بسم الله الرحمن الرحيم
BIOMECHANICS OF SKELETAL MUSCLES

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Muscles

- **cardiac muscle**: composes the heart
- **Smooth muscle**: lines hollow internal organs
- **skeletal (striated or voluntary) muscle**: attached to skeleton via tendon & perform movement
Characteristics of Skeletal Muscle

- Skeletal muscle 40-45% of body weight
  - more than 430 muscles
  - 80 pairs produce vigorous movement

- Dynamic & static work
  - **Dynamic**: locomotion & positioning of segments
  - **Static**: maintains body posture

- **Irritability** – ability to receive and respond to a stimulus

- **Contractility** – ability to shorten when an adequate stimulus is received
Characteristics of skeletal Muscles

- Muscle cells are elongated
- Two attachments (origin & insertion)
- Contraction of muscles is due to the movement of microfilaments
- All muscles share some terminology
  - Prefix *myo* refers to muscle
  - Prefix *mys* refers to muscle
  - Prefix *sarco* refers to flesh
• Epimysium - ensheaths the entire muscle.
• Perimysium – around a fascicle (bundle) of fibers
• Endomysium – around single muscle fiber
masseter
pectorals
biceps
abdominals
quadriceps
deltoids
trapezius
triceps
biceps
calf muscles
Skeletal Muscle Attachments

- Epimysium blends into a connective tissue attachment
  - Tendon – cord-like structure
  - Aponeuroses – sheet-like structure
- Sites of muscle attachment
  - Bones
  - Connective tissue coverings
Composition & structure of skeletal muscles

• Two parts
  • Muscle spindle (intrafusal fibers & extrafusal fibers)
  • Golgi tendon organs
• Characteristics on bases of color of muscles fibers:
  • Red fibers (slow twitch)
  • White fibers (fast twitch)
Microscopic Anatomy of Skeletal Muscle

- Cells are multinucleate
- Nuclei are just beneath the sarcolemma
Sarcoplasmic reticulum

- Network of tubules & sacs
- Parallel to myofibrils
- Enlarged & fused at junction between A & I bands: transverse sacs (terminal cisternae)
- Triad \{terminal cisternae of transverse tubule\}
- T system: duct for fluids help in propagation of electrical stimulus for contraction (action potential)
- Sarcoplasmic reticulum store calcium
Bands of myofibrils

**A bands:** thick filaments in central of sarcomeres

**I bands:** thin filaments not overlap with thick filaments

**Z line:** short elements that links thin filaments

**H zone:** gap between ends of thin filaments in center of A band

**M line:** transverse & longitudinally oriented linking proteins for adjacent thick filaments
Organization of the sarcomere: contractile unit of muscle fibers

(c) Sarcomere (segment of a myofibril)
ARRANGEMENT OF MYOFILAMENTS

The arrangement of thick and thin myofilaments forms light and dark alternating bands (striations) along the myofibril.

Features of these bands are identified by letters.
Molecular composition of myofibril

- Myosin composed of individual molecules each has a globular head and tail
- Cross-bridge: actin & myosin overlap (A band)
- Actin has double helix; two strands of beads spiraling around each other
- Troponin & tropomysin regulate making and breaking contact between actin & myosin
Molecular basis of muscle contraction

- Myosin filaments have heads (extensions, or cross bridges)
- Myosin and actin overlap somewhat during contraction
- At rest, there is a bare zone that lacks actin filaments
The Sliding Filament Theory

- Activation by nerve causes myosin heads (crossbridges) to attach to binding sites on the thin filament.
- Myosin heads then bind to the next site of the thin filament.
**Molecular basis of muscle contraction**

- **Sliding filament theory:**
  - Relative movement of actin & myosin filaments yields active sarcomere shortening
  - Myosin heads or cross-bridges generate contraction force
  - Sliding of actin filaments toward center of sarcomere: decrease in I band and decrease in H zone as Z lines move closer
Cross Bridge Cycle - the Components

Cross-bridge binding sites

Actin
**Molecular basis of muscle contraction**

- **Motor unit:**
  - Muscle supplied by nerve contain both sensory & motor fibers lie in anterior horn of spinal cord or in nucleus of cranial nerves influenced by many sources.
  - Motor neuron and muscle to which it supplied called motor unit.
  - Motor neuron divide 5-150 branches each of which terminates in a motor end plate beneath sarcolemma.
Effect of Acetylcholine

Diagram showing the effect of acetylcholine on a cell membrane.

- Synaptic cleft
- Binding site
- Na⁺ (Sodium ion)
- Cell membrane
- Acetylcholine
- K⁺ (Potassium ion)
- Na⁺ (Sodium ion)
- Ion channel
- Cytoplasm in postsynaptic cell

Diagram on the left shows the resting state with K⁺ ions out and Na⁺ ions in.
Diagram on the right shows the activated state with K⁺ ions out and Na⁺ ions in, due to acetylcholine binding.

(fppt.com)
1. At -40 mV, Na+ channels open & Na+ ions flood inside.
2. At +50 mV, Na+ channels close & K+ channels open so that K+ ions flood outside.
3. Voltage decreases to -90 mV & K+ channels close.
4. Na-K Pump restores potential to -70mV in 1-2 mSec.
1. Acetylcholine (ACh) is released from the axon terminal of a motor neuron and binds to receptors in the motor end plate. This binding elicits an end-plate potential, which triggers an action potential in the muscle cell.

2. Action potential propagates along the sarcolemma and down T tubules.

3. The action potential triggers Ca^{2+} release from SR.

4. Ca^{2+} binds to troponin, exposing myosin-binding sites.

5. Crossbridge cycle begins (muscle fiber contracts).

6. Ca^{2+} is actively transported back into lumen of SR following the action potential.

7. Tropomyosin blocks myosin-binding sites (muscle fiber relaxes).
A muscle fiber contracts when all sarcomere shorten simultaneously in an all-or-nothing fashion, which is called a Twitch.

The mechanism by which the electric signal triggers the chemical events of contraction is known as Excitation-contraction coupling.
• An action potential is initiated and propagated in a motor axon.
• This action potential causes the release of acetylcholine from the axon terminals at the neuromuscular junction.
• Acetylcholine is bound to receptor sites on the motor end plate membrane.
• Acetylcholine increases the permeability of the motor end plate to sodium and potassium ions, producing an end-plate potential.
• The end-plate potential depolarizes the muscle membrane sarcolemma, generating a muscle action potential that is propagated over the membrane surface.
1. Myosin cross bridge attaches to the actin myofilament

2. Working stroke—the myosin head pivots and bends as it pulls on the actin filament

3. New ATP attaches to myosin head

4. As ATP is split into ADP and P_i, cocking of the myosin head occurs

5. As new ATP attaches to the myosin head, the cross bridge detaches

ATP hydrolysis
Actin molecules in thin myofilament

**BINDING** Myosin cross bridge binds to actin molecule.

Myosin cross bridge

**Z line**

**POWER STROKE** Cross bridge bends, pulling thin myofilament inward.

**DETACHMENT** Cross bridge detaches at end of power stroke and returns to original conformation.

**BINDING** Cross bridge binds to more distal actin molecule; cycle repeated.

(a)
### Muscle Differentiation (types of fibers)

<table>
<thead>
<tr>
<th></th>
<th>I (slow-twitch oxidative)</th>
<th>IIA (fast-twitch oxidative glycolytic)</th>
<th>IIB fast-twitch glycolytic</th>
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</thead>
<tbody>
<tr>
<td>Contraction speed</td>
<td>Slow</td>
<td>fast</td>
<td>fast</td>
</tr>
<tr>
<td>Myosin-ATPase activity</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Primary source of ATP production</td>
<td>Oxidative phosphorylation</td>
<td>Oxidative phosphorylation</td>
<td>Anaerobic glycolysis</td>
</tr>
<tr>
<td>No. of mitochondria</td>
<td>Many</td>
<td>Many</td>
<td>Few</td>
</tr>
<tr>
<td>Capillaries</td>
<td>Many</td>
<td>Many</td>
<td>Few</td>
</tr>
<tr>
<td>Myoglobin contents</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Muscle Color</td>
<td>Red</td>
<td>Red</td>
<td>White</td>
</tr>
<tr>
<td>Glycogen content</td>
<td>Low</td>
<td>Intermediate</td>
<td>High</td>
</tr>
<tr>
<td>Glycolytic enzyme activit</td>
<td>low</td>
<td>intermediate</td>
<td>High high</td>
</tr>
<tr>
<td>Fiber diameter</td>
<td>small</td>
<td>Intermediate</td>
<td>Large</td>
</tr>
<tr>
<td>Rate of fatigue</td>
<td>slow</td>
<td>Intermediate</td>
<td>Fast</td>
</tr>
</tbody>
</table>
The Musculotendinous Unit

- Tendon- spring-like elastic component in series with contractile component (proteins)
- Parallel elastic component (epimysium, perimysium, endomysium, sarcolemma)

PEC: parallel elastic component
CC: contractile component
SEC: series elastic component
The tendons and the connective tissues in and around the muscle belly are **Viscoelastic** structures determine mechanical properties of muscle.

- When stretched during active contraction or passive extension of a muscle, tension is produced and **energy is stored**; when they **recoil** with muscle relaxation, this energy is released.

- The series elastic fibers are more important in the production of tension than are the parallel elastic fibers.
Dispensability and elasticity of the elastic components

- Keep the muscle in **readiness** for contraction smooth production and transmission of tension during contraction.
- Assure that the contractile elements **return to their original** (resting) positions when contraction is terminated
- Prevent the passive **overstretch** thereby lessening the danger of muscle injury.
• Absorb energy proportional to the rate of force application and to dissipate energy in a time dependent manner.

• when a person attempts to stretch and touch the toes???
• Use of Electromyography

• **Time relationship** between the onset of electrical activity in the muscle and actual contraction of the muscle or muscle fiber.
Summation and Tetanic Contraction

• Neural stimulation – **impulse**
• Mechanical response of a motor unit – **twitch**—single stimulus

• **Tonic type:** motor units that require more than a single stimulus before the initial development of tension.

• Following stimulation there is an interval of a few milliseconds known as the **latency period** before the tension in the muscle fibers begins to rise.
• The time from the start of tension development to peak tension is the **contraction time**

• Time from peak tension until the tension drops to zero is the **relaxation time**

• **Muscle fiber makeup**

  • Some muscle fibers contract with a speed of only 10 m sec, others may take 100 m sec or longer.

  • An action potential lasts only approximately 1 to 2 m sec
When mechanical responses to successive stimuli are added to an initial response, the result is known as **summation**.

If a second stimulus occurs during the latency period of the first muscle twitch, it produces no additional response and the muscle is said to be **completely refractory**.
Summation and tetanic contraction
• The greater **the frequency of stimulation** of the muscle fibers, the greater the tension produced in the muscle as a whole.

  • A **maximal frequency** will be reached beyond which the tension of the muscle no longer increases.

  • when this maximal tension is sustained as a result of summation, the muscle is said to contract **tetanically**.

  • Rapidity of stimulation outstrips the contraction relaxation
Generation of muscle tetanus

Note: muscle is controlled by frequency modulation from neural input very important in functional electrical stimulation
Wave summation & tetanization

Critical frequency

- Force of contraction vs. time (msec)
- Curves for different frequencies (100/sec, 60/sec, 40/sec, 25/sec, 15/sec, 10/sec)

62
• All-or-nothing event
• 2 ways to increase tension:
  • Stimulation rate
  • Recruitment of more motor unit
• Size principle
  • Smallest Motor Units recruited first
  • Largest Motor Units last
Types Of Muscle Contraction

• Isometric muscle work ..... (torque not overcome resistance)

• Isotonic muscle work .........
  • Concentric Muscle work
  • Eccentric Muscle work

Isoinertial muscle work (against same resistance ... isometric & isotonic)
Isokinetic muscle work (same speed)
The total force that a muscle can produce is influenced by its mechanical properties

- Force – length characteristics
- Force – velocity characteristics
- Muscle Modeling
- Neuromuscular system dynamics
Muscle contract isometrically & tetanically.

Change in tension with length of muscle fibers

- Resting 2.0-2.25 um max. no. of cross bridges; max. tension
- 2.25-3.6 um no. of cross bridge ↓
- < 1.65 um overlap of actin no. of cross bridge ↓
Length-tension Relationship

![Diagram showing the length-tension relationship in muscles.](image)

- **Relative Tension**
  - 0.5
  - 1.0

- **Sarcomere Length (µm)**
  - 1.27
  - 1.65
  - 2.0
  - 2.25
  - 3.6

- **Length Intervals**
  - 2.25–3.6 µm
  - 2.0–2.25 µm
  - <1.65 µm
• Maximal tension is produced when the muscle fiber is approximately at its "slack," or resting, length.

• If the fiber is held at shorter lengths: the tension falls off slowly at first and then rapidly.

• If the fiber is lengthened beyond the resting length: tension progressively decreases.
• The tension produced by both active components and passive components must be taken into account

• **Active tension:** represents the tension developed by the contractile elements of the muscle

• **Passive tension:** muscle surpasses its resting length and the non-contractile muscle belly is stretched.
• **Passive tension** is mainly developed in the parallel and series elastic components
  
  • When the **belly contracts**, the combined active and passive tensions produce the total tension exerted
  
  • When a muscle is **progressively stretched** beyond its resting length, the passive tension rises and the active tension decreases
  
  • **One joint muscles** normally are not stretched enough for the passive tension to play an important role, but the case is different for **two-joint muscles**
- Shortening is less with increasing load = concentric contraction
- Lengthening is more rapid with increasing load in eccentric contractions.
Force-time Relationship

• The **longer the contraction time**, the greater is the force developed, up to the point of maximum tension

• Slower contraction leads to greater force production because **time** is allowed for the tension produced

• Active contraction process is of **sufficient duration**
Effect of skeletal muscle architecture

• The arrangement of the contractile components affects the contractile properties of the muscle

• The more sarcomeres lie in series, the longer is myofibril

• The more sarcomeres lie parallel the larger the cross-sectional area of the myofibril will be
• The **force** the muscle can produce is proportional to the **cross-section** of the myofibril

• The velocity and the excursion (**working range**) that the muscle can produce are proportional to the **length of myofibril**
• Muscles with shorter fibers and a larger cross-sectional area are designed to produce force. E.g. quadriceps muscle.

• Muscles with long fibers are designed for excursion and velocity. The Sartorius muscle has longer fibers and a smaller cross-sectional area and is better suited for high excursion.
Effect Of Pre-stretching

• VARIED RESULTS
• Some evidence shows that muscle perform more work when it shortens in a concentrically contracted state immediately after being light stretched ....than when it shortened from state of isometric contraction.
• Strong evidences that stretching (Static) may reduce the performance or force production in the muscles.??????
Effect Of Temperature

• A rise in muscle temperature causes an increase in conduction velocity across the sarcolemma \( \rightarrow \) Increasing the frequency of stimulation \( \rightarrow \) production of muscle force

• Rising of the muscle temperature from 6 to 34°C results in an almost linear increase of the tension ratio
• ↑ed temperature= ↑ed enzymatic activity of muscle metabolism, ↑ed efficiency of muscle contraction

• **Increased elasticity** of the collagen in the series and parallel elastic components causes Increased **extensibility** of the muscle-tendon unit.

• increases the force production of the muscle
Muscle temperature increase

- by metabolism, by the release of the energy of contraction, and by friction as the contractile components slide over each other
• At **low temperature 10°C**, it has been shown that the maximum shortening velocity and the isometric tension are inhibited significantly → due to **Decreased pH (acidosis)** in the muscle.

• At physiological temperature PH....
Effect Of Fatigue

• The ability of a muscle to contract and relax on availability of adenosine triphosphate ATP
  • ATP breakdown should balance the ATP Synthesis (depend on muscle contraction frequency)
  • Imbalance results in muscle fatigue
  • Drop in tension after prolonged stimulation is muscle fatigue
  • Chances of Fatigue are even greater in tetanic phase
  • Rest interval recovers ATP........
Sources of ATP in muscle

- Creatine phosphate
- Substrate Phosphorylation during anaerobic glycolysis.
- Oxidative Phosphorylation in the mitochondria.
• When contraction begins myosin ATPase rapidly breaks down ATP.

• The increase in adenosine diphosphate (ADP) and phosphate (Pi) concentrations resulting from this breakdown ultimately leads to increased rates of oxidative Phosphorylation and glycolysis.
• After a **short lapse** metabolic pathways begin to deliver ATP at a high rate.

• During this interval the energy for ATP formation is provided by **Creatine phosphate**, which offers the most rapid means of forming ATP in the muscle cell.
• **At moderate rates of muscle activity**, most of the required ATP = process of oxidative Phosphorylation.

• **During intense exercise**= ATP is broken down rapidly= limited cell's ability to replace ATP by oxidative Phosphorylation= **inadequate delivery of oxygen** to the muscle by the circulatory system.
• The **glycolytic pathway** operates at a much faster rate and produces much smaller amounts of ATP from the breakdown of glucose.

• It can also proceed in the **absence of oxygen** to form **lactic acid** as its end product.

• During **intense exercise**, anaerobic glycolysis becomes an additional source for rapidly supplying the muscle with ATP.
• The **glycolytic pathway** has the disadvantage of requiring large amounts of glucose for the production of small amounts of ATP.

• Finally **myosin ATPs** may breakdown faster than glycolysis can replace it & fatigue occur rapidly.

• After a period of intense exercise, much of the muscle glycogen may have been converted to **lactic acid**.
• For muscle to be returned to its original state, creatine phosphate re-synthesized & glycogen stores replaced.

• Both process require energy, muscle continue to use oxygen at a rapid rate though it stopped contracting. This oxygen from deep breathing after strenuous exercise
• 20-25% energy used
• when muscle is operating in its most efficient state, a maximum of only approximately 45% of the energy is used for contraction
• Dissipation energy
Consequences of fatigue

• Muscle fatigue results in lack of coordination of movement
  • Skill of the person in performing a given action is affected by fatigue
  • Reduction in accuracy, control and speed of contraction which may predispose an individual to injury
Muscle Fiber Differentiation

- Endurance athletes have type I fibers in abundance e.g. Marathon Runners
- Sprinters have Type II fibers in abundance
• In the average population, approximately 50 to 55% of muscle fibers are **type I**

• Approx. 30 to 35 percent are **type II A**, and approx. are 15 percent **type II B**, but these percentages vary greatly among individuals.

• Genetically determined

• Type of training
Muscle Injuries

- Muscle injuries comprise contusion, laceration, ruptures, ischemia, compartment syndromes, and denervation.
- These injuries weaken the muscles, decreased ROM, cause muscle wasting, and significant disability.
Muscle Remodeling
Effects of disuse and immobilization

• Detrimental effects
• Muscle atrophies on a microstructural and macrostructural level, such as decreased numbers and size of fiber
• Biochemical changes occur and affect aerobic and anaerobic energy production.
• Immobilization in a lengthened position has a less deleterious effect
• Program of **immediate or early motion** may prevent muscle atrophy after injury or surgery
  
• Cannot be reversed through the use of only **isometric exercises** in case of applied plasters
  
• Partly **mobile casts** in used
• **Human muscle biopsy**: the type I fibers that atrophy with immobilization; their cross-sectional area decreases and their potential for oxidative enzyme activity is reduced

• Early motion

• When muscle is placed under tension: afferent (sensory) impulses from the intrafusal muscle spindles will increase, leading to increased stimulation of the type I fiber (extrafusal fibers)
• Although **intermittent isometric exercise** may be sufficient to maintain the metabolic capacity of the type II fiber

• Type I fiber (the postural fiber) requires a more **continuous impulse**.

• **Electric stimulation** may prevent the decrease in type I fiber size...

• Fibers affected may be in accordance with the sports involved
Effects of physical training

• Physical training increases the cross-sectional area of all muscle fibers: increase in muscle bulk and strength, Relative percentage of fiber types.
• **Stretching** increases muscle flexibility, maintains and augments the range of joint motion, and increases the elasticity and length of the Musculotendinous unit.

• Relative Role of muscle spindles: extrafusal fibers and intrafusal fibers

• Role of Golgi tendon Organs: GTO’S