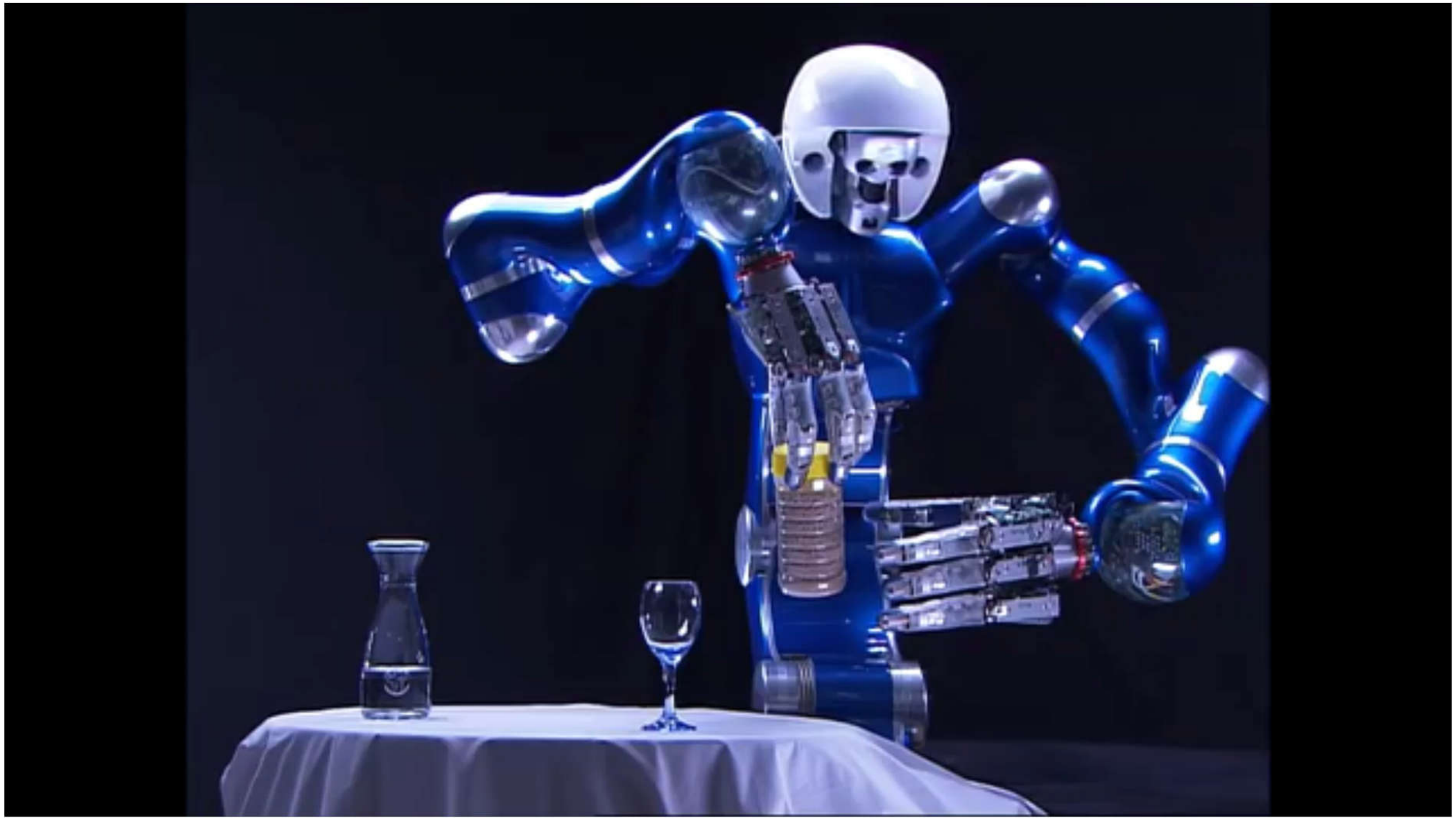
Human Motor Systems

Lei Zhang

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

Autonomous Robotics: Action, Perception, and Cognition (ST 2022)
Prof. Dr. Gregor Schöner
Teaching unit: Human motor systems (30.06.2022)

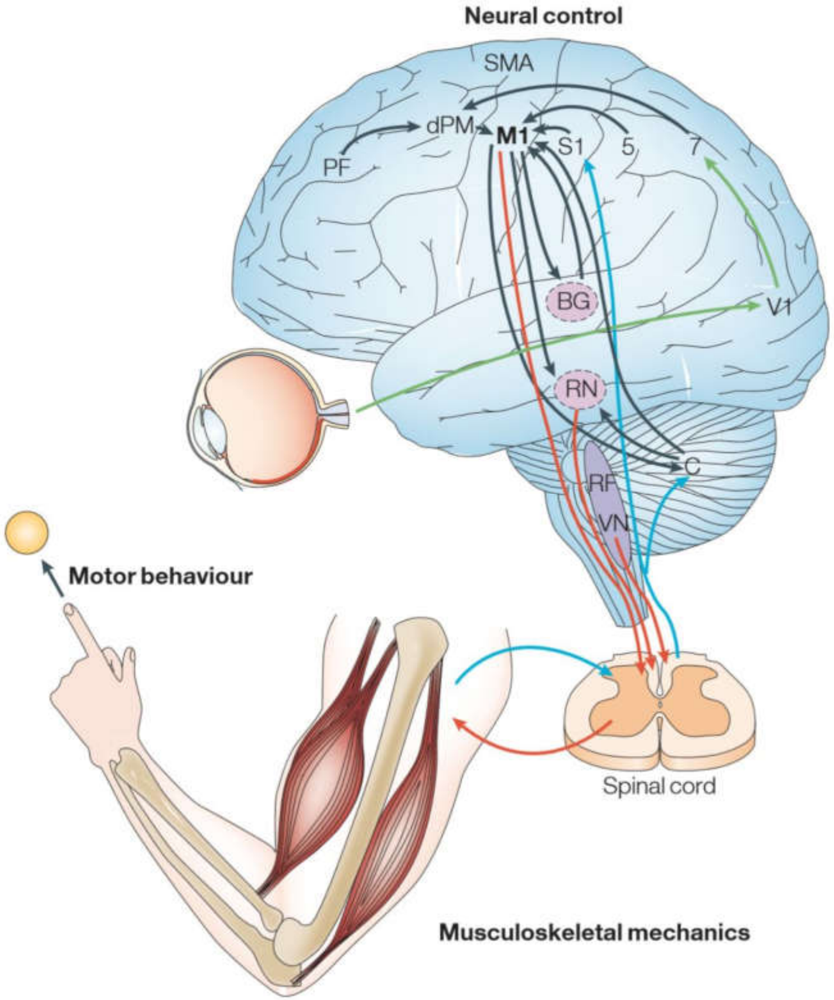


Video: The humanoid robot Rollin' Justin, Institute of Robotics and Mechatronics, German Aerospace Center

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



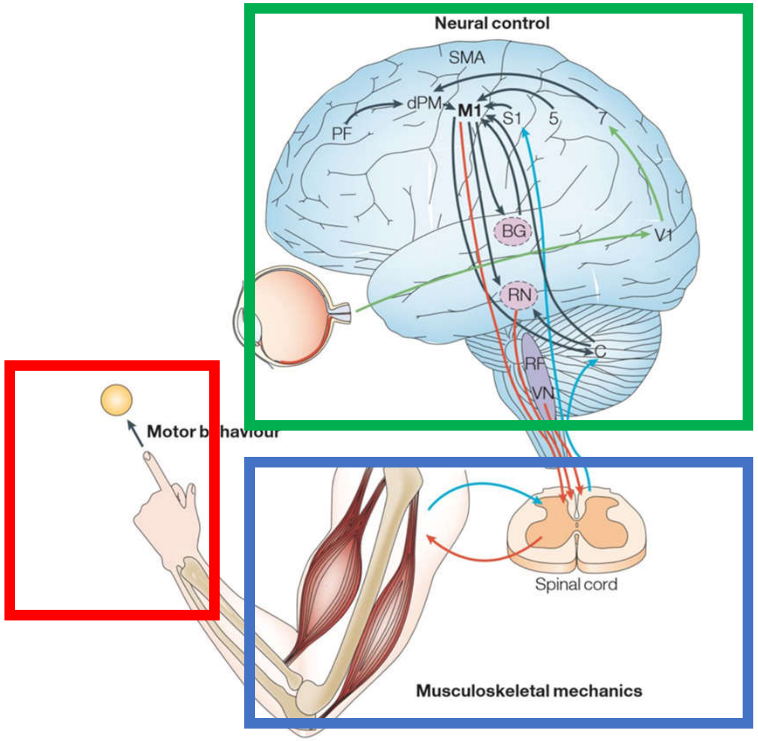
Scott. Nature Reviews Neuroscience 2004

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

- Muscles

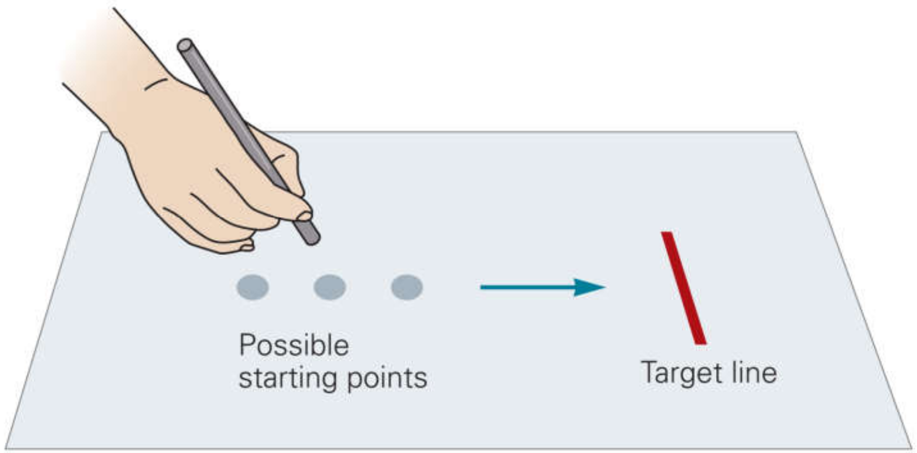
Outlines

- **How movements look like?**
  - kinematic patterns
- **How muscles work?**
  - muscles, motoneurons, reflexes, spinal cord
- **How the brain works in movement generation?**
  - neuroanatomy, function

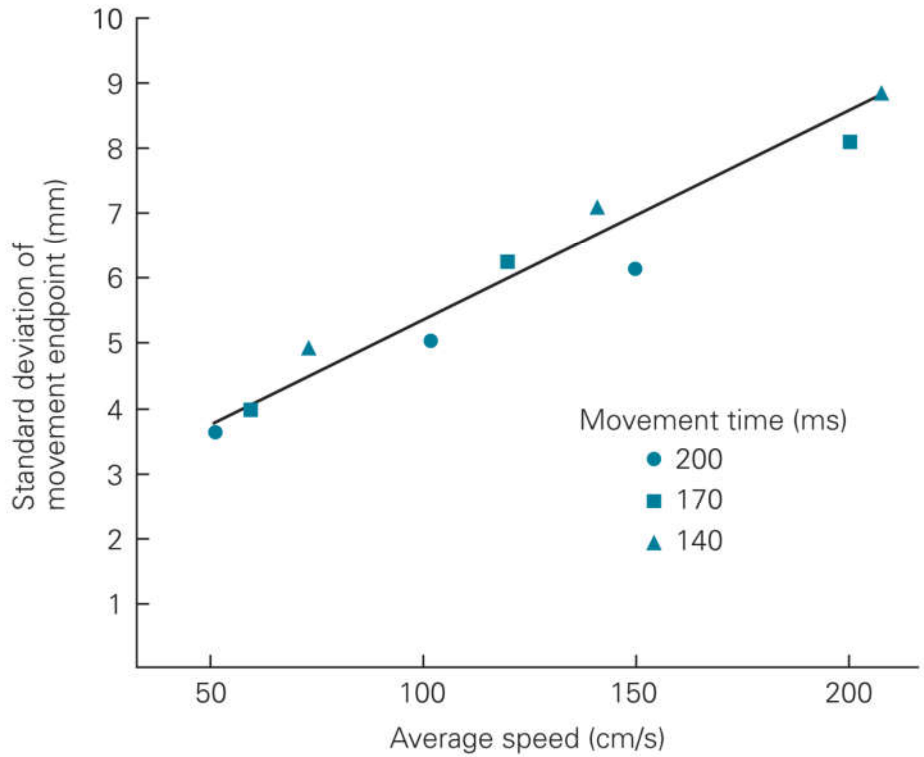


Kinematic regularity

- The speed-accuracy trade-off



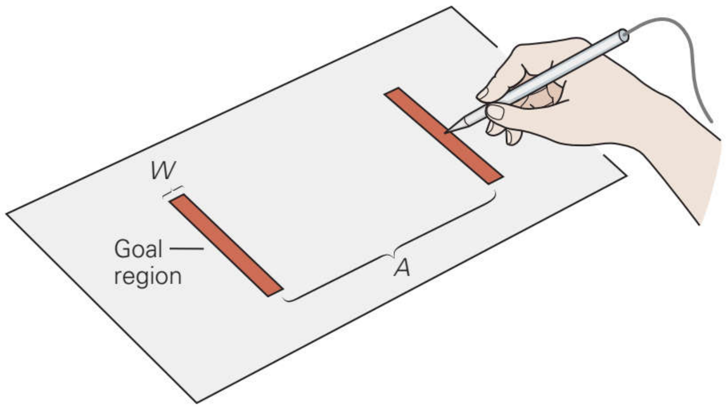
- Three initial positons
- Different movement times (140, 170, or 200ms)
- Variability in proportion to speed (force)



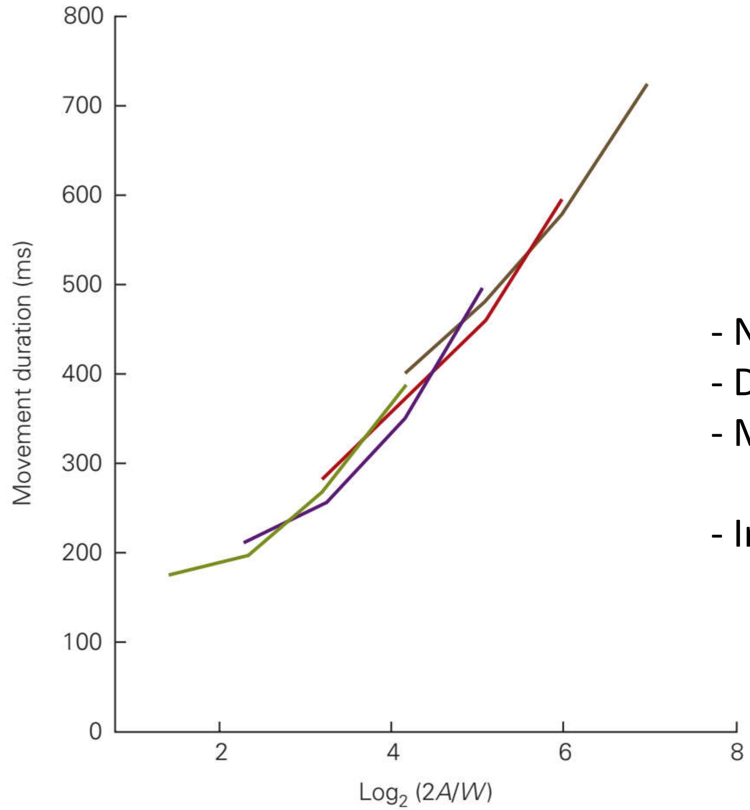
Kandel et al. Figure 33-4

Kinematic regularity

- Fitt's law describes the speed-accuracy trade-off



$$Movement\ duration = a + b * log_2(\frac{2A}{W})$$



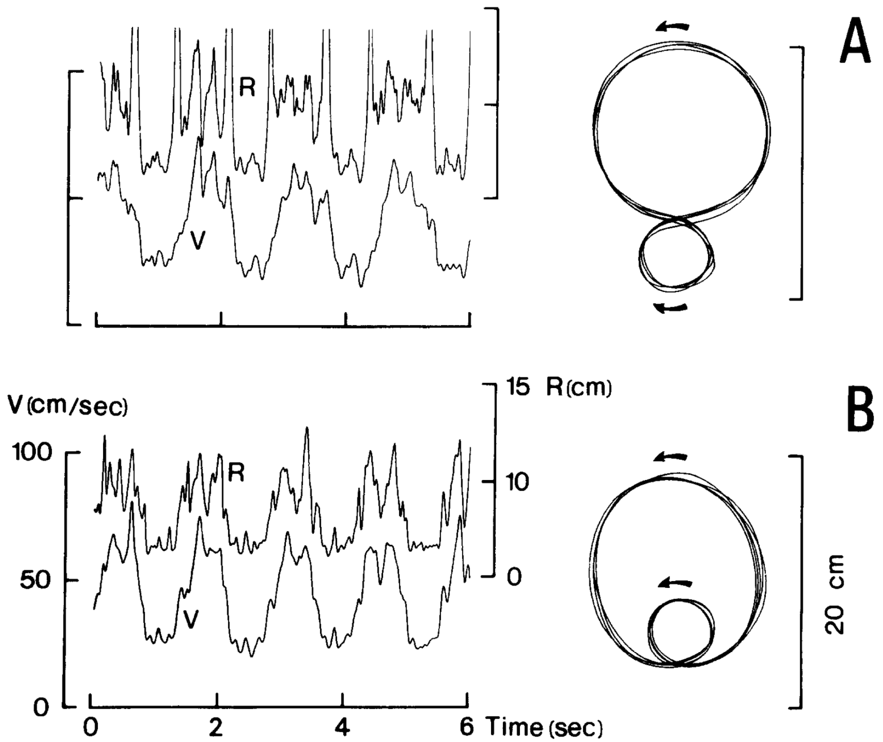
- Narrow and wide targets (W)
- Different distances (A)
- Move as fast as possible

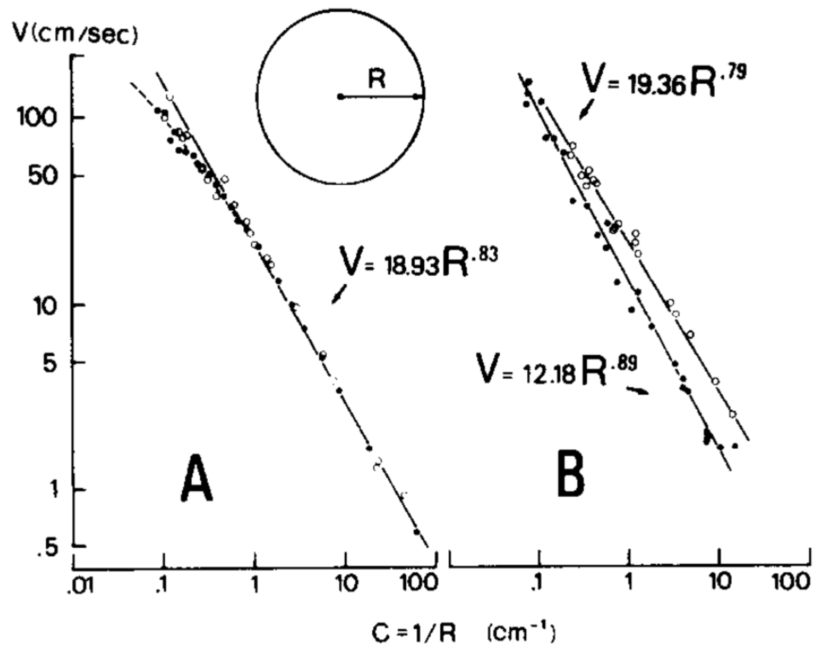
- Index of difficulty: $log_2(\frac{2A}{W})$

Kandel et al. Figure 33-8

Kinematic regularity

- Velocity* (V) vs. curvature** (C) obeys "power-law"



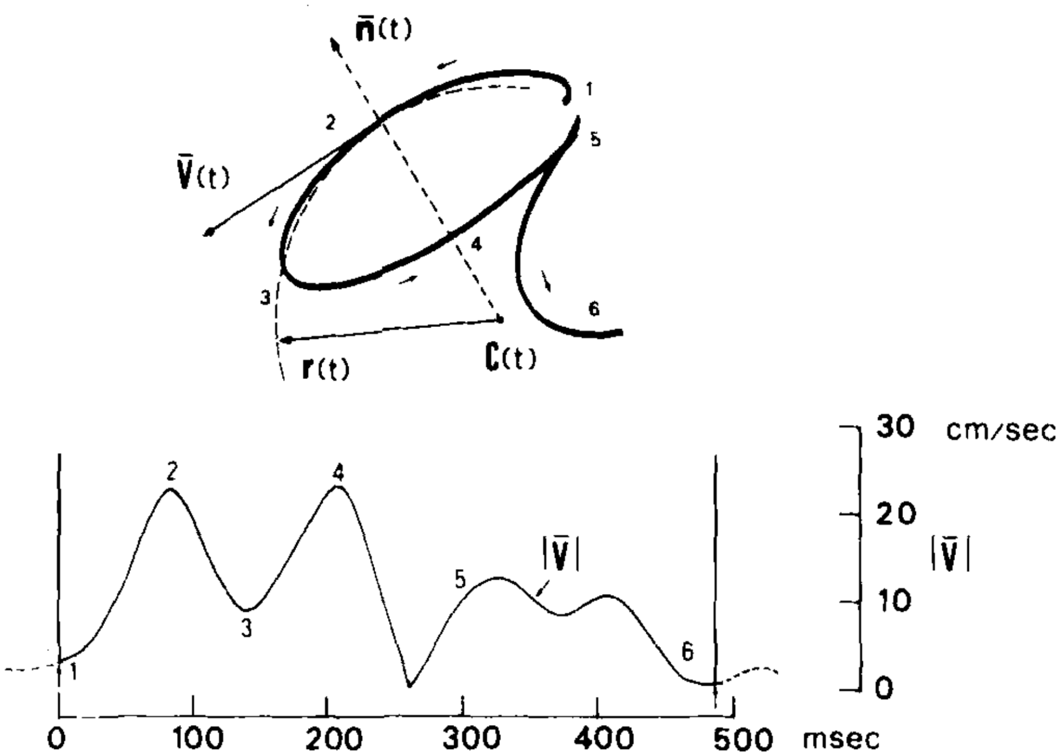


Viviani and McCollum 1983

*Tangential velocity ** C=1/R

Kinematic regularity

- Velocity (V) vs. curvature (C) obeys “power-law”

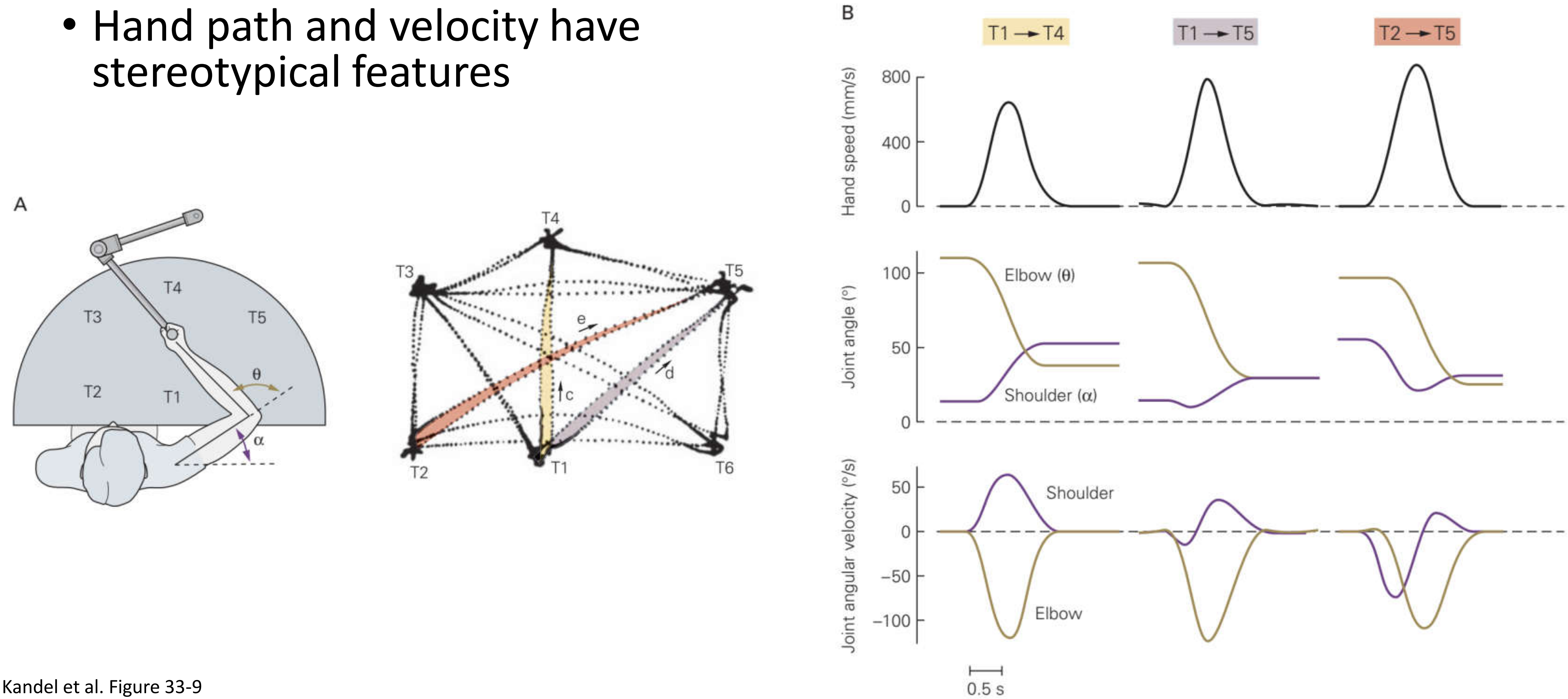


Viviani and Terzuolo 1980

- Smaller C (=1/R): larger V
- Points when movement direction is inverted: V goes to zero.

Kinematic regularity

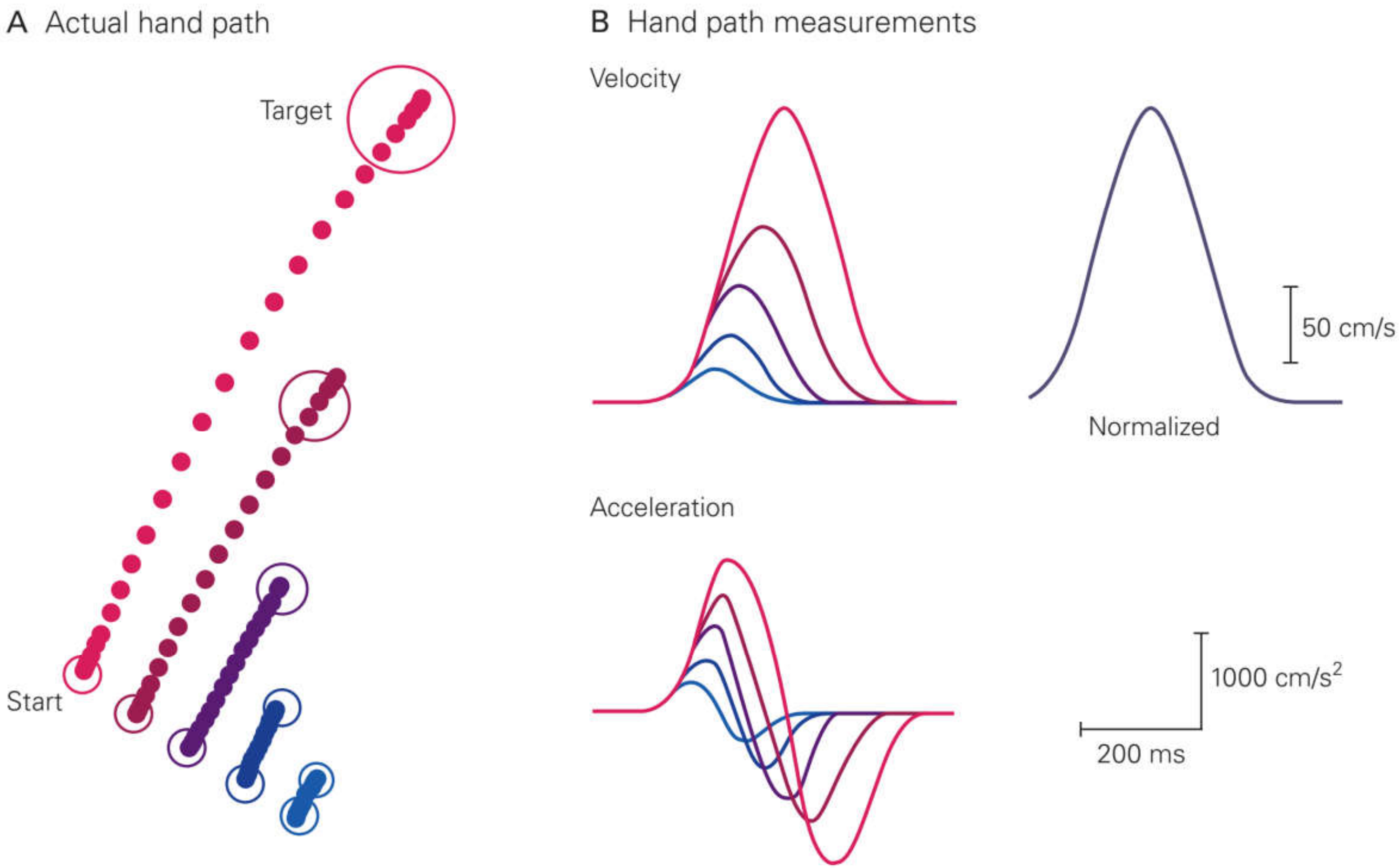
- Hand path and velocity have stereotypical features



Kandel et al. Figure 33-9

Kinematic regularity

- Velocity and acceleration as a function of distance



Kandel et al. Figure 33-12

Kinematic regularity

- Minimum jerk model

Smoothness can be quantified as a function of jerk, which is the time derivative of acceleration (Hogan 1984)

$$\text{jerk} \;\; \dddot{x}(t) = \frac{d^3 x(t)}{dt^3}$$

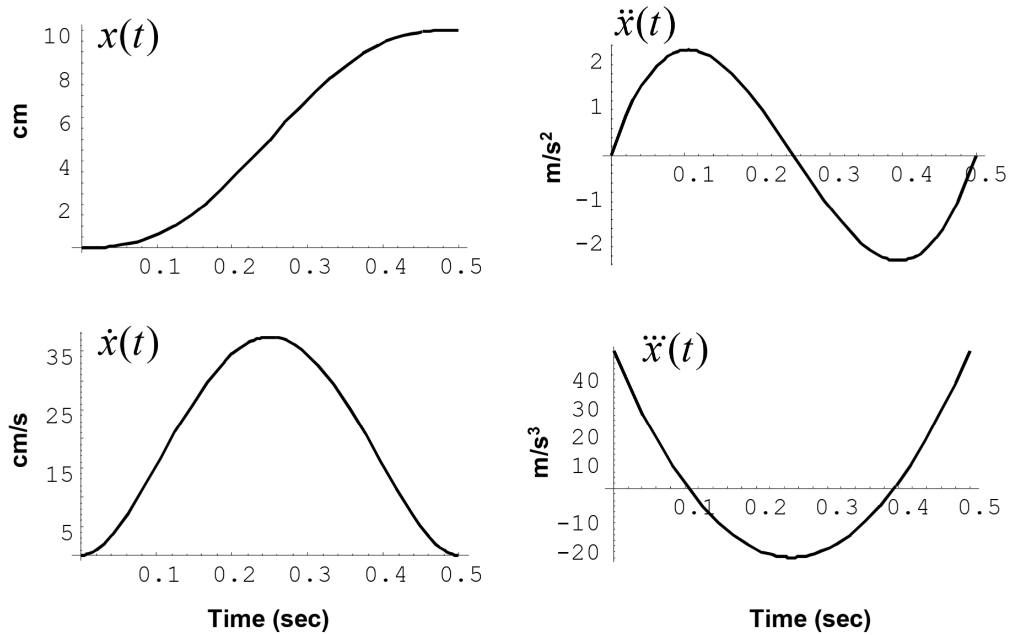
Minimum jerk cost

$$\int_{t=t_i}^{t_f} \dddot{x}_1(t)^2 \, dt$$

Solution: Minimum jerk trajectory

$$x(t) = x_i + (x_f - x_i)\left(10(t/d)^3 - 15(t/d)^4 + 6(t/d)^5\right)$$

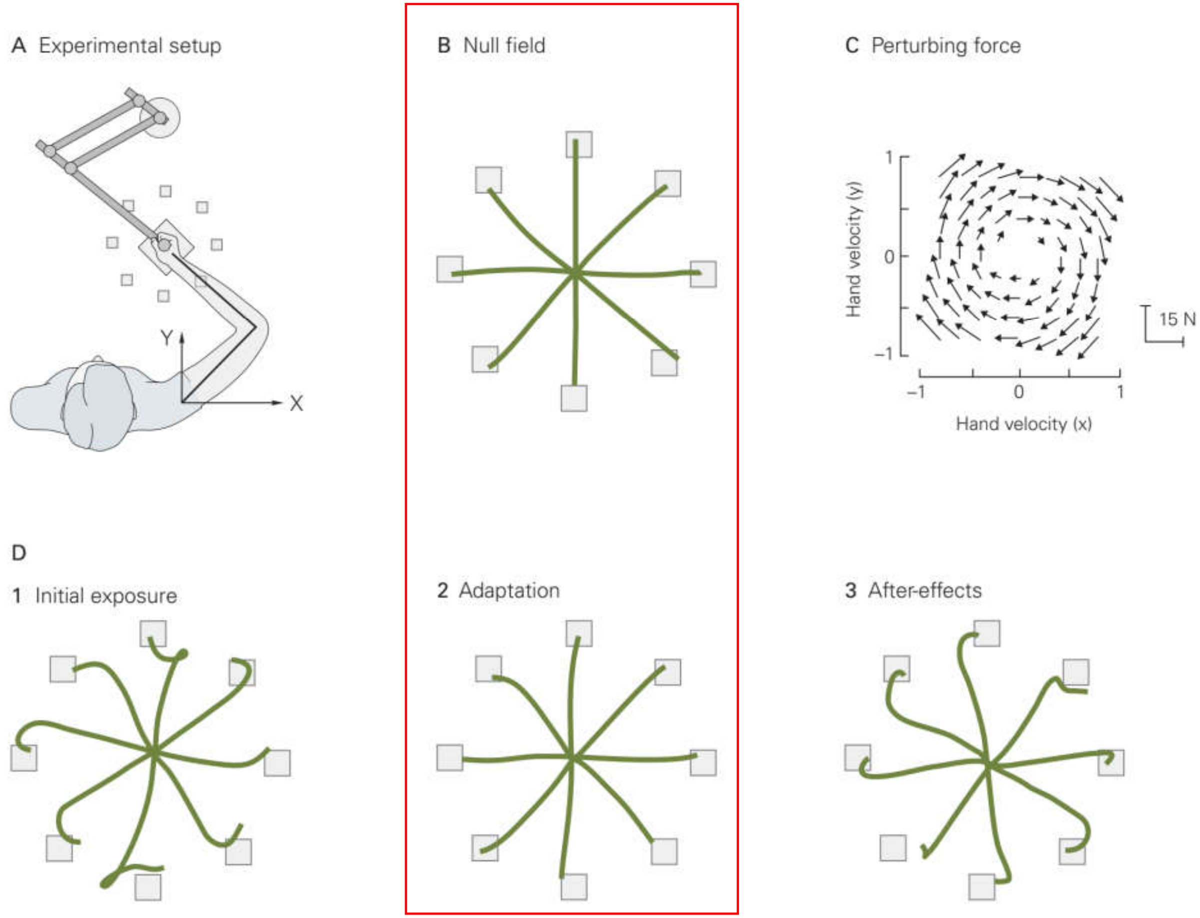
i: initial; f: final; d: movement duration



Complete derivation see: https://courses.shadmehrlab.org/Shortcourse/minimumjerk.pdf

Kinematic regularity

- Reaching movements are straight (no obstacles)



Kandel et al. Figure 33-9

Summary: How movements look like?

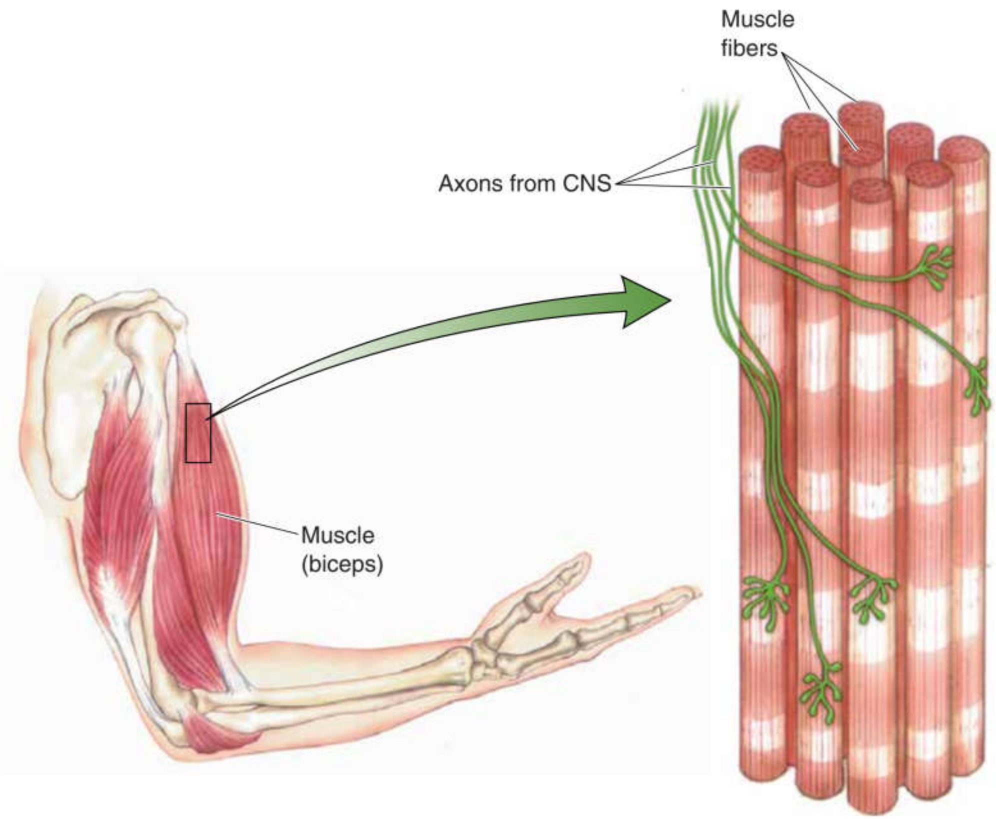
Human movements have certain kinematic patterns:

- Speed-accuracy trade-off – Fitt's law
- Velocity vs. curvature - power law
- Bell-shaped hand velocity – minimum jerk model
- Force field adaptation (straight reaching movements)

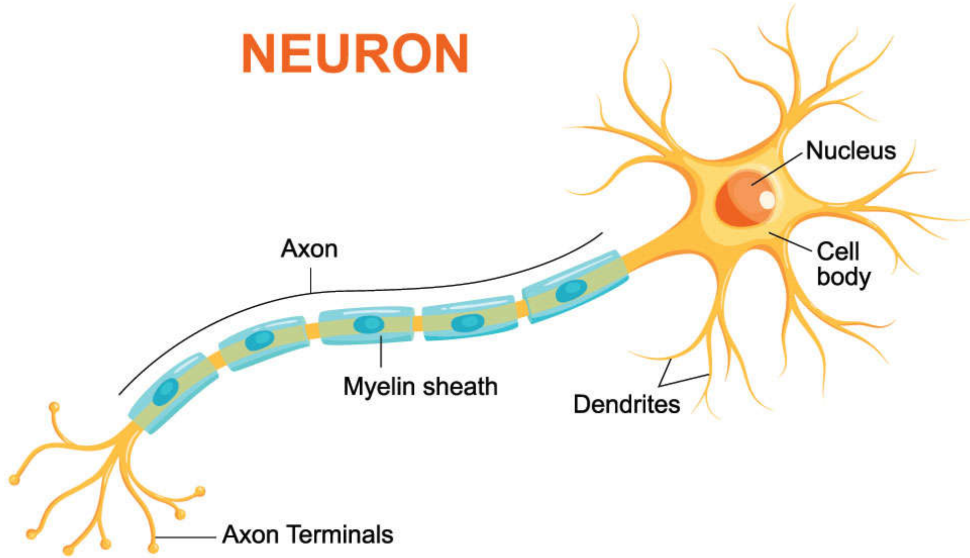
“To move things is all that mankind can do, for such the sole executant is muscle, whether whispering a syllable or felling a forest.”

Sir Charles Sherrington

Muscle structure and motor neuron



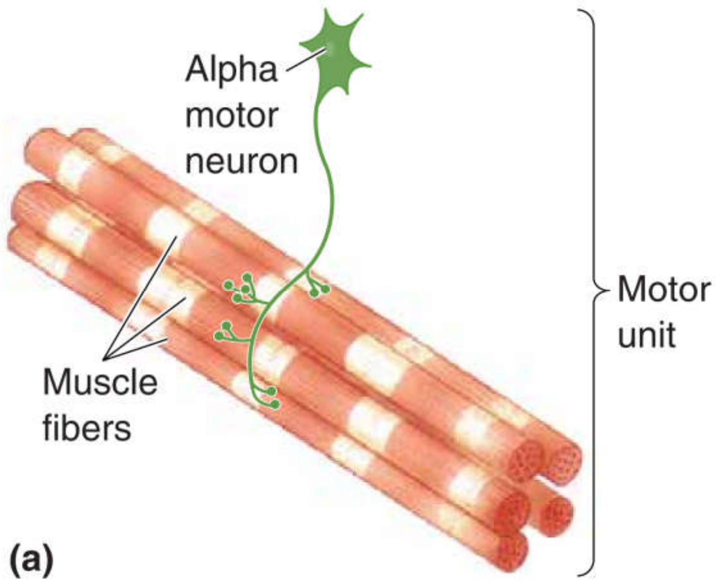
Bear et al. Figure 13-1

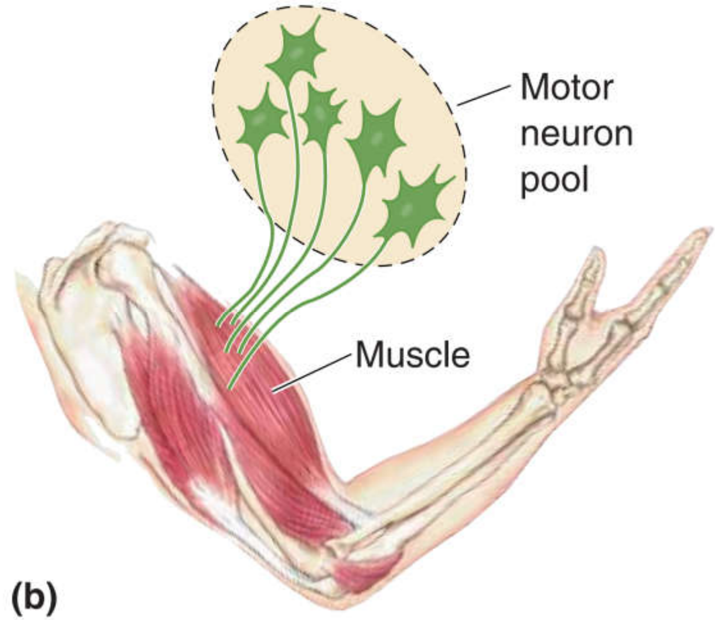


https://www.sciencenewsforstudents.org/article/explainer-what-is-a-neuron

Each muscle fiber is innervated by a single axon

Muscle structure and motor neuron



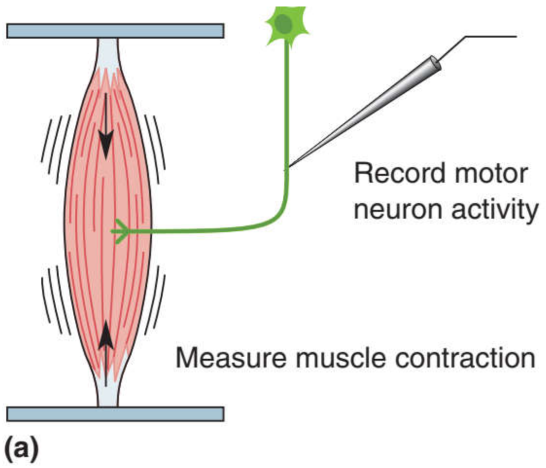


Bear et al. Figure 13-7

Each motor neuron innervates multiple muscle fibers

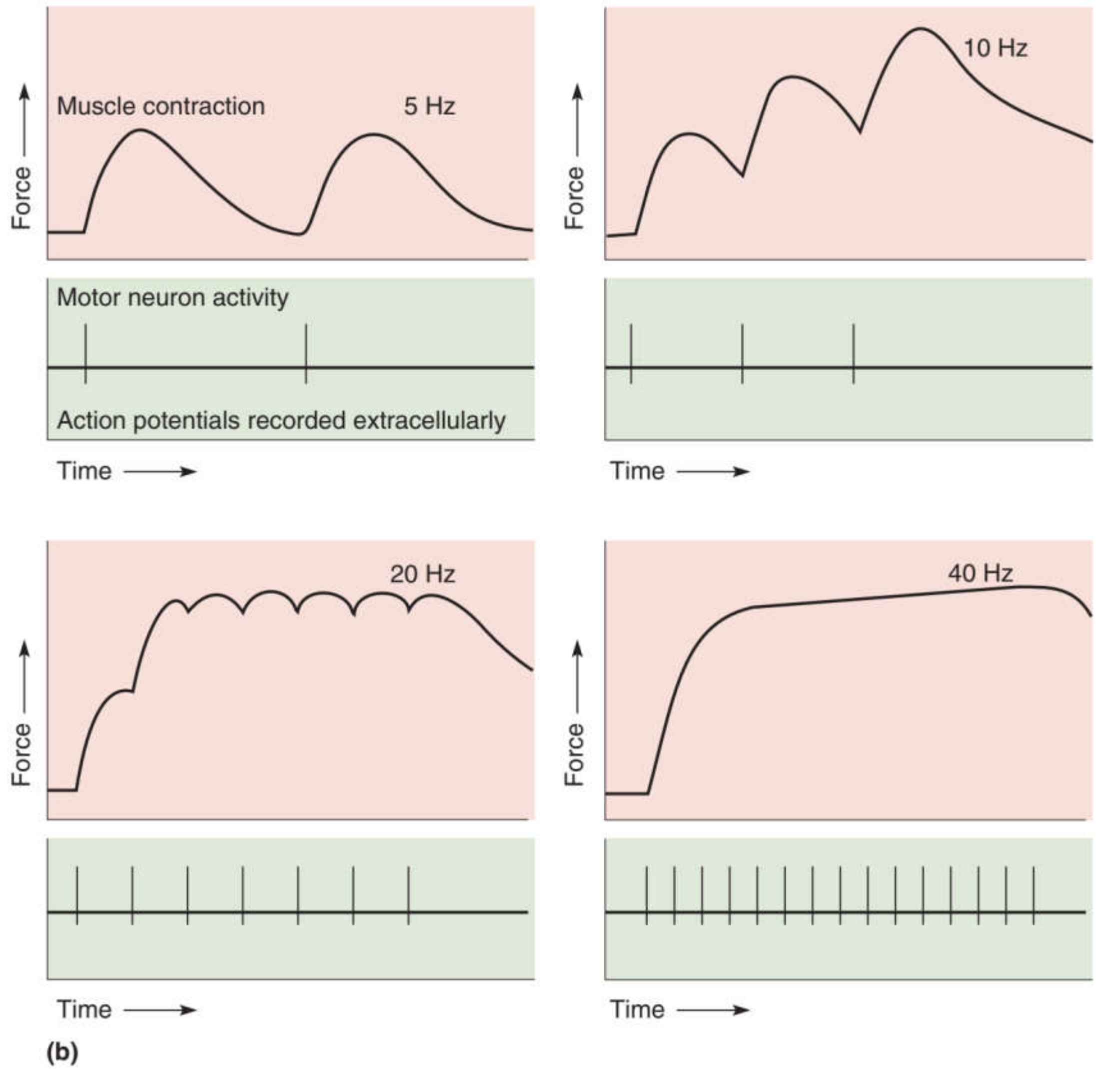
Each muscle is innervated by multiple motor neurons

Muscle force generation



Single action potential => twitch

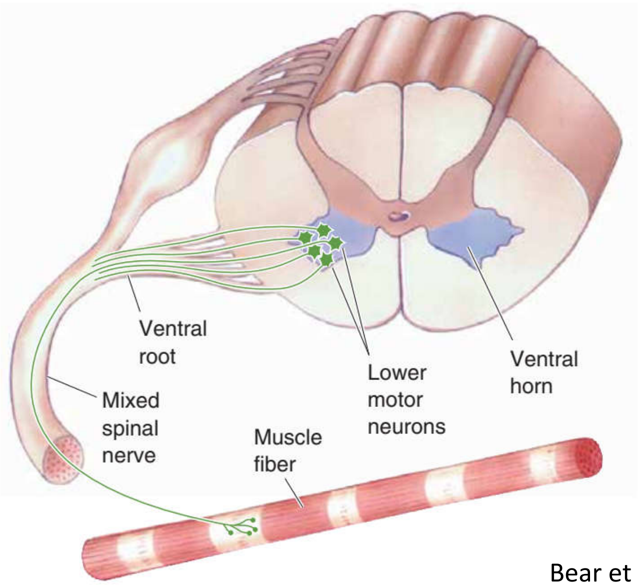
Summation of twitches => sustained contraction



Bear et al. Figure 13-8

Motor and sensory pathways

Motor

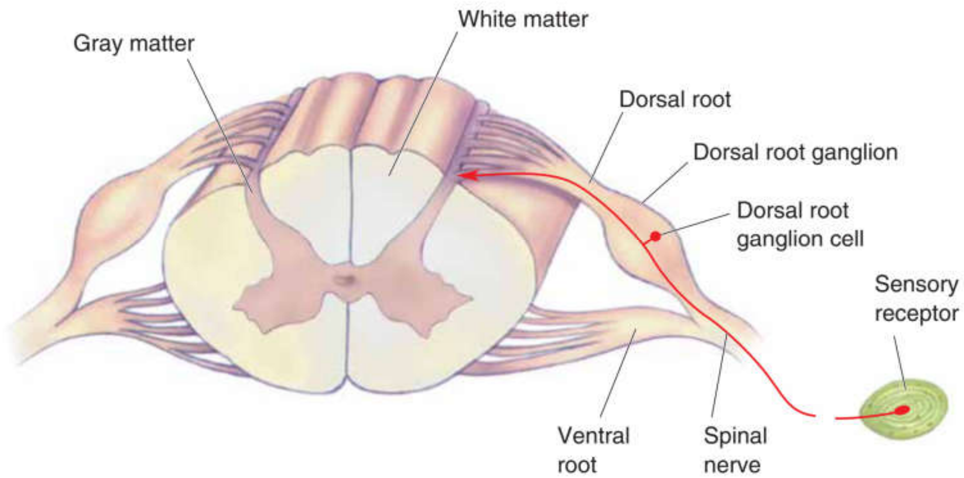


Bear et al. Figure 13-4

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

Sensory

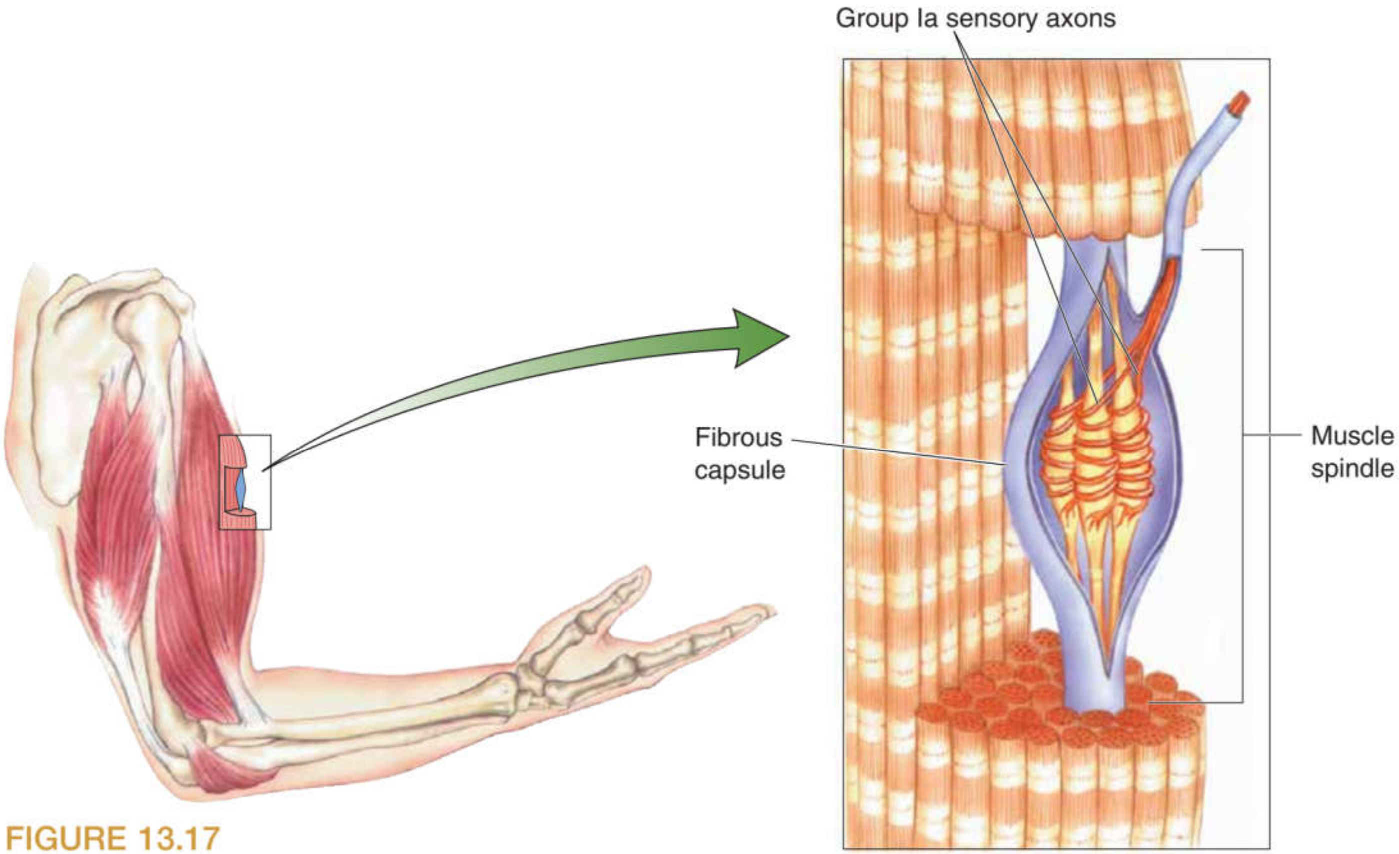
Grey matter: cell bodies
White matter: axons



Bear et al. Figure 12-9

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

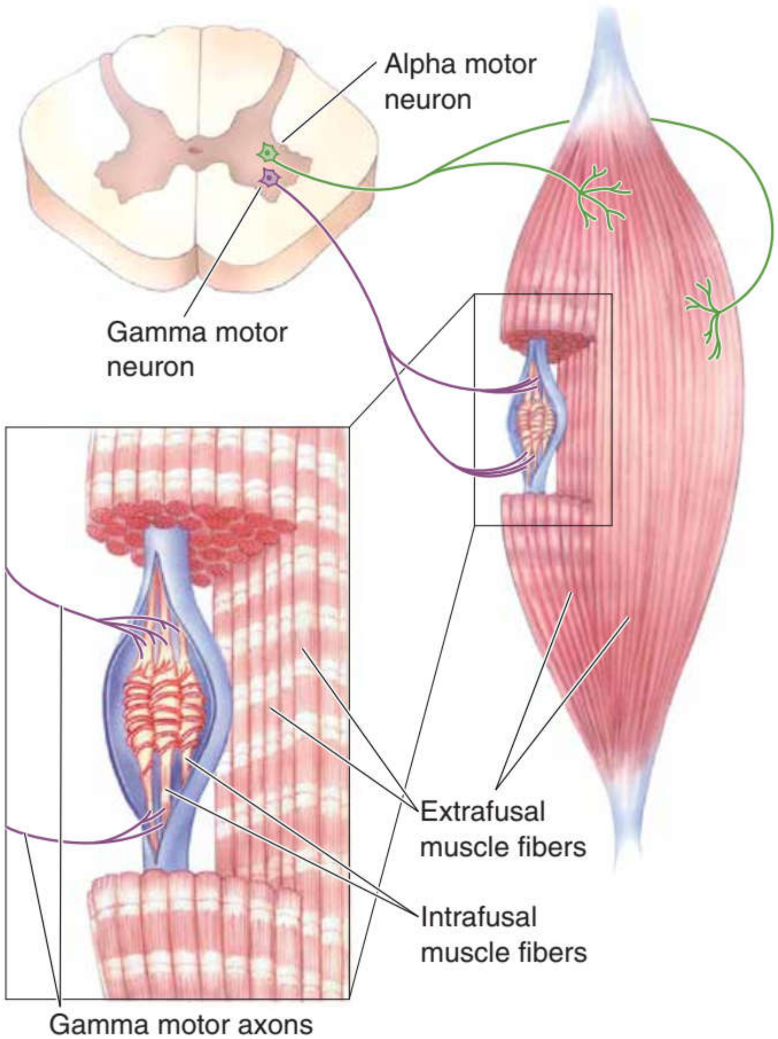
Muscle spindle structure



▲ FIGURE 13.17
A muscle spindle and its sensory innervation.

Bear et al.

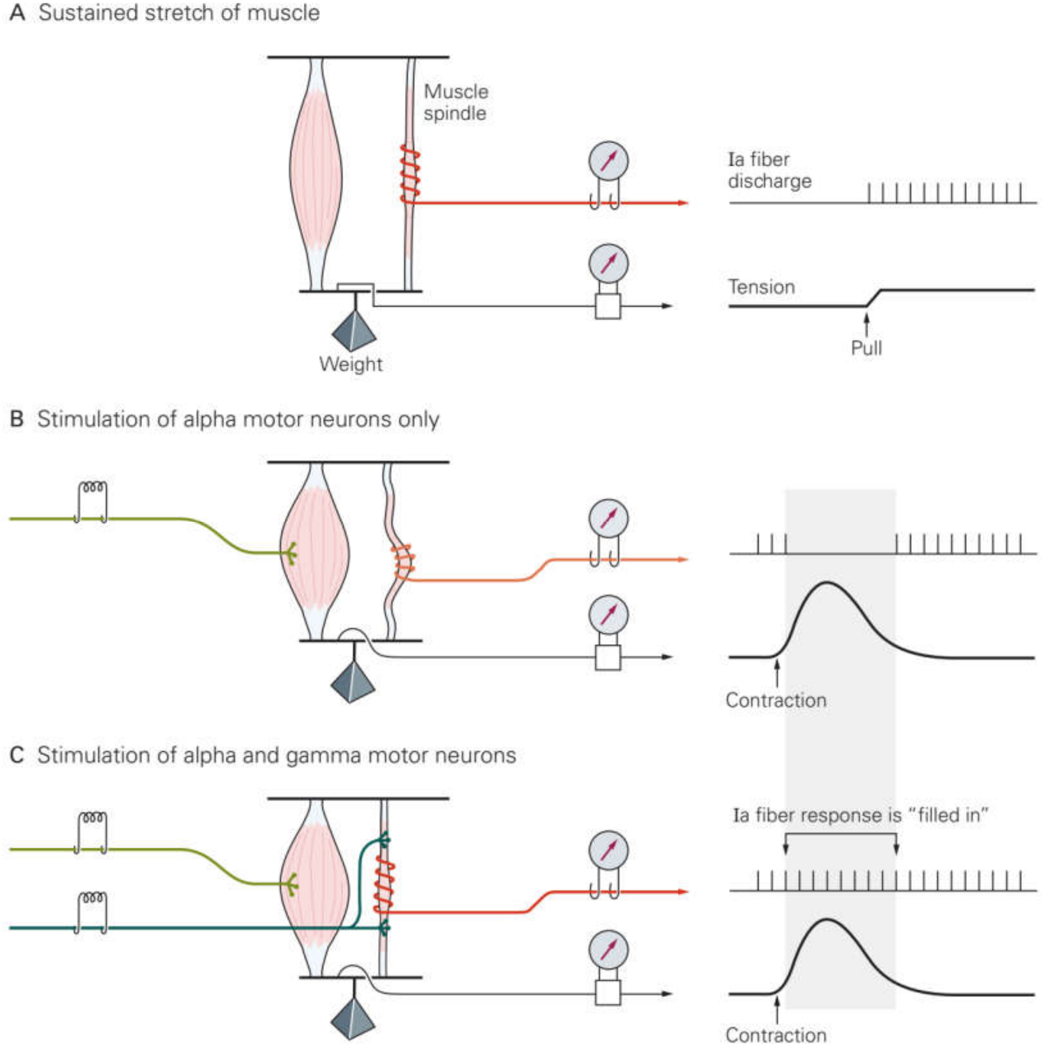
Muscle spindle structure



Bear et al. Figure 13-20

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

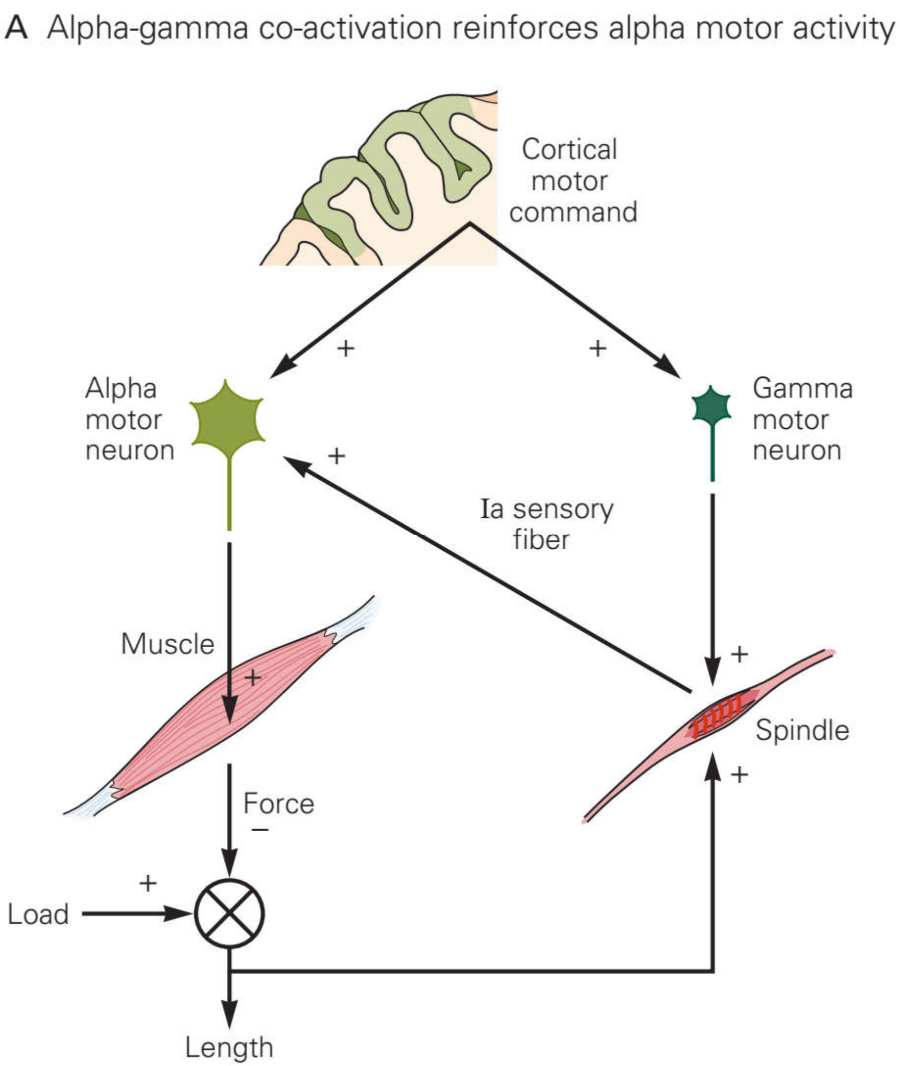
Gamma motor neuron function

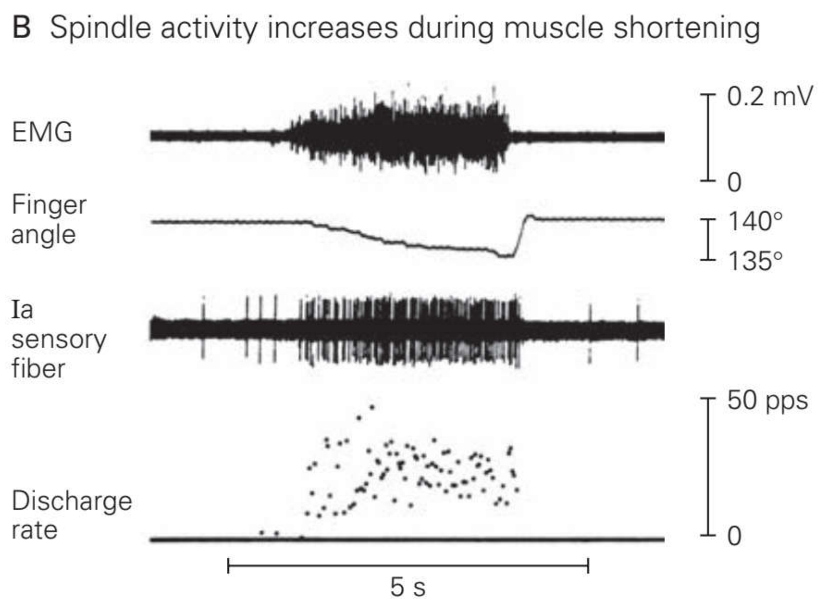


Kandel et al. Figure 35-9

- Gamma motor neuron adjusts the sensitivity of Ia sensory fibers

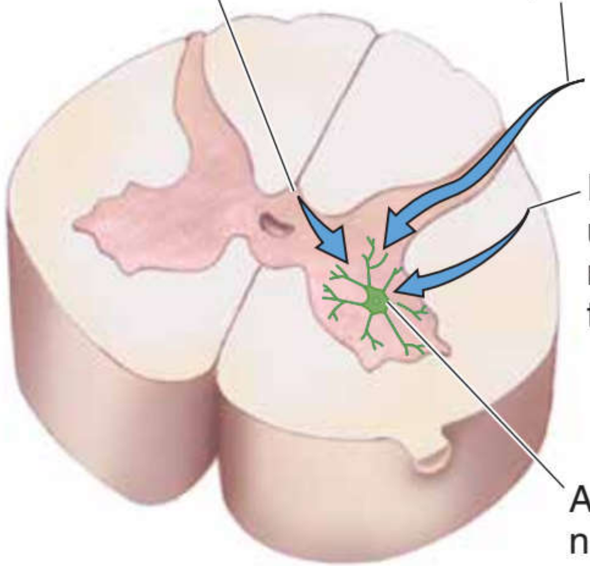
Gamma motor neuron function





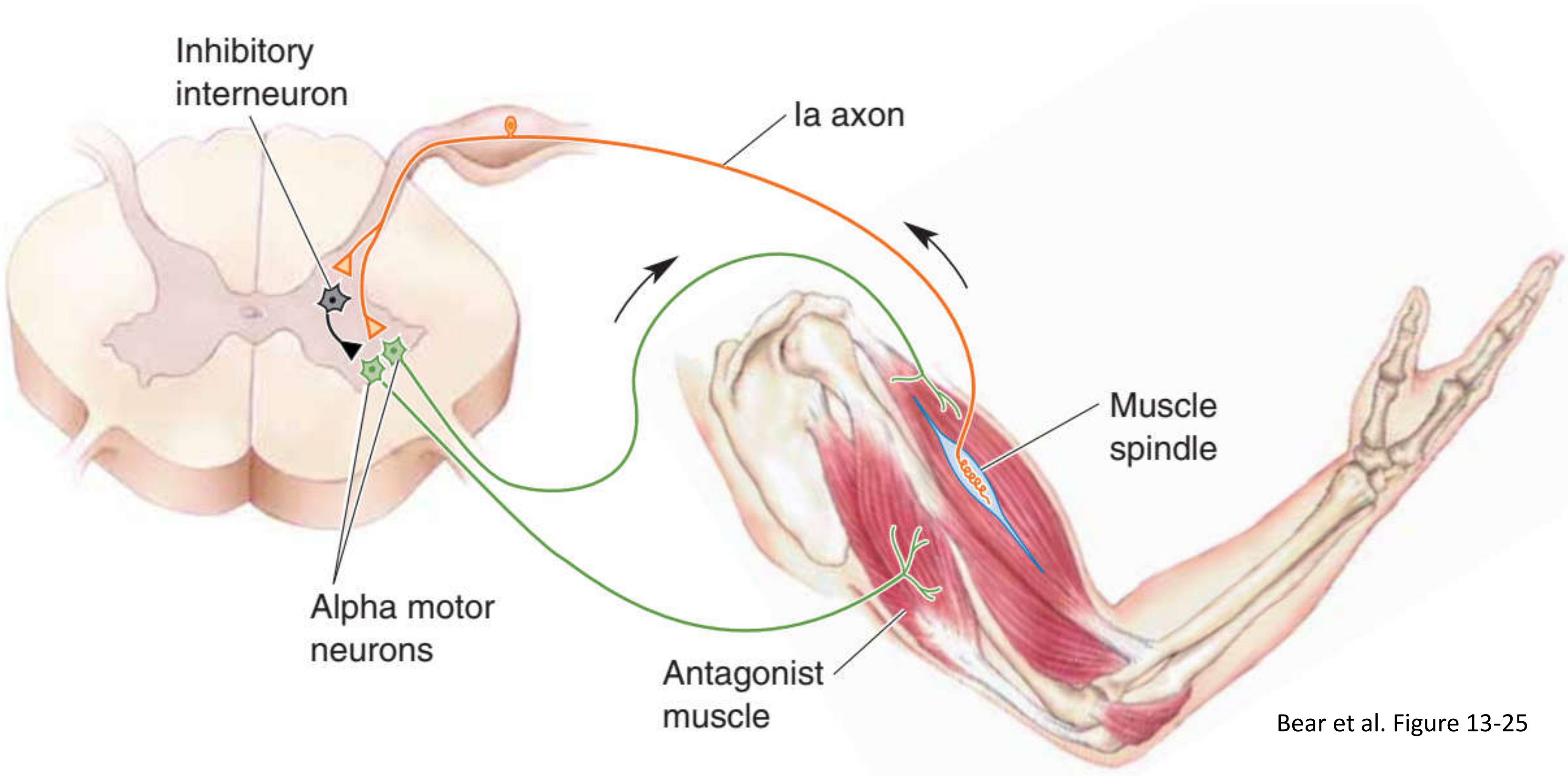
Kandel et al. Figure 35-12

Three sources of inputs to Alpha motor neuron



Bear et al. Figure 13-9

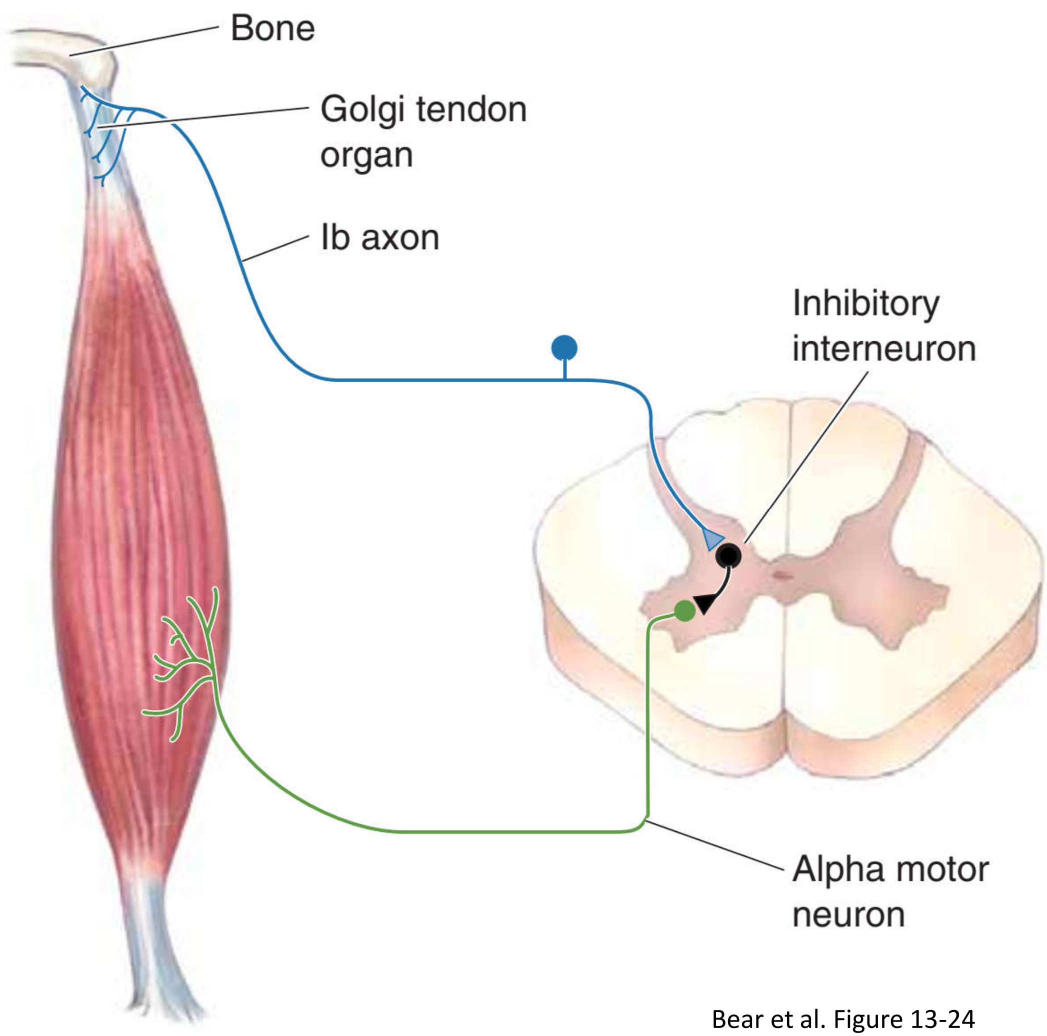
Stretch reflex and reciprocal inhibition



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

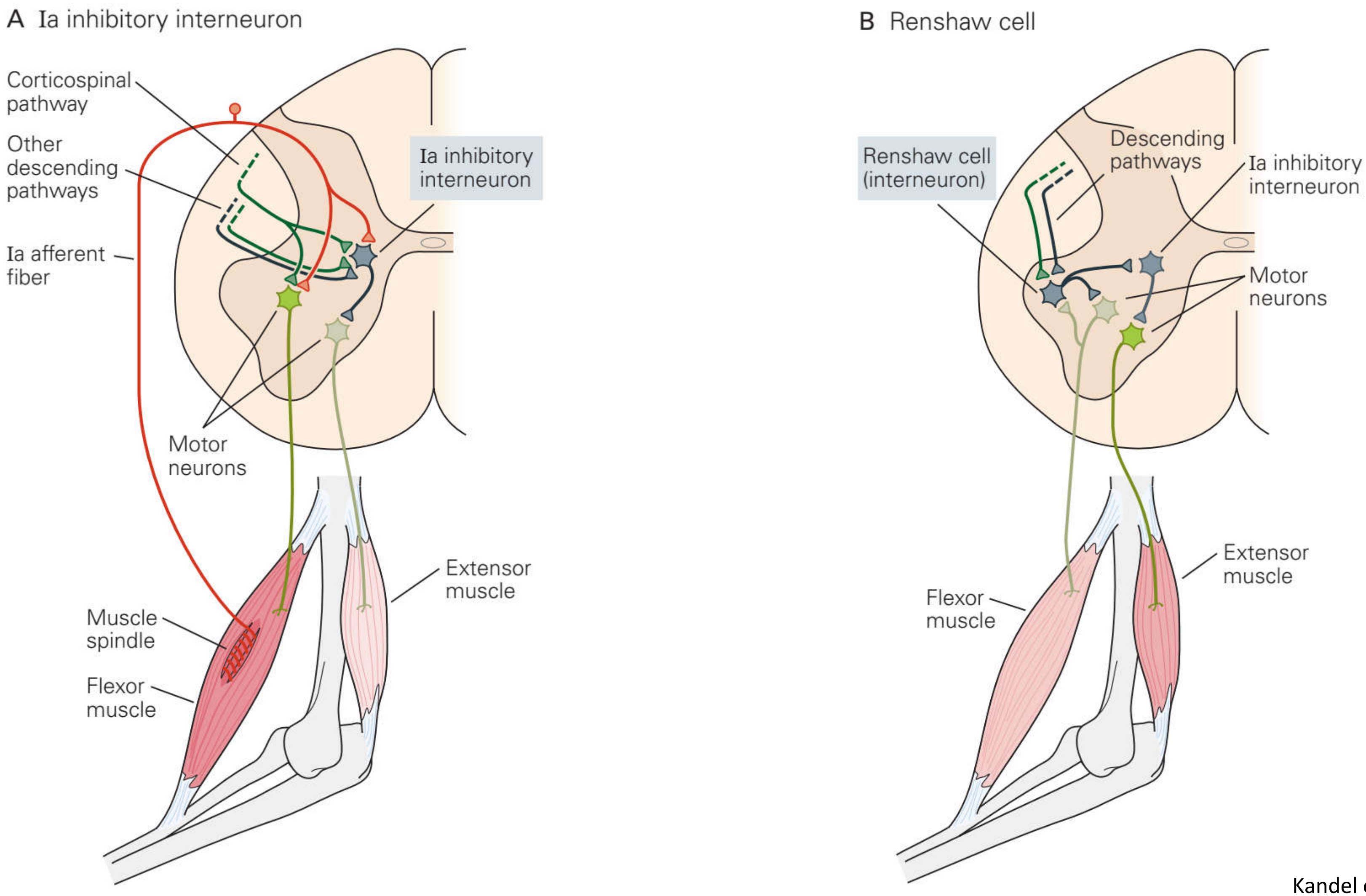
Golgi tendon organ circuit



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

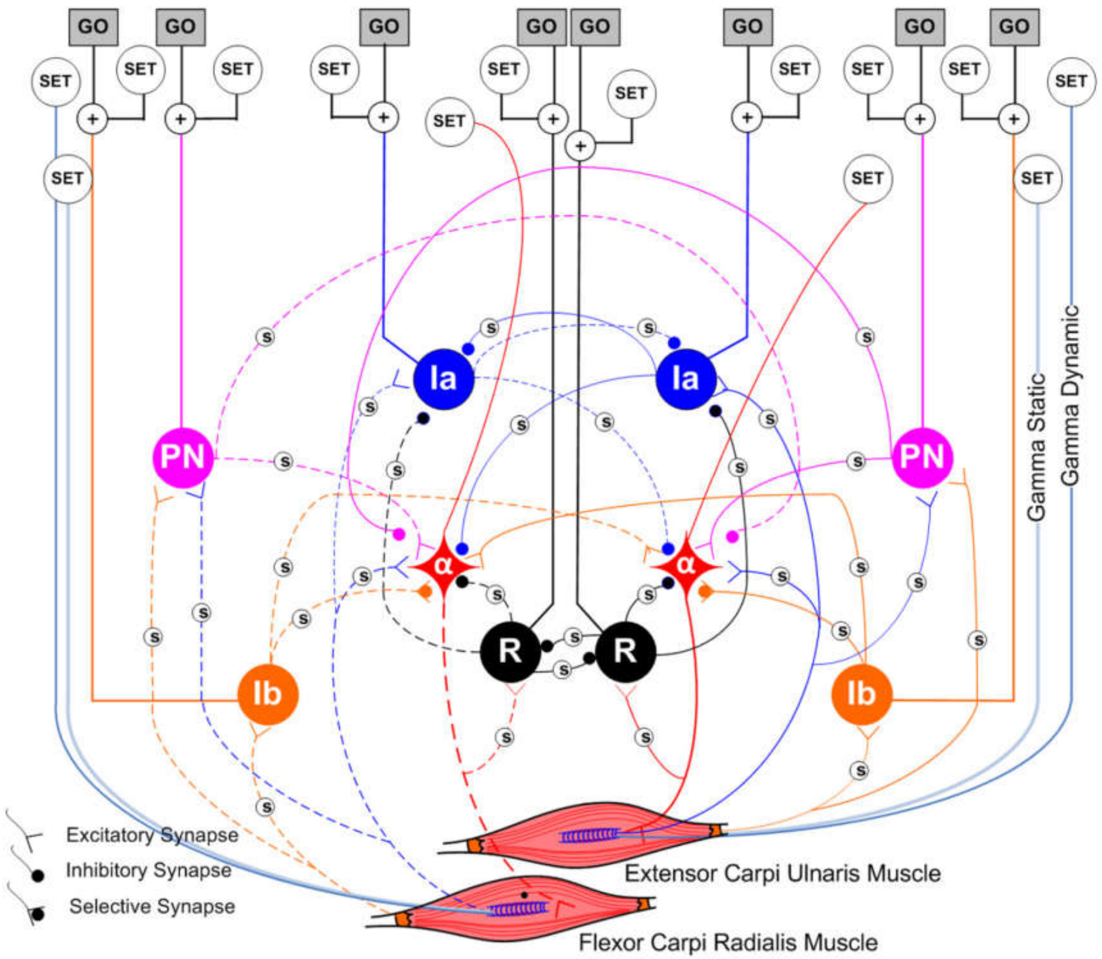
Bear et al. Figure 13-24

Reciprocal inhibition and Renshaw cell

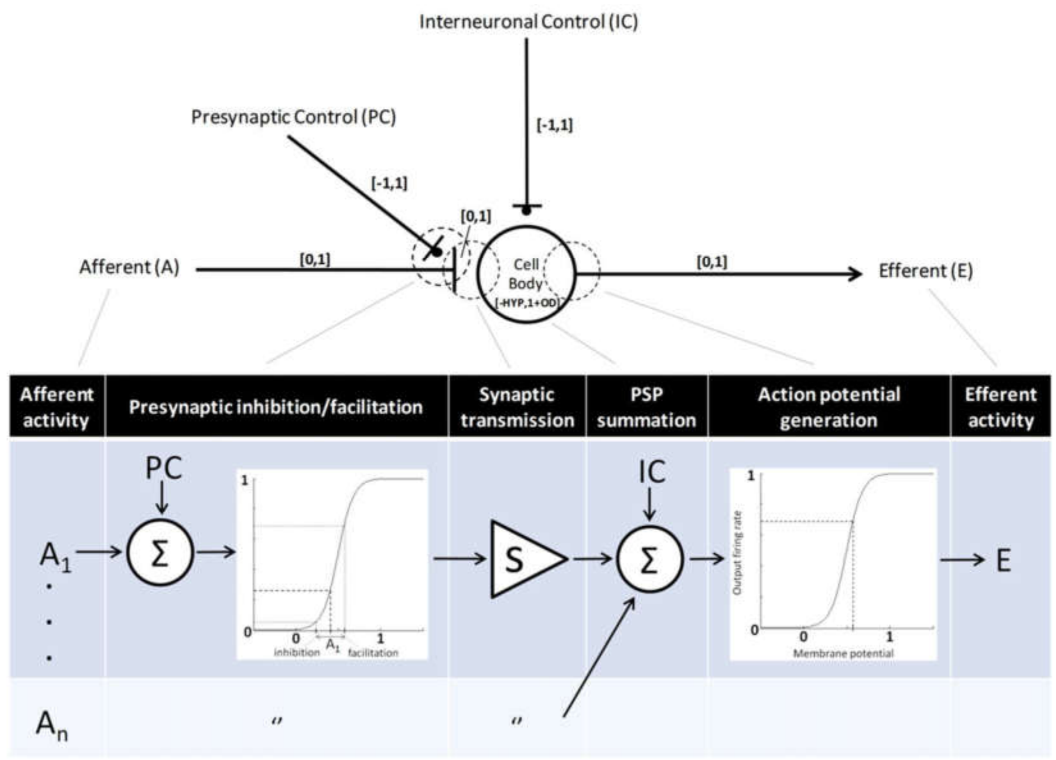


Kandel et al. Figure 35-5

Modelling of spinal reflexes

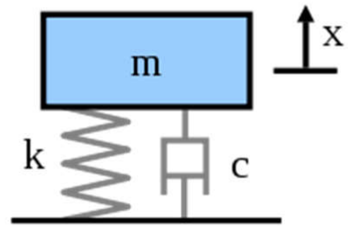


Raphael, Tsianos, Loeb 2010

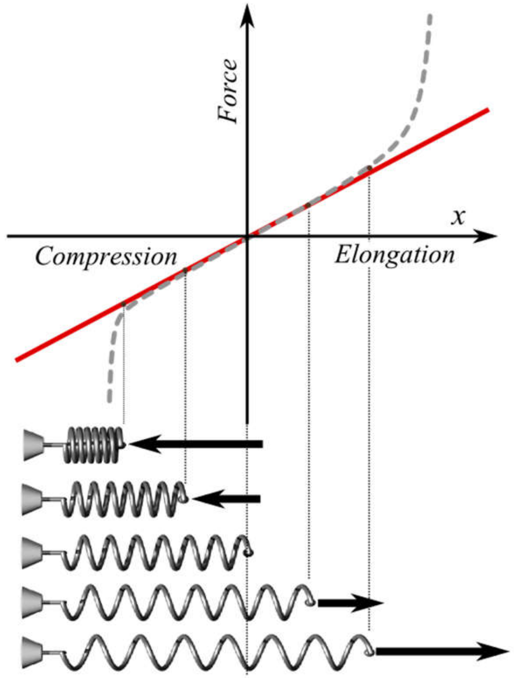


Tsianos, Goodner, Loeb 2014

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



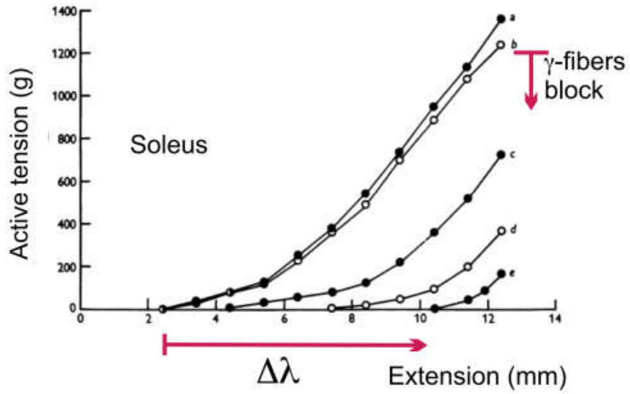
https://en.wikipedia.org/

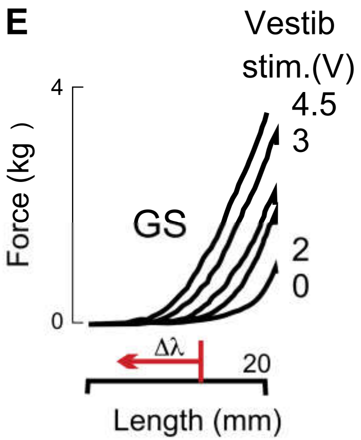
- Biological muscle-joint system has a similar “spring-like behavior”
  - But note: muscles can only pull, not push
  - A joint with agonist and antagonist muscles work bidirectional
  - Both passive mechanics and reflexes contribute

Experimental measurement of muscle elastic property

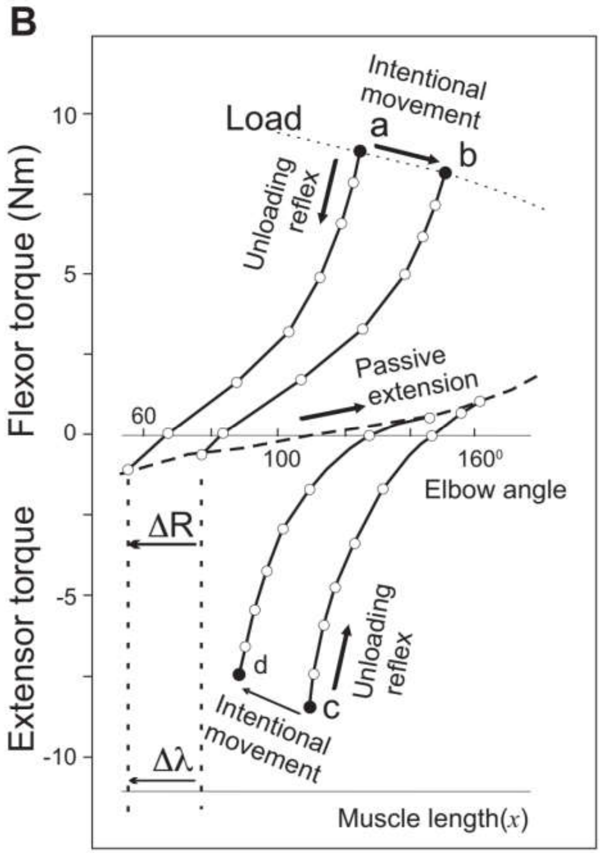
- The resting length (λ) of the "spring" can be modified by brain descending command

Cat leg muscles

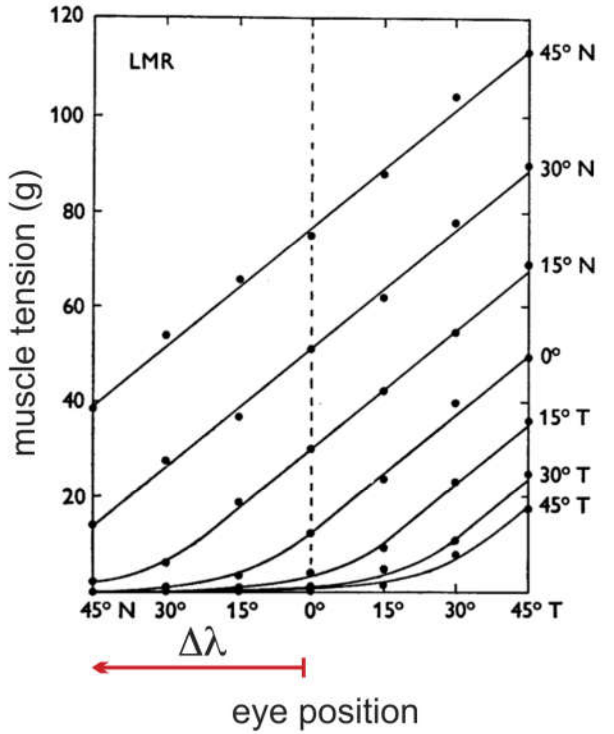




Human arm muscles

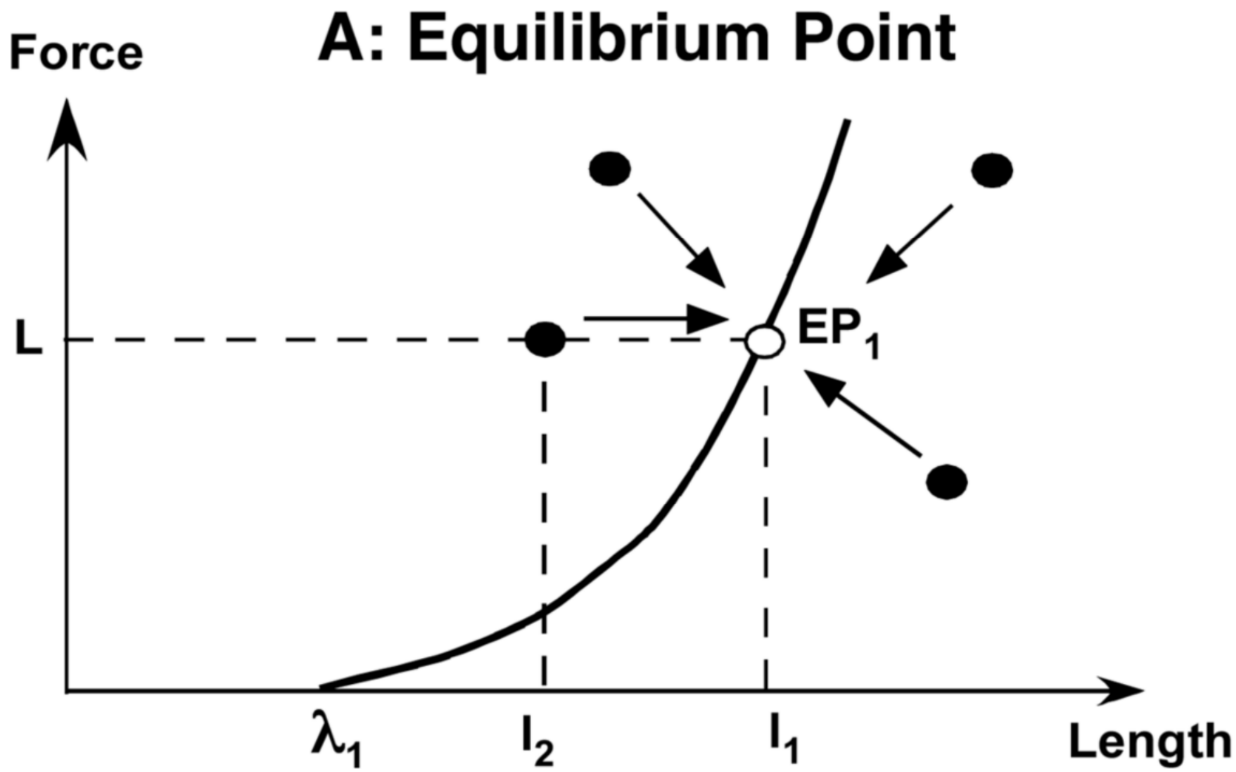


Human eye muscles



Reviewed in Feldman and Zhang, J Neurophysiol. 2020

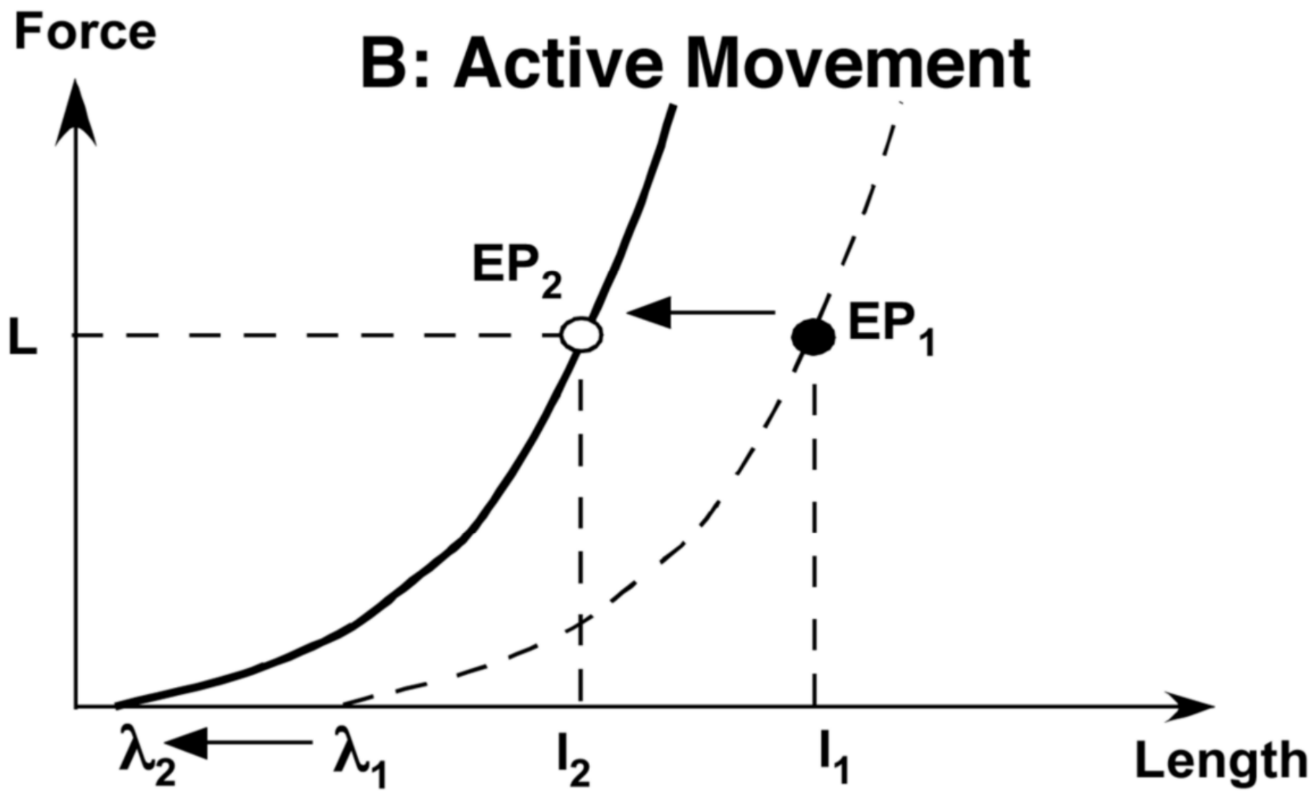
The mass-spring model



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

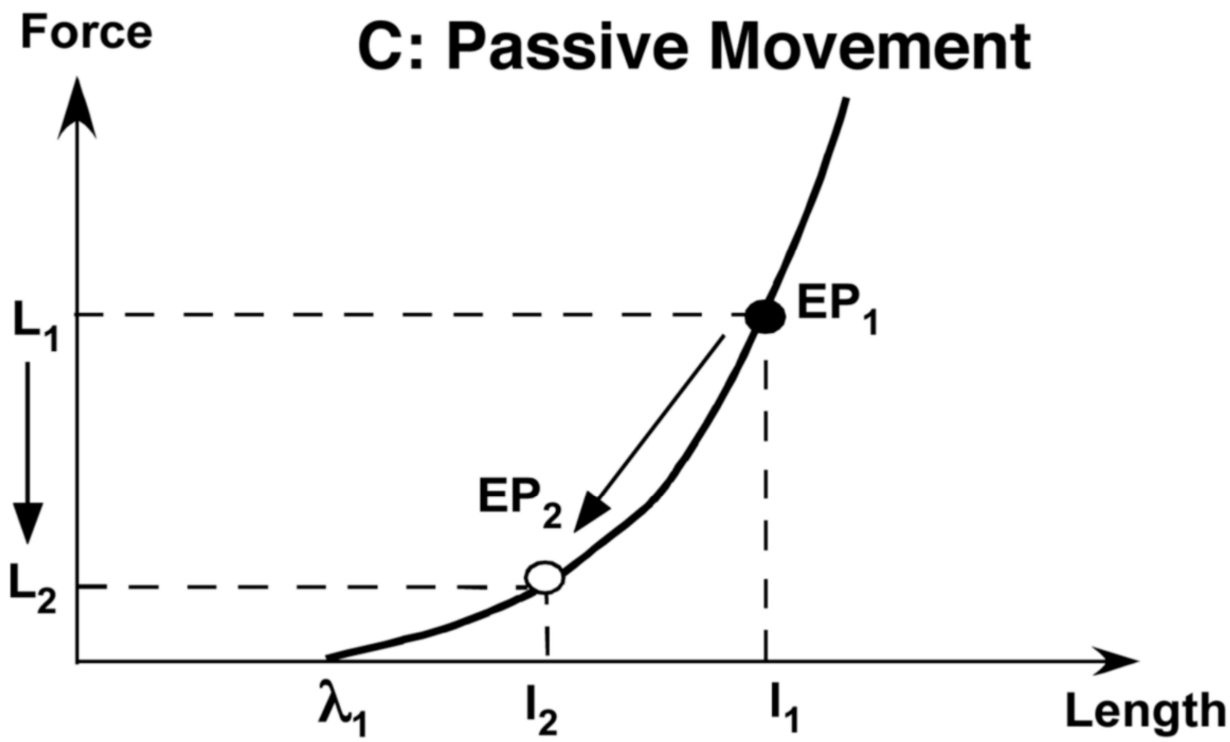
Movement emerges due to the interaction between muscular system and external load



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

Latash. J Hum Kinet 2009

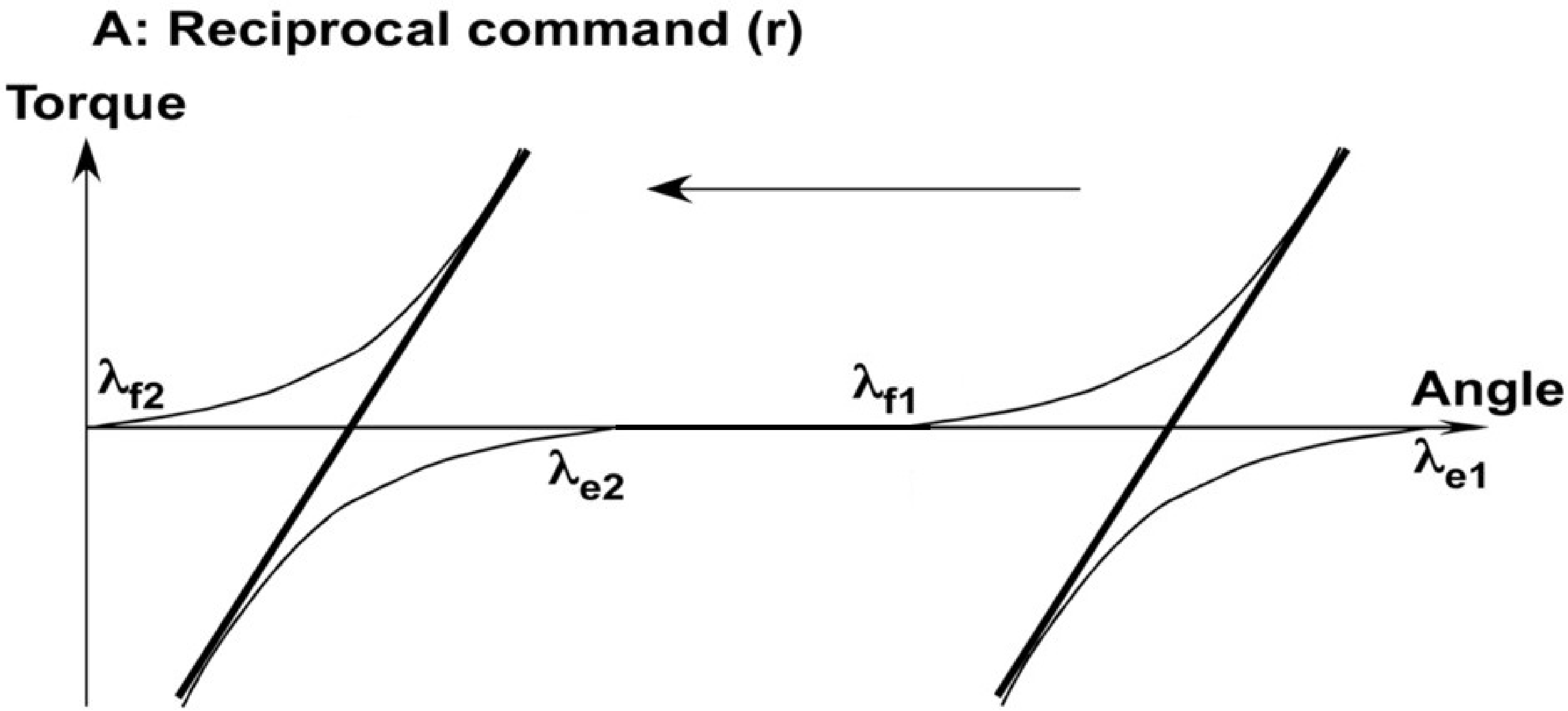
Movement emerges due to the interaction between muscular system and external load



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

Latash. J Hum Kinet 2009

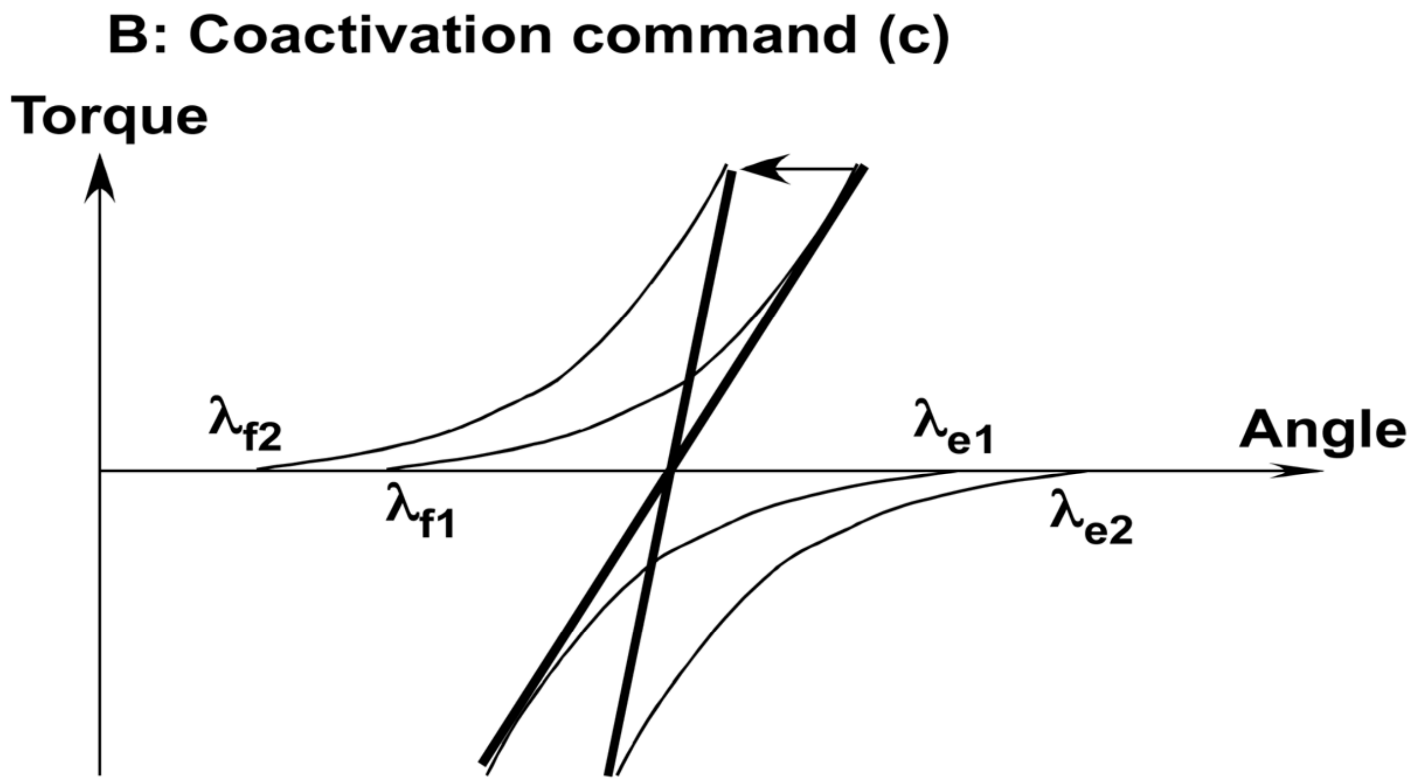
Movement emerges due to the interaction between muscular system and external load



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

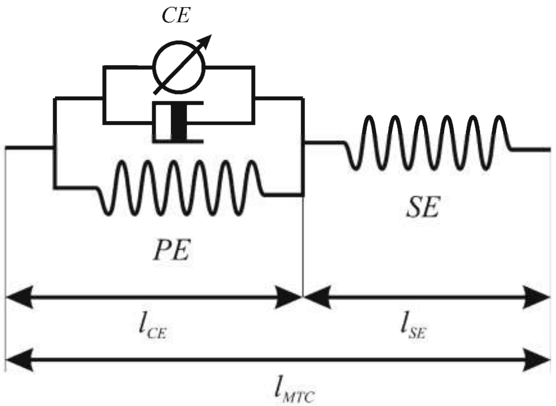
Movement emerges due to the interaction between muscular system and external load

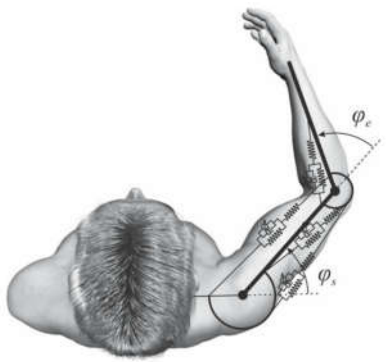


Shifts of λf and λe in opposite directions lead to a change in the slope of the joint characteristic

Latash. J Hum Kinet 2009

Biomechanical models

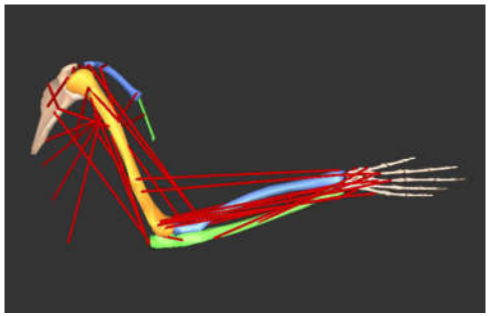




CE: Contractile element
SE: Series elastic element
PE: Parallel elastic element
l_{MTC}: Muscle-tendon complex length

Kistemarker et al. 2007

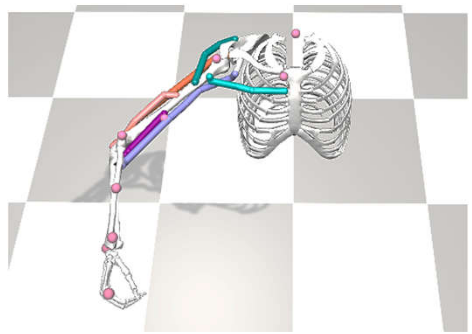
OpenSim model



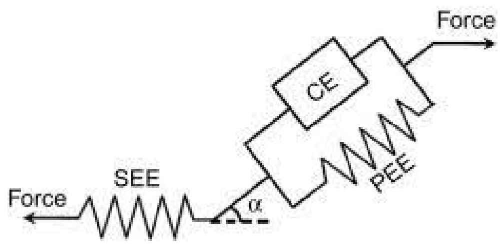
Chan&Moran 2006

Current research topic:

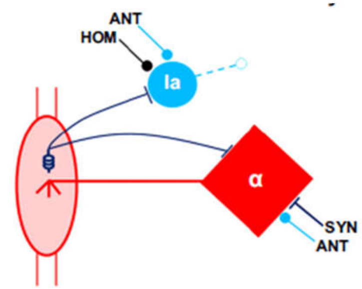
Using theorectial models of arm reaching (incl. reflex loops) to study the temporal structure of neural descending control signals



Mechanical model



Muscle model

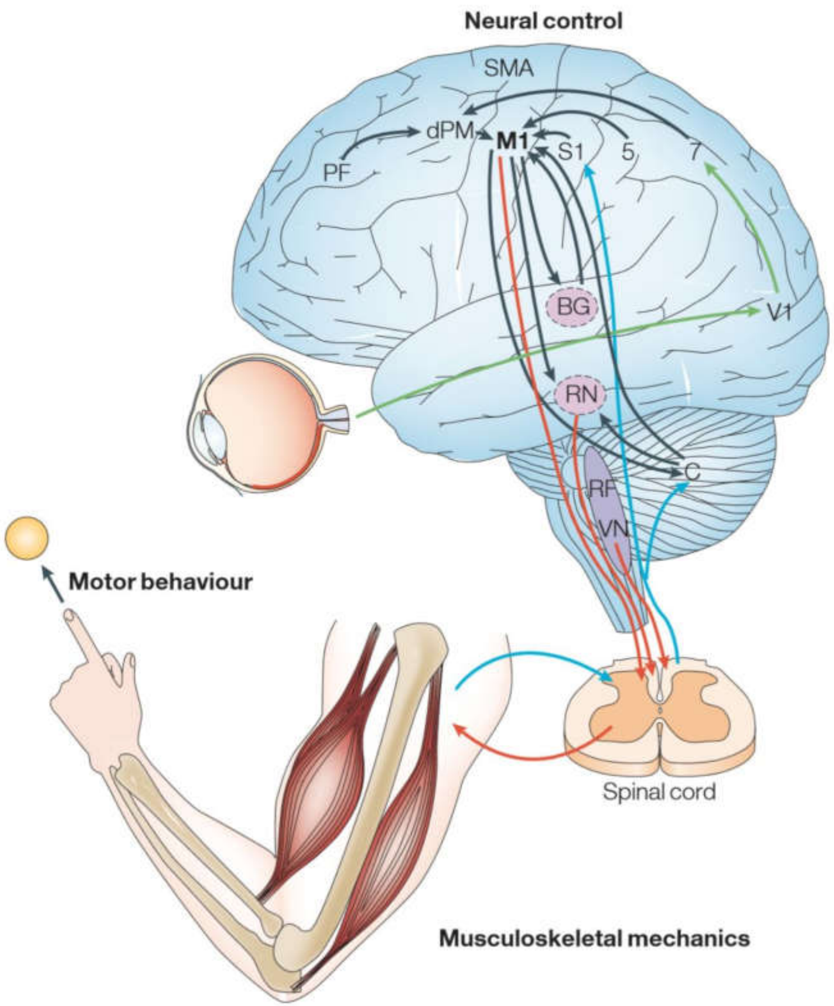


Reflex model

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

Overview of human motor system



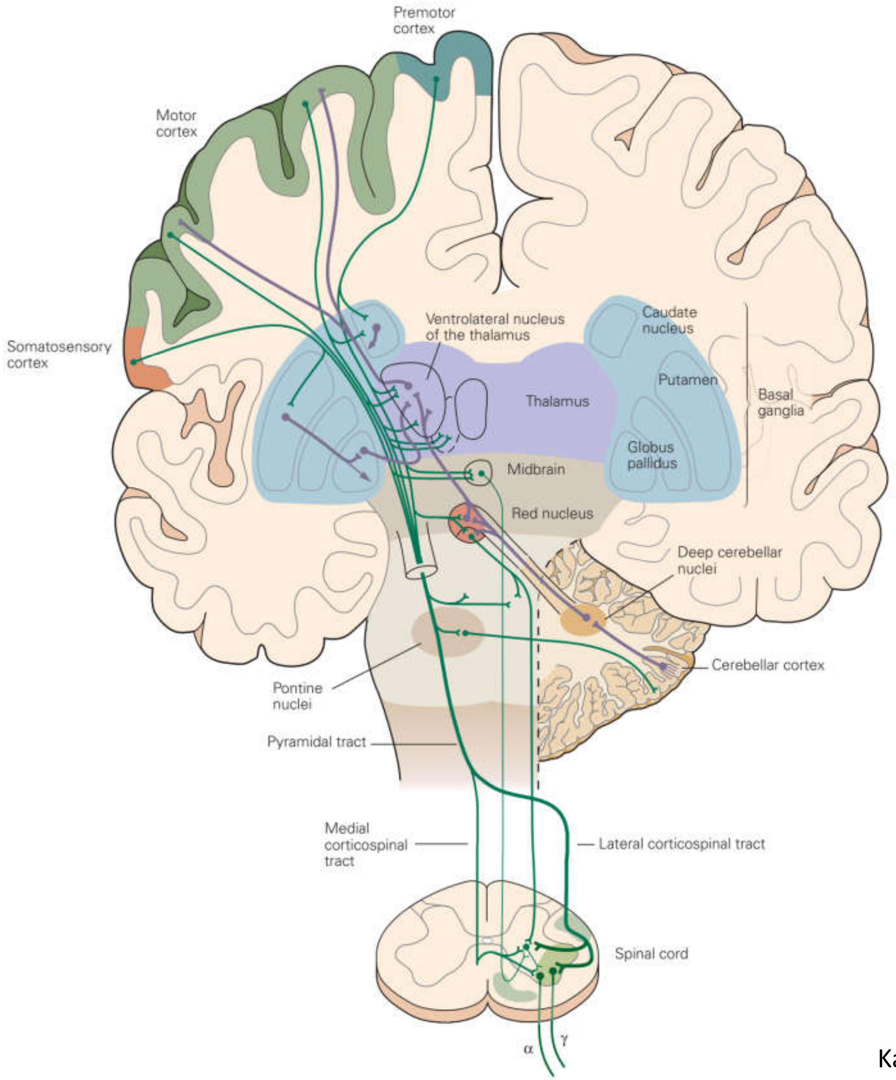
Scott. Nature Reviews Neuroscience 2004

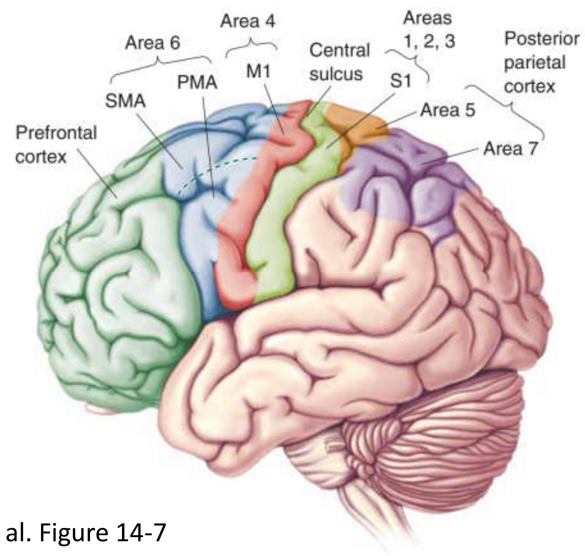
- Central nervous system (CNS)
  - Brain
  - Spinal cord

- Muscles

Human brain circuits for movement generation

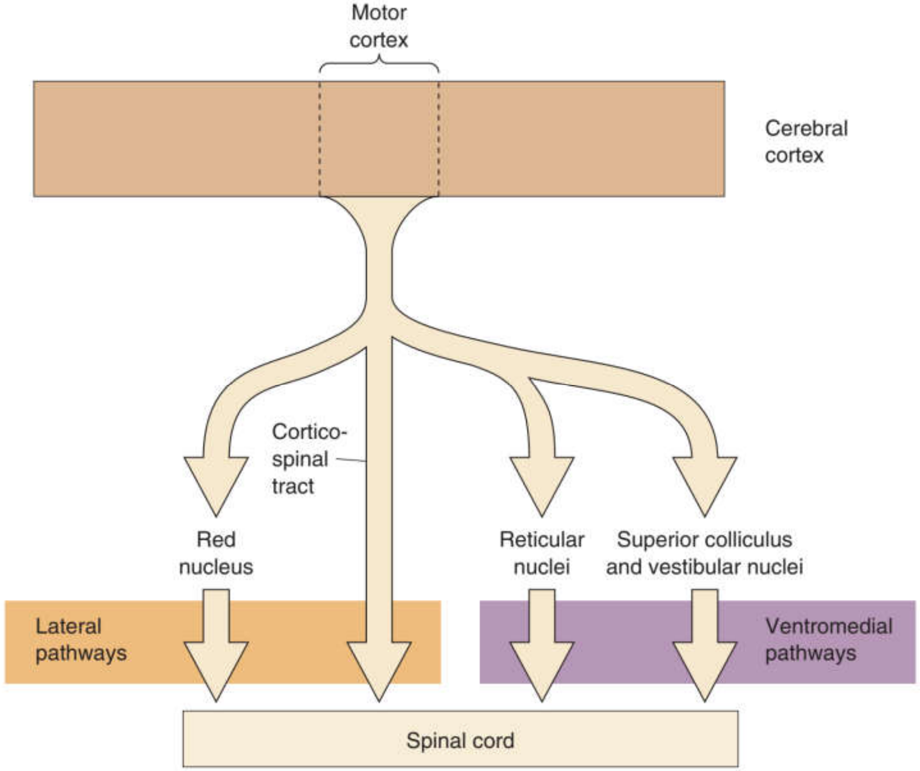
- Motor cortex
- Cerebellum
- Basal ganglia



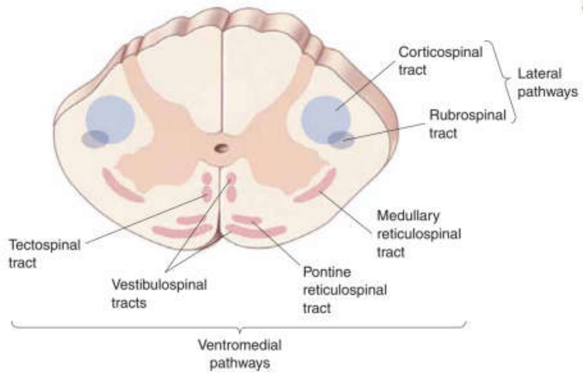


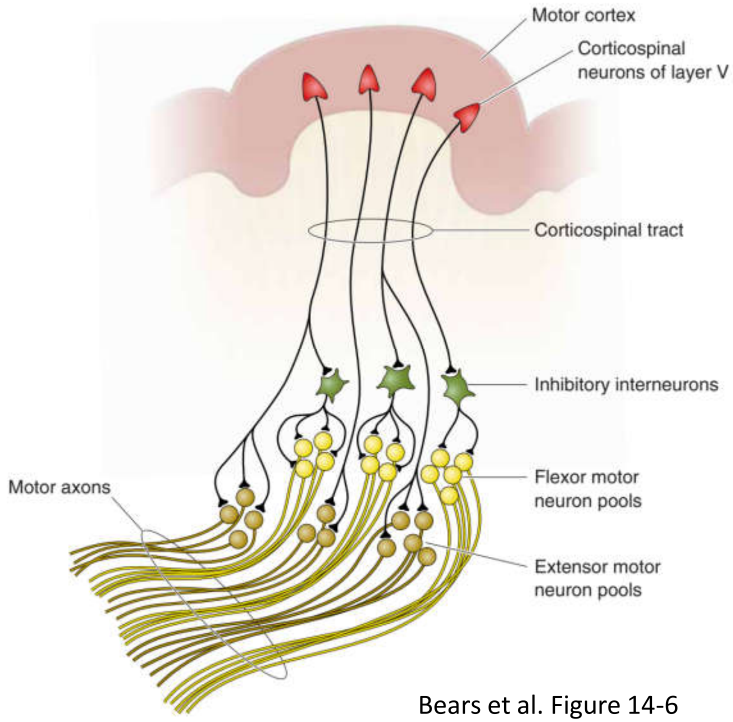
Kandel et al. Figure 14-7

Motor Cortex – descending control of spinal cord



Bears et al. Figure 14-6

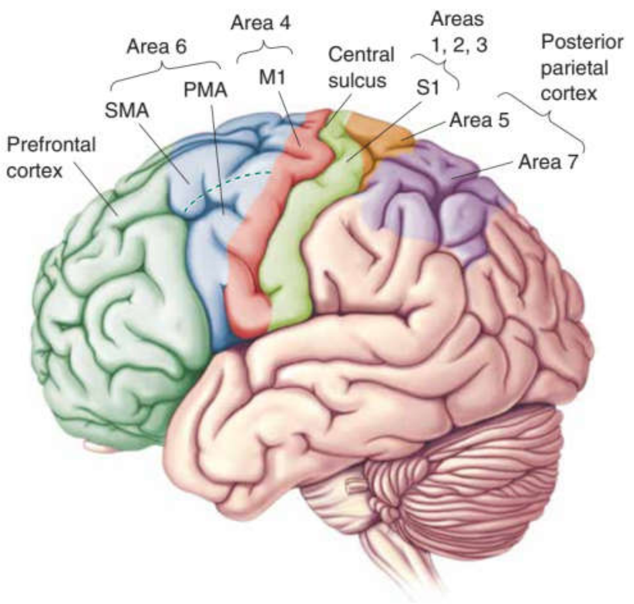




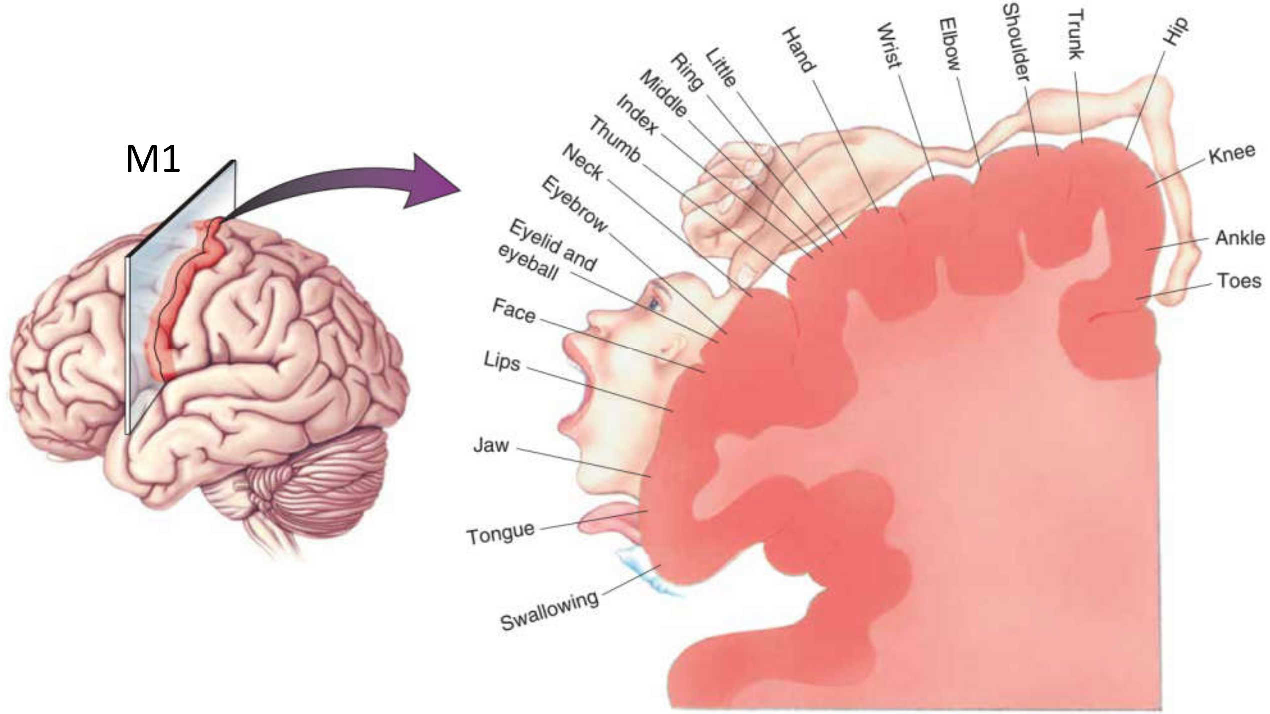
Bears et al. Figure 14-6

Motor Cortex:

Primary cortex (M1)
Premotor area (PMA)
Supplementary motor area(SMA)



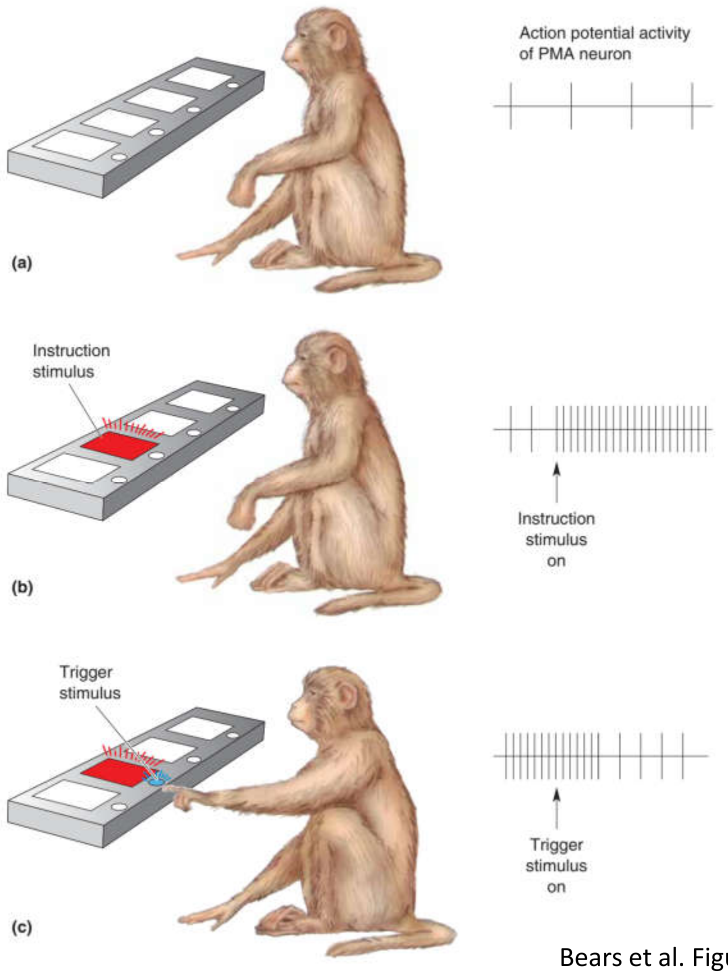
Bears et al. Figure 14-7



Bears et al. Figure 14-8

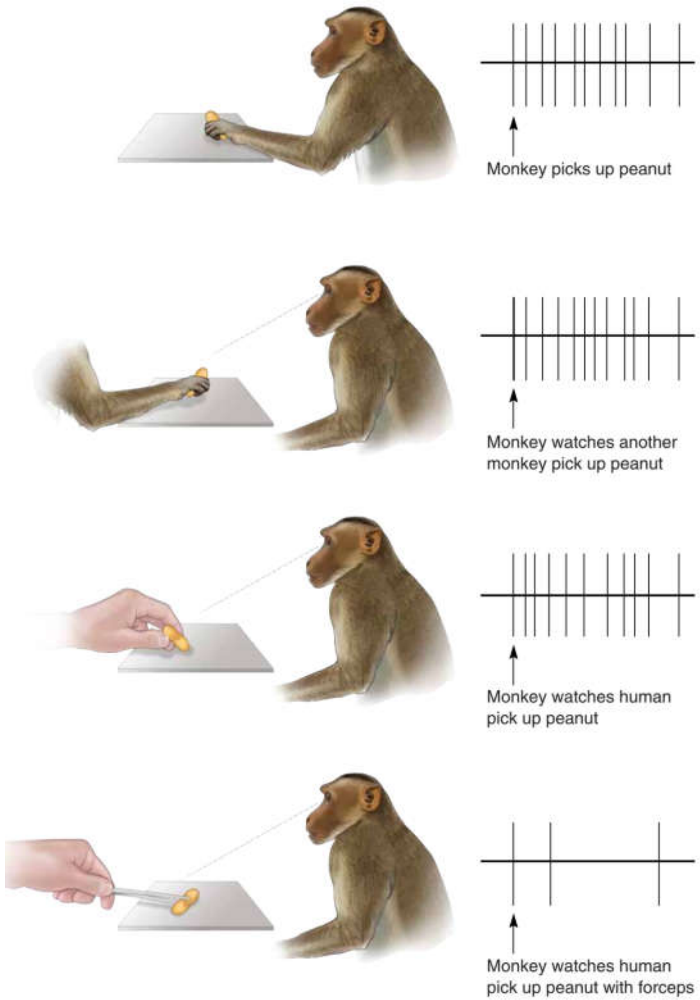
Premotor area (PMA)

Discharge of PMA neuron before a movement



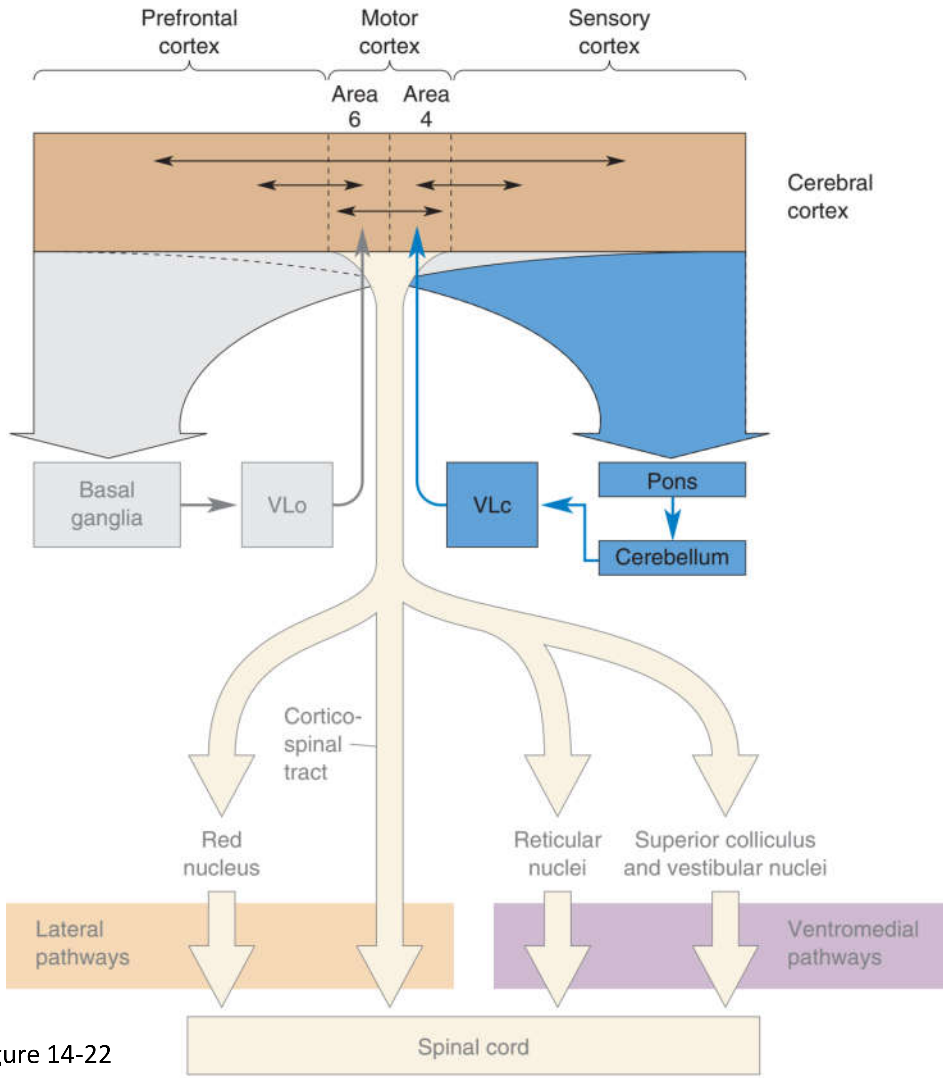
Bears et al. Figure 14-9

Discharge of a mirror neuron in PMA

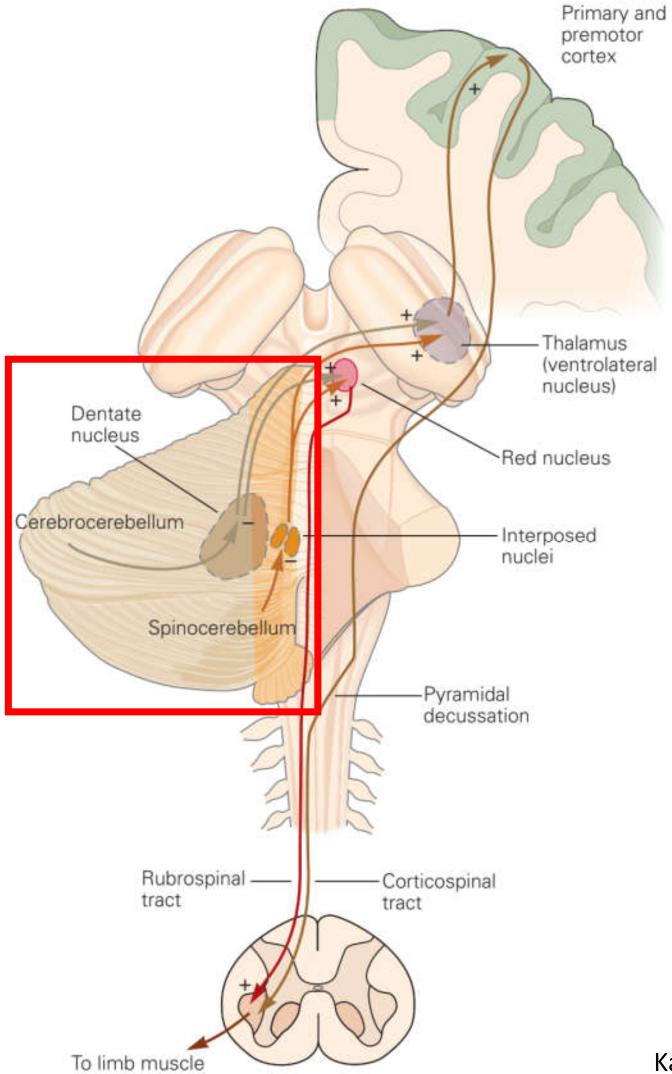


Bears et al. Figure 14-10

Cerebellum: coordination of movement

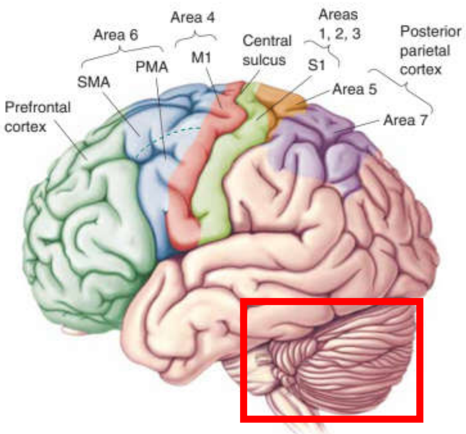


Bears et al. Figure 14-22

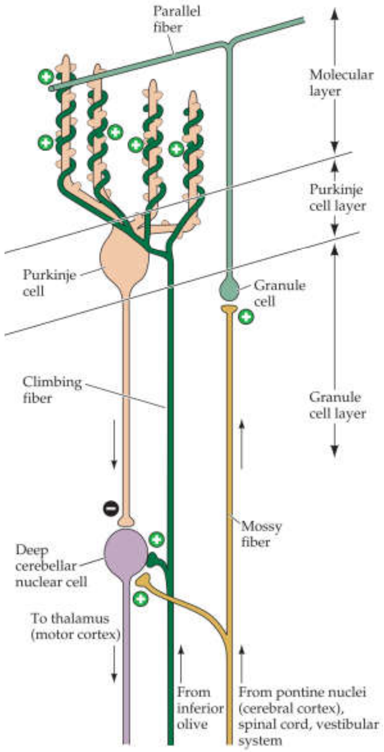


Kandel et al. Figure 42-7

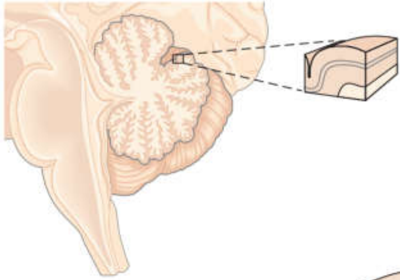
Cerebellum: anatomy

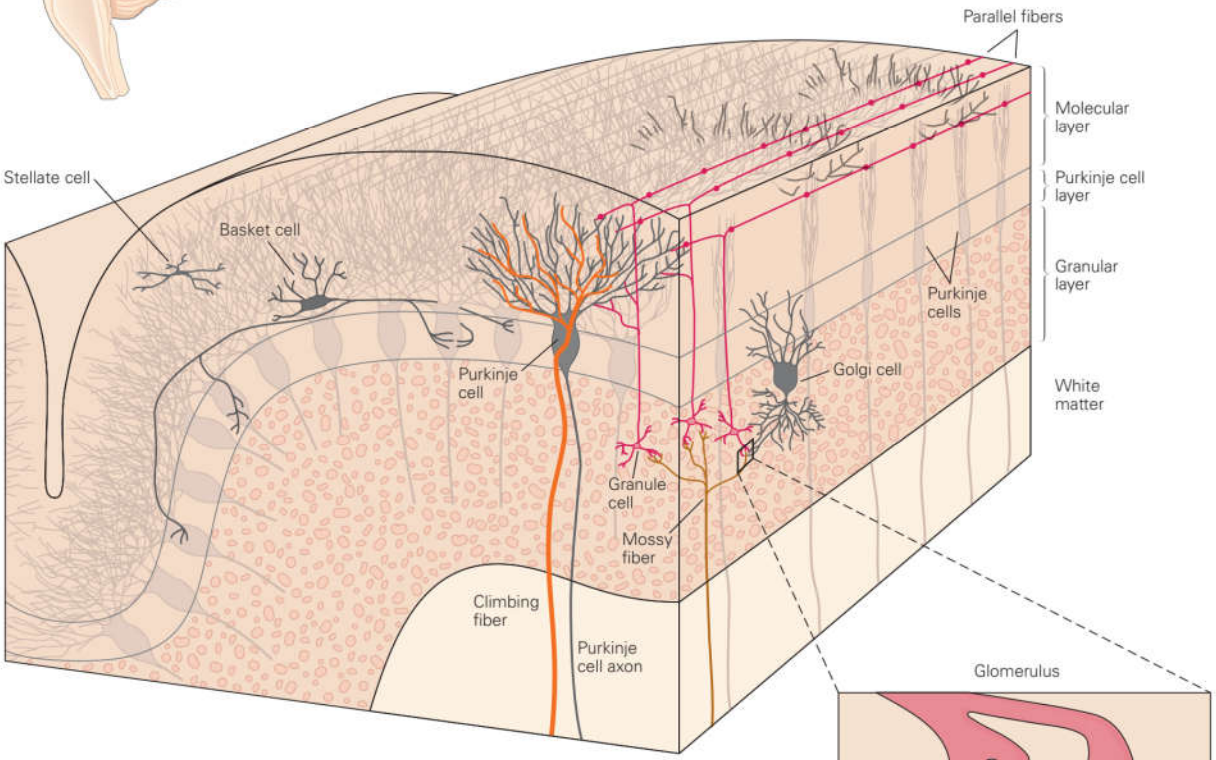


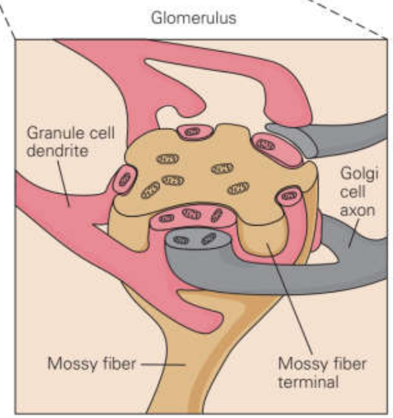
Bears et al. Figure 14-7



Kandel et al. Figure 42-4



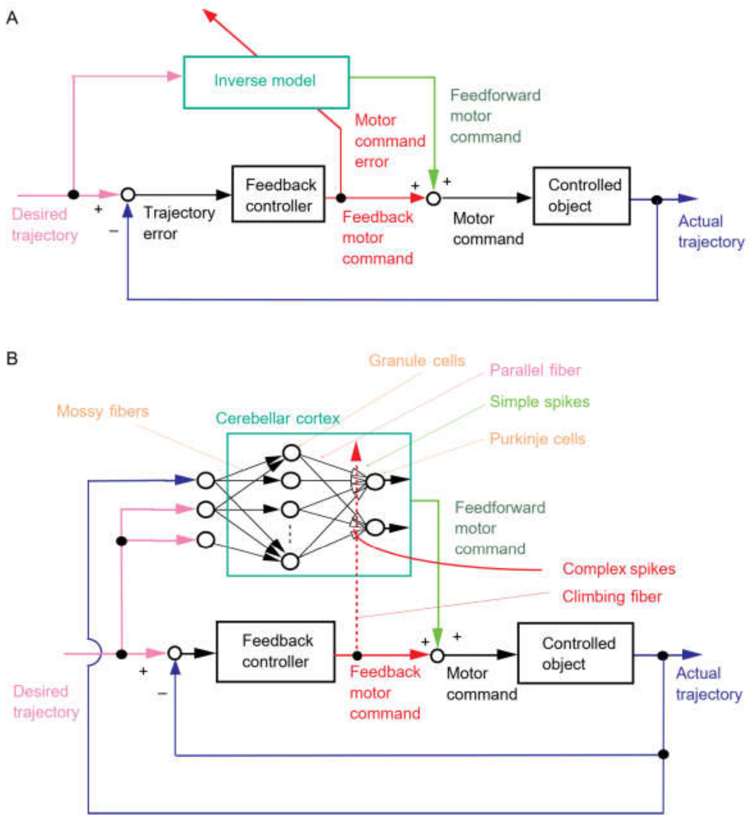




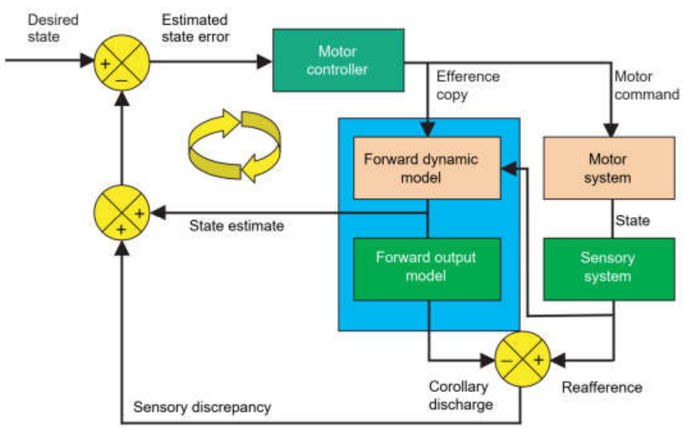
- Climbing fiber
- Purkinjie cell
- Mossy fiber
- Granule cell

Cerebellum - control model

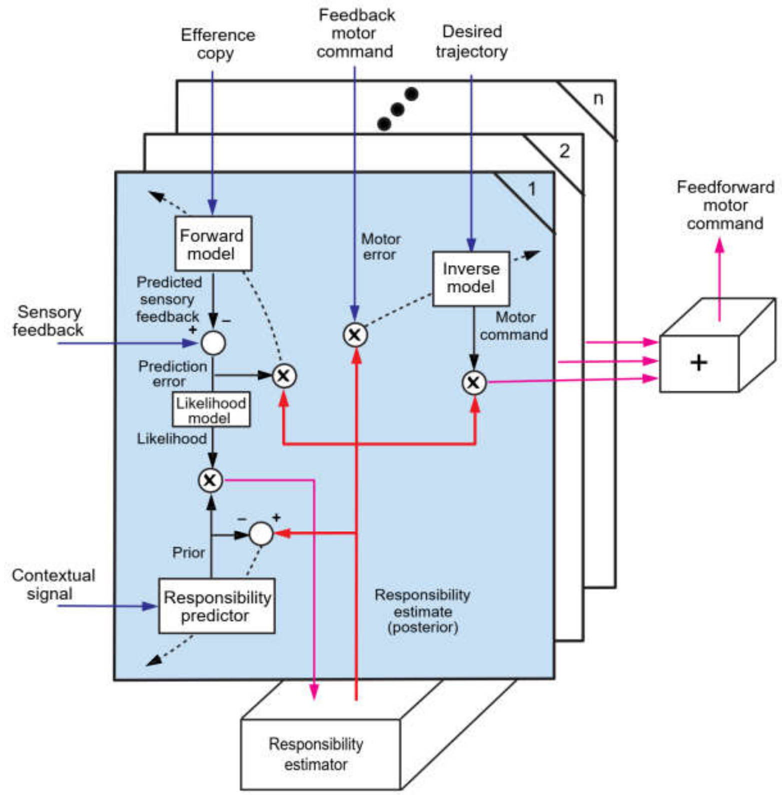
Inverse model (Feedback error-learning)



Forward model (Smith-predictor)



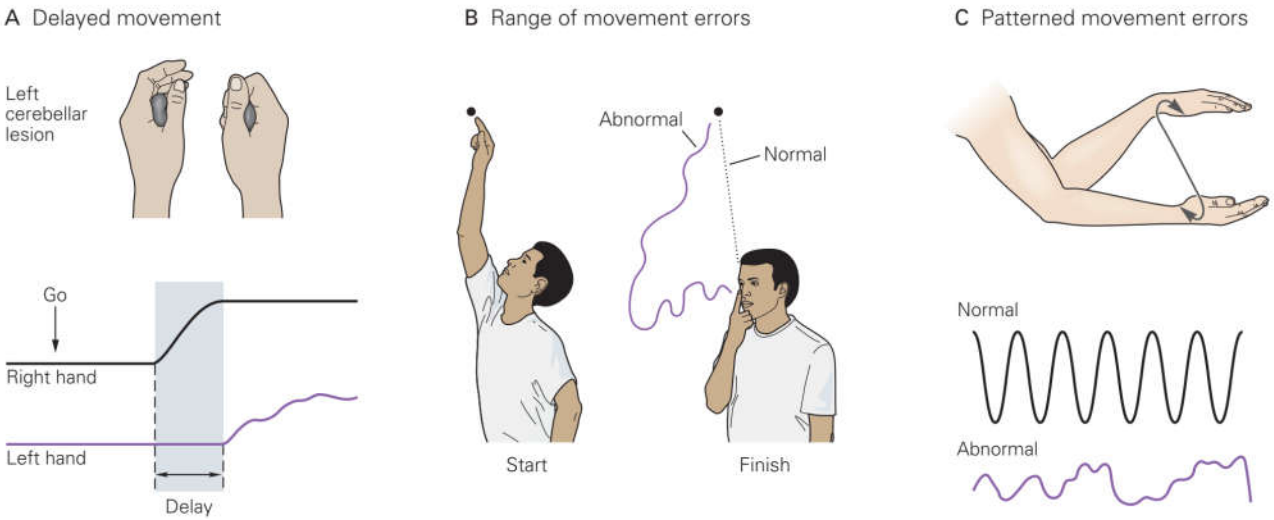
Multiple paired forward-inverse models

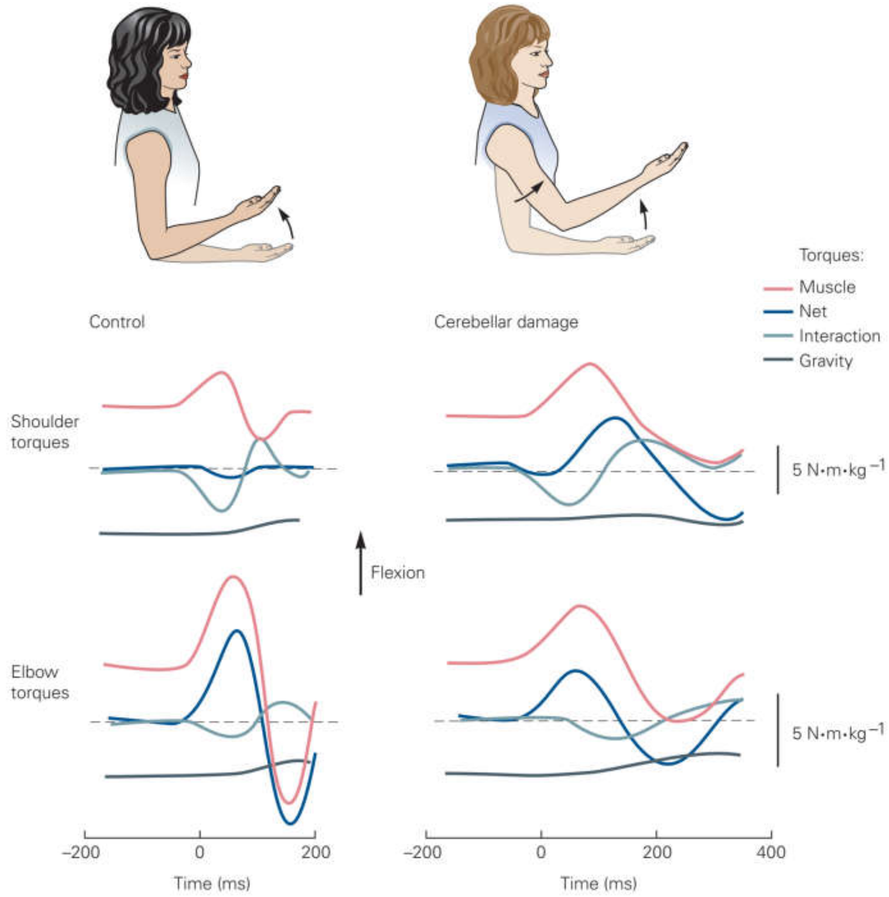


Wolpert et al. 1998

Cerebellum: diseases

Deficits in coordination and timing

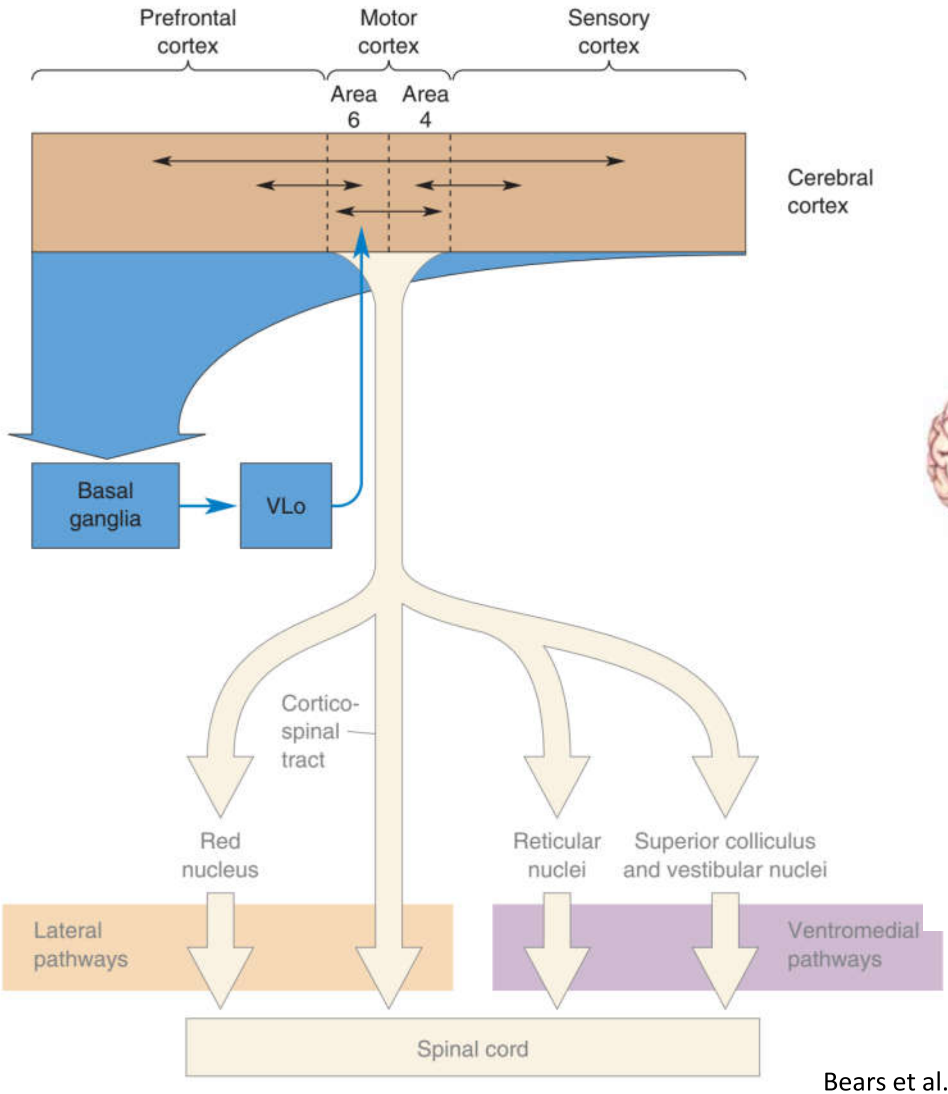




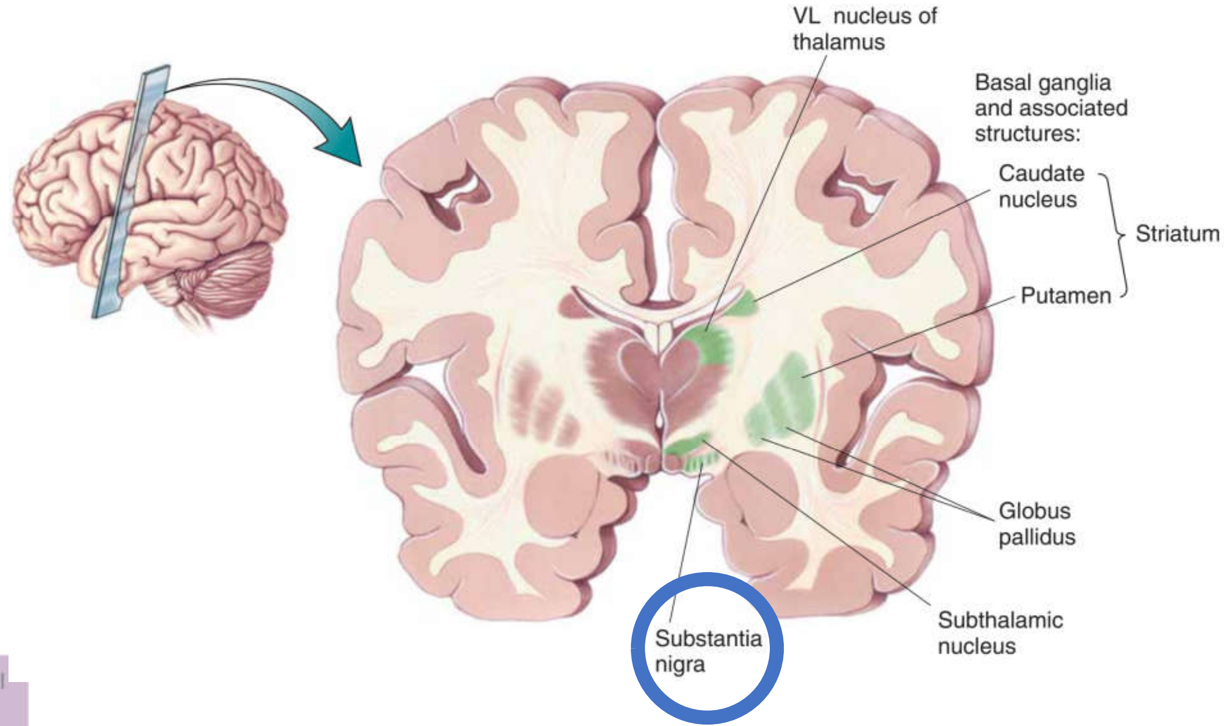
Kandel et al. Figure 42-1

Kandel et al. Figure 42-11

Basal ganglia: modulation of movement

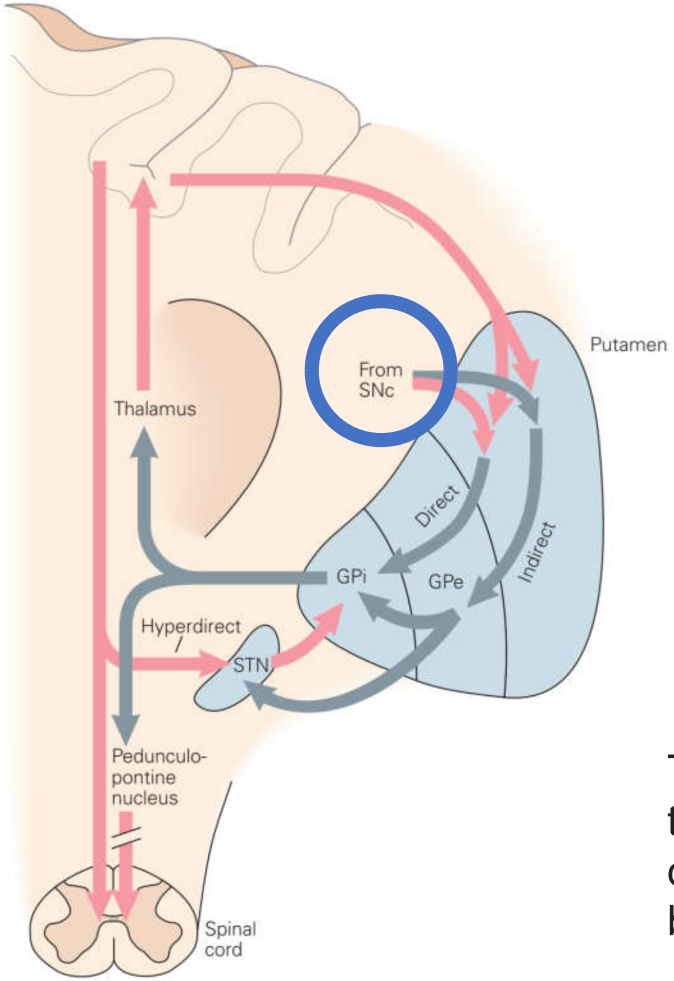


Bears et al. Figure 14-11



Bears et al. Figure 14-12

Basal ganglia: neural loop



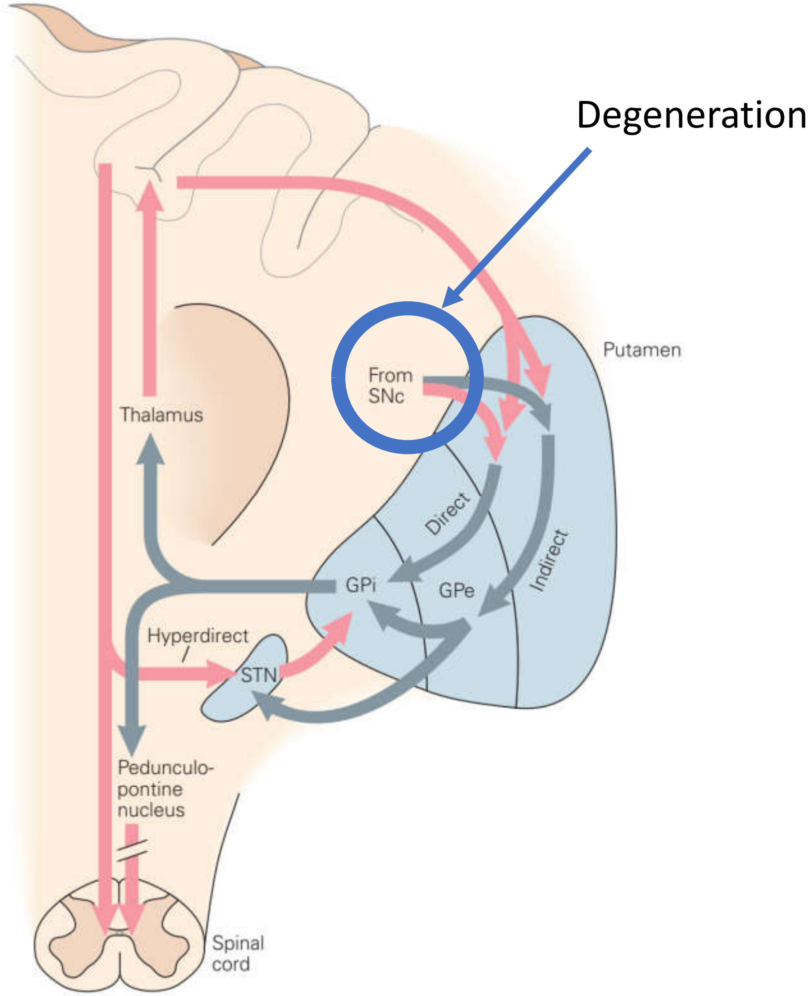
Kandel et al. Figure 43-2

The **substantia nigra** (SNc) is the source of the striatal input of the neurotransmitter dopamine, which plays an important role in basal ganglia function

Basal ganglia: Parkinson‘s disease

Parkinson‘s disease

- Resting tremor
- Rigidity/Freezing
- No tremor when moving
- Cause: loss of dopaminergic neurons
- Why such neurons die is unknown



Basal ganglia: Parkinson‘s disease

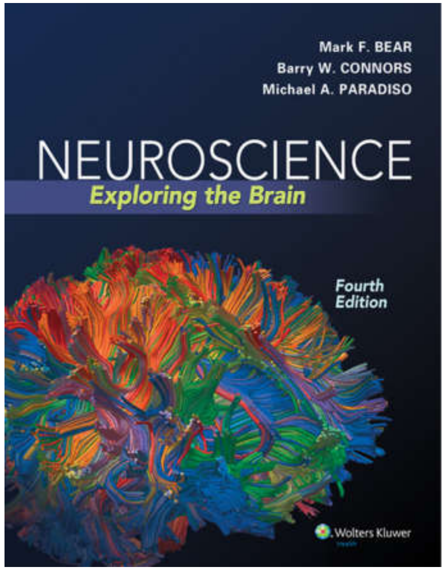
Video: Cycling for Freezing Gait in Parkinson's Disease. www.youtube.com

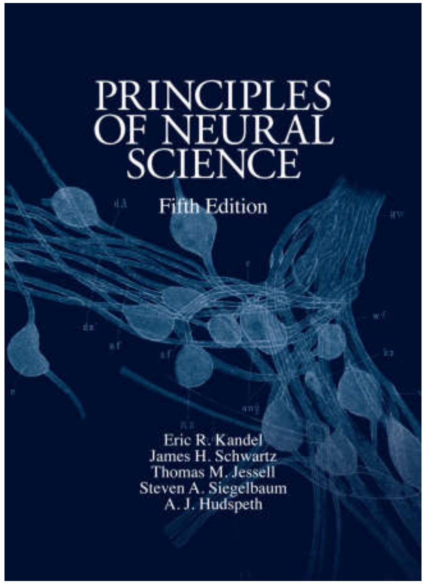
Summary: How the brain works in movement generation?

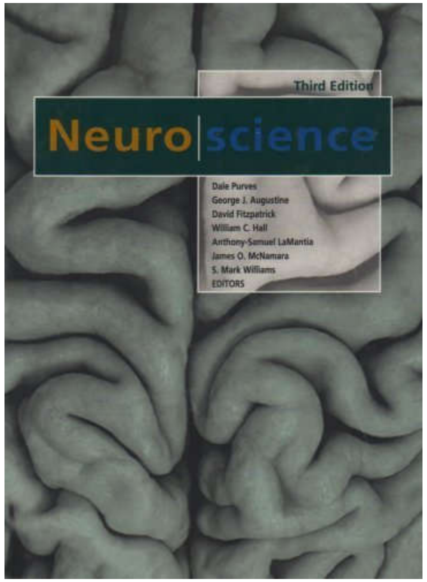
- **Motor cortex** involves in the planning, control, and execution of voluntary movements
- **Cerebellum** coordinates voluntary movements
- **Basal ganglia** strongly interconnects with several brain regions for movement production

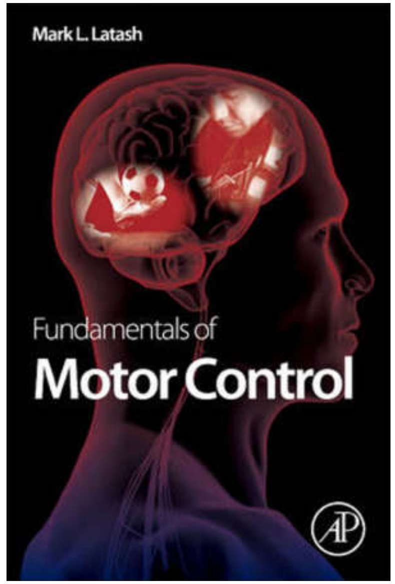
Conclusions

- Human movements have regular kinematic patterns.
- Muscle forces are driven by descending activations and modulated by spinal reflex loops.
- Several brain regions are directly involved in movement and interconnected. Deficts in those regions cause movement disorders.









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