Muscle Contraction (Review)

https://www.youtube.com/watch?v=BVcgO4p88AA&ab_channel=AlilaMedicalMedia

- **Effect of Actin and Myosin Filament Overlap on Tension Developed by the Contracting Muscle**
  - **Fig. 6-8**: the effect of sarcomere length and amount of myosin-actin filament overlap on the active tension developed by a contracting muscle fiber.
  - Maximum contraction occurs when there is maximum overlap between the actin and cross-bridges of the myosin
  - The greater the number of cross-bridges pulling the actin filaments, the greater the strength of contraction.
- **Effect of Muscle Length on Force of Contraction in the Whole Intact Muscle**
  - **Fig. 6-9**: Relation of muscle length to tension in the muscle both before and during muscle contraction. The top curve of Figure 6–9 is similar to that in Figure 6–8,
  - but the curve in Figure 6–9 depicts tension of the intact, whole muscle rather than of a single muscle fiber.
  - The whole muscle has a large amount of connective tissue in it; also, the sarcomeres in different parts of the muscle do not always contract the same amount.
  - Therefore, the curve has somewhat different dimensions from those shown for the individual muscle fiber, but it exhibits the same general form for the slope *in the normal range of contraction,* as noted in Figure 6–9.

Length-tension Plot

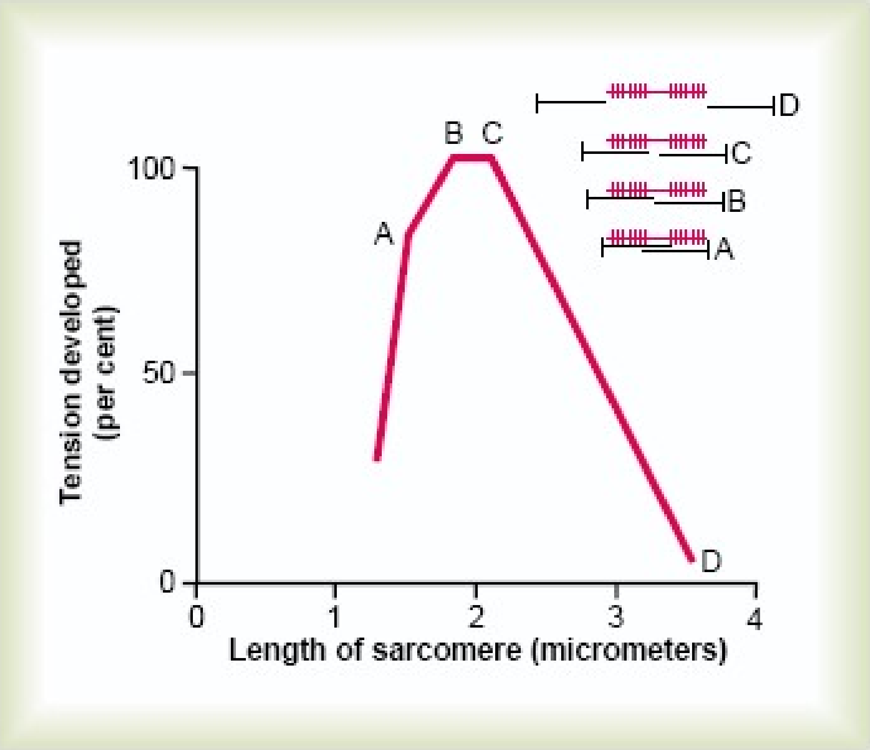


Figure 6–8

Length-tension diagram for a single fully contracted sarcomere, showing maximum strength of contraction when the sarcomere is 2.0 to 2.2 micrometers in length. At the upper right are the relative positions of the actin and myosin filaments at different sarcomere lengths from point A to point D. (Modified from Gordon AM, Huxley AF, Julian FJ: The length-tension diagram of single vertebrate striated muscle fibers. J Physiol 171:28P, 1964.)

- The greater the number of cross-bridges pulling the action filaments, the greater the strength of contraction

Relation of Muscle Length vs. Tension

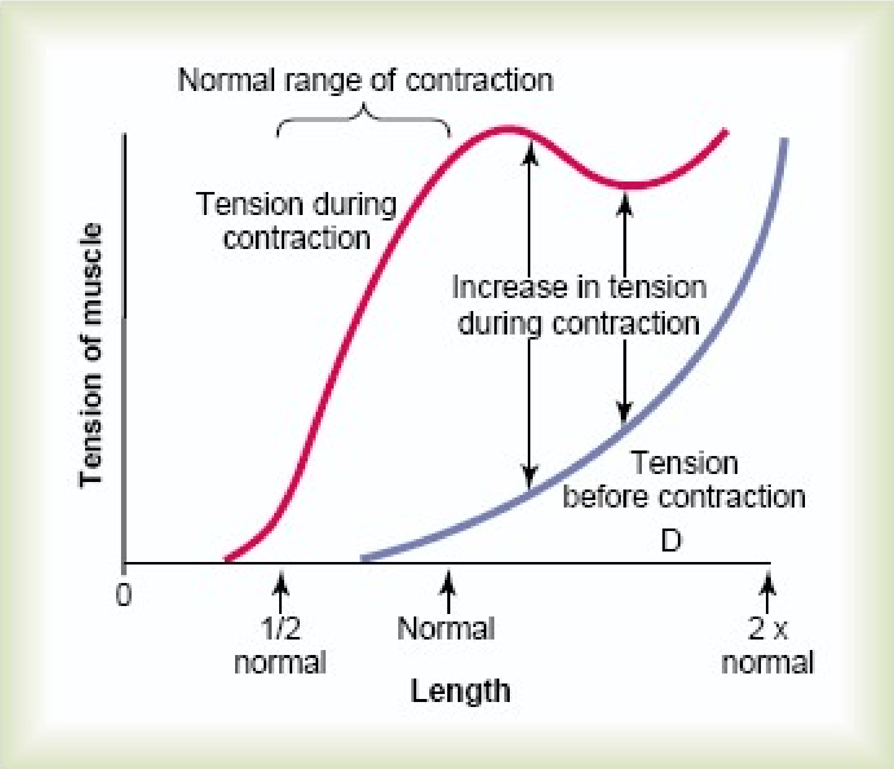


Figure 6–9

Relation of muscle length to tension in the muscle both before and during muscle contraction.

- This time, a whole muscle, not a single muscle fiber.
- Same info as the previous slides, but differ slightly.
- Why? Many Sacomeres and muscle fibers, and connective tissues

In Figure 6–9 that when the muscle is at its normal *resting* length, which is at a sarcomere length of about 2 micrometers, it contracts upon activation with the approximate maximum force of contraction. However, the *increase* in tension that occurs during contraction, called *active tension*, decreases as the muscle is stretched beyond its normal length—that is, to a sarcomere length greater than about 2.2 micrometers.

Relation of Contraction Velocity vs. Load

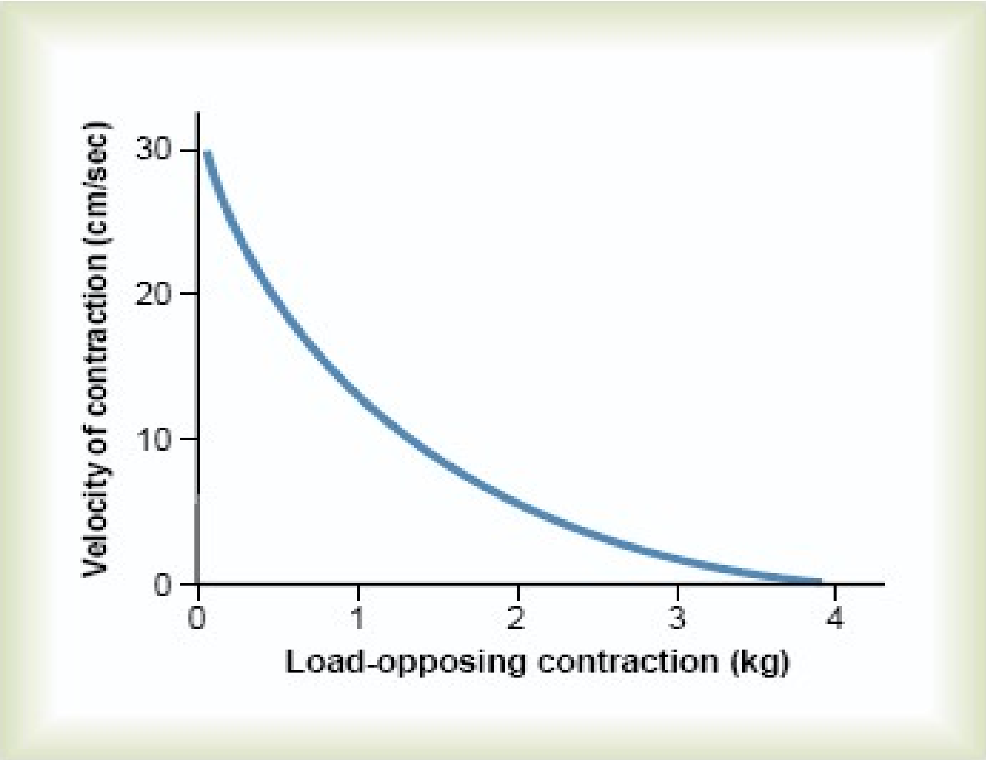


Figure 6–10

Relation of load to velocity of contraction in a skeletal muscle with a cross section of 1 square centimeter and a length of 8 centimeters.

- A skeletal muscle contracts rapidly with no load.
- With load, the velocity of contractions slows down.
- W(ork)=L(oad)xD(istance)

Energy Sources for Muscle Contraction

- Muscle contraction depends on energy supplied by ATP to actuate the walk-along mechanism (i.e., cross-bridges pulling the actin filaments).
- Also small amount of energy required for (1) pumping calcium ions from sarcoplasm into sarcoplasmic reticulum (2) pumping sodium and potassium ions for muscle fiber action potentials
- Energy sources for <u>rephosphorylation</u> (i.e., ADP is <u>rephosphorylated</u> to form new ATP)

(1) Phosphocreatine (PCr): used to reconstitute ATP. Phosphocreatine is cleaved (화학결합분리) releasing energy which causes bonding of new phosphate ion to ADP to reconstitute ATP.

One molecule of phosphocreatine produces 1 ATP molecule

(2) Glycolysis of glycogen (포도당): reconstitute ATP and phosphocreatine.

Glycolysis (해당작용) 해당과정은 glucose가 분해되어 2분자의 피루브산(pyruvic acid)을 만드는 과정으로 세포질에서 이루어지며, 이 과정에서 2 분자의 ATP가 만들어지고, 4개의 전자를 잃고 2분자의 NADH가 만들어진다 (Glycolysis = Glycose – 글루코스 + Lysis - 분해)

(3) Oxidative metabolism (산화작용): combine oxygen, glycolysis products, and food (e.g., carbohydrates, fats, protein) to produce ATP. Covers 95% of sustained and long term muscle contraction.

TCA Cycle : TCA generates 2 ATP

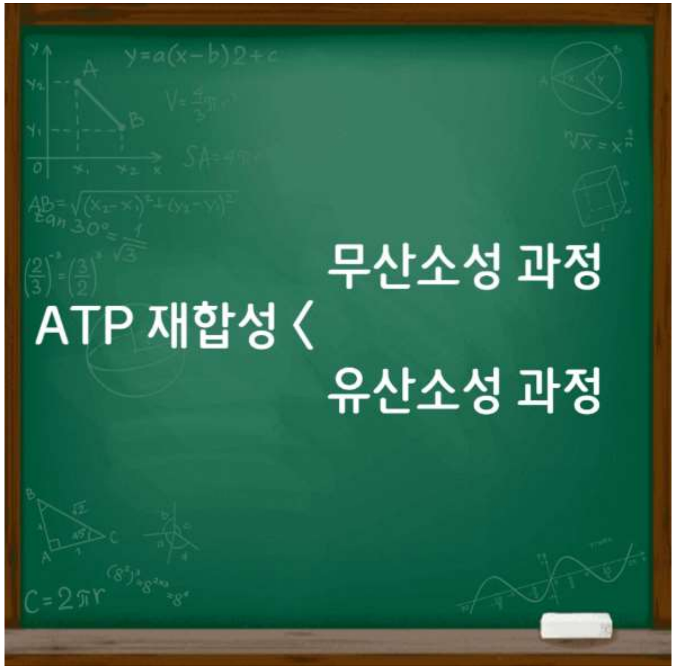
Approximately 30 - 32 ATP molecules are generated from the electron transport chain

근육 수축할 때 사용하는 에너지인 ATP는 다음 3가지 과정을 통해 생산할 수 있습니다.

1. ATP-PCr system
2. 해당작용
3. 산화작용

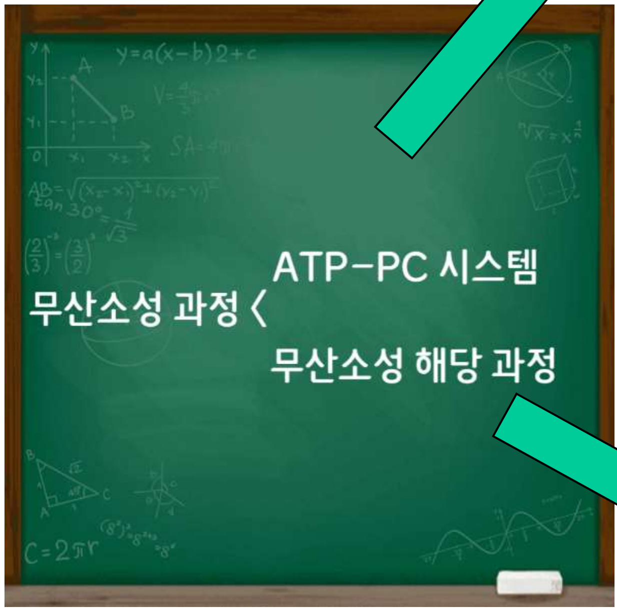
무산소성 에너지생성시스템

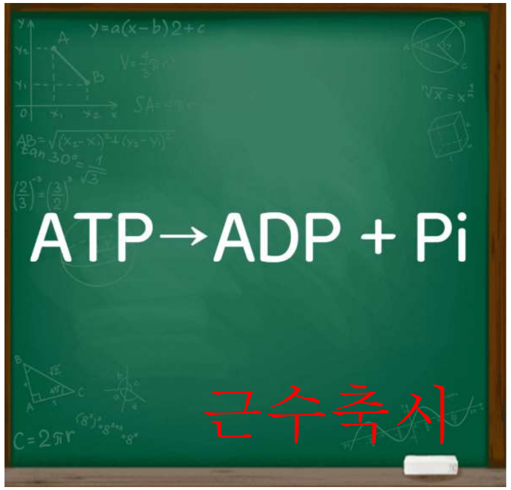
유산소성 에너지생성시스템

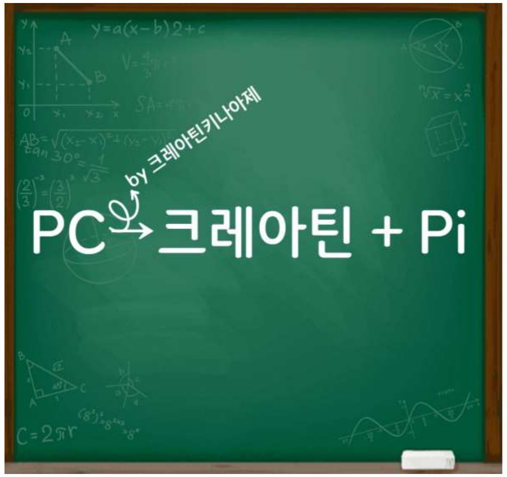

무산소성 과정
ATP 재합성 〈
유산소성 과정


무산소성
ATP 생성 과정에
대해 알아보자

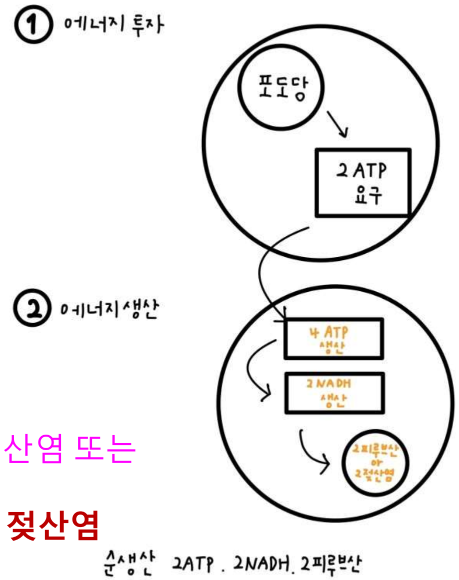

유산소성
ATP 생성 과정에
대해 알아보자







- PCr가 분해되면서 방출하는 에너지로 ADP와 Pi를 결합하여, ATP를 재합성
- 운동시 2~7초 동안 사용. 빠른 에너지 생성 및 소모
- 단거리 고강도 운동에 사용



해당작용은 포도당/글리코겐(탄수화물)을 분해시켜 젖산염 또는 피루브산염을 형성한다

포도당 한 분자당 2개의 순수ATP와 피루브산염 또는 젖산염 2분자를 생산한다

Energy Sources for Muscle Contraction

Theoretically, one glucose molecule can generate up to 38 ATP molecules during cellular respiration. However, due to inefficiencies in the process, the actual yield is closer to 30-32 ATP per glucose.

Here's a breakdown of the ATP production:

Glycolysis: 2 ATP are produced directly.

Krebs Cycle: 2 ATP are produced directly.

Electron Transport Chain: 34 ATP are produced from the NADH and FADH2 generated during glycolysis and the Krebs cycle.

Total: 2 + 2 + 34 = 38 (theoretical maximum).

In reality, the actual ATP yield is closer to 30-32 due to leaky membrane and transport costs.

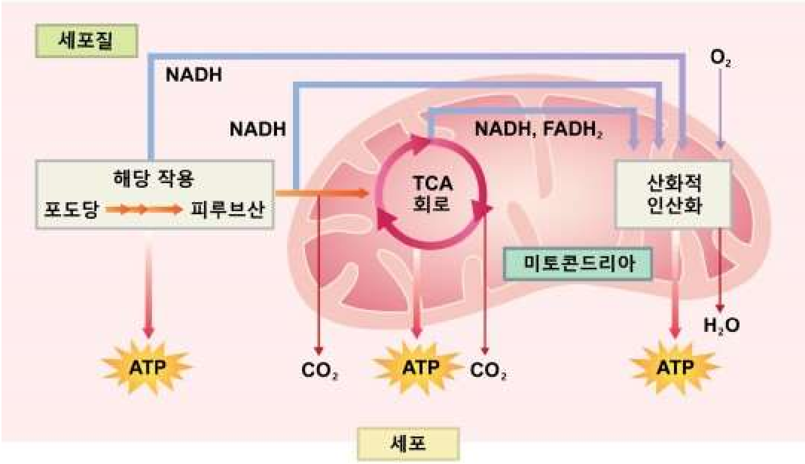
A theoretical yield of 38 ATP per glucose molecule, this number assumes optimal conditions and doesn't account for leakages or losses in efficiency

Skeletal muscles generate ATP primarily through a combination of anaerobic and aerobic pathways. Anaerobic pathways, like glycolysis, produce a small amount of ATP (2 ATP per glucose) quickly. Aerobic pathways, primarily occurring in the mitochondria through the citric acid cycle and electron transport chain, produce significantly more ATP (around 32-34 ATP per glucose). The total ATP produced depends on the intensity and duration of muscle activity.

Energy Sources for Muscle Contraction

Special importance for sports physiology

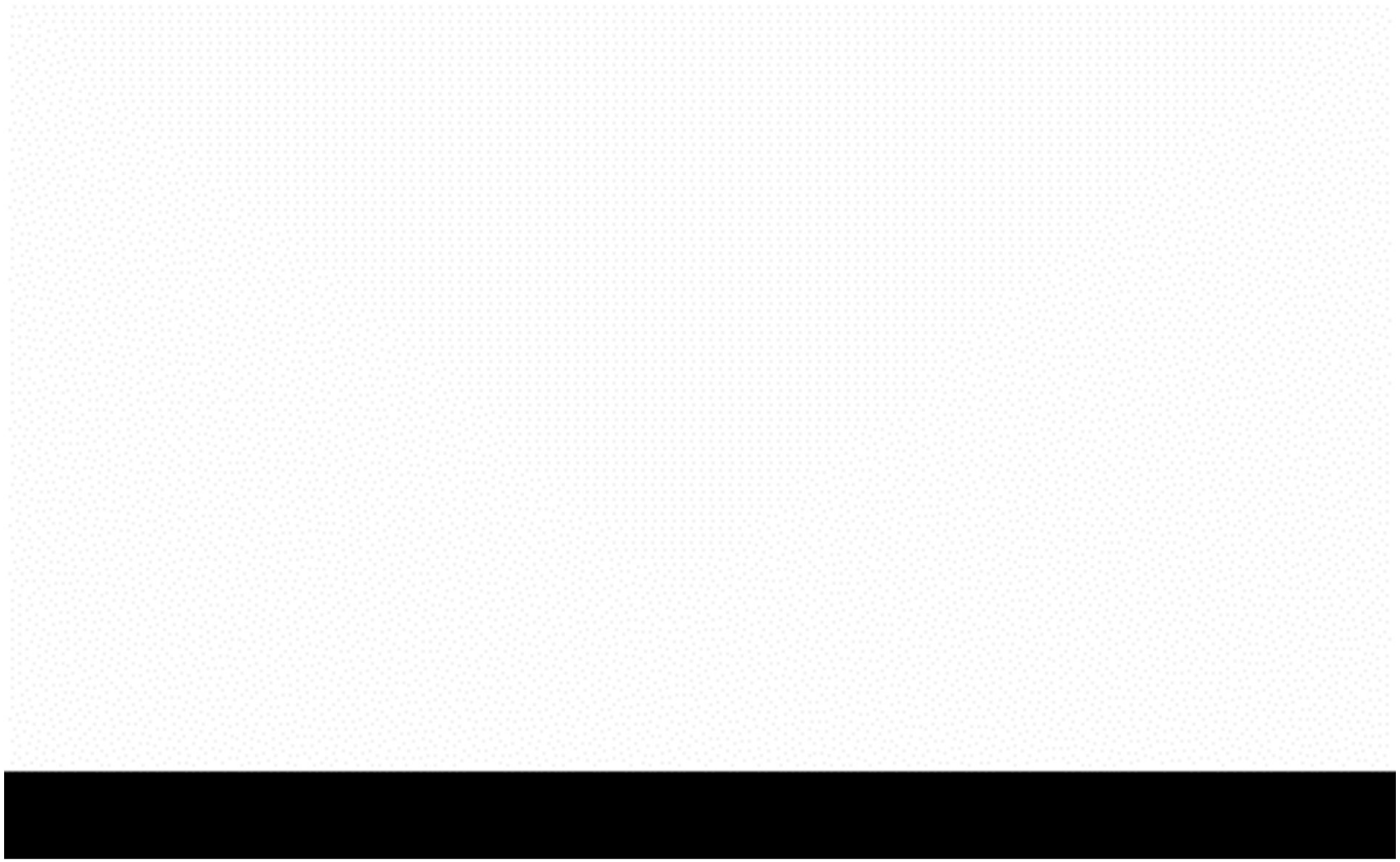
- Importance of glycolysis
  1. Glycolysis reactions can occur in the absence of oxygen
  2. Glycolysis is about 2.5 times faster in ATP formation with oxygen



- The **Krebs cycle** (크랩스가 발견) or **TCA cycle (tricarboxylic acid cycle)** or **Citric acid cycle** is a series of enzyme catalyzed reactions occurring in mitochondria to generate ATP.

- 해당작용**(glycolysis)**의 마지막 산물인 **pyruvate**가 이산화탄소**,** 수소이온**,** 및 전자로 산화되어 분해되며 **ATP**가 형성**.**

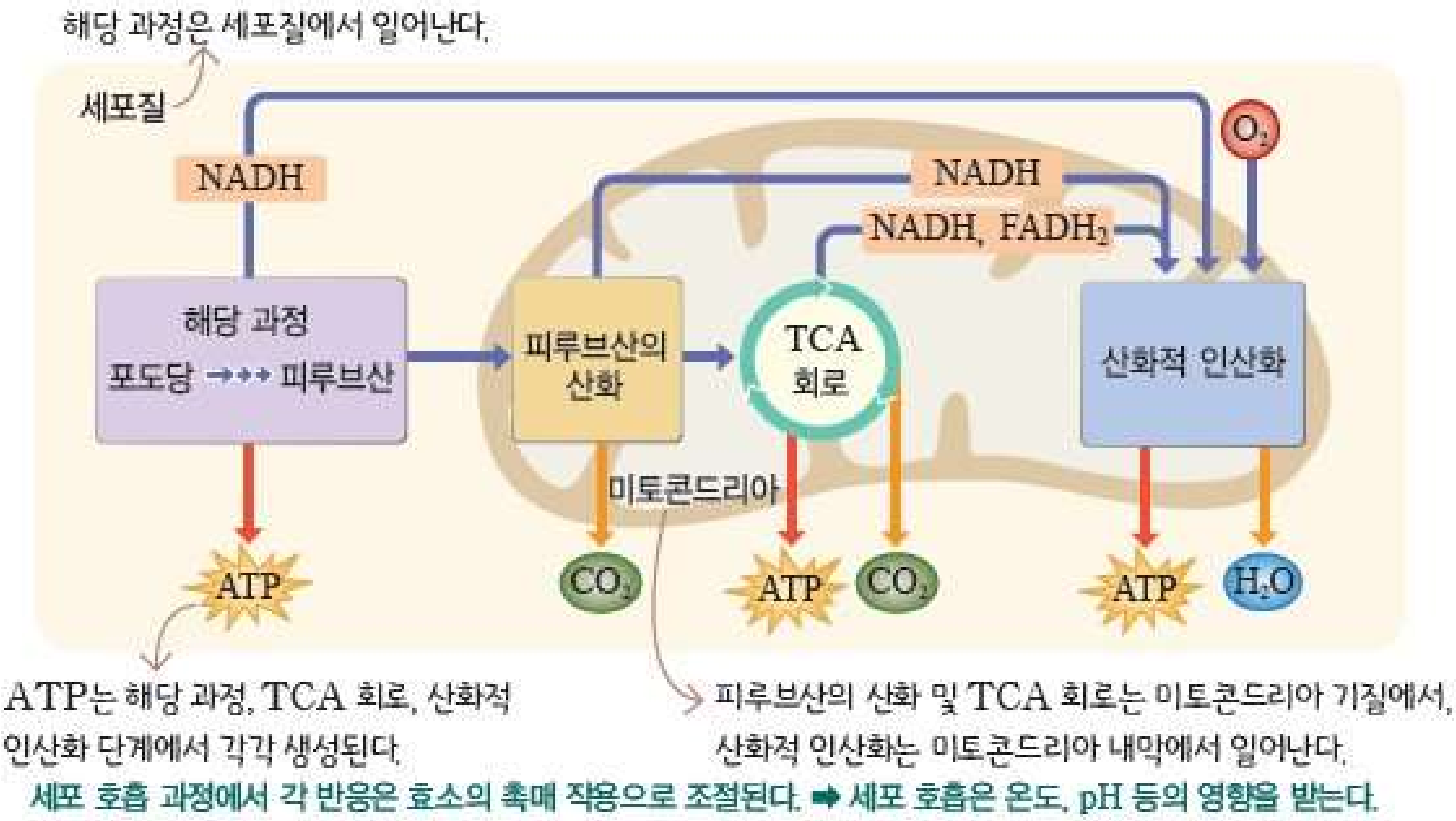
ATP Production in Skeletal Muscle



https://www.youtube.com/watch?v=zRlQvOrjYYo&ab_channel=KevinPetti%2CPh.D.

Oxidative Phosphorylation (산화적 인산화)

- 세포질에서 이루어지는 해당과정
- 미토콘드리아 내부 매트릭스에서 이루어지는 TCA 회로에서 산출된 전자 공여체인 NADH와 $FADH_2$를 이용해 미토콘드리아의 내막과 막간공간의 수소이온 농도 구배(기울기)를 형성한 뒤, 이를 에너지원으로 이용해 ADP에 인산을 붙여 ATP를 만드는 과정.



- **TCA** 회로의 존재 의의는 피루브산을 산화하는 과정에서 산화적 인산화 반응과 짝을 이루어 고등 동물의 생명 유지에 필요한 에너지원인 **ATP**를 생산.
- 산소가 **TCA** 회로에 직접 사용되지는 않지만 산소의 존재는 필수적임
- 무산소 상태에서 젖산(**LACTATE**) 생성 (고강도 운동 시, 젖산 축적. 운동선수의 근육통 및 피로 회복을 위해서, 신속한 젖산 제거 필요)
- 유산소 상태에서는 산소를 소모하여 **CO_2**와 **H_2O** 생성

Efficiency of Muscle Contraction

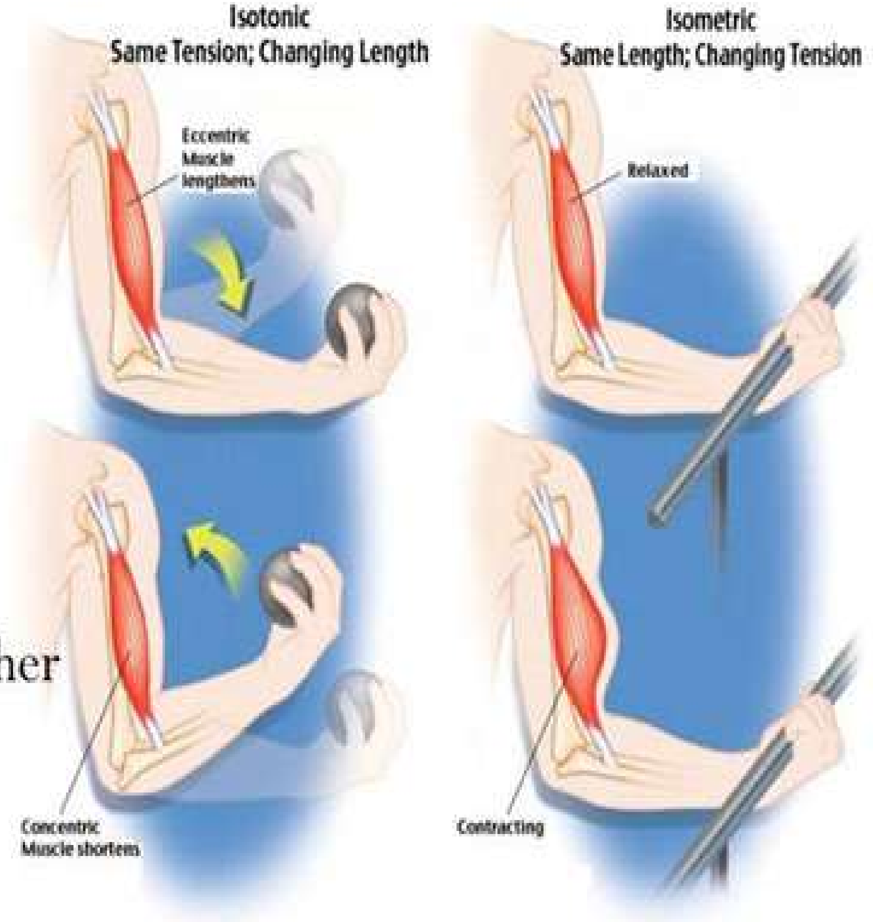
- Efficiency of muscle contraction: how much energy is converted into work, not heat.
- Percentage of input energy to muscle converted into work is less than 25%. The remainder becoming heat. => low efficiency.
- Why ?
  - One half of energy in food gets lost during formation of ATP
  - Only 40~45% of energy in ATP is converted into work.
  - Also during contraction, small amount of maintenance heat is produced
  - Rapid contraction needs to overcome muscle friction, reducing also the efficiency of contraction.

Characterization of Whole Muscle Contraction

- **Muscle twitches**: instantaneous electrical excitation of the nerve to a muscle or by passing a short electrical stimulus through the muscle induces a single, sudden contraction
- Isometric versus isotonic contraction
  - **Isometric**: muscle does not shorten during contraction (Fig. 6-11). Muscle contracts against a force transducer without decreasing the muscle length.
    - Used to compare functional characteristics of different muscle types
  - **Isotonic**: muscle does shorten, but tension on muscle remains constant throughout contraction (Fig. 6-11). Muscle shortens against a fixed load.

Isometric And Isotonic Exercise

- **Isotonic Contractions**
  - Concentric – muscle shortens and does work
  - Eccentric – muscle generates force as it lengthens
- **Isometric Contractions**
  - Tension builds but muscle neither shortens or lengthens
  - Maintains posture



Isotonic & Isometric Systems

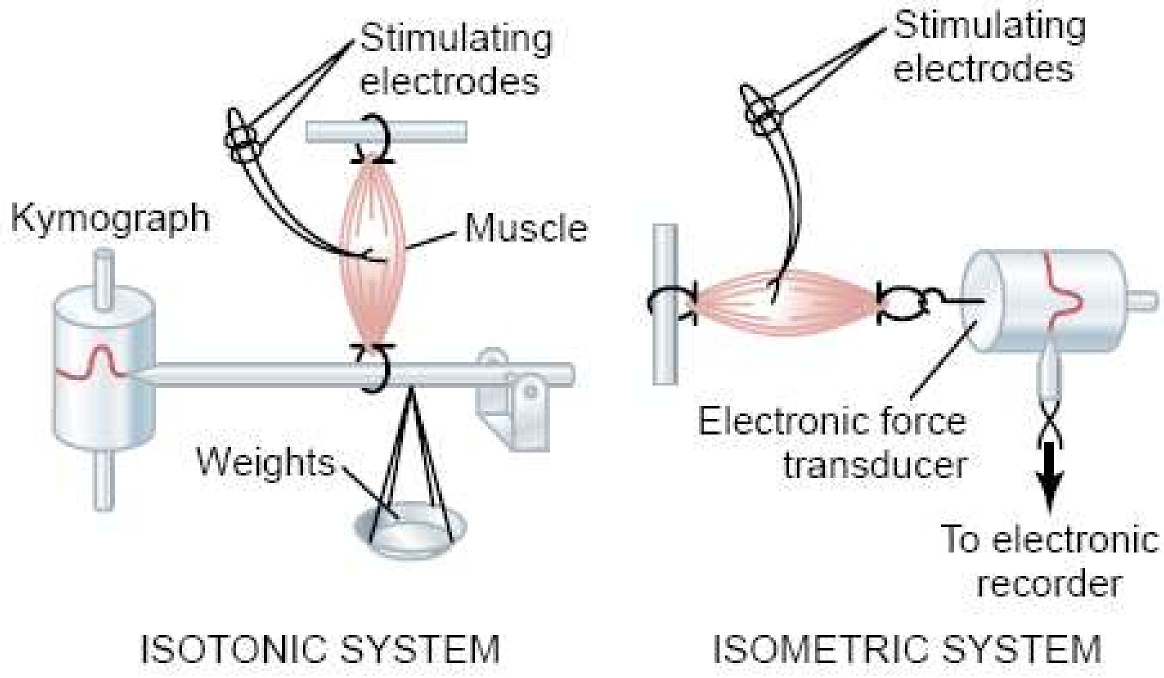


Figure 6–11

Isotonic and isometric systems for recording muscle contractions.

Isometic vs. Isotonic

- https://www.youtube.com/watch?v=8UzdS-9hD4w&ab_channel=NonstopNeuron

Characteristics of isometric twitches recorded from different muscles

- Mechanical characteristics of muscle contraction differ among muscles.
- Different size of muscles and different duration of isometric contractions (Fig. 6-12)
- Fast vs. Slow muscle fibers
  - Muscle is composed of a mixture of fast and slow muscle fibers
  - Fast fibers react rapidly
  - Slow fibers respond slowly with prolonged duration
- Fast fiber characteristics (next slide)
- Slow fiber characteristics (next-next slide)
- Roles of fast and slow fibers
  - Fast fibers for rapid and powerful muscle contraction (e.g., jumping and short-distance powerful running)
  - Slow fibers for prolonged and continued muscle activity (e.g., marathon)

Duration of Isometric Contractions

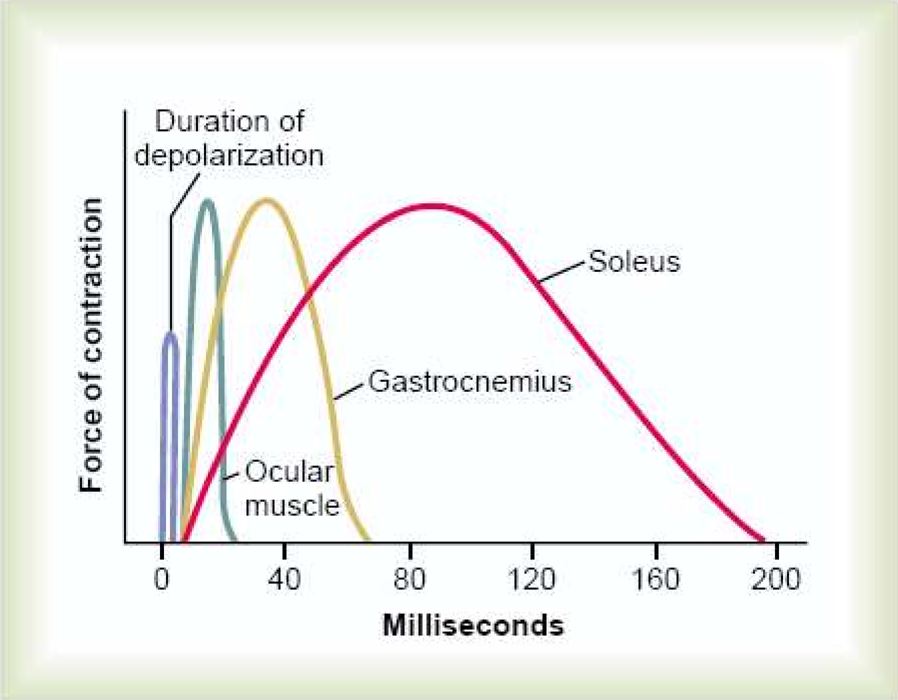


Figure 6–12

Duration of isometric contractions for different types of mammalian skeletal muscles, showing a latent period between the action potential (depolarization) and muscle contraction.

- Characteristics of isometric contractions
- Fig. 6-12: 3 different types of the skeletal muscles

Fast Fiber Characteristics

(1) Large fibers for great strength of contraction.

(2) Extensive sarcoplasmic reticulum for rapid release of calcium ions to initiate contraction.

(3) Large amounts of glycolytic enzymes for rapid release of energy by glycolytic process.

(4) Less extensive blood supply because oxidative metabolism is of secondary importance.

(5) Fewer mitochondria

***(glycolysis-해당작용: metabolic pathway that converts glucose into pyruvate, producing ATP)**

Slow Fiber Characteristics

(1) Smaller fibers.

(2) Also innervated by smaller nerve fibers.

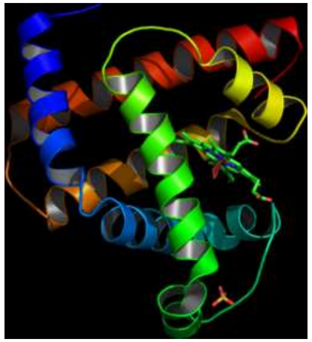
(3) More extensive blood vessel system and capillaries to supply extra amounts of oxygen.

(4) Greatly increased numbers of mitochondria, also to support high levels of oxidative metabolism.

(5) Fibers contain large amounts of myoglobin, an iron containing protein similar to hemoglobin in red blood cells. Myoglobin combines with oxygen and stores it until needed; this also greatly speeds oxygen transport to the mitochondria. The myoglobin gives the slow muscle a reddish appearance and the name *red muscle,* whereas a deficit of red myoglobin in fast muscle gives it the name *white muscle.*

*Myoglobin: an iron- and oxygen-binding protein found in muscle. Carries blood oxygen to muscle tissues

Myoglobin

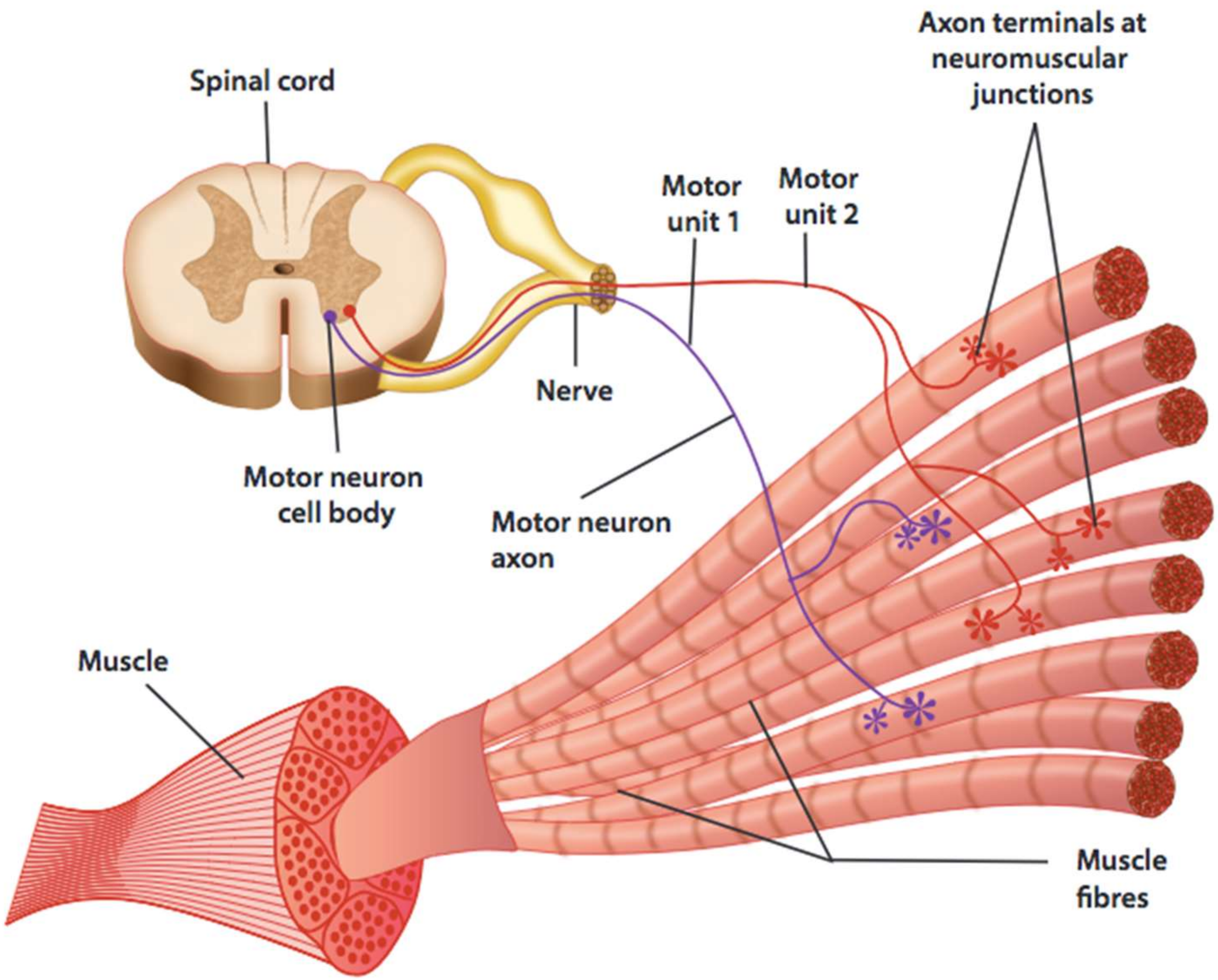


Mechanics of Skeletal Muscle Contraction

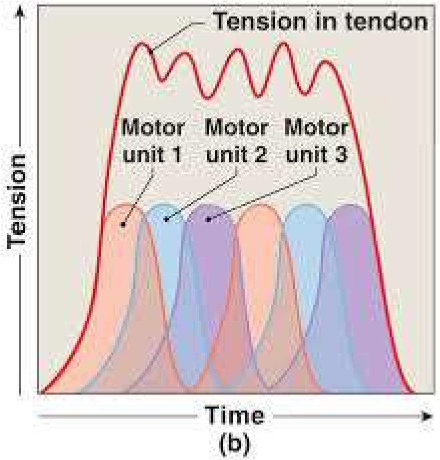
- **Motor Unit**:
  - All the muscle fibers innervated by a single motor nerve fiber are called a motor unit (picture)
  - Large muscle without fine control have several hundred muscle fibers in a motor unit.
  - Small muscles that react rapidly and have fine control, have few muscle fibers
- Muscle Contractions of Different Force – **Force Summation**
  - Summation: adding together of individual twitch contractions to increase the intensity of overall muscle contraction
  - Summation in two ways

    (1) Multiple fiber summation: increase the number of motor units contracting simultaneously.

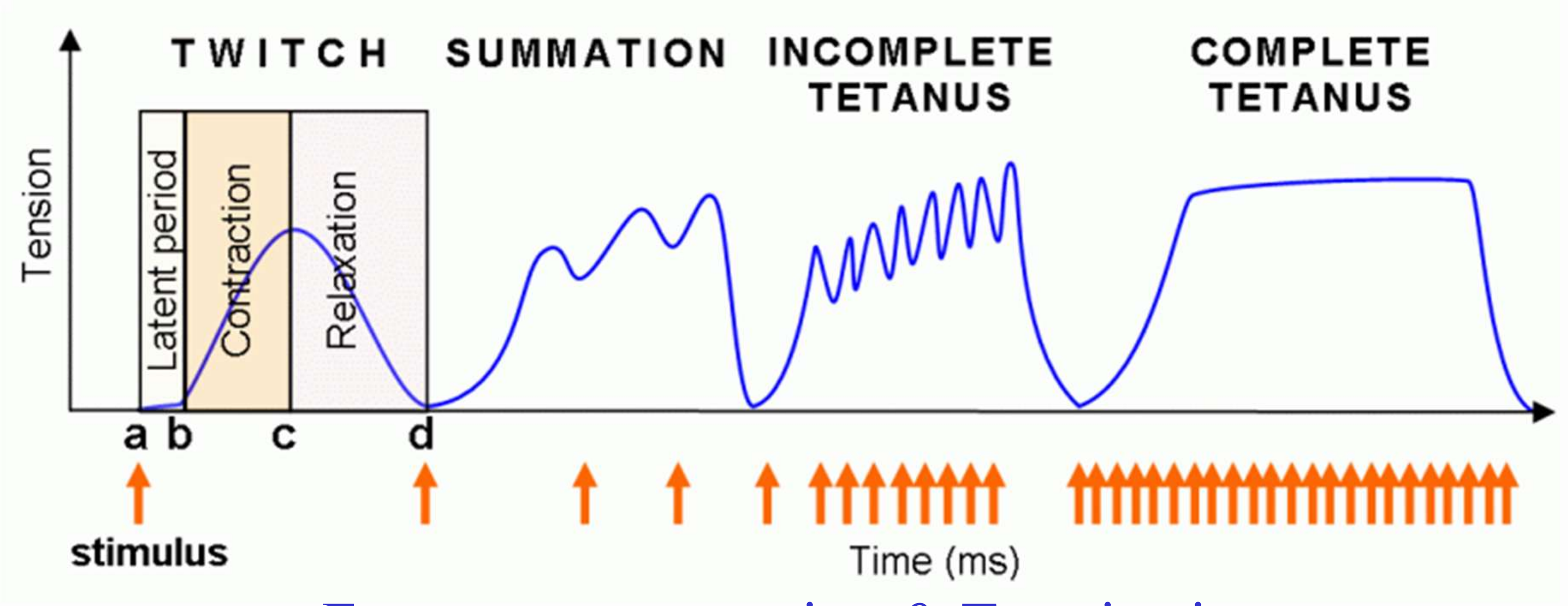
    (2) Frequency summation (Fig. 6-13): increase the frequency of contraction (leads to tetanization).
  - Maximum strength of contraction: 3~4kg/cm^2



Axon of motor neurons extend from the spinal cord to the muscle.
There each axon divides into a number of axon terminals that form neromuscular junctions with muscle fibers scattered throughout the muscle.



Multiple fiber summation



Frequency summation & Tetanization

Frequency Summation & Tetanization

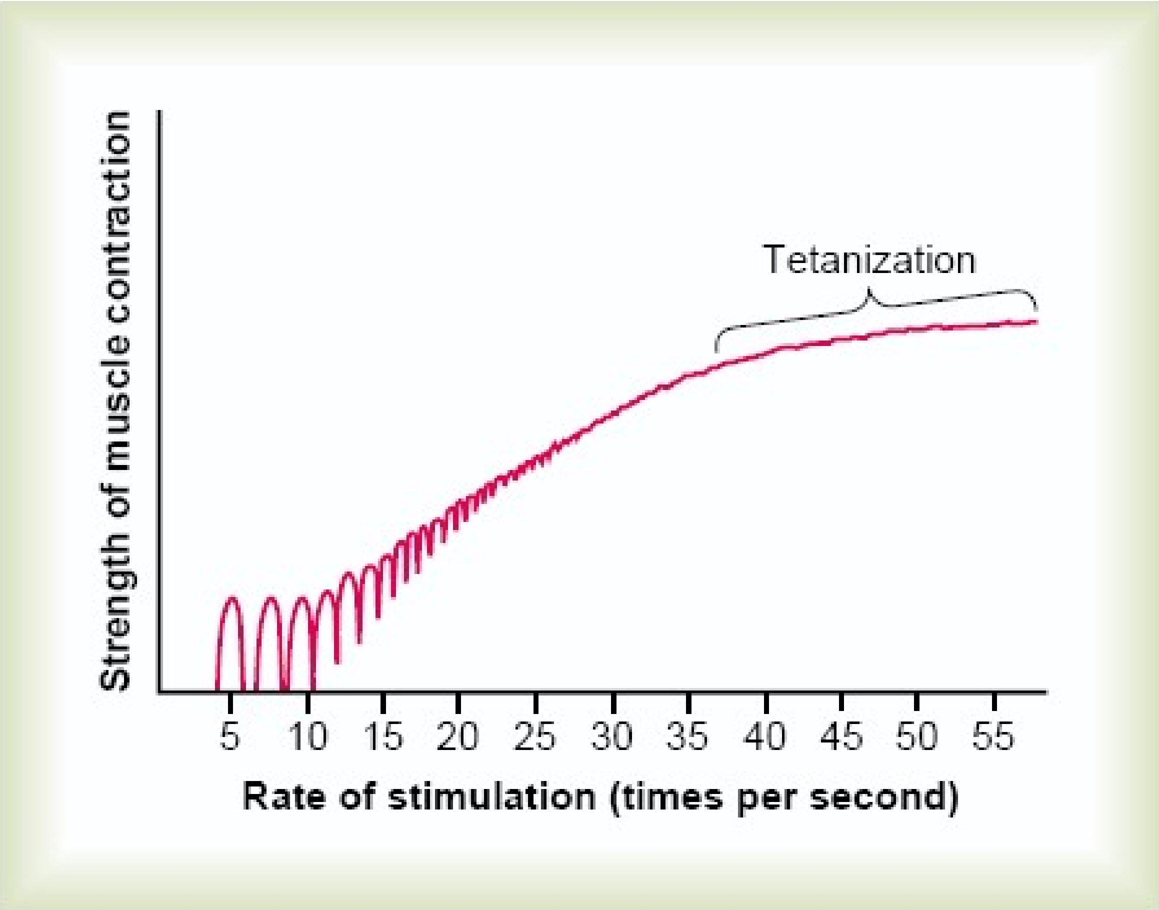
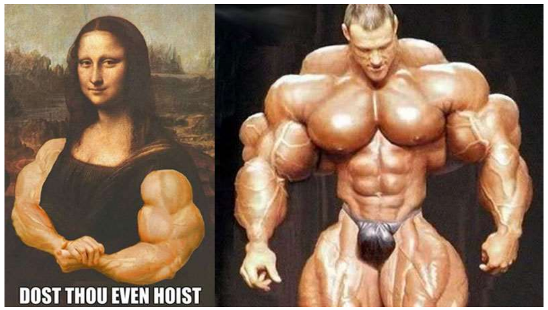


Figure 6–13

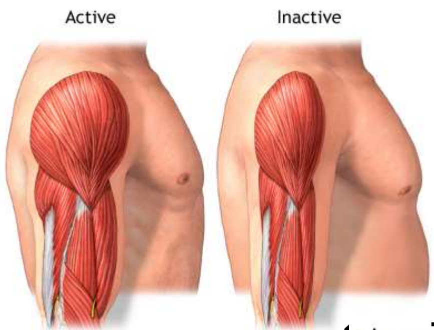
Frequency summation and tetanization.

What is tetanization?

- **Skeletal muscle tone**: when muscles at rest, a certain amount of tautness(팽팽함) remains.
- **Muscle fatigue** due to prolonged and strong contraction of muscles.
  – Fatigue increases proportional to the rate of depletion of muscle glycogen
  – Reduction in the transmission of nerve signal
  – Interruption of blood flow, loss of oxygen
- Remodeling of Muscle to Match Function
  – Muscle hypertrophy: muscle enlargement
  – Muscle atrophy: muscle decrease



hypertrophy




atrophy

Muscle Denervation

- When a muscle **loses its nerve supply**, it no longer receives the contractile signals that are required to maintain normal muscle size. Therefore, **atrophy begins almost immediately**.
- **After about 2 months**, **degenerative changes also begin** to appear in the muscle fibers themselves. If the nerve supply to the muscle grows back rapidly, **full return of function can occur in as little as 3 months**, but from that time onward, the capability of functional return becomes less and less, with no further return of function after 1 to 2 years.
- In the final stage of **denervation atrophy**, most of the muscle fibers are **destroyed** and **replaced by fibrous and fatty tissue.** The fibers that do remain are composed of a long cell membrane with a lineup of muscle cell nuclei but with **few or no contractile properties** and **little or no capability of regenerating myofibrils** if a nerve does regrow.
- The fibrous tissue that replaces the muscle fibers during denervation atrophy also has a tendency to continue **shortening** for many months, which is called ***contracture***.
- Therefore, one of the most important problems in the **practice of physical therapy** is to keep atrophying muscles from developing debilitating and disfiguring contractures. This is achieved by **daily stretching of the muscles or use of appliances that keep the muscles stretched during the atrophying process.**

Rigor Mortis

- Several hours after death, all the muscles of the body go into a state of ***contracture*** called "**rigor mortis**"; that is, the muscles contract and become **rigid, even without action potentials**.
- This rigidity results from **loss of all the ATP**, which is required to cause separation of the cross-bridges from the actin filaments during the relaxation process.
- The muscles remain in rigor until the muscle proteins deteriorate about 15 to 25 hours later
- All these events occur more rapidly at higher temperatures.