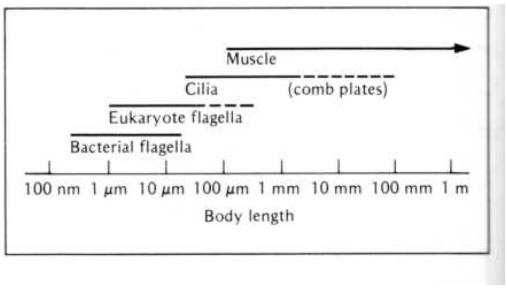
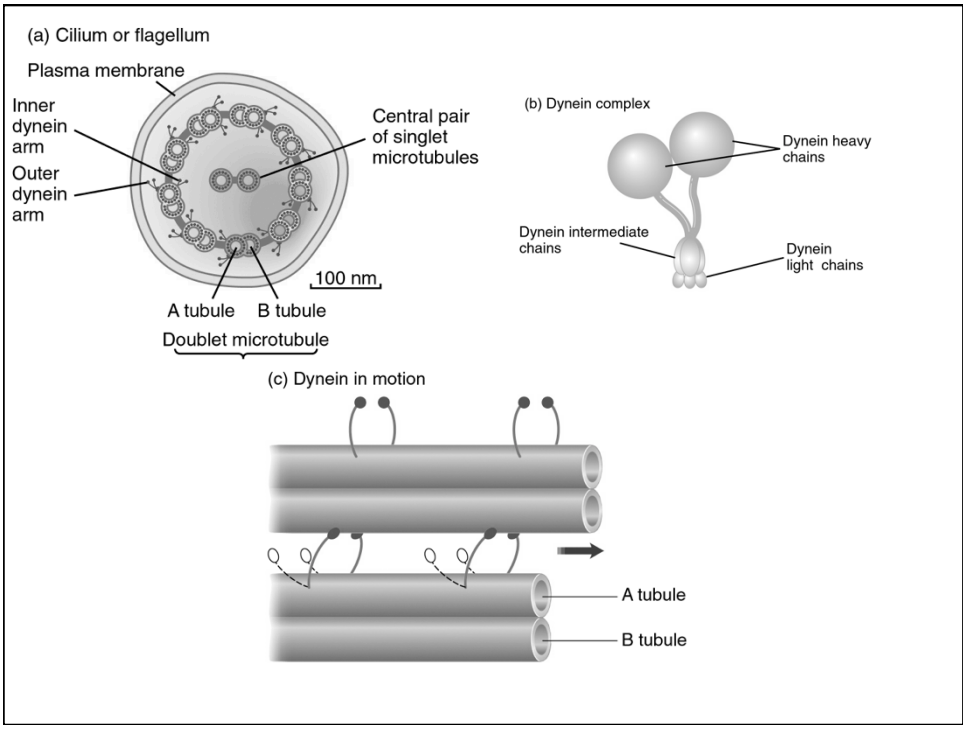
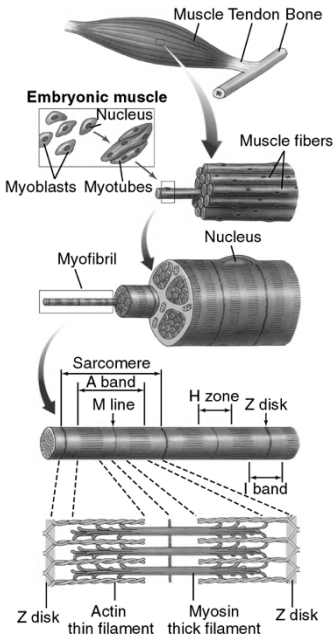
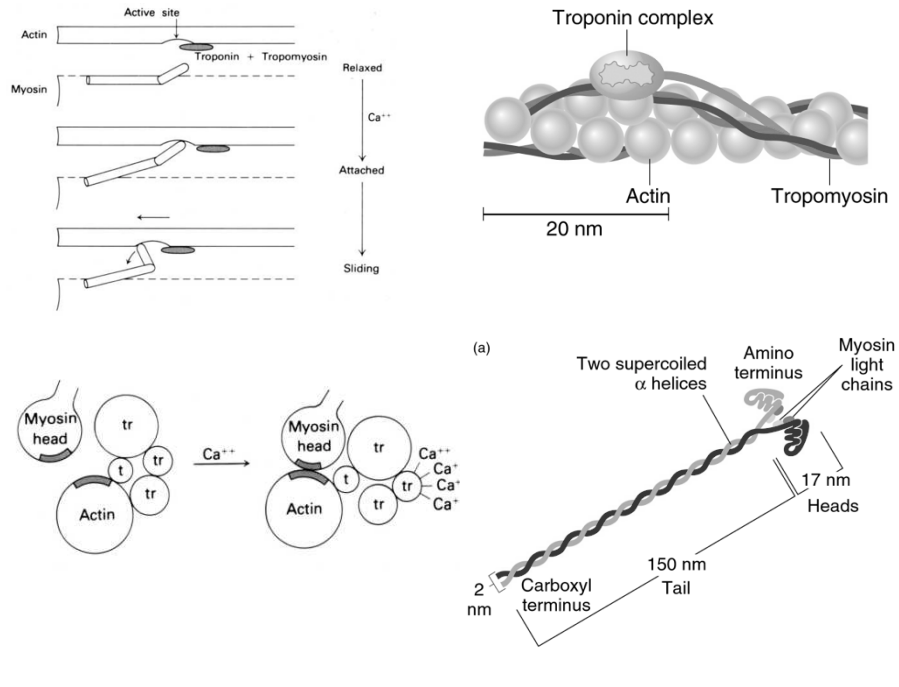
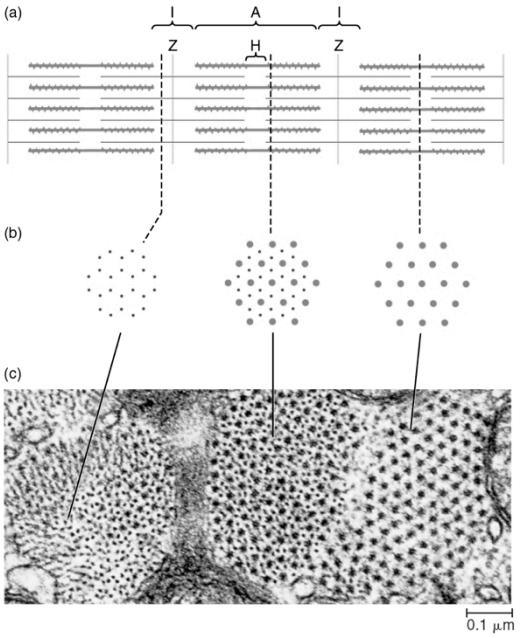
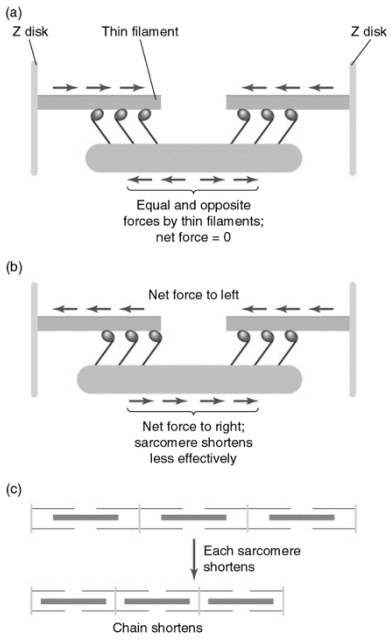

Muscle
Cilia
(comb plates)
Eukaryote flagella
Bacterial flagella
100 nm 1 μm 10 μm 100 μm 1 mm 10 mm 100 mm 1 m
Body length

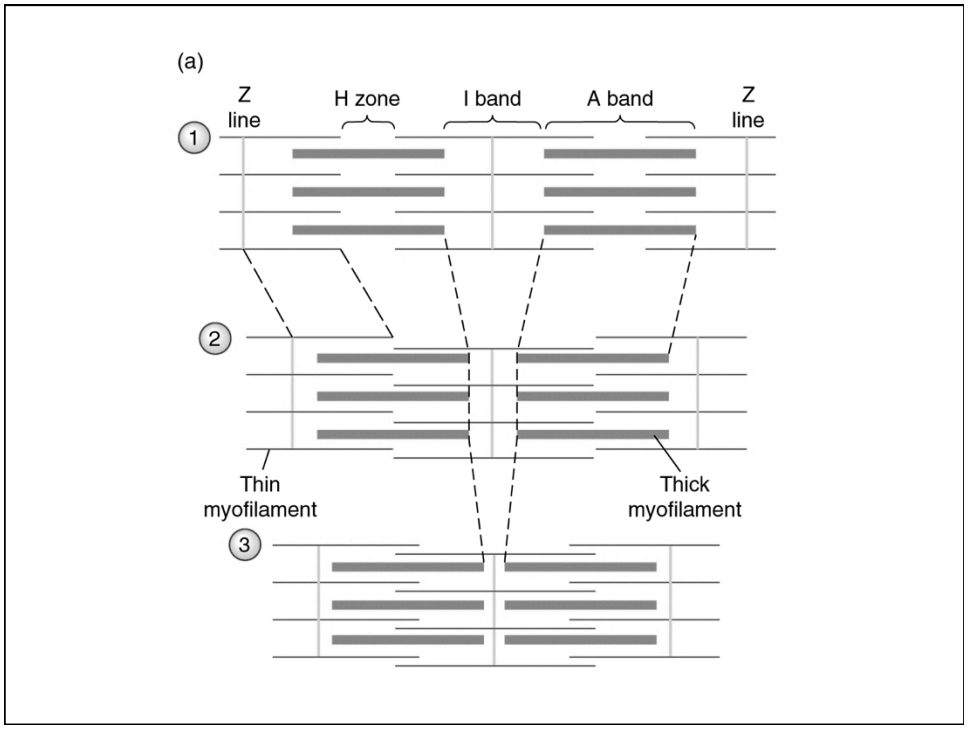

(a) Cilium or flagellum
Plasma membrane
Inner dynein arm
Outer dynein arm
Central pair of singlet microtubules
100 nm
A tubule
B tubule
Doublet microtubule
(b) Dynein complex
Dynein heavy chains
Dynein intermediate chains
Dynein light chains
(c) Dynein in motion
A tubule
B tubule

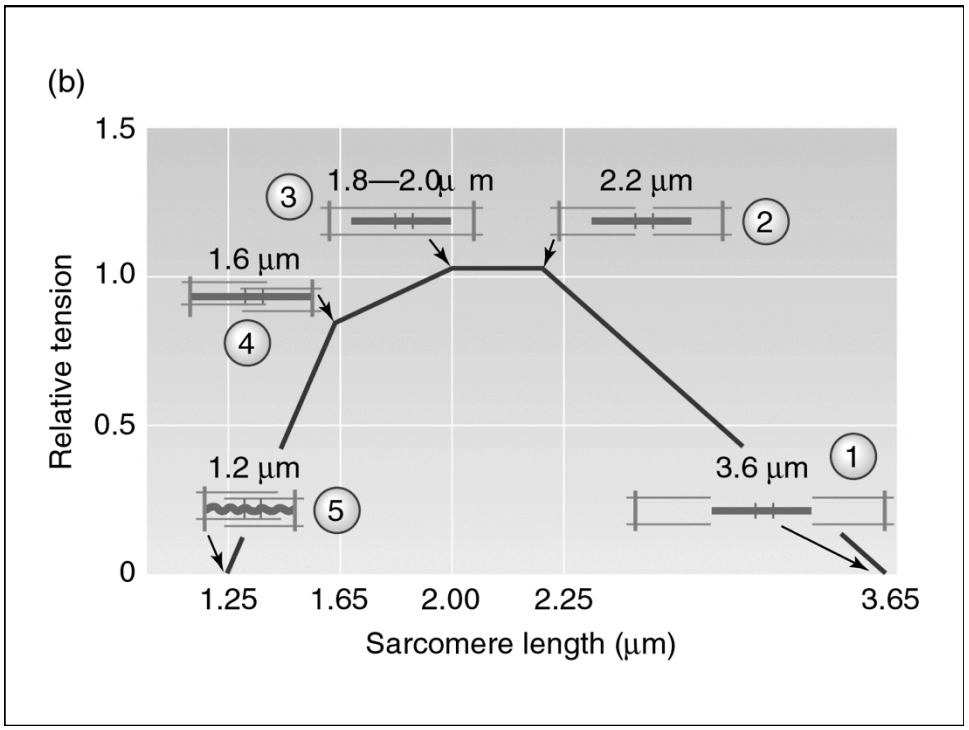

Muscle Tendon Bone
Embryonic muscle
Nucleus
Muscle fibers
Myoblasts
Myotubes
Nucleus
Myofibril
Sarcomere
A band
M line
H zone
Z disk
I band
Z disk
Actin
thin filament
Myosin
thick filament
Z disk

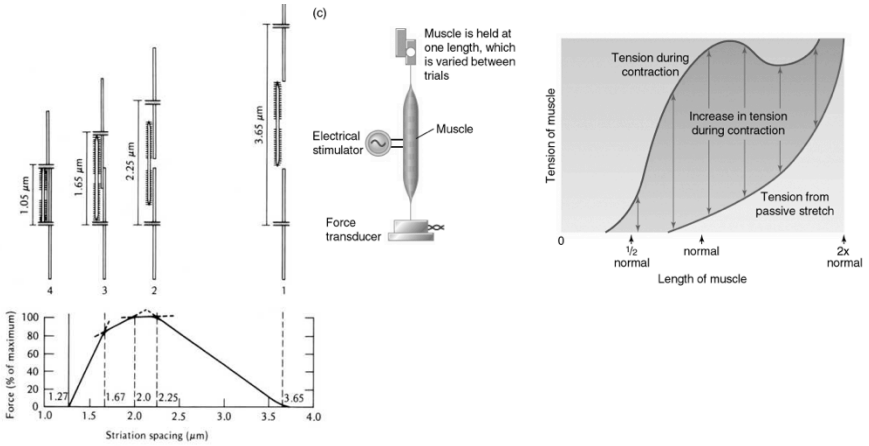

Active site
Actin
Troponin + Tropomyosin
Myosin
Relaxed
Ca++
Attached
Sliding
Troponin complex
Actin
Tropomyosin
20 nm
Myosin head
tr
t
tr
tr
Actin
Ca++
Myosin head
tr
t
tr
tr
Actin
Ca++
Ca+
Ca+
Ca+
(a)
Two supercoiled α helices
Amino terminus
Myosin light chains
17 nm
Heads
150 nm
Tail
2 nm
Carboxyl terminus

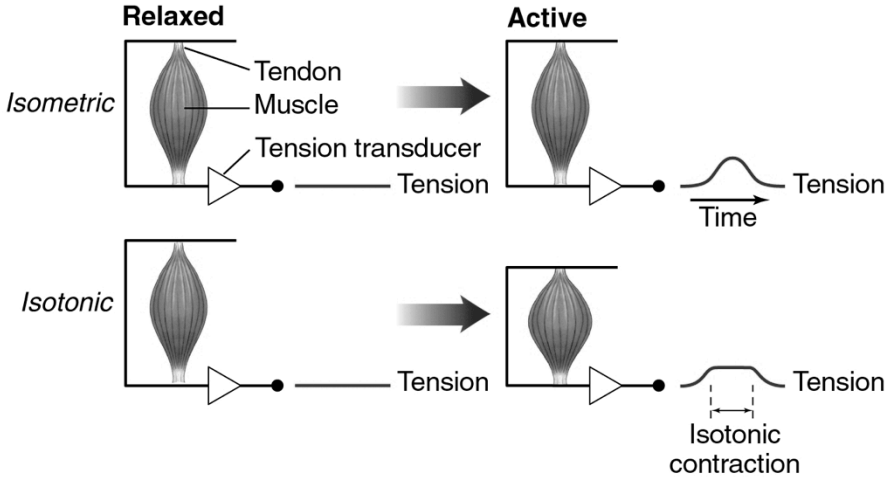

(a)
I
A
I
Z
H
Z
(b)
(c)
0.1 μm

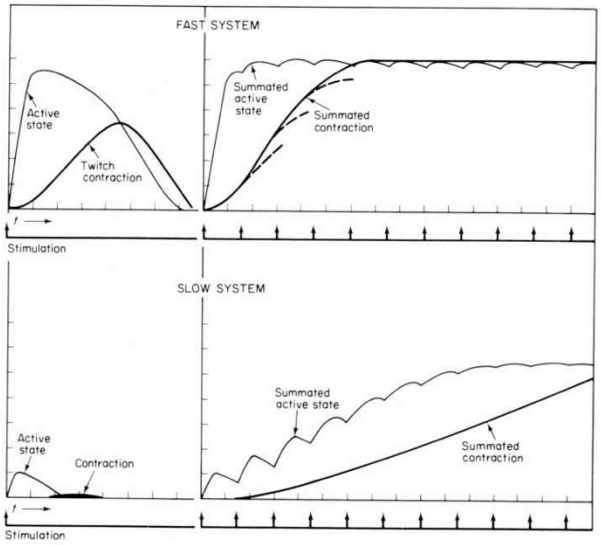

(a)
Z disk
Thin filament
Z disk
Equal and opposite
forces by thin filaments;
net force = 0
(b)
Net force to left
Net force to right;
sarcomere shortens
less effectively
(c)
Each sarcomere
shortens
Chain shortens

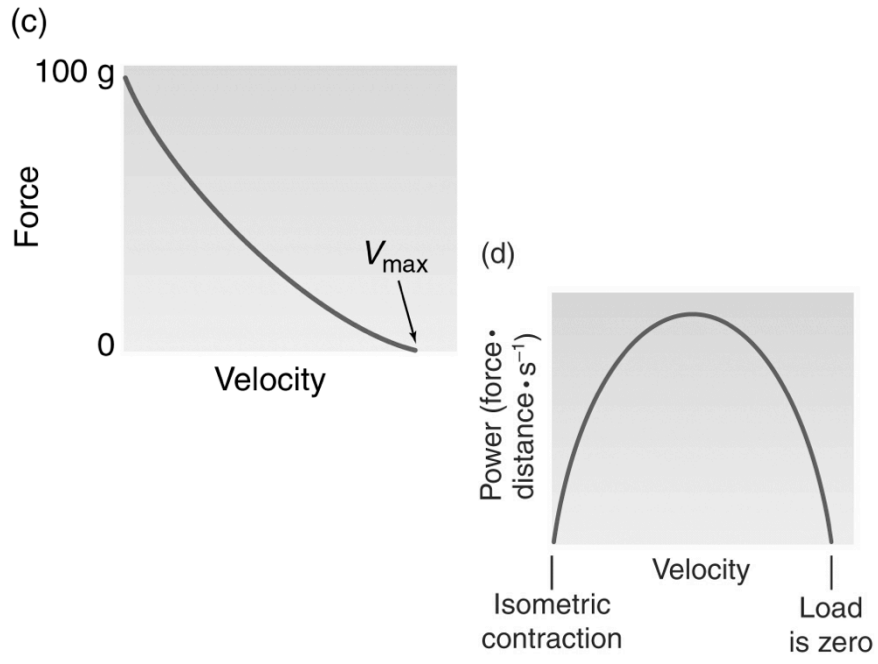

(a)
Z line
H zone
I band
A band
Z line
1
2
Thin myofilament
Thick myofilament
3

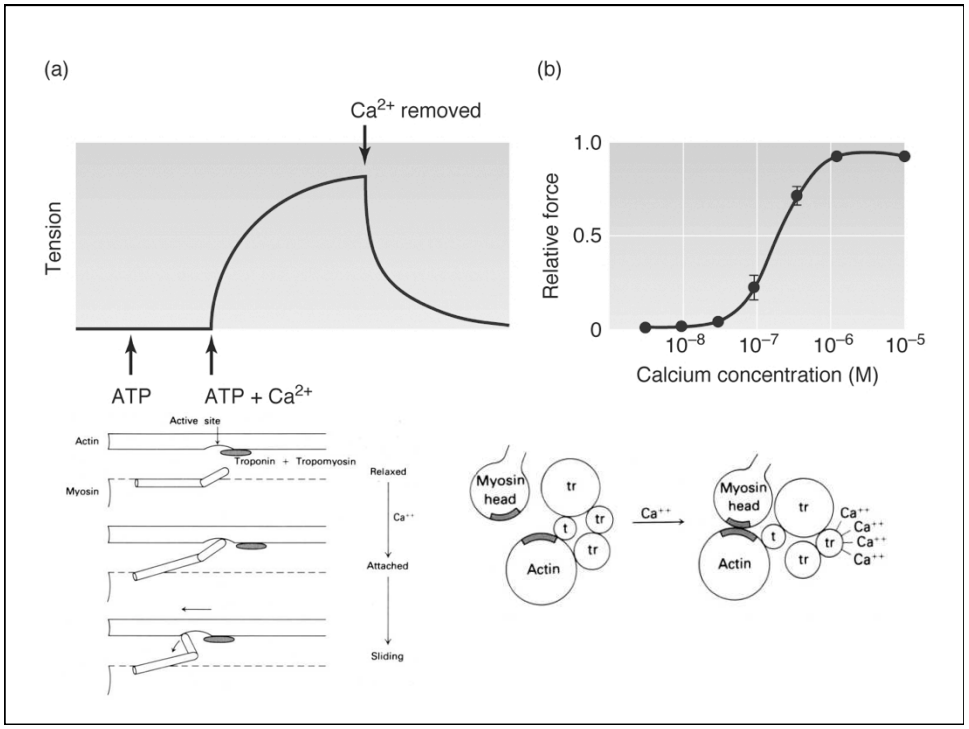

(b)
Relative tension
1.5
1.0
0.5
0
1.8—2.0μ m
2.2 μm
1.6 μm
1.2 μm
3.6 μm
1.25
1.65
2.00
2.25
3.65
Sarcomere length (μm)

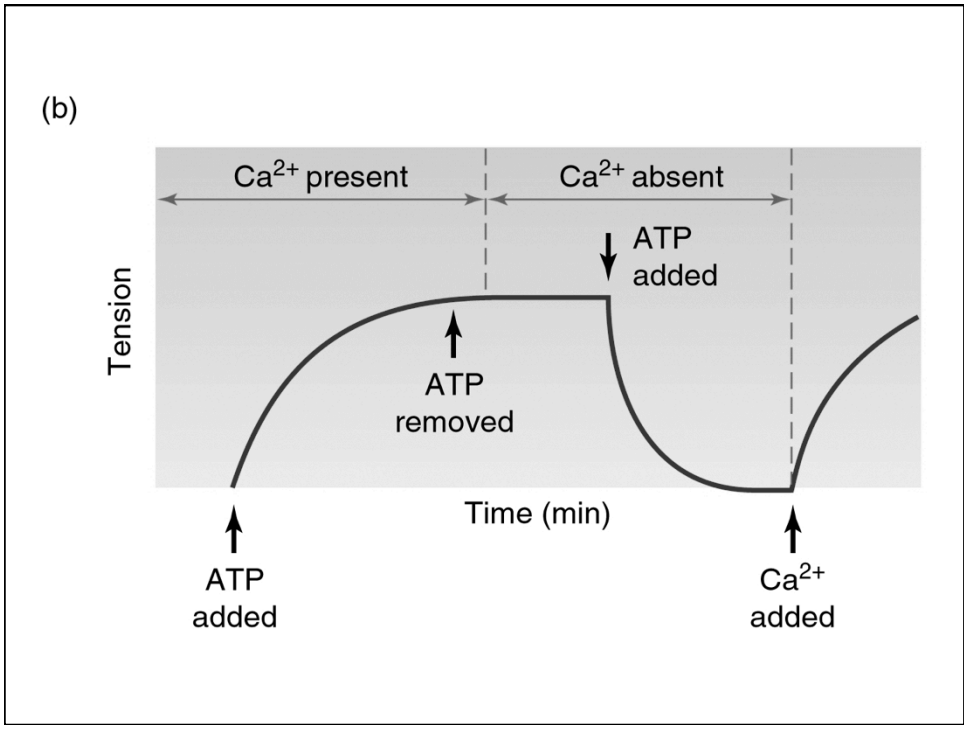

(c)
Muscle is held at one length, which is varied between trials
Electrical stimulator
Muscle
Force transducer
1.05 μm
1.65 μm
2.25 μm
3.65 μm
4
3
2
1
Force (% of maximum)
Striation spacing (μm)
1.27
1.67
2.0
2.25
3.65
Tension during contraction
Increase in tension during contraction
Tension from passive stretch
Tension of muscle
0
½ normal
normal
2x normal
Length of muscle

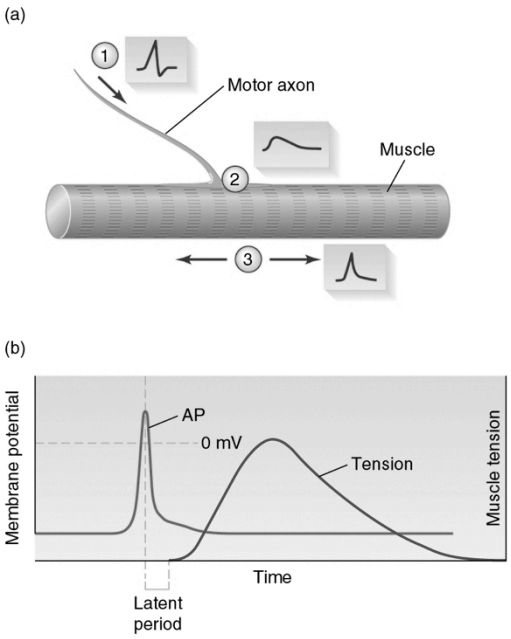

Relaxed
Active
Isometric
Tendon
Muscle
Tension transducer
Tension
Tension
Time
Isotonic
Tension
Tension
Isotonic contraction

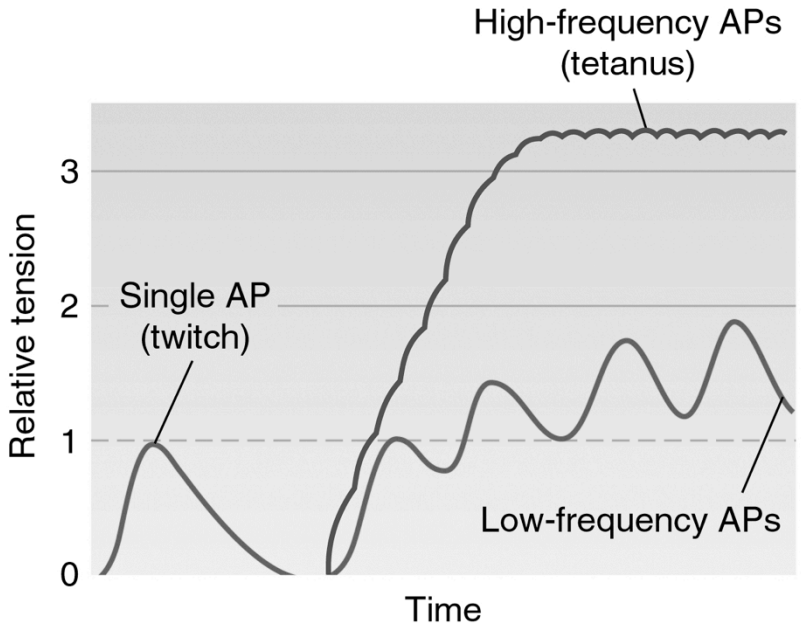

FAST SYSTEM
Active state
Twitch contraction
Summated active state
Summated contraction
t
Stimulation
SLOW SYSTEM
Active state
Contraction
Summated active state
Summated contraction
t
Stimulation

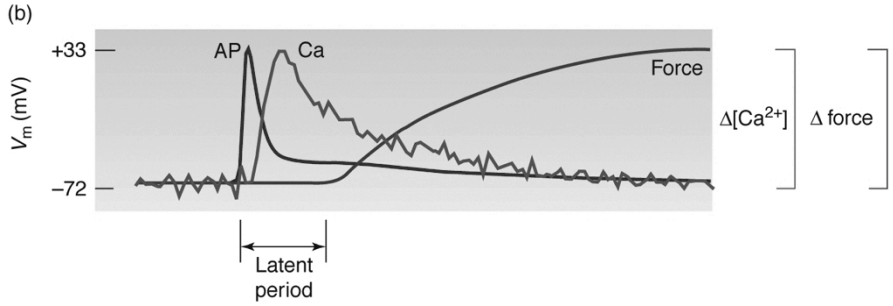

(c)
100 g
Force
0
$V_{max}$
Velocity
(d)
Power (force • distance • $s^{-1}$)
Velocity
Isometric contraction
Load is zero

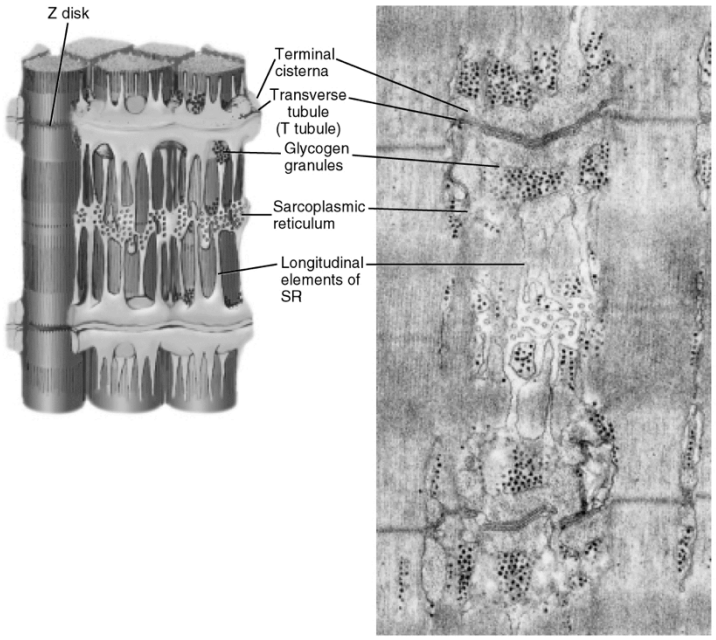

(a)
(b)
Ca2+ removed
Tension
ATP
ATP + Ca2+
Relative force
1.0
0.5
0
10−8
10−7
10−6
10−5
Calcium concentration (M)
Active site
Actin
Troponin + Tropomyosin
Myosin
Relaxed
Ca++
Attached
Sliding
Myosin head
tr
t
Actin
Ca++

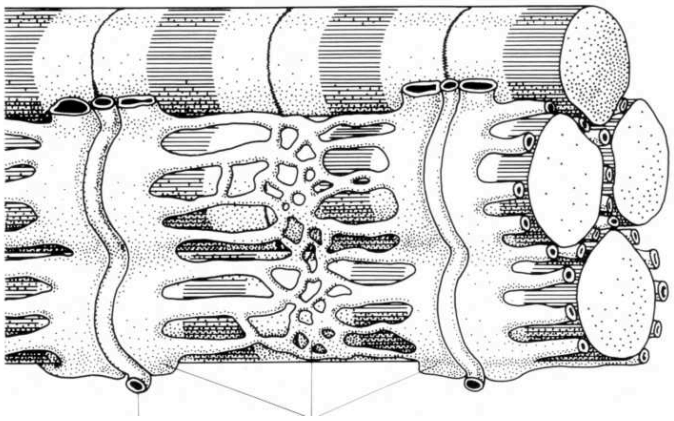

(b)
Ca2+ present
Ca2+ absent
ATP added
ATP removed
Tension
Time (min)
ATP added
Ca2+ added


(a)
1
Motor axon
Muscle
2
3
(b)
Membrane potential
AP
0 mV
Tension
Muscle tension
Time
Latent
period


High-frequency APs
(tetanus)
Relative tension
3
2
1
0
Single AP
(twitch)
Low-frequency APs
Time


(b)
+33
–72
$V_m$ (mV)
AP
Ca
Force
Δ[Ca2+]
Δ force
Latent
period


Z disk
Terminal
cisterna
Transverse
tubule
(T tubule)
Glycogen
granules
Sarcoplasmic
reticulum
Longitudinal
elements of
SR



*Stimulation*

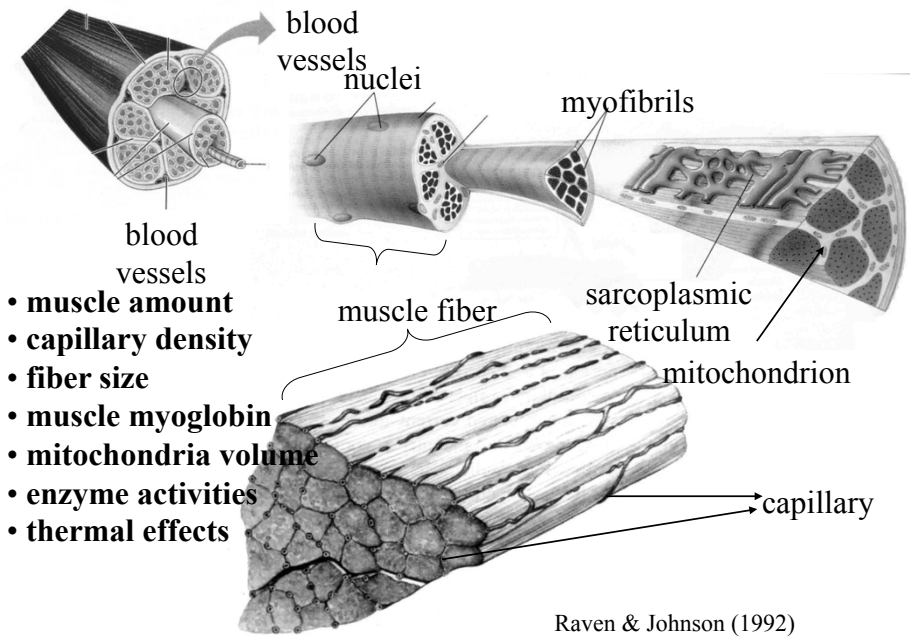
1 Sarcolemma depolarized
2 T-system depolarized
3 $Ca^{2+}$ released from sarcoplasmic reticulum
4 $Ca^{2+}$ diffuses to thin filament

*Contraction*

5 $Ca^{2+}$ binds to troponin
6 Troponin–$Ca^{2+}$ complex removes tropomyosin blockage of actin sites
7 Heads of thick filament (containing preexisting myosin–ATP complex) form cross-bridges to actin strand
8 Hydrolysis of ATP induces conformational changes in heads that cause cross-bridges to swivel

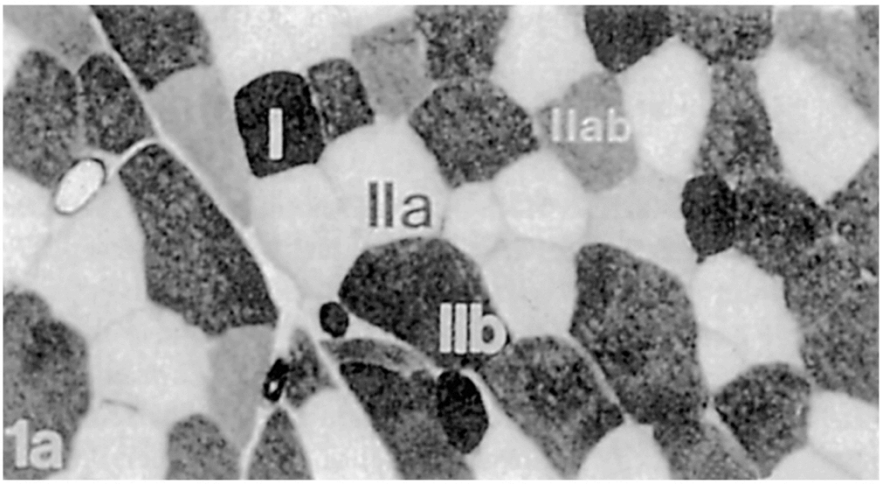
*Relaxation*

9 $Ca^{2+}$ sequestered from thin filament by sarcoplasmic reticulum
10 $Ca^{2+}$ diffuses from thin filament toward sarcoplasmic reticulum
11 $Ca^{2+}$ released from troponin–$Ca^{2+}$ complex
12 Troponin permits tropomyosin return to blocking position
13 Myosin–actin cross-bridges break
14 ATP–myosin complex re-formed in heads of thick filament




- **muscle amount**
- **capillary density**
- **fiber size**
- **muscle myoglobin**
- **mitochondria volume**
- **enzyme activities**
- **thermal effects**

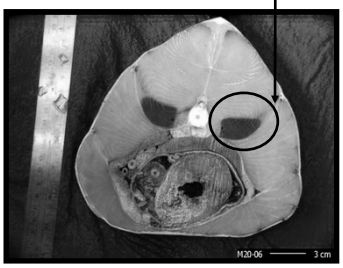
Raven & Johnson (1992)
Mathieu-Costello & Hepple (2002)



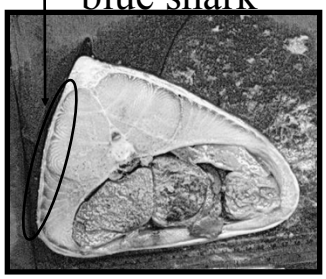
# Different red muscle positions

Internal External

mako shark




blue shark



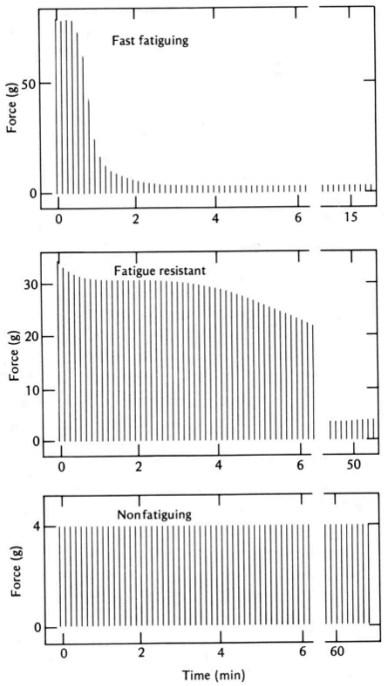


*Table 10-1* **Properties of twitch (phasic) fibers in mammalian skeletal muscles**

| Property | Slow oxidative (type I) | Fast oxidative (type IIa) | Fast glycolytic (type IIb) |
|---|---|---|---|
| Fiber diameter | ↓ | ↔ | ↑ |
| Force per cross-sectional area | ↓ | ↔ | ↑ |
| Rate of contraction ($V_{max}$) | ↓ | ↑ | ↑ |
| Myosin ATPase activity | ↓ | ↑ | ↑ |
| Resistance to fatigue | ↑ | ↔ | ↓ |
| Number of mitochondria | ↑ | ↑ | ↓ |
| Capacity for oxidative phosphorylation | ↑ | ↑ | ↓ |
| Enzymes for anaerobic glycolysis | ↓ | ↔ | ↑ |

*Source:* Adapted from Sherwood, 2001. Key = ↓ Low ↔ Intermediate ↑ High

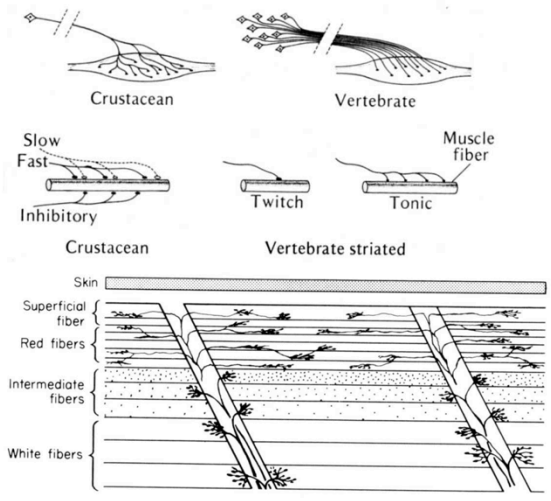
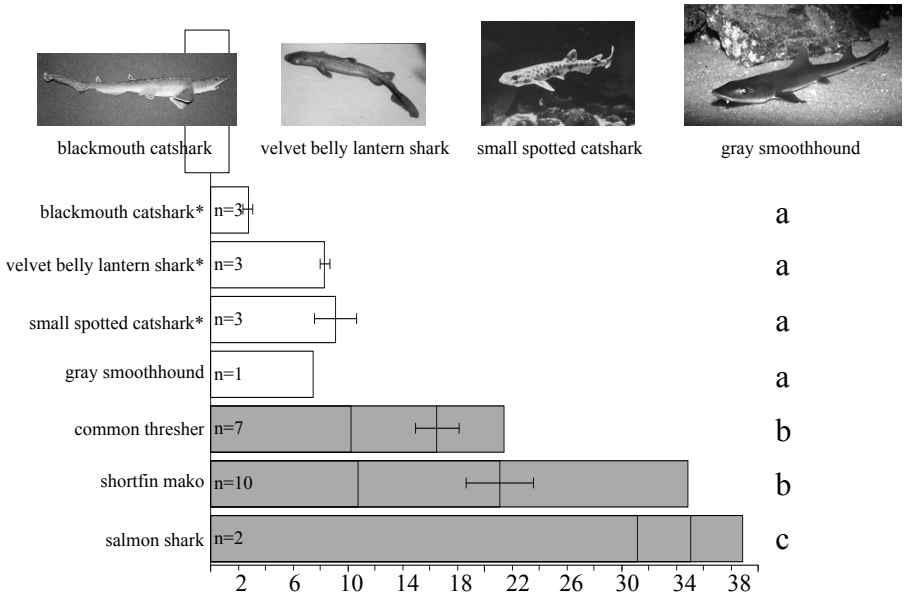


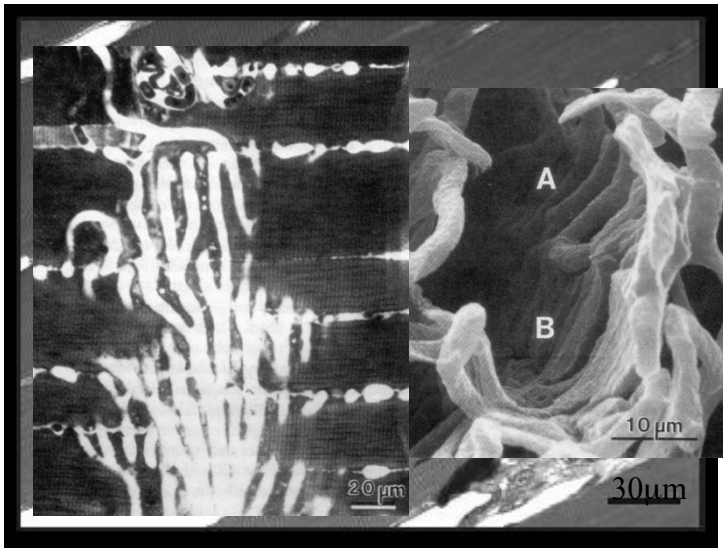

**Fig. 19.21** Innervation of different muscle types in a dogfish myotome. White fibers are innervated only at their myoseptal ends by a characteristic basket-like arrangement which clasps the end of the muscle; the red fibers possess several motor terminations which curve around and along the muscle fiber with numerous small swellings distributed at short intervals. [From Bone, 1966: J. Marine Biol. Assoc. U.K., *46*: 329.]




*Kryvi *et al*. (1981)

values = mean ± SEM

9.7 kg mako RM




Longitudinal sections

Mathieu-Costello *et al*. (199