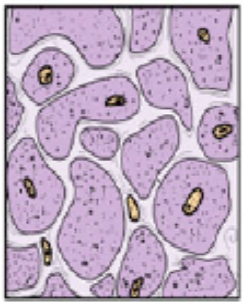


Strong, quick discontinuous voluntary contraction

Nuclei

Cardiac muscle

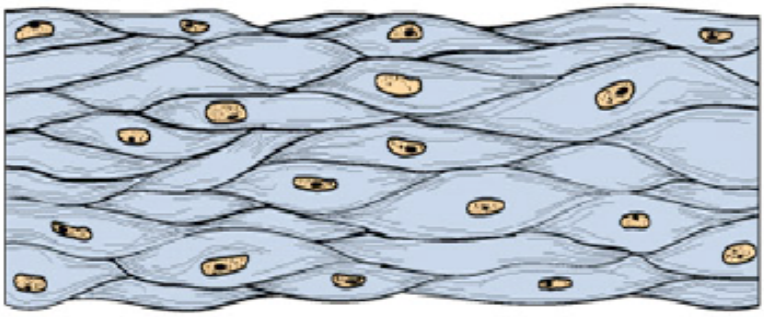


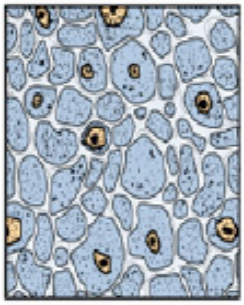


Strong, quick continuous involuntary contraction

Intercalated disks

Smooth muscle





Weak, slow involuntary contraction

TABLE 9.3 Comparison of Skeletal, Cardiac, and Smooth Muscle

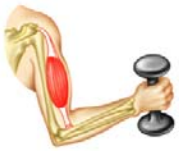
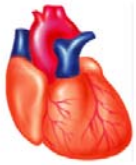
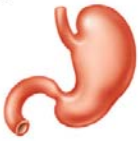
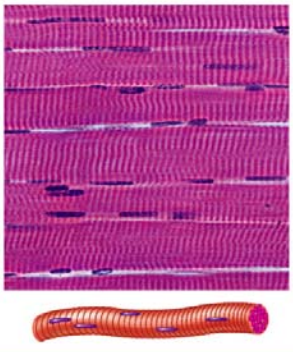
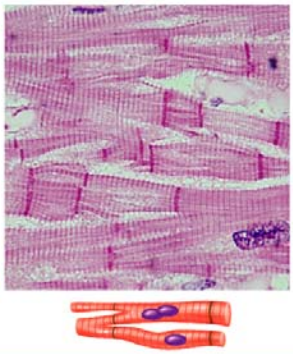
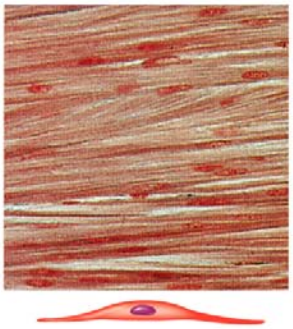
CHARACTERISTIC	SKELETAL	CARDIAC	SMOOTH
Body location	Attached to bones or (some facial muscles) to skin 	Walls of the heart 	Single-unit muscle in walls of hollow visceral organs (other than the heart); multiunit muscle in intrinsic eye muscles, airways, large arteries 
Cell shape and appearance	Single, very long, cylindrical, multinucleate cells with obvious striations 	Branching chains of cells; uni- or binucleate; striations 	Single, fusiform, uninucleate; no striations 

TABLE 9.3 Comparison of Skeletal, Cardiac, and Smooth Muscle

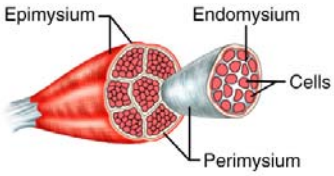
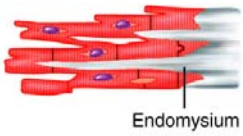
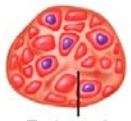
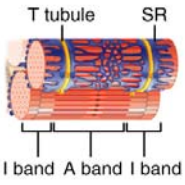
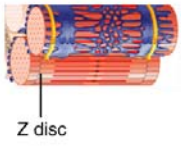
CHARACTERISTIC	SKELETAL	CARDIAC	SMOOTH
Connective tissue components	Epimysium, perimysium, and endomysium 	Endomysium attached to fibrous skeleton of heart 	Endomysium 
Presence of myofibrils composed of sarcomeres	Yes	Yes, but myofibrils are of irregular thickness	No, but actin and myosin filaments are present throughout; dense bodies anchor actin filaments
Presence of T tubules and site of invagination	Yes; two in each sarcomere at A-I junctions 	Yes; one in each sarcomere at Z disc; larger diameter than those of skeletal muscle 	No; only caveolae
Elaborate sarcoplasmic reticulum	Yes	Less than skeletal muscle (1–8% of cell volume); scant terminal cisternae	Equivalent to cardiac muscle (1–8% of cell volume); some SR contacts the sarcolemma

TABLE 9.3 Comparison of Skeletal, Cardiac, and Smooth Muscle

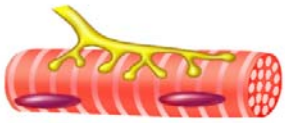
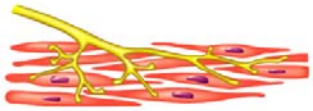
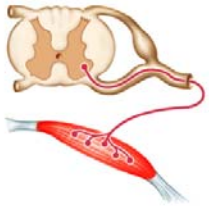
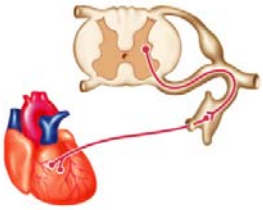
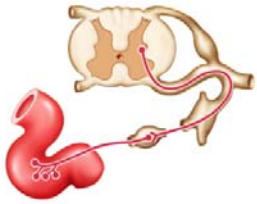
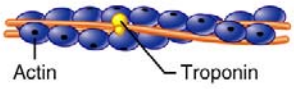
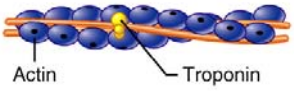
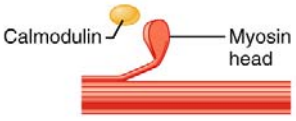
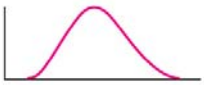
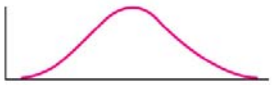
CHARACTERISTIC	SKELETAL	CARDIAC	SMOOTH
Presence of gap junctions	No	Yes; at intercalated discs	Yes; in single-unit muscle
Cells exhibit individual neuromuscular junctions	Yes	No	Not in single-unit muscle; yes in multiunit muscle
			
Regulation of contraction	Voluntary via axon terminals of the somatic nervous system	Involuntary; intrinsic system regulation; also autonomic nervous system controls; hormones; stretch	Involuntary; autonomic nerves, hormones, local chemicals; stretch
			
Source of Ca^{2+} for calcium pulse	Sarcoplasmic reticulum (SR)	SR and from extracellular fluid	SR and from extracellular fluid

TABLE 9.3 Comparison of Skeletal, Cardiac, and Smooth Muscle

CHARACTERISTIC	SKELETAL	CARDIAC	SMOOTH
Site of calcium regulation	Troponin on actin-containing thin filaments	Troponin on actin-containing thin filaments	Calmodulin in the sarcoplasm
			
Presence of pacemaker(s)	No	Yes	Yes (in single-unit muscle only)
Effect of nervous system stimulation	Excitation	Excitation or inhibition	Excitation or inhibition
Speed of contraction	Slow to fast	Slow	Very slow
			
Rhythmic contraction	No	Yes	Yes in single-unit muscle
Response to stretch	Contractile strength increases with degree of stretch (to a point)	Contractile strength increases with degree of stretch	Stress-relaxation response
Respiration	Aerobic and anaerobic	Aerobic	Mainly aerobic

to resume:

Connective Tissue of Muscles
• Endomysium
– Areolar connective
– Around each muscle fiber
• Perimysium
– Sheath around fascicle
• Fascicle = bundle of muscle fibers

Connective Tissue of Muscles
• Epimysium
– Sheath around group of fascicles
• Fascia
– Covering outside epimysium
• The function of these tissues is protection

Muscle Attachments
• Tendon
– Connective tissue layers come together at end of muscle
– Attaches to bone

Muscle Attachments
• Origin
– Attachment to an immovable bone
• Insertion
– Attachment to a moveable bone

Nerves
• Each muscle has many nerves
• Each fiber has a nerve connection
• Transmissions cause muscles to contract

Function of Blood Vessels
• Supply Oxygen
• Supply ATP or other nutrients
• Remove wastes
• Muscles usually have high metabolism

Microscopic Muscle Anatomy
• Multiple nuclei
• Sarcolemma
– Cell membrane
– Contains myoglobin for O2 storage
• Sarcoplasmic Reticulum
– Type of smooth endoplasmic reticulum
– Releases ionic calcium
– Surrounds myofibrils

Microscopic Muscle Anatomy
• Myofibrils
– Organelles
– Contractile element
– Units = sarcomeres
– A band
• Dark, thick filament
• Myosin
– I band
• Light, thin filament
• Actin
– Z-line

• Midpoint of I band
• Defines sarcomere

Microscopic Muscle Anatomy
• T-tubule
– Transverse tubule
– Runs between sarcoplasmic reticulum
– Channels extracellular fluid
– Acts as telegraph to myofibril
• Mitochondria are very abundant

Muscle Contraction
• Shortening of sarcomeres
• Sliding filament theory
– Actin slides past myosin
– Cross bridges cause movement
• Mysoin head attracts to progressive sites on actin
• Works like a ratchet
– Contraction occurs as long as Ca++ and ATP are present

Muscle Fiber Types
• Most skeletal muscles are a mixture of muscle fiber types
– Red
• Slow twitch
• Abundant myogolbin
– White
• Fast twitch
• Little myoglobin
– Intermediate

Cardiac Tissue
• T-Tubules are short and broad
• Single, central nuclei
• Cardiac cells attached to cardiac cells at intercalated disc

Cardiac Tissue
• Totally anaerobic
– Abundant myoglobin
– Large numbers of mitochondria
• Contract by stimulation from pacemaker cells

Smooth Muscle
• Cause constriction of hollow organs
– Peristalsis = squeezing rhythmically
• Controlled by autonomic nervous system

Smooth Muscle
• No sarcomeres
– Actin & myosin fibers are present
• No T-tubules
• Spindle shaped cells with 1 nucleus
• Sarcoplasmic reticulum reduced
• Ca++ from extracellular fluid

Smooth Muscle
• Very slow contraction
• Mainly anaerobic
• Has muscle tone

• Stretching muscle causes slower contractions
– No expulsive contractions

Muscle Cell Replacement
• All types originate from myoblasts
• Skeletal muscle
– Do not divide
– Myoblast-like cells produce some new cells
– Satellite cells help repair injured muscle
– Repair is slow

Muscle Cell Replacement
• Smooth muscle
– Cells can divide
– Hyperplasia
• Divide rapidly in uterus during pregnancy and puberty
– Smooth muscle cells secrete their own connective tissue
• Cardiac muscle
– Cells are not replaced or repaired

Muscle Tissue Disorders
• Muscular Dystrophy
– Muscle fibers degenerate
– Fat and connective tissue replaces muscle

Muscle Tissue Disorders
• Fibromyalgia
– Chronic pain syndrome
– Severe musculoskeletal pain
– Widespread in body
– Cause is unknown

Related Clinical Terms
• Spasm
– Sudden involuntary muscle twitch
– Often due to chemical imbalance
• Strain
– Tearing of a portion of a muscle

Organization of Skeletal Muscles
• Parallel
• Convergent
• Pennate
• Circular

• Parallel
– Fascicles run parallel to long axis of muscle
– Strap-like or spindle-shaped muscles
– Great shortening ability (large movement)
– Little power

• Convergent
– Muscles converge toward tendon
– Broad origin
– Powerful muscles

• Pennate
– Fascicles are obliquely attached

– Several forms
• Unipennate
• Bipennate
• multipennate

• Circular
– Arranged in rings
– Sphincters or squeezers

Tension Relationship of Muscles
• Most skeletal muscles work like lever systems
• Lever = rigid structure
– Bone in human body
• Fulcrum = fixed point of movement
– Joint in human body
• Muscle apply force to bones

Tension Relationship of Muscles
• Mechanical advantage
– Less effort is needed to lift weight
– Not very common in the human body

Tension Relationship of Muscles
• Mechanical disadvantage
– More force than the weight to be lifted
– This action increases speed
– Common in human muscles

Muscle Terminology
• Insertion
– Attachment to moveable bone
• Origin
– Attachment to fixed, immovable bone
• During contraction, insertion moves towards origin
Actions of Muscles
• Muscles can be classified by their movement
– Agonist
– Antagonist
– Synergist
– Fixator

• Agonist
– Prime mover
– Provides major force for a specific movement
– Ex: biceps brachii

• Antagonist
– Reverse action of agonist
– Often stretched in the relaxed state
– Ex: triceps brachii

• Synergist
– Aids in action of an agonist
– Can prevent other actions like rotation
– Many small muscles that span joints are examples

• Fixator
– Immobalizes a bone
– Ex.: subscapularis

Naming of Skeletal Muscles
• Location of a muscle
• Ex.: temporalis
– Overlies temporal bone

• Relative size of muscle
– Ex: gluteus maximus
gluteus medius
gluteus minimus

• Shape of muscle
– Ex.: deltoid

• Direction of muscle fibers
– Ex: external oblique

• Number of origins
• Ex.: biceps brachii

• Location or origin and/or insertion
– Origin listed 1st if both are used
– Ex.: sternocleidomastoid
• Origin = sternum
• Origin = clavicle
• Insertion = mastoid

• Action of muscle
• Ex.: extensor carpi radialis longus
– Extension of wrist (carpals)
– Lies close to radius
– Longer than other wrist muscles

Muscles of the Human Body
• Over 600 muscles present

Related Clinical Terms
• Charley Horse
– Tearing of a muscle followed by bleeding into the muscle
– Severe pain

• Shin Splint
– Swelling of the anterior tibialis muscle
– Muscle swells and cuts off its own circulation
– Pressure against nerve causes pain