# **HUMAN PHYSIOLOGY** (normal)

## **LECTURE 2.** Physiology of the Muscles

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# Muscle Tissue

A primary tissue type, divided into

- **Skeletal** muscle
- **Cardiac** muscle
- **Smooth** muscle

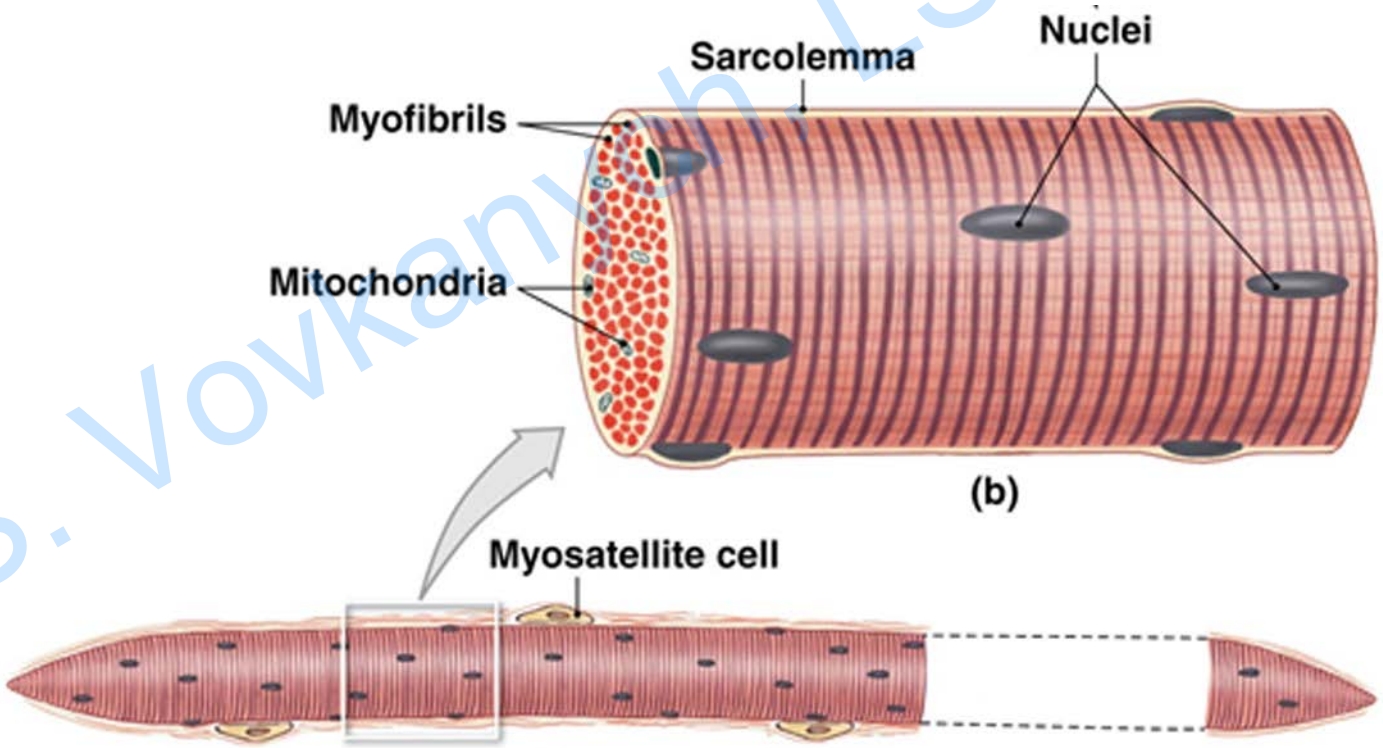
Skeletal Muscle Structures

- Muscle tissue (muscle cells or **fibers**)
- Connective tissues
- Nerves
- Blood vessels

# Skeletal Muscle Fibers

Muscle fiber (cell):

- The **sarcolemma** (the cell membrane of a muscle fiber)
- The **sarcoplasm** (cytoplasm of muscle fiber)



# Skeletal Muscle Fibers

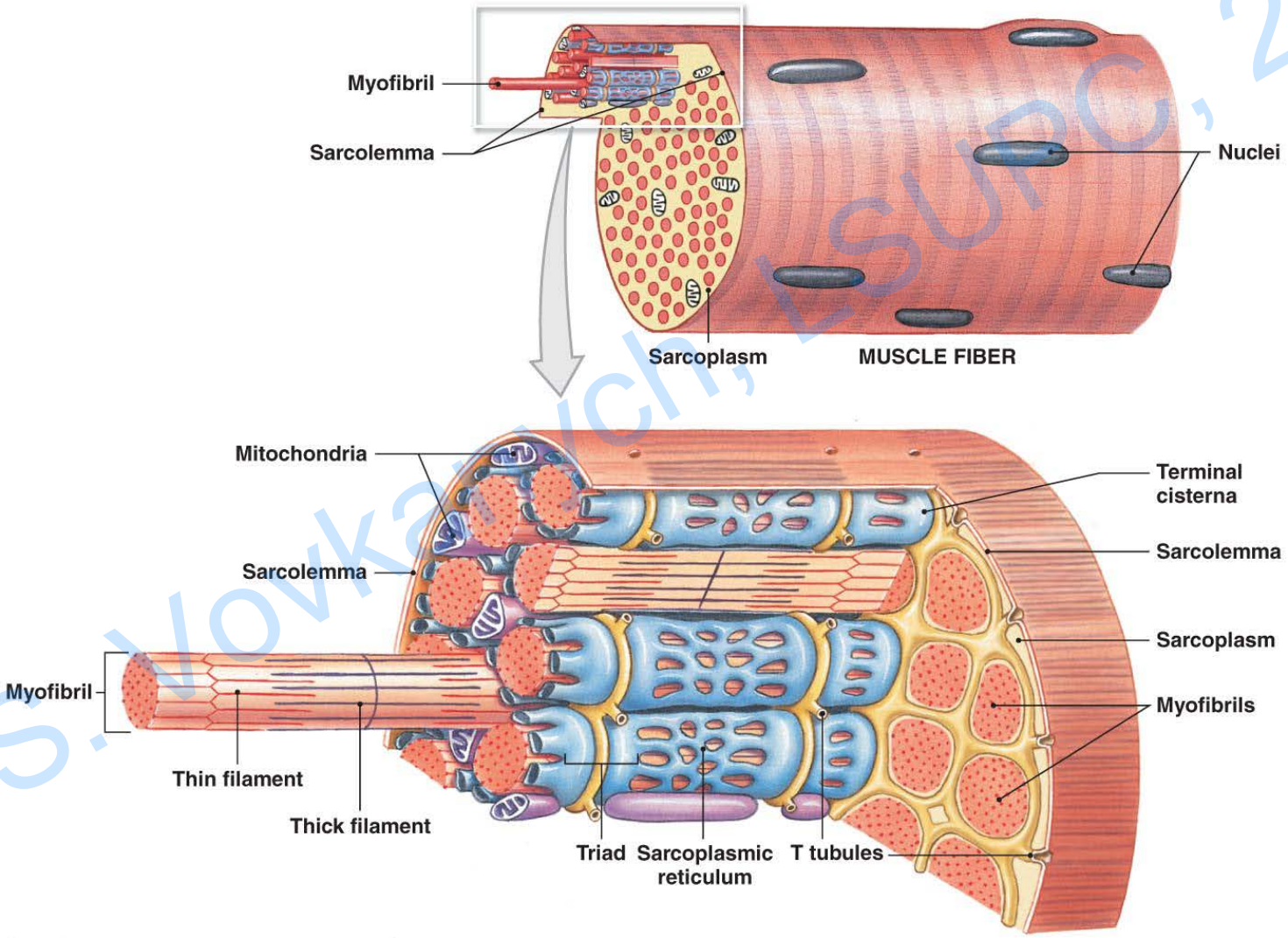
The **sarcolemma**:

- **Transverse tubules (T tubules) -** transmit **action potential** through cell, allow entire muscle fiber to contract simultaneously
- **Neuromuscular (myoneural) junctions** (motor end-plates) – important in the excitation-contraction coupling

The **sarcoplasm**:

- **Organelles** - multiple nuclei, mitochondria, **sarcoplasmic reticulum** , glycogen granules, and others
- **Myofibrils -** lengthwise subdivisions within muscle fiber, made up of bundles of protein **filaments** (**myofilaments**), responsible for muscle contraction

# Skeletal Muscle Fibers



# Skeletal Muscle Fibers

## Sarcoplasmic reticulum (SR)

- A membranous structure surrounding each myofibril
- Forms chambers (**terminal cisternae**) attached to T tubules
- Plays an important role in the **electromechanical coupling**

  Forms the **triad -** formed by one **T tubule** and two **terminal cisternae**
- Cisternae contains $Ca^{2+}$ (*via* ion pumps) and release $Ca^{2+}$ into **sarcomeres** to begin muscle contraction

# Skeletal Muscle Fibers

**Myofibrils** are divided into **Sarcomeres**

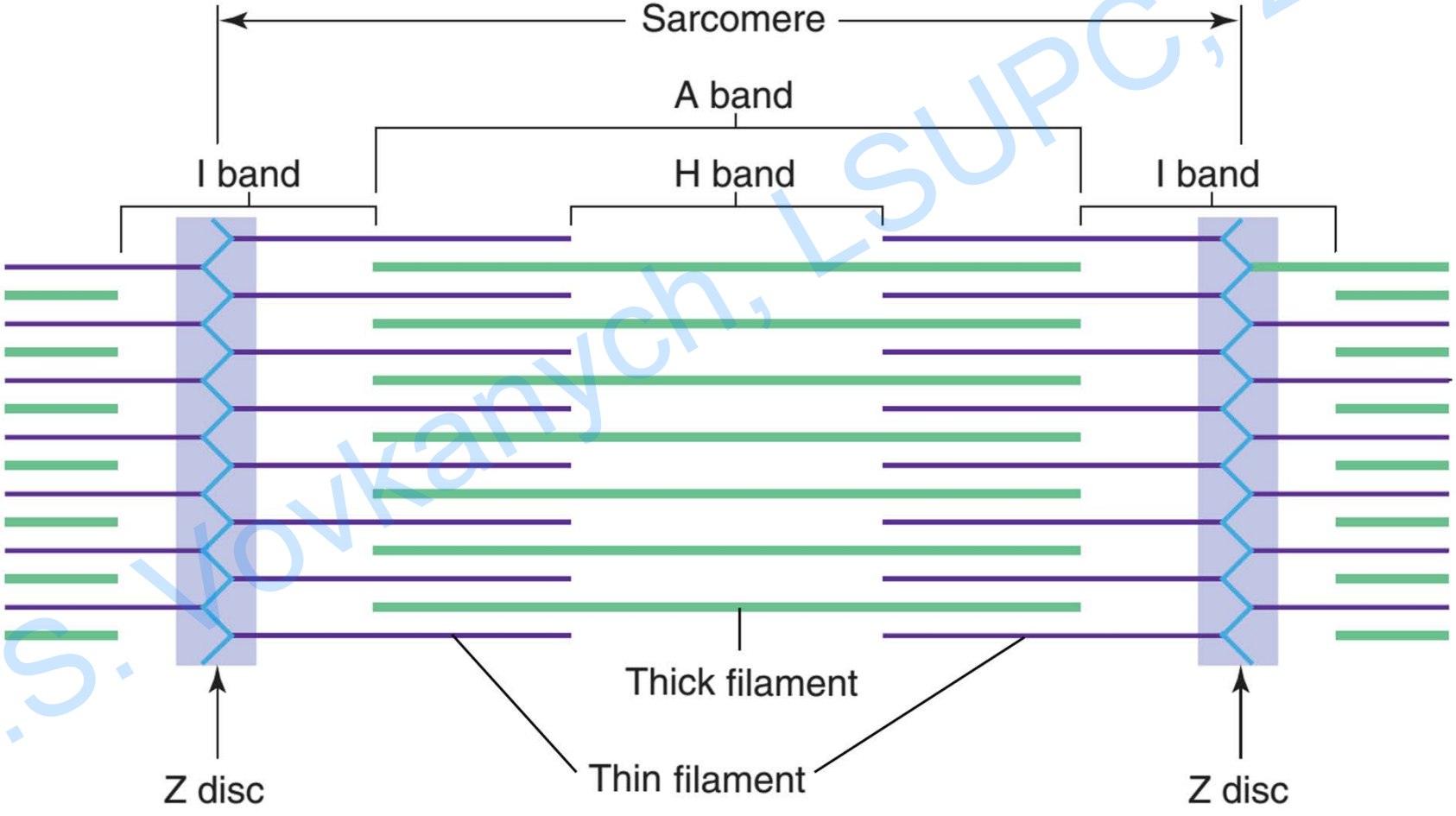
**Sarcomeres** (part of myofibril between two Z lines)

- The contractile units of muscle
- Structural units of **myofibrils**

**Muscle (and myofibtils) striations**

- **A bands -** dark bands (thick and thin filaments overlap)
- **I bands** - light bands (thin filaments)
- **H zone** - contains only thick (myosin) filaments
- **M line** – at the center of the **A band,** at midline of sarcomere
- **Z lines** - the centers of the **I bands,** at two ends of sarcomere

# The Sarcomere Structure



# Thin Filament Structure

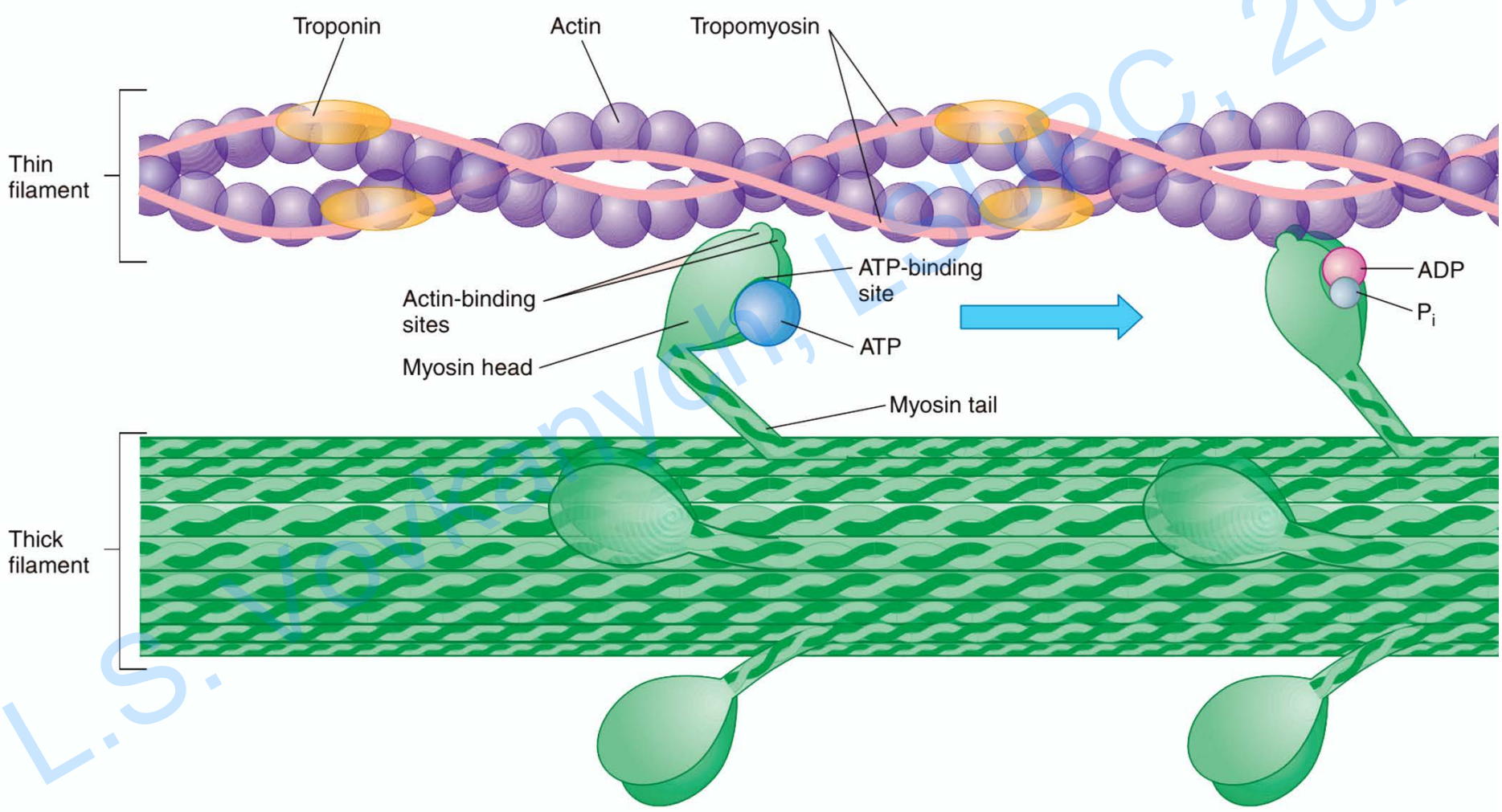
- Four Thin Filament Proteins
  - **F-actin (Filamentous actin)**
    - Is two twisted rows of globular G-actin
    - The active sites on G-actin strands bind to myosin
  - **Nebulin**
    - Holds F-actin strands together
  - **Tropomyosin**
    - Is a double strand
    - Prevents actin–myosin interaction
  - **Troponin**
    - A globular protein
    - Binds tropomyosin to G-actin
    - Controlled by $Ca^{2+}$

# Thick Filaments Structure

- Contain twisted **myosin** subunits
- Contain **titin** strands that recoil after stretching
- The **mysosin** molecule
  - **Tail -** binds to other myosin molecules
  - **Head -** made of two globular protein subunits, reaches the nearest thin filament

- **Myosin Action**
  - During contraction, myosin heads
    - Interact with actin filaments, forming cross-bridges
    - Pivot, producing motion

# The Filaments Structure



# Skeletal Muscle Contraction

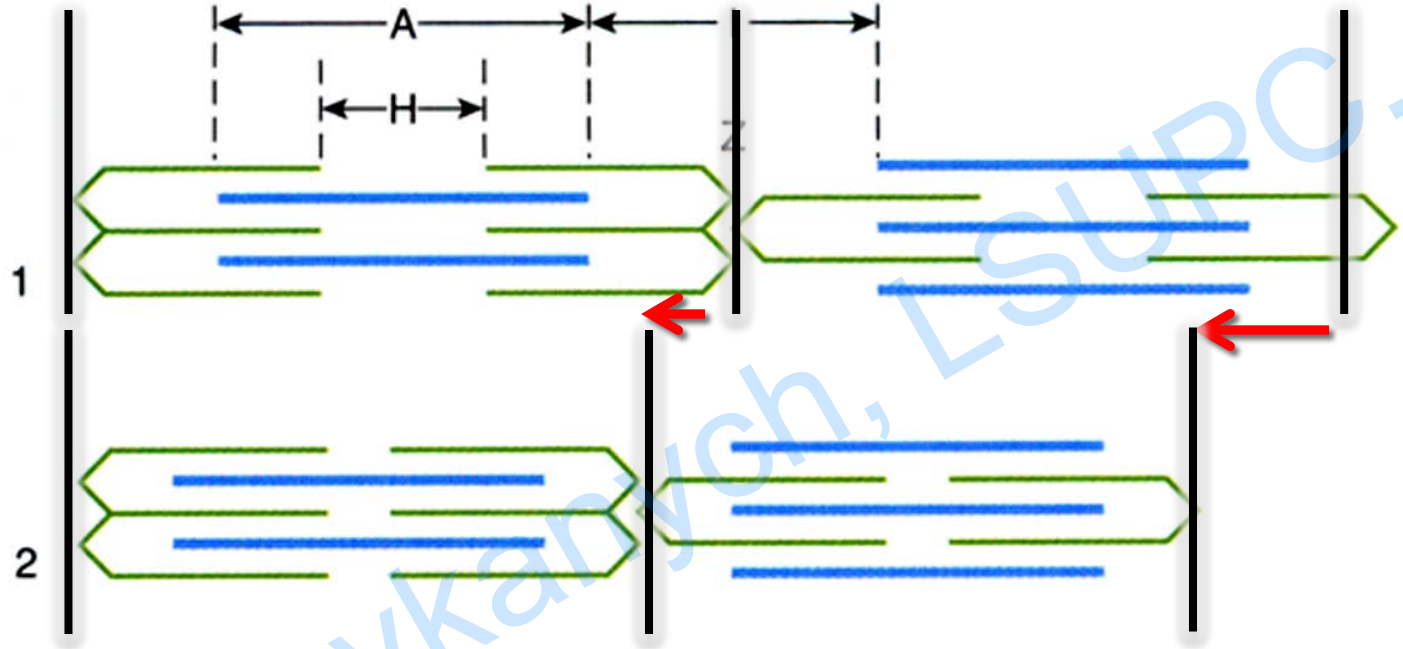
**Sliding filament theory**

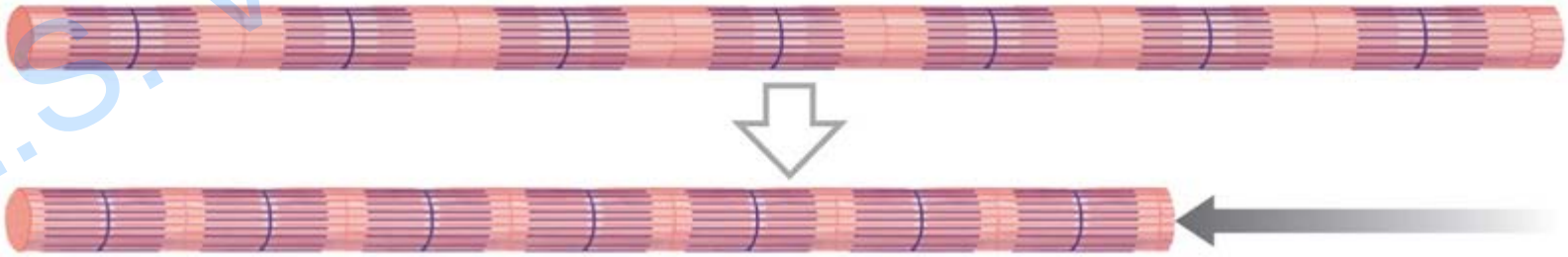
- Thin filaments of sarcomere **slide** toward M line, alongside thick filaments
- The width of A zone stays the same
- Z lines move closer together

**Fiber Shortening**

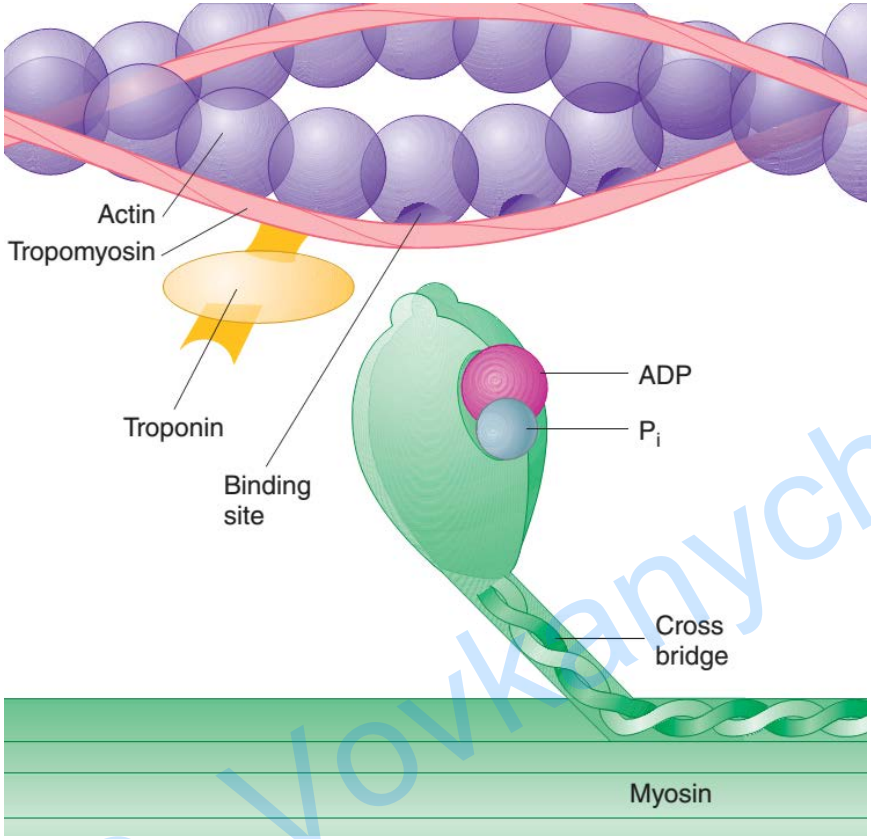
- As sarcomeres shorten, muscle pulls together, producing *tension*

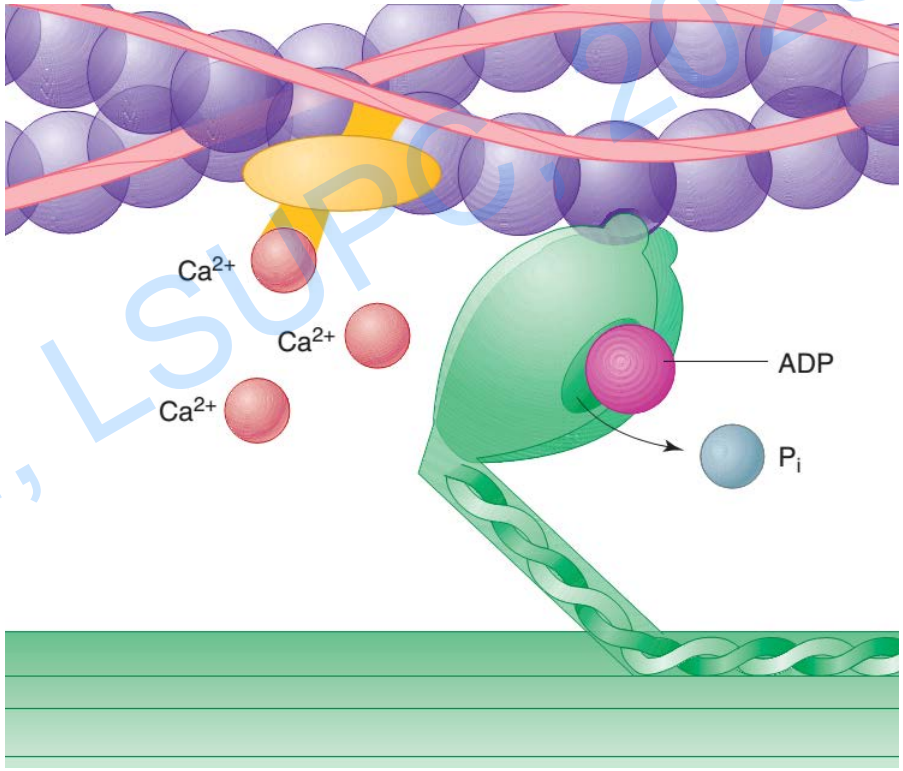
# Sliding Filament Theory



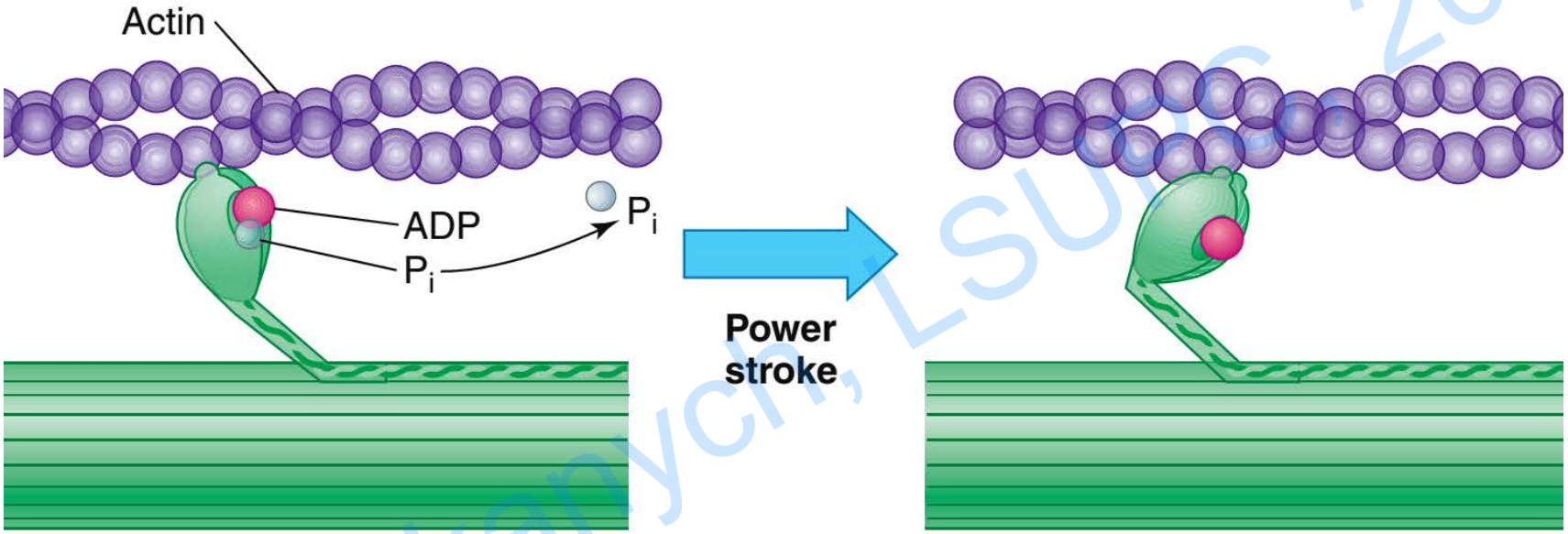
# Initiating of Contraction



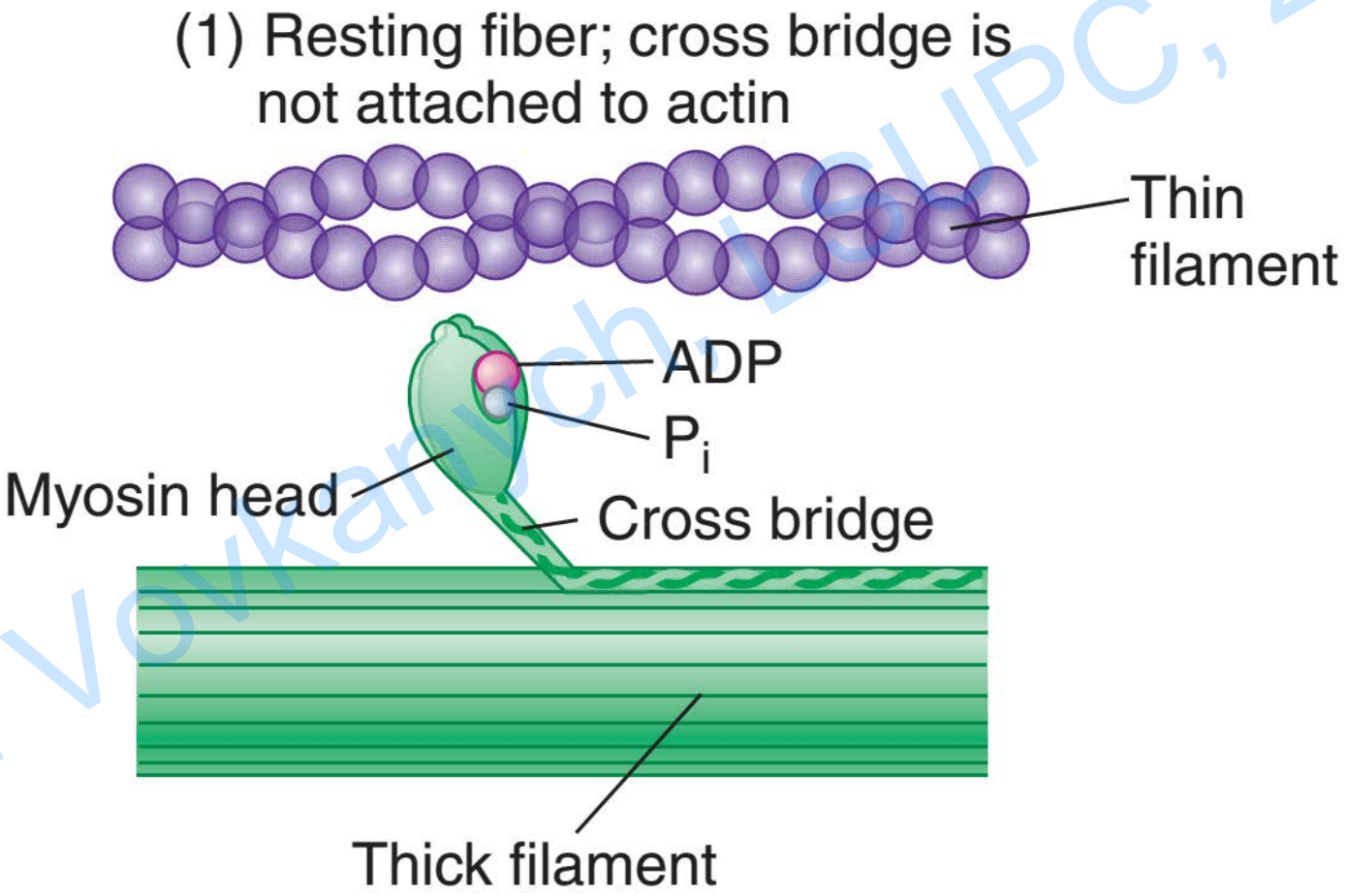

- $Ca^{2+}$ binds to receptor on **troponin** molecule
- **Troponin–tropomyosin complex** changes
- Exposes **active site** of **F-actin**

# Mechanism of Filaments Sliding



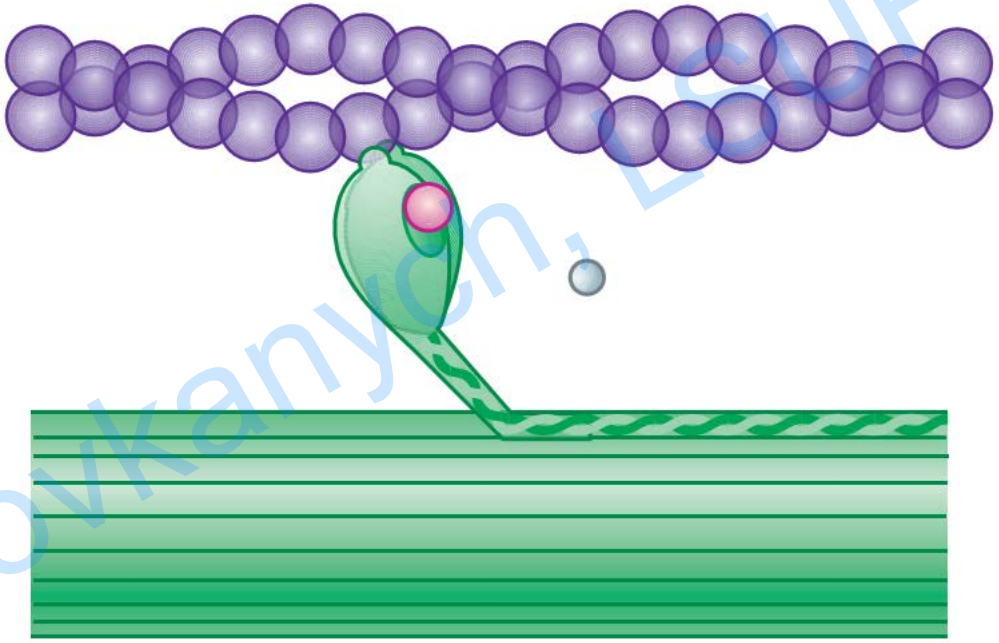

Sliding of the filaments is produced by **power strokes** of myosin **cross bridges**, which **pull** the thin filaments (actin) over the thick filaments (myosin). After the myosin head binds to actin to form a cross bridge, inorganic phosphate (Pi) is released. This causes a conformational change in the myosin head, resulting in a power stroke.

# The Cross-Bridge Cycle



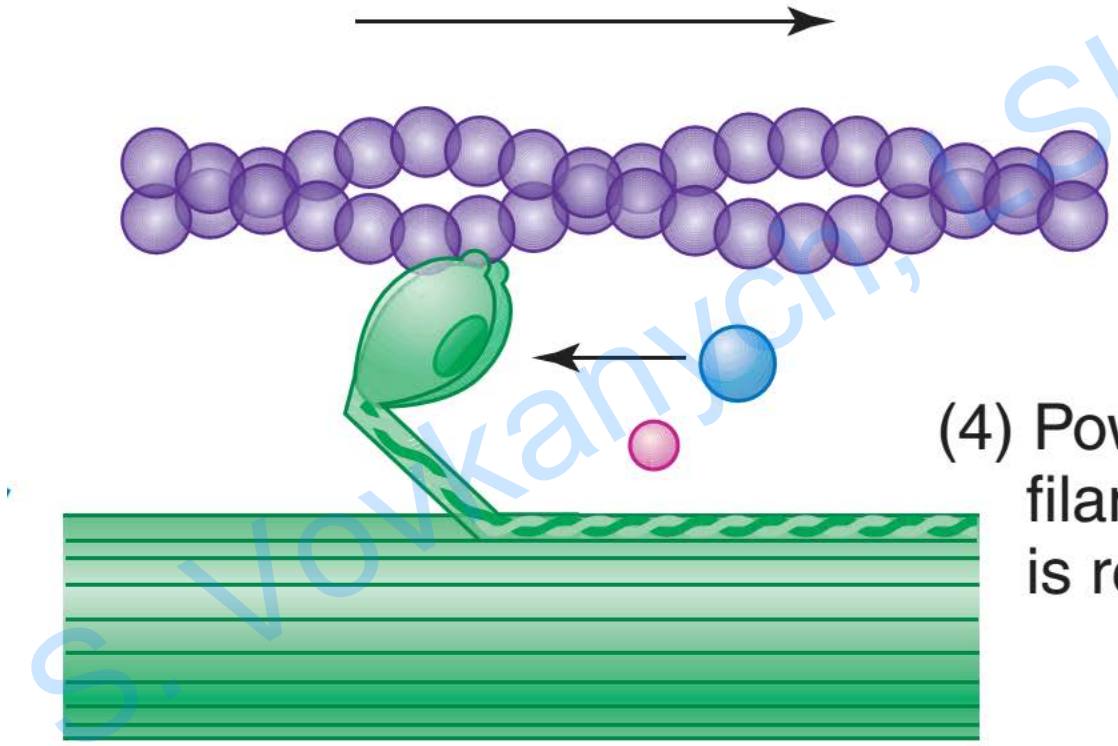
# The Cross-Bridge Cycle

(2) Cross bridge binds to actin



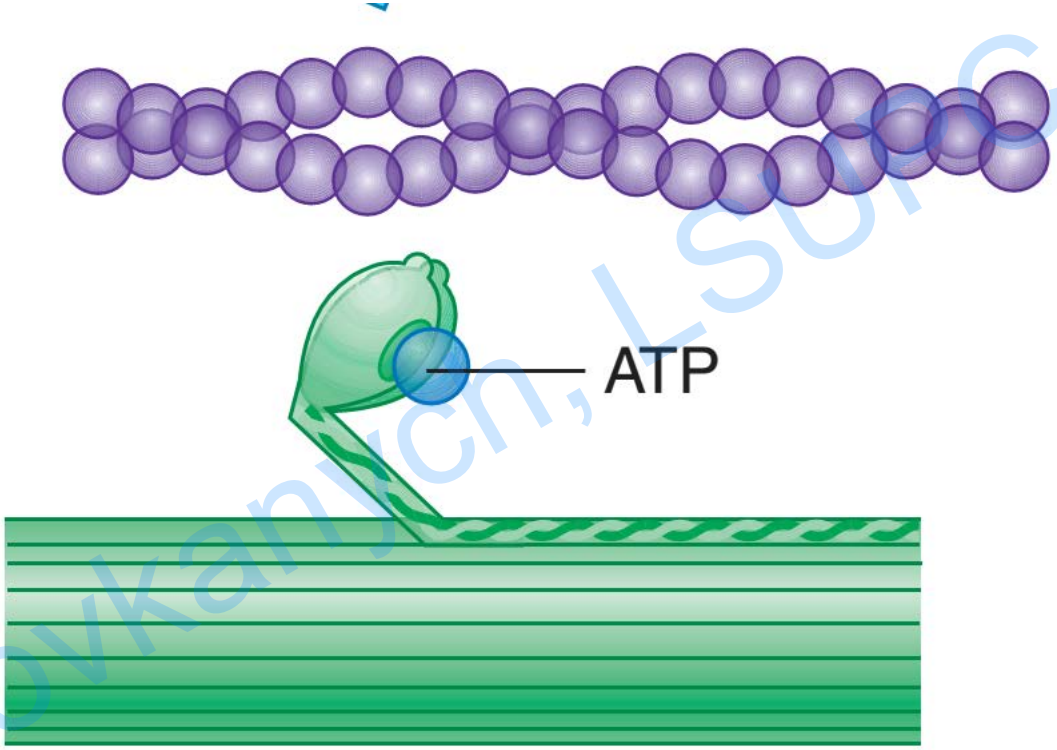
(3) $P_i$ is released, causing conformational change in myosin

# The Cross-Bridge Cycle



(4) Power stroke causes filaments to slide; ADP is released

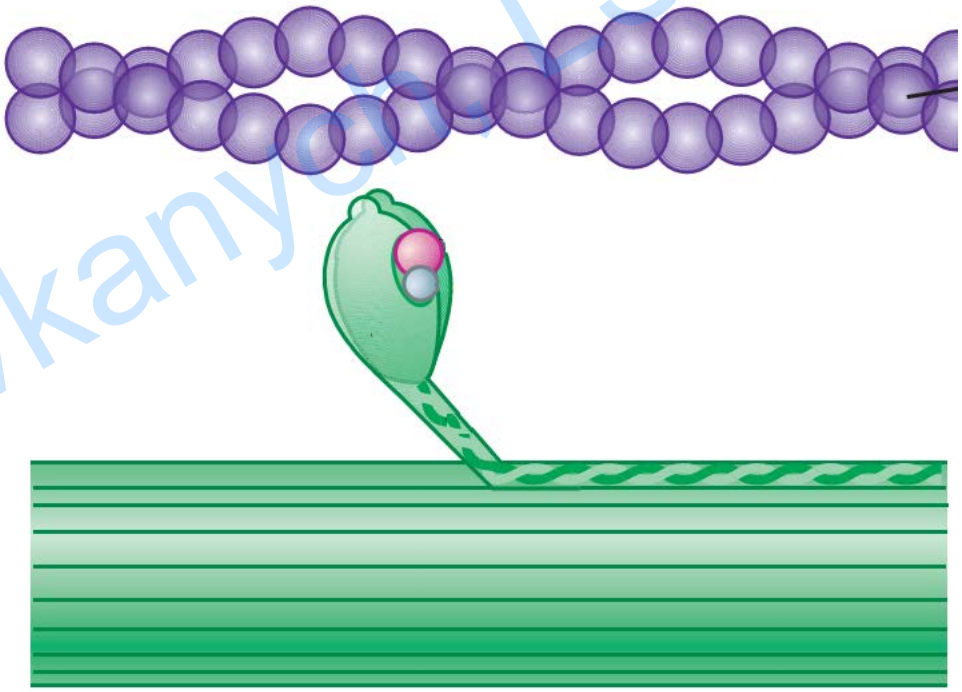
# The Cross-Bridge Cycle



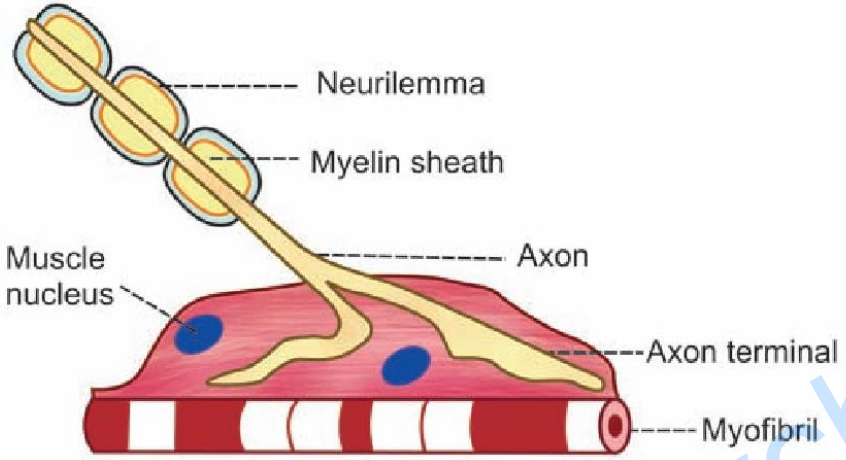

(5) A new ATP binds to myosin head, allowing it to release from actin

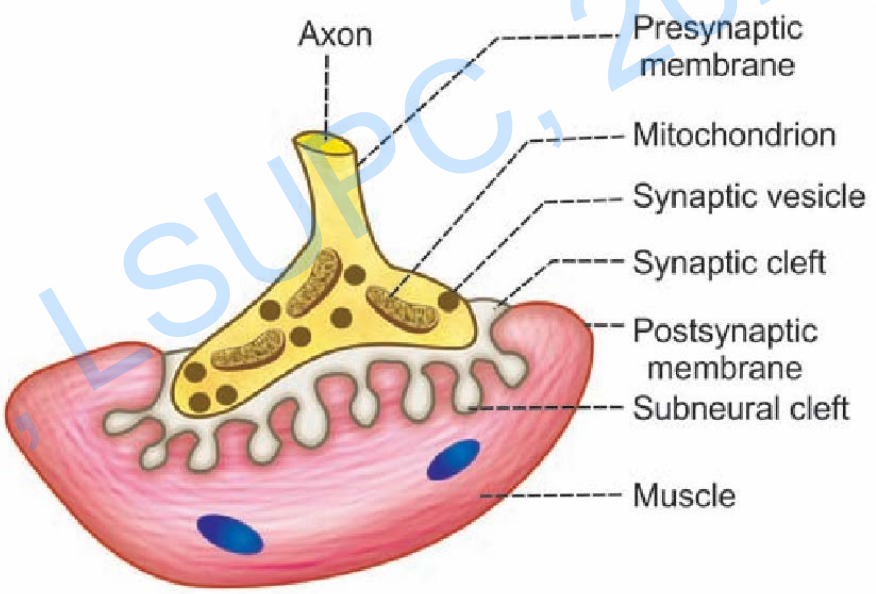
# The Cross-Bridge Cycle

(6) ATP is hydrolyzed, causing cross bridge to return to its original orientation



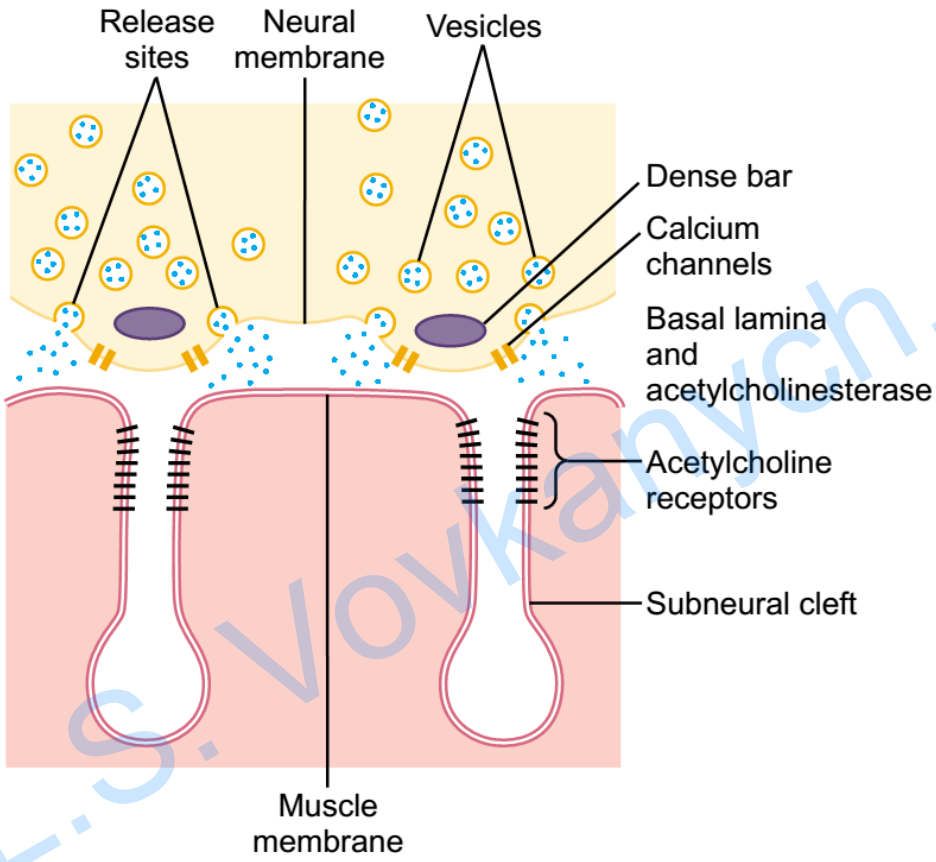
# The Neuromuscular Junction

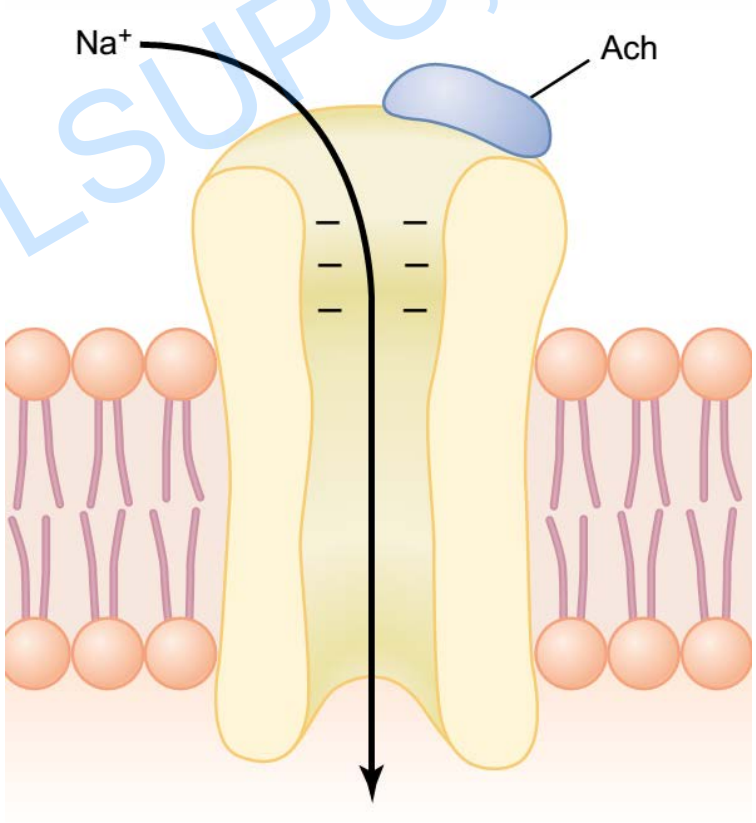



- **Action potential** (electrical signal) travels along nerve axon and ends at **synaptic (axon) terminal**
- Synaptic terminal releases **neurotransmitter** (**acetylcholine or ACh**) into the synaptic cleft (gap between synaptic terminal and motor end plate)

# The Neuromuscular Junction

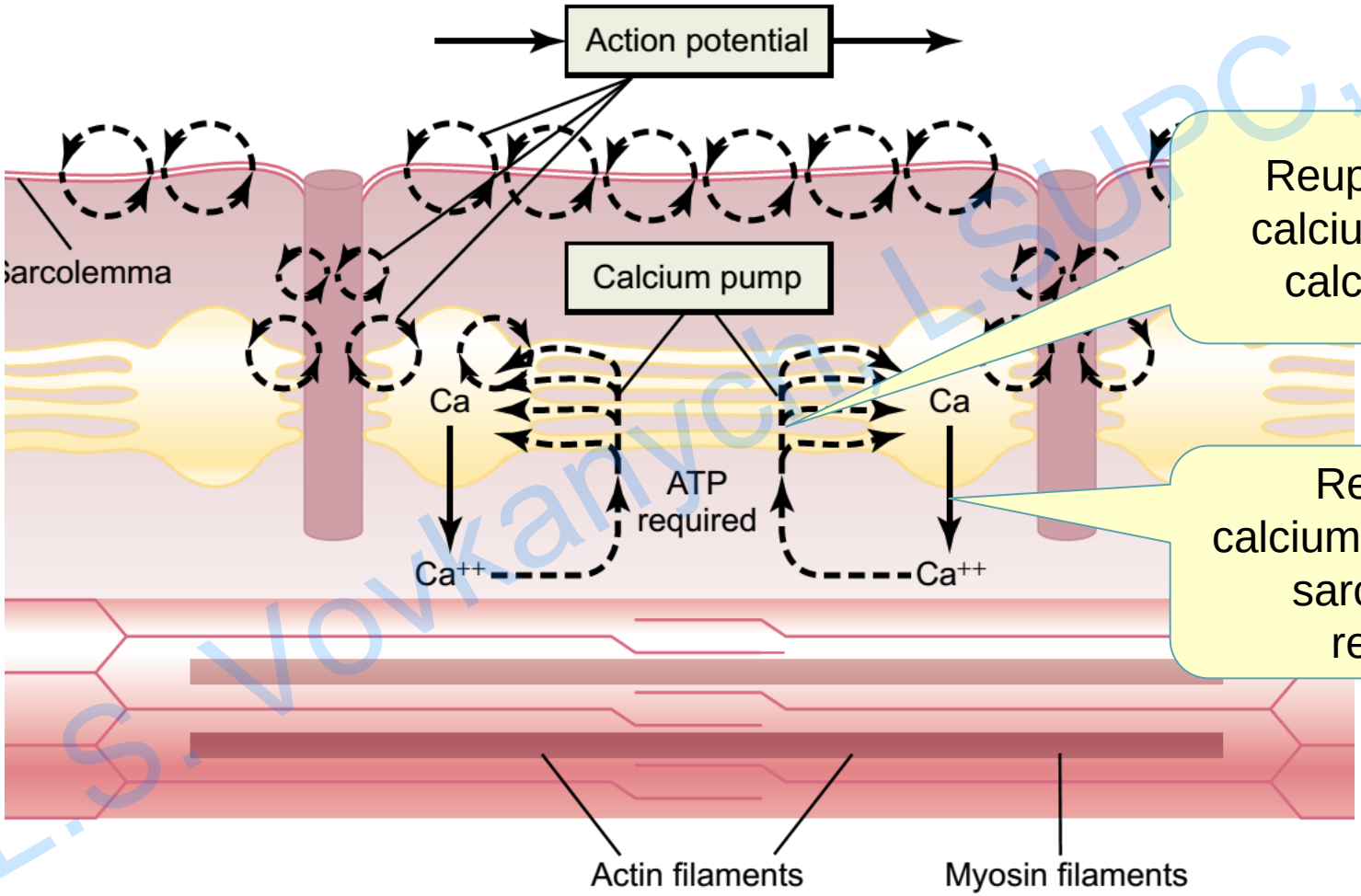


# Excitation-Contraction Coupling

- **Acetylcholine**, through its interaction with receptors in the muscle cell membrane (sarcolemma), **produces action potentials** that are regenerated across the sarcolemma.
- The membranes of the transverse tubules (**T tubules**) are continuous with the sarcolemma and **conduct action potentials** deep into the muscle fiber.
- Action potentials in the T tubules **stimulate the release of Ca2+** from the terminal cisternae of the sarcoplasmic reticulum.
- Ca2+ released into the sarcoplasm **attaches to troponin**, causing a change in its structure.

# Excitation-Contraction Coupling

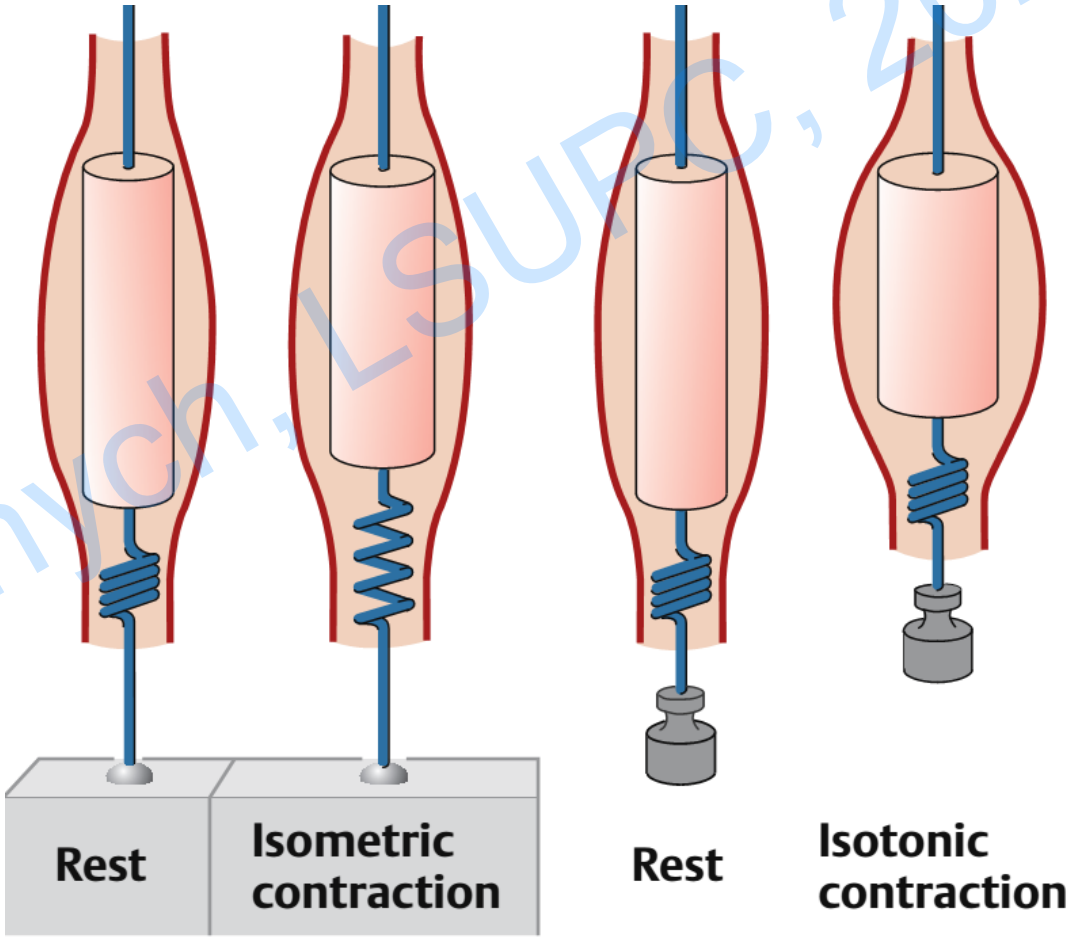



Reuptake of the calcium ions by a calcium pump

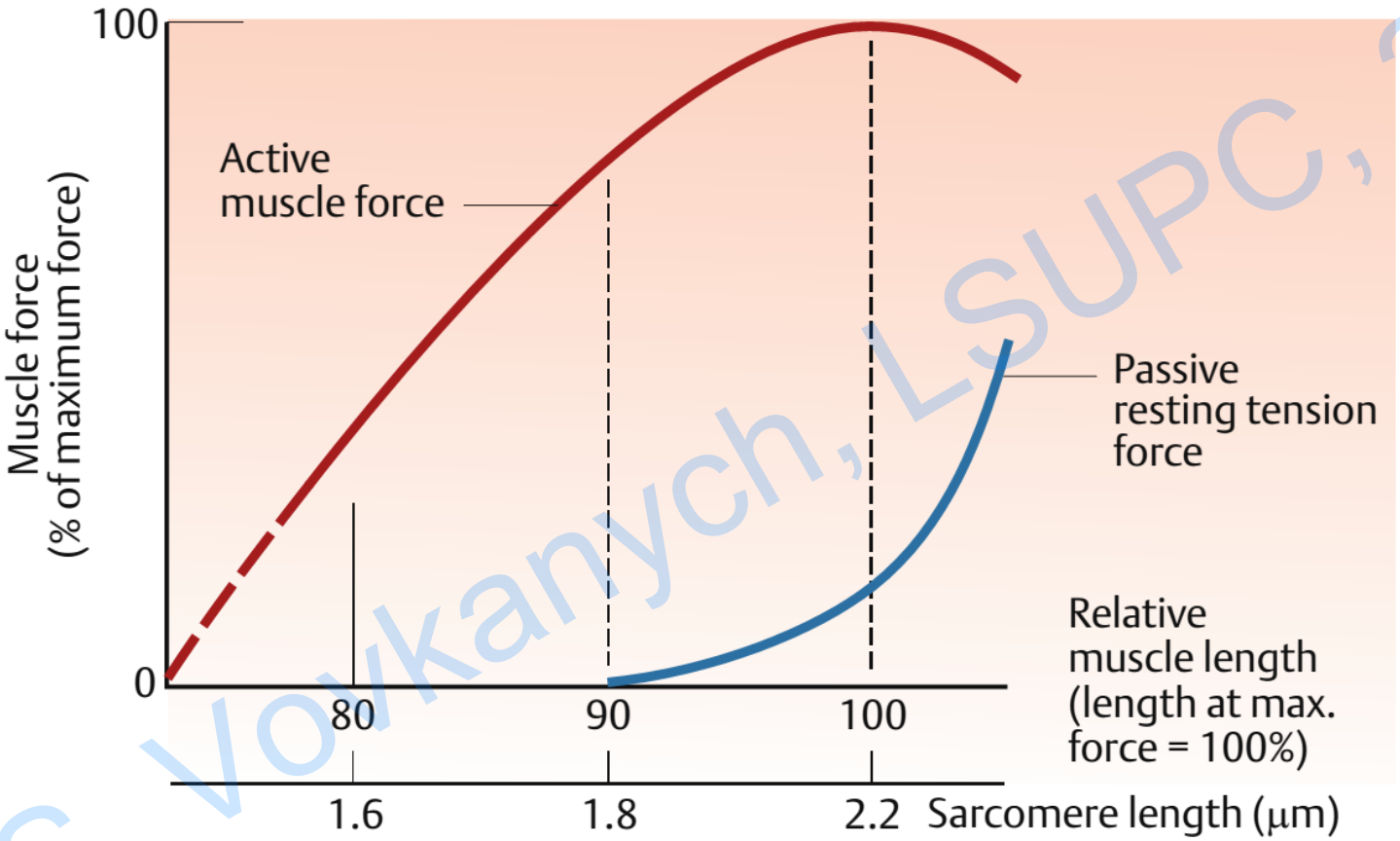
Release of calcium ions from the sarcoplasmic reticulum

# Types of Muscle Contractions

- **Isometric contraction** - muscle force ("tension") varies, the length of the muscle remains constant
- **Isotonic contraction** - the length of the muscle changes, muscle force remains constant
- **Auxotonic contraction -** muscle length and force both vary simultaneously



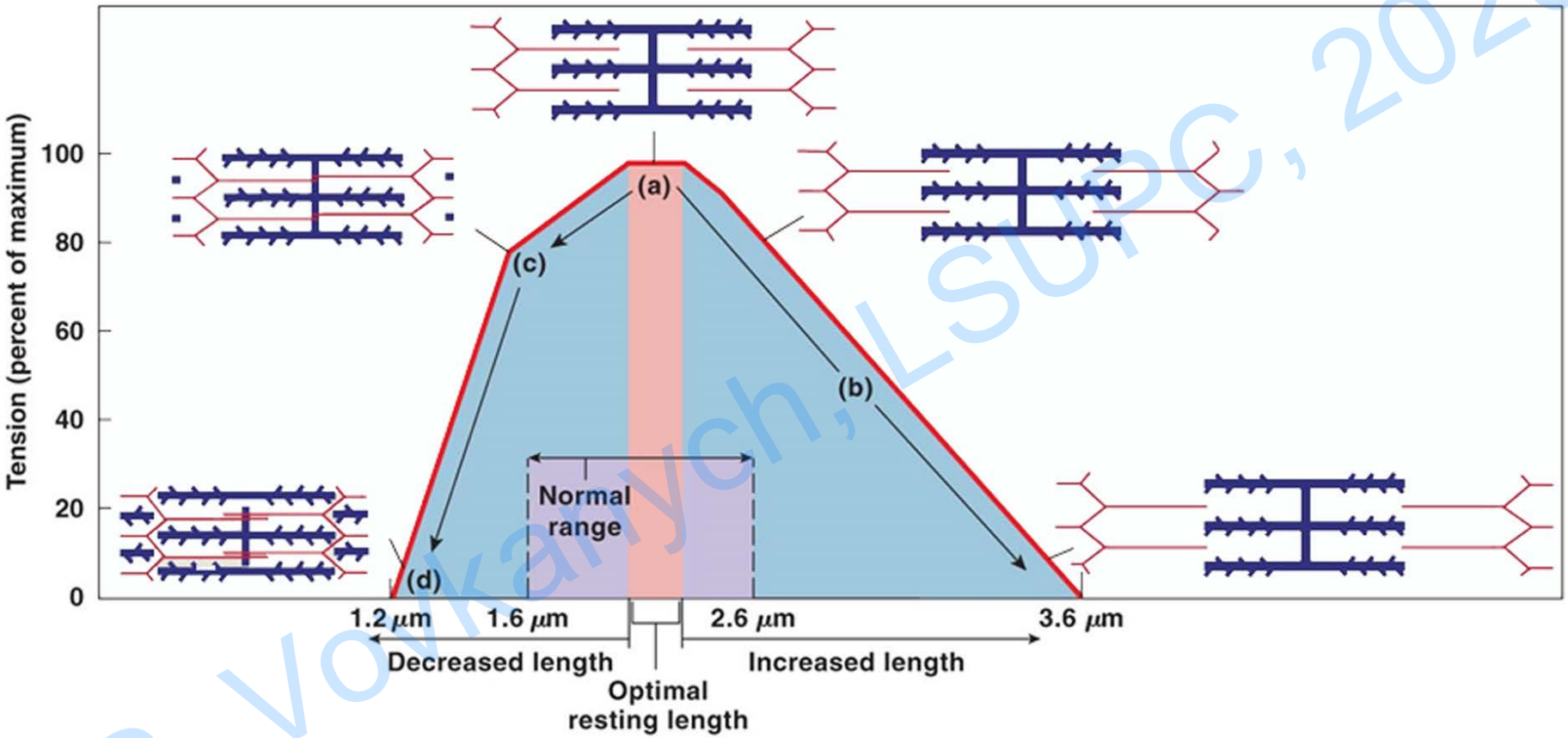
# The Force-Length Curve






The **total force** of the **isometric contraction** is the sum of its **active force** and its **extension force** (increases exponentially, generated mainly by the **titin** molecules that counteract passive stretching) at rest

# Muscle Force and Sarcomere Length



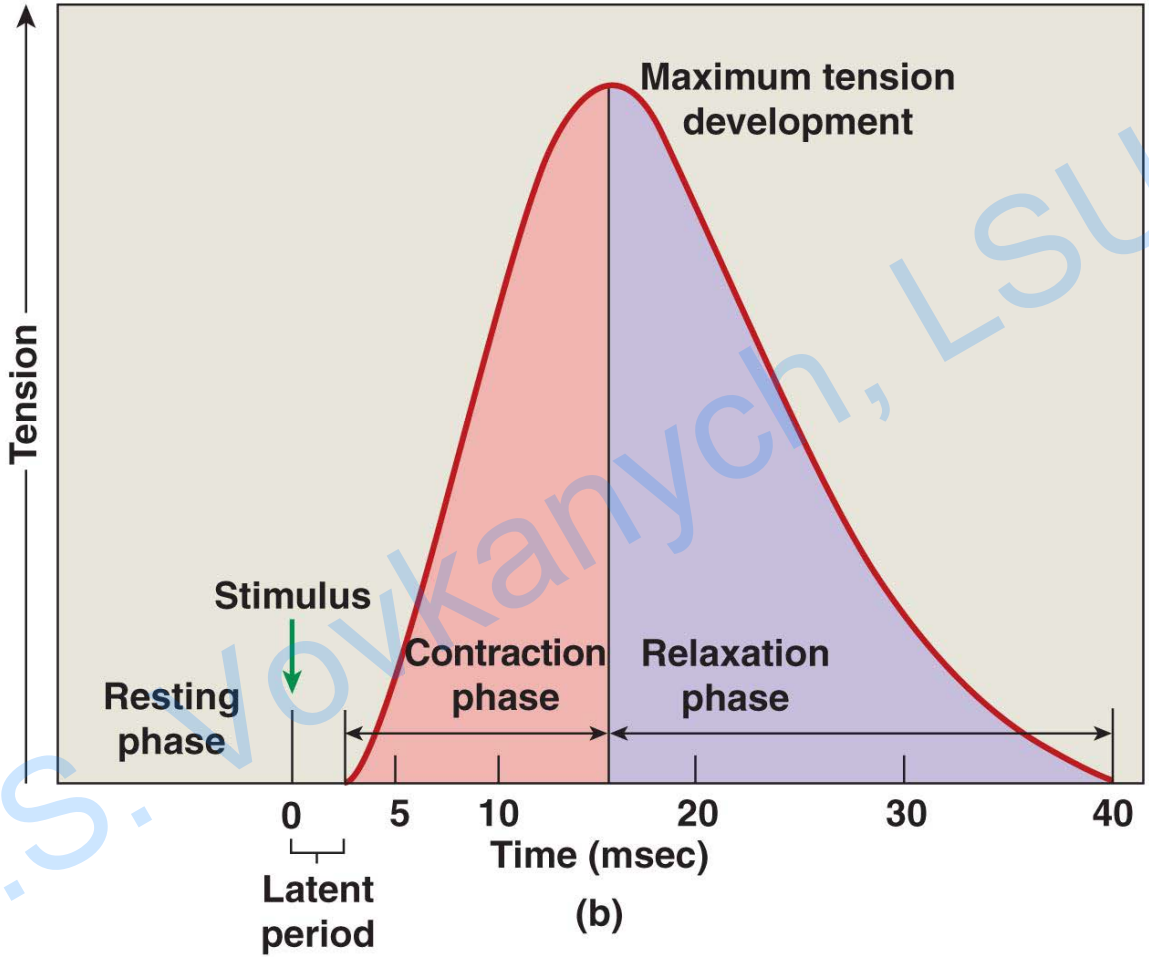

The active force is determined by the magnitude of all potential actinmyosin interactions. It varies in accordance with the initial sarcomere length. Skeletal muscle can develop **maximum active (isometric) force** from its **resting length.**

# Single Contraction

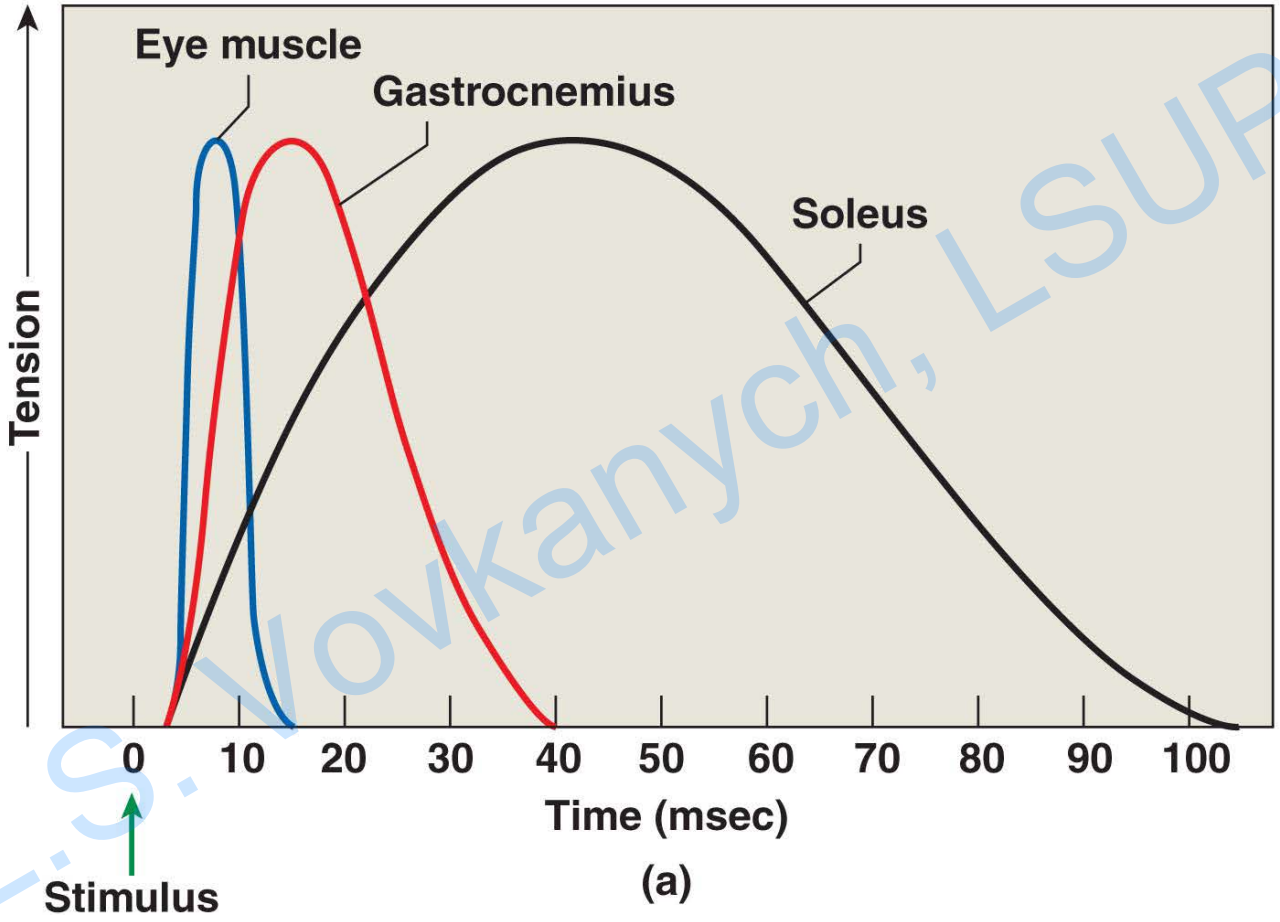
Three Phases of Single Contraction

- **Latent period before contraction**
  - The action potential moves through sarcolemma
  - Causing $Ca^{2+}$ release
- **Contraction phase**
  - Calcium ions bind
  - Tension builds to peak
- **Relaxation phase**
  - $Ca^{2+}$ levels fall
  - Active sites are covered
  - Tension falls to resting levels

# Three Phases of Single Contraction



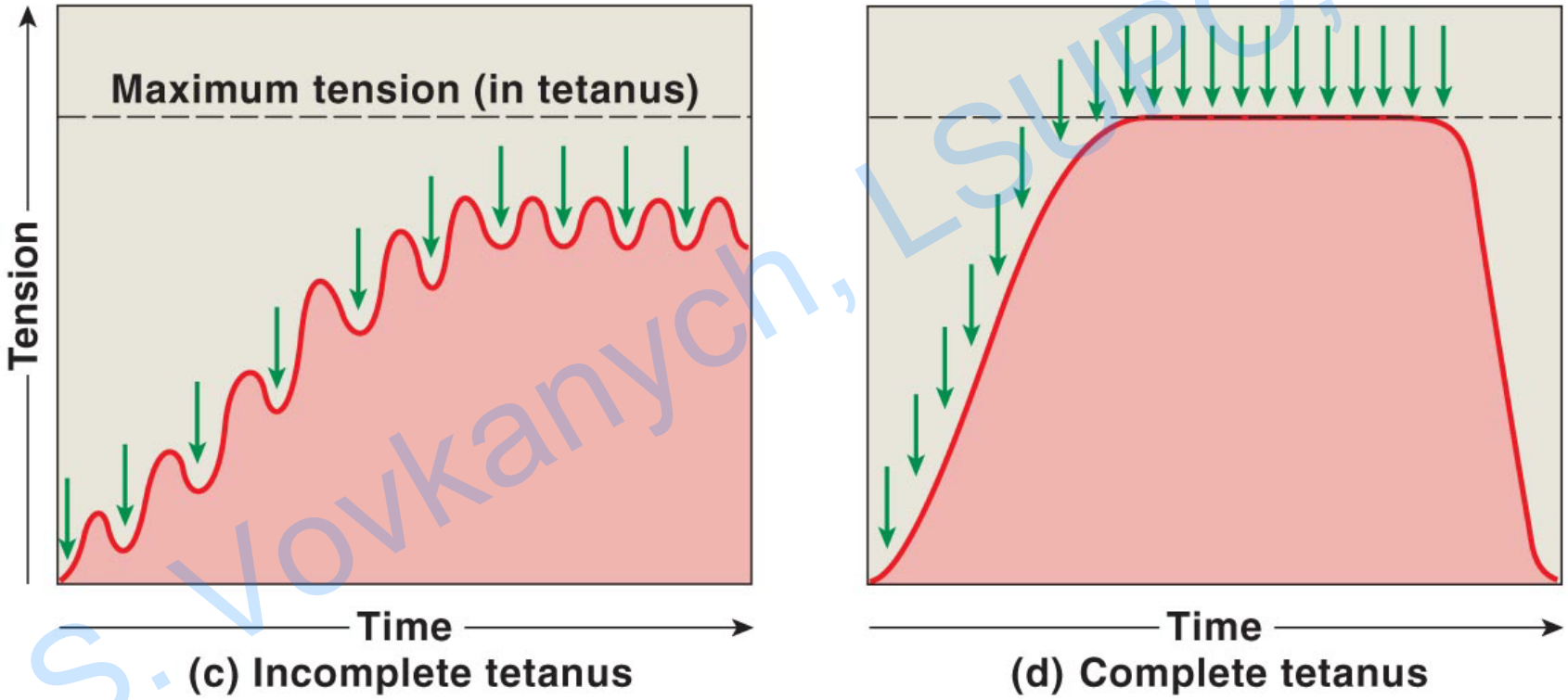
# The Velocity of Muscles Contraction



# Regulation of Contraction Force

- **Gradation of Contraction Force** is achieved by
  - Variable *recruitment* of **motor units**
  - Changing the **action potential** *frequency*
    - *Single stimulus* leads to the
      - **Single Contraction** (does not induce maximum shortening of muscle fiber)
    - *Repeated stimuli* at some frequency results in tetanic contractions
      - **Incomplete Tetanus** (muscle is not allowed to end relax, twitches high level of tension)
      - **Complete Tetanus** (stimulation frequency is high, muscle never *begins* to relax, and is in **continuous contraction)**

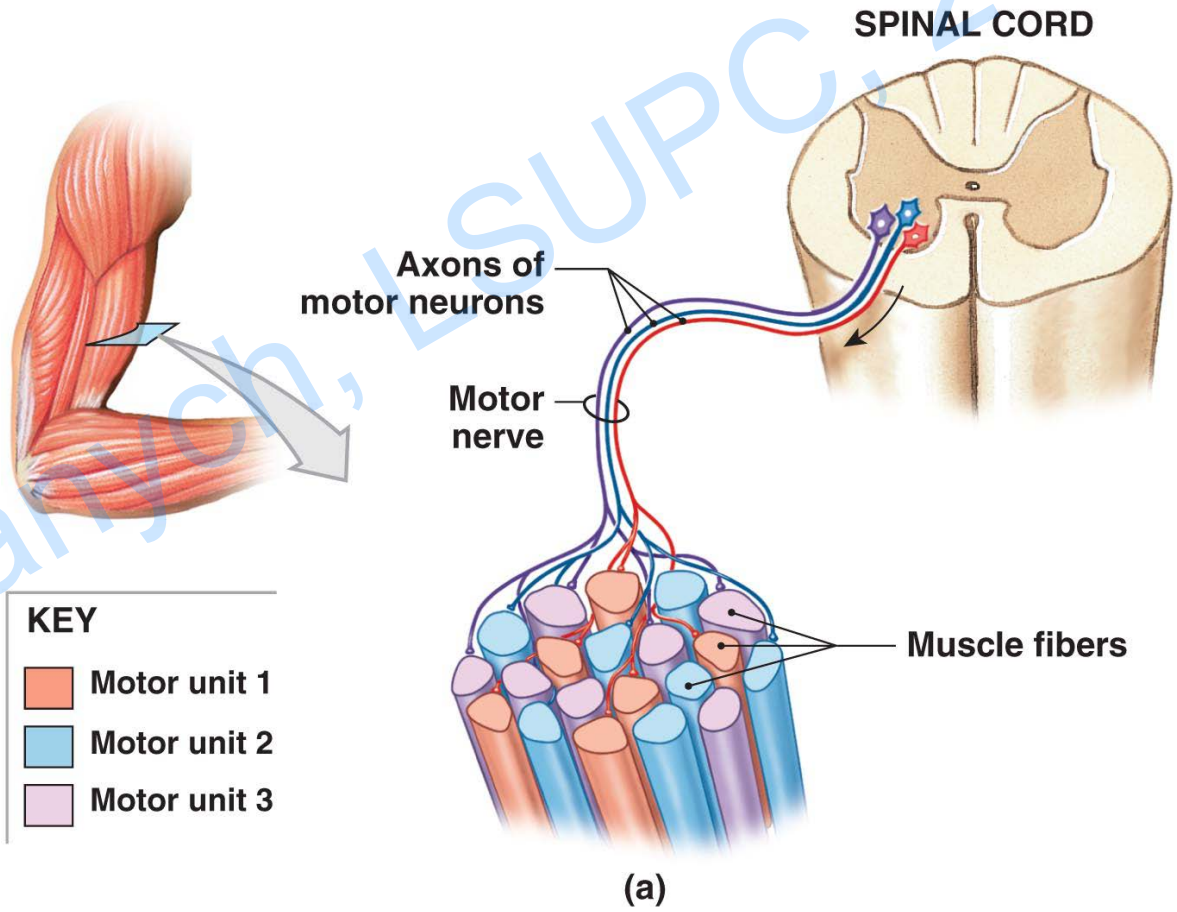
# Incomplete and Complete Tetanus



# Motor Units of Skeletal Muscle

**Motor Unit (MU)**

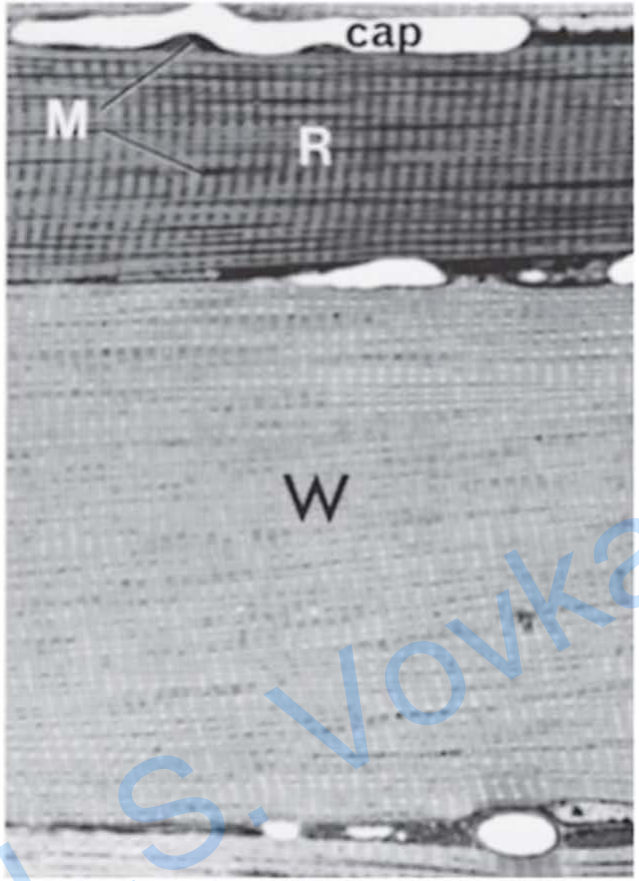
- One **motor neuron** (splits into collaterals with terminal branches)
- All **muscle fibers** (from 25 muscle fibers in mimetic muscles to over 1000 in temporal muscle) innervated by it.



# Muscle Fiber Types

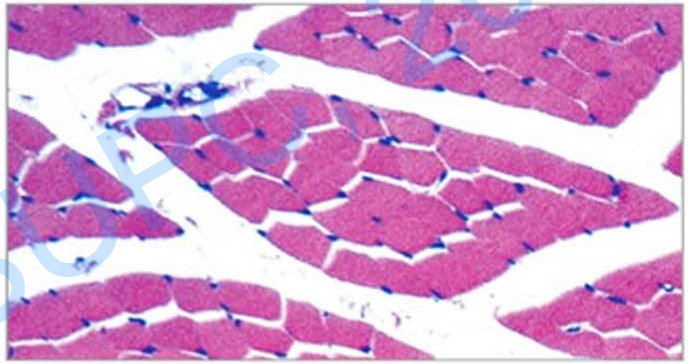
- Three Types of Skeletal Muscle Fibers
  - **Fast** fibers
  - **Slow** fibers
  - **Intermediate** fibers

# Muscle Fiber Types



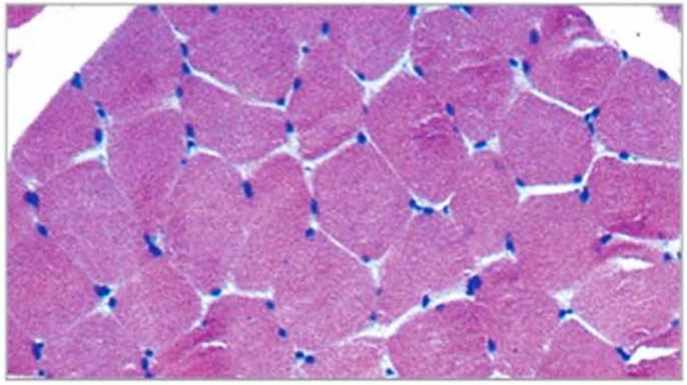

LM × 783

Slow fibers
Smaller diameter, darker color due to myoglobin; fatigue resistant



Slow LM × 171

Fast fibers
Larger diameter, paler color; easily fatigued

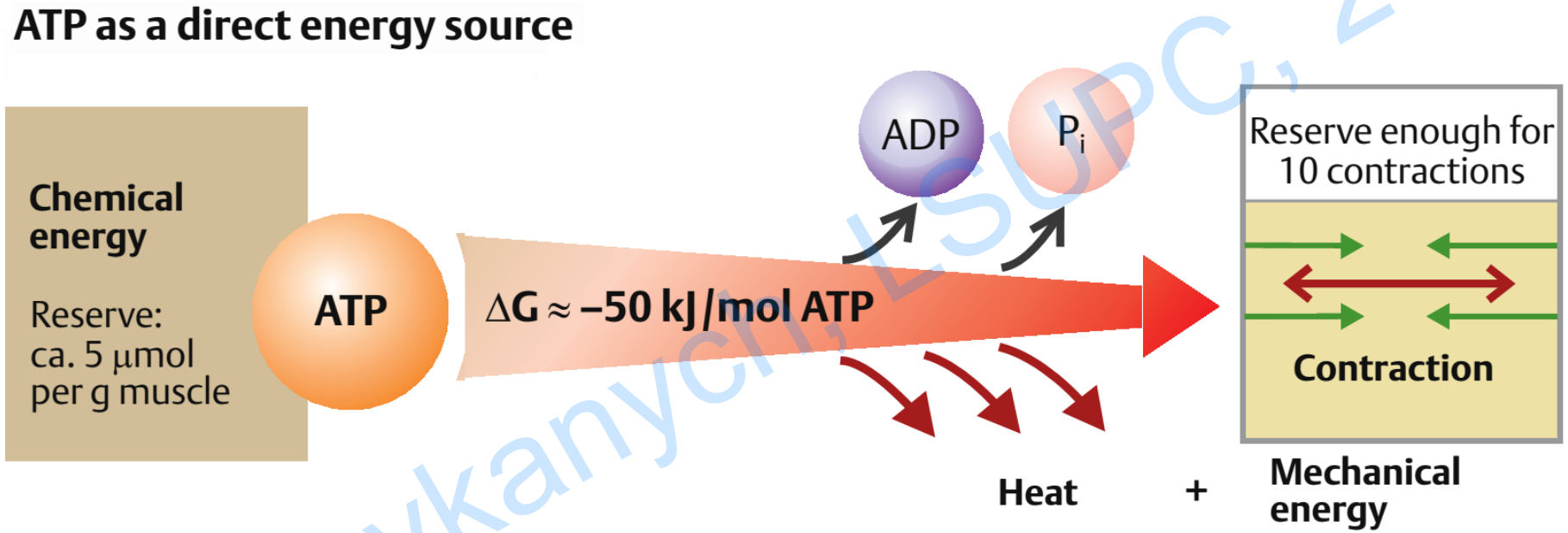


Fast LM × 171

# Muscle Fiber Types

| Property | Slow | Intermediate | Fast |
|---|---|---|---|
| **Cross-sectional diameter** | Small | Intermediate | Large |
| **Tension** | Low | Intermediate | High |
| **Contraction speed** | Slow | Fast | Fast |
| **Fatigue resistance** | High | Intermediate | Low |
| **Myoglobin content** | High | Low | Low |
| **Mitochondria** | Many | Low | Few |
| **Glycolytic enzyme** | Low | High | High |
| **ATP generation** | Lipids, carbohydrates, amino acids (aerobic) | Primarily carbohydrates (anaerobic) | Carbohydrates (anaerobic) |
| **Alternative names** | Type I, S (slow), red, SO (slow oxidative), slow-twitch oxidative | Type II-A, FR (fast resistant), fast-twitch oxidative | Type II-B, FF (fast fatigue), white, fast-twitch |

# Energy Supply for Muscle Contraction



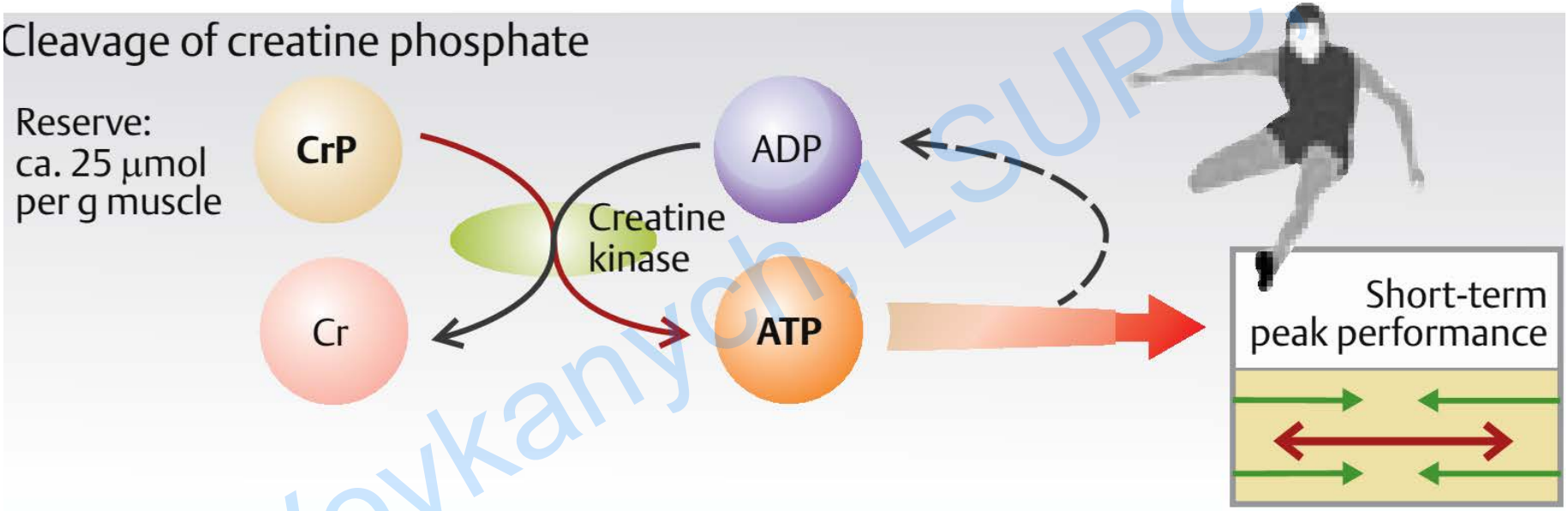

**Adenosine triphosphate (ATP)** is a direct source of chemical energy for muscle contraction. Amount of ATP is limited - only enough to take a sprinter some 10 to 20 m

# Energy Supply for Muscle Contraction

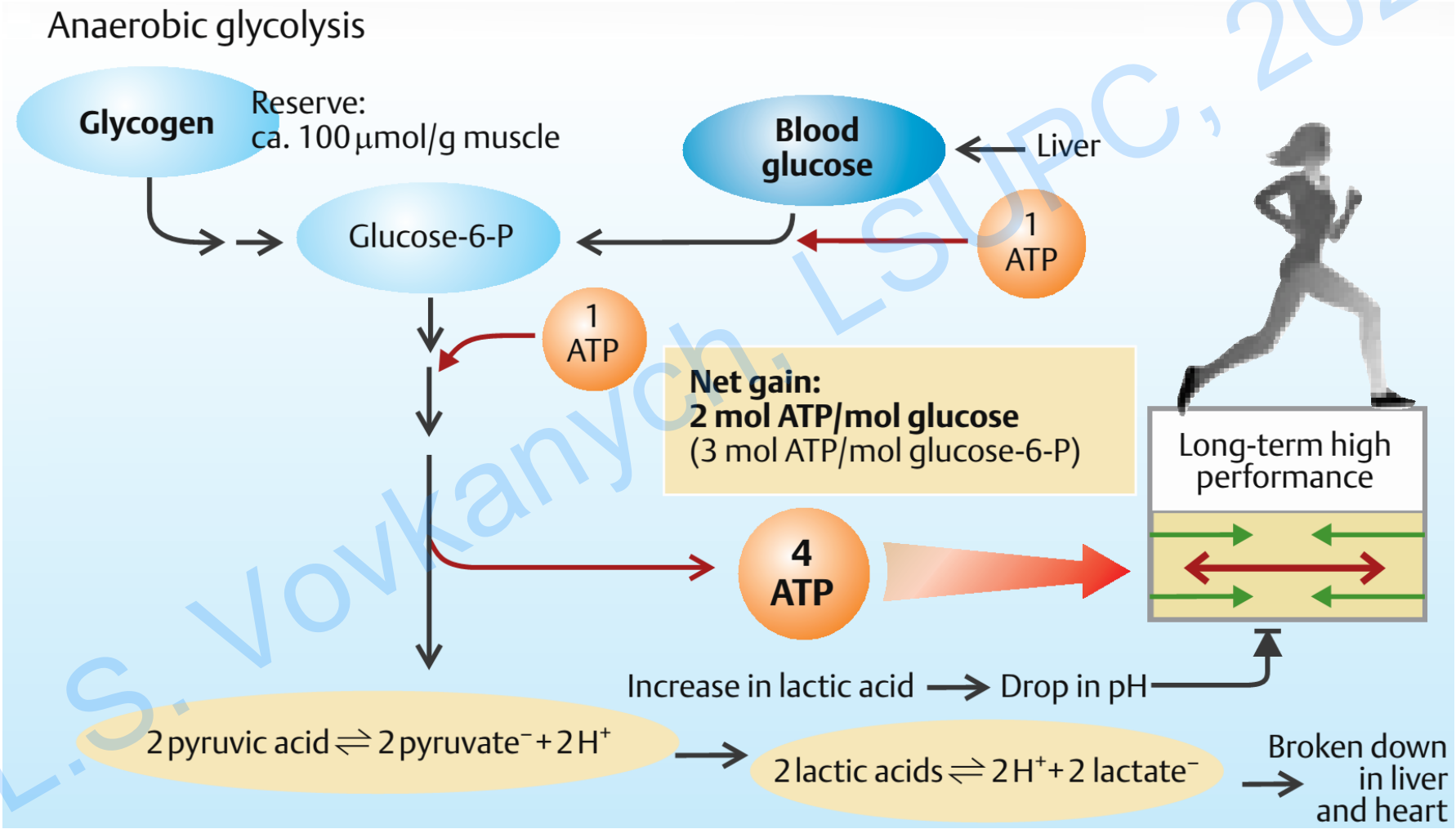
The three routes of **ATP regeneration** are:

- **Dephosphorylation of creatine phosphate** - *rapid ATP regeneration* sufficient for short-term high-performance bursts of 10–20 s
- **Anaerobic glycolysis** - *muscle glycogen* is converted via glucose-6-phosphate to lactic acid, yielding 3 ATP molecules for each glucose residue. During *light exercise*, lactate is broken down
- **Aerobic oxidation** of glucose and fatty acids. **Aerobic regeneration of ATP** from glucose (about 32 ATP per glucose residue) or fatty acids is required for *sustained exercise*

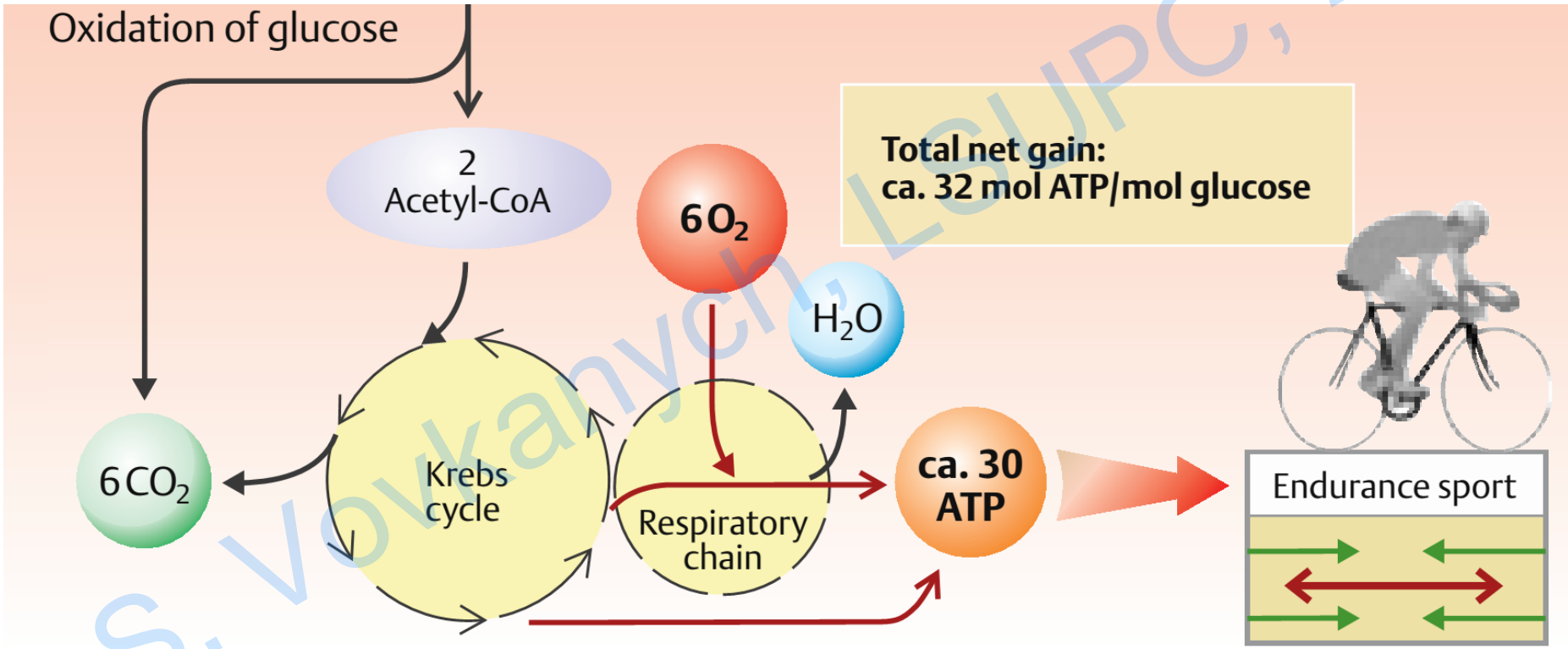
# Dephosphorylation of Creatine Phosphate



# Anaerobic Glycolysis



# Aerobic Oxidation



# References


Martini R., Nath J. **Fundamentals of Anatomy & Physiology.** Eighth Edition

Guyton, Arthur C. **Textbook of medical physiology** / Arthur C. Guyton, John E. Hall. - 11th ed.

Sembulingam K., Sembulingam P. **Essentials of Medical Physiology**. Sixth Edition

Scanlon, Valerie C. **Essentials of anatomy and physiology** / Valerie C. Scanlon, Tina Sanders. — 5th ed.

**Fox: Human Physiology.** Eighth Edition

Silbernagl S., Despopoulos A. **Color Atlas of Physiology.** 6th edition