Biomechanics of Skeletal Muscle

Contents

- Muscle types:
  - cardiac muscle: composes the heart
  - smooth muscle: lines hollow internal organs
  - skeletal (striated or voluntary) muscle: attached to skeleton via tendon & movement
- Skeletal muscle 40-45% of body weight
  - > 430 muscles
  - ~ 80 pairs produce vigorous movement
- Dynamic & static work
  - Dynamic: locomotion & positioning of segments
  - Static: maintains body posture

I. Composition & structure of skeletal muscle

Structure & organization

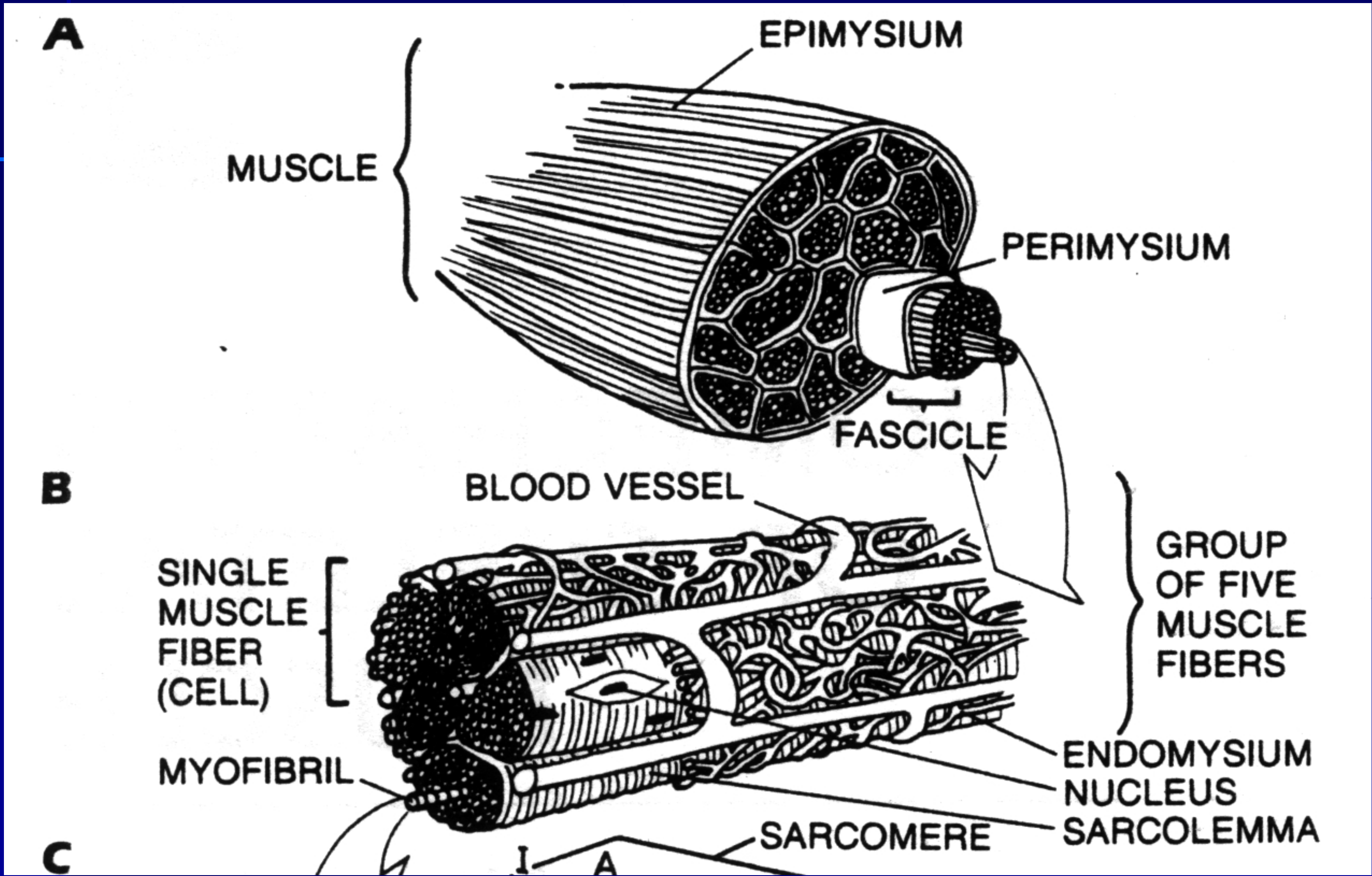
• Muscle fiber: long cylindrical multi-nuclei cell 10-100 μm ϕ

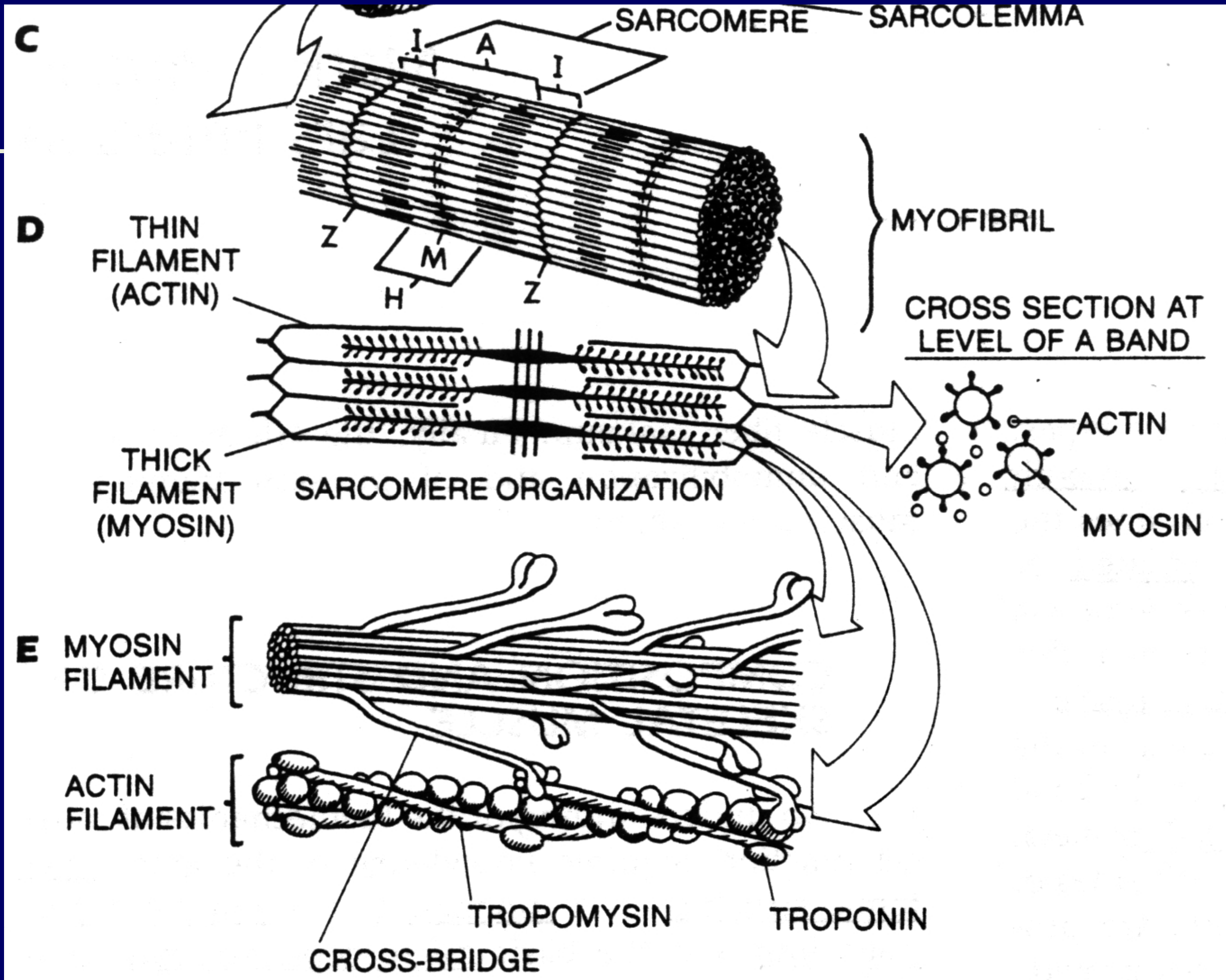
fiber $\rightarrow$*endomysium* $\rightarrow$ fascicles $\rightarrow$ **perimysium** $\rightarrow$ epimysium (fascia)

• Collagen fibers in perimysium & epimysium are continuous with those in tendons

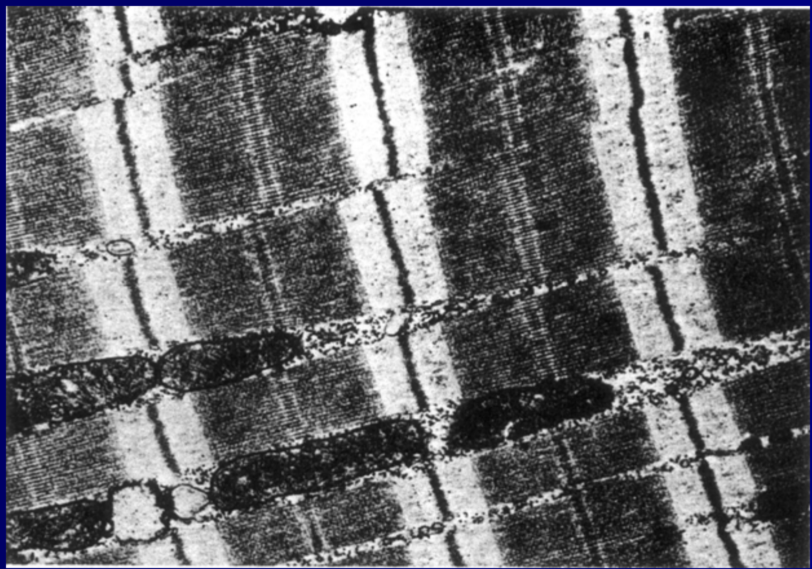
• {thin filament (actin 5nm ϕ) + thick filament (myosin 15 nm ϕ)}

$\rightarrow$ myofibrils (contractile elements, 1μm ϕ) $\rightarrow$muscle fiber


A
EPIMYSIUM
MUSCLE
PERIMYSIUM
FASCICLE
B
BLOOD VESSEL
SINGLE MUSCLE FIBER (CELL)
GROUP OF FIVE MUSCLE FIBERS
ENDOMYSIUM
NUCLEUS
MYOFIBRIL
SARCOMERE
SARCOLEMMA
C
I
A


C
SARCOMERE
SARCOLEMMA
I
A
I
MYOFIBRIL
D
THIN
FILAMENT
(ACTIN)
Z
M
H
Z
CROSS SECTION AT
LEVEL OF A BAND
ACTIN
THICK
FILAMENT
(MYOSIN)
SARCOMERE ORGANIZATION
MYOSIN
E
MYOSIN
FILAMENT
ACTIN
FILAMENT
TROPOMYSIN
TROPONIN
CROSS-BRIDGE

Bands of myofibrils



A bands: thick filaments in central of sarcomere

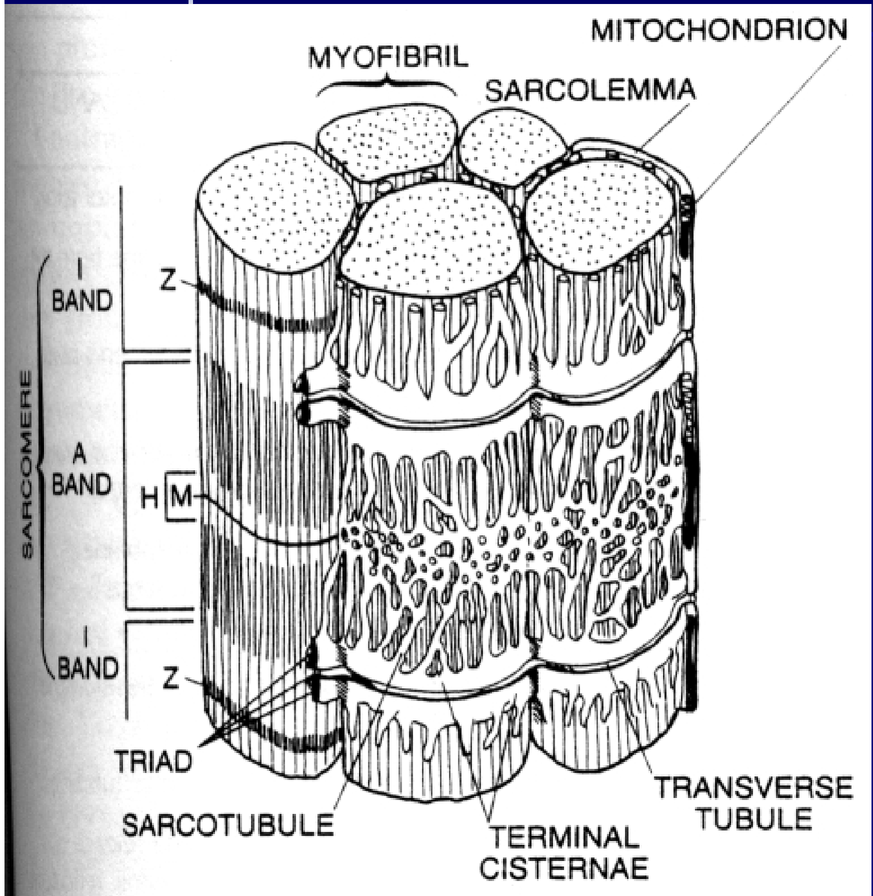
Z line: short elements that links thin filaments

I bands: thin filaments not overlap with thick filaments

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

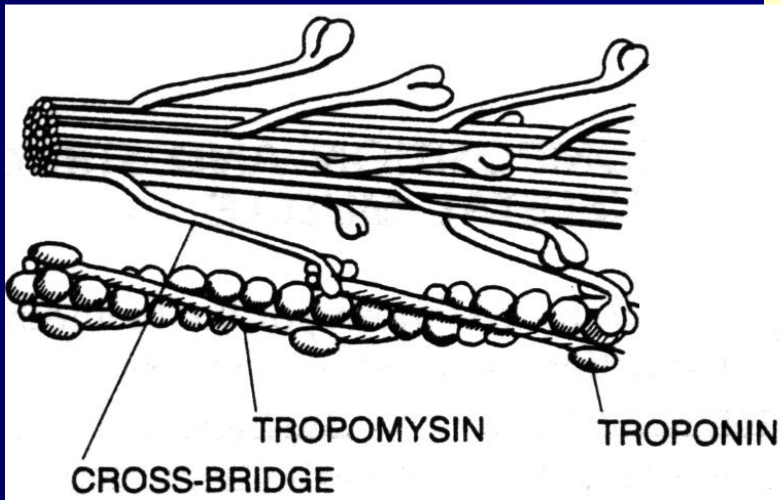
M line: transverse & longitudinally oriented linking proteins for adjacent thick filaments

Sarcoplasmic reticulum



- network of tubules & sacs;
- parallel to myofibrils
- enlarged & fused at junction between A & I bands: transverse sacs (terminal cisternae)
- Triad {terminal cisternae, transverse tubule}
- T system: duct for fluids & propogation of electrical stimulus for contraction (action potential)
- Sarcoplasmic reticulum store calcium

Molecular composition of myofibril

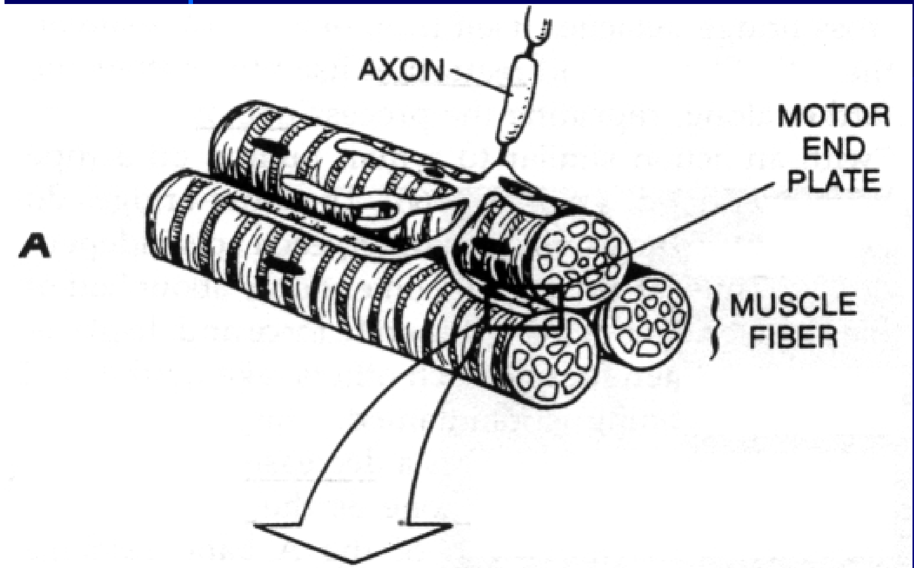


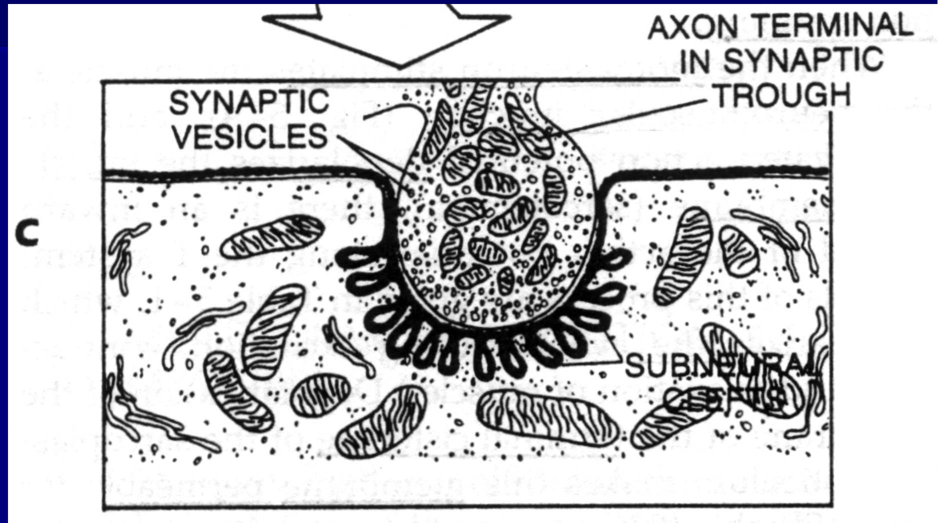
- Myosin composed of individual molecules each has a globular head and tail
- Cross-bridge: actin & myosin overlap (A band)
- Actin has double helix; two strands of beads spiraling around each other
- troponin & tropomysin regulate making and breaking contact between actin & myosin

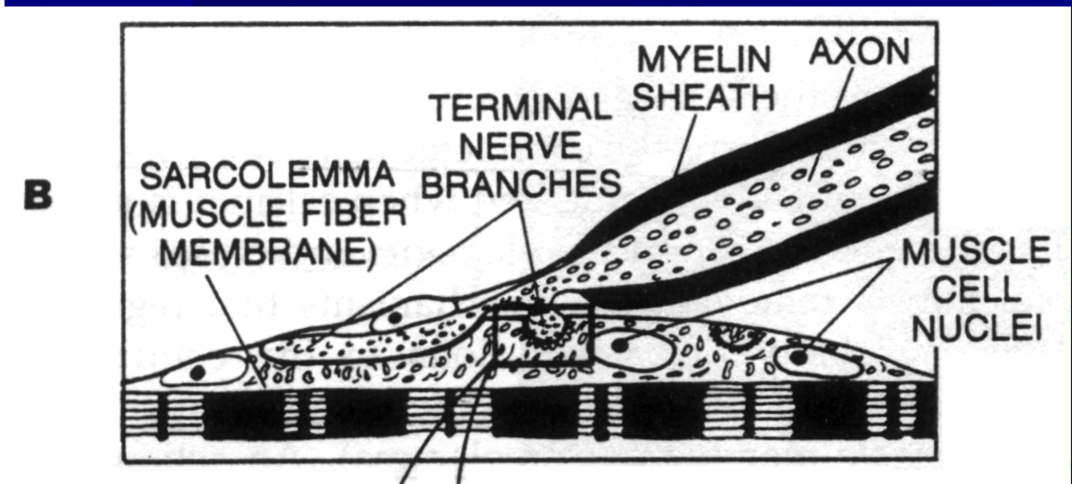
Molecular basis of muscle contraction

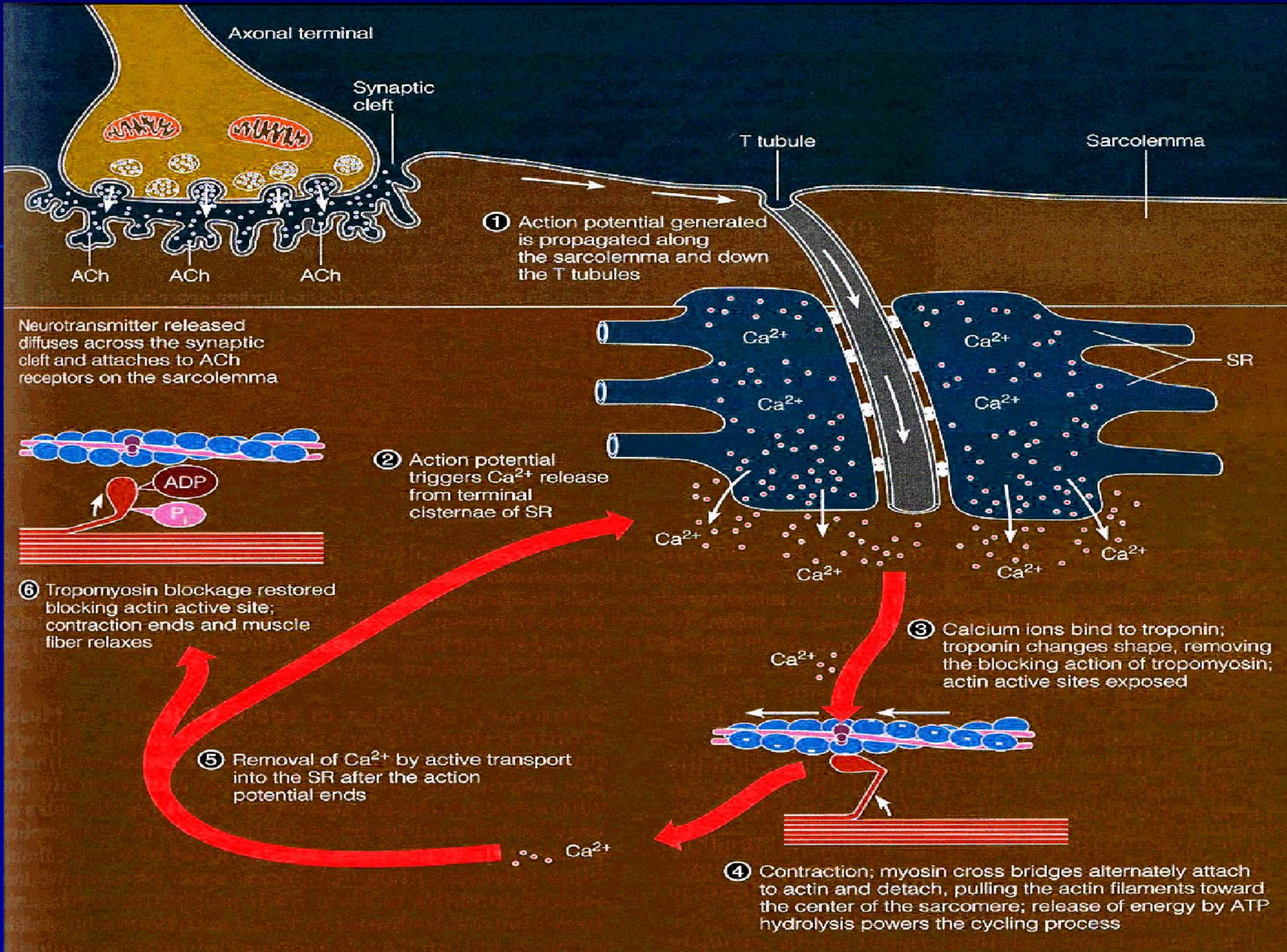
- Sliding filament theory: relative movement of actin & myosin filaments yields active sarcomere shortening
- Myosin heads or cross-bridges generate contraction force
- Sliding of actin filaments toward center of sarcomere: decrease in I band and decrease in H zone as Z lines move closer

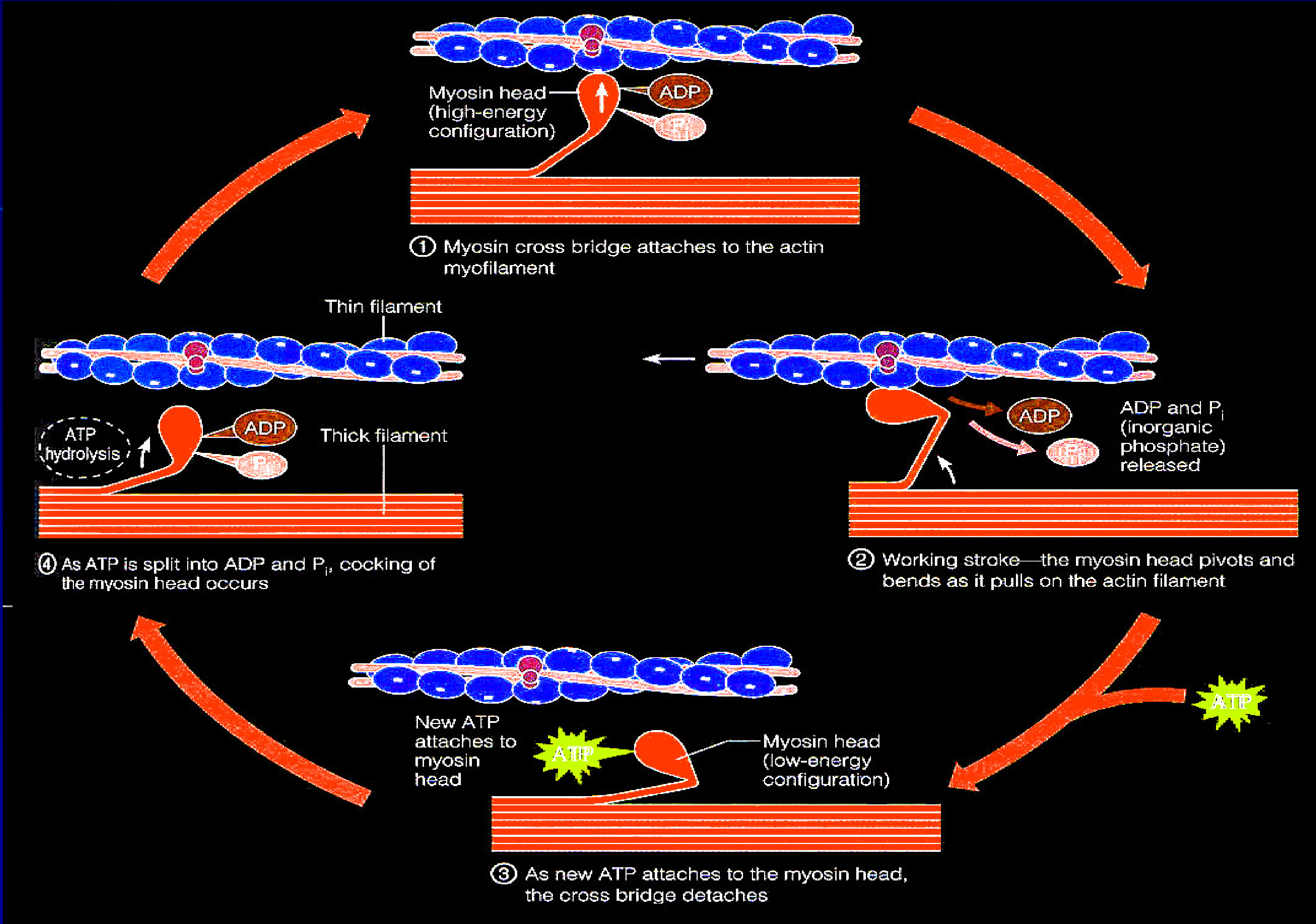
Motor unit


A
AXON
MOTOR END PLATE
MUSCLE FIBER


C
AXON TERMINAL IN SYNAPTIC TROUGH
SYNAPTIC VESICLES
SUBNEURAL


B
MYELIN SHEATH
AXON
TERMINAL NERVE BRANCHES
SARCOLEMMA (MUSCLE FIBER MEMBRANE)
MUSCLE CELL NUCLEI


Axonal terminal
Synaptic cleft
T tubule
Sarcolemma
ACh
ACh
ACh
① Action potential generated is propagated along the sarcolemma and down the T tubules
Neurotransmitter released diffuses across the synaptic cleft and attaches to ACh receptors on the sarcolemma
Ca2+
Ca2+
Ca2+
Ca2+
SR
ADP
Pi
② Action potential triggers Ca2+ release from terminal cisternae of SR
Ca2+
Ca2+
Ca2+
Ca2+
⑥ Tropomyosin blockage restored blocking actin active site; contraction ends and muscle fiber relaxes
③ Calcium ions bind to troponin; troponin changes shape, removing the blocking action of tropomyosin; actin active sites exposed
Ca2+
⑤ Removal of Ca2+ by active transport into the SR after the action potential ends
Ca2+
④ Contraction; myosin cross bridges alternately attach to actin and detach, pulling the actin filaments toward the center of the sarcomere; release of energy by ATP hydrolysis powers the cycling process

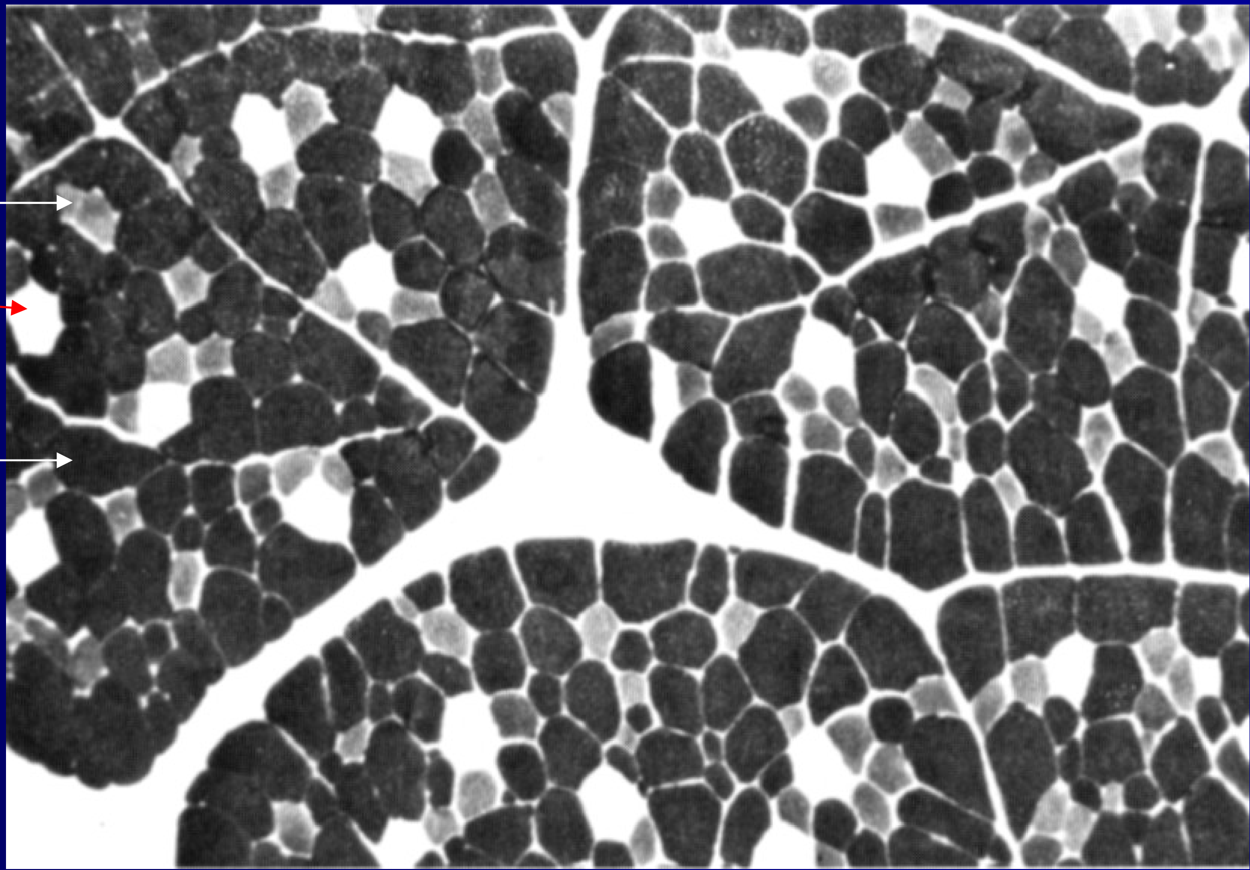

Myosin head (high-energy configuration)
ADP
P_i
① Myosin cross bridge attaches to the actin myofilament
Thin filament
Thick filament
ATP hydrolysis
ADP
P_i
④ As ATP is split into ADP and P_i, cocking of the myosin head occurs
ADP
P_i
ADP and P_i (inorganic phosphate) released
② Working stroke—the myosin head pivots and bends as it pulls on the actin filament
ATP
New ATP attaches to myosin head
ATP
Myosin head (low-energy configuration)
③ As new ATP attaches to the myosin head, the cross bridge detaches

Histology of muscle

Type IIA

Type IIB

Type I

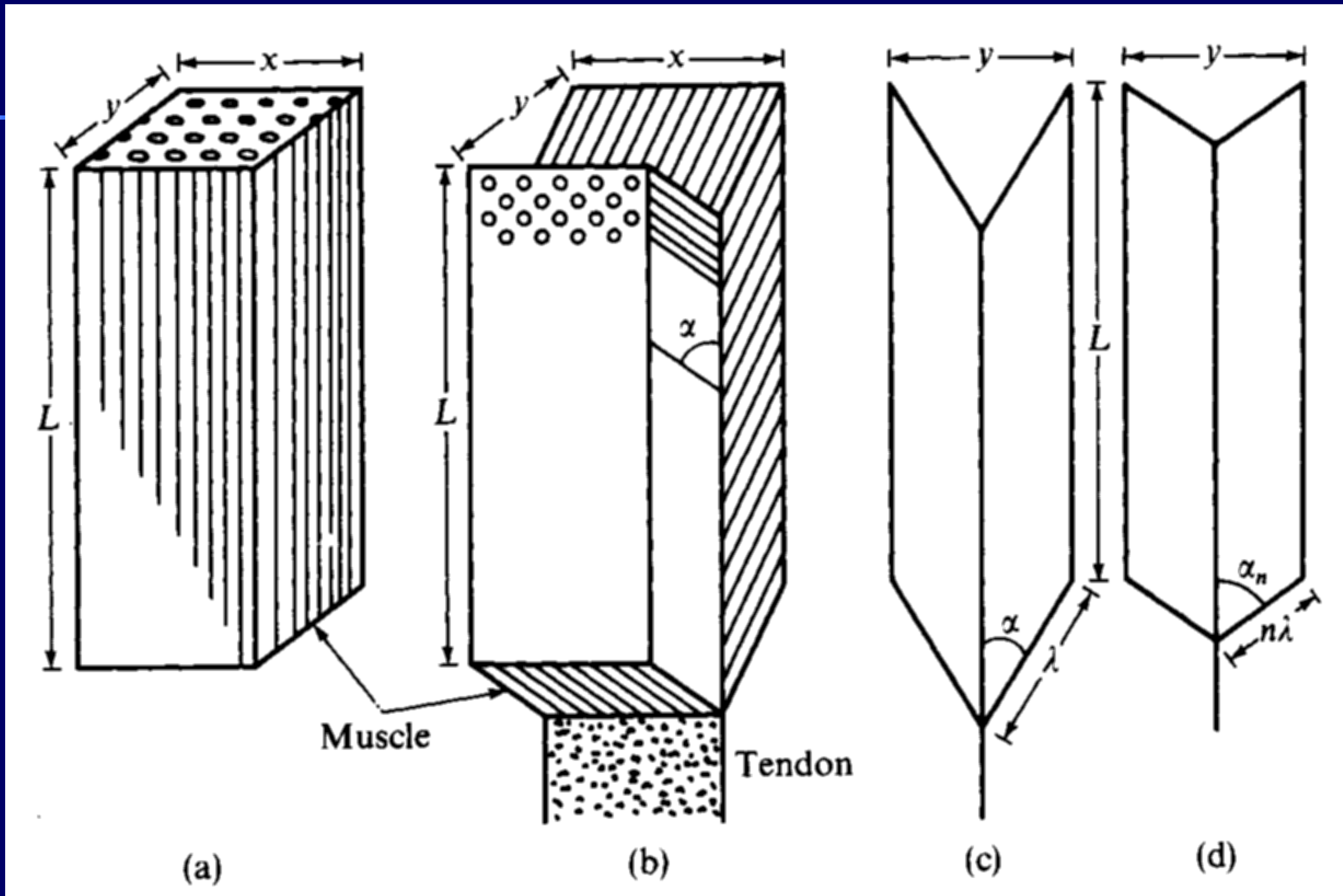


Eye muscle (Rectus lateralis); Myofibrillar ATPase stain, PH 4.3

Muscle Differentiation (types of fibers)

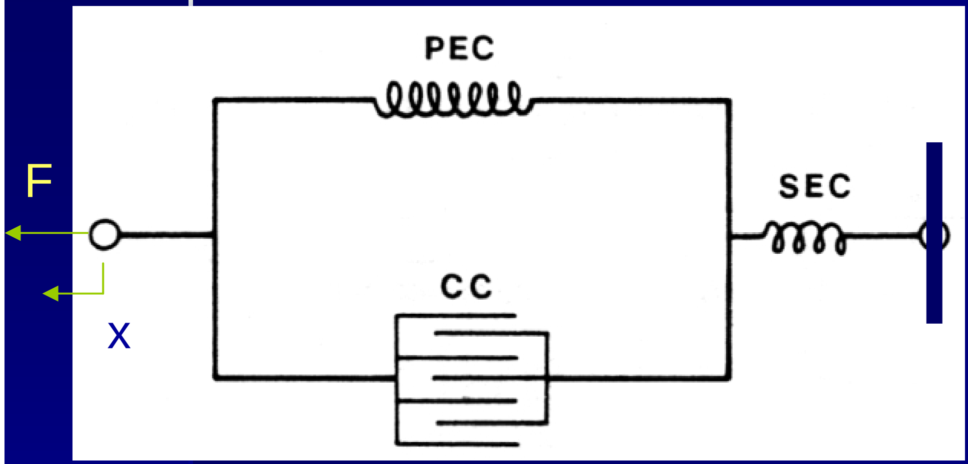
	I (slow-twitch oxidative)	**IIA** (fast-twitch oxidative glycolytic)	**IIB** fast-twitch glycolytic
Contraction speed	Slow	fast	fast
Myosin-ATPase activity	Low	High	High
Primary source of ATP production	Oxidative phosphorylation	Oxidative phosphorylation	Anaerobic glycolysis
Glycolytic enzyme activity	Low	Intermediate	High
No. of mitochondria	Many	Many	Few
Capillaries	Many	Many	Few
Myoglobin contents	High	High	Low
Muscle Color	Red	Red	White
Glycogen content	Low	Intermediate	High
Fiber diameter	small	Intermediate	Large
Rate of fatigue	slow	Intermediate	Fast

Functional arrangement of muscle



α pinnated angle of muscle

The Musculotendinous Unit



PEC: parallel elastic component
CC: contractile component
SEC: series elastic component

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

II. Mechanics of Muscle Contraction

- Neural stimulation – impulse
- Mechanical response of a motor unit - twitch

$$F(t) = F_0 \frac{t}{T} e^{-\frac{t}{T}}$$

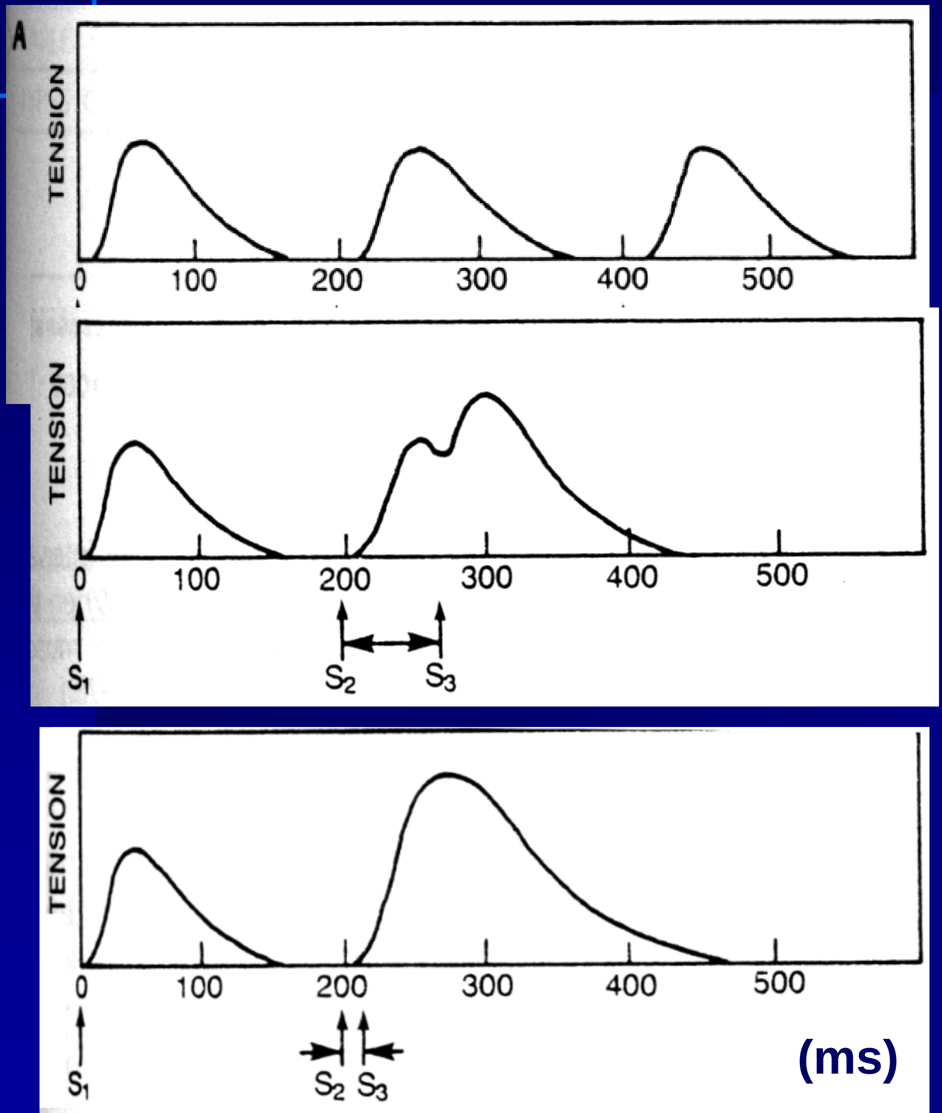
T: twitch or contraction time, time for tension to reach maximum

F_0: constant of a given motor unit

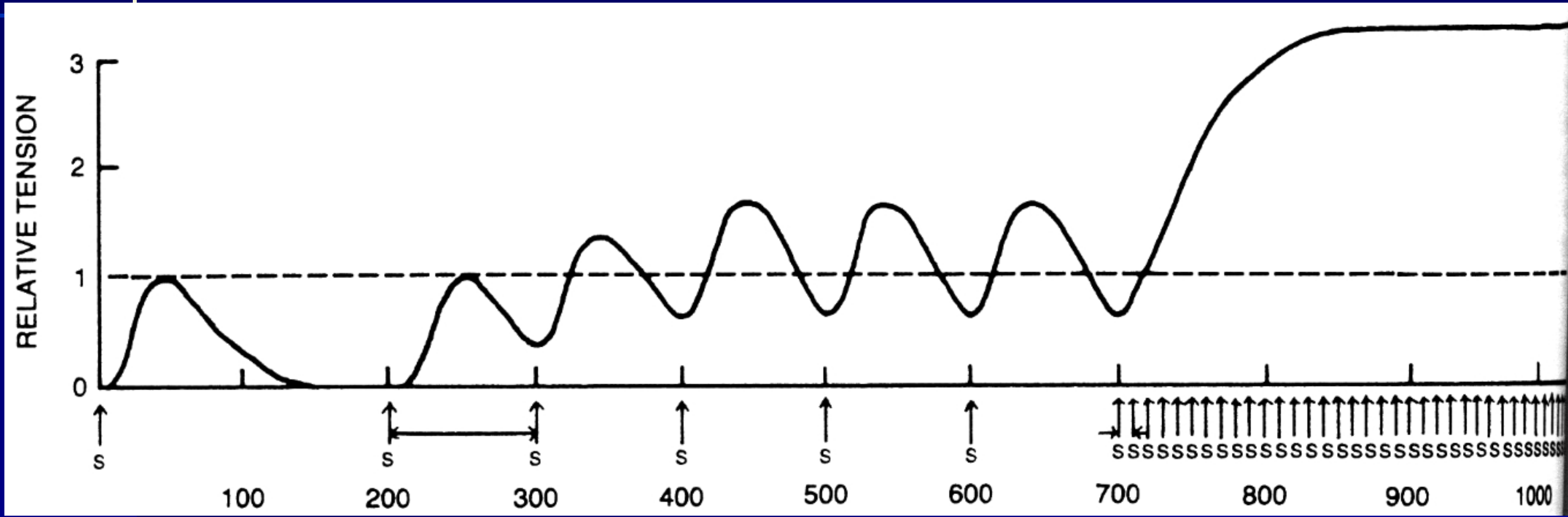
Averaged T values

Tricep brachii 44.5 ms	Soleus 74.0 ms
Biceps brachii 52.0 ms	Medial Gastrocnemius 79.0 ms
Tibialis anterior 58.0 ms	

Summation and tetanic contraction

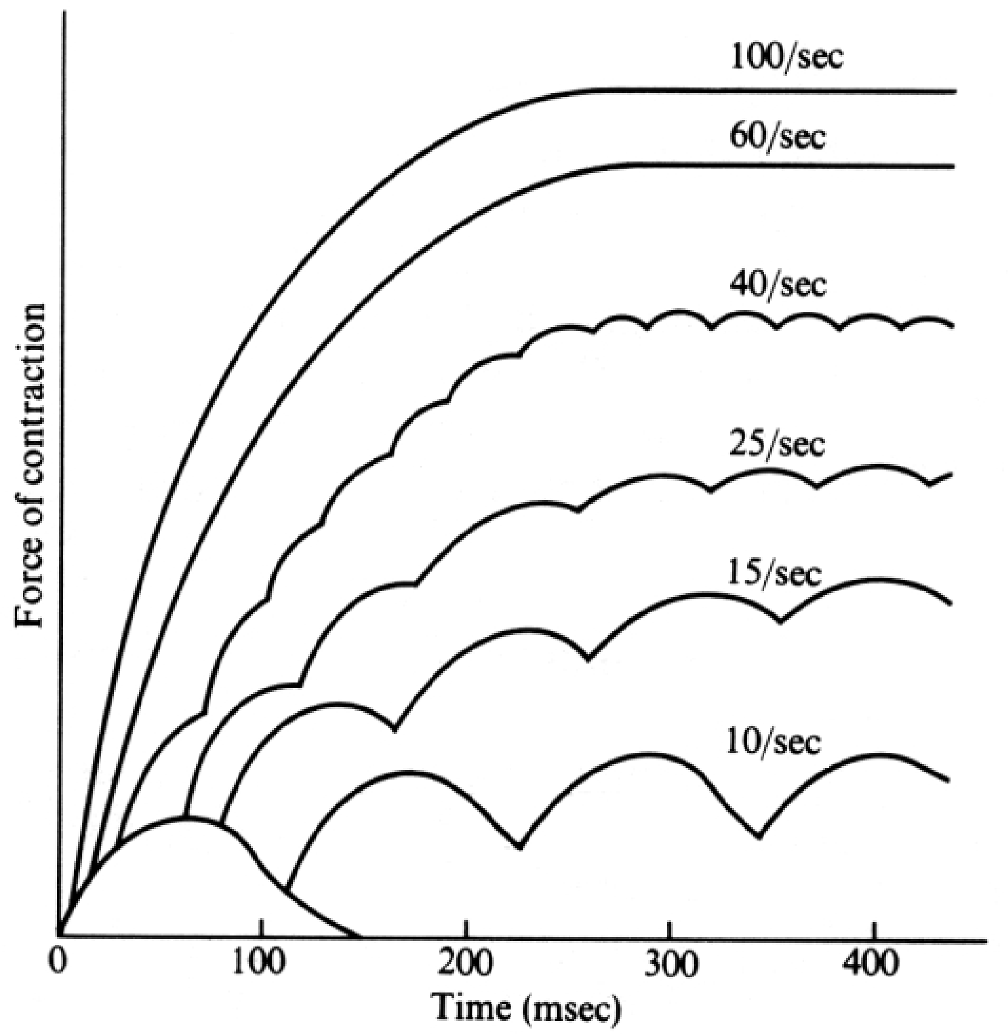


Generation of muscle tetanus



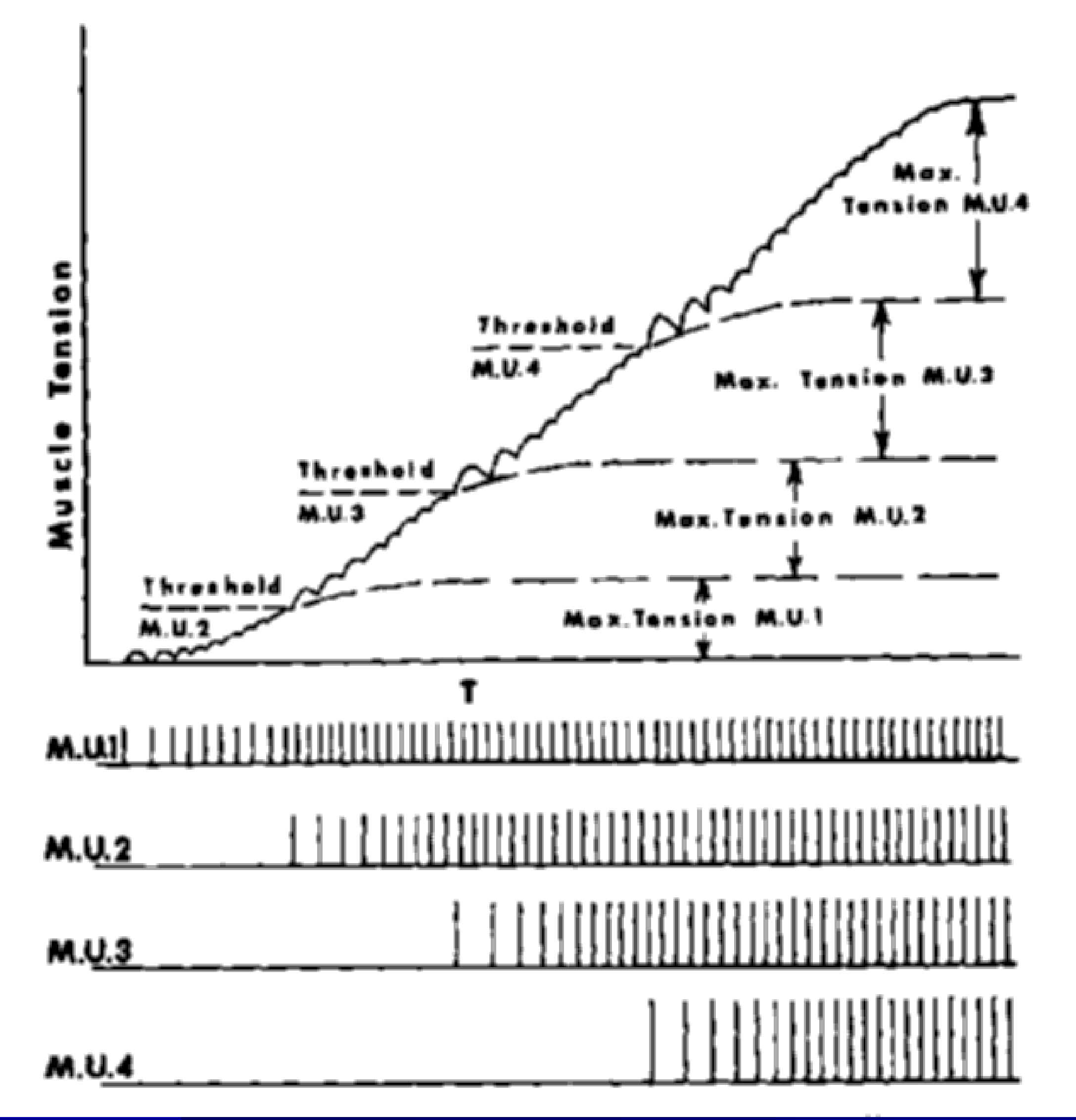
Note: muscle is controlled by frequency modulation from neural input very important in functional electrical stimulation

Wave summation & tetanization



Critical frequency

Motor unit recruitment



All-or-nothing event

2 ways to increase tension:

- Stimulation rate
- Recruitment of more motor unit

Size principle

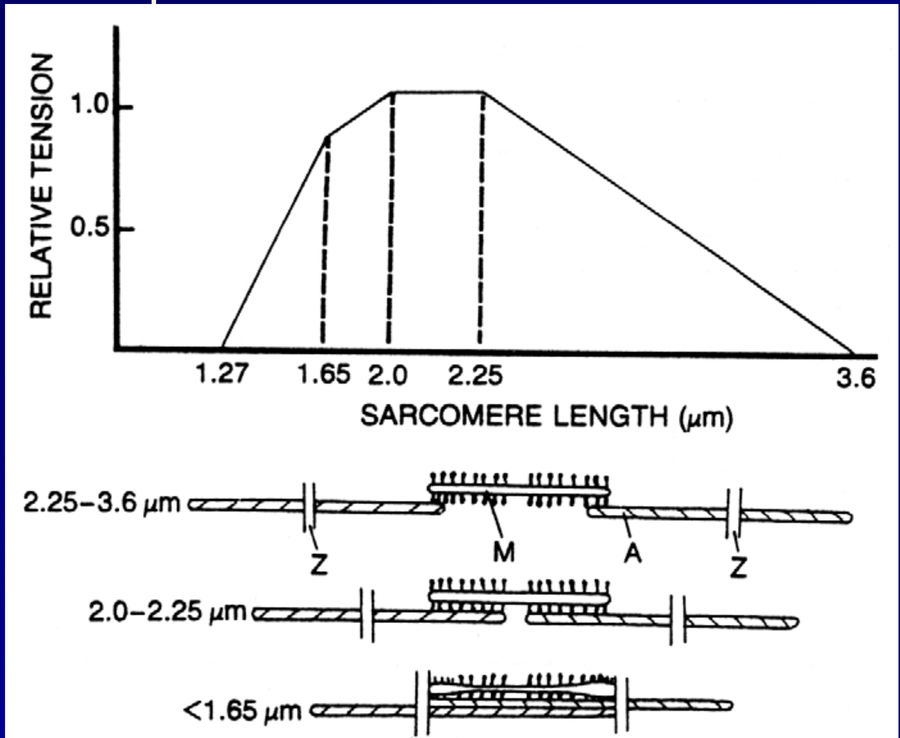
Smallest m.u. recruited first

Largest m.u. last

III. Force production in muscle

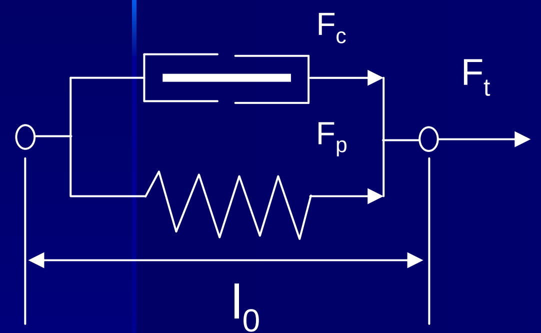
- Force –length characteristics
- Force – velocity characteristics
- Muscle Modeling
- Neuromuscular system dynamics

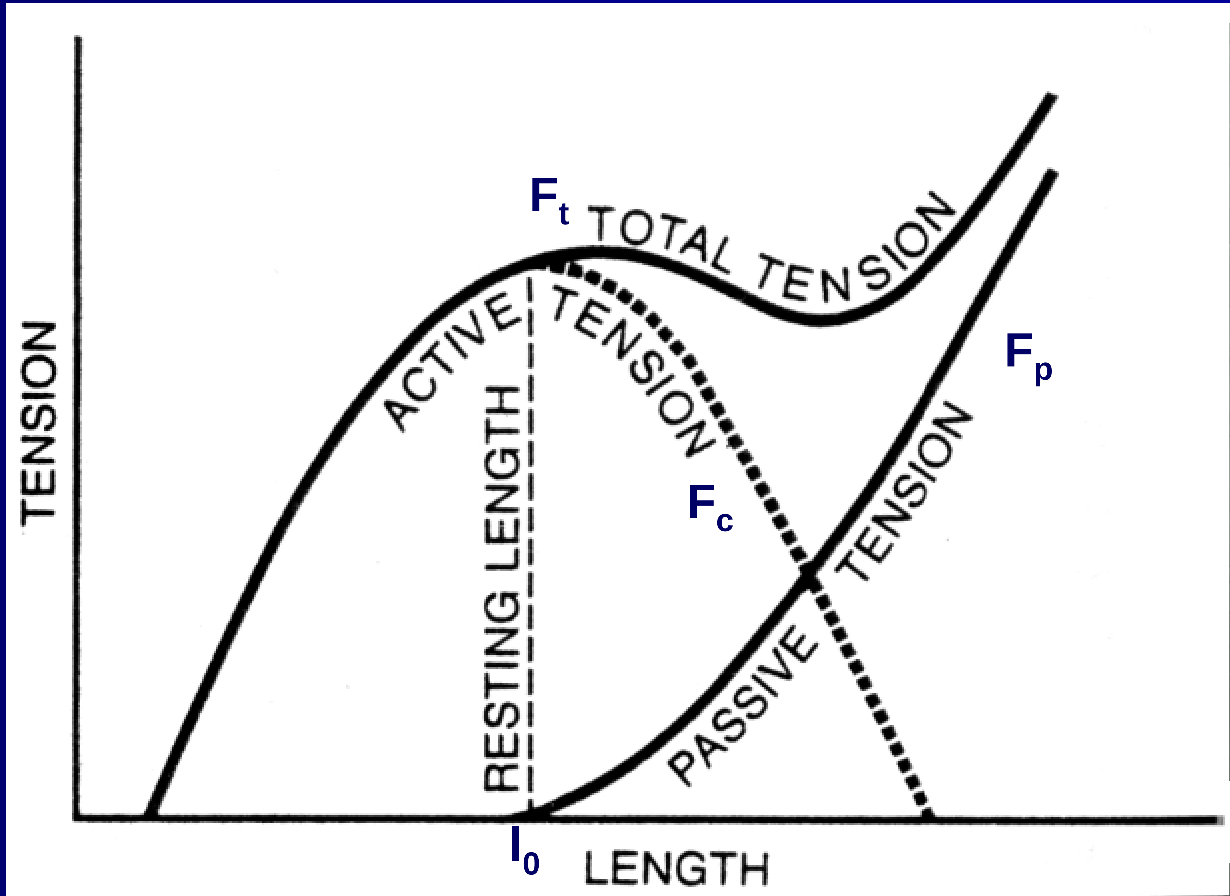
3-1 Force-length curve of contractile component



- 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 ↓

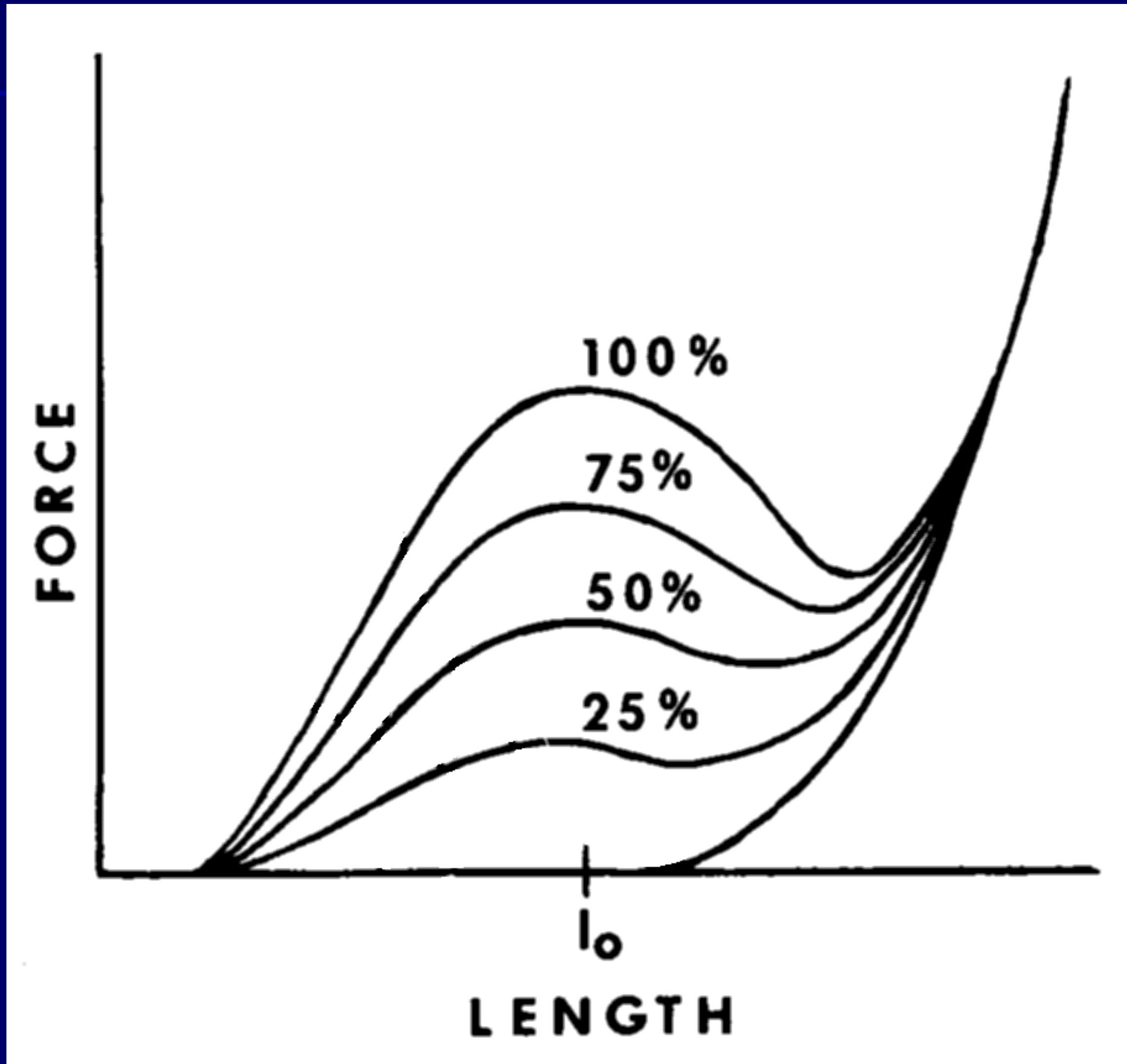
Influence of parallel elastic component



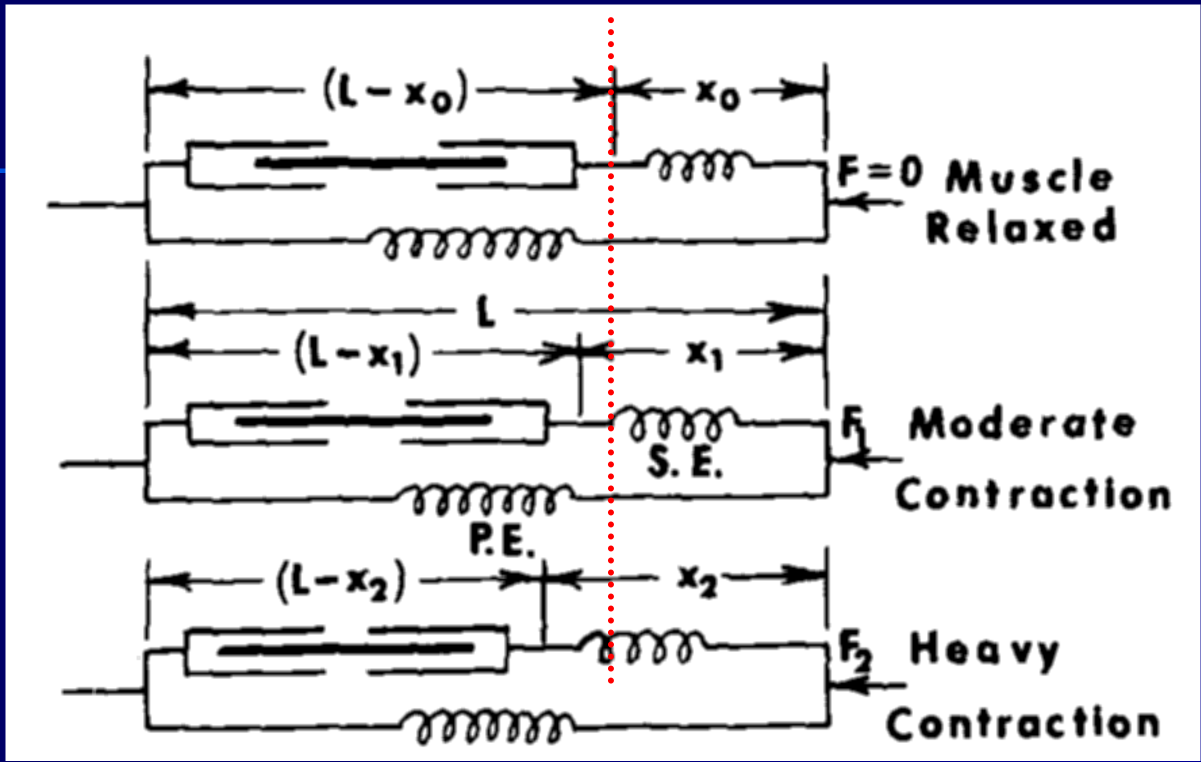


Note: F_c is under voluntary control & F_p is always present

Overall force-length characteristics of a muscle

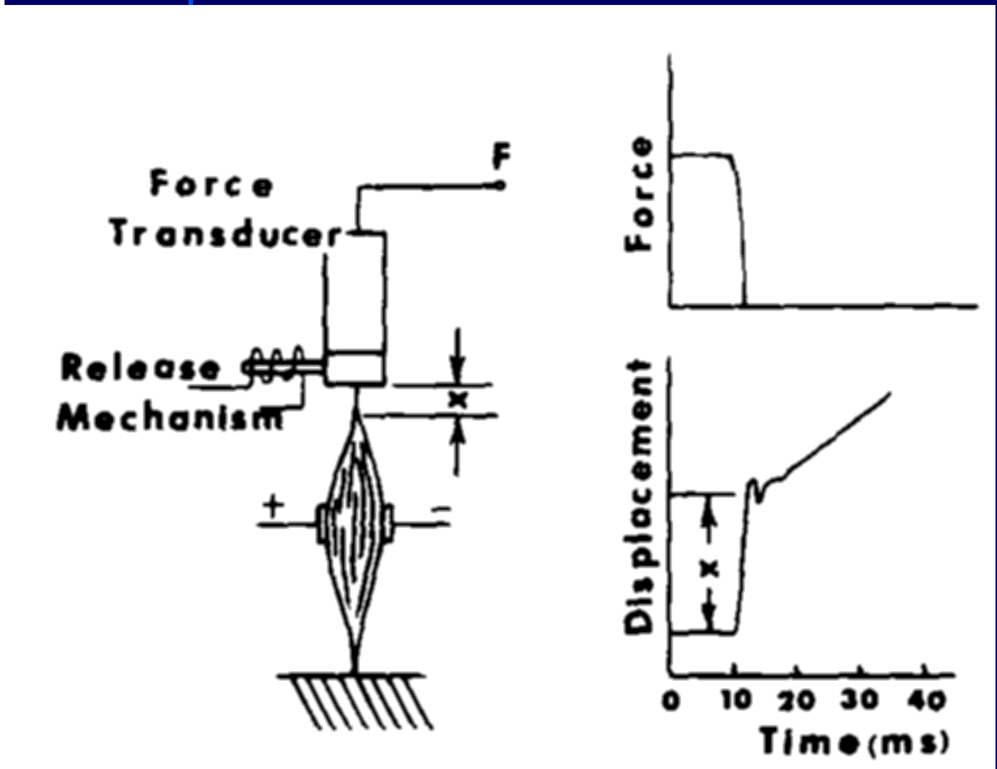


Series Elastic Component



- Tendon & other series tissue
- Lengthen slightly in isometric contraction
- Series component can store energy when stretched prior to an explosive shortening

Quick-release for determining elastic constant of series



- Muscle is stimulated to build tension
- Release mechanism is activated
- Measure instantaneous shortening x while force is kept constant
- Contractile element length kept constant during quick release

$$K_{SC} = \frac{F}{x}$$

In vivo force-length measurement

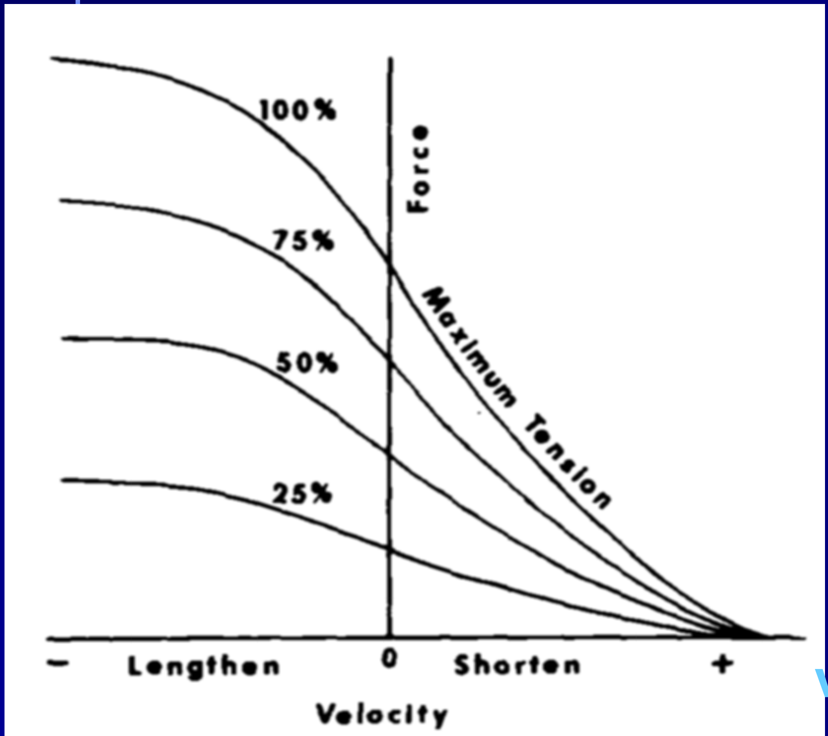
- Human *in vivo* experiments (MVC)
- *Challenges:*
  - Impossible to generate a max. voluntary contraction for a single agonist without activating remaining agonist
  - Only moment & angle are measurable. Moment depends on muscle force and moment arm.

3-2 Force-Velocity Characteristics

- Concentric contraction
  - Muscle contracts and shortening, positive work was done on external load by muscle
  - Tension in a muscle decreases as it shortens
- Eccentric contraction
  - Muscle contracts and lengthening, external load does work on muscle or negative work done by muscle.
  - Tension in a muscle increases as it lengthens by external load

Force-velocity characteristics of skeletal muscle (Hill model)

eccentric concentric



$$F = \frac{(F_0 + a)b}{v + b} - a$$

F_0 = max. isometric tension

a = coefficient of shortening heat

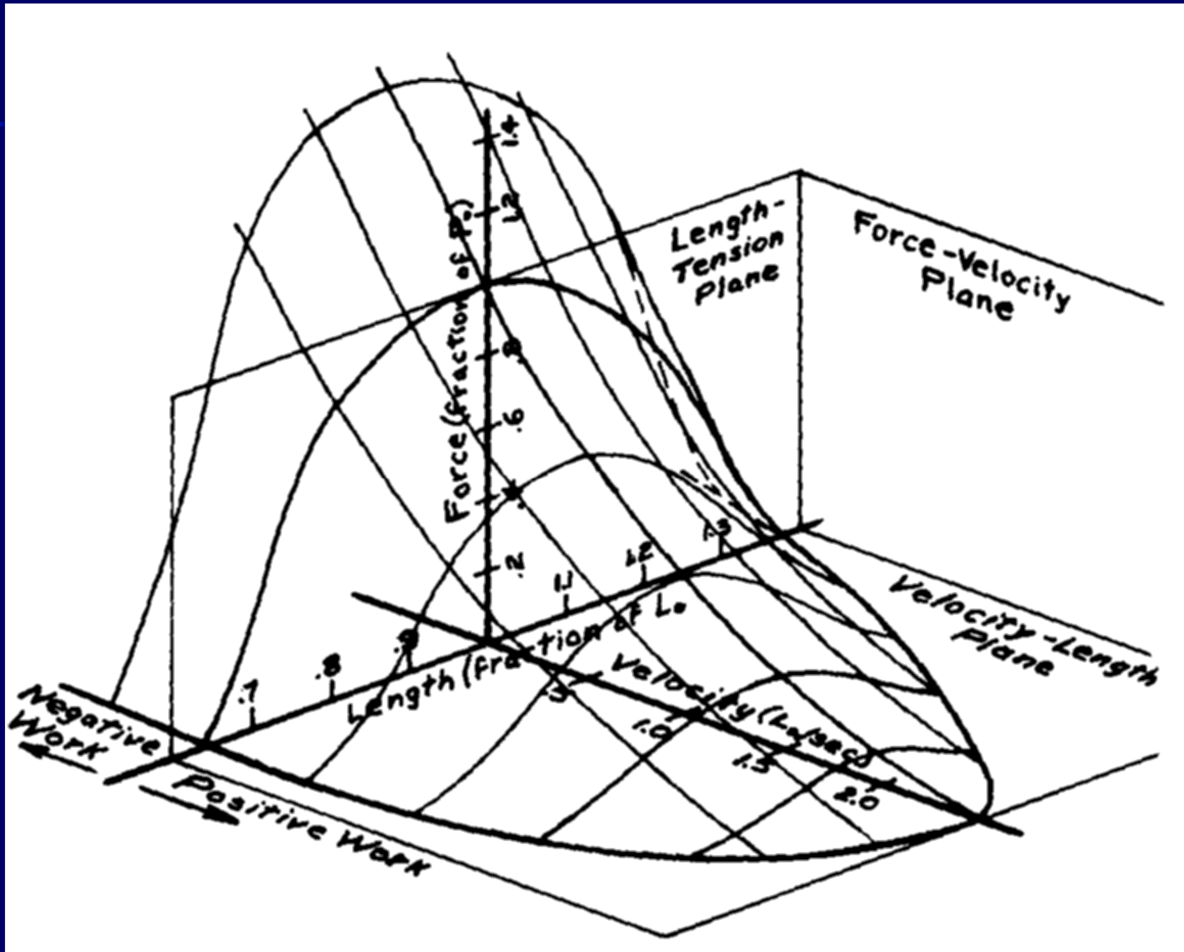
v_0 = max. velocity when F = 0

$$b = \frac{a\, v_0}{F_0}$$

Increased tensions in eccentric due to:

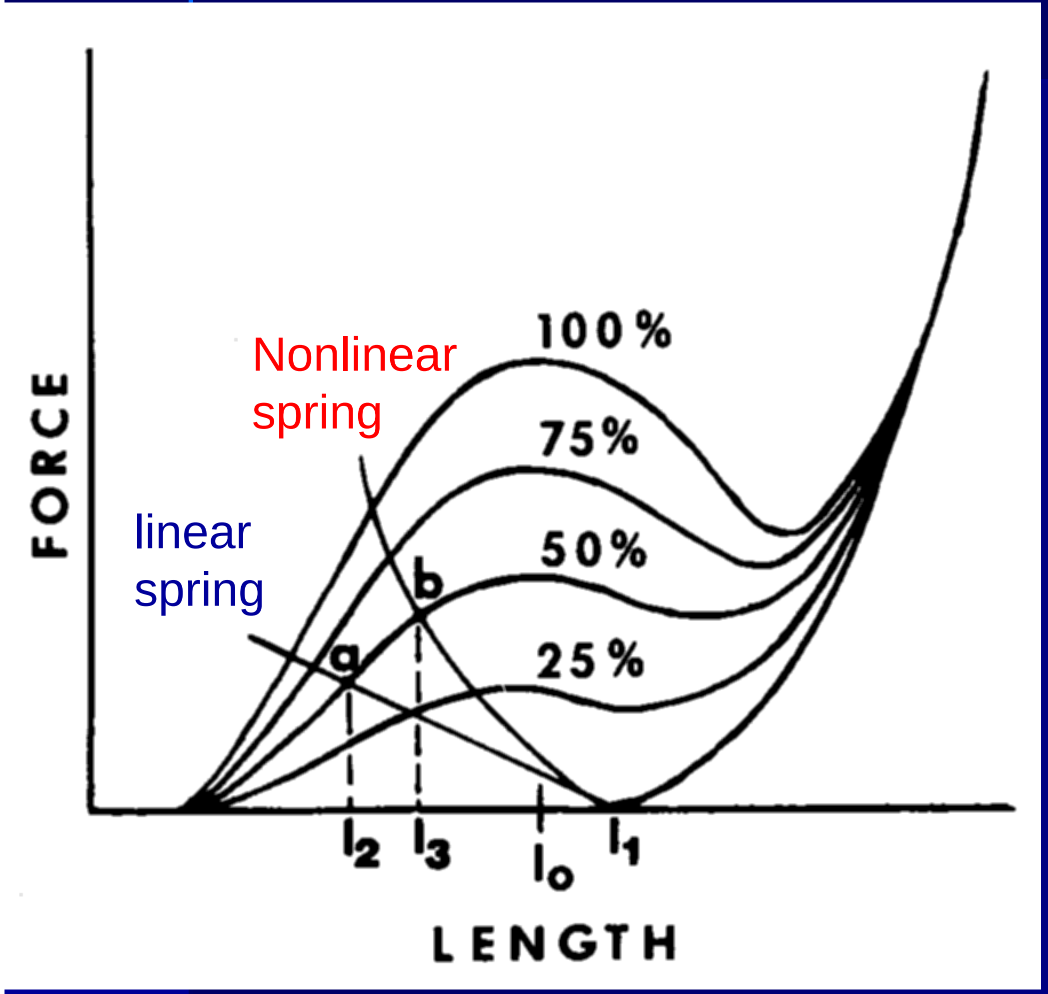
- Cross bridge breaking force > holding force at isometric length
- High tendon force to overcome internal damping friction

Length and velocity versus Force



Note: maximum contraction condition; normal contractions are fraction of the maximum force

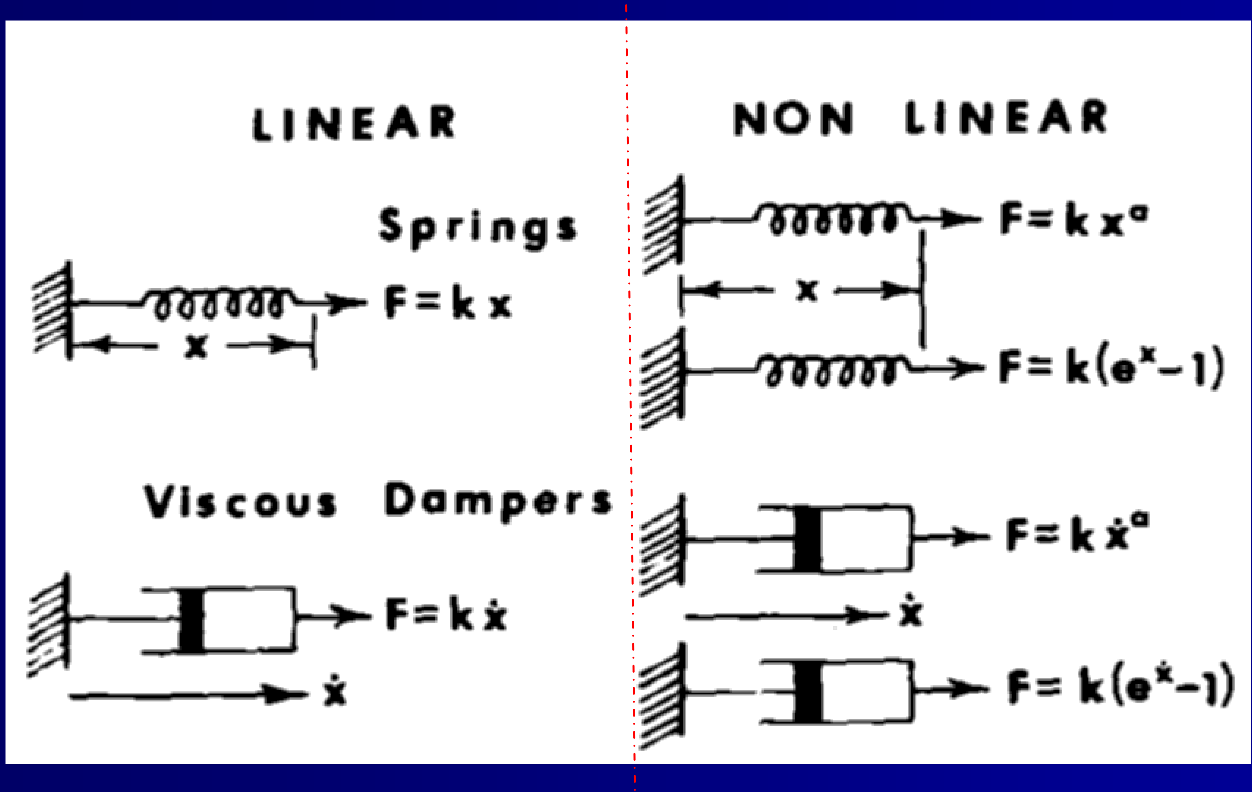
Equilibrium of load and muscle force

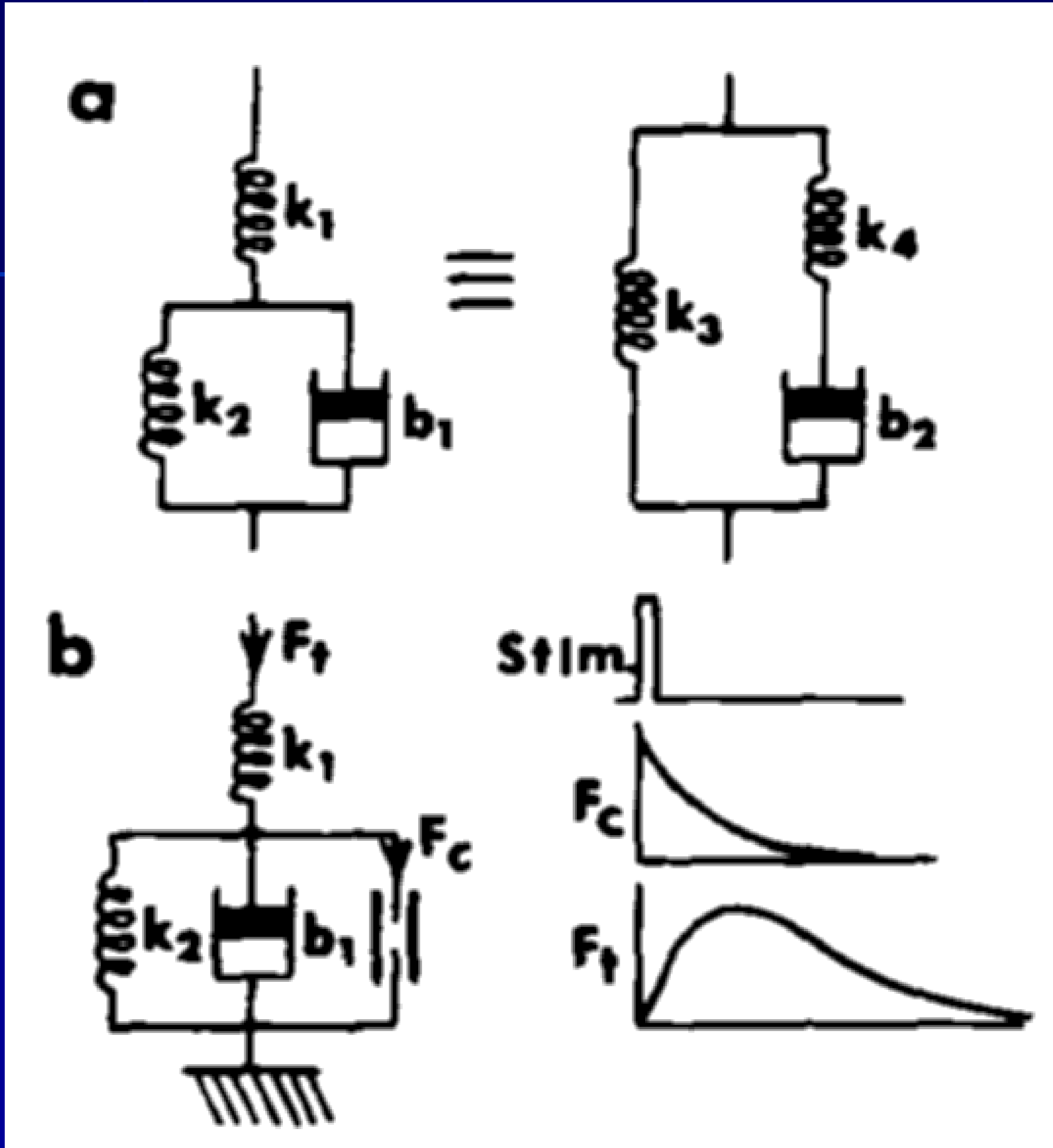


- Muscle force is function of length, velocity and activation
- The load determines activation and length of muscle by the equilibrium condition
- Load: spring-like, inertial, viscous damper

3-3 Muscle Modeling

Elements of Hill model other than contractile element





- Derive equations of motion
- Estimated parameters based on Experimental data & model Simulation (least squares)

. Numerical simulation

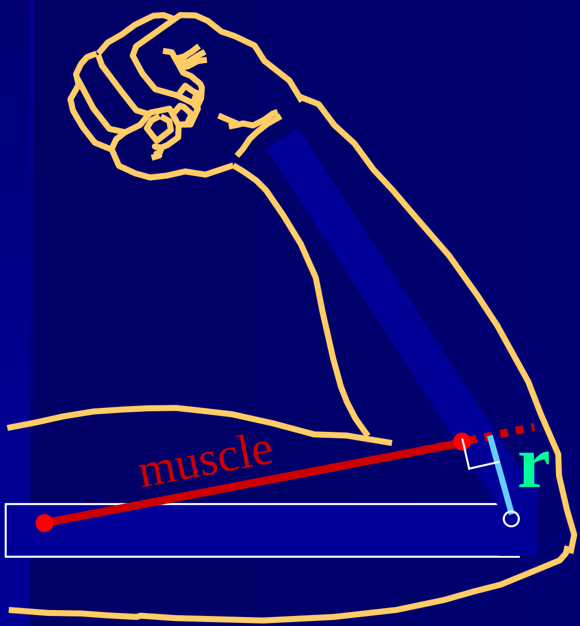
3-4 Neuromuscular system dynamics

Muscle force

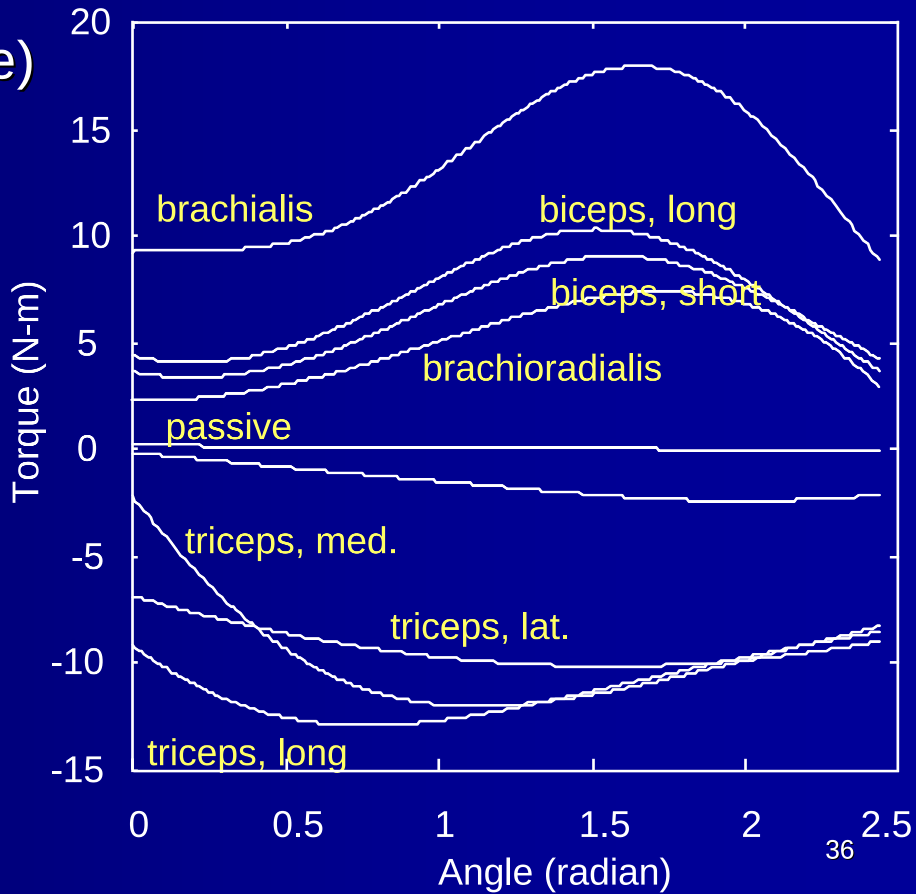
$F = F_0 * Act * F_{LT} * F_{FV}$

$T = r(\theta) * F(L(\theta), V, A)$

$F_0 = F_0$(pinnated angle, PCSA, fiber type)

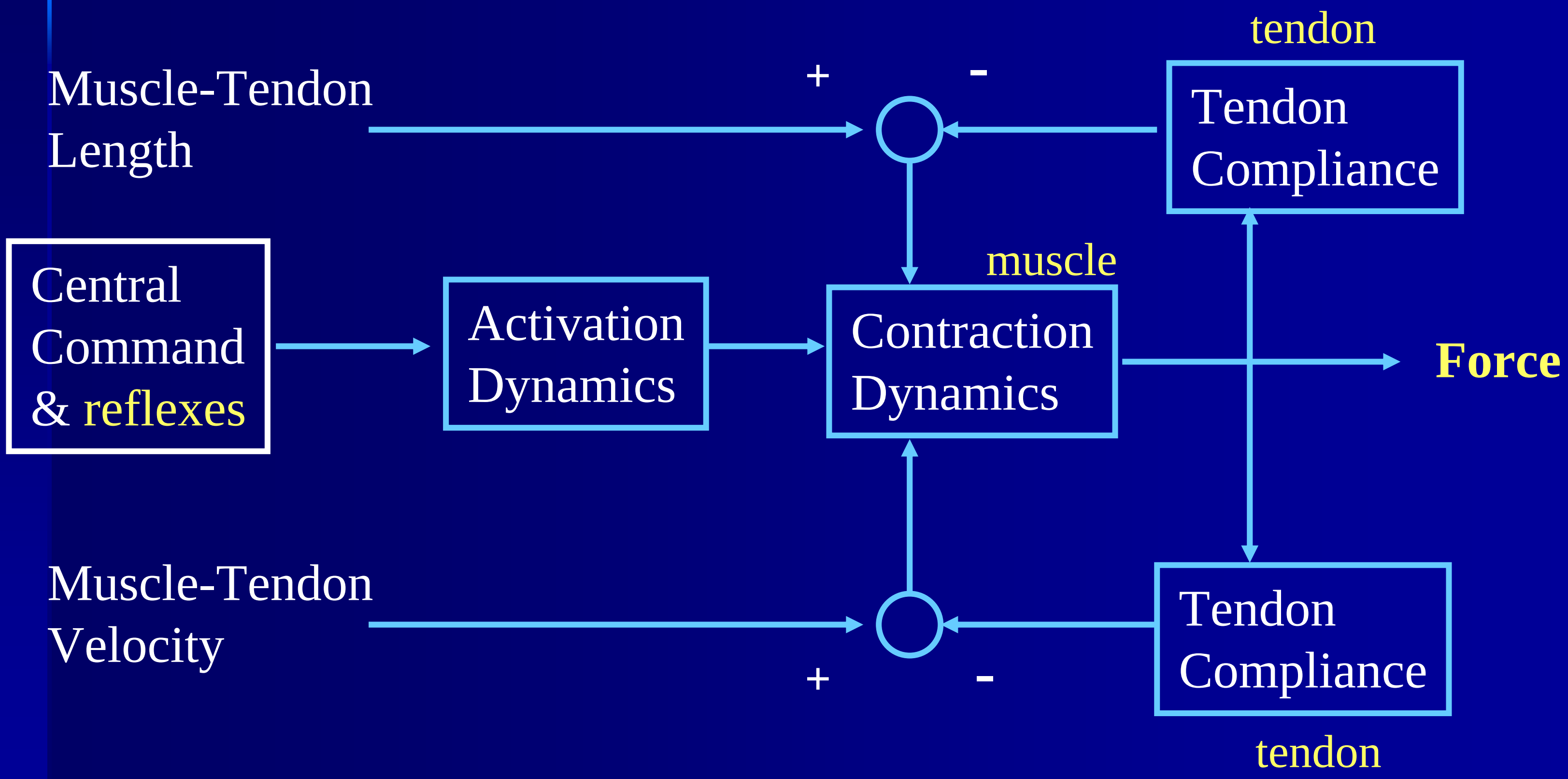


Max torque due to each muscle

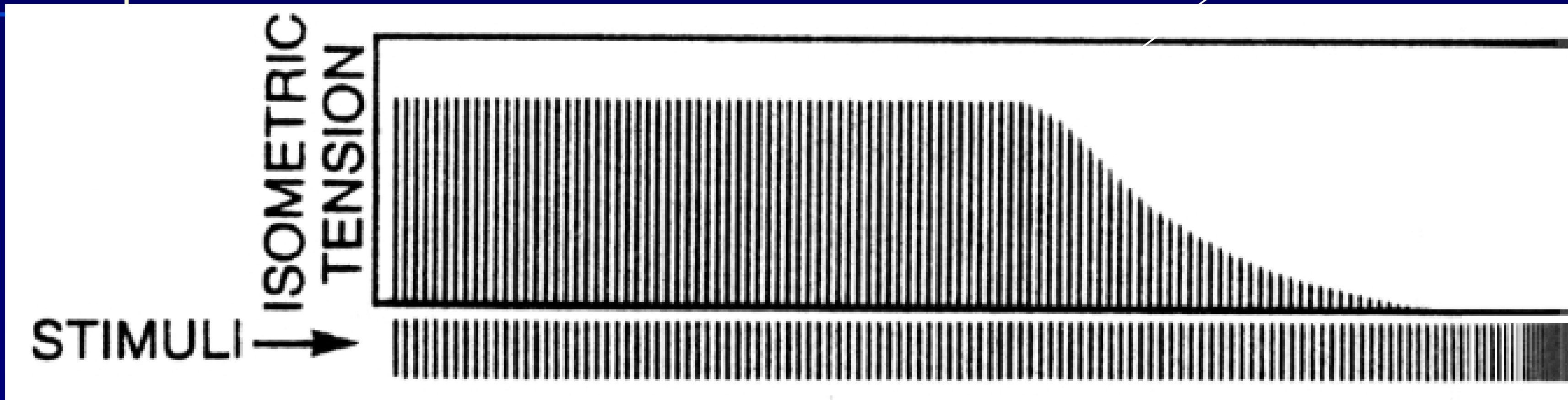


Note: feedback mechanism in neuromuscular system

Neuromuscular system modeling



Muscle fatigue



Drop in tension followed prolonged stimulation.
Fatigue occurs when the stimulation frequency outstrips rate of replacement of ATP, the twitch force decreases with time

V. Muscle Remodeling

- Effects of Disuse and Immobilization
  - Immediate or early motion may prevent muscle atrophy after injury or surgery
  - Muscle fibers regenerate in more parallel orientation, capillariaztion occurred rapidly, tensile strength returned more quickly
  - Atrophy of quadriceps developed due to immobilization can not be reversed by isometric exercises.
  - Type I fibers atrophy with immobilization; cross-sectional area decreases & oxidative enzyme activity reduced
  - Tension in muscle afferent impulses from intrafusal muscle spindle increases & leading to increase stimulation of type I fiber

- Effects of Physical Training
  – Increase cross-sectional area of muscle fibers, muscle bulk & strength
  – Relative percentage of fiber types also changes
  – In endurance athletes % type I, IIA increase
  – Stretch out of muscle-tendon complex increases elasticity & length of musculo-tendon unit; store more energy in viscoelastic & contractile components
  – Roles of muscle spindle & Golgi tendon organs: inhibition of spindle effect & enhance Golgi effect to relax muscle and promote further lengthening.

V. Summary

- Structure unit of muscle: fiber
- Myofibrils are composed of actin & myosin
- Sliding filament theory & cross-bridge
- Calcium ion & contractivity
- Motor unit: a single neuron & all muscle fibers innervated by it
- Force production depends on length, velocity, muscle composition & morphology (Hill model)

References

- D.A. Winter, Biomechanics and Motor Control of Human Movement, 2nd ed. John Wiley & Sons, NY, 1990.
- M. Nordin & V.H. Frankel, Basic Biomechanics of the Musculoskeletal System, 2ne ed., Lea & Febiger, London, 1989.
- Y.C. Fung, Biomechanics: Mechanical Properties of Living Tissues, 2nd ed., Speinger-Verlag, NY, 1993.