General physiology
Second semester 2023-2024
lecture 26
Skeletal Muscle Mechanics

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Lecture objectives

- Define muscle twitch and relate the electrical and mechanical activity of the muscle
- Describe what happens during an isotonic and isometric contraction .
- Define preload and after load and their effect on muscle mechanics
- Explain the length–tension relationship in sarcomere and hole skeletal muscle and cardiac muscles
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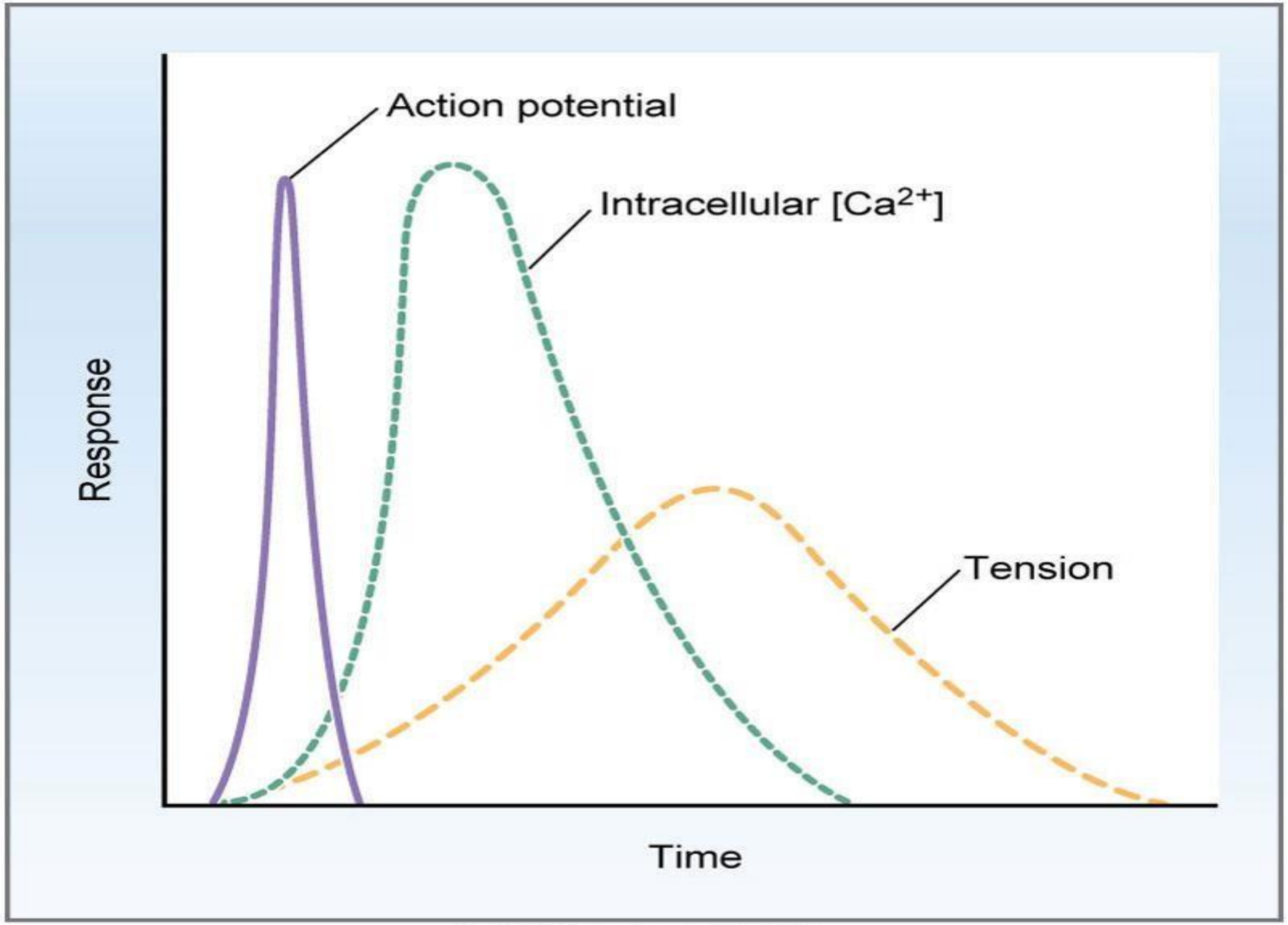
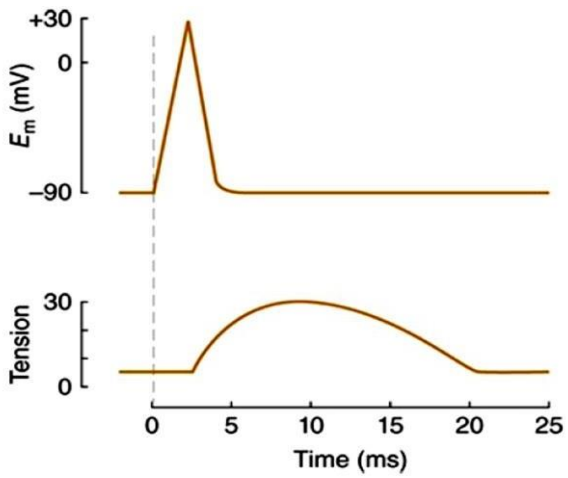
- Explain the force–velocity relationship in skeletal muscle; explain the basis for the *V*max. And How does the load affect
- shortening and velocity of shortening?
- Define motor unit and describe the relation of the size of the motor unit to affects the type of skeletal muscle movement
- Explain how whole muscle strength of contraction can be graded
- Define motor unit recruitment and frequency summation
- Define the phenomena of tetany and treppe
- Compare and contrast of different properties of fast and slow muscle

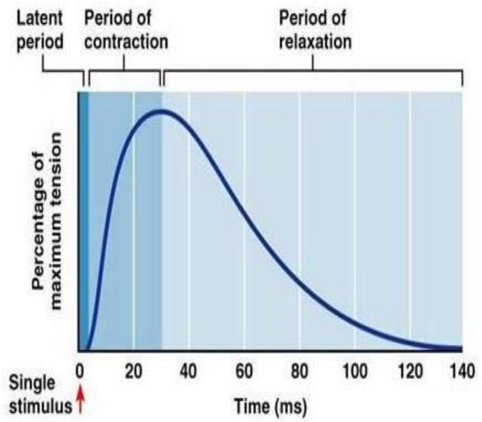
Temporal sequence of events in excitation-contraction coupling in skeletal



The electrical and mechanical responses of a mammalian skeletal muscle

- Muscle Twitch
- A single action potential causes a brief contraction followed by relaxation.
- **Latency 2 msec**
- duration of the twitch varies with the type of muscle being tested.
- “Fast” muscle fibers, primarily those concerned with fine, rapid, precise movement, have twitch durations as short as 7.5 ms.
- “Slow” muscle fibers, principally those involved in strong, gross, sustained movements, have twitch durations up to 100 ms.





Mechanical properties of muscle contraction
Length tension relationship

A length-tension diagram for a single fully contracted Sarcomere It shows the effect of sarcomere length and the amount of myosin- actin filament overlap on the active tension developed by a contracting muscle fiber

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.*

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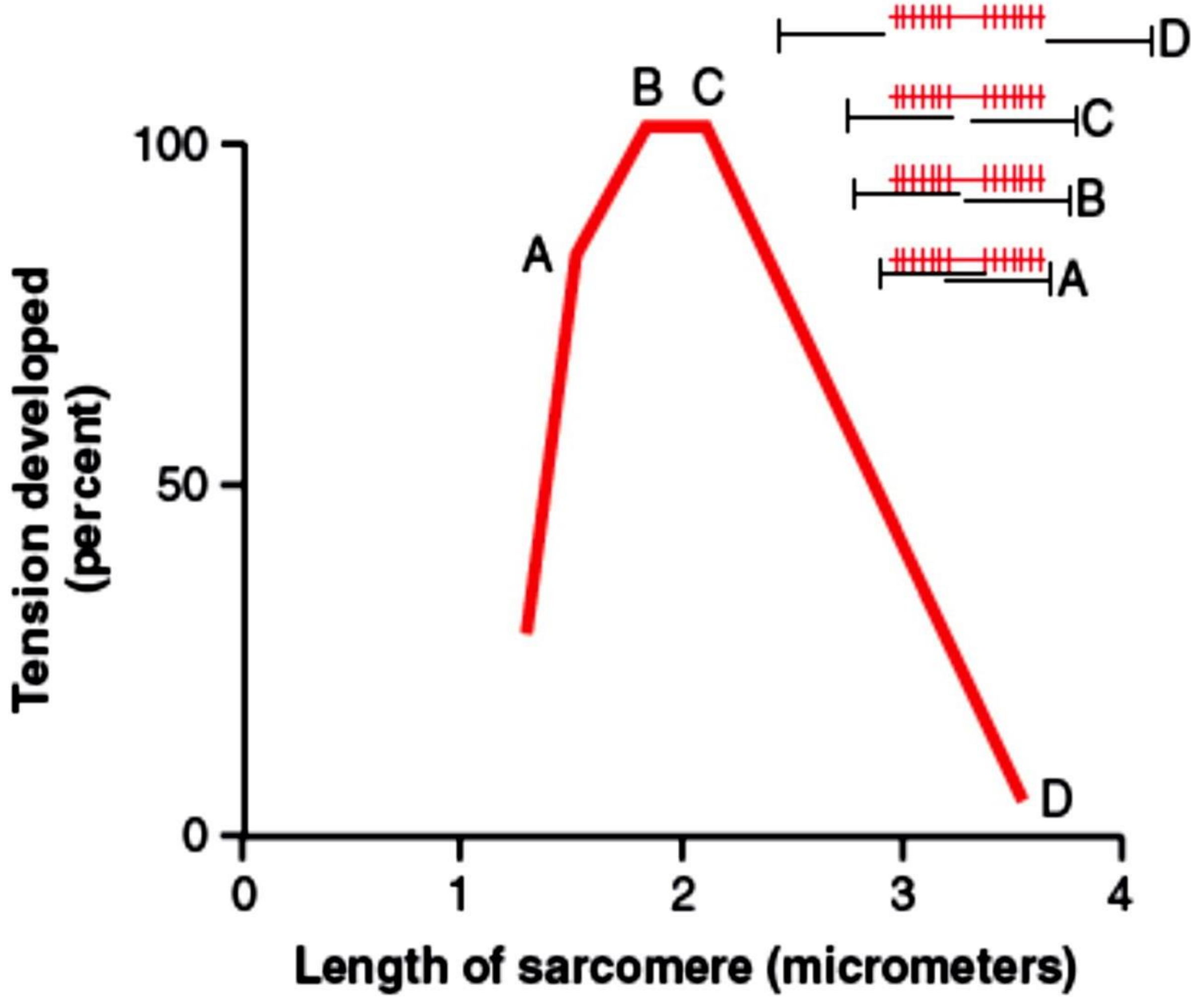
Amount of Actin and Myosin Filament Overlap Determines Tension Developed by the Contracting Muscle



Effect of Muscle Length on Force of Contraction in the Whole Intact isolated Muscle
Relation of muscle length to tension in the isolated muscle both before and during muscle contraction

Active tension cannot be measured directly What can be measured?

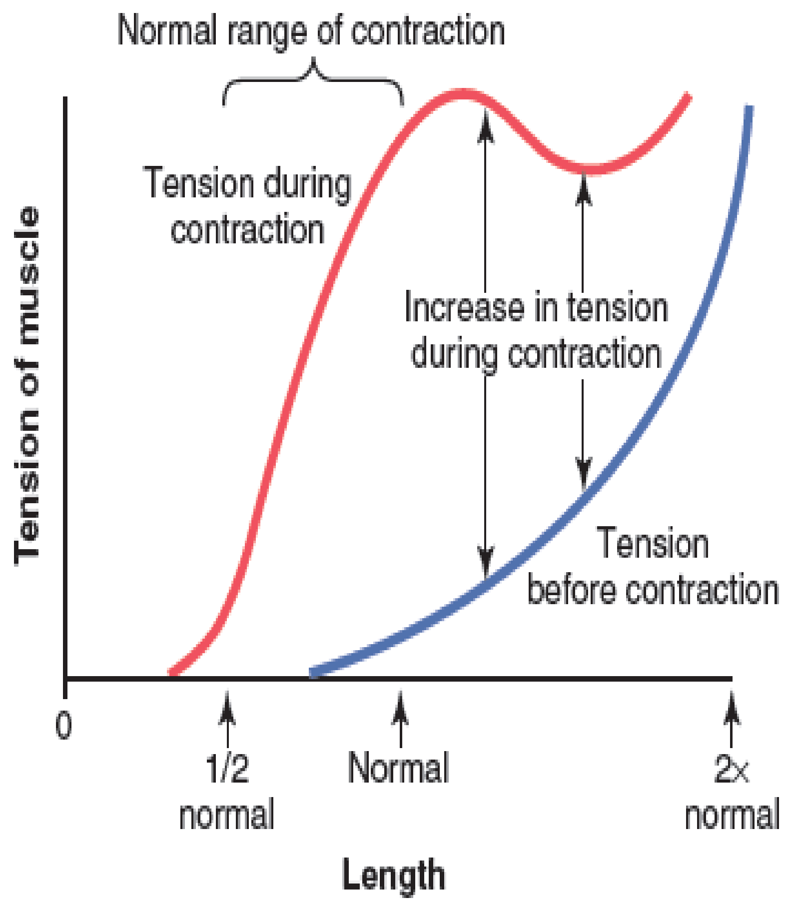
(1) passive tension - *tension required to extend a resting muscle*

(2) (2) total tension - *active tension and passive combined*

The active or developed tension is the difference between the total tension and the passive tension. It is the tension that the muscle produces during the contraction..

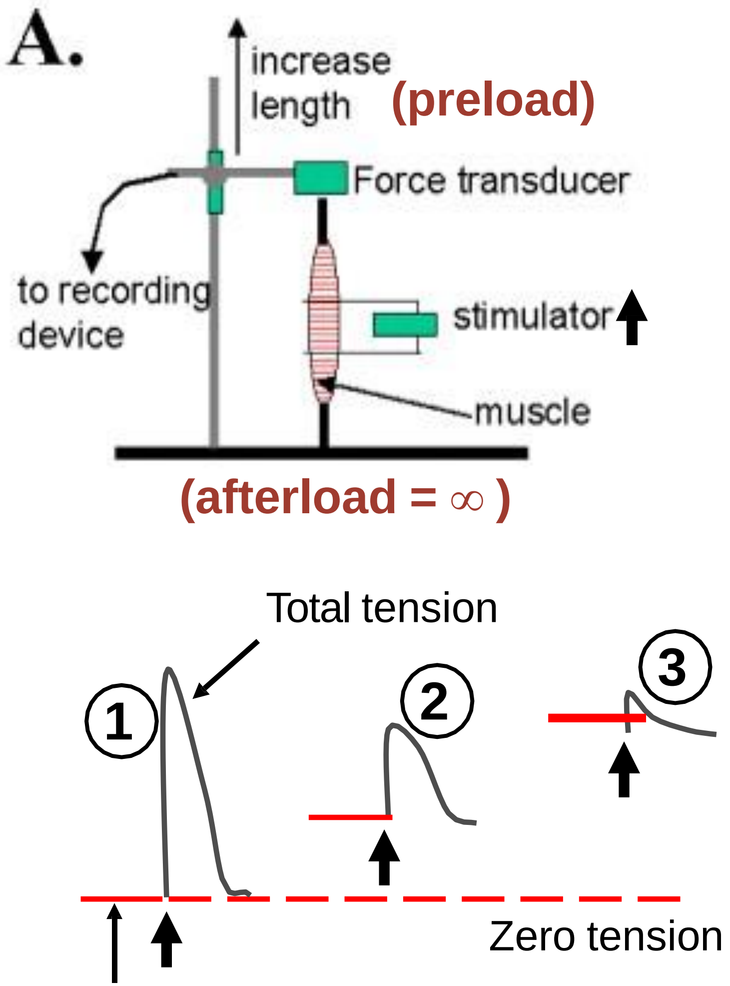
when the muscle is at its normal *resting* length, which is at a sarcomere length of about 2 micrometers, it contracts on activation with the approximate maximum force of contraction. However, the *increase* in tension that occurs during contraction, called *active tension*, decreases as the muscle is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

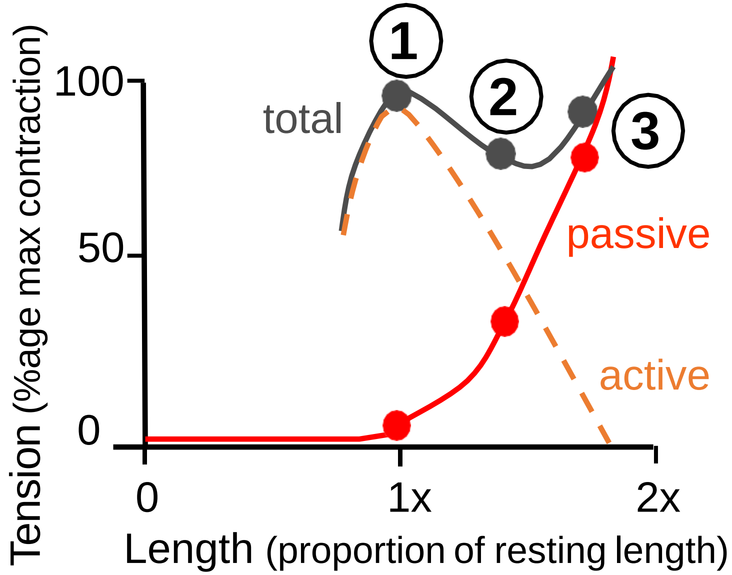
Note that active tension falls away linearly with increasing resting length



Muscle length or preload

Length-tension relation – the experiment

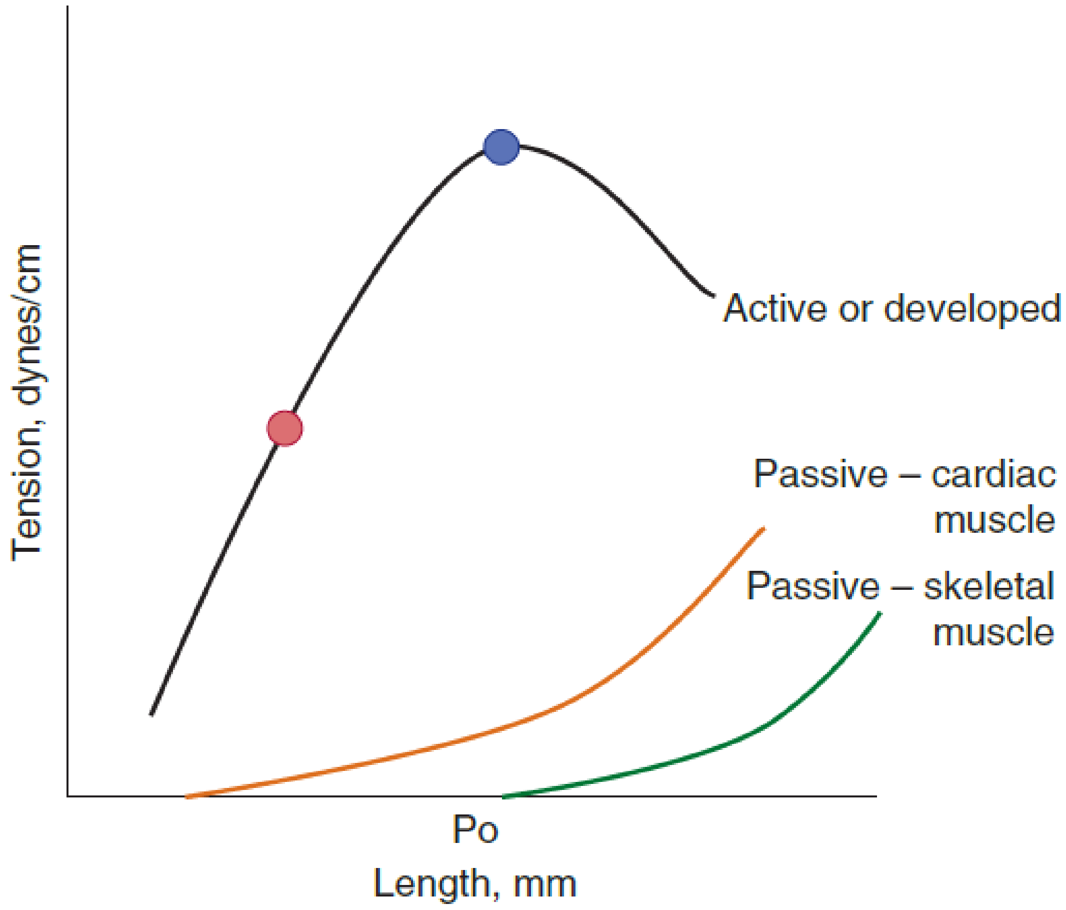




Comparison of the length tension relationship of skeletal and cardiac muscle

Note that in skeletal muscle, the fibers are usually operating at the blue point—resting length is optimum because most skeletal muscle
is held in place by the bones and resting length cannot vary greatly.

Cardiac muscle normally operates at lower (red point) than optimum length and therefore has reserve capacity to increase tension development, that is, have stronger contractions, when resting length is increased



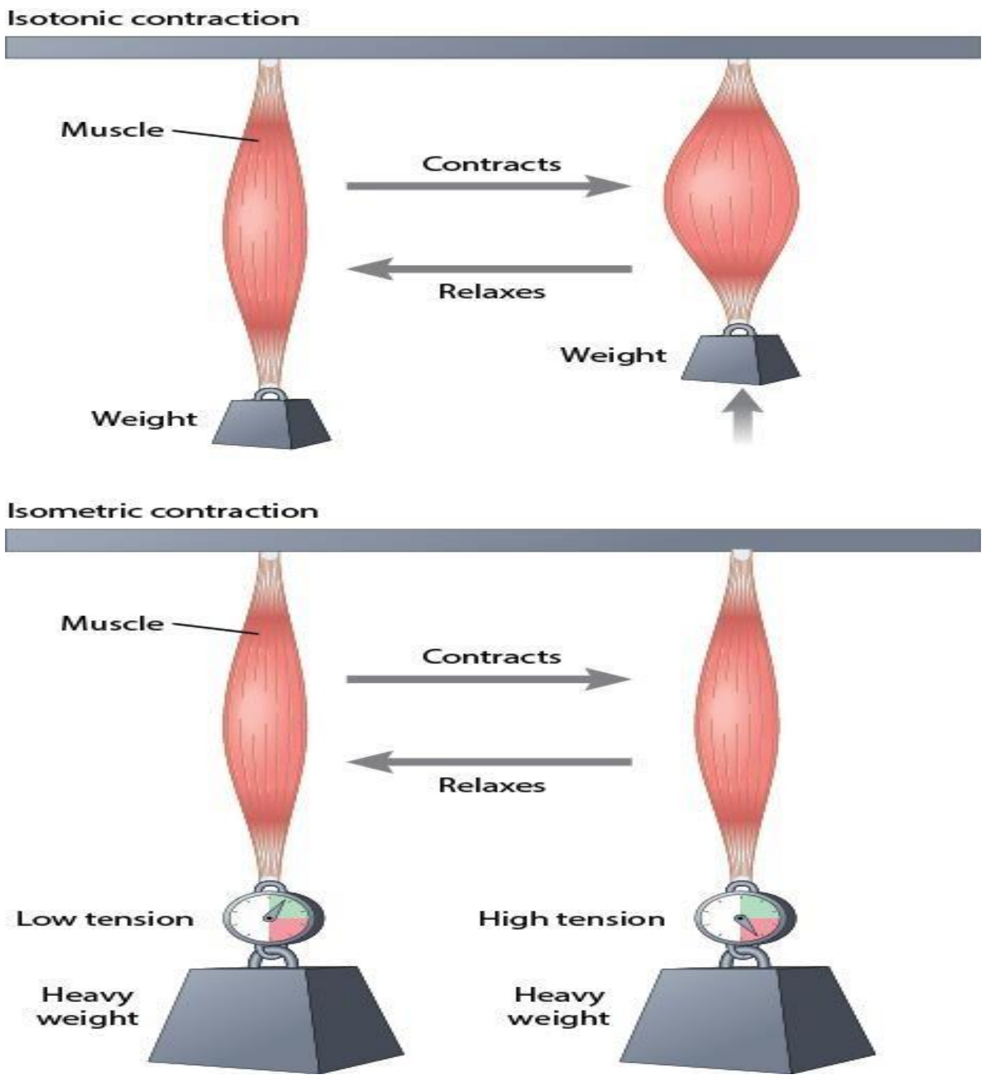
The length tension relationship in cardiac muscle and skeletal muscle

- **Differences are primarily due to the presence of passive tension at shorter length in cardiac muscles due to**
- Anatomic differences in structure of skeletal muscle (all of the fibers in parallel) and cardiac muscle (fibers exist in a basket weave-type pattern)
- The properties of the noncontractile components in skeletal muscle versus cardiac muscle.
  - in skeletal muscle, the fibers are usually operating at an optimal resting length because most skeletal muscle is held in place by the bones and resting length cannot vary greatly.
- Cardiac muscle normally operates at lower than optimum length and therefore has reserve capacity to increase tension development, that is, have stronger contractions, when resting length is increased.
- In the intact heart, cardiac cell resting length is set by the volume in the ventricle(EDV) at the end of diastole (the relaxed state of cardiac muscle).

Isometric and isotonic contractions

.Isotonic contraction occurs when the force of the muscle contraction is greater than the load and the tension on the muscle remains constant during the contraction; when the muscle contracts, it shortens and moves the load.

Isometric contraction occurs when the load is greater than the force of the muscle contraction; the muscle creates tension when it contracts, but the overall length of the muscle does not change.



Isotonic and isometric systems for recording muscle contractions

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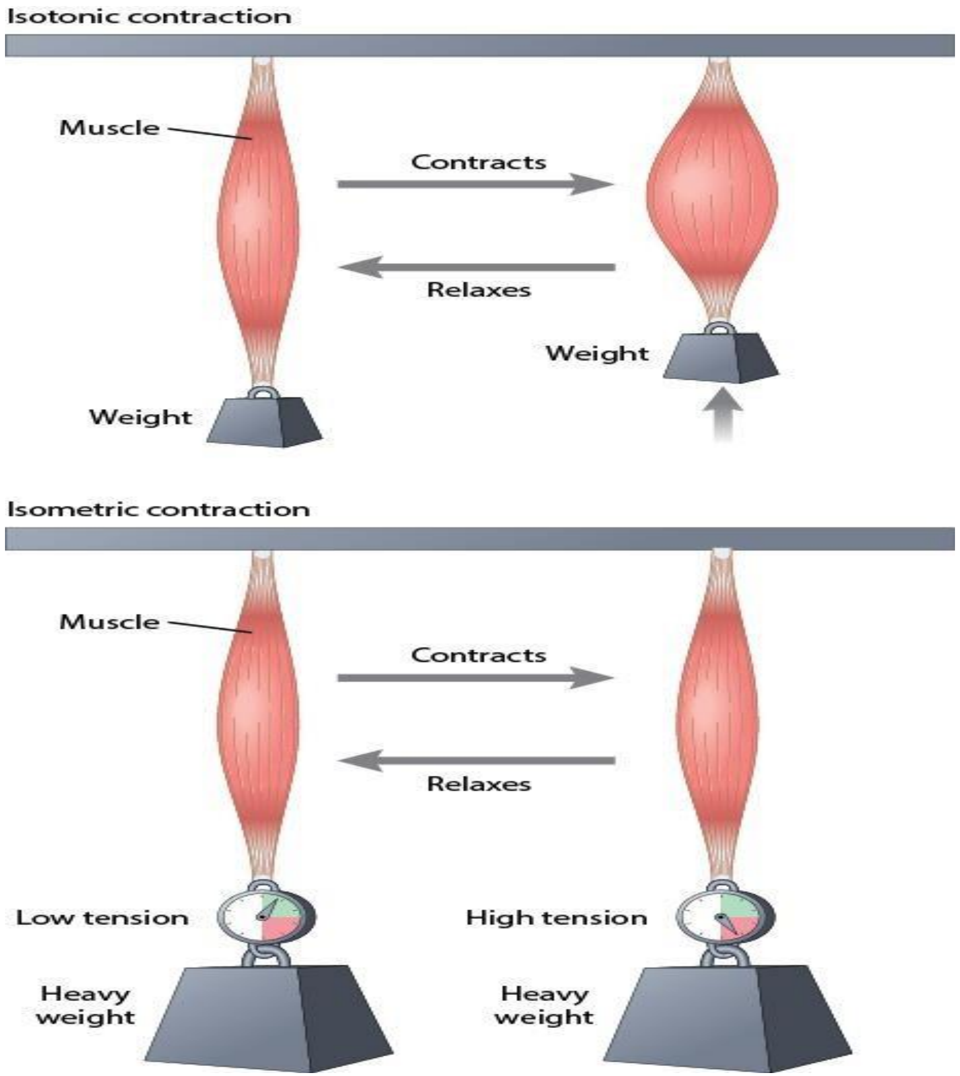
Isometric and isotonic contractions

- Isotonic: muscle shortens. Important for:
  1. For body movements
  2. Moving external objects

- Isometric: no muscle shortening. Important for:
  1. Maintaining posture (keep legs stiff while standing)
  2. Supporting objects in a fixed place



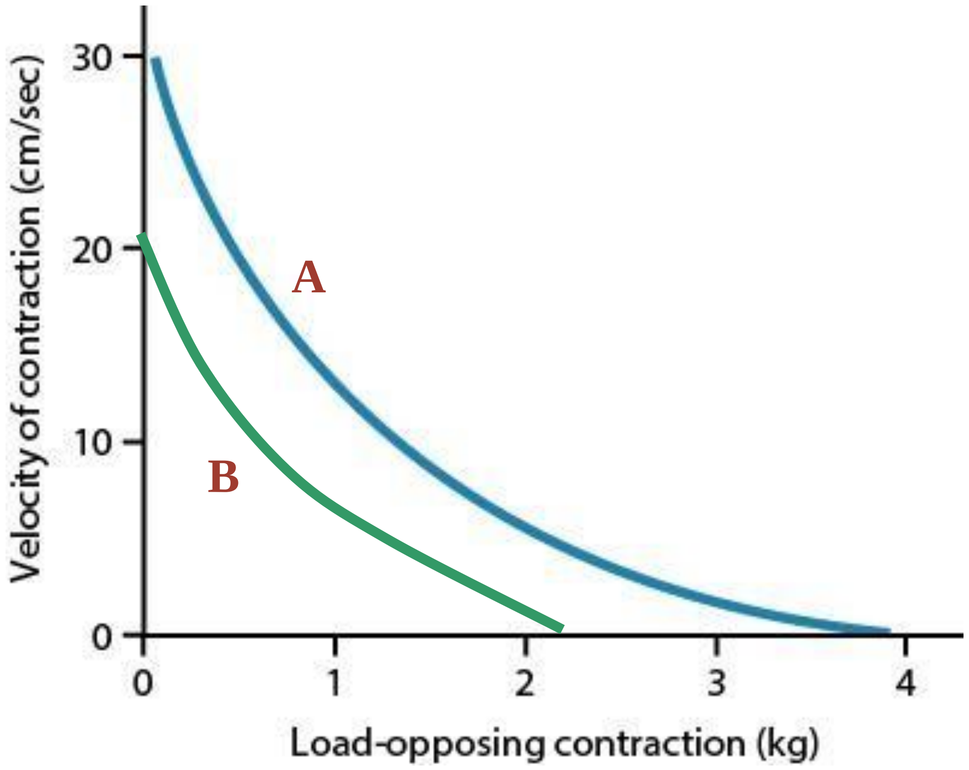
Relationship of Contraction Velocity to Load

The force–velocity curve is generated from the study of isolated muscle during isotonic contractions

no afterload:
- maximum velocity at minimum load

increased afterload:
- contraction velocity decreases

contraction velocity is zero when afterload = max force of contraction



A: larger, faster muscle (white muscle)
B: smaller, slower muscle (red muscle)

Types of skeletal muscle

- speed of twitch contraction -

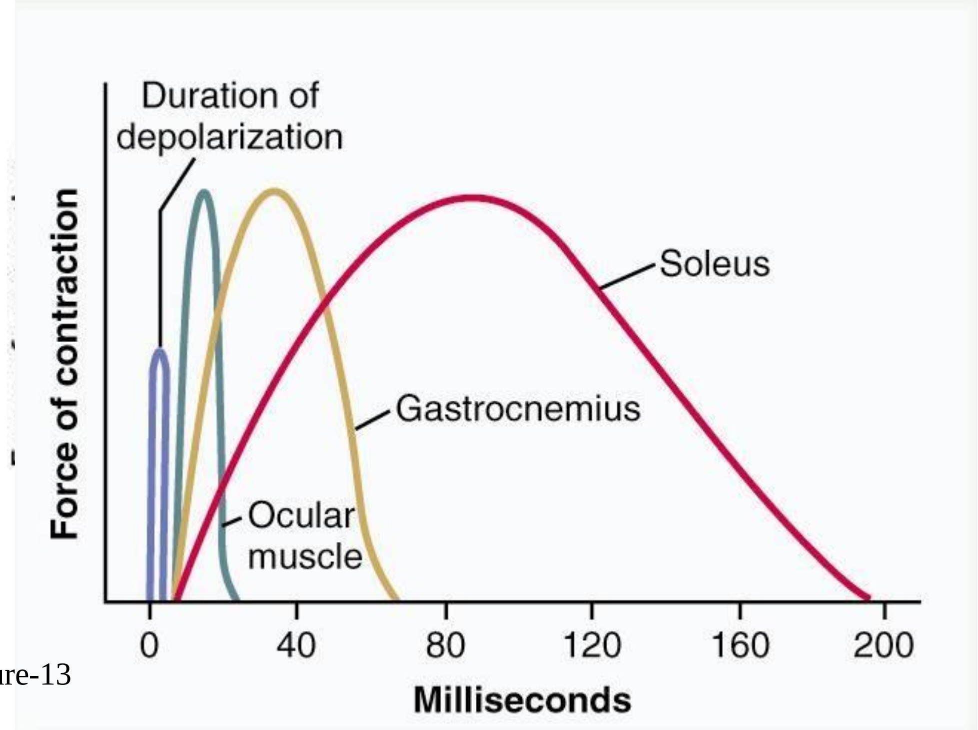


Figure-13

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

- Speed of contraction determined by V_{max} of myosin ATPase.
  - **High V_{max}** ***(fast, white)***
    - rapid cross bridge cycling
    - *rapid rate of shortening (fast fiber)*
  - **Low V_{max}** ***(slow, red)***
    - slow cross bridge cycling
    - slow rate of shortening (slow fiber)
- Most muscles contain both types of fiber, but proportions differ
- All fibers in a particular motor unit will be of the same type, i.e., fast or slow.

Fast and slow fibers types

Slow Fibers (Type 1, Red Muscle).

- Slow fibers are smaller than fast fibers.
- Slow fibers are also innervated by smaller nerve fibers.
- Compared with fast fibers, slow fibers have a more extensive blood vessel system and more capillaries to supply extra amounts of oxygen.
- Slow fibers have greatly increased numbers of mitochondria to support high levels of oxidative metabolism.
- Slow fibers contain large amounts of myoglobin

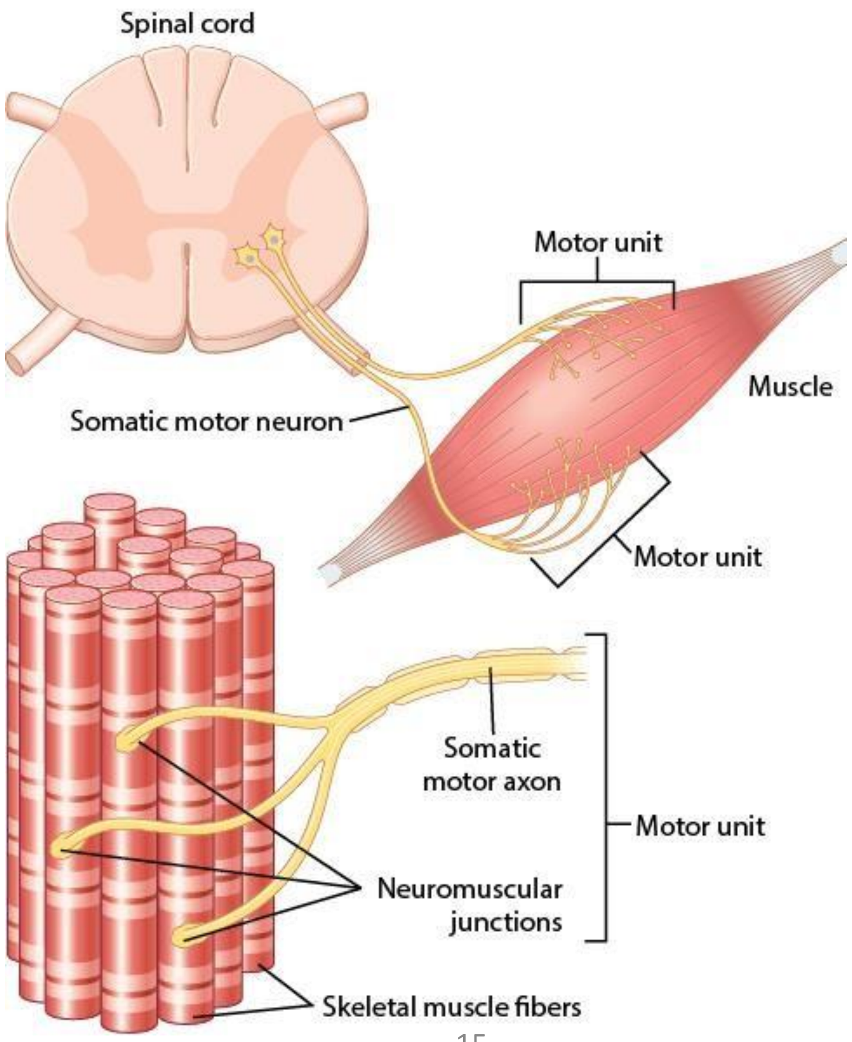
Fast fibers Type , white muscles

- Are large for great strength of contraction.
- have an extensive sarcoplasmic reticulum is present for rapid release of calcium ions to initiate contraction.
- Have Large amounts of glycolytic enzymes are present for rapid release of energy by the glycolytic process.
- Have less extensive blood supply than do slow fibers because oxidative metabolism is of secondary importance.
- have fewer mitochondria than do slow fibers, also because oxidative metabolism is secondary.
- A deficit of red myoglobin in fast muscle gives it the name *white muscle.*

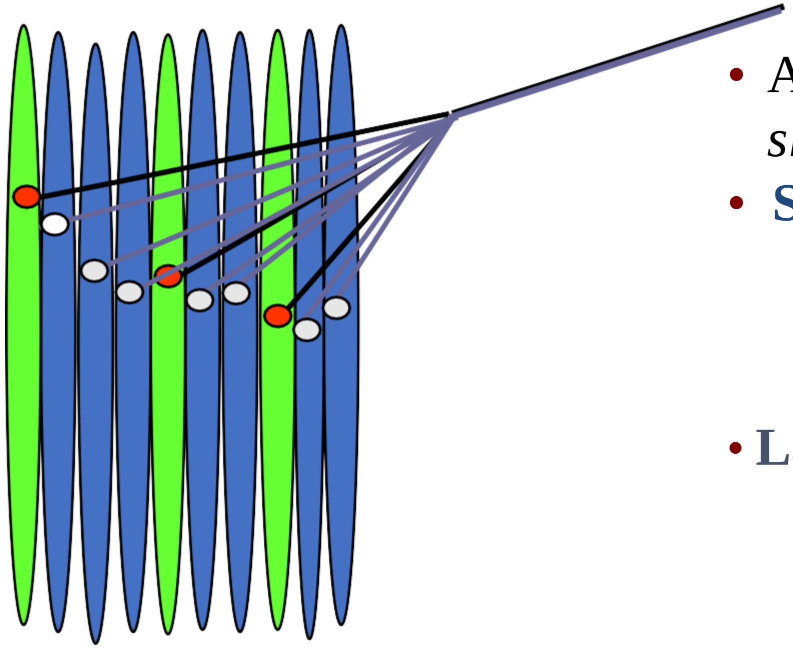
Motor Unit

A collection of muscle fibers innervated by a single motor neuron

A motor unit consists of a motor neuron and the group of skeletal muscle fibers it innervates. A single motor axon may branch to innervate several muscle fibers that function together as a group. Although each muscle fiber is innervated by a single motor neuron, an entire muscle may receive input from hundreds of different motor neurons.



Motor Unit (cont.)



- All fibers are same type *(fast or slow)* in a given motor unit
- **Small motor units** *(e.g., larnyx, extraocular)*
  - as few as 10 fibers/unit
  - precise control
  - rapid reacting
- **Large motor units** *(e.g., quadriceps muscles)*
  - as many as 1000 fibers/unit
  - coarse control
  - slower reacting
- Motor units overlap, which provides coordination
-

Muscle Contractions of Different Force.
Force Summation.

- *Summation* means the adding together of individual twitch contractions to
increase the intensity of overall muscle contraction.

- Summation occurs in two ways:
- (1) Recruitment of motor units by : increasing the number of motor units
contracting simultaneously, which is called *multiple fiber summation*

- 2) by increasing the frequency of contraction, which is called *frequency summation* and can lead to *tetanization*

Muscle contraction – *force summation*

Force summation:
increase in contraction intensity as a result of the additive effect of individual twitch contractions

(1) Multiple fiber summation:

- results from an ***increase in the number of motor units*** contracting simultaneously (fiber recruitment)
- **Size principle**

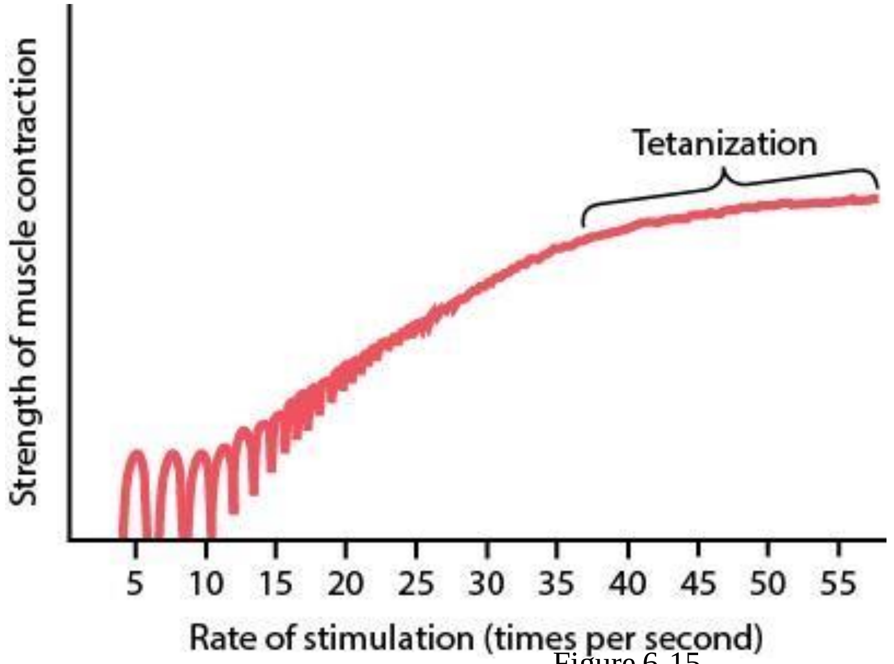
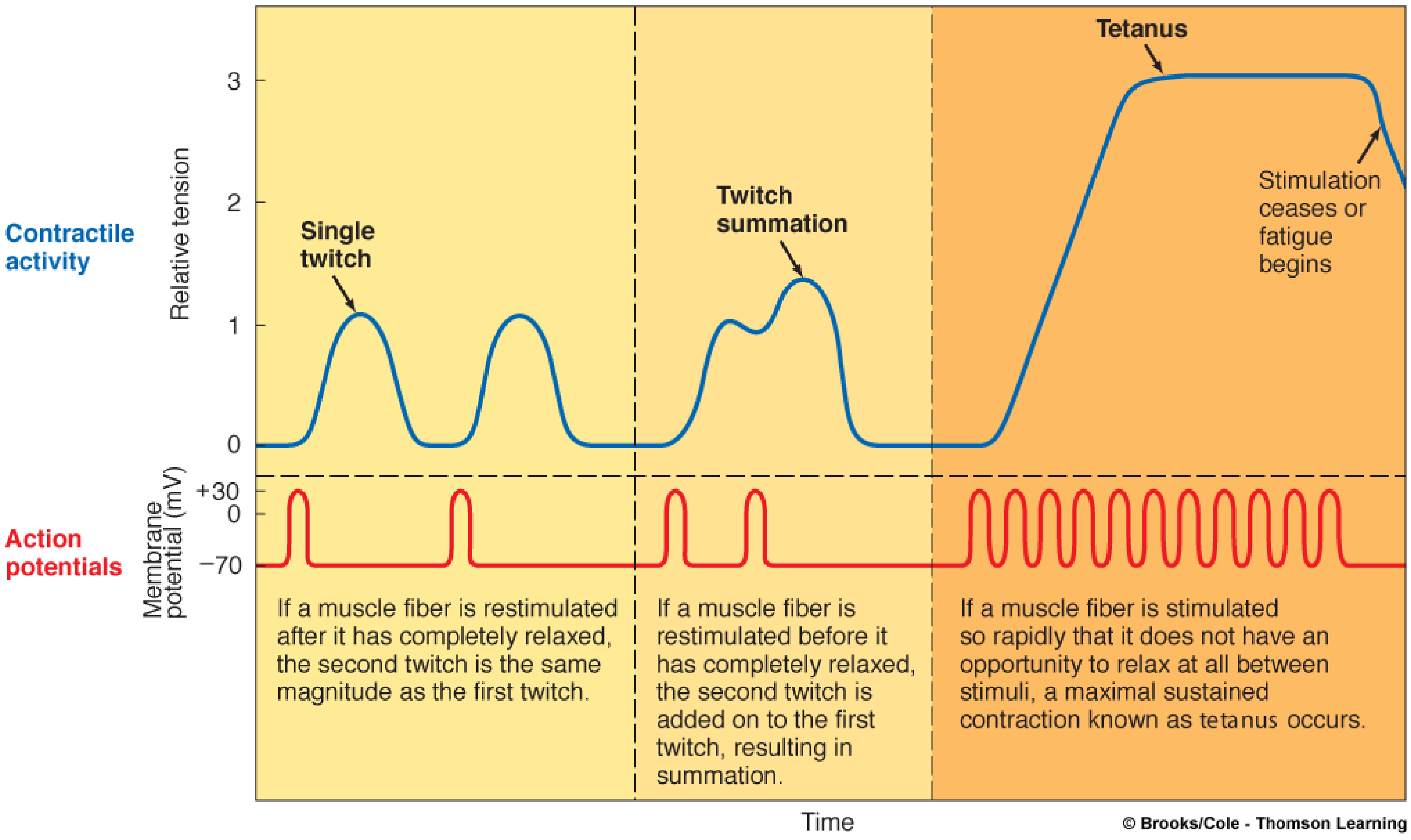


Figure 6-15

(2) Frequency summation: results from an ***increase in the frequency of contraction*** of a single motor unit

High frequency stimulation Tetany and summation



Summary
Determinants of Whole-Muscle Tension in Skeletal Muscle

- **Number of Fibers Contracting**
- Number of motor units recruited*
- Number of muscle fibers per motor unit
- Number of muscle fibers available to contract (size of muscle)
- **Tension Developed by Each Contracting Fiber**
- Frequency of stimulation (twitch summation and tetanus)*
- Length of fiber at onset of contraction (length–tension relationship)
- Extent of fatigue
- Type of fiber (fatigue-resistant oxidative or fatigue-prone glycolytic)
- Thickness of fiber (strength training and testosterone)

The Staircase Effect (Treppe)

- When a muscle begins to contract after a long period of rest, its initial strength of contraction is smaller than the strength of muscle later.
- That is, the strength of contraction increases to a plateau, a phenomenon called the *staircase effect*, or *treppe.*
- it is believed to be caused primarily by increasing calcium ions in the cytosol because of the release of more and more ions from the sarcoplasmic reticulum with each successive muscle action potential

Energy for muscle contraction

- Most of the energy required for muscle contraction is used to trigger the walk-along mechanism whereby the cross-bridges pull the actin filaments, but small amounts are required for the following:
- (1) pumping calcium ions from the sarcoplasm into the sarcoplasmic reticulum after the contraction is over; and
- (2) pumping sodium and potassium ions through the muscle fiber membrane to maintain an appropriate ionic environment for the propagation of muscle fiber action potentials
- The concentration of ATP in the muscle fiber, about 4 millimolar, is sufficient to maintain full contraction for only 1 to 2 seconds at most. The ATP is split to form ADP, which transfers energy from the ATP molecule to the contracting machinery of the muscle fiber

Energy for muscle contraction

ADP rephosphorylation and generation of newer ATP

- The first source of energy that is used to reconstitute the ATP is the substance *phosphocreatine*, which carries a high-energy phosphate bond similar to the bonds of ATP. Therefore, phosphocreatine is instantly cleaved, and its released energy causes bonding of a new phosphate ion toto reconstitute the ATP.
- Glycolysis Rapid enzymatic breakdown of the glycogen to pyruvic acid and lactic acid liberates energy that is used to convert ADP to ATP; the ATP can then be used directly to energize additional muscle contraction
- *Oxidative metabolism*, which means combining oxygen with the end products of glycolysis and with various other cellular foodstuffs to liberate ATP. *More than 95% of all energy used by the muscles for sustained long-term contraction is derived from oxidative metabolism.*

Mechanisms of excitation-contraction coupling and relaxation in cardiac muscle.

ATP, Adenosine triphosphate.
RyR, ryanodine
receptor Ca2+ release channel;
SERCA, sarcoplasmic reticulum
Ca2+-ATPase