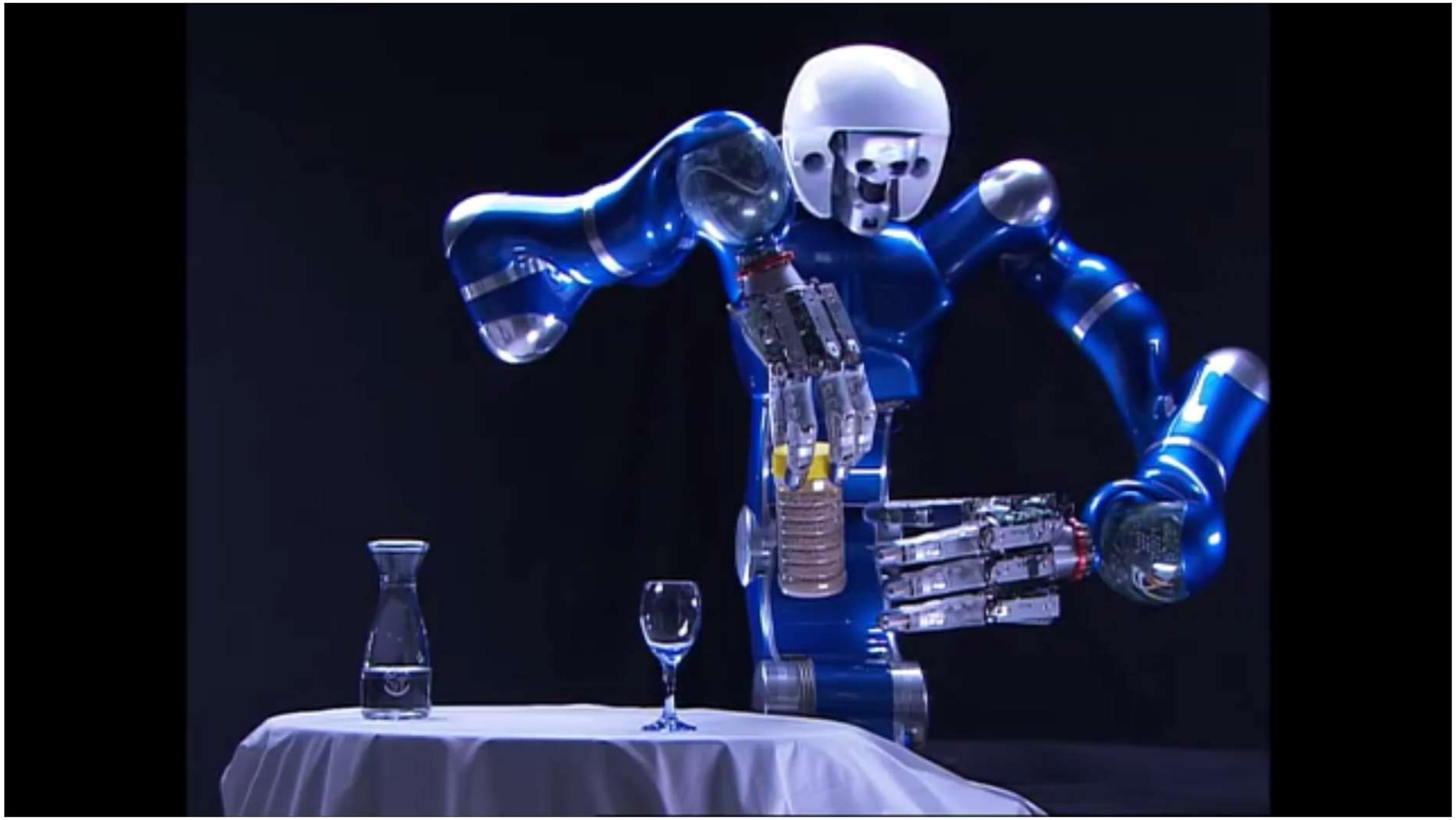
Human Motor Systems

Lei Zhang

Institute for Neural Computation
Ruhr-Universität Bochum
lei.zhang@ini.rub.de

Autonomous Robotics: Action, Perception, and Cognition (ST 2025)
Prof. Dr. Gregor Schöner
Teaching unit: Human motor systems (03.07.2025)

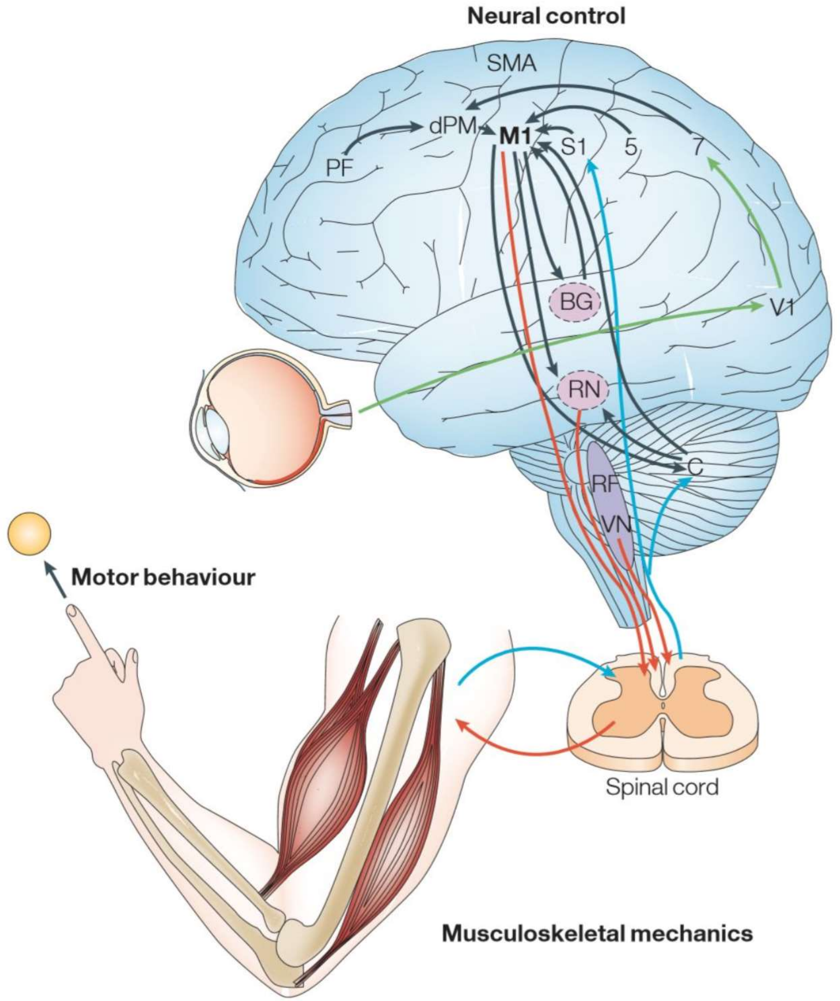


Video: The humanoid robot Rollin' Justin, Institute of Robotics and Mechatronics, German Aerospace Center

Video: Individual cycle sport stacking world record 4.753s, Malaysia 2019 (Chan Keng Ian)

Robot	Human
Powerful torque motor	Sluggish muscles
Conduction delay <1ms	Conduction delay > 20ms
Accurate sensors	Noisy sensory receptors

Overview of human motor system



Scott. Nature Reviews Neuroscience 2004

- Central nervous system (CNS)
  - Brain
  - Spinal cord

- Muscles

Outlines

- **How muscles work?**

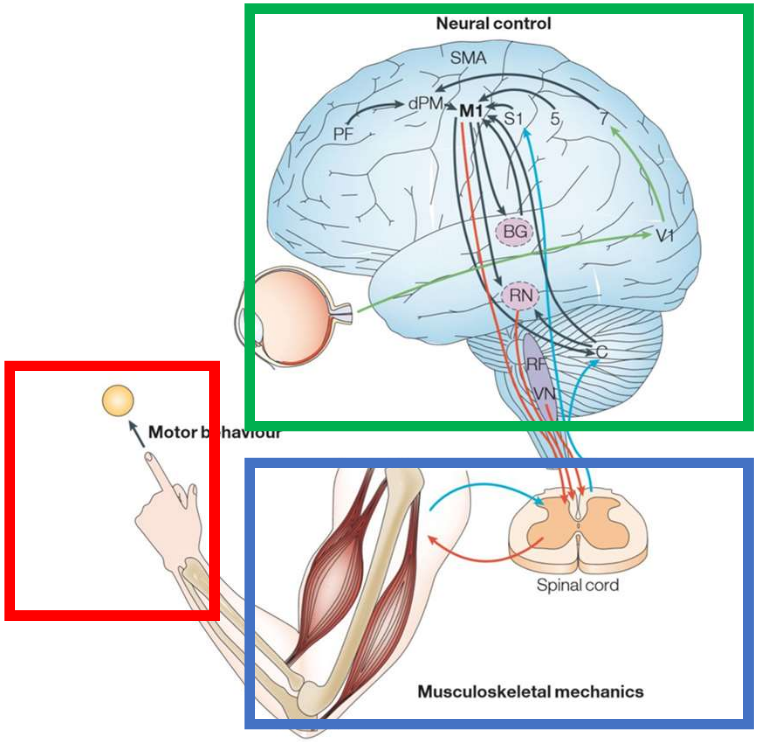
  - muscles, motoneurons, reflexes, spinal cord

- **How movements look like?**

  - kinematic patterns

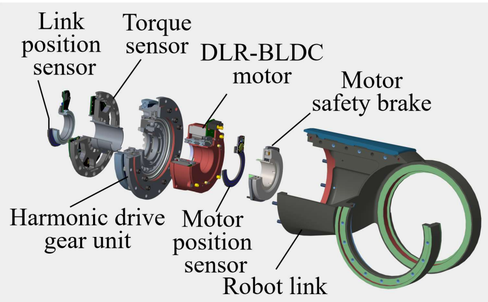
- **How the brain works in movement generation?**

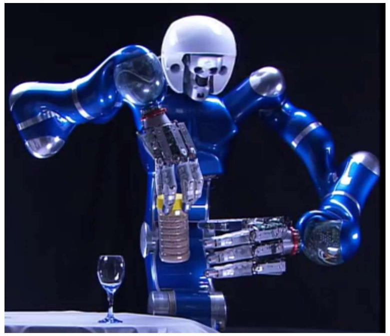
  - neuroanatomy, function



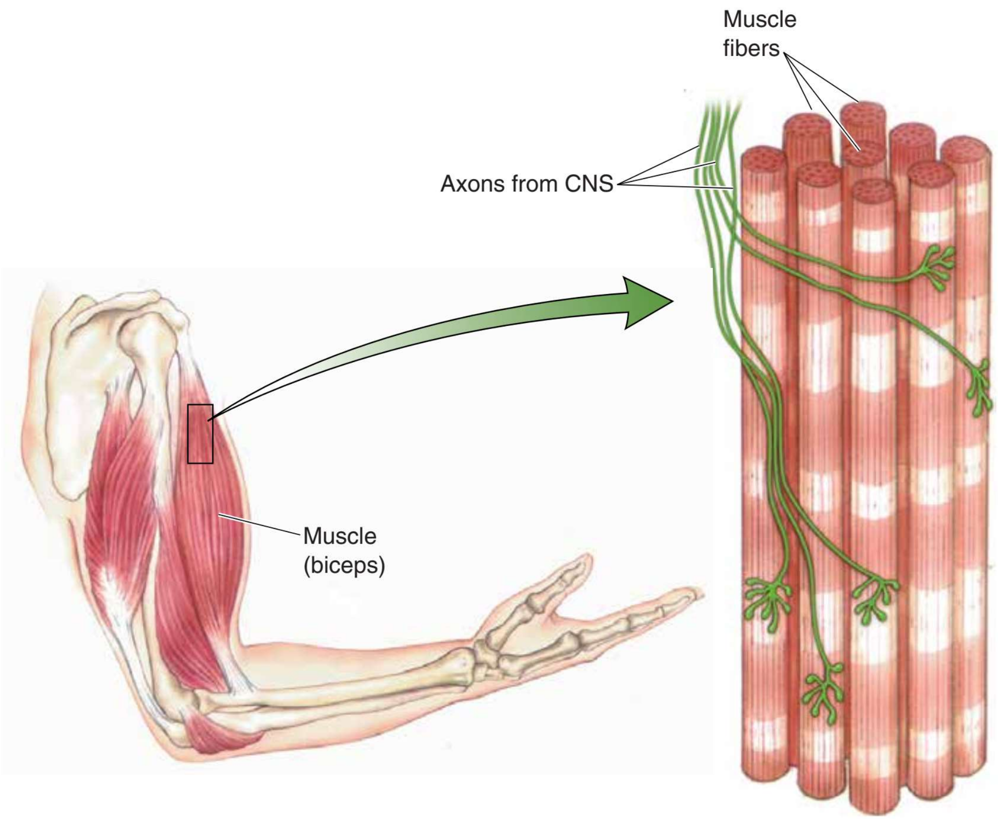
“To move things is all that mankind can do, for such the sole executant is muscle, whether whispering a syllable or felling a forest.”

Sir Charles Sherrington

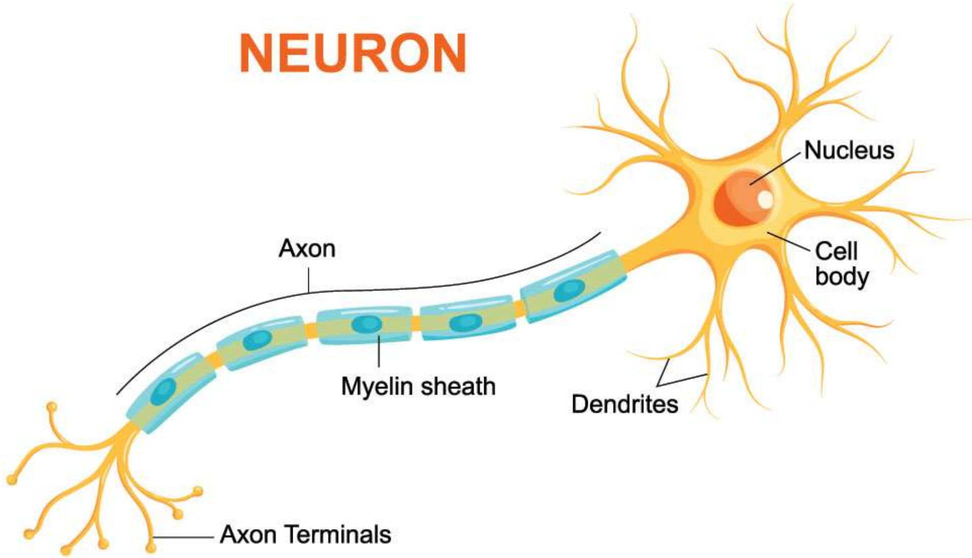




Muscle structure and motor neuron



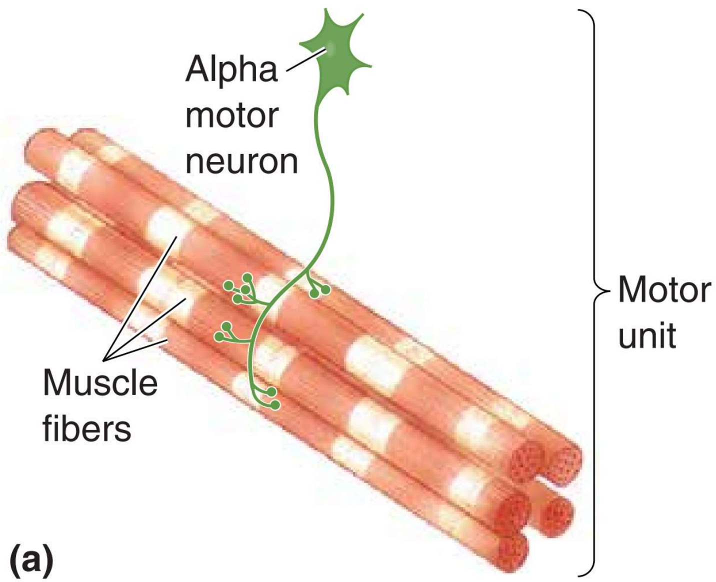
Bear et al. Figure 13-1

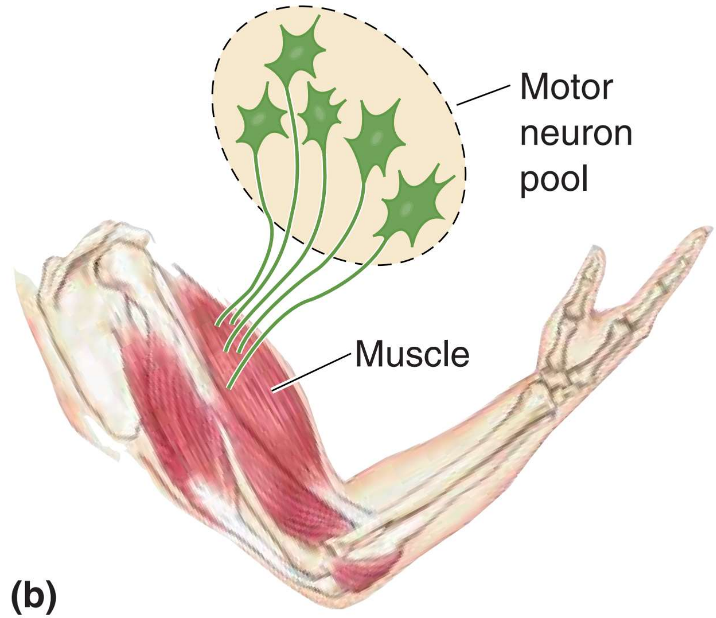


https://www.sciencenewsforstudents.org/article/explainer-what-is-a-neuron

Each muscle fiber is innervated by a single axon

Muscle structure and motor neuron



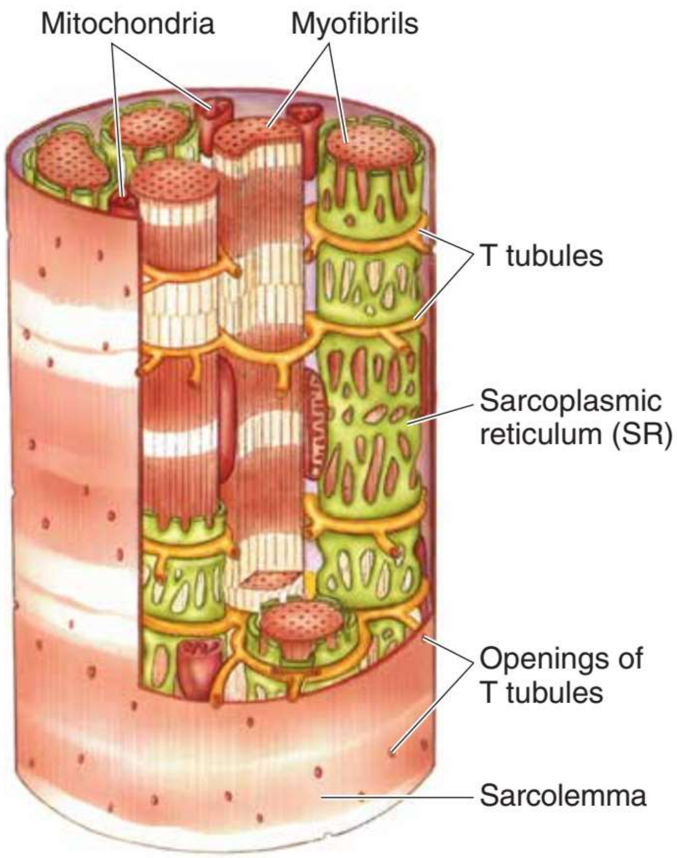


Bear et al. Figure 13-7

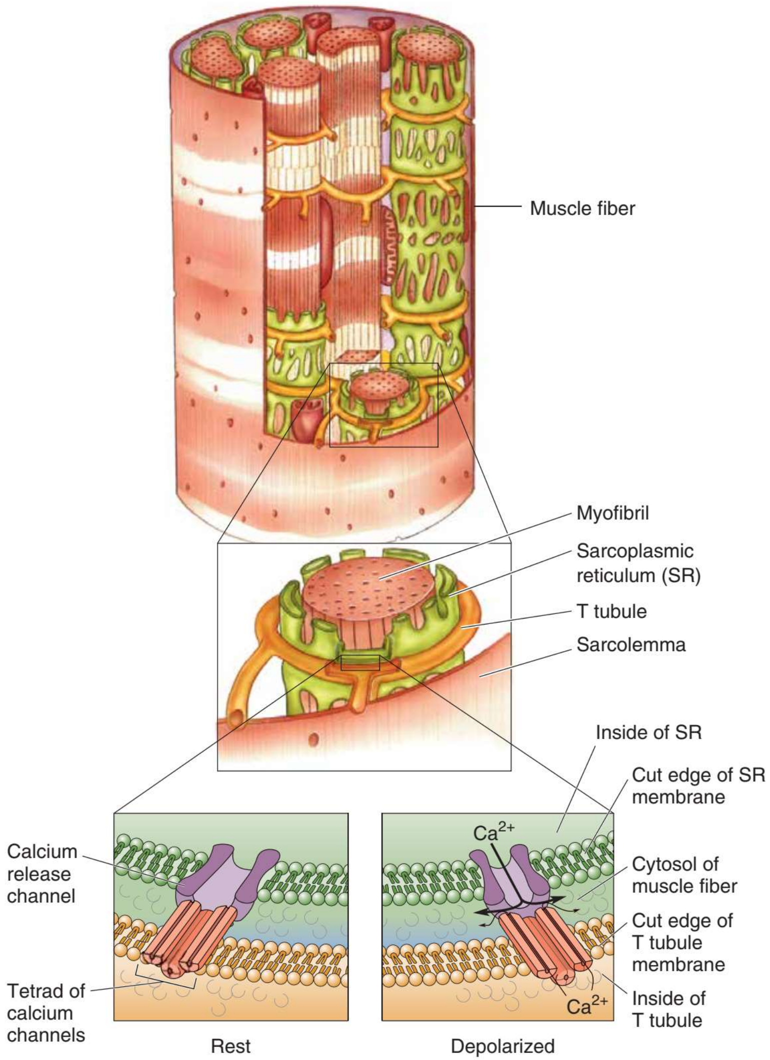
Each motor neuron innervates multiple muscle fibers

Each muscle is innervated by multiple motor neurons

Muscle fiber structure

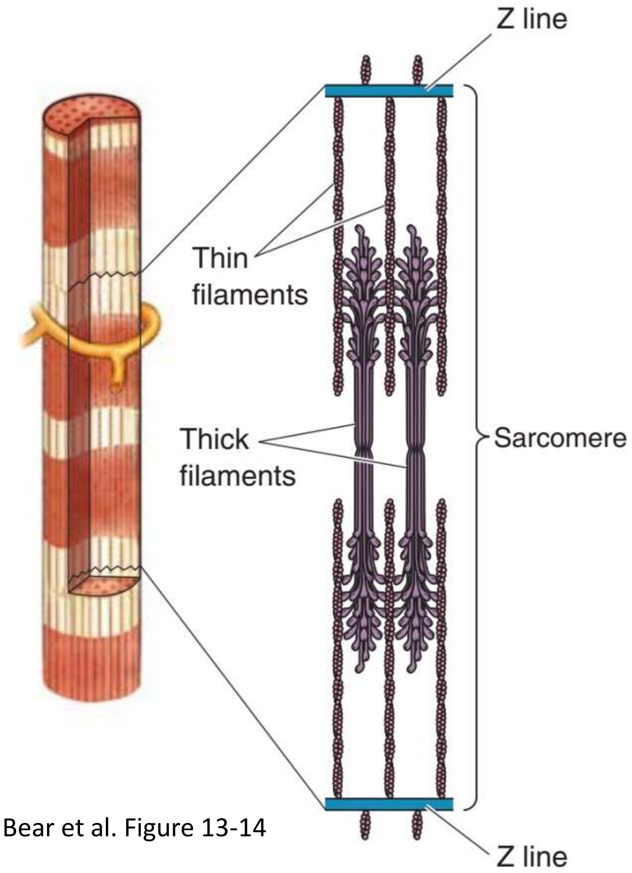


T tubules conduct electrical activity from the surface membrane into the depths of the muscle fiber



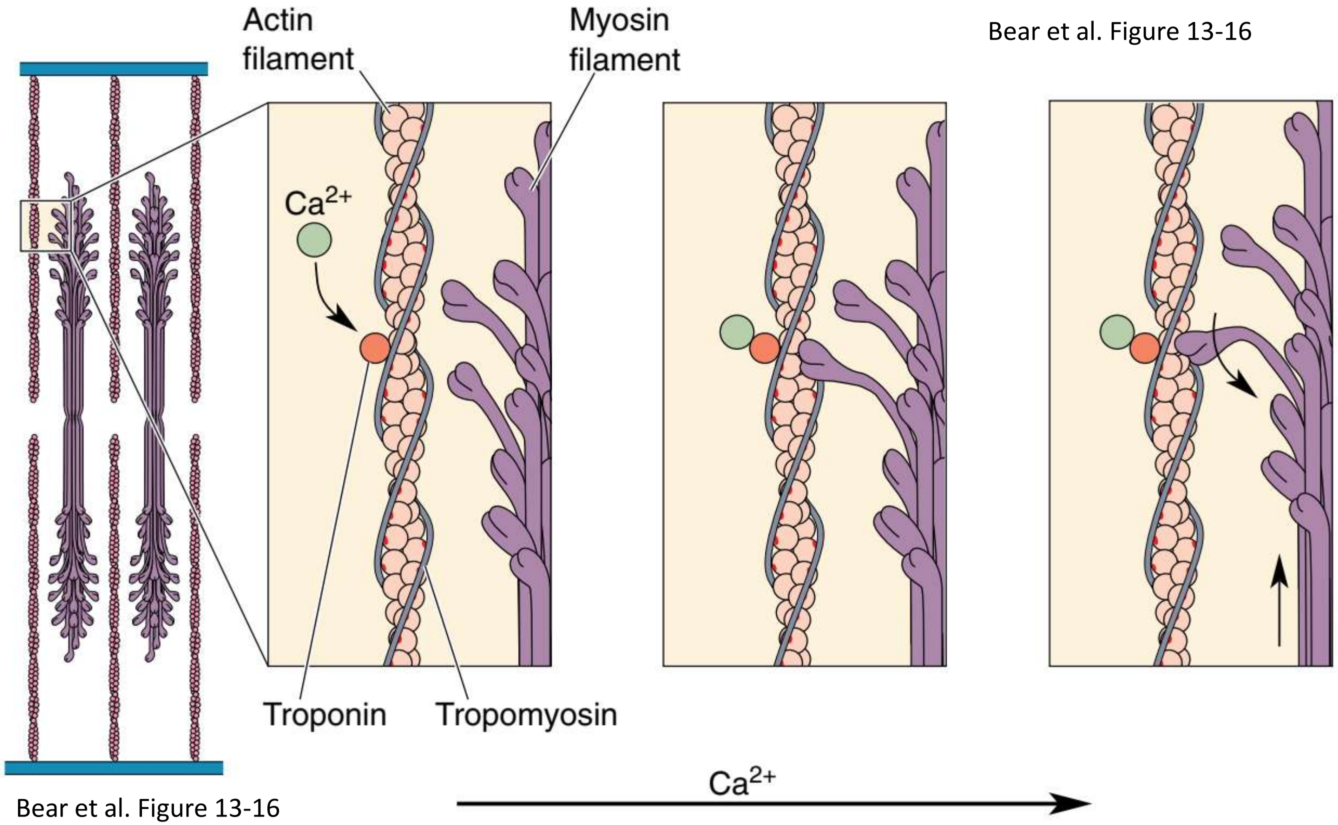
Bear et al. Figures 13-12 and 13

The molecular basis of muscle contraction



Bear et al. Figure 13-14

The myofibril

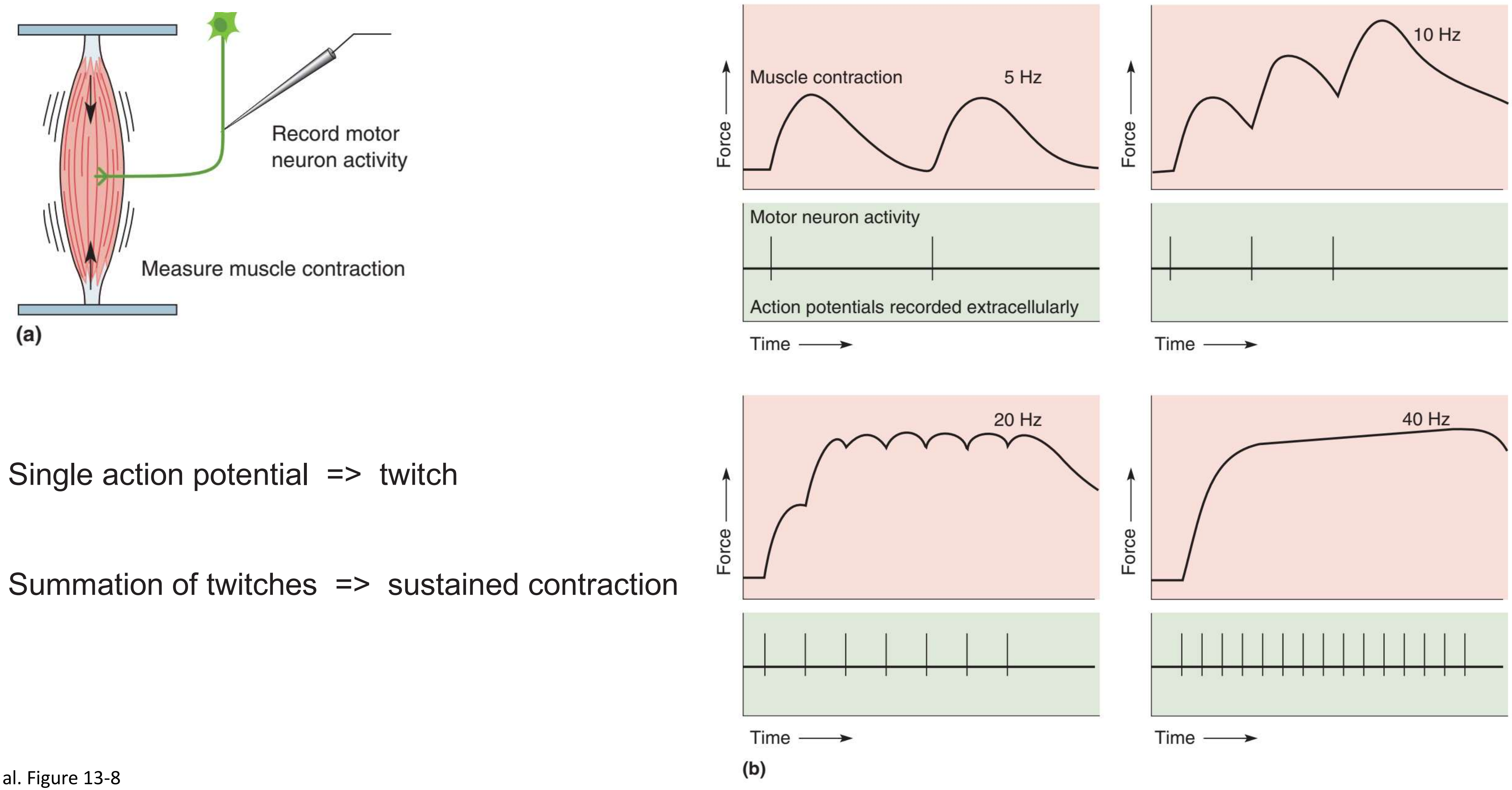


Bear et al. Figure 13-16

Bear et al. Figure 13-16

The myosin walk

Muscle force generation

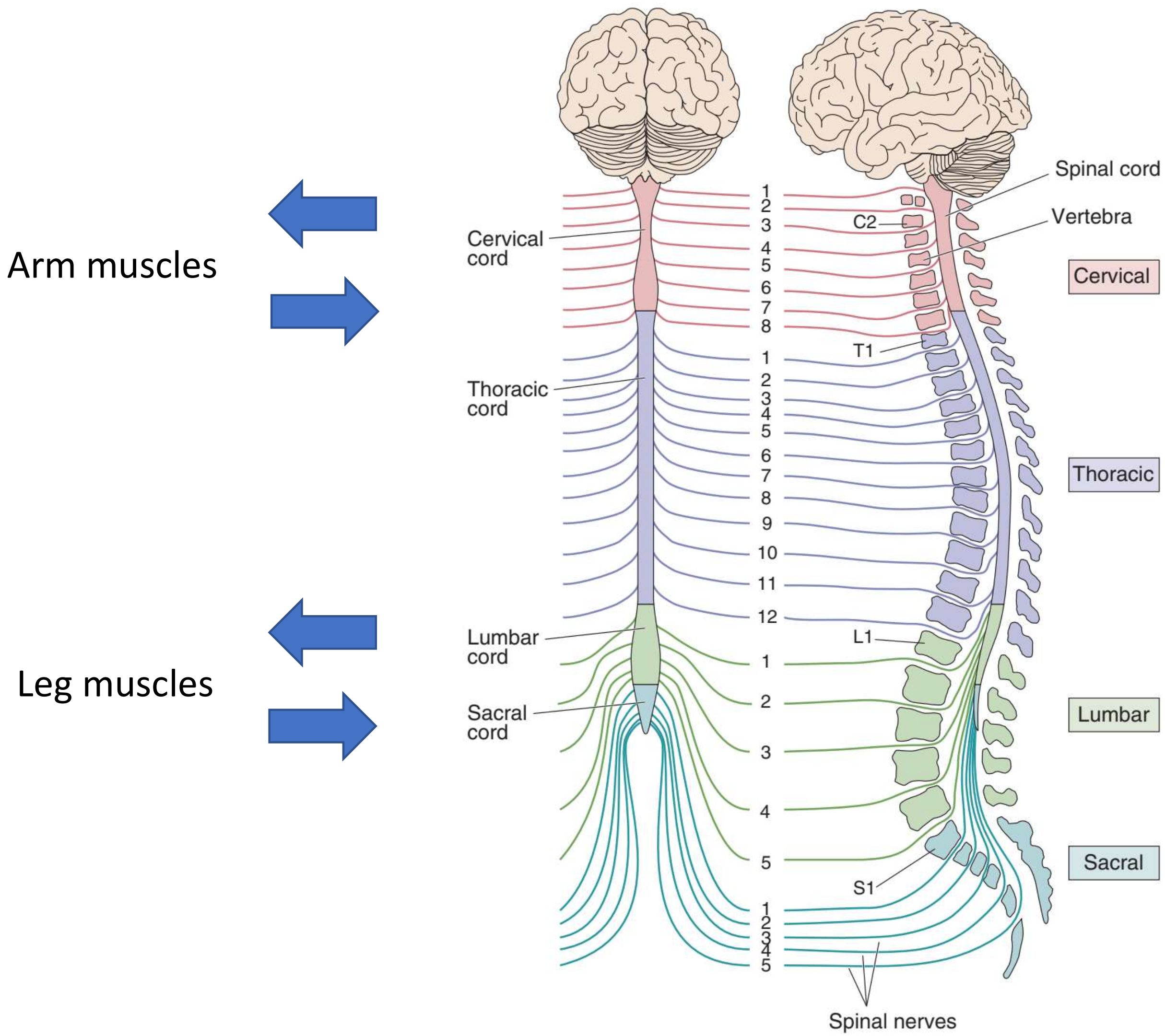


Single action potential => twitch

Summation of twitches => sustained contraction

Bear et al. Figure 13-8

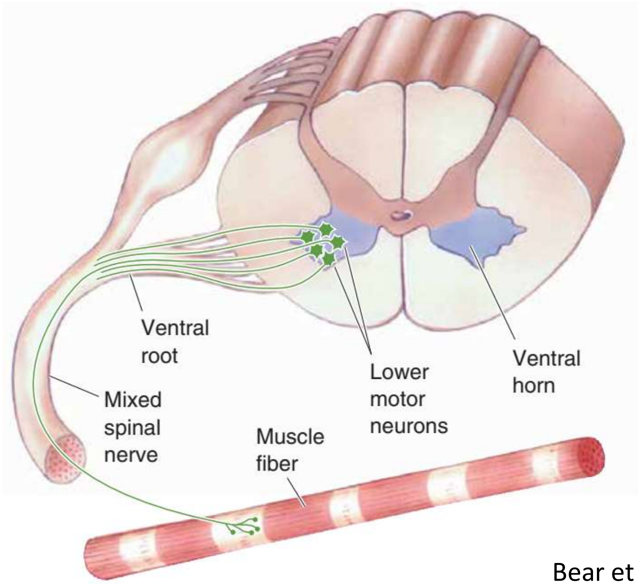
The human spinal cord



Bear et al. Figure 12-11

Motor and sensory pathways

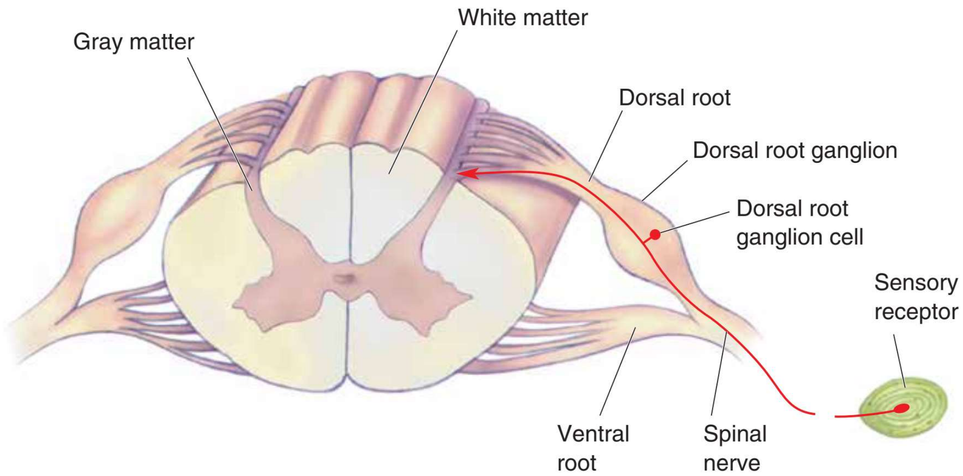
Motor



Bear et al. Figure 13-4

Sensory

Grey matter: cell bodies
White matter: axons

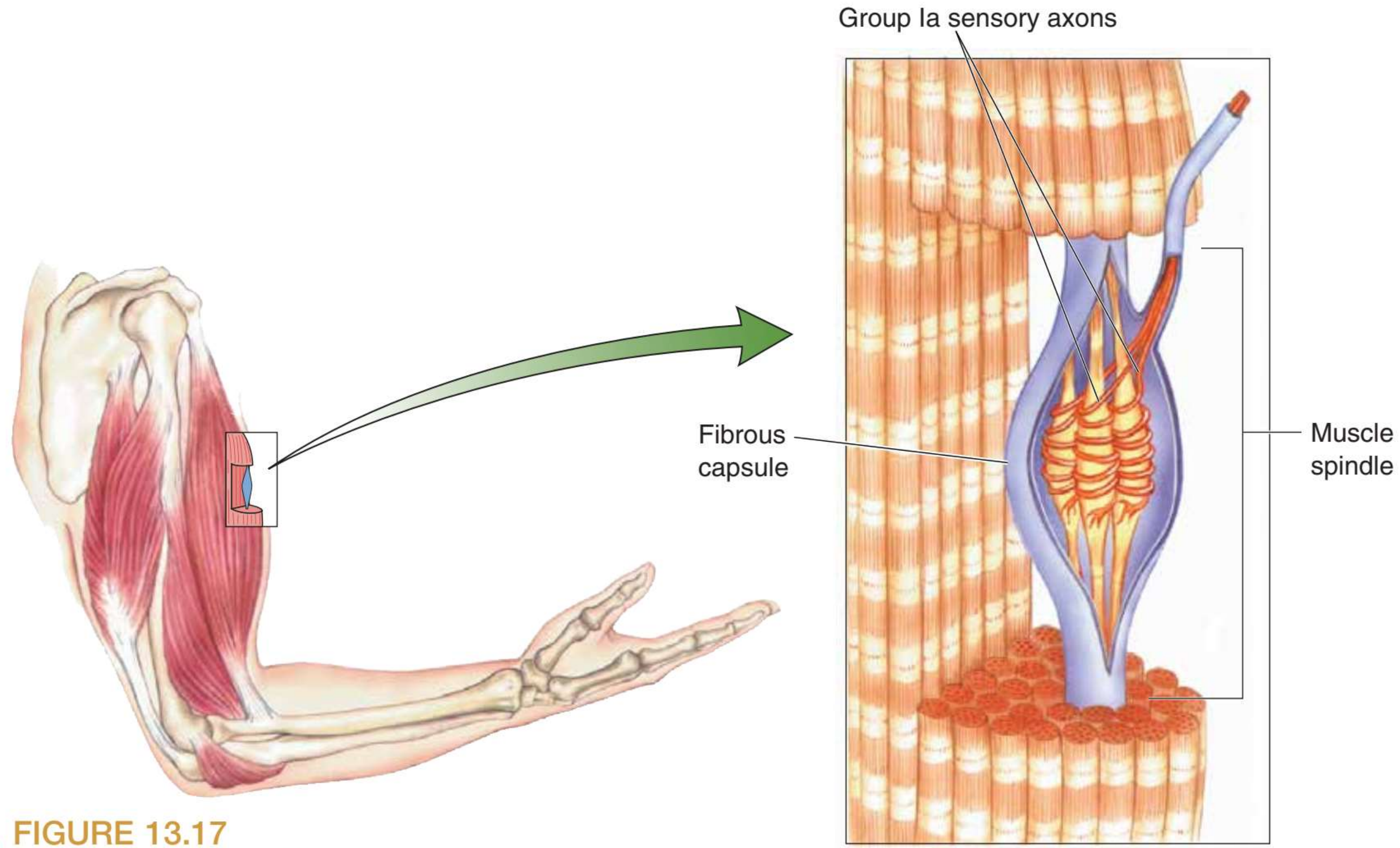


Bear et al. Figure 12-9

The ventral horn of the spinal cord contains motor neurons that innervate skeletal muscle fibers.

Sensory signals enter the spinal cord through the dorsal roots. Cell bodies of sensory neurons lie in the dorsal root ganglia

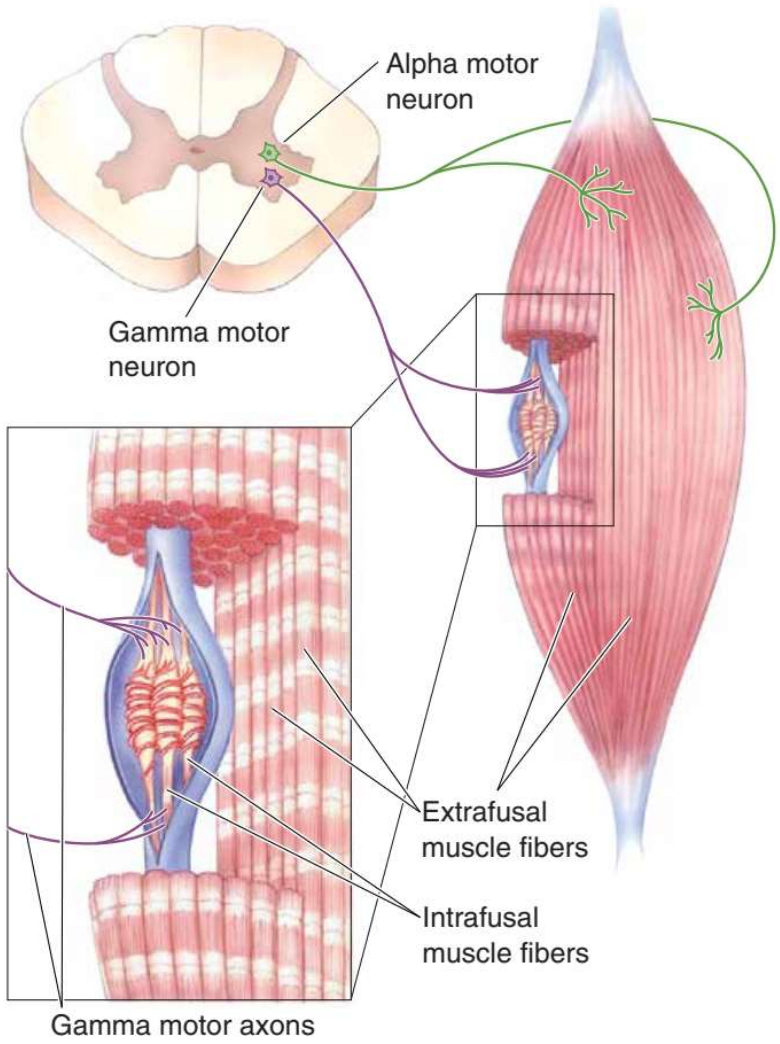
Muscle spindle structure



▲ FIGURE 13.17
A muscle spindle and its sensory innervation.

Bear et al.

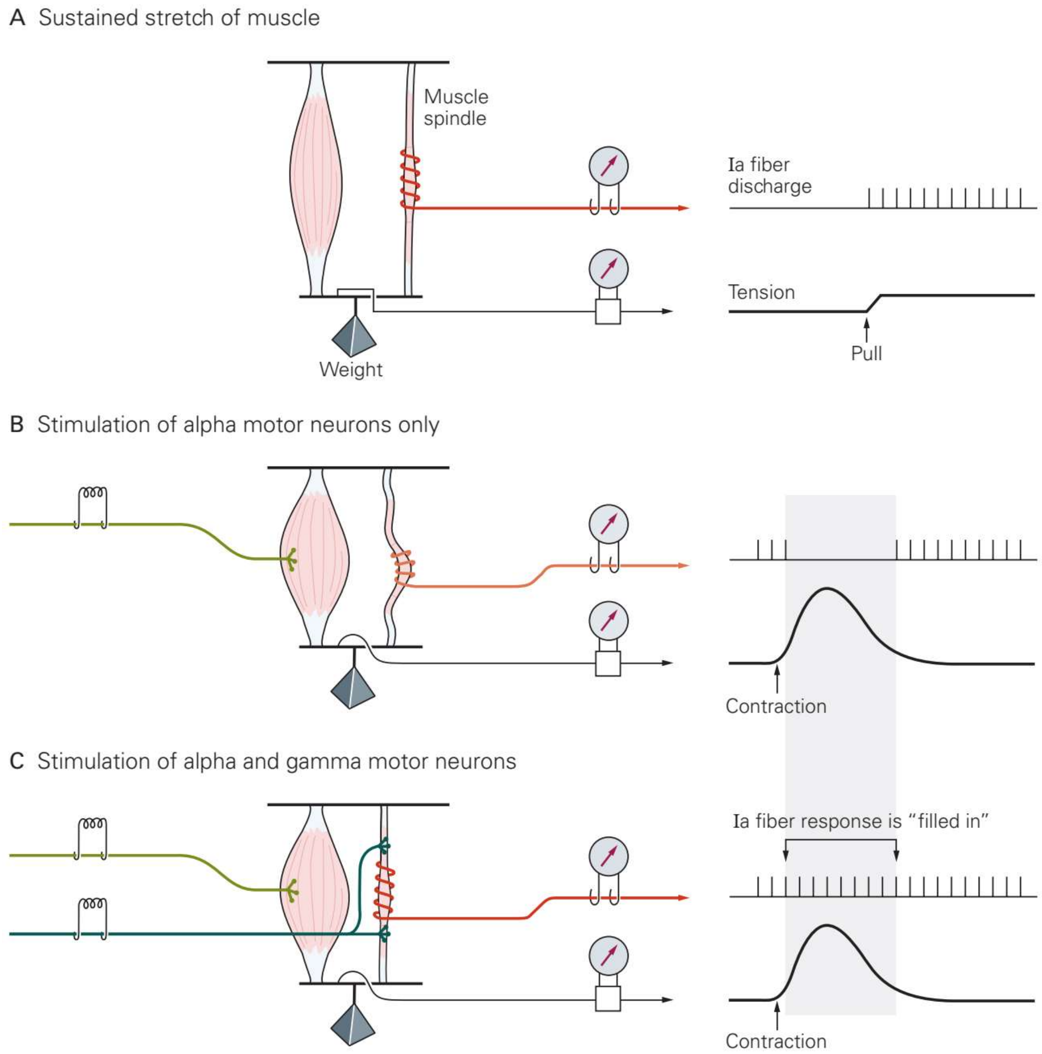
Muscle spindle structure



Bear et al. Figure 13-20

Muscle fibers	Innervation	Force production
Extrafusal	Alpha MN	Yes
Intrafusal	Gamma MN	No

Gamma motor neuron function

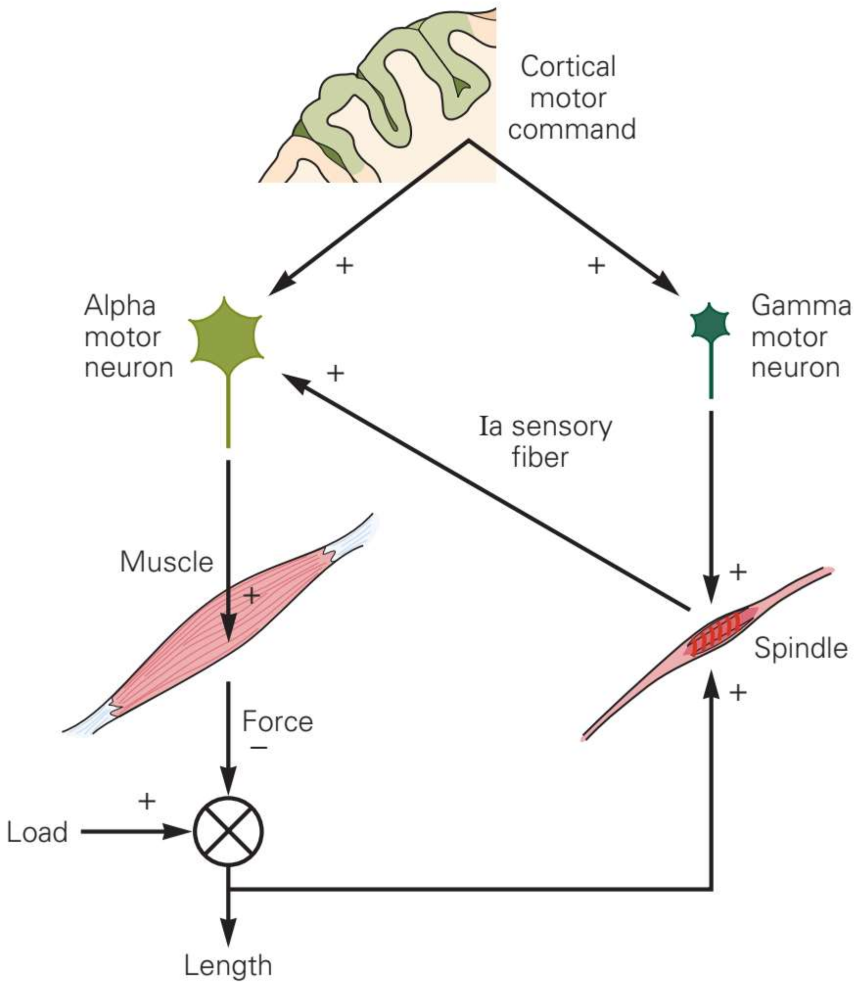


Kandel et al. Figure 35-9

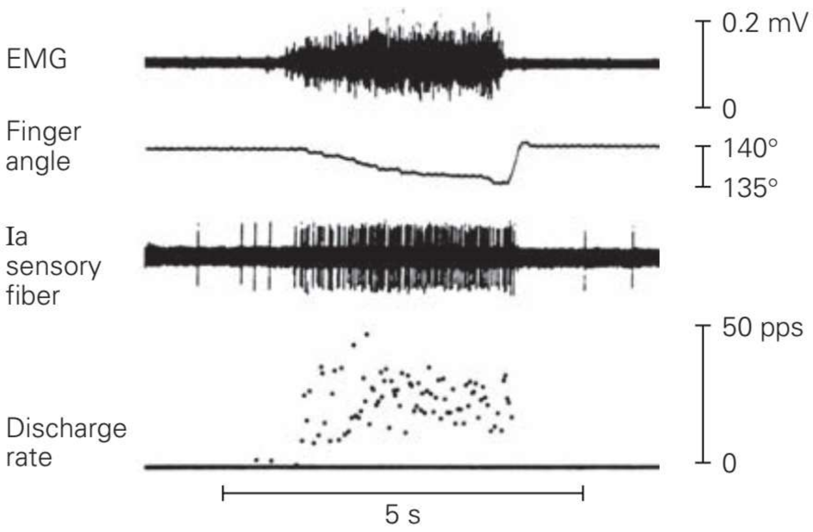
- Gamma motor neuron adjusts the sensitivity of Ia sensory fibers

Gamma motor neuron function

A Alpha-gamma co-activation reinforces alpha motor activity

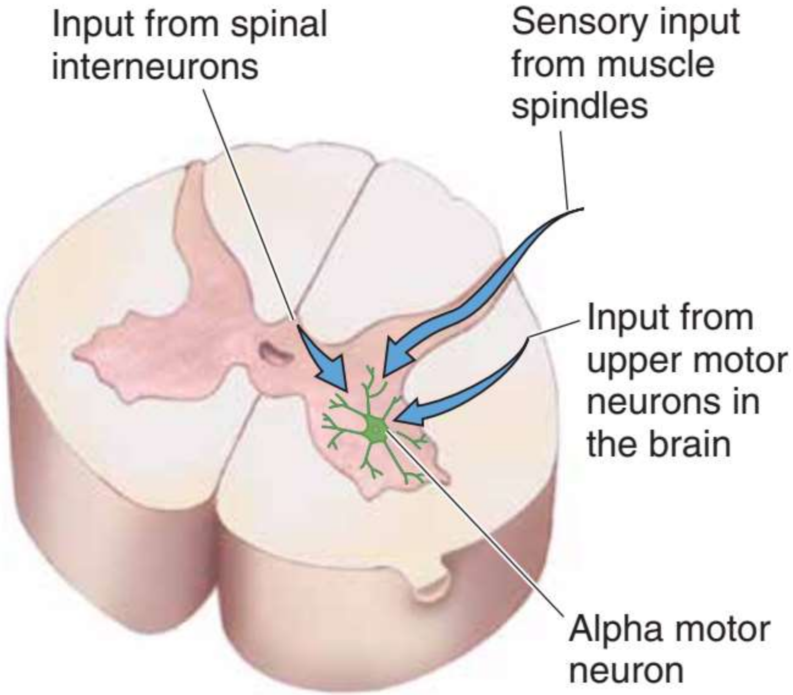


B Spindle activity increases during muscle shortening



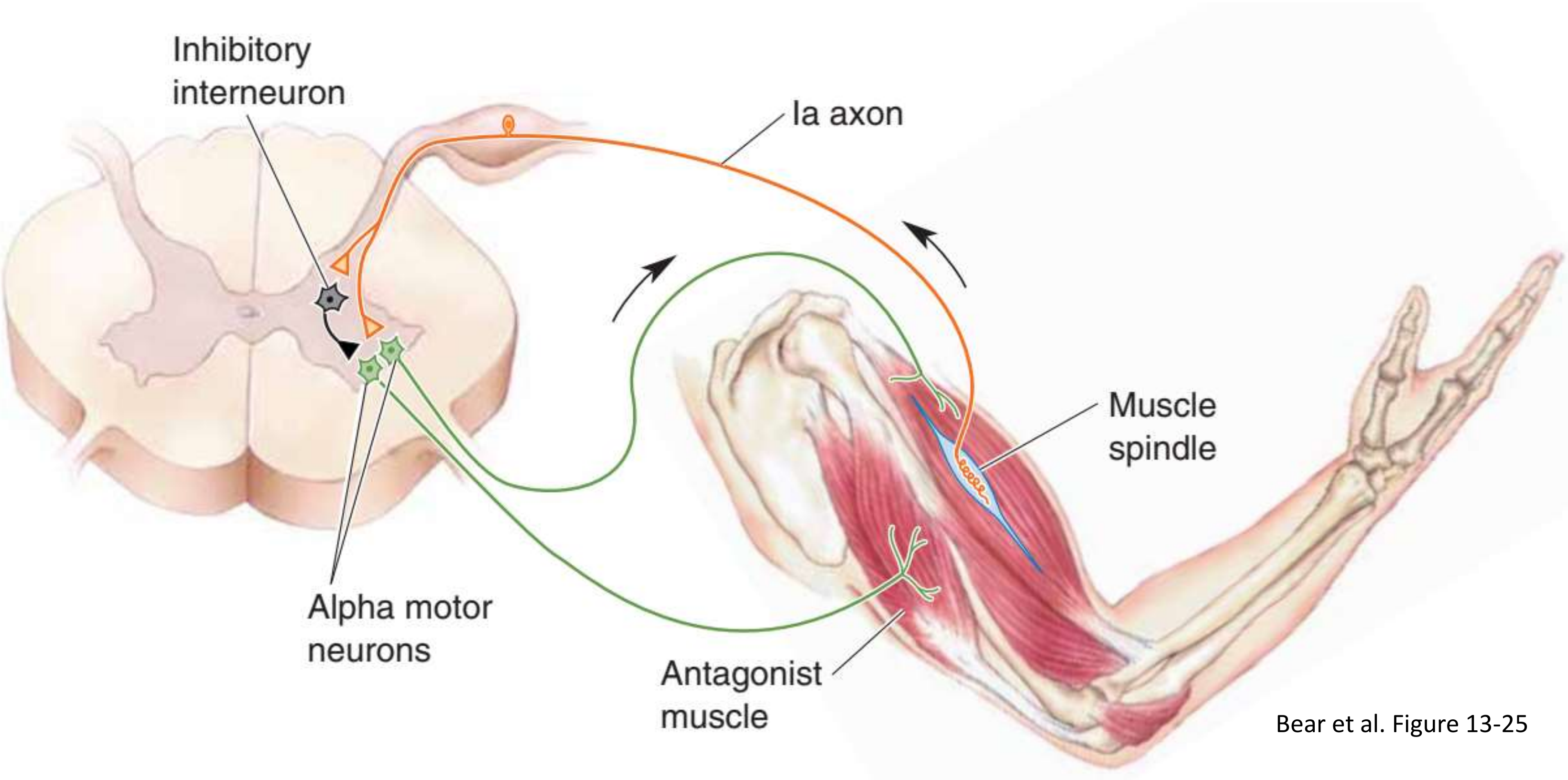
Kandel et al. Figure 35-12

Three sources of inputs to Alpha motor neuron



Bear et al. Figure 13-9

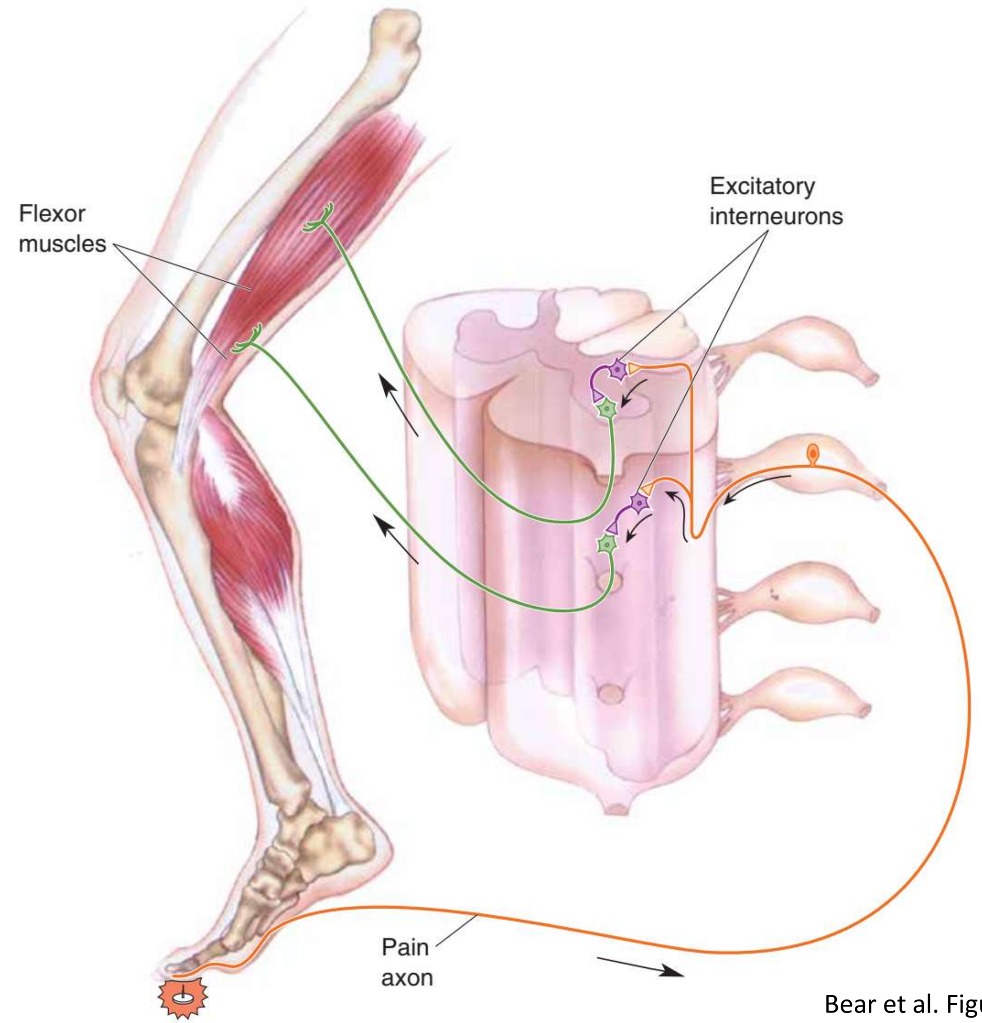
Stretch reflex and reciprocal inhibition



Bear et al. Figure 13-25

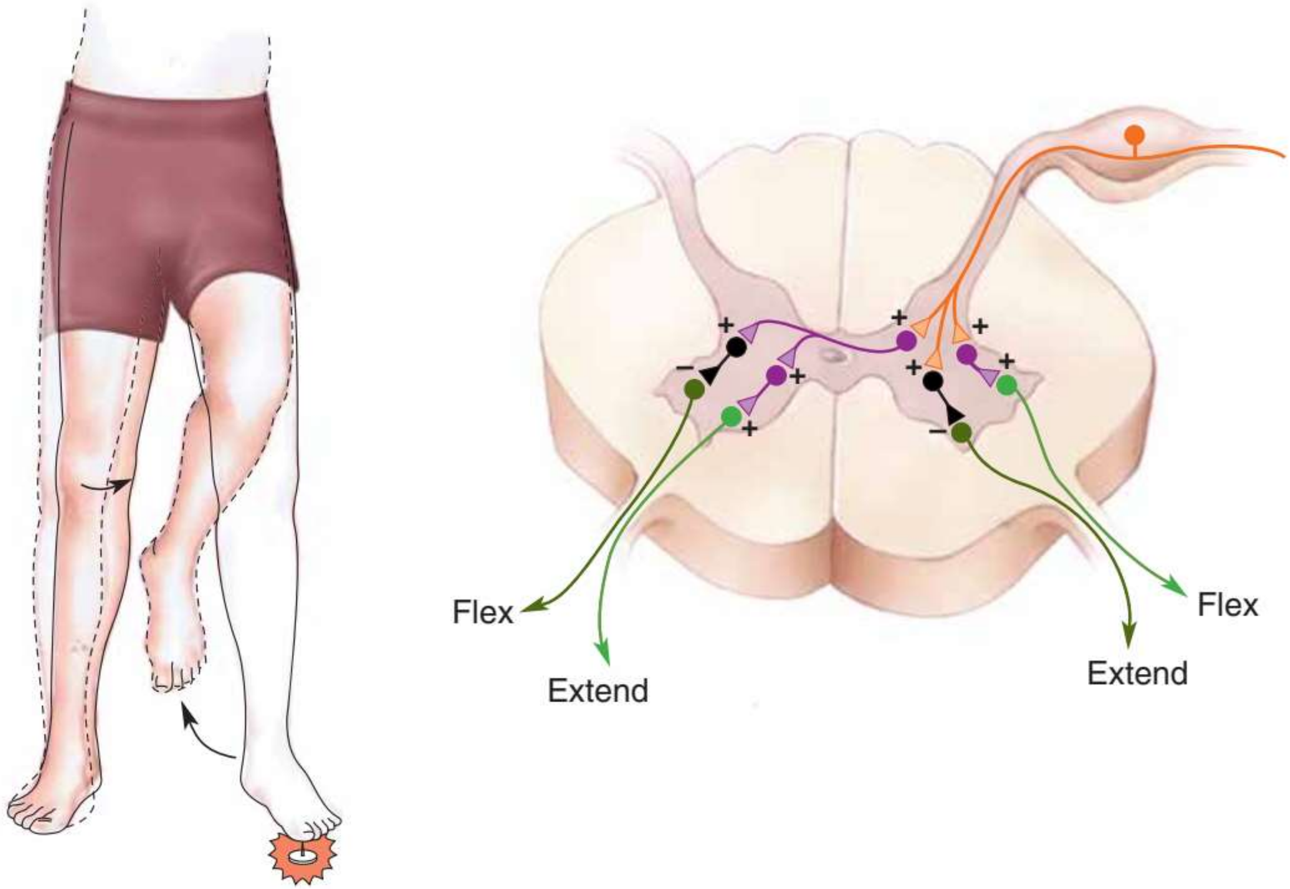
Muscle stretched – Ia axon activity increases – alpha MN activity of the same muscle increases – the same muscle shortened
(length increases) – alpha MN activity of the opposite muscle decreases – the opposite muscle relaxed

Flexor withdrawal reflex



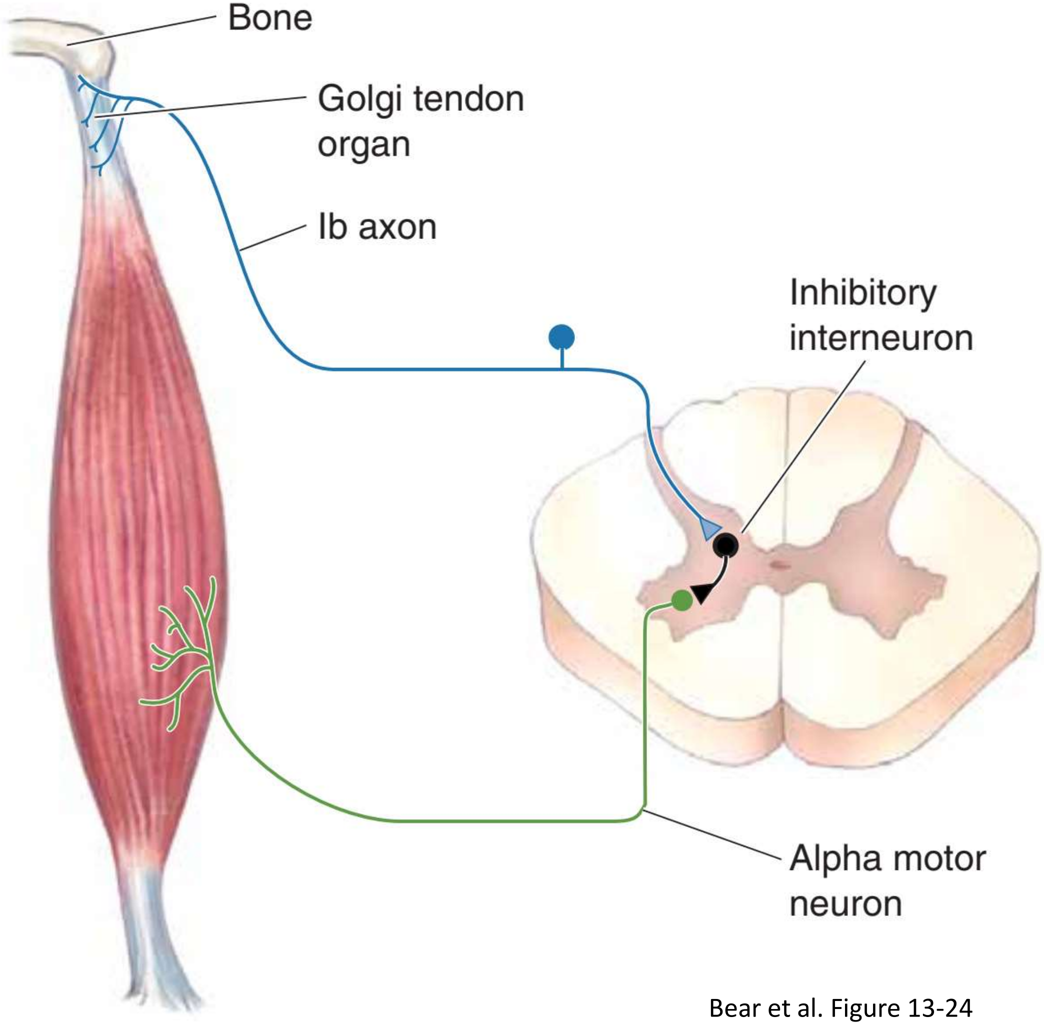
Bear et al. Figure 13-26

Crossed-extensor reflex



Bear et al. Figure 13-27

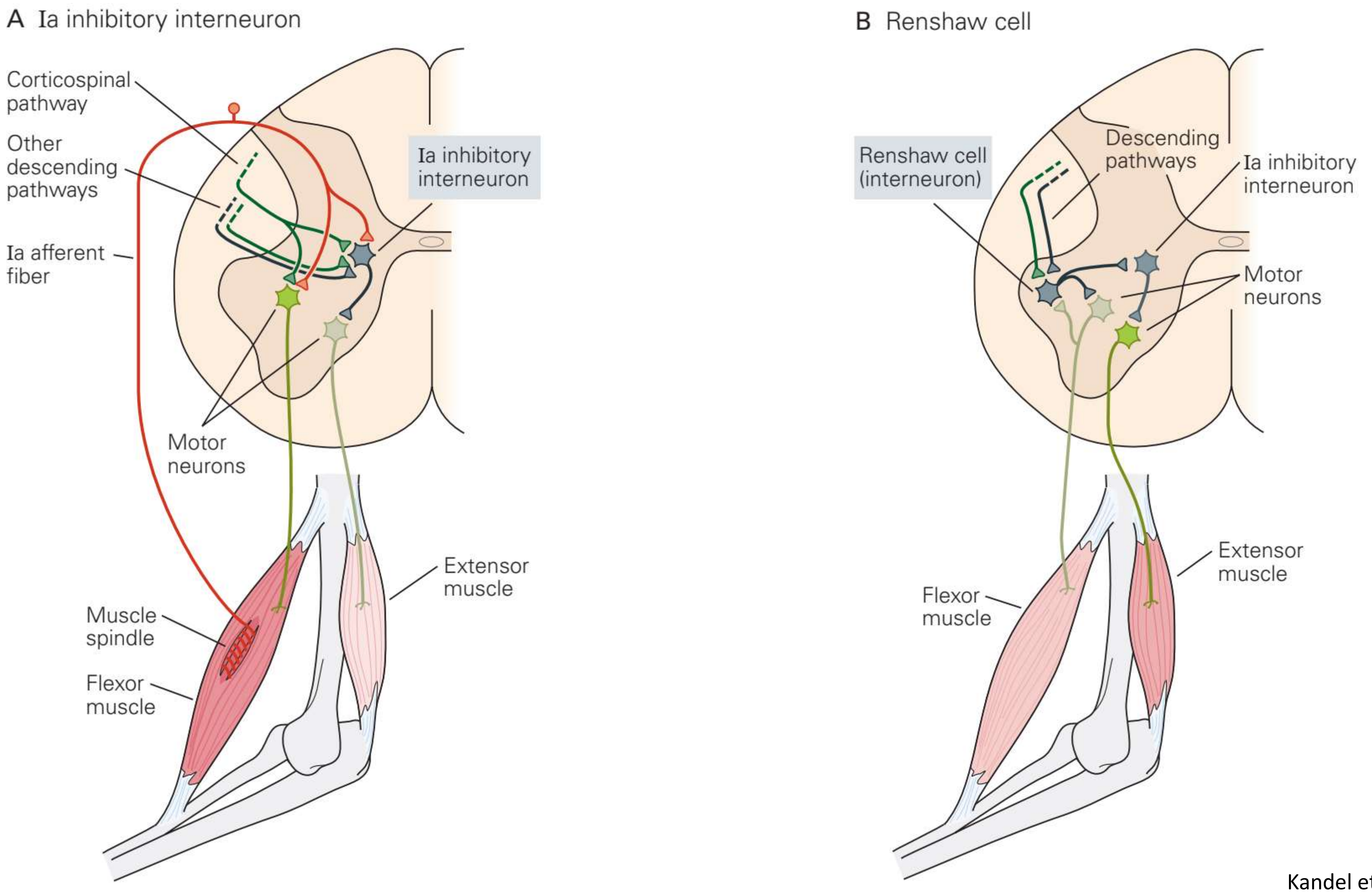
Golgi tendon organ circuit



The Ib axon of the Golgi tendon organ excites an inhibitory interneuron, which inhibits the alpha motor neurons of the same muscle

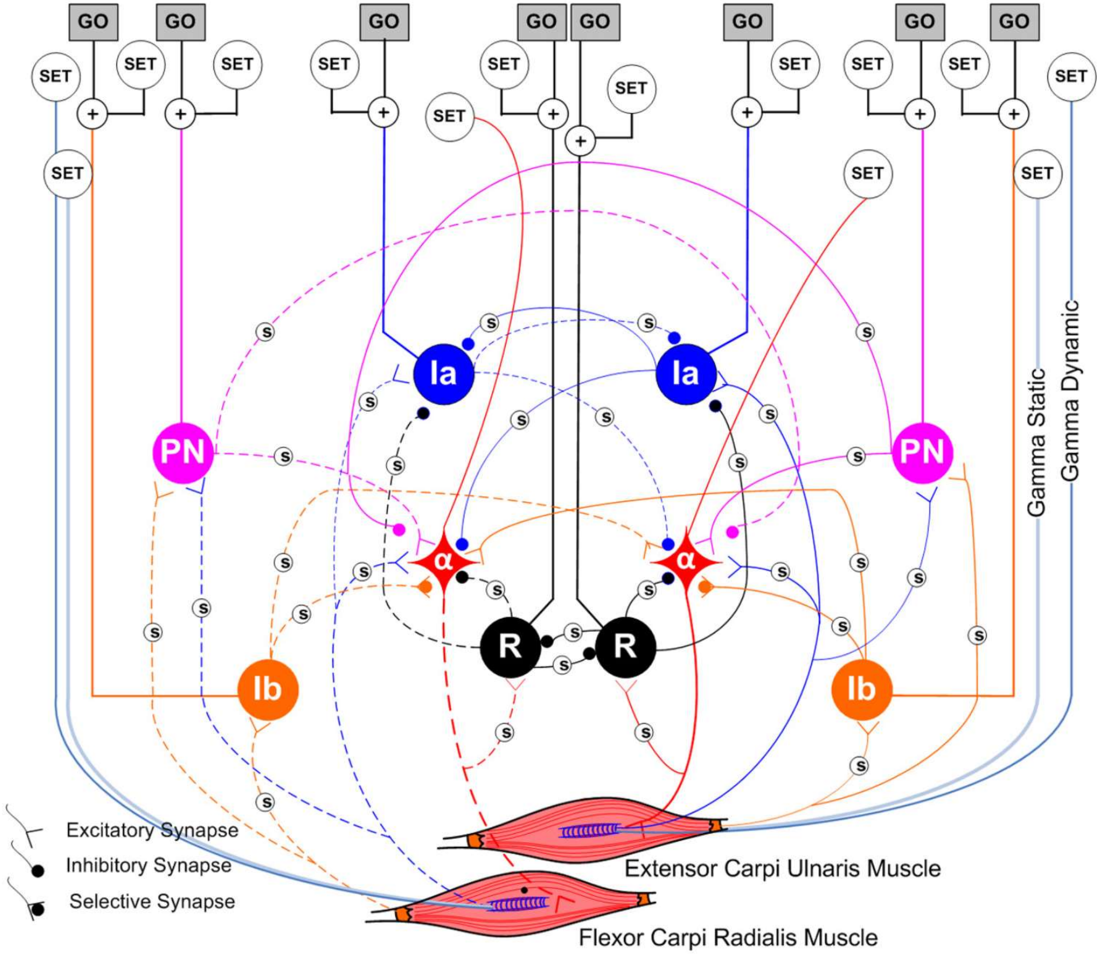
Bear et al. Figure 13-24

Reciprocal inhibition and Renshaw cell

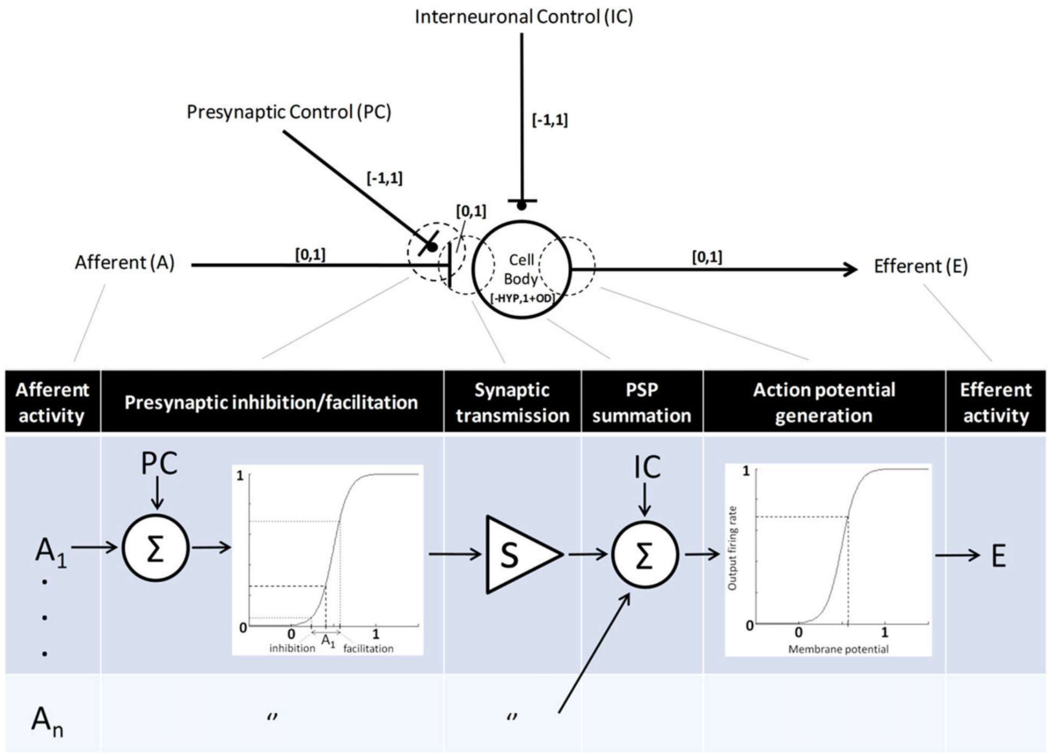


Kandel et al. Figure 35-5

Modelling of spinal reflexes

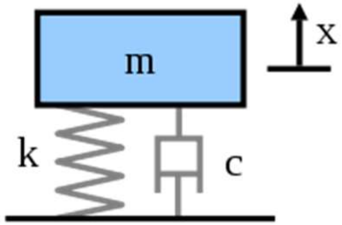


Raphael, Tsianos, Loeb 2010



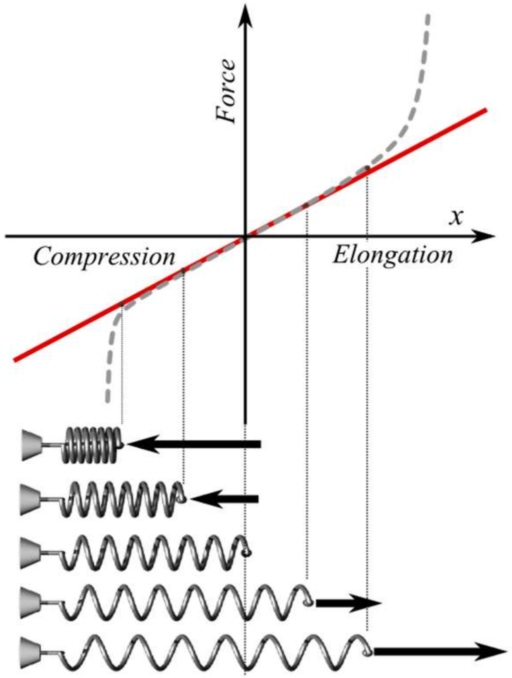
Tsianos, Goodner, Loeb 2014

The mass-spring model of muscles



- A physical mass-spring-damping system:
  - Elastic component k: proportional to position
  - Viscous component c: resistance depends on velocity

- Biological muscle-joint system has a similar “spring-like behavior”
  - But note: muscles can only pull, not push
  - A joint with agonist and antagonist muscles work bidirectional
  - Both passive mechanics and reflexes contribute

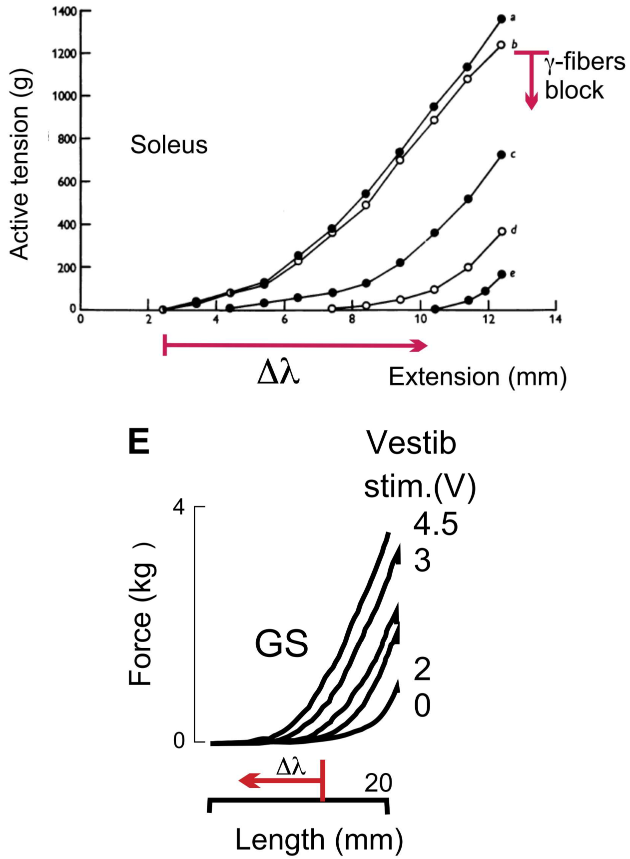


https://en.wikipedia.org/

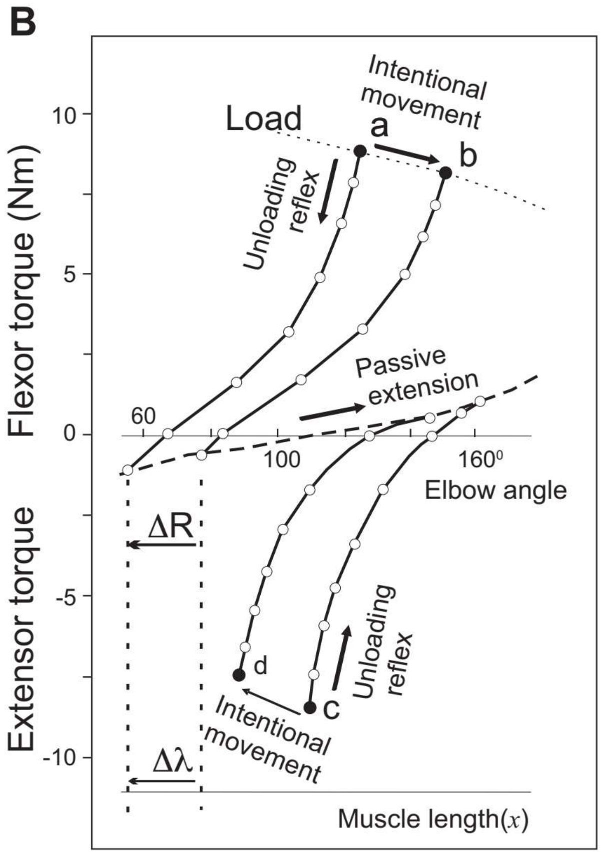
Experimental measurement of muscle elastic property

- The resting length (λ) of the “spring” can be modified by brain descending command

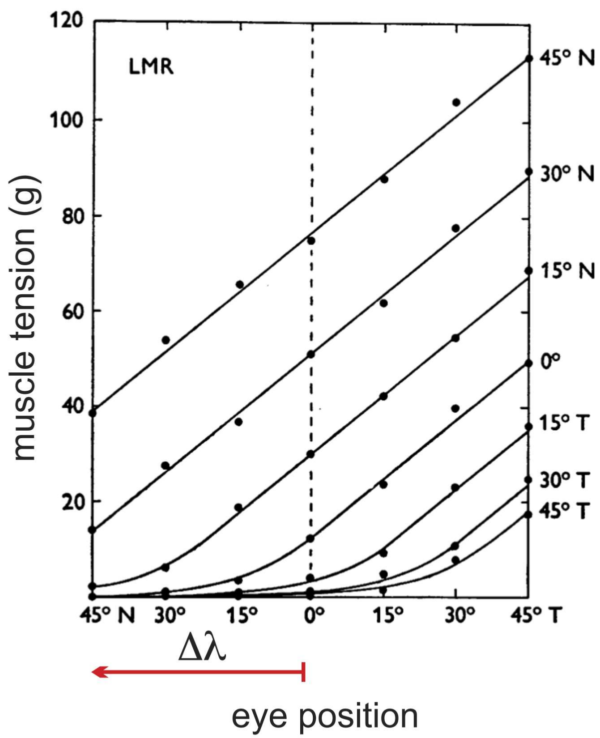
Cat leg muscles



Human arm muscles

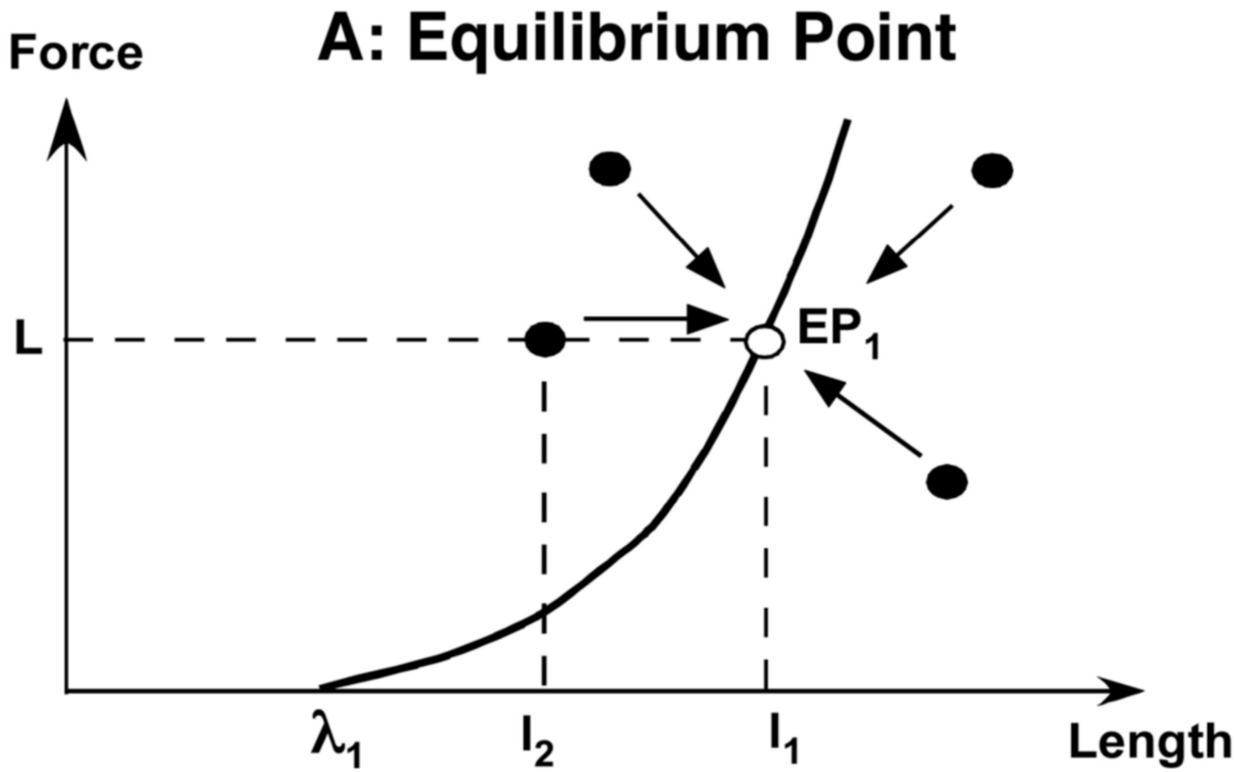


Human eye muscles



Reviewed in Feldman and Zhang, J Neurophysiol. 2020

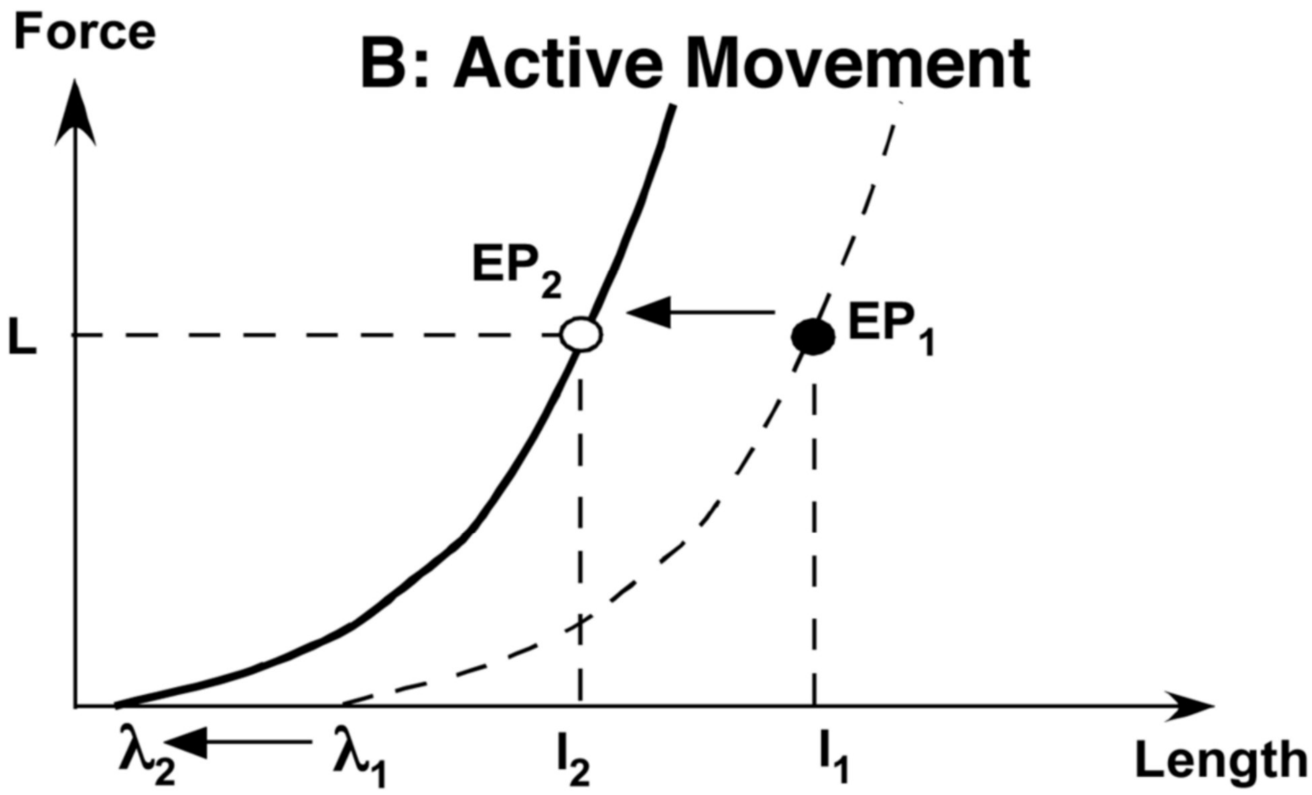
The mass-spring model



λ is the muscle length when external force = muscle force =0 (analogous to spring‘s resting length)
Stabilization of EP is contributed by muscle passive mechanics and reflexes

Latash. J Hum Kinet 2009

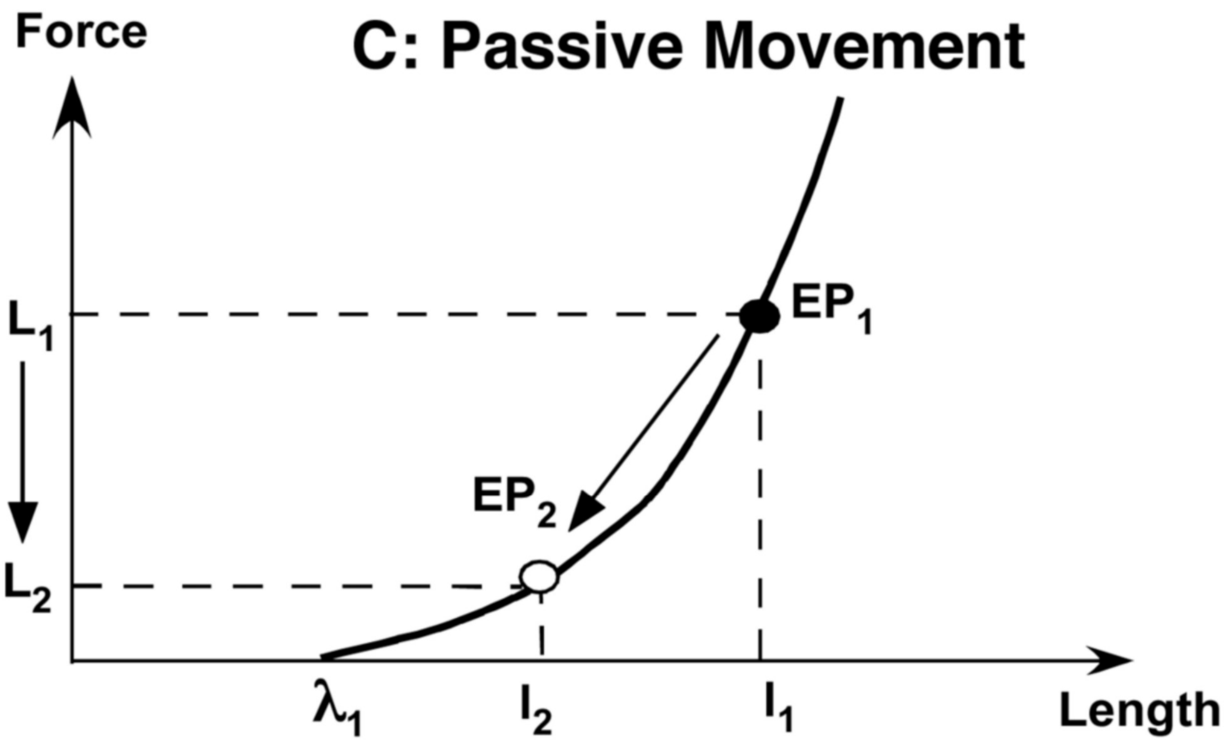
Movement emerges due to the interaction between muscular system and external load



The force-length characteristics do not change. Change of λ results in change of EP

Latash. J Hum Kinet 2009

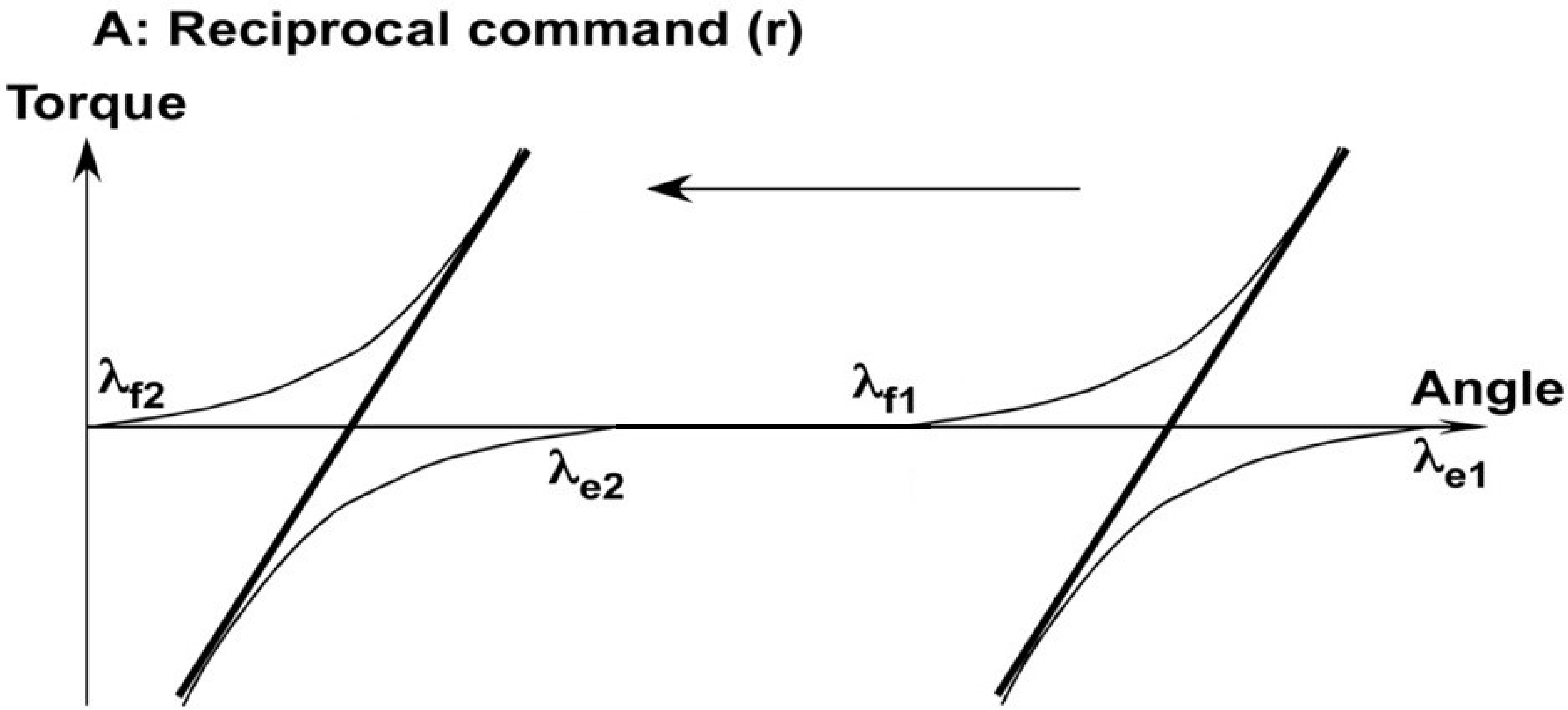
Movement emerges due to the interaction between muscular system and external load



Change of external force (L) results in change of EP

Latash. J Hum Kinet 2009

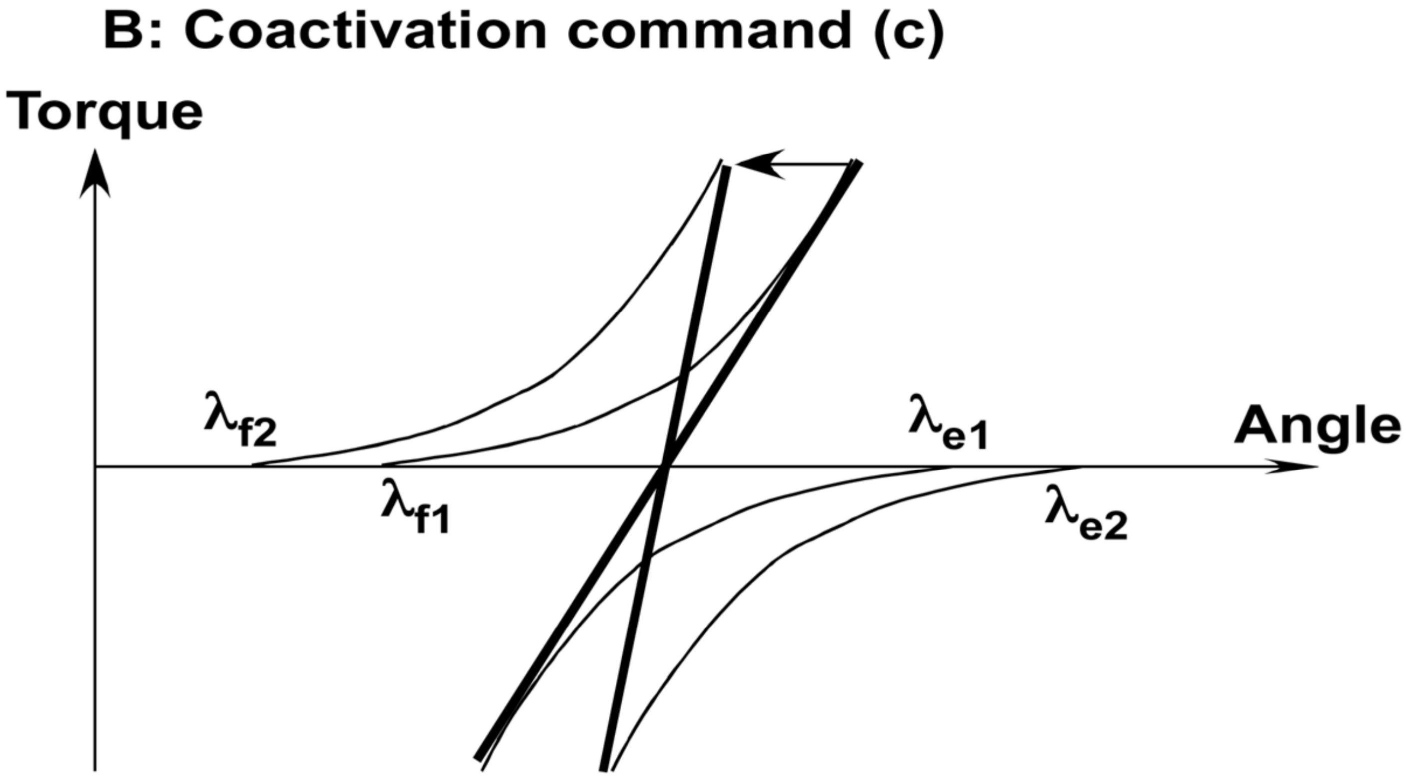
Movement emerges due to the interaction between muscular system and external load



The joint torque-angle characteristic (thick lines) is the algebraic sum of the corresponding muscle characteristics. Shifts of both λf and λe in the same direction result in a shift of the joint characteristic parallel to the angle axis.

Latash. J Hum Kinet 2009

Movement emerges due to the interaction between muscular system and external load

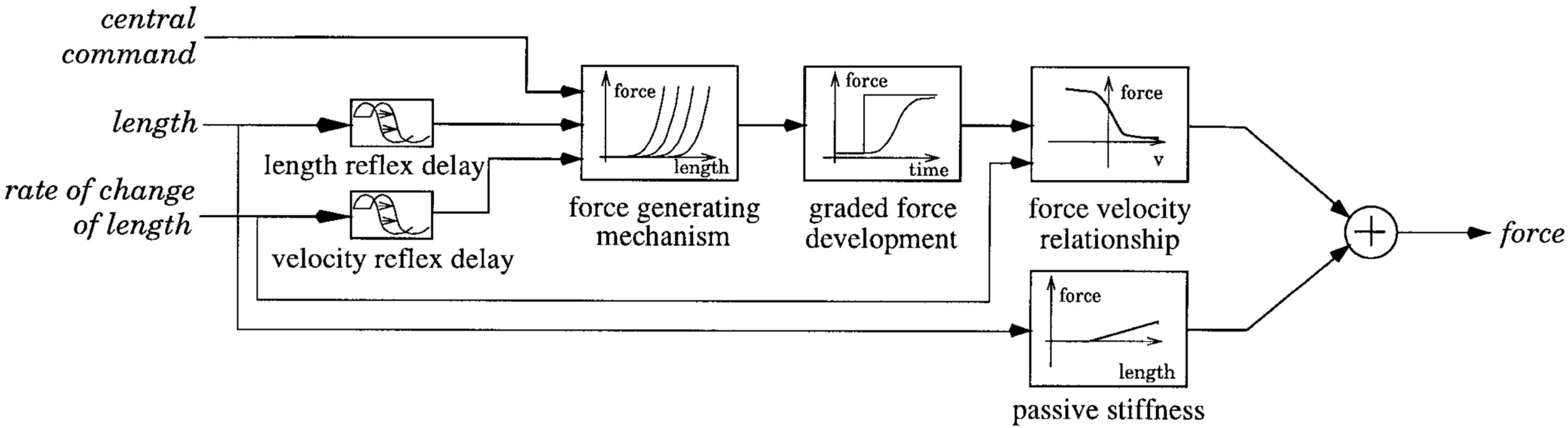


Shifts of λf and λe in opposite directions lead to a change in the slope of the joint characteristic

Latash. J Hum Kinet 2009

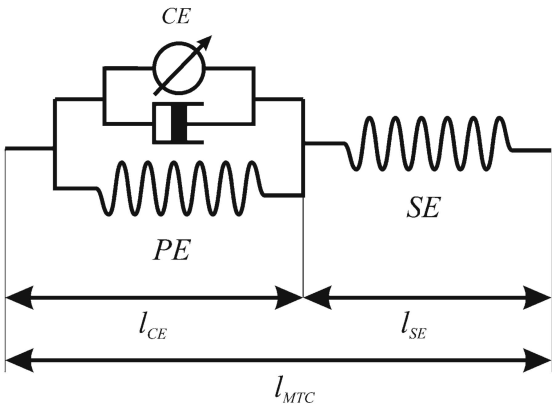
The mass-spring model – a modelling study

Muscle model (one λ / central command per muscle):

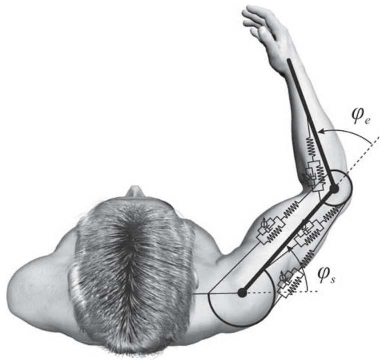


Gribble et al. J Neurophysiol. 1998

Biomechanical models

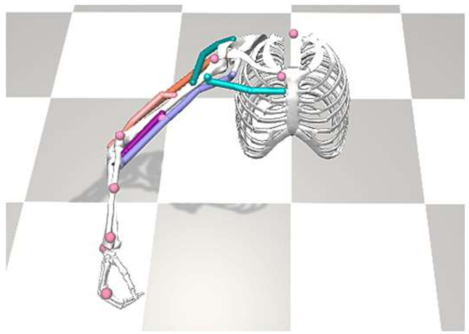


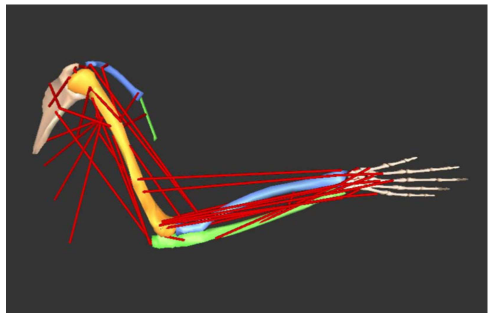
CE: Contractile element
SE: Series elastic element
PE: Parallel elastic element
l_{MTC}: Muscle-tendon complex length



Kistemarker et al. 2007

OpenSim model

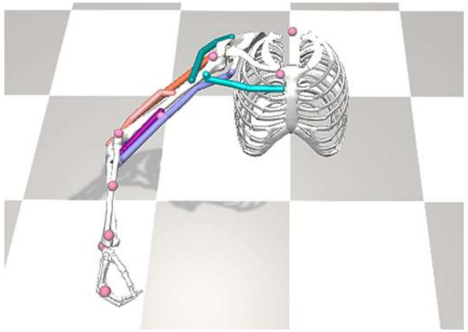




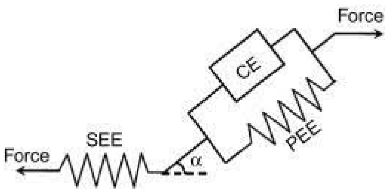
Chan&Moran 2006

Current research topic:

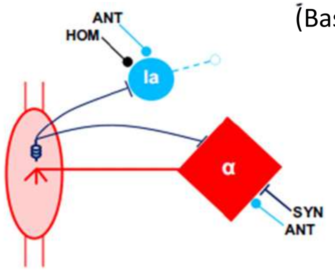
Using theorectial models of arm reaching (incl. reflex loops) to study the temporal profile of neural descending control signals



Mechanical model



Muscle model



Reflex model

The mathematical model:

$$A(t) = [l(t-d) - \lambda(t) + \mu(t)\dot{l}(t-d)]^{+}$$

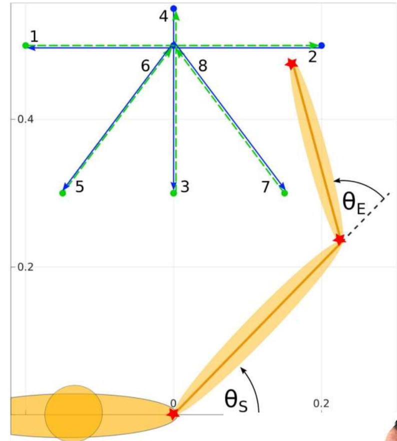
$$\tilde{M} = \rho[\exp(cA) - 1]$$

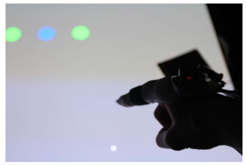
$$\tau^{2}\ddot{M} + 2\tau\dot{M} + M = \tilde{M}$$

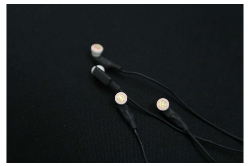
$$F = M[f1 + f2 \text{ atan } (f3 + f4\, \dot{l})] + k(l - r)$$

(Based on the model of Gribble et al. 1998)

Experimental setup:



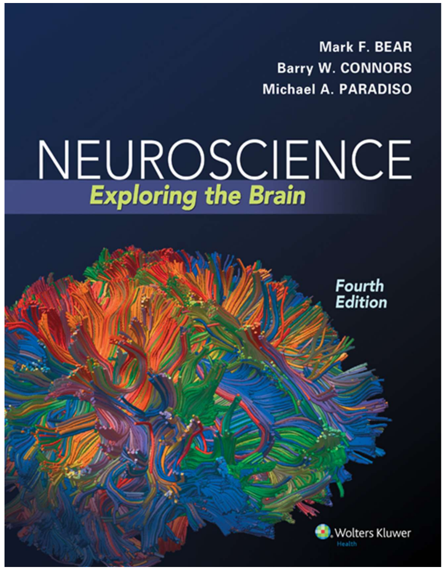


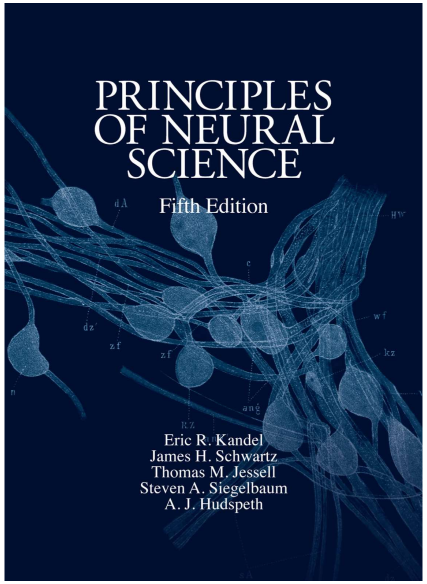


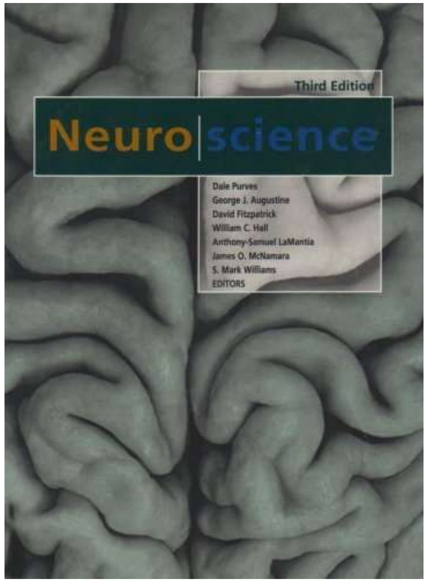
Motion and electromyographic recordings

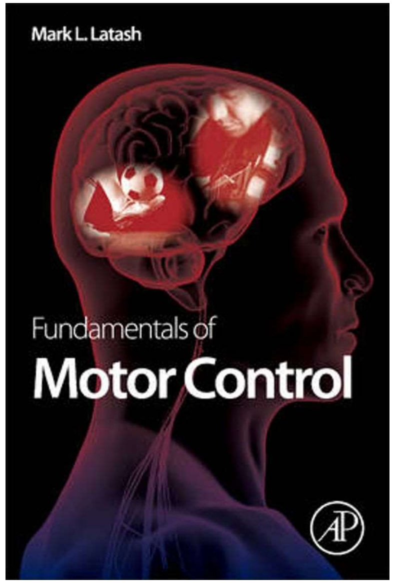
Summary: How muscles work?

- Muscles are the actuators for movement
- Muscle spindle senses muscle length
- Spinal reflex loops modulate motor output
- Muscles act as a non-linear mass-spring model









Textbooks:

- [1] Bear et al. Neuroscience: Exploring the Brain, 4th Edition, 2016
- [2] Kandel et al. Principles of neural science, 5th Edition, 2013
- [3] Purves et al. Neuroscience. 3rd Edition, 2004
- [4] Latash. Fundamentals of motor control. 1st Edition, 2012