Depolarization

- Initially, this is a local electrical event called end plate potential
- Later, it ignites an action potential that spreads in all directions across the sarcolemma

Action Potential: Electrical Conditions of a Polarized Sarcolemma

- The outside (extracellular) face is positive, while the inside face is negative
- This difference in charge is the resting membrane potential

Action Potential: Electrical Conditions of a Polarized Sarcolemma

- The predominant extracellular ion is Na^+
- The predominant intracellular ion is K^+
- The sarcolemma is relatively impermeable to both ions

Action Potential: Depolarization and Generation of the Action Potential

- An axonal terminal of a motor neuron releases ACh and causes a patch of the sarcolemma to become permeable to Na^+ (sodium channels open)

Action Potential: Depolarization and Generation of the Action Potential

- Na^+ enters the cell, and the resting potential is decreased (depolarization occurs)
- If the stimulus is strong enough, an action potential is initiated

Action Potential: Propagation of the Action Potential

- Polarity reversal of the initial patch of sarcolemma changes the permeability of the adjacent patch
- Voltage-regulated Na^+ channels now open in the adjacent patch causing it to depolarize

Action Potential: Propagation of the Action Potential

- Thus, the action potential travels rapidly along the sarcolemma
- Once initiated, the action potential is unstoppable, and ultimately results in the contraction of a muscle

Action Potential: Repolarization

- Immediately after the depolarization wave passes, the sarcolemma permeability changes
- Na^+ channels close and K^+ channels open

- K^+ diffuses from the cell, restoring the electrical polarity of the sarcolemma

Action Potential: Repolarization

- Repolarization occurs in the same direction as depolarization, and must occur before the muscle can be stimulated again (refractory period)
- The ionic concentration of the resting state is restored by the Na^+-K^+ pump

Excitation-Contraction Coupling

- Once generated, the action potential:
  - Is propagated along the sarcolemma
  - Travels down the T tubules
  - Triggers Ca^{2+} release from terminal cisternae
- Ca^{2+} binds to troponin and causes:
  - The blocking action of tropomyosin to cease
  - Actin active binding sites to be exposed

Excitation-Contraction Coupling

- Myosin cross bridges alternately attach and detach
- Thin filaments move toward the center of the sarcomere
- Hydrolysis of ATP powers this cycling process
- Ca^{2+} is removed into the SR, tropomyosin blockage is restored, and the muscle fiber relaxes

Excitation-Contraction Coupling

Role of Ionic Calcium (Ca^{2+}) in the Contraction Mechanism

- At low intracellular Ca^{2+} concentration:
  - Tropomyosin blocks the binding sites on actin
  - Myosin cross bridges cannot attach to binding sites on actin
  - The relaxed state of the muscle is enforced

Role of Ionic Calcium (Ca^{2+}) in the Contraction Mechanism

- At higher intracellular Ca^{2+} concentrations:
  - Additional calcium binds to troponin (inactive troponin binds two Ca^{2+})
  - Calcium-activated troponin binds an additional two Ca^{2+} at a separate regulatory site

Role of Ionic Calcium (Ca^{2+}) in the Contraction Mechanism

- Calcium-activated troponin undergoes a conformational change
- This change moves tropomyosin away from actin's binding sites

Role of Ionic Calcium (Ca^{2+}) in the Contraction Mechanism

- Myosin head can now bind and cycle
- This permits contraction (sliding of the thin filaments by the myosin cross bridges) to begin

Sequential Events of Contraction

- Cross bridge formation – myosin cross bridge attaches to actin filament
- Working (power) stroke – myosin head pivots and pulls actin filament toward M line
- Cross bridge detachment – ATP attaches to myosin head and the cross bridge detaches
- "Cocking" of the myosin head – energy from hydrolysis of ATP cocks the myosin head into the high-energy state

Sequential Events of Contraction

Contraction of Skeletal Muscle Fibers

- Contraction – refers to the activation of myosin's cross bridges (force-generating sites)
- Shortening occurs when the tension generated by the cross bridge exceeds forces opposing shortening
- Contraction ends when cross bridges become inactive, the tension generated declines, and relaxation is induced

Contraction of Skeletal Muscle (Organ Level)

- Contraction of muscle fibers (cells) and muscles (organs) is similar
- The two types of muscle contractions are:
  - Isometric contraction – increasing muscle tension (muscle does not shorten during contraction)
  - Isotonic contraction – decreasing muscle length (muscle shortens during contraction)

Motor Unit: The Nerve-Muscle Functional Unit

- A motor unit is a motor neuron and all the muscle fibers it supplies
- The number of muscle fibers per motor unit can vary from four to several hundred
- Muscles that control fine movements (fingers, eyes) have small motor units

Motor Unit: The Nerve-Muscle Functional Unit

Motor Unit: The Nerve-Muscle Functional Unit

- Large weight-bearing muscles (thighs, hips) have large motor units
- Muscle fibers from a motor unit are spread throughout the muscle; therefore, contraction of a single motor unit causes weak contraction of

the entire muscle

Muscle Twitch

- A muscle twitch is the response of a muscle to a single, brief threshold stimulus
- The three phases of a muscle twitch are:
  - Latent period – first few milli-seconds after stimulation when excitation-contraction coupling is taking place

Muscle Twitch

  - Period of contraction – cross bridges actively form and the muscle shortens
  - Period of relaxation – Ca^{2+} is reabsorbed into the SR, and muscle tension goes to zero

Graded Muscle Responses

- Graded muscle responses are:
  - Variations in the degree of muscle contraction
  - Required for proper control of skeletal movement
- Responses are graded by:
  - Changing the frequency of stimulation
  - Changing the strength of the stimulus

Muscle Response to Varying Stimuli

- A single stimulus results in a single contractile response – a muscle twitch
- Frequently delivered stimuli (muscle does not have time to completely relax) increases contractile force – wave summation

Muscle Response to Varying Stimuli

- More rapidly delivered stimuli result in incomplete tetanus
- If stimuli are given quickly enough, complete tetanus results

Muscle Response: Stimulation Strength

- Threshold stimulus – the stimulus strength at which the first

observable muscle contraction occurs

- Beyond threshold, muscle contracts more vigorously as stimulus strength is increased
- Force of contraction is precisely controlled by multiple motor unit summation
- This phenomenon, called recruitment, brings more and more muscle fibers into play

Stimulus Intensity and Muscle Tension

Treppe: The Staircase Effect

- Staircase – increased contraction in response to multiple stimuli of the same strength
- Contractions increase because:
  - There is increasing availability of Ca^{2+} in the sarcoplasm
  - Muscle enzyme systems become more efficient because heat is increased as muscle contracts

Treppe: The Staircase Effect