HUMAN MOTOR CONTROL

Emmanuel Guigon

Institut des Systèmes Intelligents et de Robotique
Sorbonne Université
CNRS / UMR 7222
Paris, France

emmanuel.guigon@sorbonne-universite.fr
e.guigon.free.fr/teaching.html

OUTLINE

1. The organization of action
Main vocabulary

2. Computational motor control
Main concepts

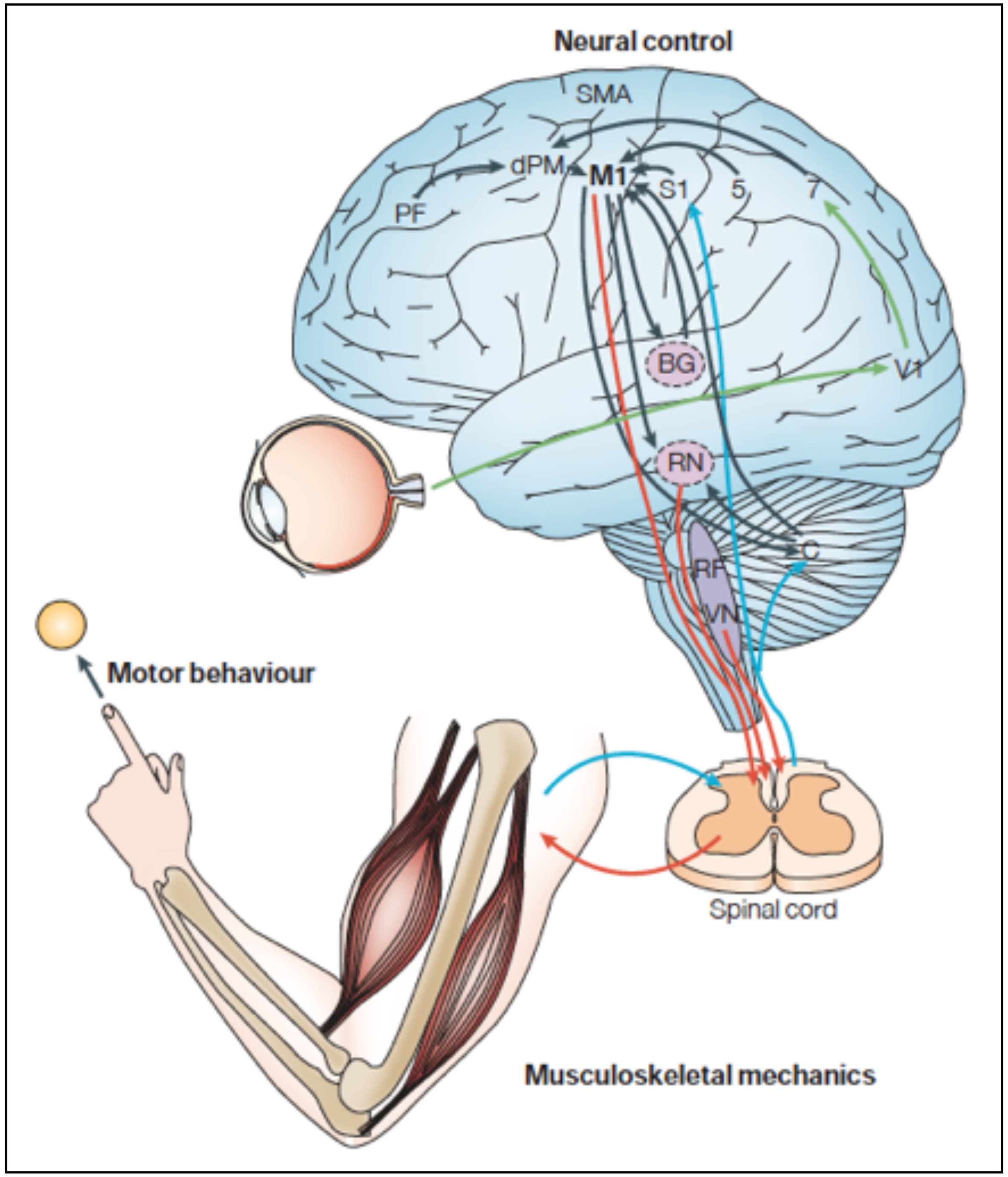
3. Biological motor control
Basic introduction

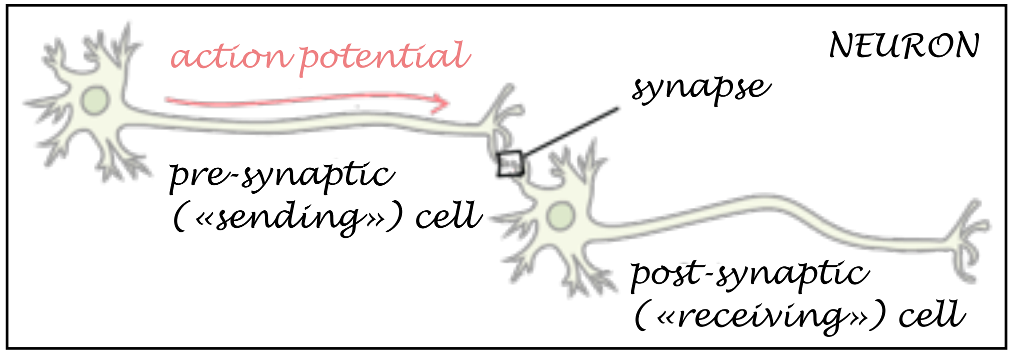
4. Models and theories
Main ideas and debates

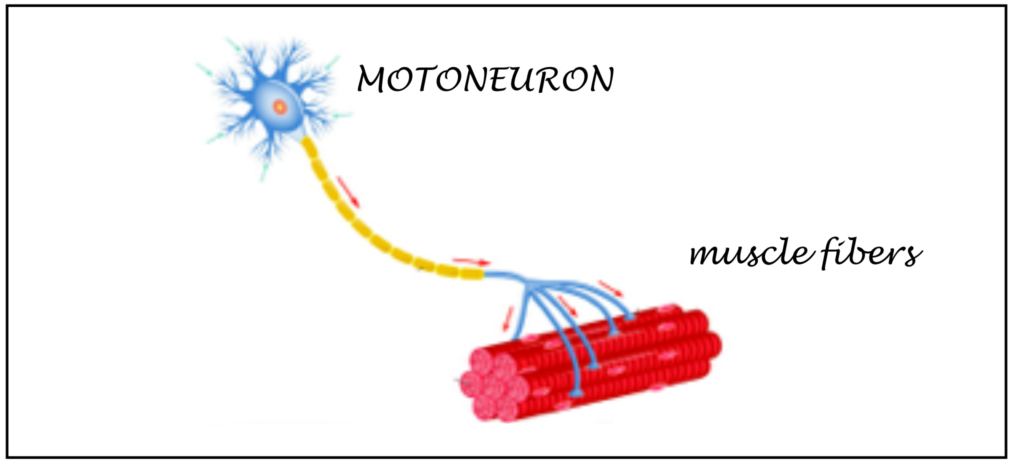
3

3. Biological motor control

OVERVIEW







— Scott, 2004, *Nat Rev Neurosci* 5:534

THE MUSCLE

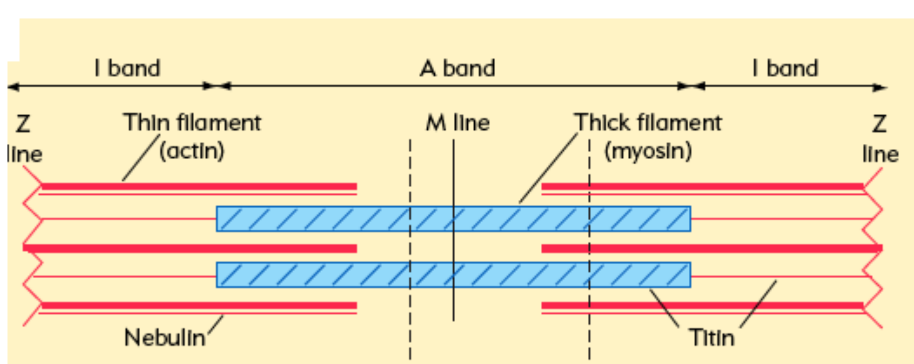
https://www.youtube.com/watch?v=jUBBW2Yb5KI

THE MUSCLE

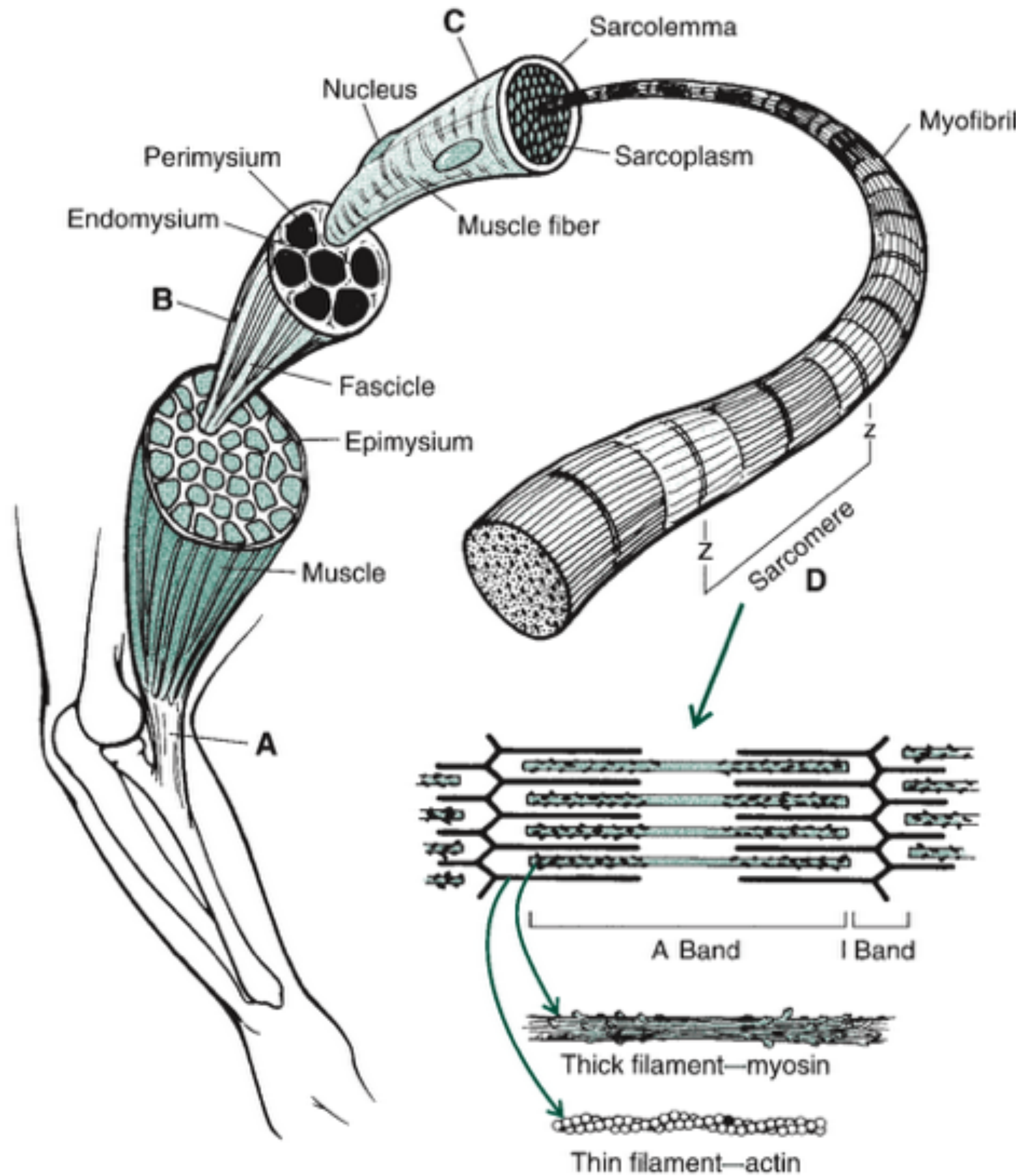
Description

muscle = set of fibers
fiber = set of myofibrils
myofibril = set of sarcomeres

sarcomere = <u>smallest contractile part</u> = thin filaments (*actin*) + thick filaments (*myosin*)



— Hamill & Knutzen, 2009, *Biomechanical Basis of Human Movement*, LWW

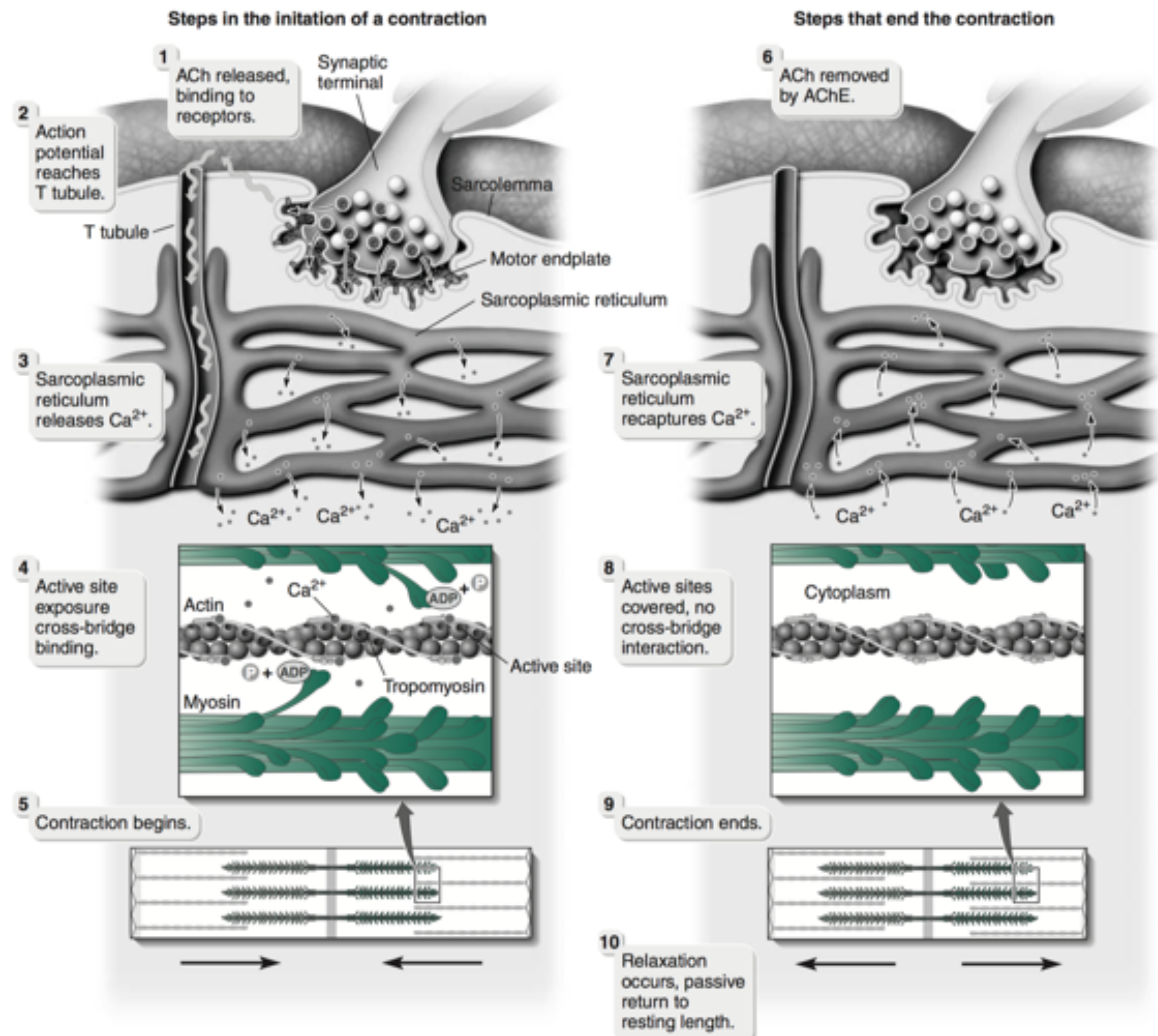


MUSCULAR CONTRACTION

Principle

depolarization of a muscle fiber ➡ increase in intracellular calcium ➡ mechanical contraction

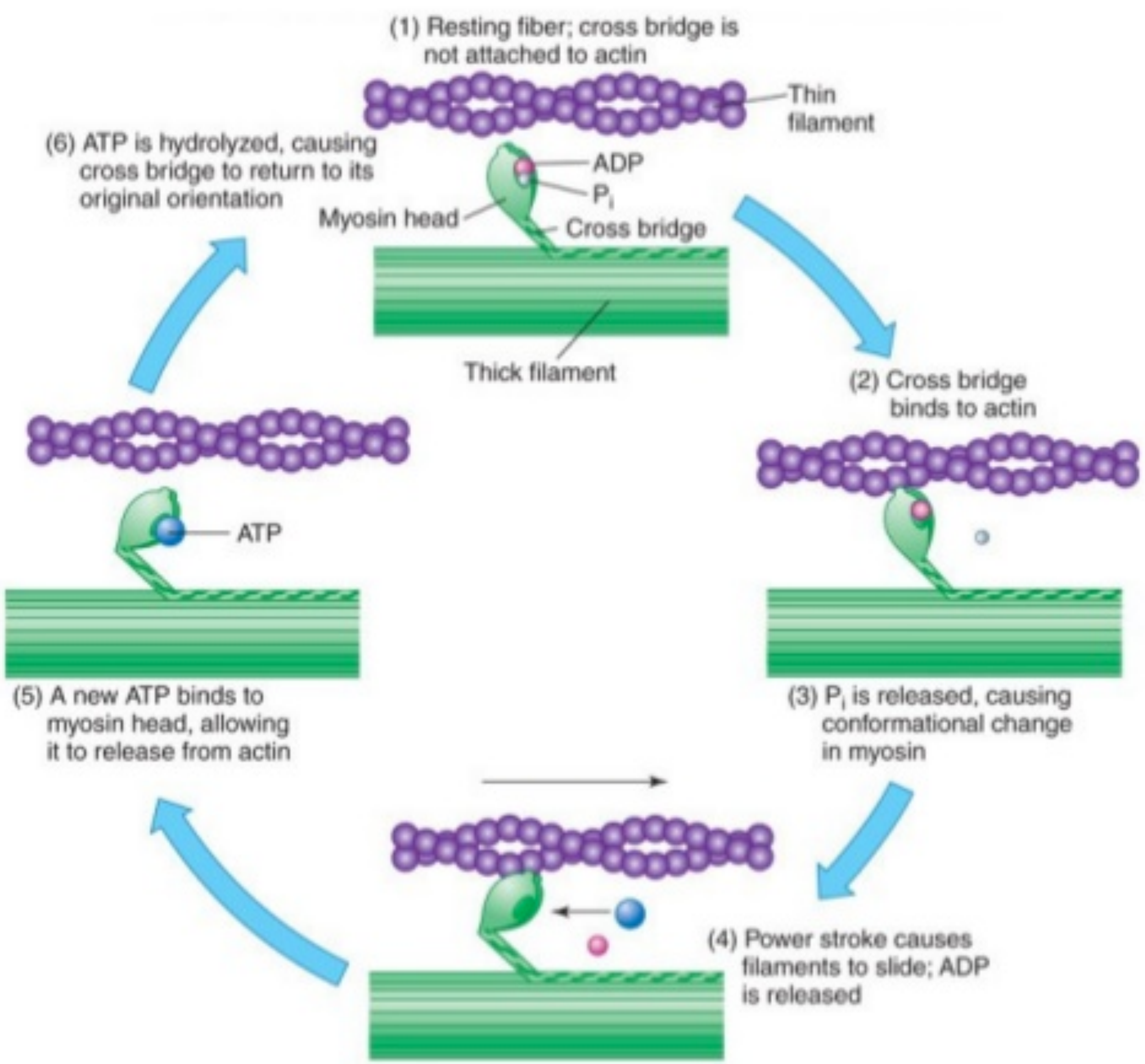
(excitation-contraction coupling)



— Hamill & Knutzen, 2009, *Biomechanical Basis of Human Movement*, LWW

MUSCULAR CONTRACTION

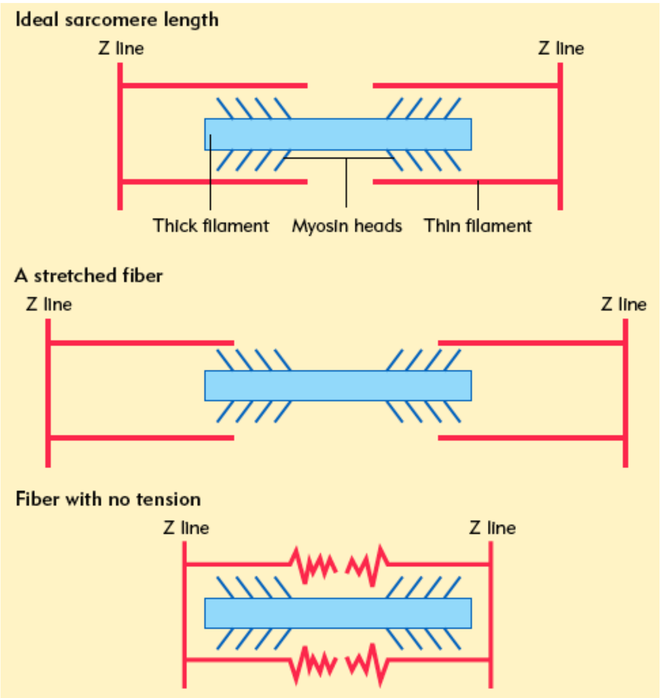
Sliding-filament theory
cyclical interactions between filaments:
— myosin heads bind on actin molecules to form a cross-bridge
— myosin heads undergo a transformation that result in a force exerted on the thin filaments

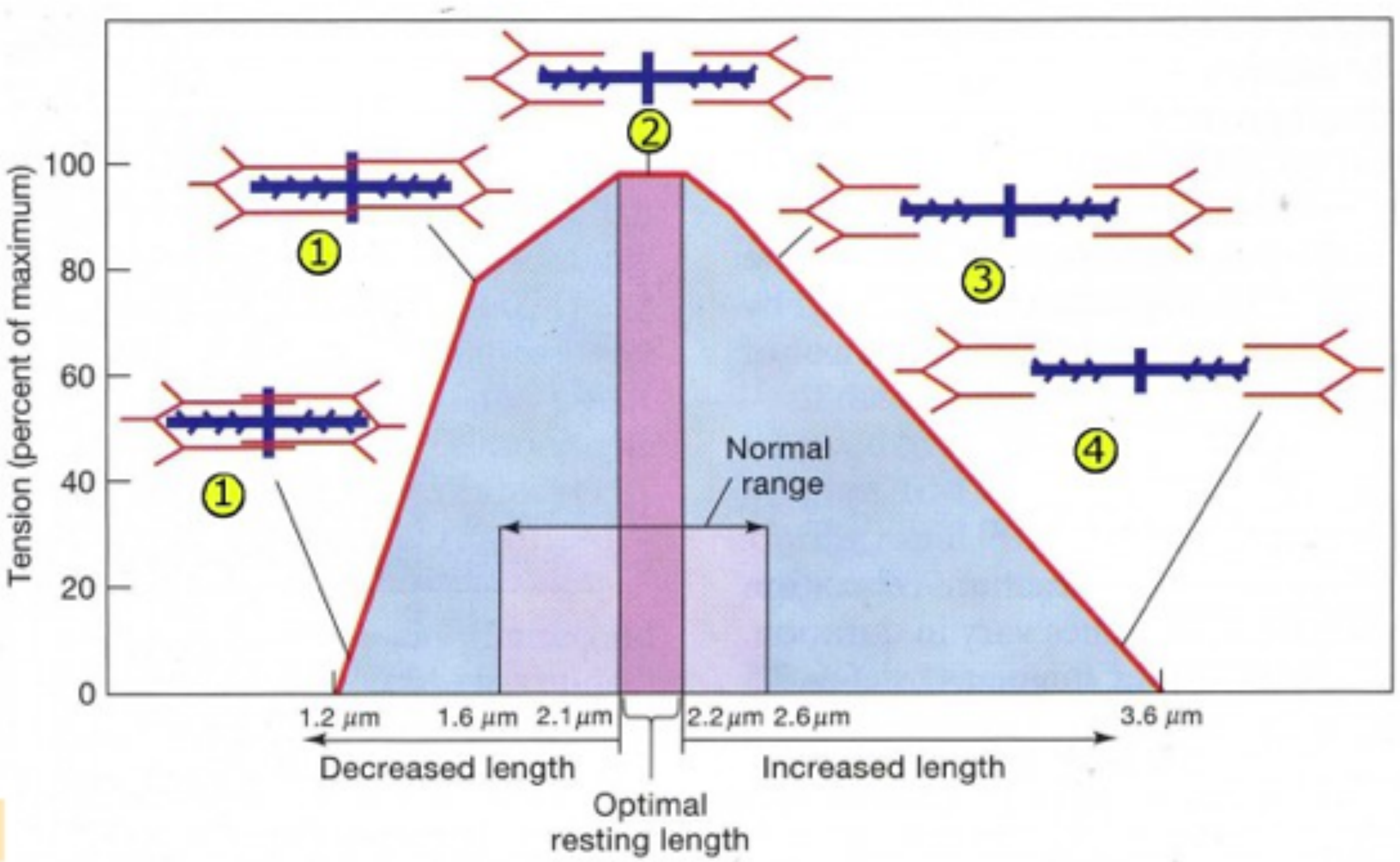


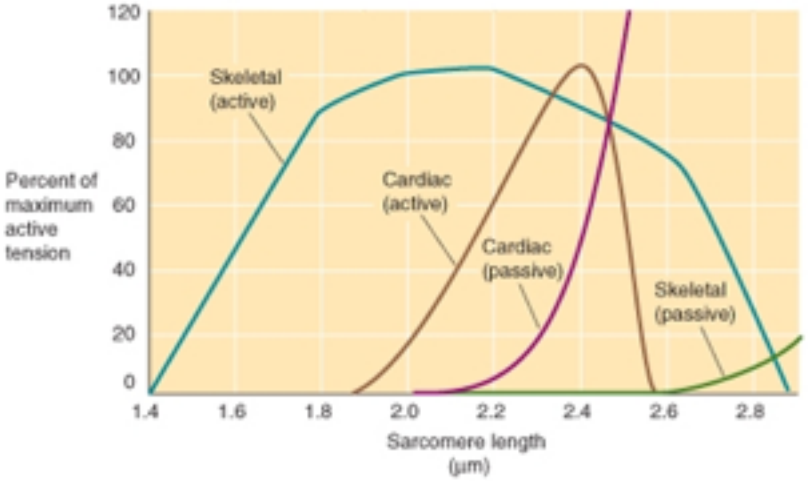
— Huxley, 1969, *Science* 164:1356

SARCOMERE FORCE

Overlap between thin and thick filaments





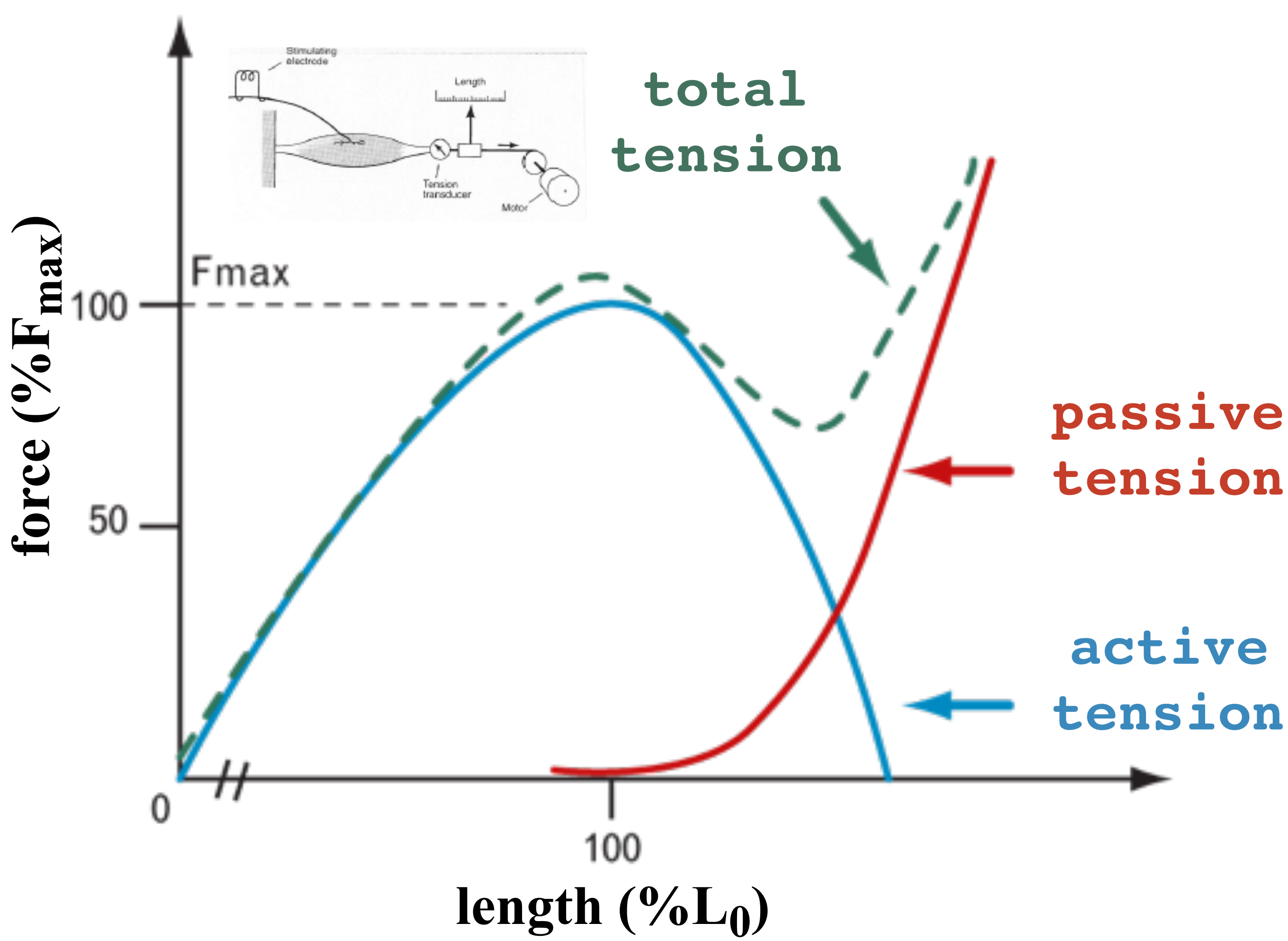


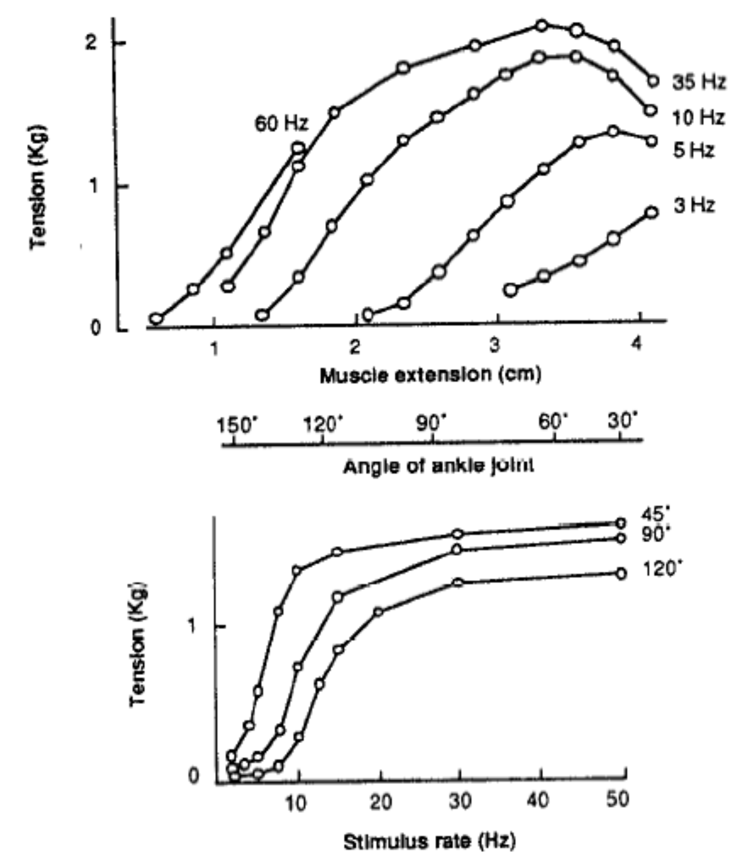
— Gordon et al., 1966, *J Physiol (Lond)* 184:170

MUSCULAR FORCE

Spring-like behavior

a muscle generates force when it is stretched beyond a threshold length — the force increases with length — the threshold changes with the stimulation level



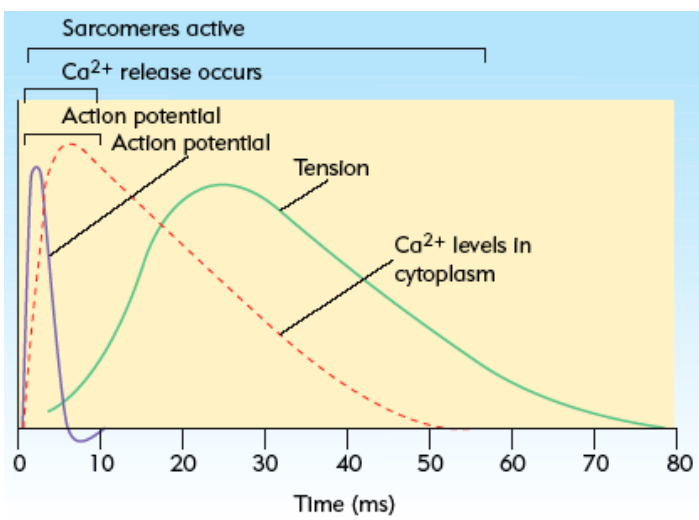


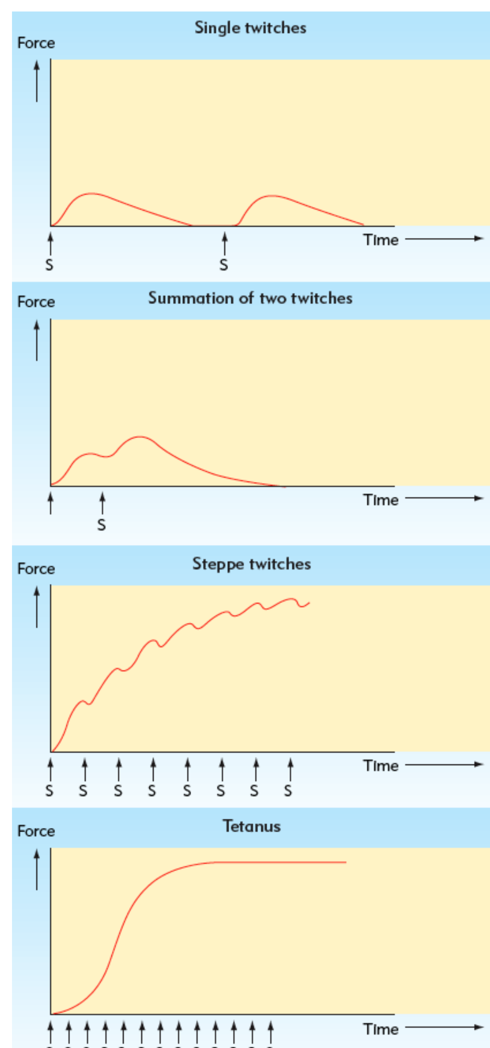
— Rack & Westbury, 1969, *J Physiol (Lond)* 204:443

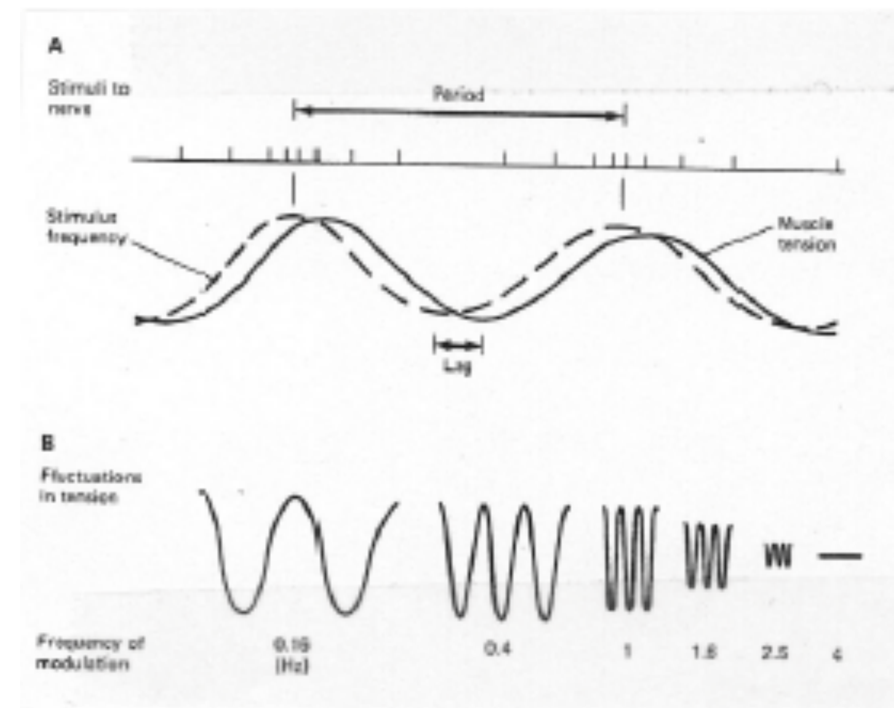
MUSCULAR FORCE

Properties

Muscular force depends on the frequency of action potentials in the motor nerve.







— Partridge, 1966, *Am J Physiol* 210:1178

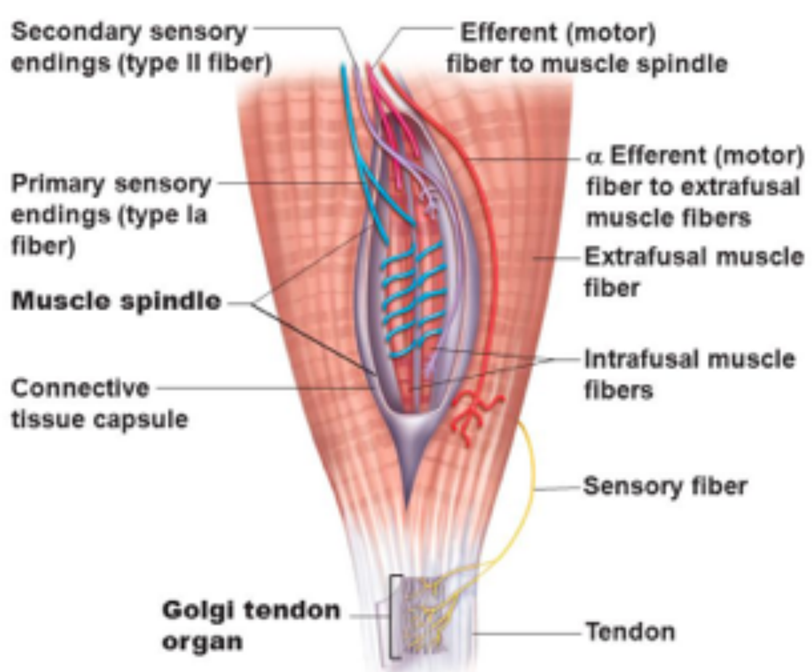
The muscle behaves as a low-pass filter. At low frequency, muscular tension varies with input frequency. When frequency increases, fluctuations disappear.

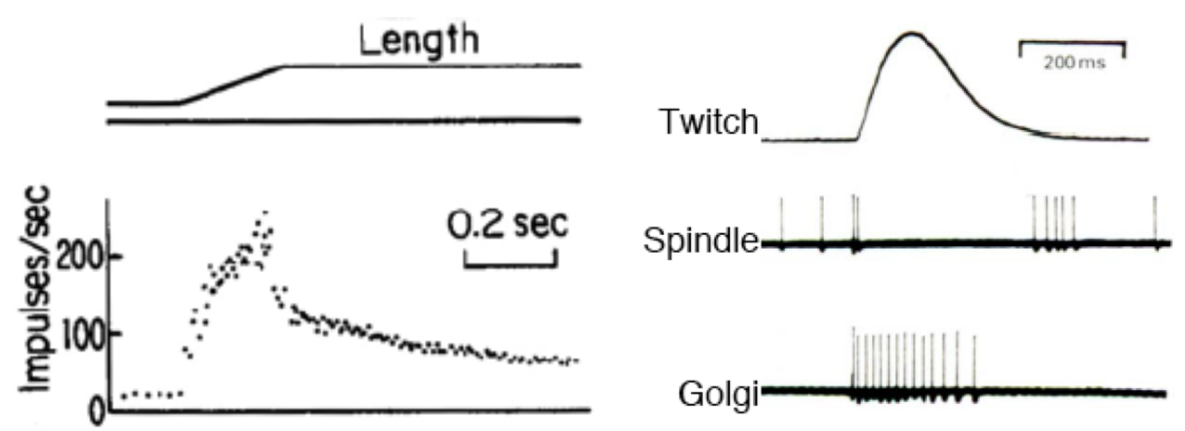
SENSORY RECEPTORS

Definition

— **spindles** are structures arranged in parallel with the muscle. They transmit information on the length and changes of length of the muscle

— **Golgi tendon organs** are structured in series with the muscle, at the junction bewteen the muscle and the tendon. They transmit information on muscular tension



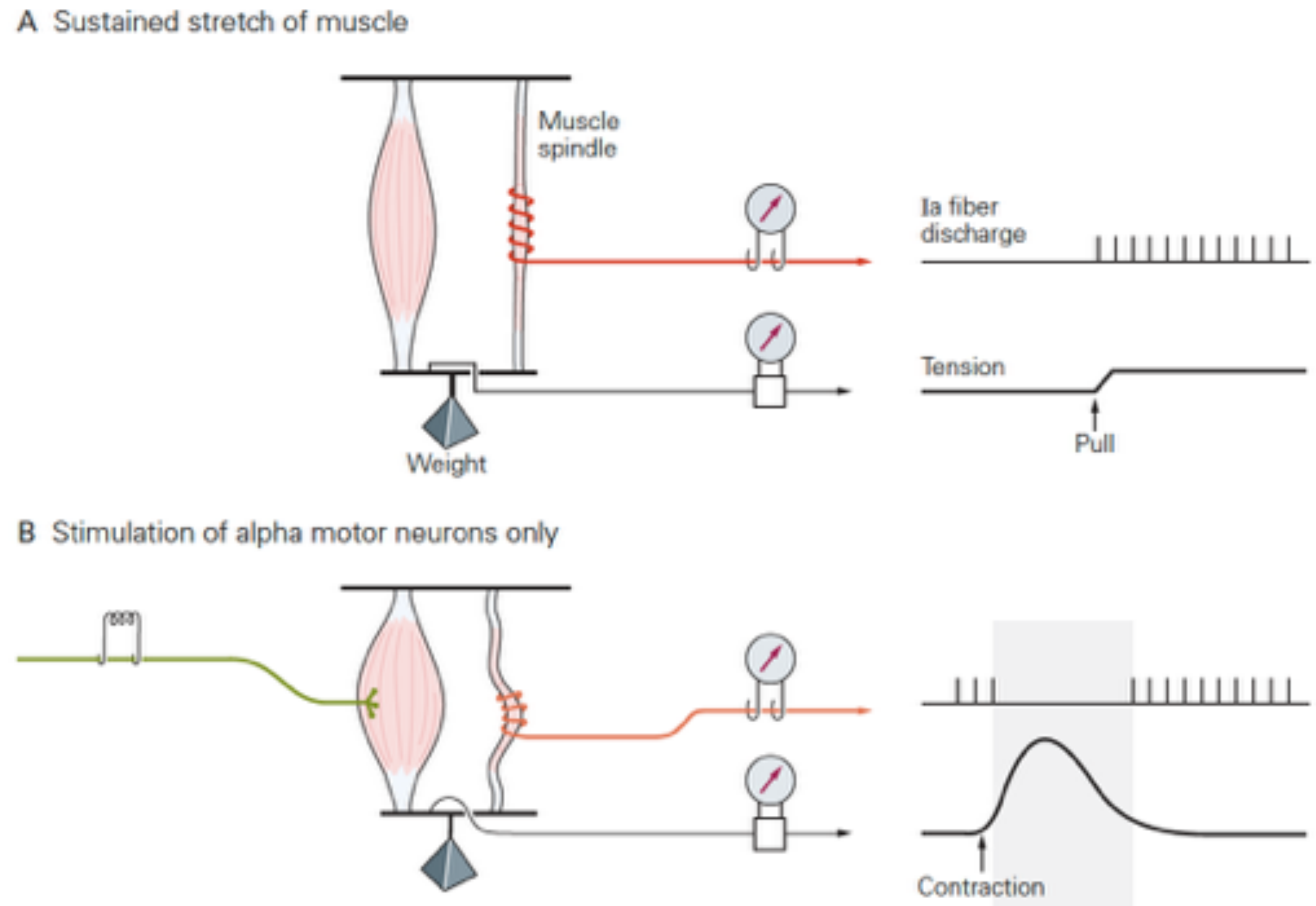


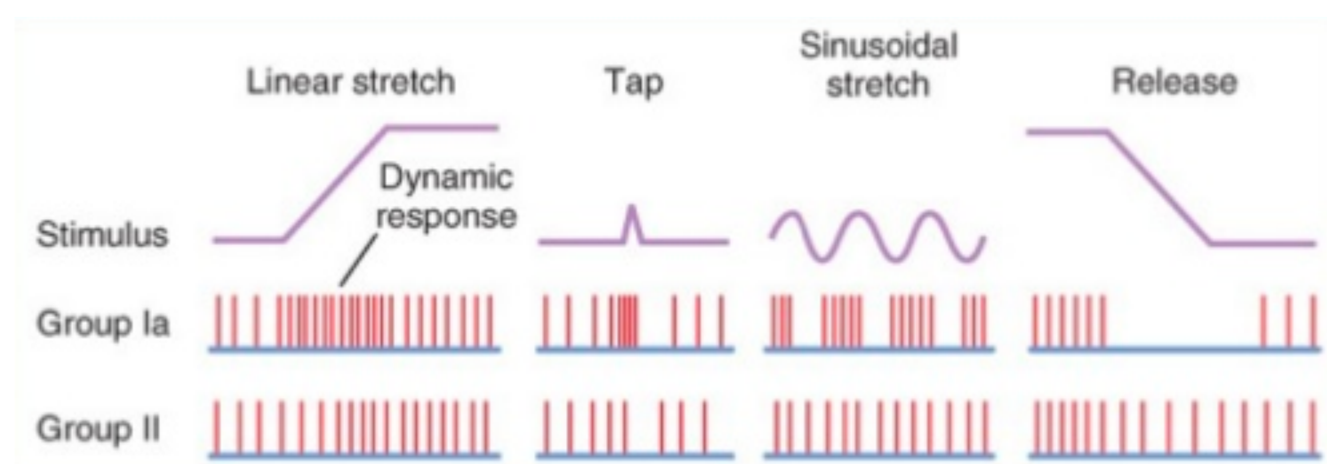
MUSCLE SPINDLES

Role

— they transmit information on the length and changes in the length of the muscle

— primary spindles (**Ia**): sensitive to length and velocity; secondary spindles (**II**): sensitive only to length

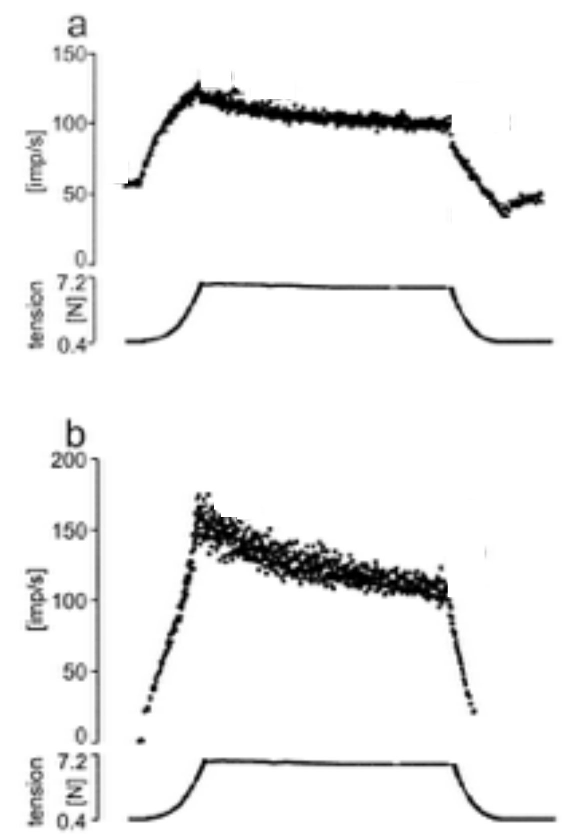


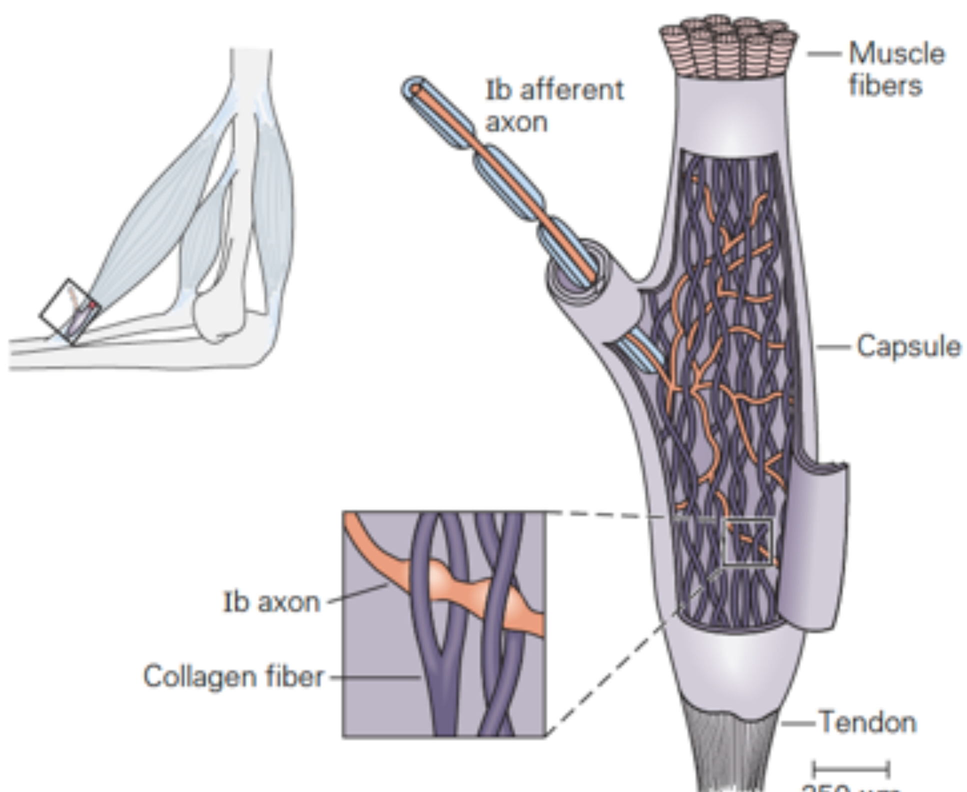


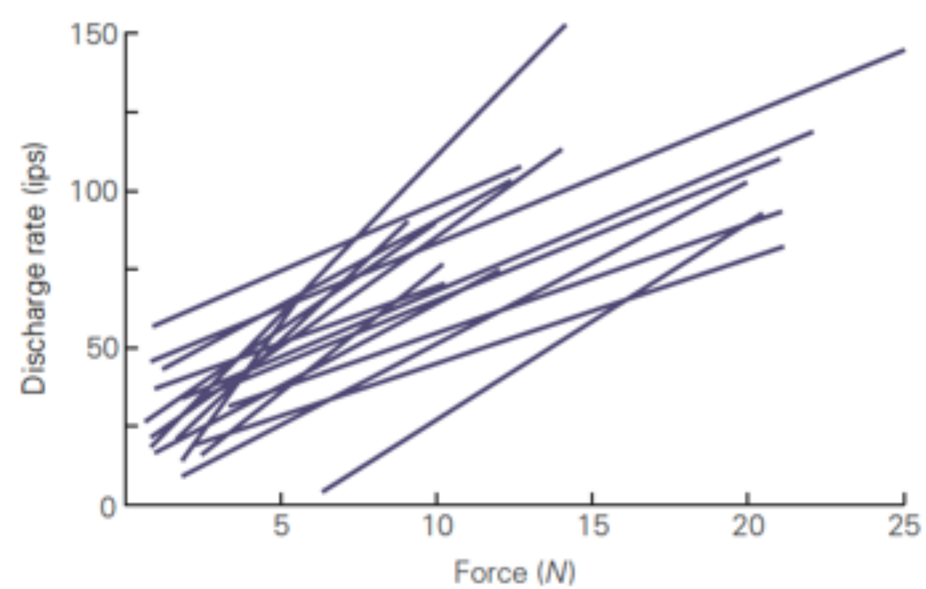
GOLGI TENDON ORGANS

Role

their discharge closely reflects the tension developed by the muscle





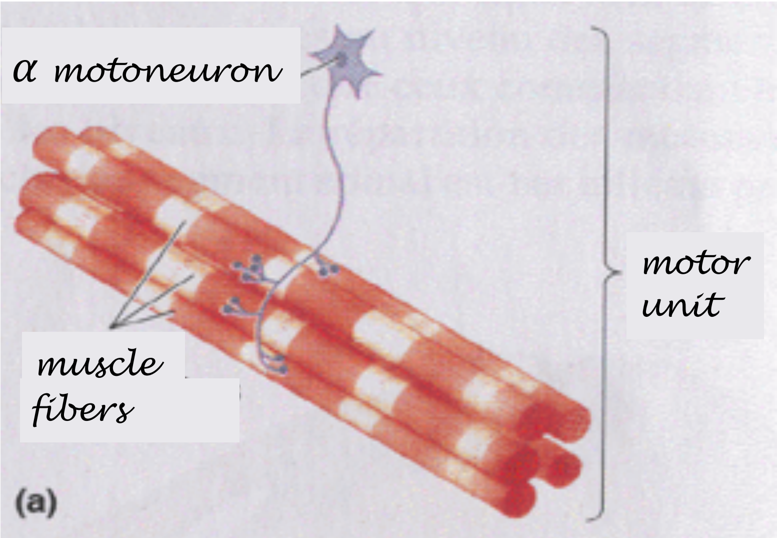


MOTOR UNIT

Most basic level of control

— A **motoneuron** (MN) is neuron whose cell body is located in the **spinal cord** and whose axon projects to a **muscle fiber**
— Each muscle fiber is innervated by a single **motoneuron**
— A **motoneuron** innervates a set of muscle fibers
— A **motor unit** is a **motoneuron** and its set of **muscle fibers**

The number of muscle fibers innervated by a MN is called the innervation ratio. This ratio is roughly proportional to the size of the muscle (10 for extraocular muscles, 100 for hand muscles). A small ratio correspond to a finer control of muscular force.

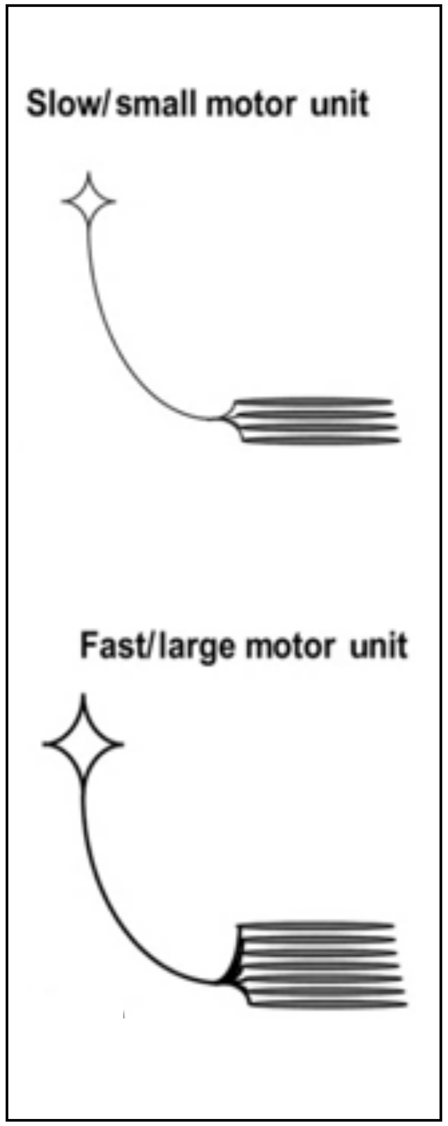


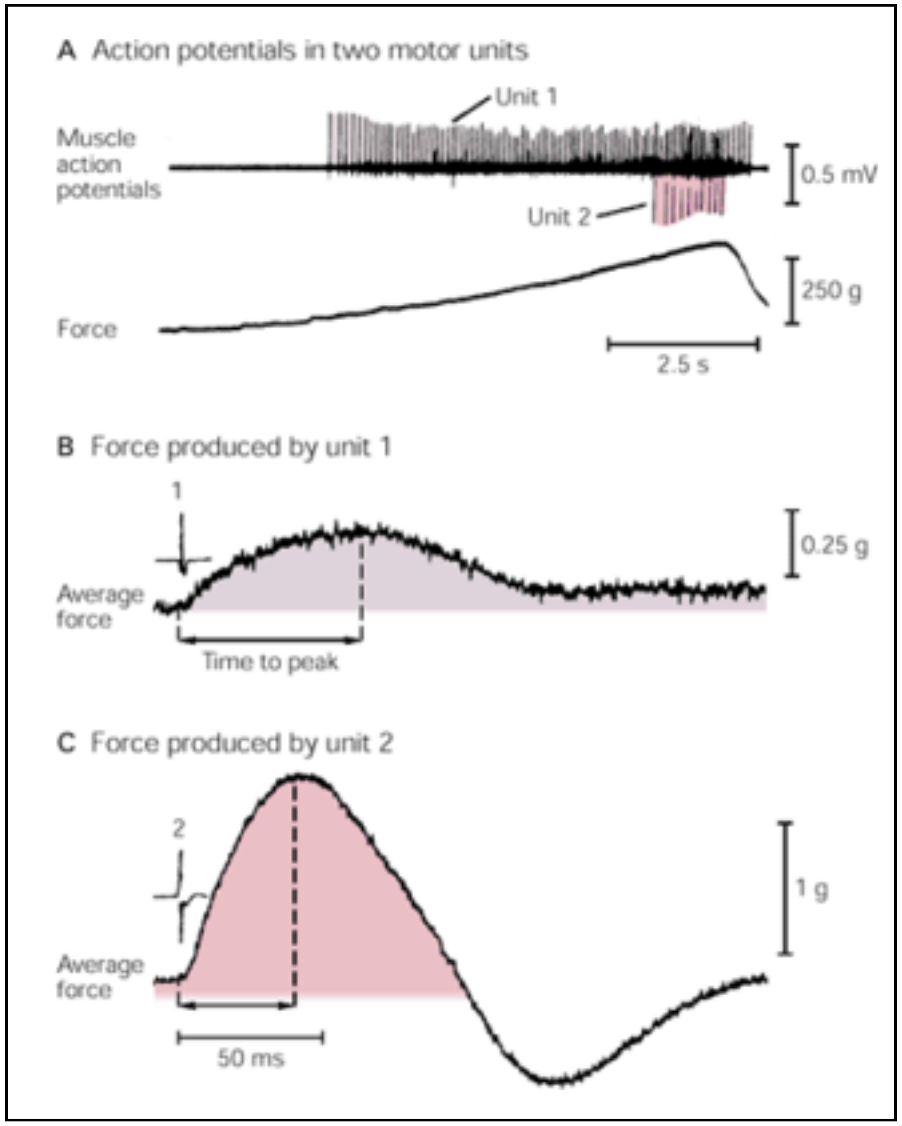
! γ motoneurons innervate muscle spindles

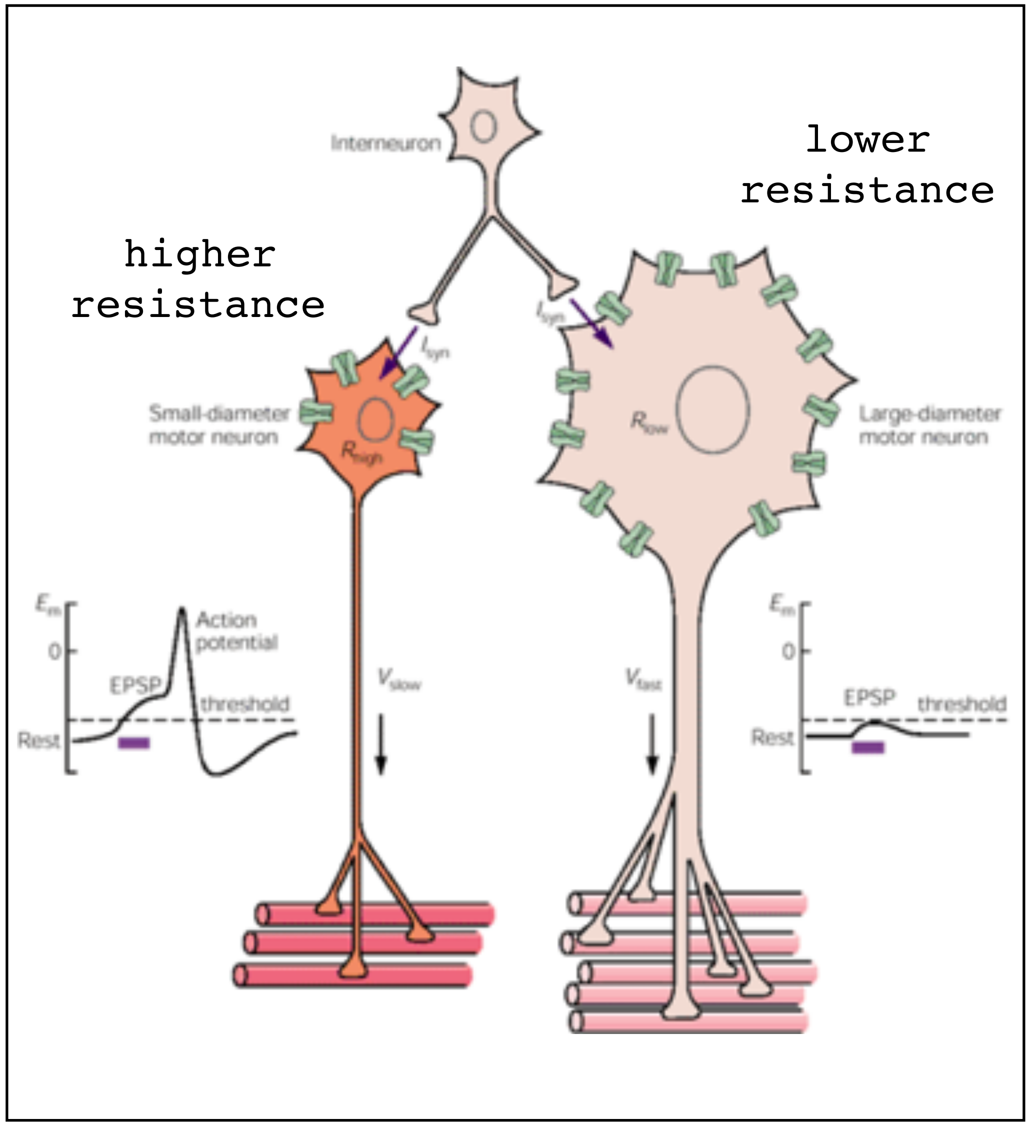
PROPERTIES OF MOTOR UNITS

Size

size of the MN, diameter of its axon, number of muscle fibers it innervates: small (slow) / large (fast) MUs





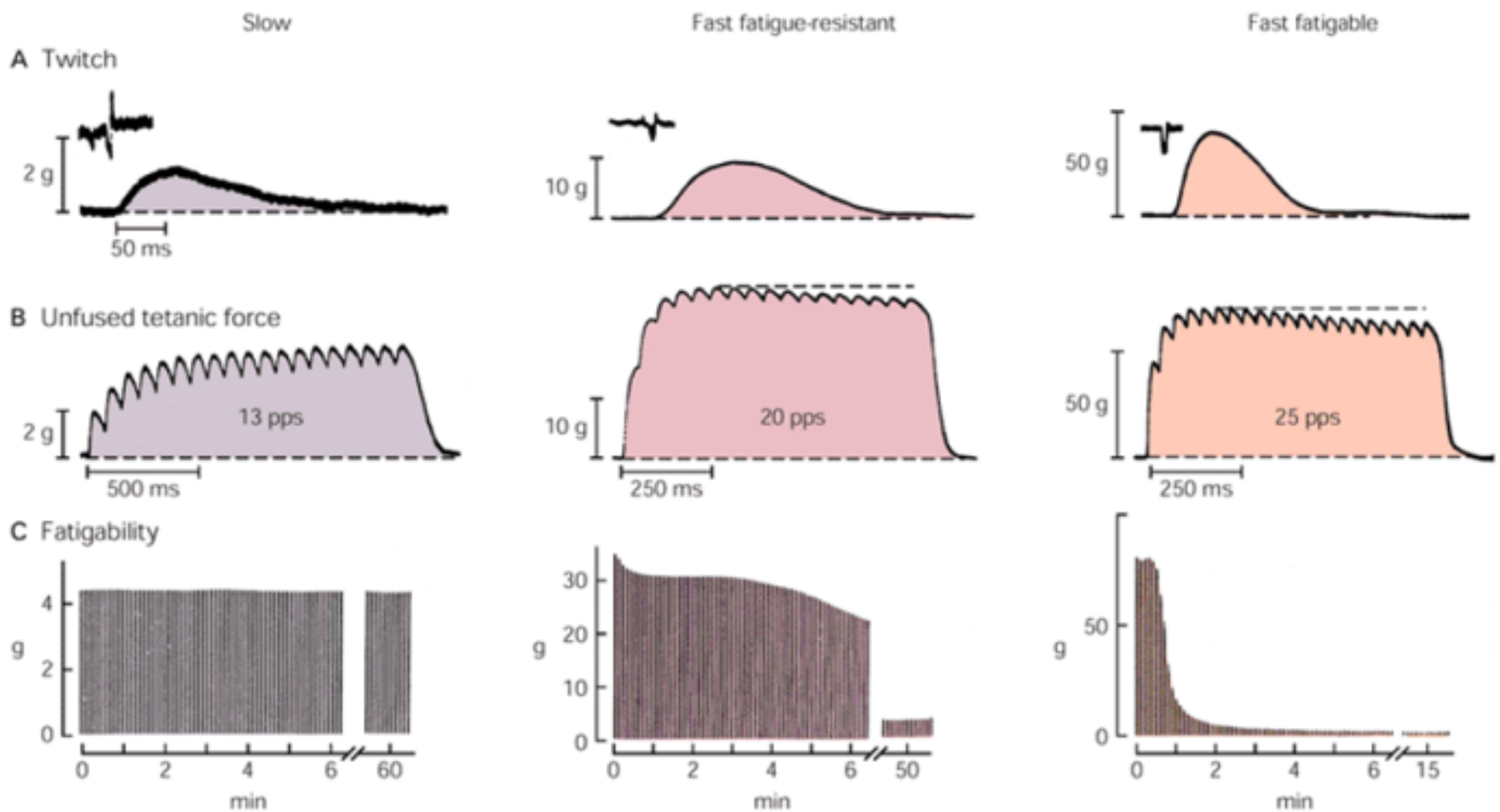


— Desmedt & Godaux, 1977, *Nature* 267:717

PROPERTIES OF MOTOR UNIT

Resistance to fatigue

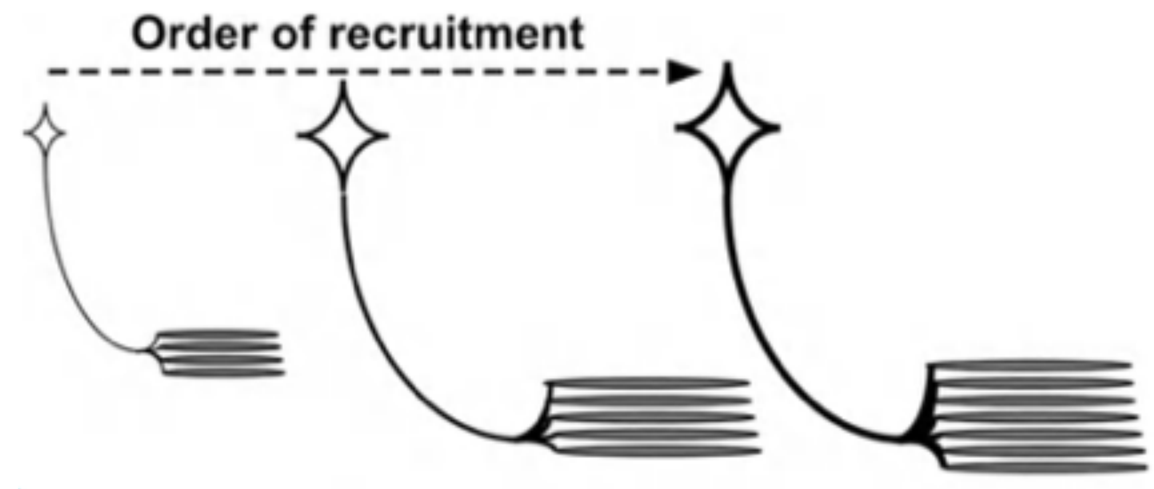
slow (great resistance), fast (wide range of resistance)



The proportions of slow, fast-resistant and fast-fatigable MUs in different limb and trunk muscles accurately reflect differences in the way muscles are used in different species.

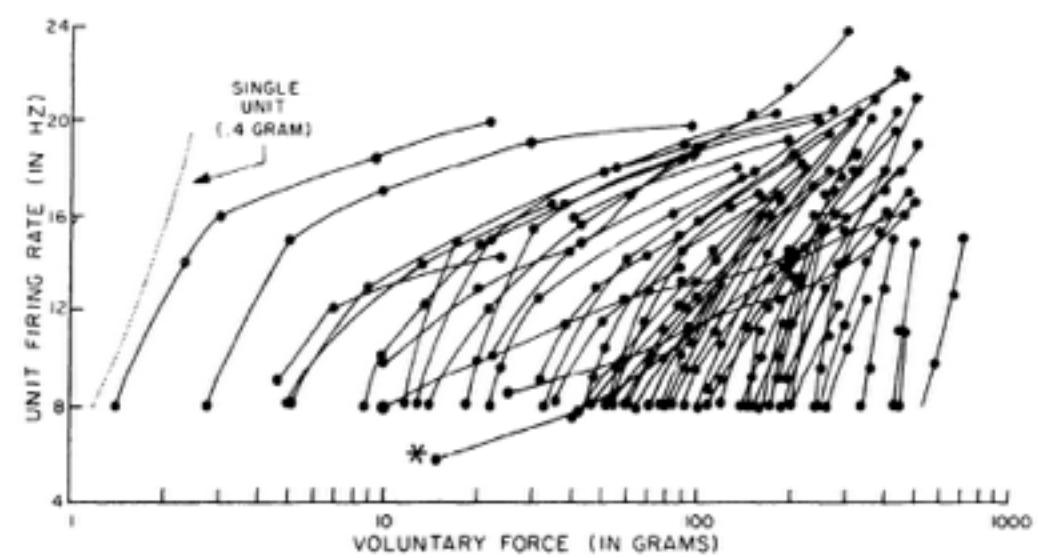
RECRUITMENT OF MOTOR UNITS

- **Size principle**
  during natural contractions MUs are recruited in an orderly fashion, from small to large motor units



— Latash, 2012, *Fundamentals of Motor Control*, Academic Press

- **Frequency modulation**
  increasing the firing frequency of already recruited MUs

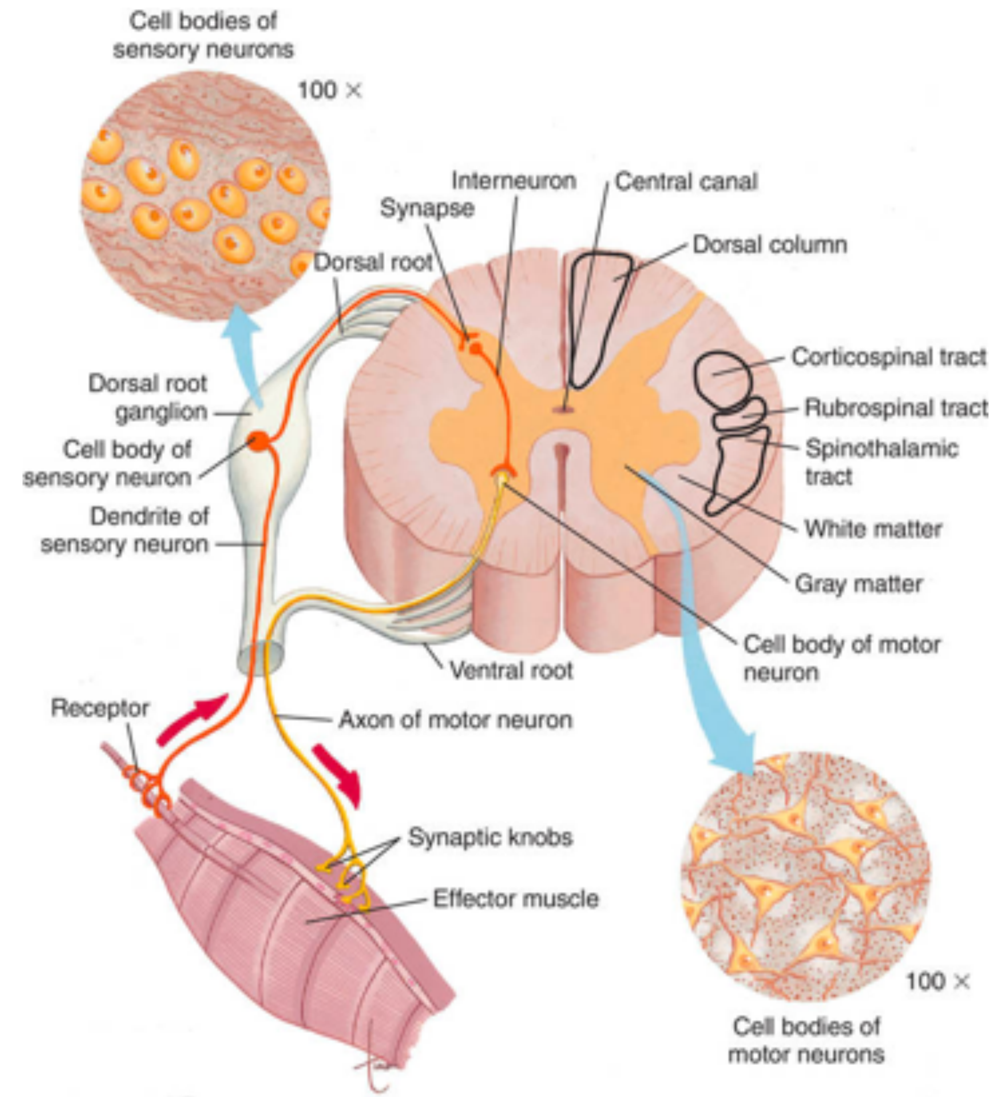


— Monster & Chan, 1977, *J Neurophysiol* 40:1432

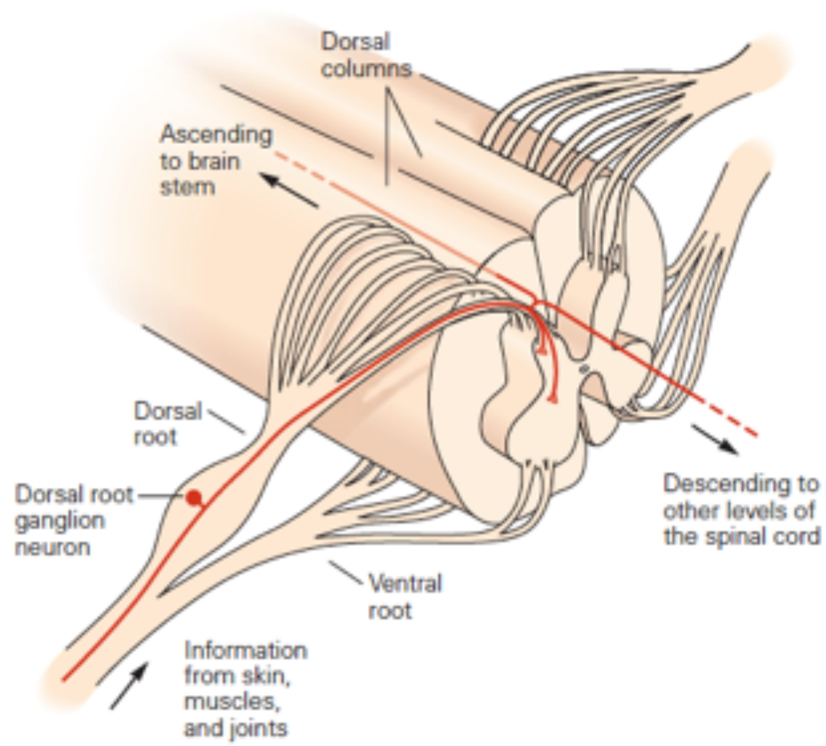
SPINAL CORD

Local organization

— MNs located in the spinal cord — afferent/dorsal roots — efferent/ventral roots — gray matter: cell body of MNs — white matter: axons — MNs grouped into pools over several segments



p



— Kandel et al., 2013, *Principles of Neural Science*, McGraw-Hill

SPINAL CORD

Global organization

Cervical vertebrae

- C1-3 Limited head control
- C4 Breathing and shoulders shrug
- C5 Lift arm with shoulder, elbow flex
- C6 Elbow flex and wrist extension
- C8 Finger flexion

Thoracic vertebrae

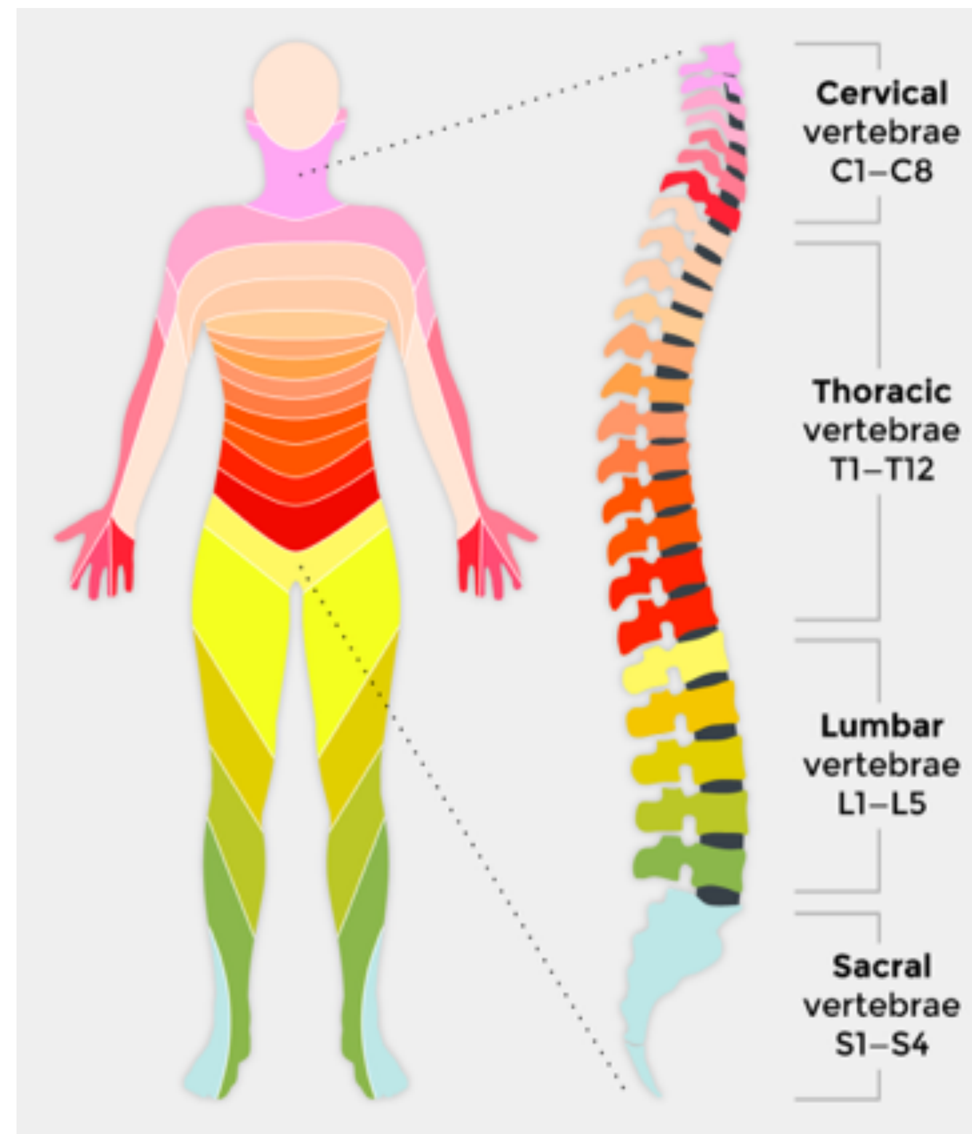
- T1 Finger movement
- T2-T12 Deep breaths, deep breathing
- T6-L1 Deep exhale of breath, stability while sitting

Lumbar vertebrae

- L1-L2 Hip flexion
- L2-L3 Hip movement toward middle of body
- L3-L4 Knee extension
- L4-L5 Ankle extension
- L5 Extension of big toe

Sacral vertebrae

- S1 Movement of foot and ankle
- S1-S2 Toe movement
- S2-S4 Function of bladder and bowel



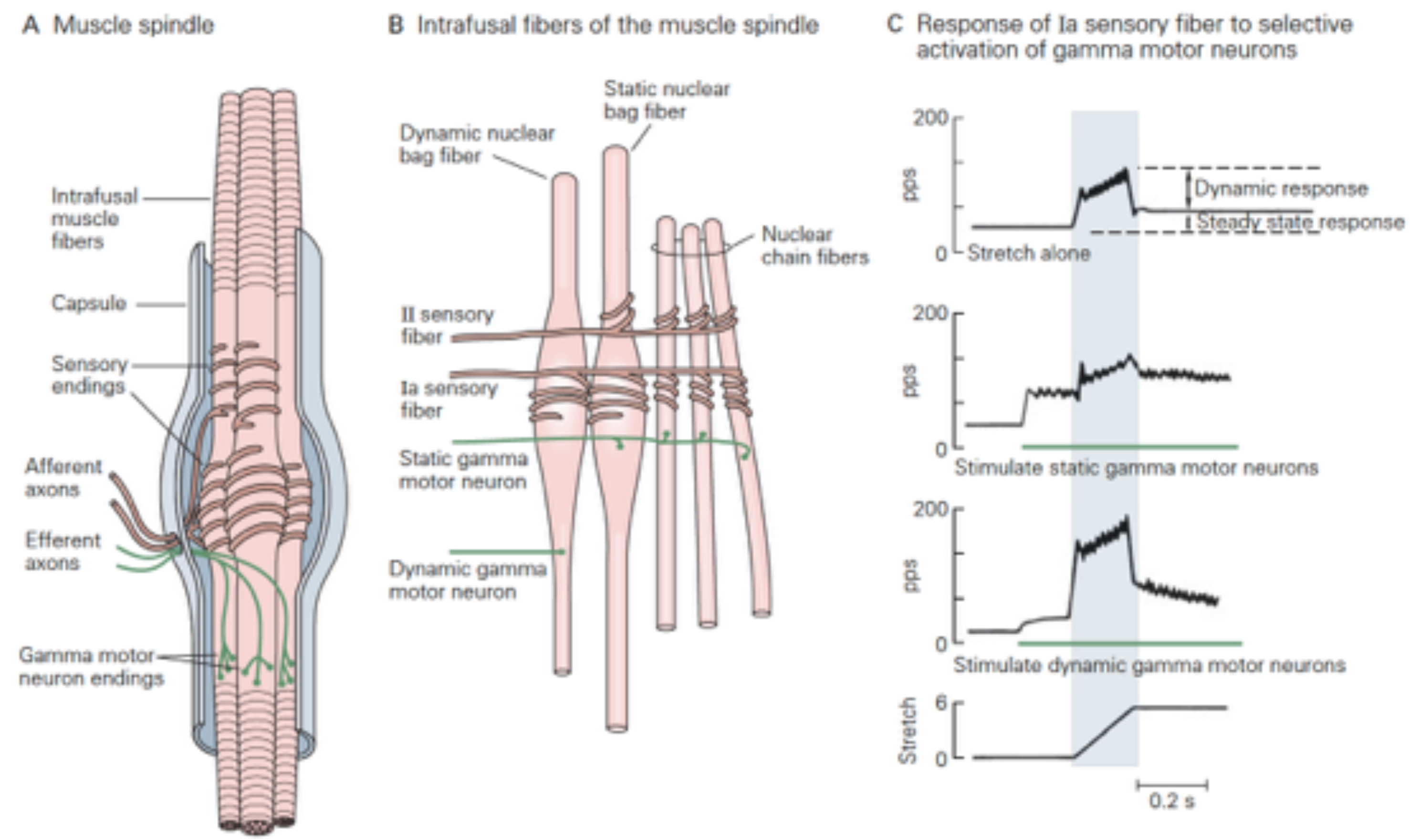
INPUT/OUTPUT OF MUSCLE SPINDLES

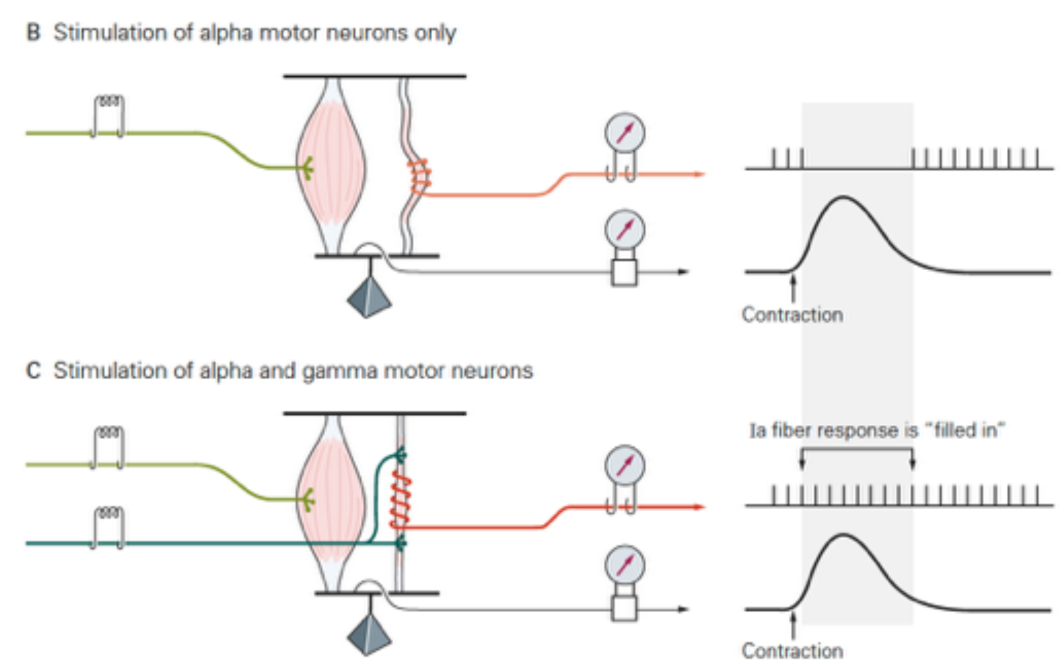
Output (afferent)

the spindles innervate **alpha** MNs through fibers Ia and II

Input (efferent)

the spindles are innervated by **gamma** MNs which modulate their **static** and **dynamic** sensitivity



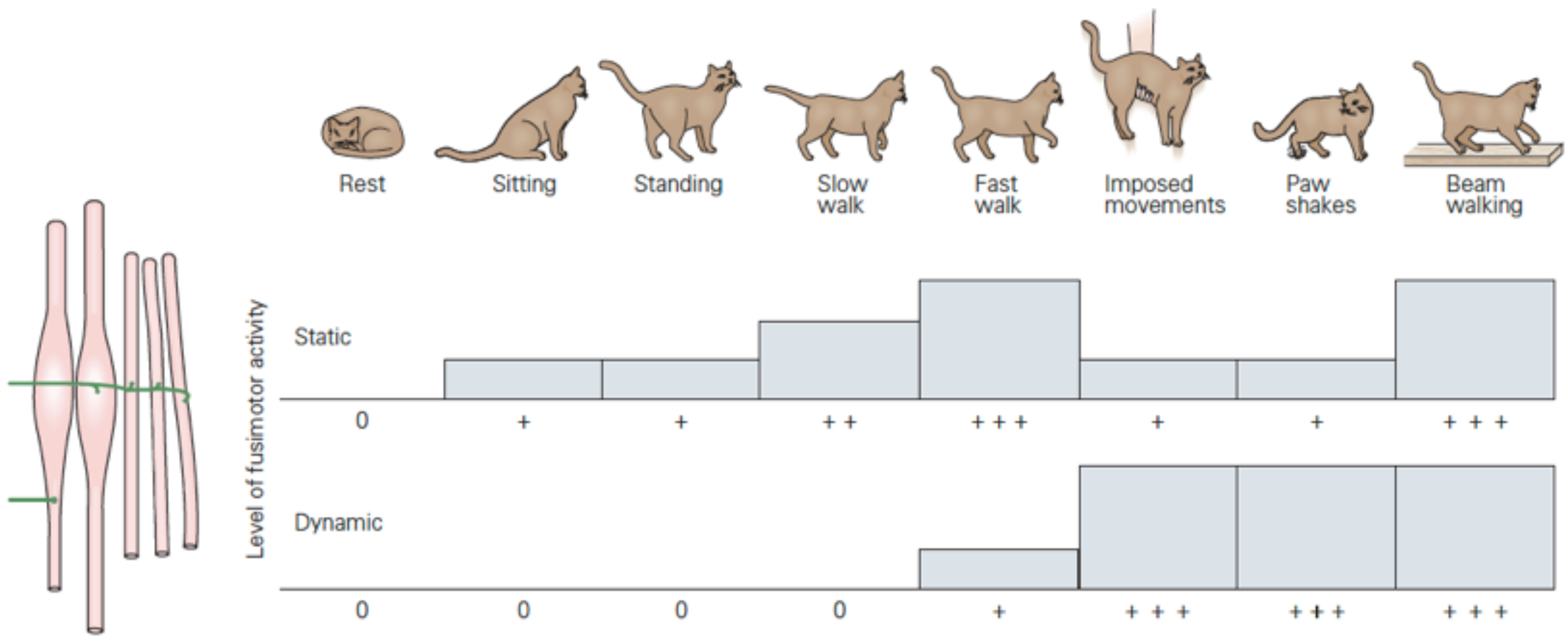



```
gamma control =
fusimotor control
```

FUSIMOTOR CONTROL

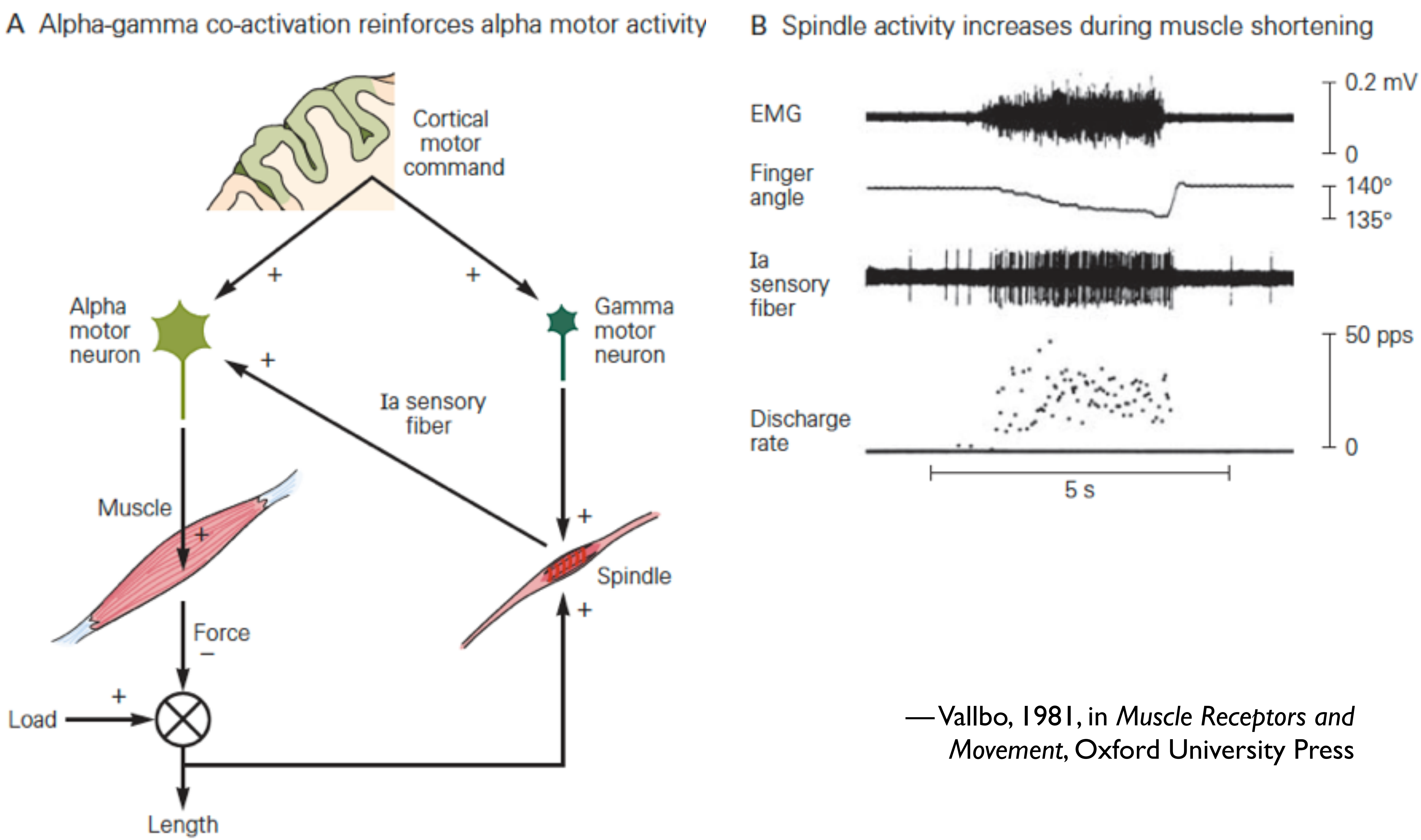
Static *vs* dynamic

during activities in which muscle length changes slowly and predictably *vs* during behaviors in which muscle length may change rapidly and unpredictably



— Prochazka et al., 1988, in *Mechanoreceptors: Development, Structure and Function*, Plenum Press

ALPHA-GAMMA COACTIVATION



—Vallbo, 1981, in *Muscle Receptors and Movement*, Oxford University Press

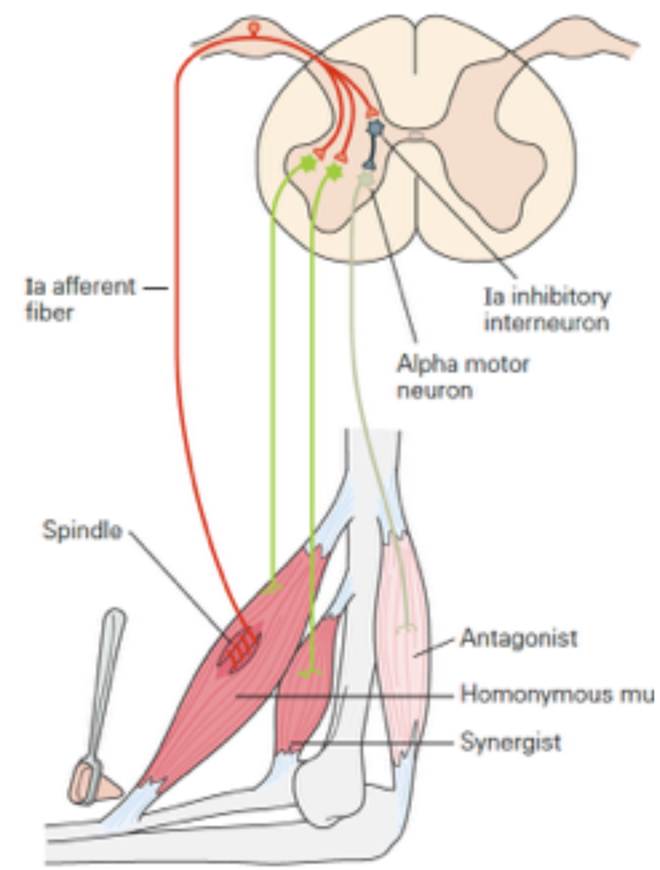
REFLEXES

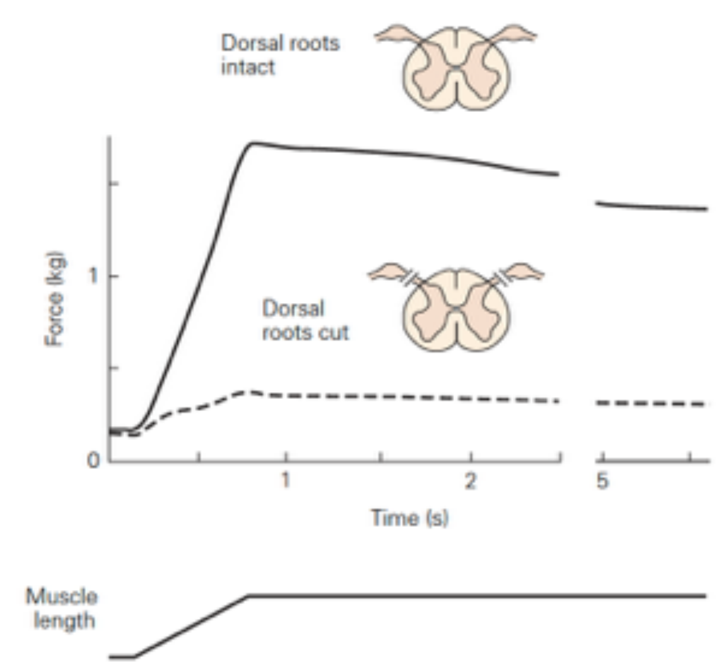
- **Definition**

— stereotyped movements elicited by activation of receptors in skin or muscle (e.g. strech reflex)

- **Modern view**

— difficult to define
— in fact, flexible and adapted to ongoing tasks
— integrated by centrally generated motor commands into complex adaptive movements

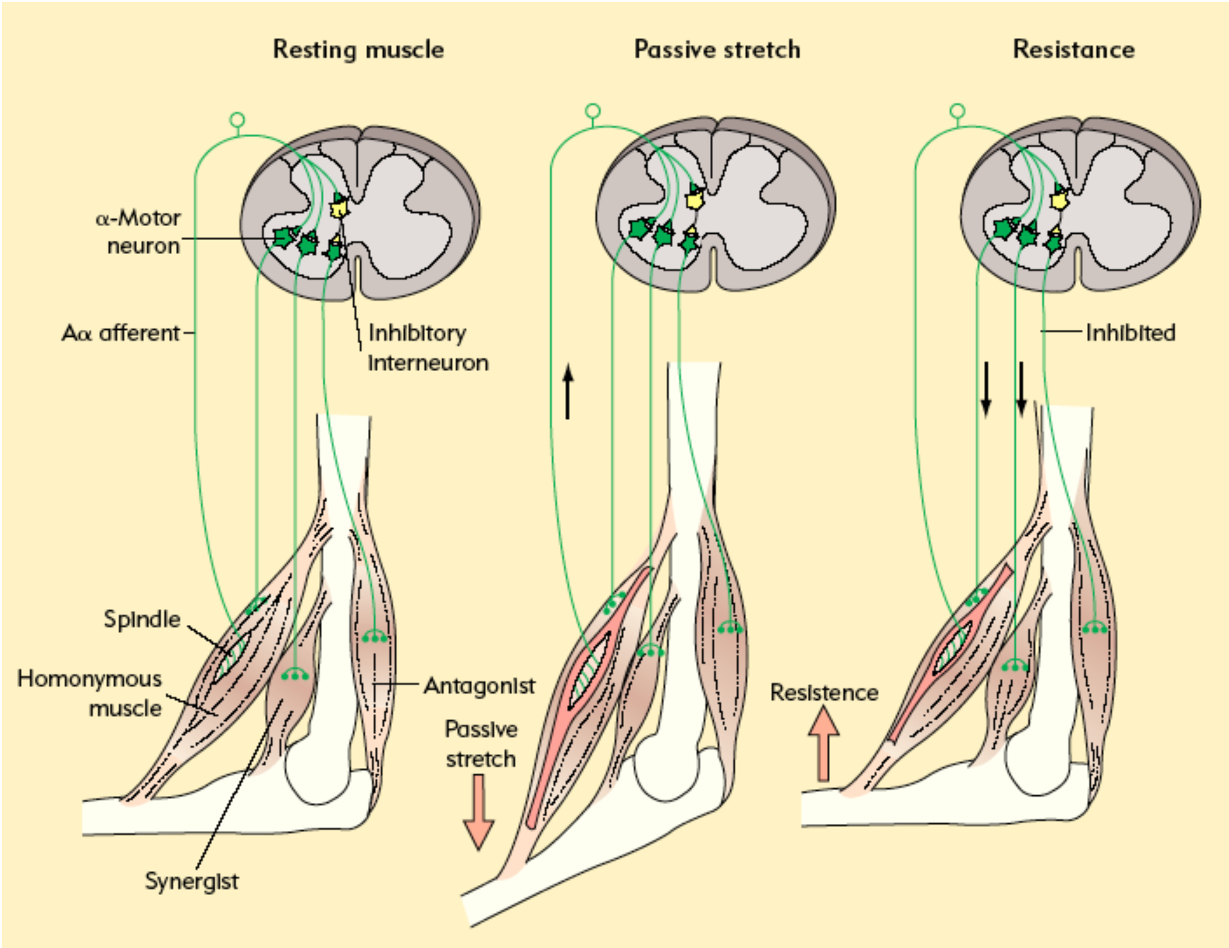


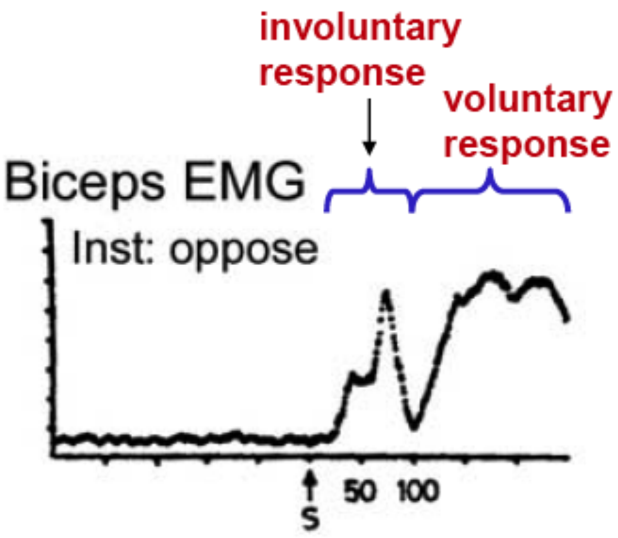


STRETCH REFLEX

Monosynptic organization

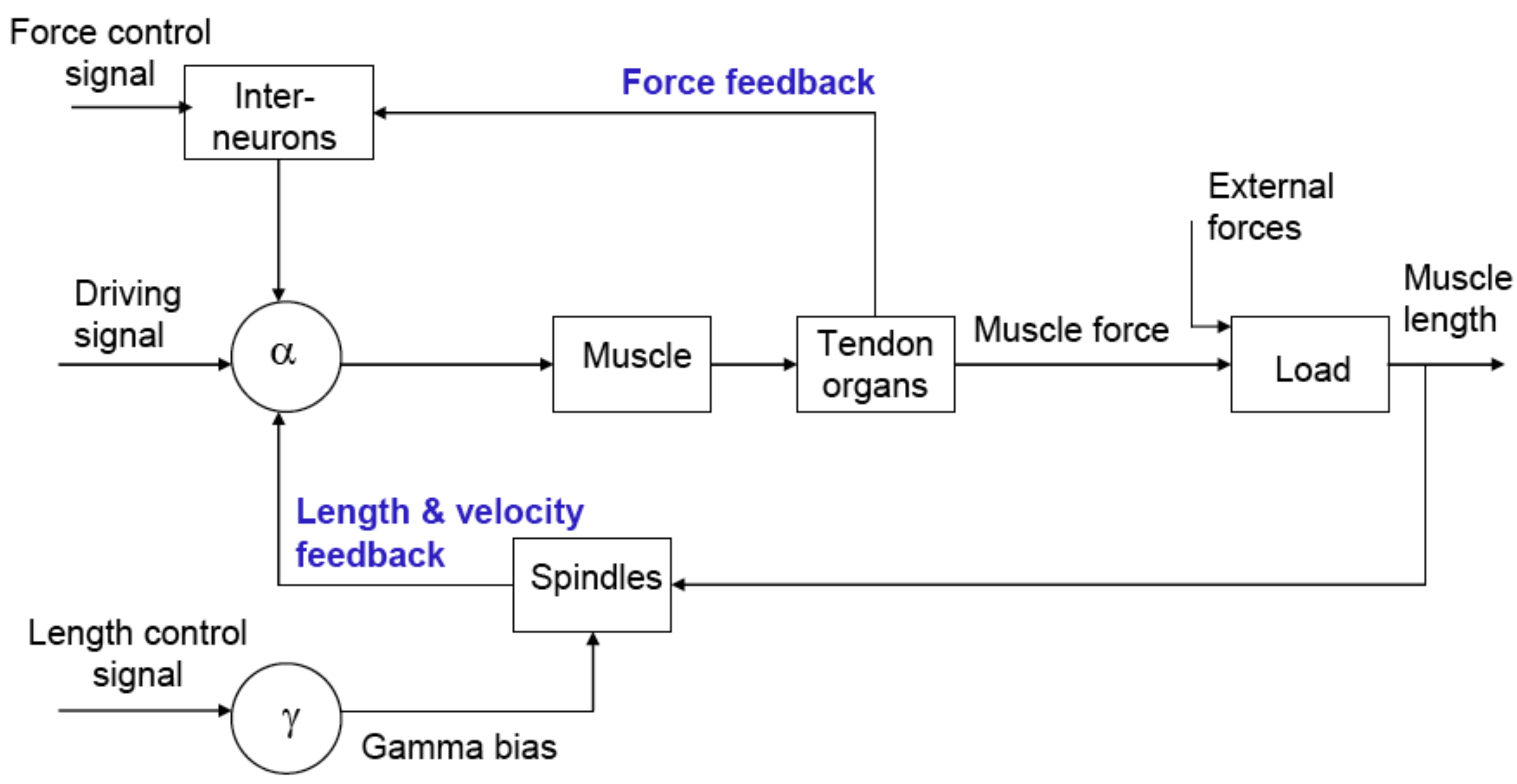
Regulates the output of a MN through a negative feedback process. The feedback gain can be modulated by the nervous system (e.g. γ MNs). Minimum delay ≈ 30 ms





STRETCH REFLEX

Negative feedback system
reduces deviations around a reference value

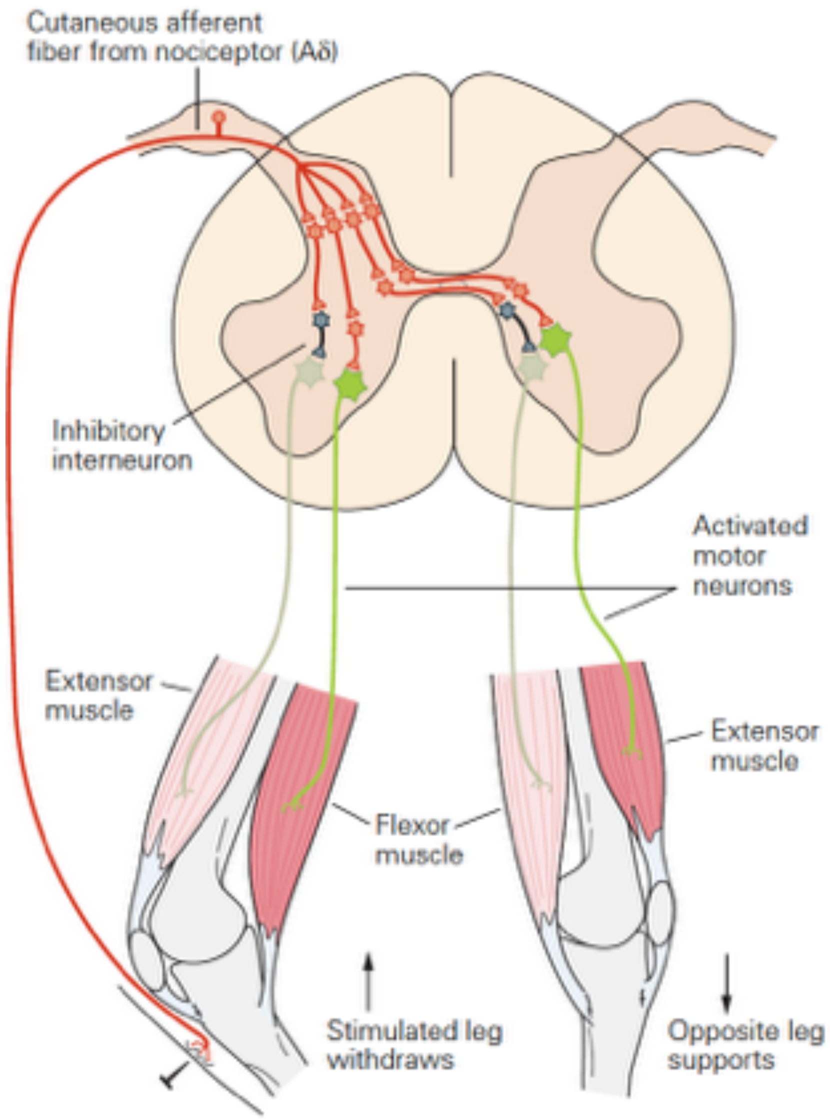


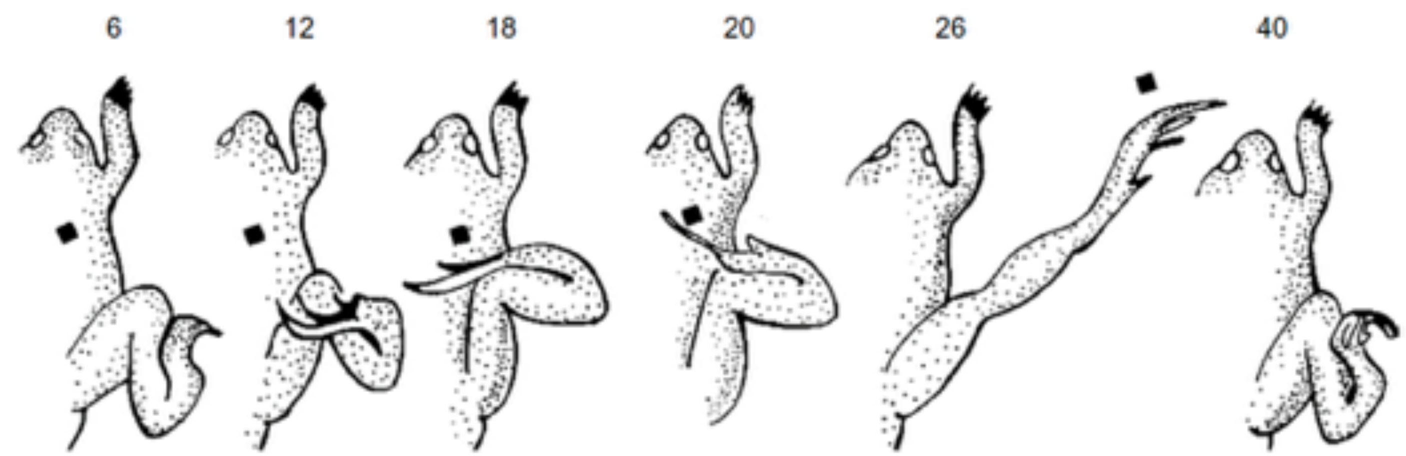
FLEXION-WITHDRAWAL REFLEX

Polysynaptic protective reflex

coordination to avoid painful stimulation

e.g. wiping in the spinal frog evoked by chemical stimulation



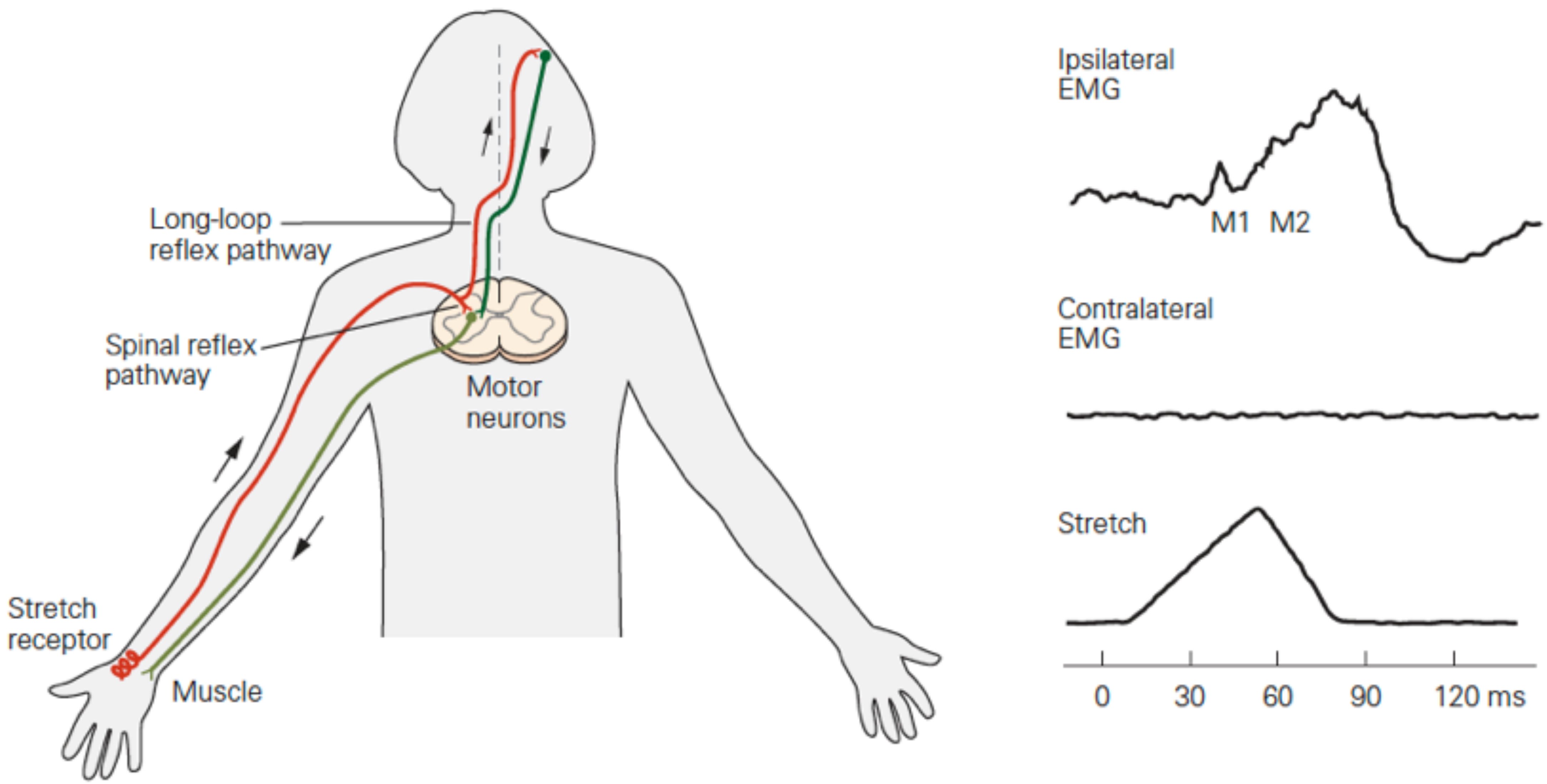


`modulated by body posture`

— Fukson et al., 1980, *Science* 209:1261

```
enhance postural support
during withdrawal of a foot
from a painful stimulus
```

SPINAL VS LONG-LOOP REFLEX



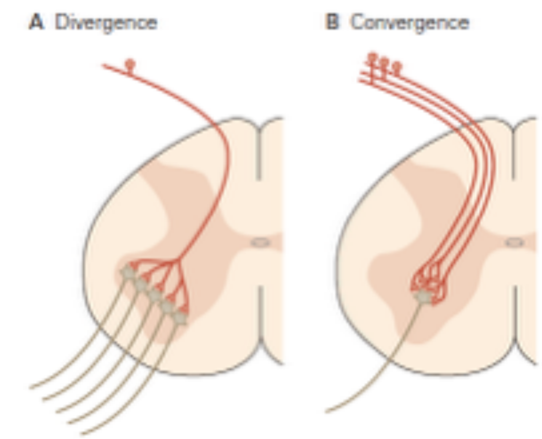
SPINAL MECHANISMS

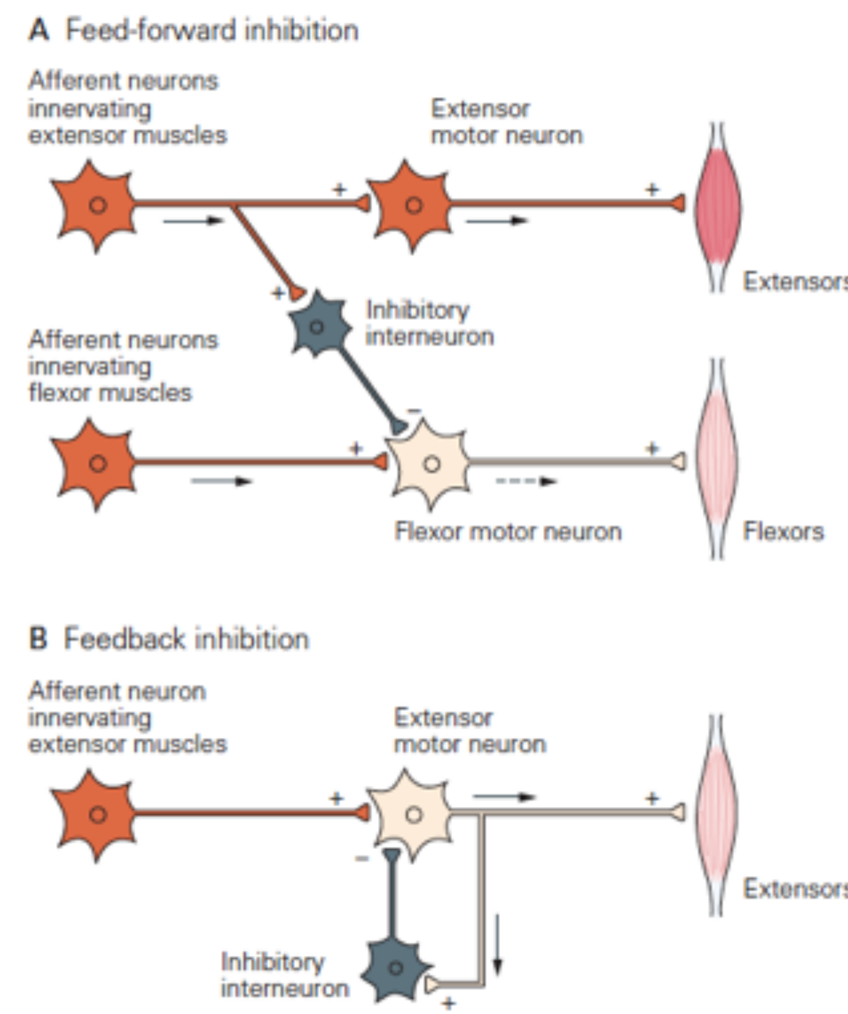
Description

— a motor act generally requires the coordination of a large number of muscles. Spinal circuits play a critical role in this coordination

— spinal reflexes form a set of elementary coordination patterns (e.g. stretch reflex). Most reflexes involve complex circuits that link several muscles or articulations

— interneurons (INs) are basic elements of reflexes. Convergence, divergence, gating, reverberation, cyclic interactions, CPG (central pattern generator)

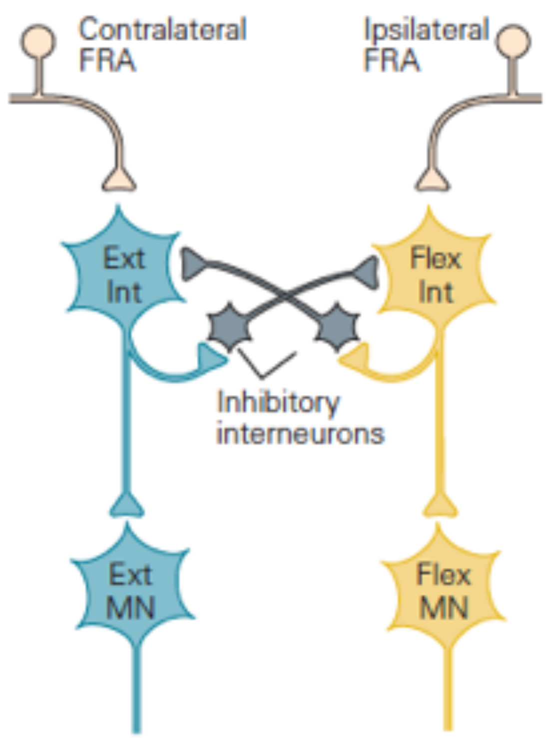




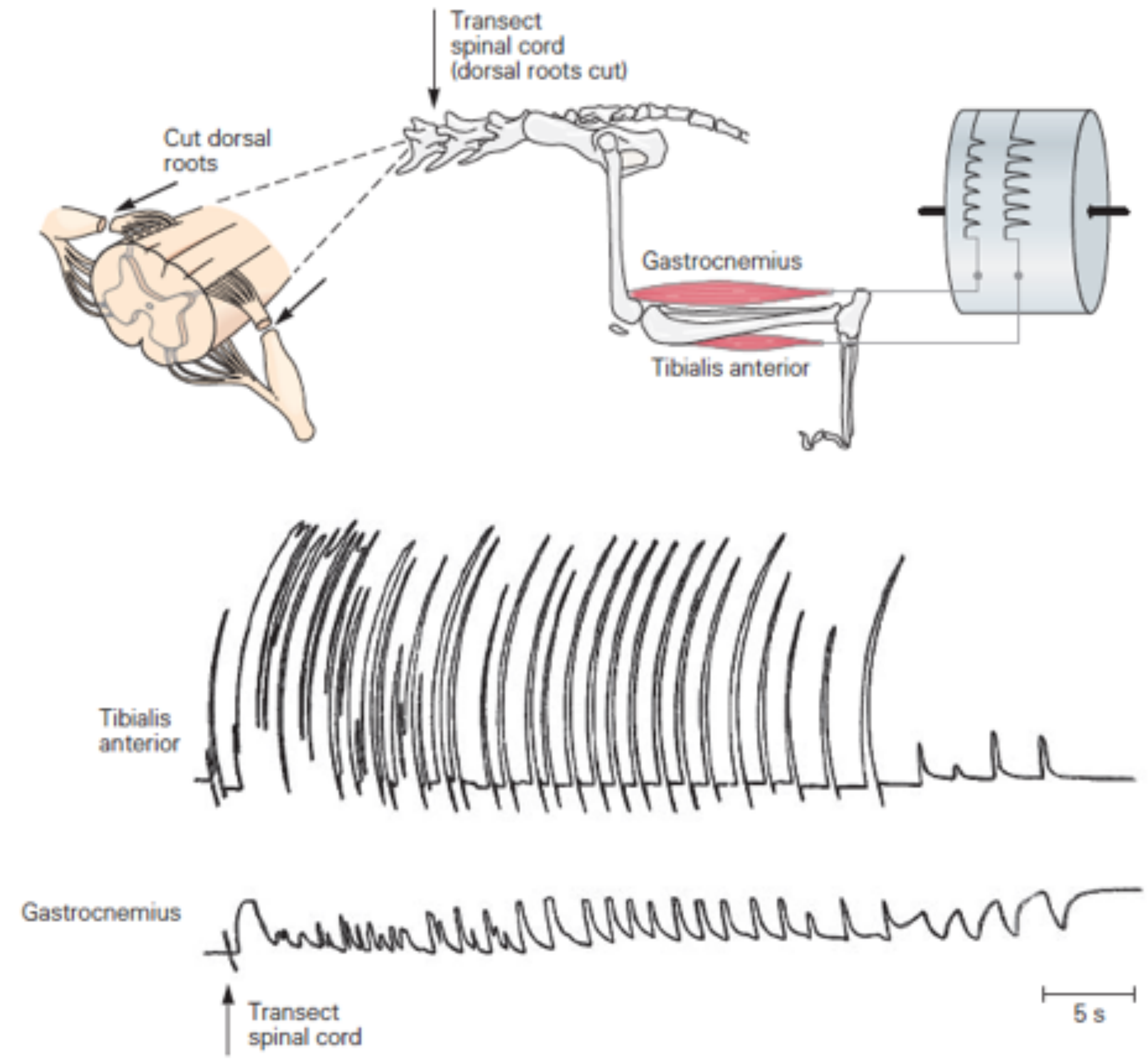
SPINAL MECHANISMS

CPG

central pattern generator
rhythmic activity for stepping is generated by networks of neurons in the spinal cord



`half-center organization`

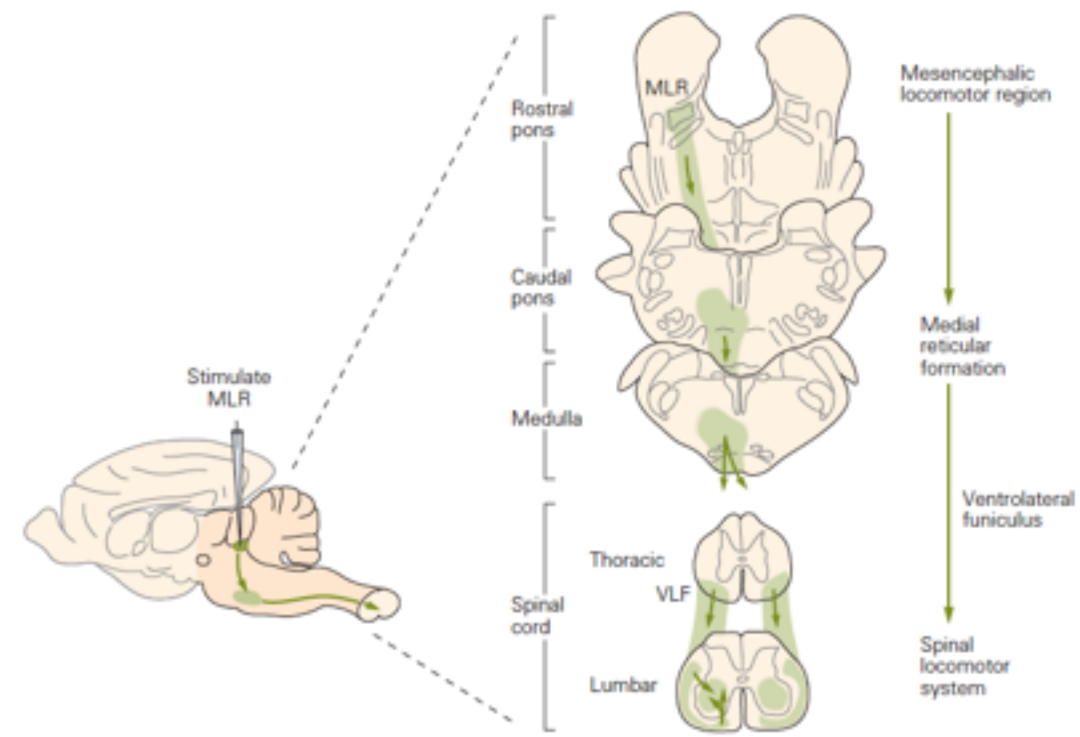


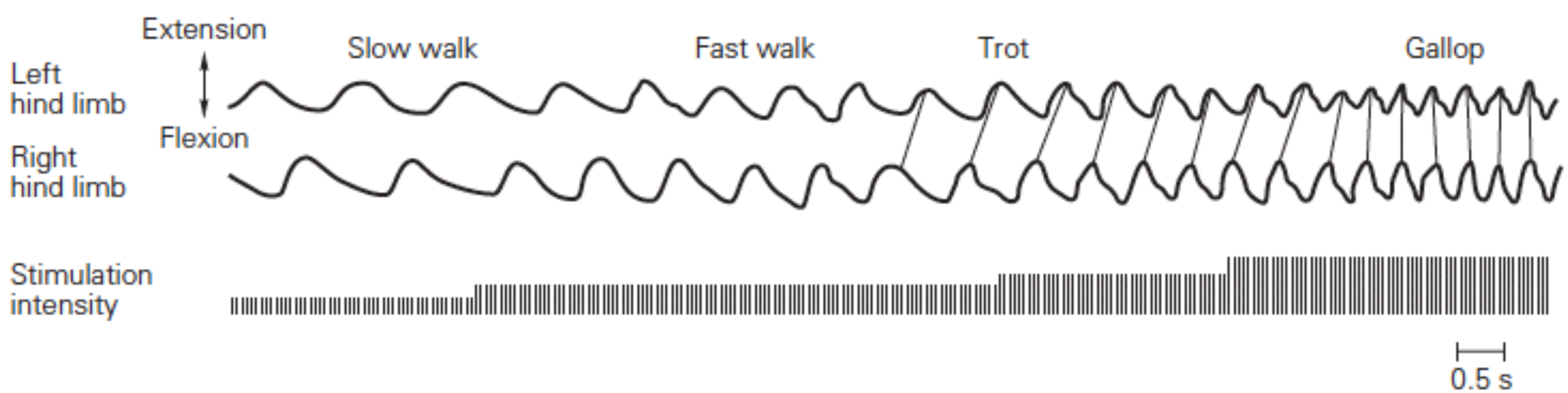
— Brown, 1911, *Proc R Soc Lond B Biol Sci* 84:308

SPINAL MECHANISMS

Locomotion

when transection isolates the whole spinal cord, electrical stimulation of the *Mesencephalic Locomotor Region* generates locomotion. As stimulation intensity increases, locomotion becomes faster. Then there is a transition between trot (alterned flexions/extensions) and gallop (simultaneous flexions/extensions)



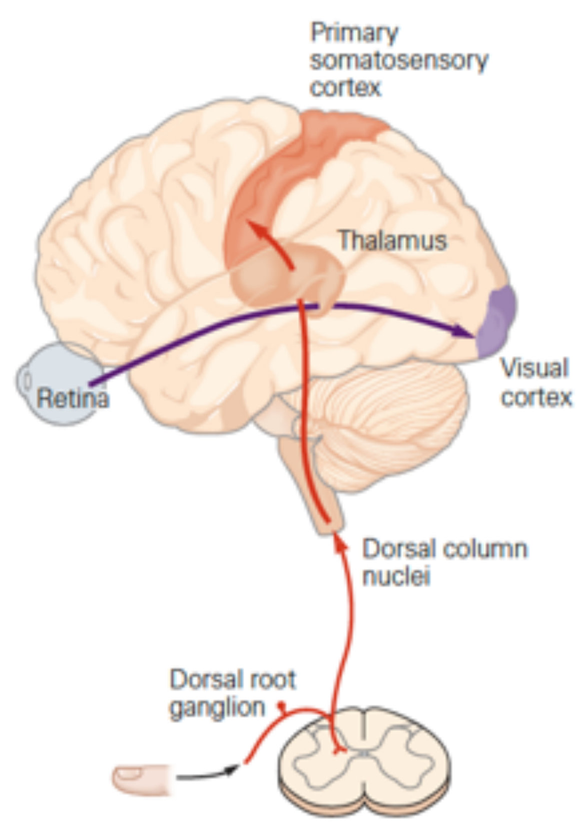


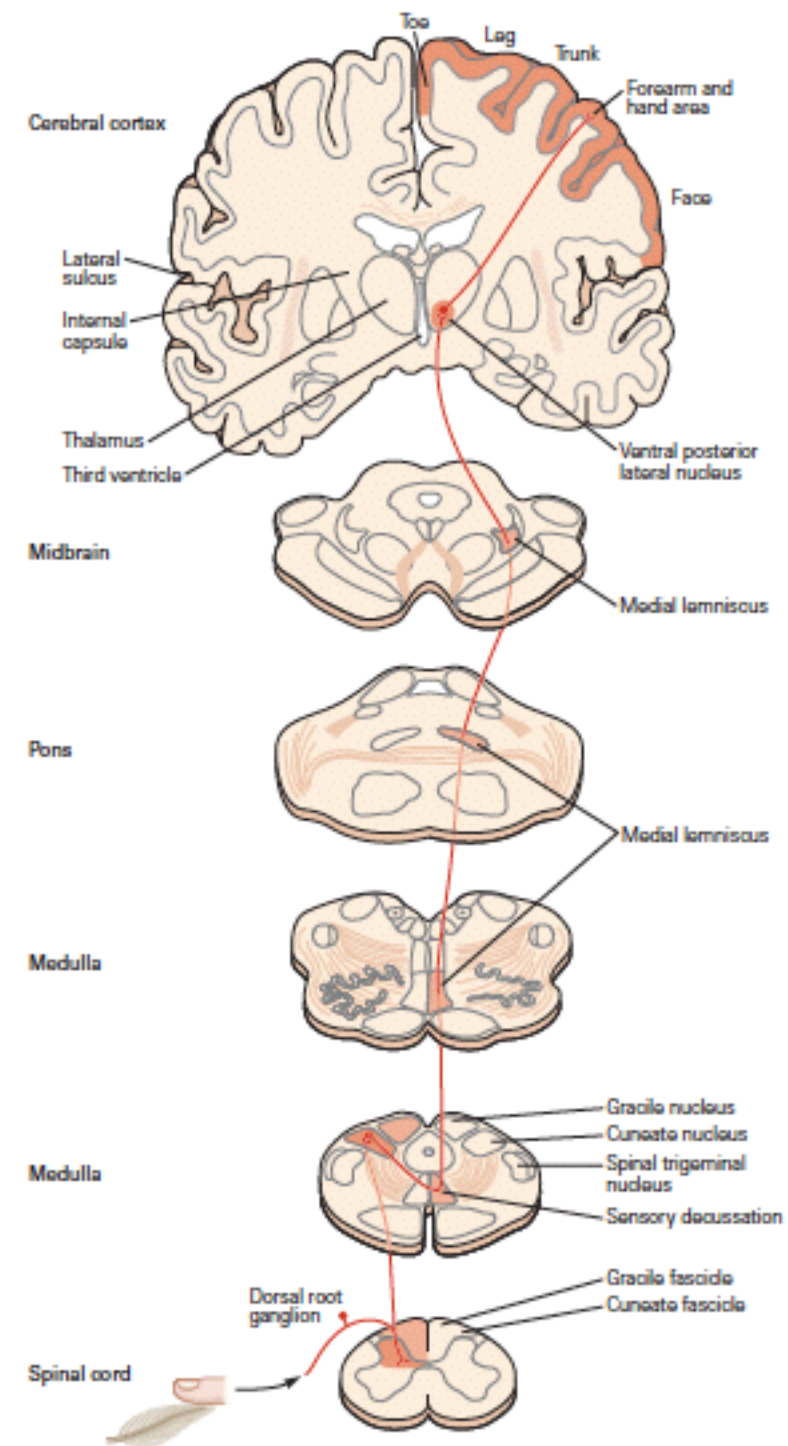
ASCENDING SYSTEMS

Two main systems

— dorsal column/median lemniscus system: transmits tactile and proprioceptive information

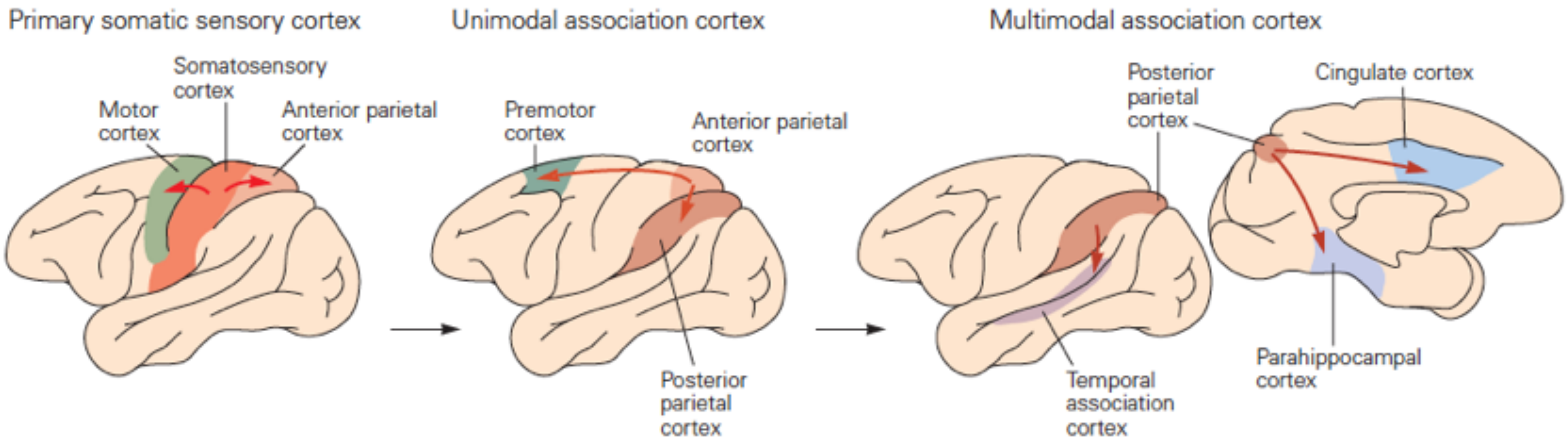
— anterolateral system: transmits pain and temperature

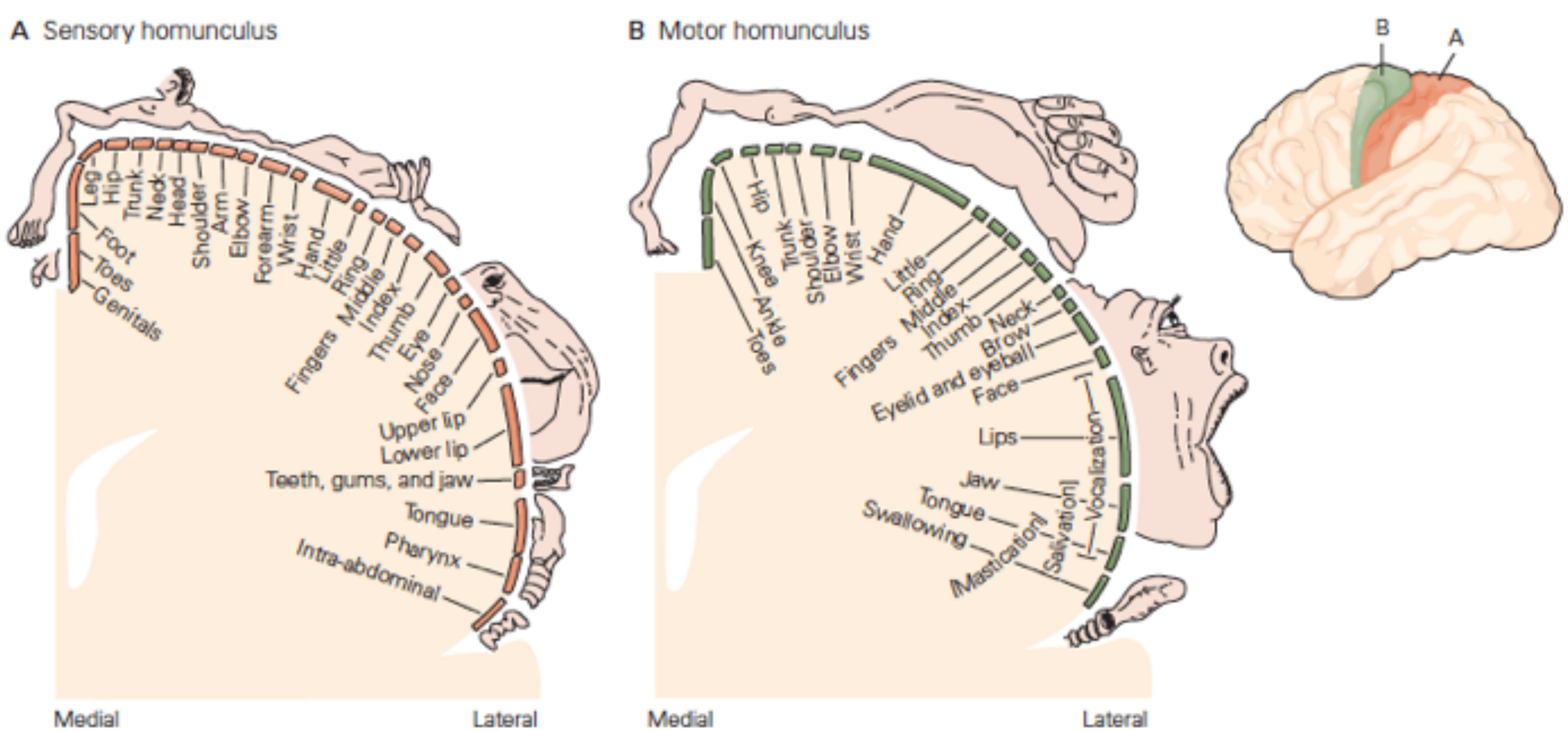




— Kandel et al., 2013, *Principles of Neural Science*, McGraw-Hill

CENTRAL REPRESENTATIONS



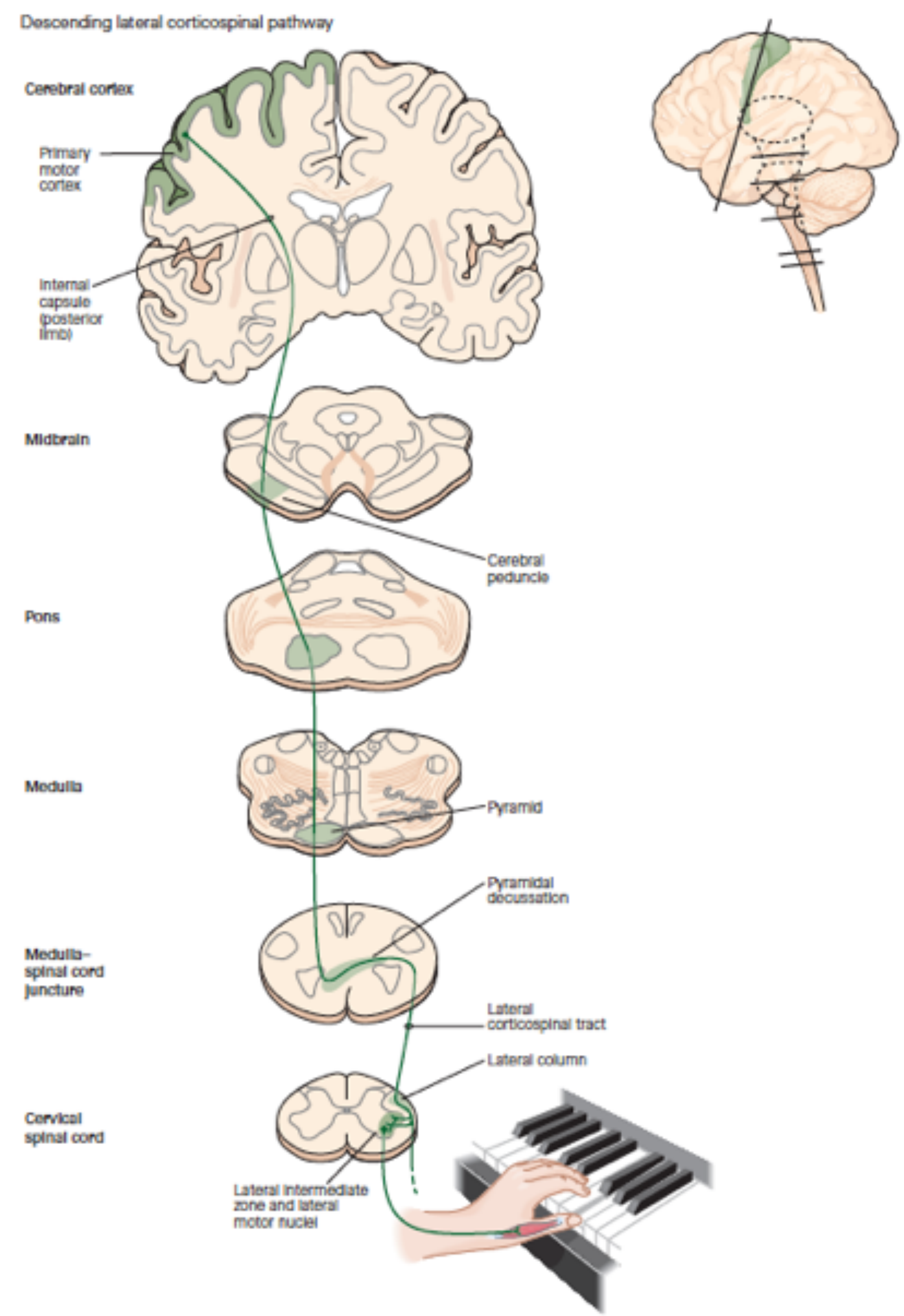


DESCENDING SYSTEMS

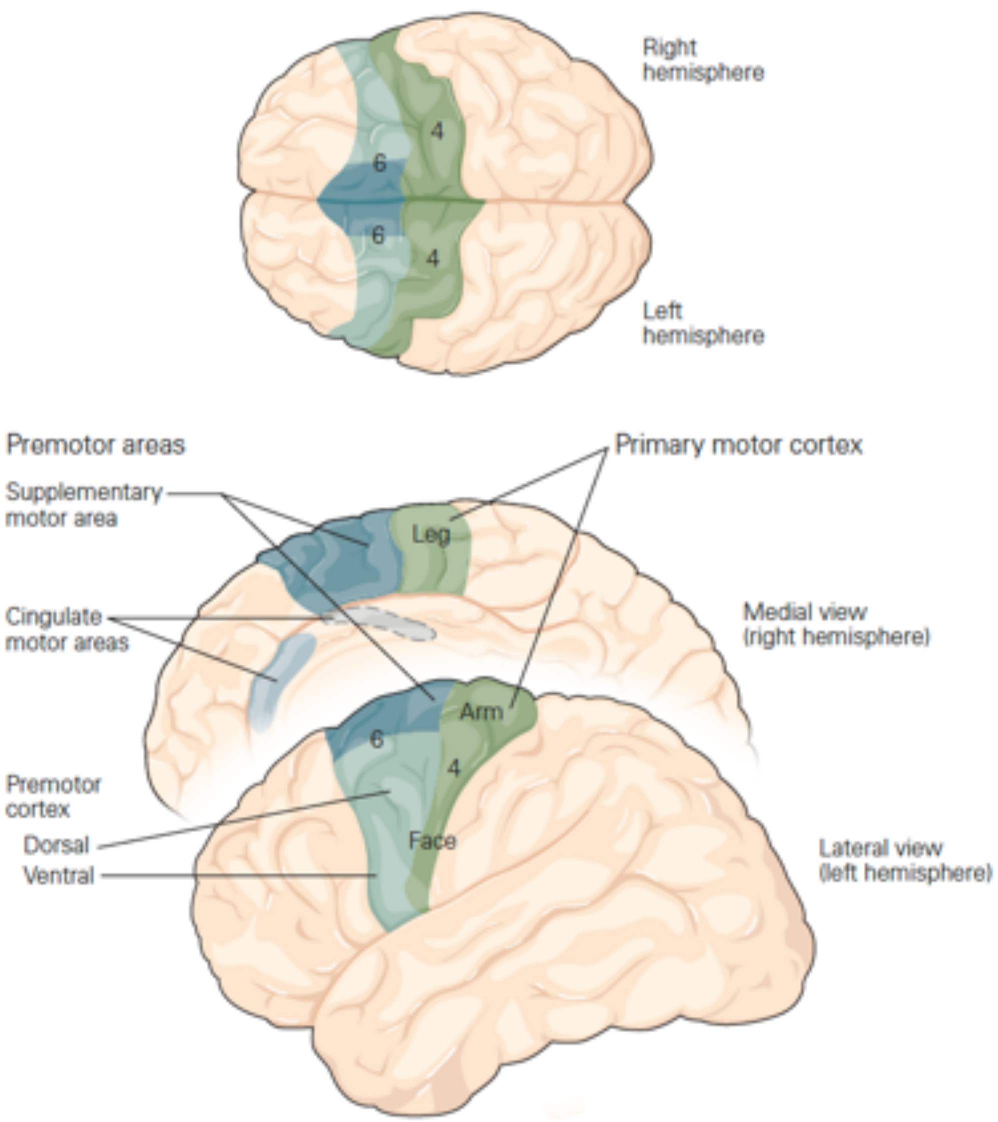
Multiple pathways

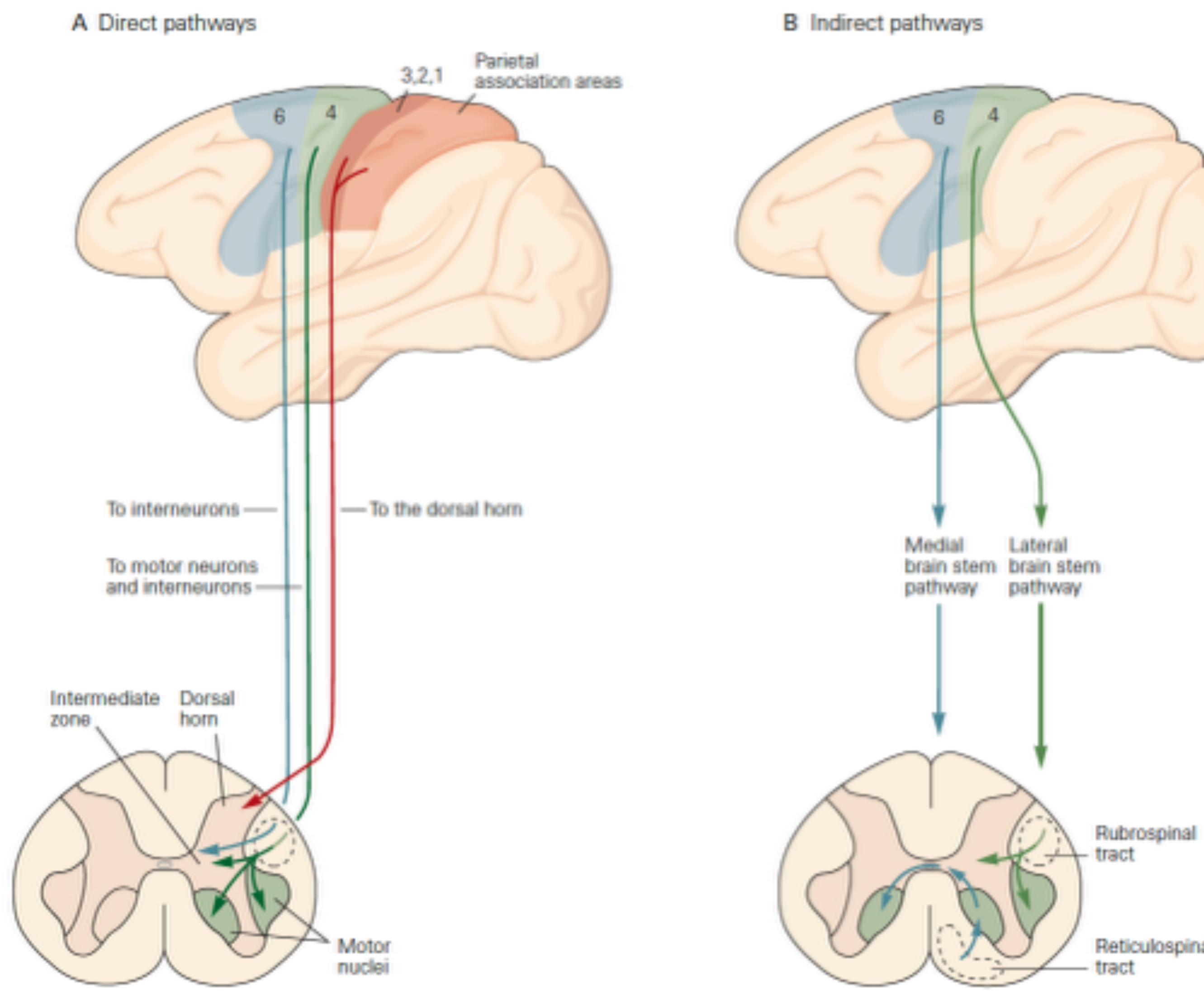
— the cortico-spinal tract is the largest pathway (1 million fibers, 30% from the primary motor cortex)

— the lateral pathway controls the distal and proximal muscles; the ventral pathway control axial muscles

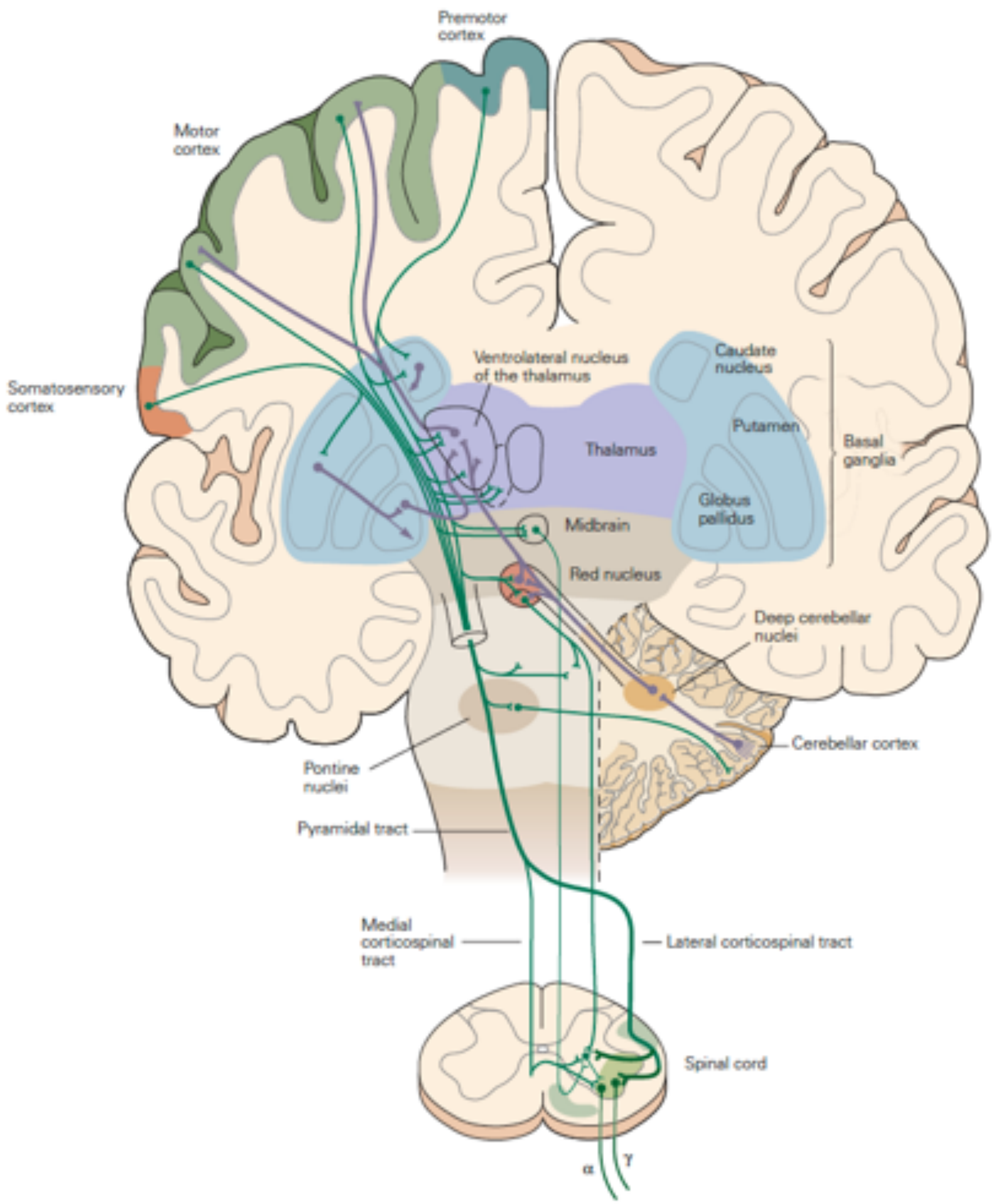


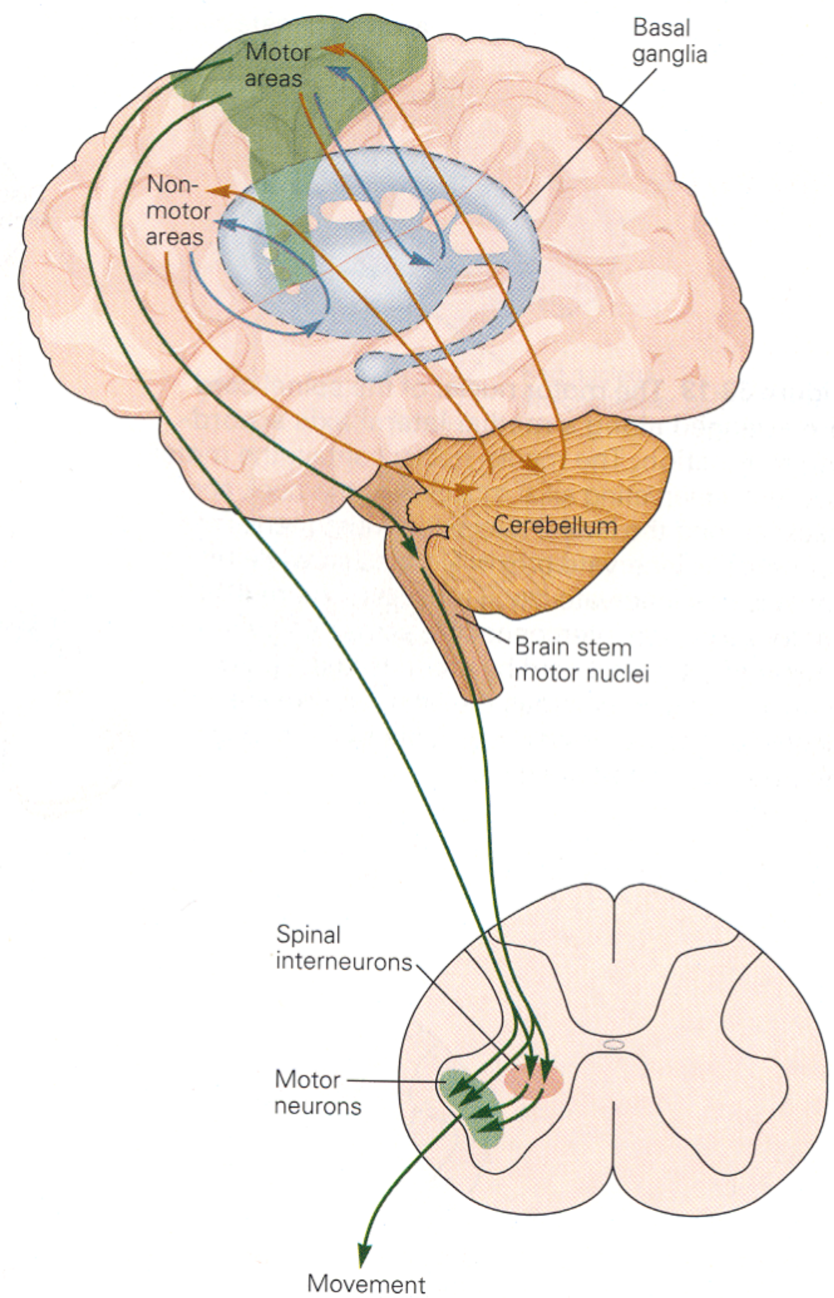
CORTICAL MOTOR AREAS





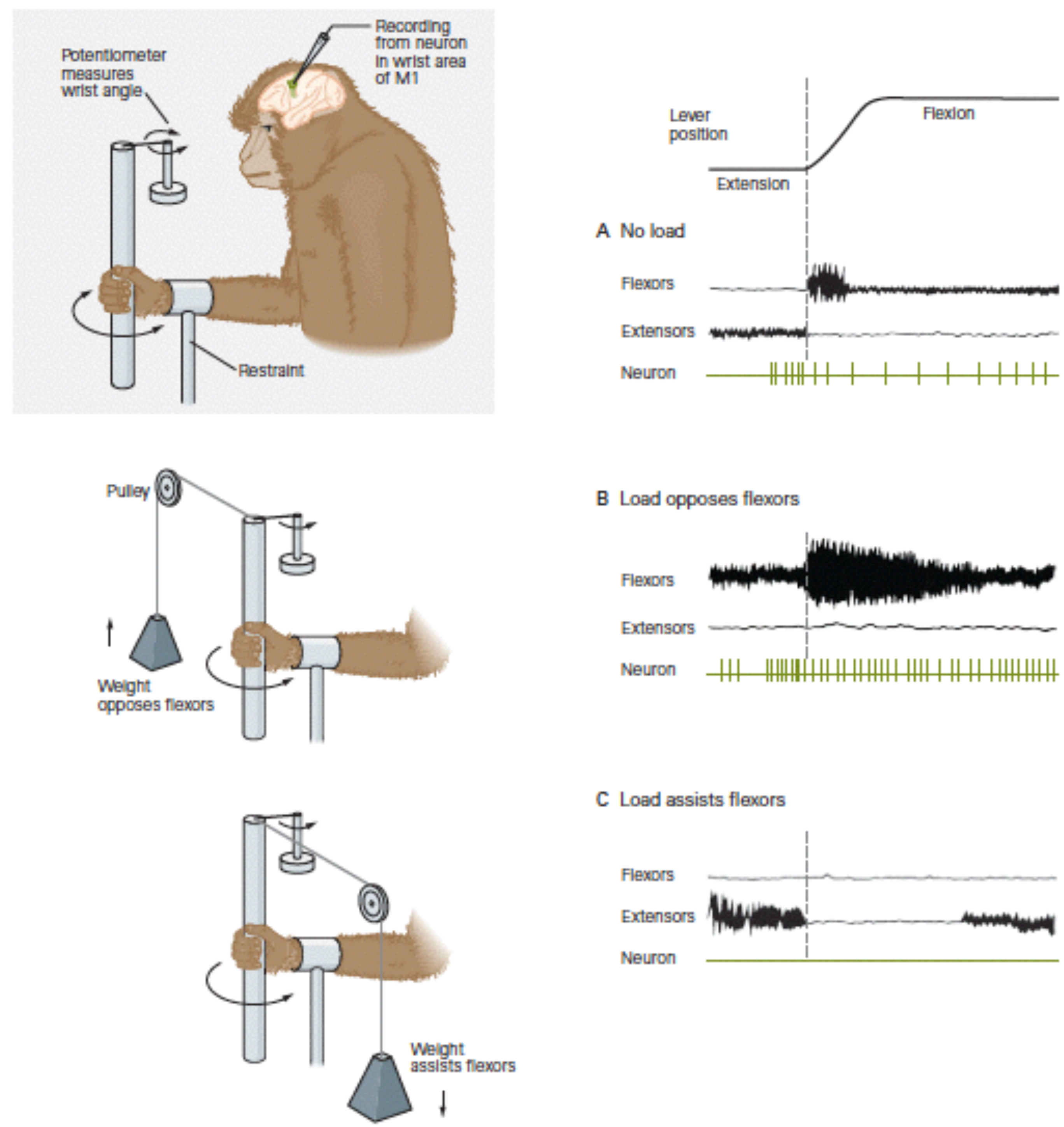
ARCHITECTURE





NEURAL PROPERTIES

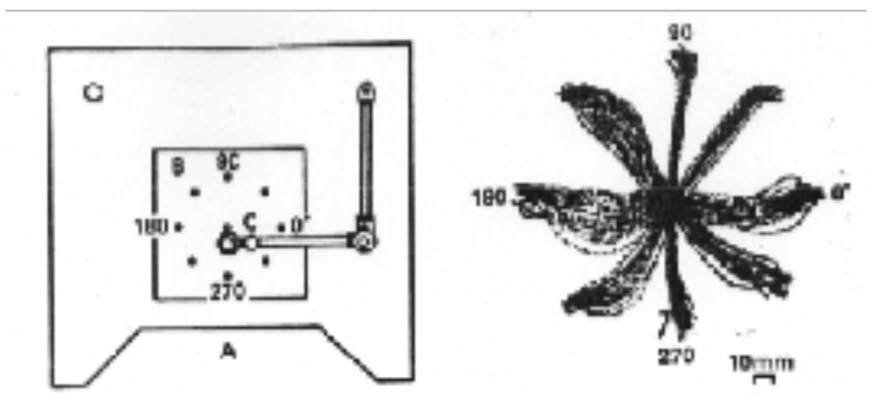
Neural activity modulated by force



— Evarts, 1968, *J Neurophysiol* 31:14

NEURAL PROPERTIES

Neural activity modulated by movement direction



— Georgopoulos et al., 1982, *J Neurosci* 2:1527