Posterior Parietal cortex
Transforming visual cues into plans for voluntary movements

Motor cortex
Initiating, and directing voluntary movements

Thalamus

Basal ganglia
Learning movements, motivation of movements, initiating movements

Cerebellum
Learning movements and coordination

Brainstem Centers
Postural control

Spinal cord
Reflex coordination → **Motor neurons**

Skeletal Muscles

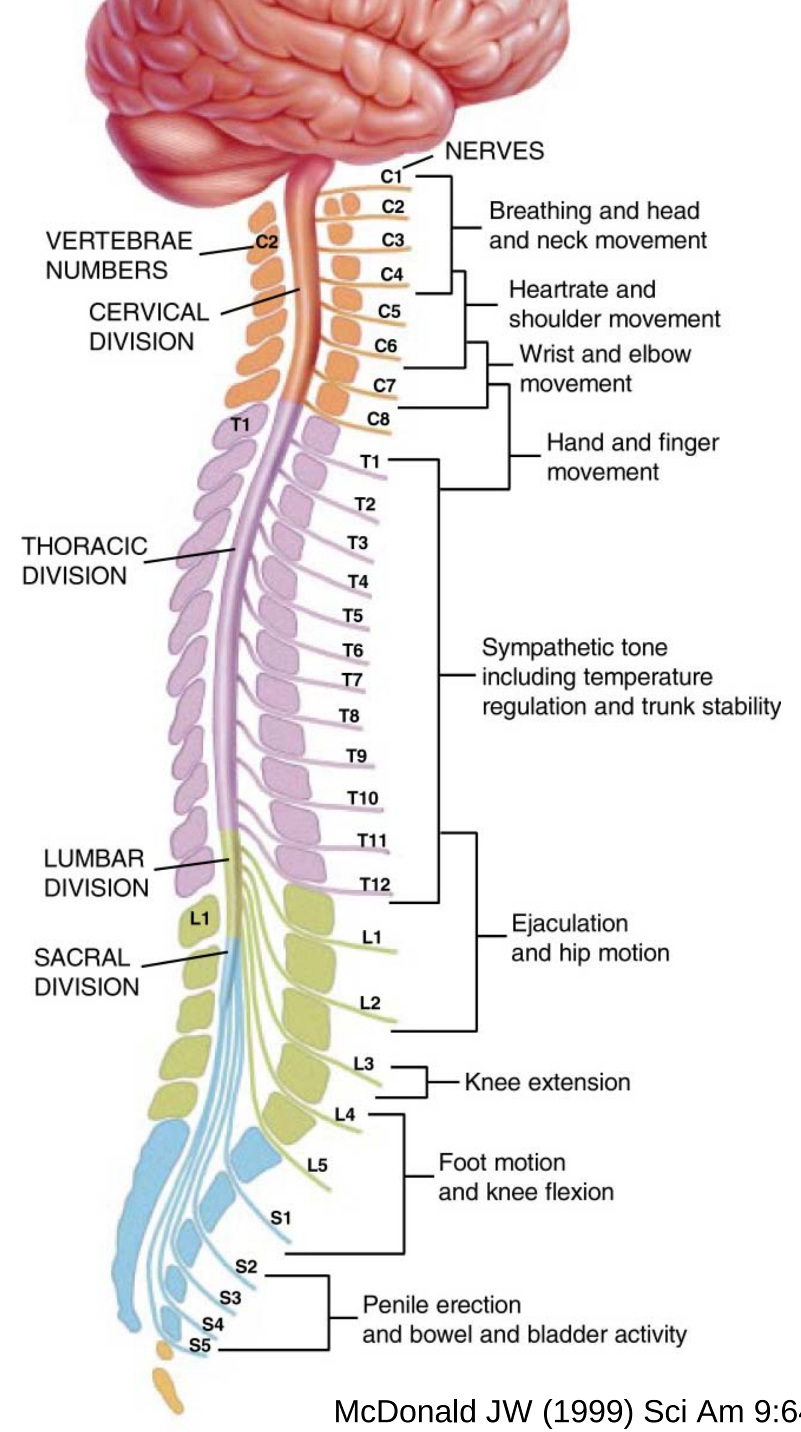
Divisions of the spinal cord:

Cervical

Thoracic

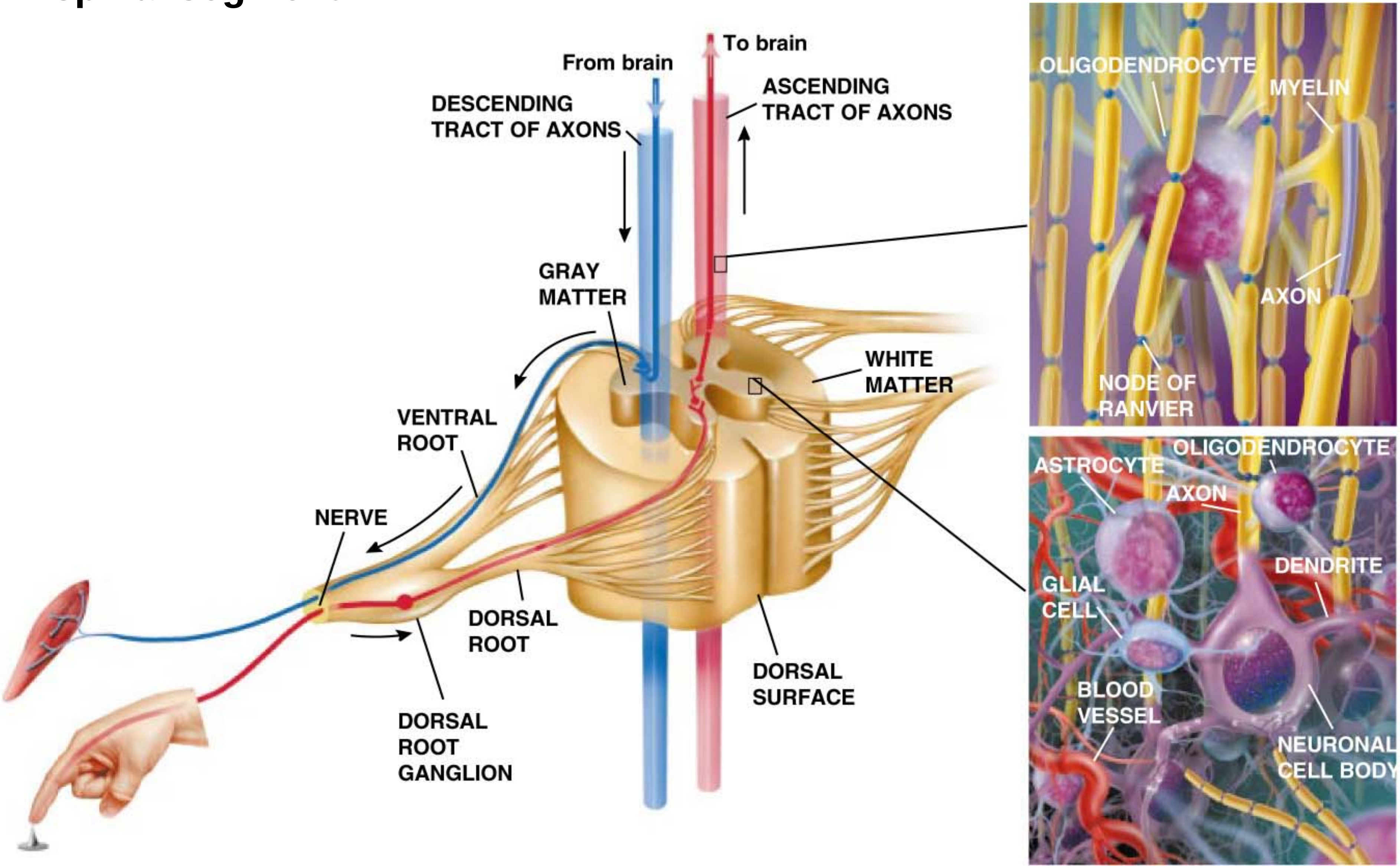
Lumbar

Sacral



McDonald JW (1999) Sci Am 9:64-73

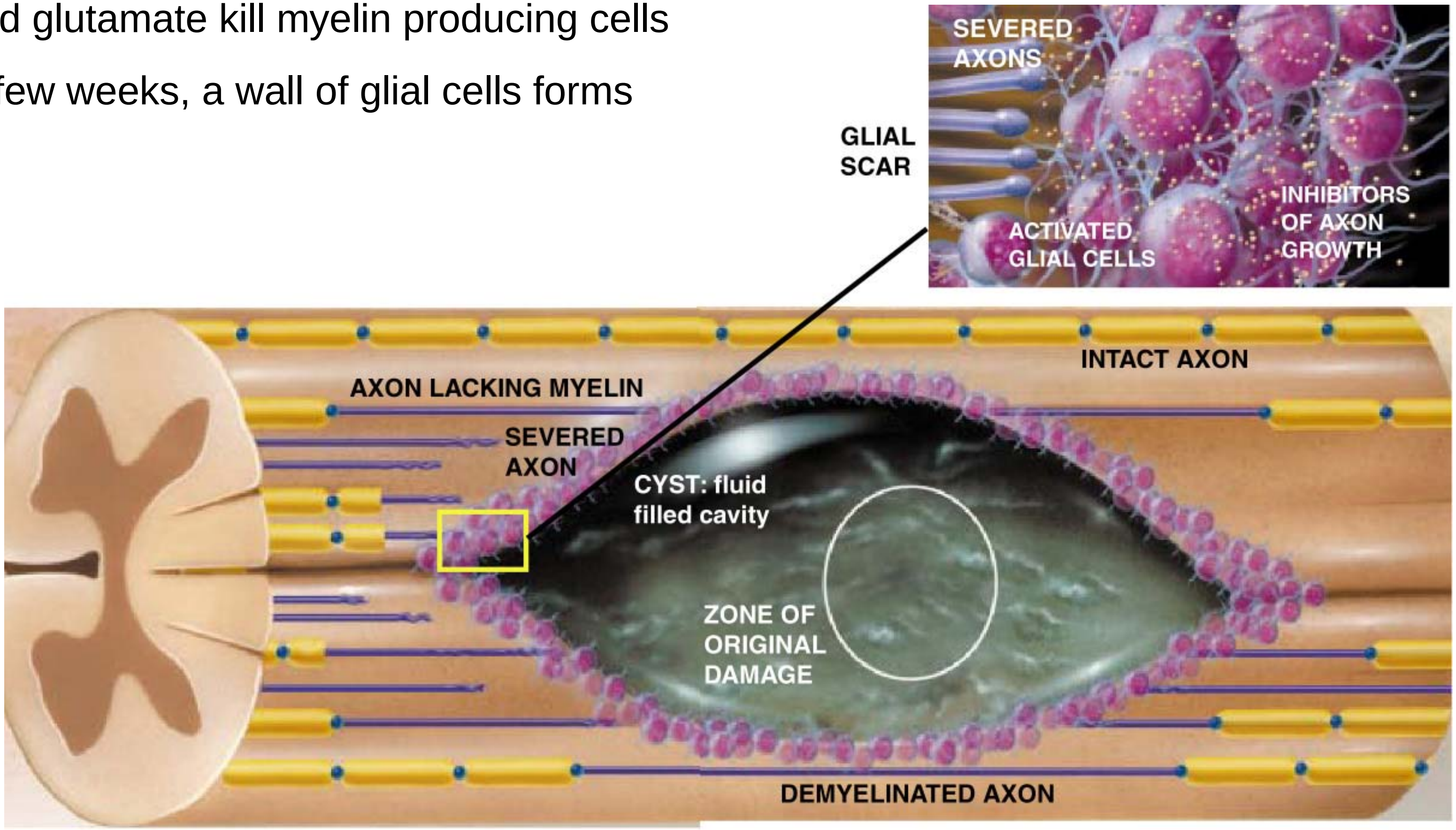
A spinal segment



McDonald JW (1999) Sci Am 9:64-73

Spinal Cord Injury

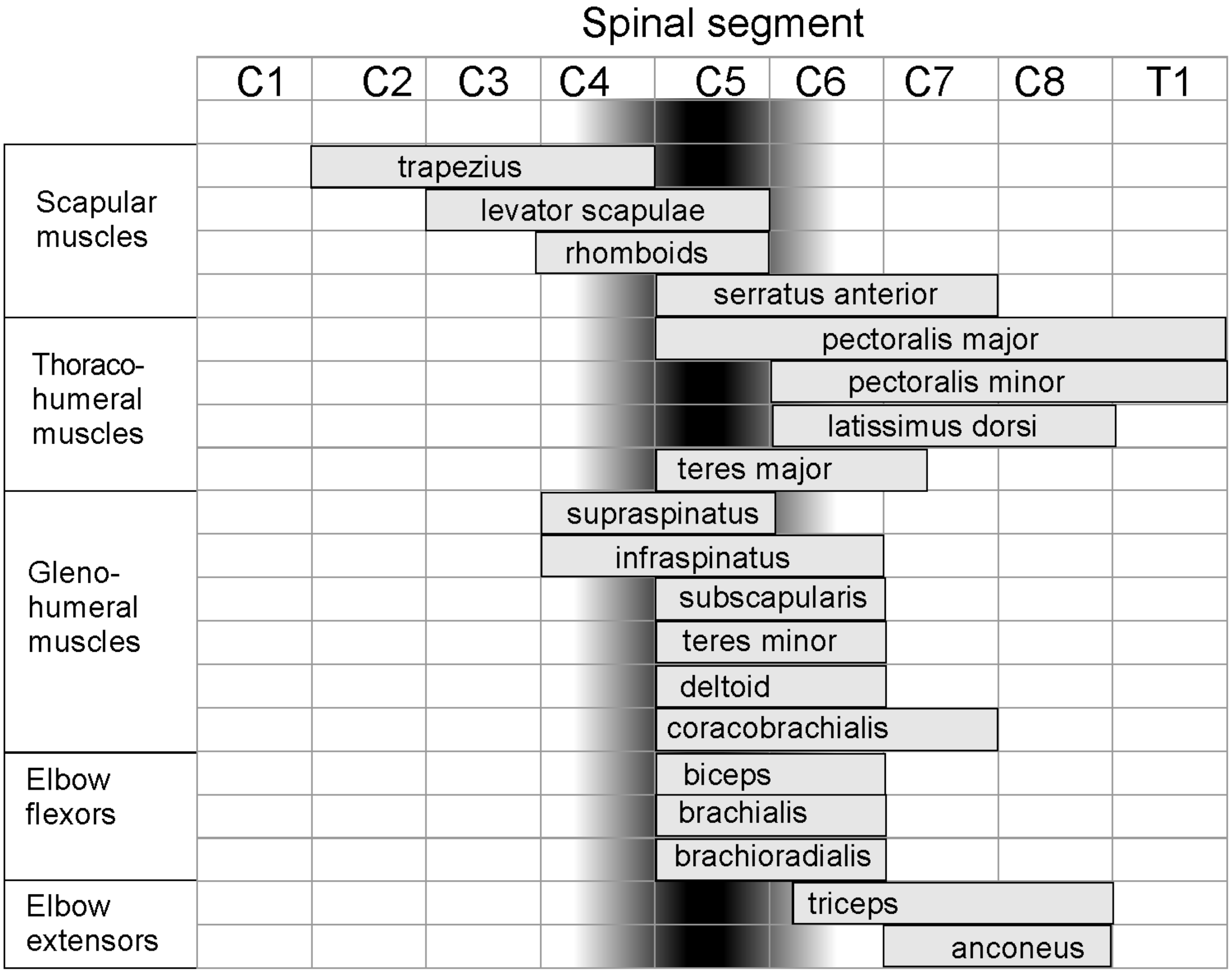
- Initial damage is likely limited to a small region
- Hemorrhaging from broken vessels swells the cord, putting pressure on healthy neurons
- Injured neurons release glutamate at very high levels, over exciting neighboring neurons
- Cyst and glutamate kill myelin producing cells
- After a few weeks, a wall of glial cells forms



McDonald JW (1999) Sci Am 9:64-73

Most common type of spinal injury in humans: C5-C6

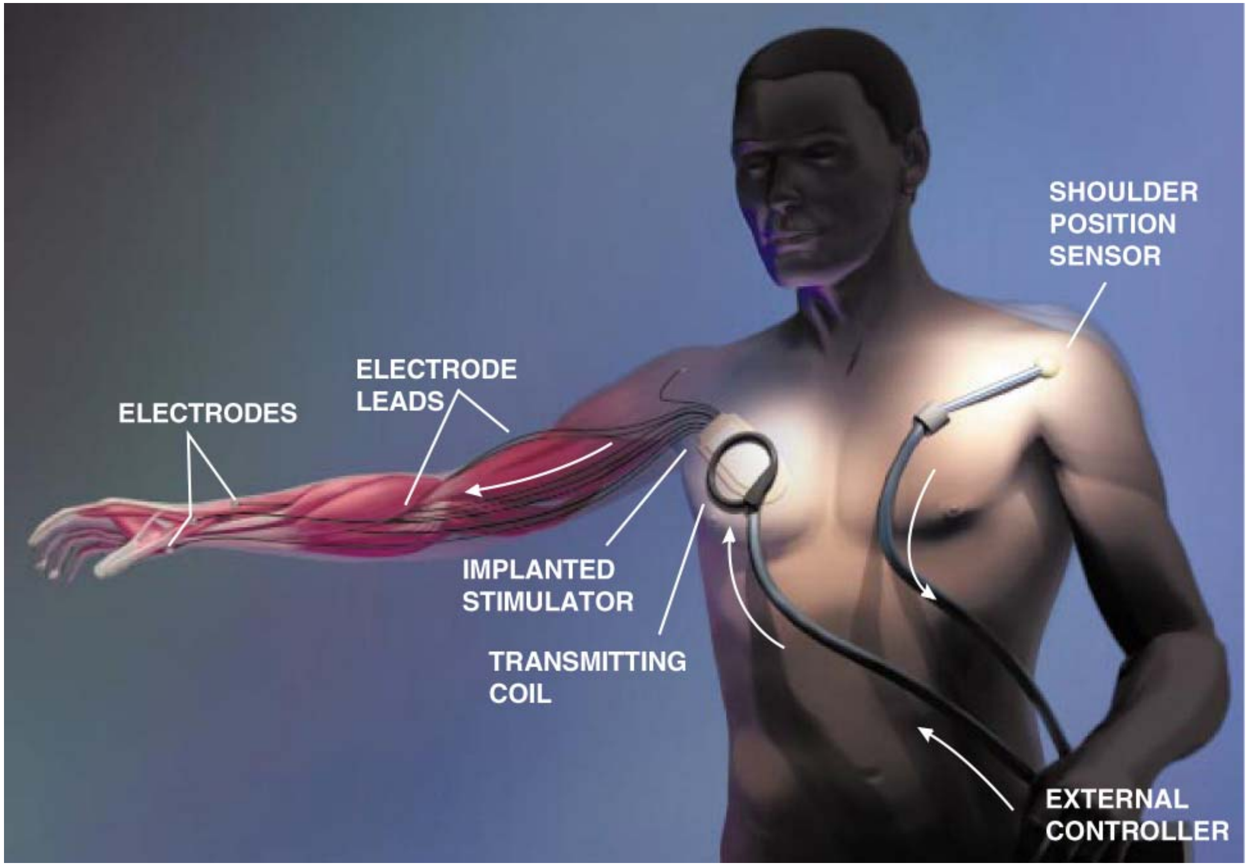
Finger muscles are controlled by motorneurons at C6 or lower.



Pat Crago, Case Western Reserve Univ.

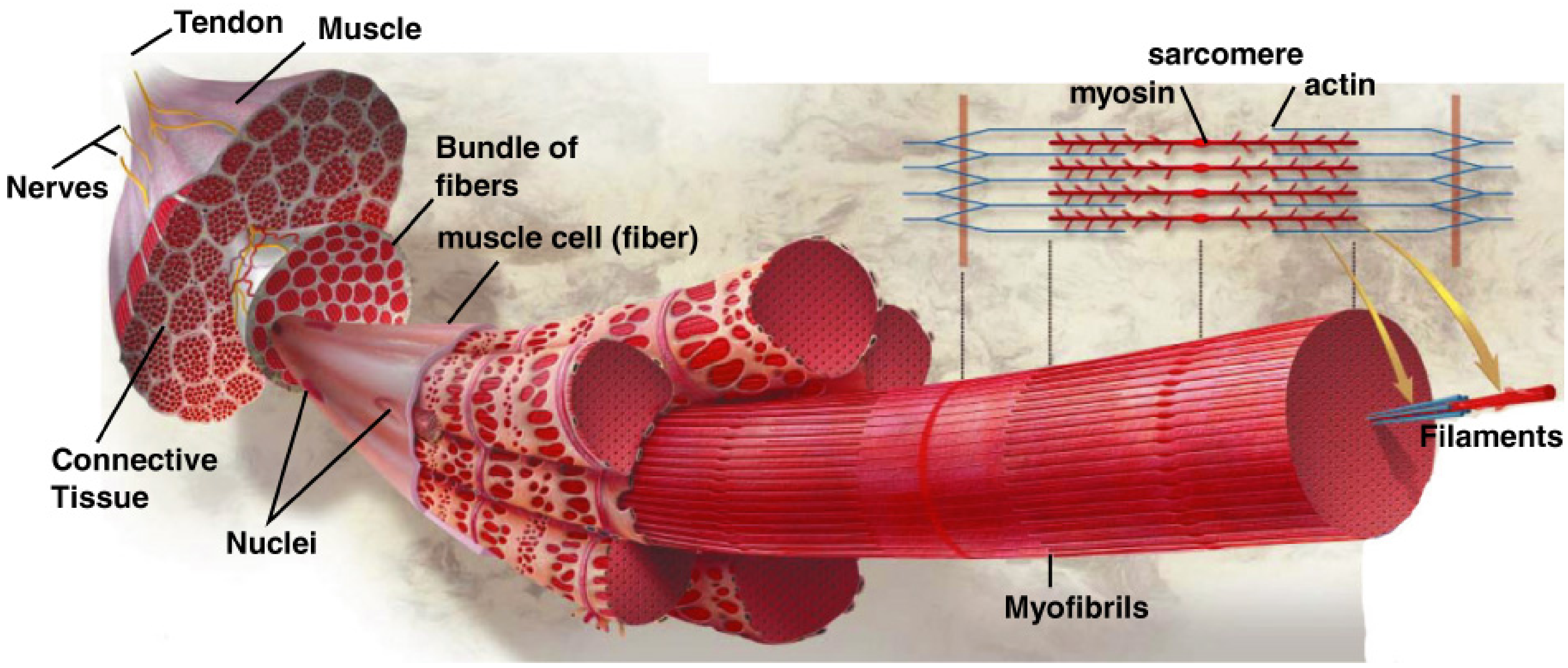
Functional Electrical Stimulation to produce a grip

C6 injury: Elevation of shoulder on the left arm signals the stimulator to produce a grip.



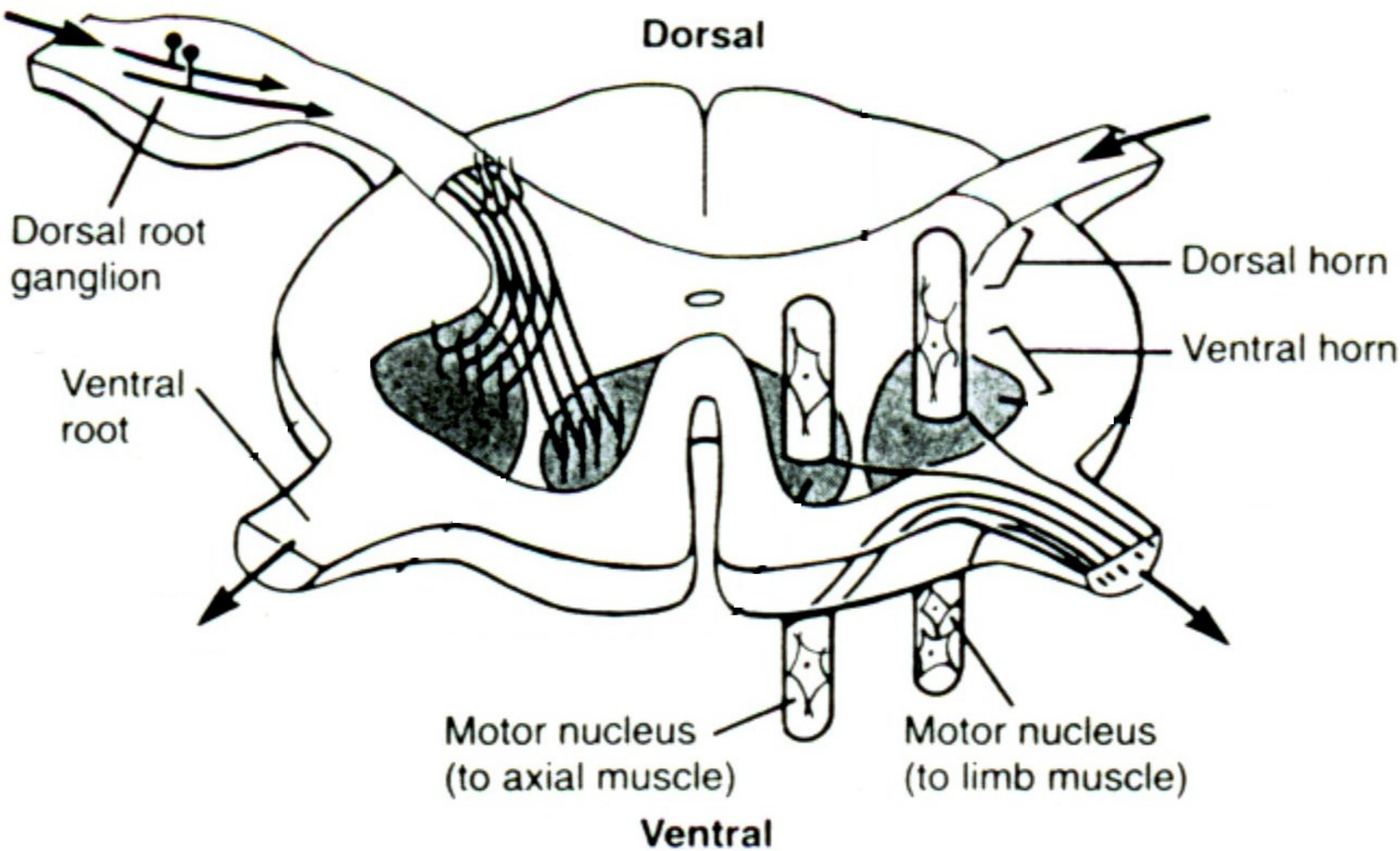
McDonald JW (1999) Sci Am 9:64-73

Pat Crago, Case Western Reserve Univ.

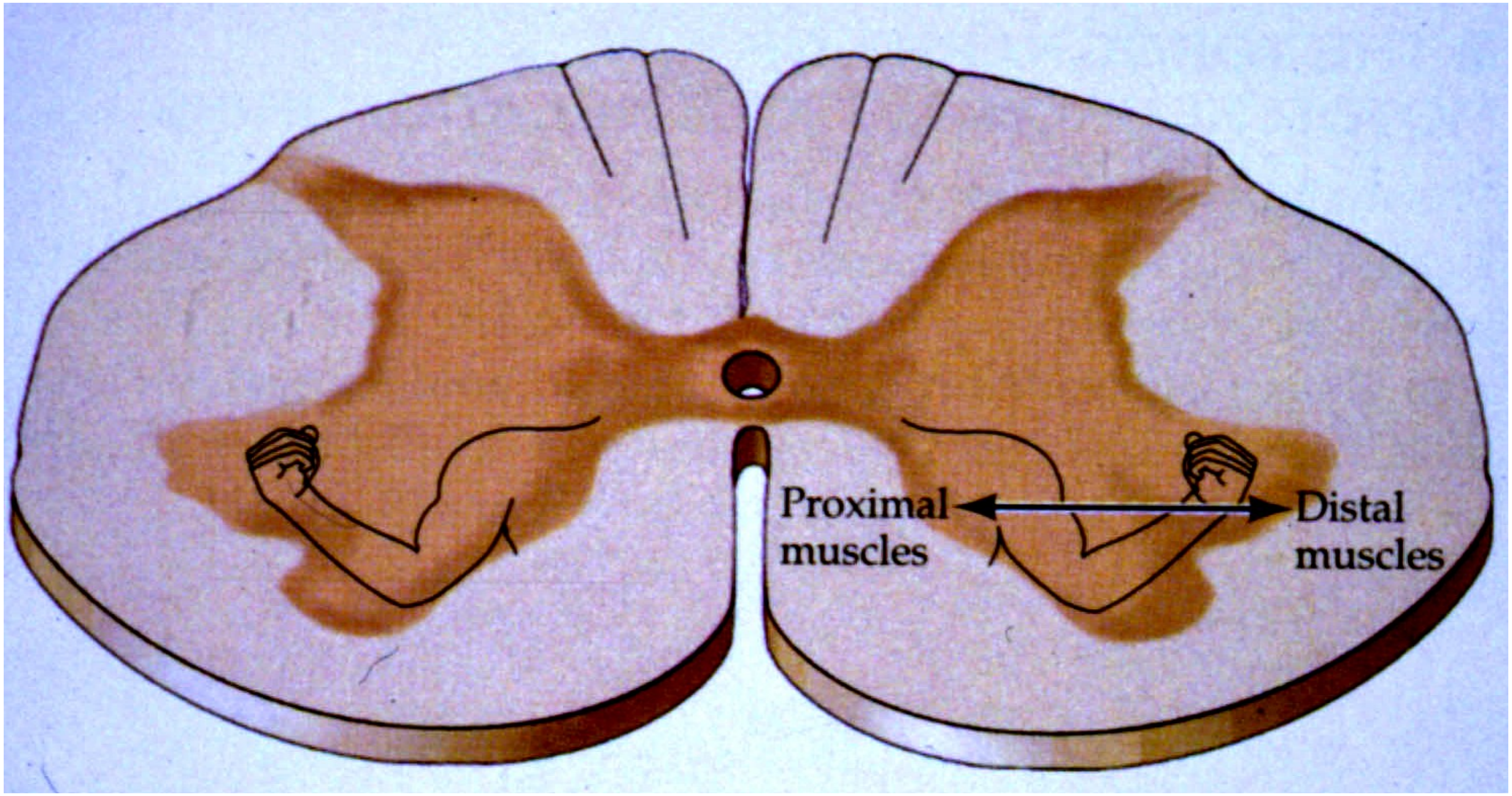


Zorpette G (1999) Sci Am

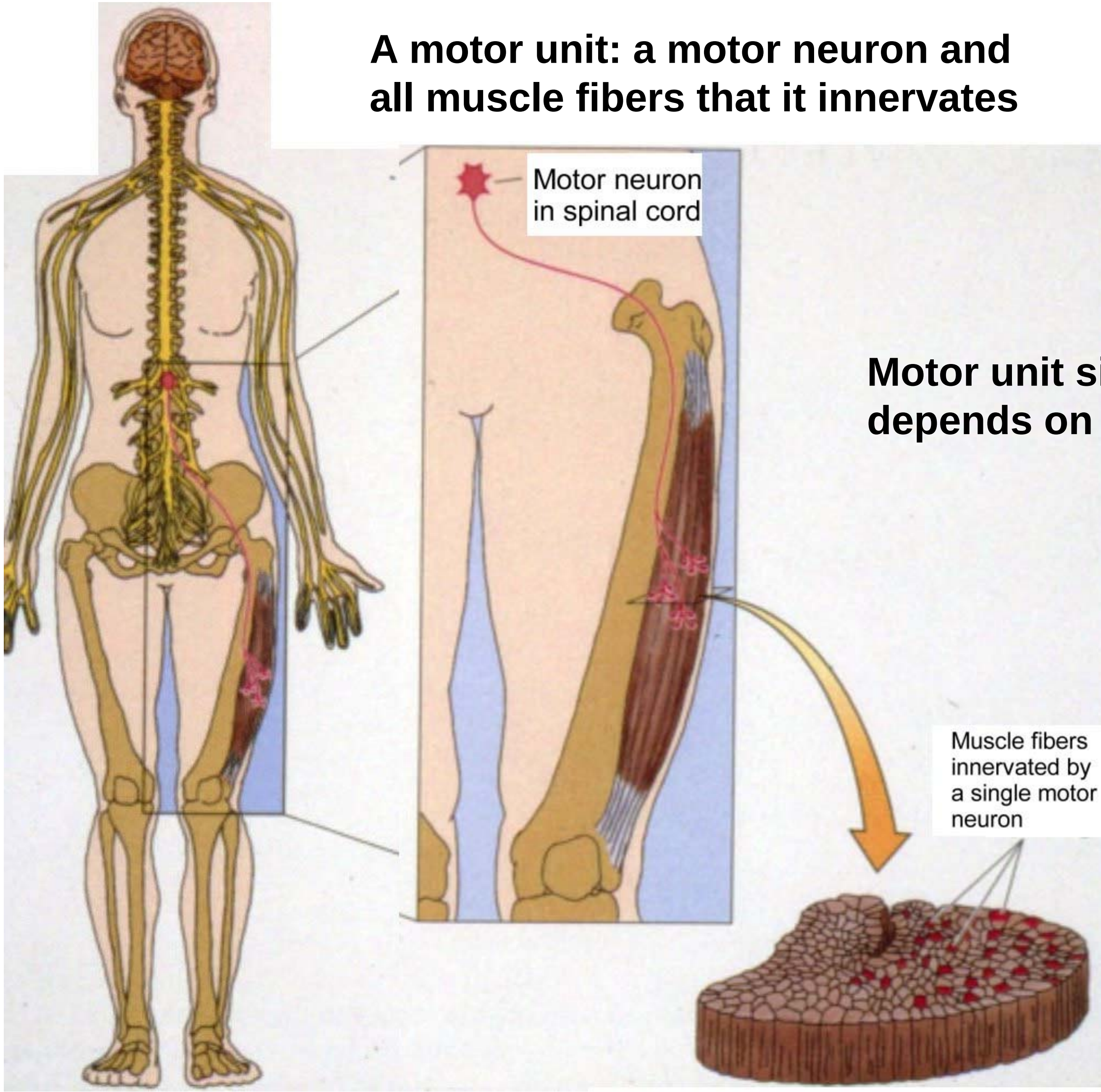
Motor neurons reside in the ventral region of the gray matter of the spinal cord. They collect into pools that innervate a single muscle.



Kandel ER et al. (1991)


Proximal muscles
Distal muscles

A motor unit: a motor neuron and all muscle fibers that it innervates



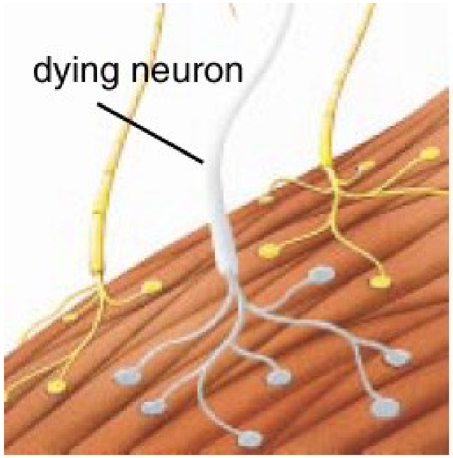
Motor unit size depends on function

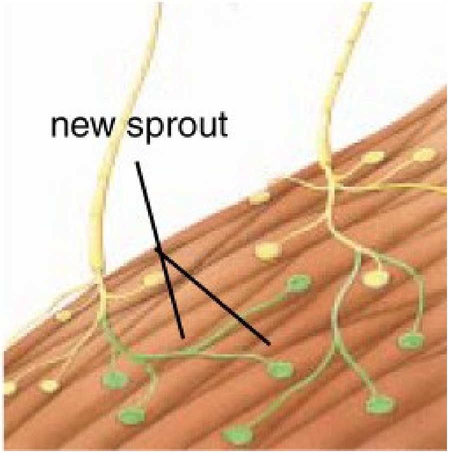
Polio

Poliovirus invades the motor neurons, killing them.

Muscle fibers in the motor unit are paralyzed.

Neighboring motor neurons grow sprouts to take over orphaned fibers, creating a giant motor unit.

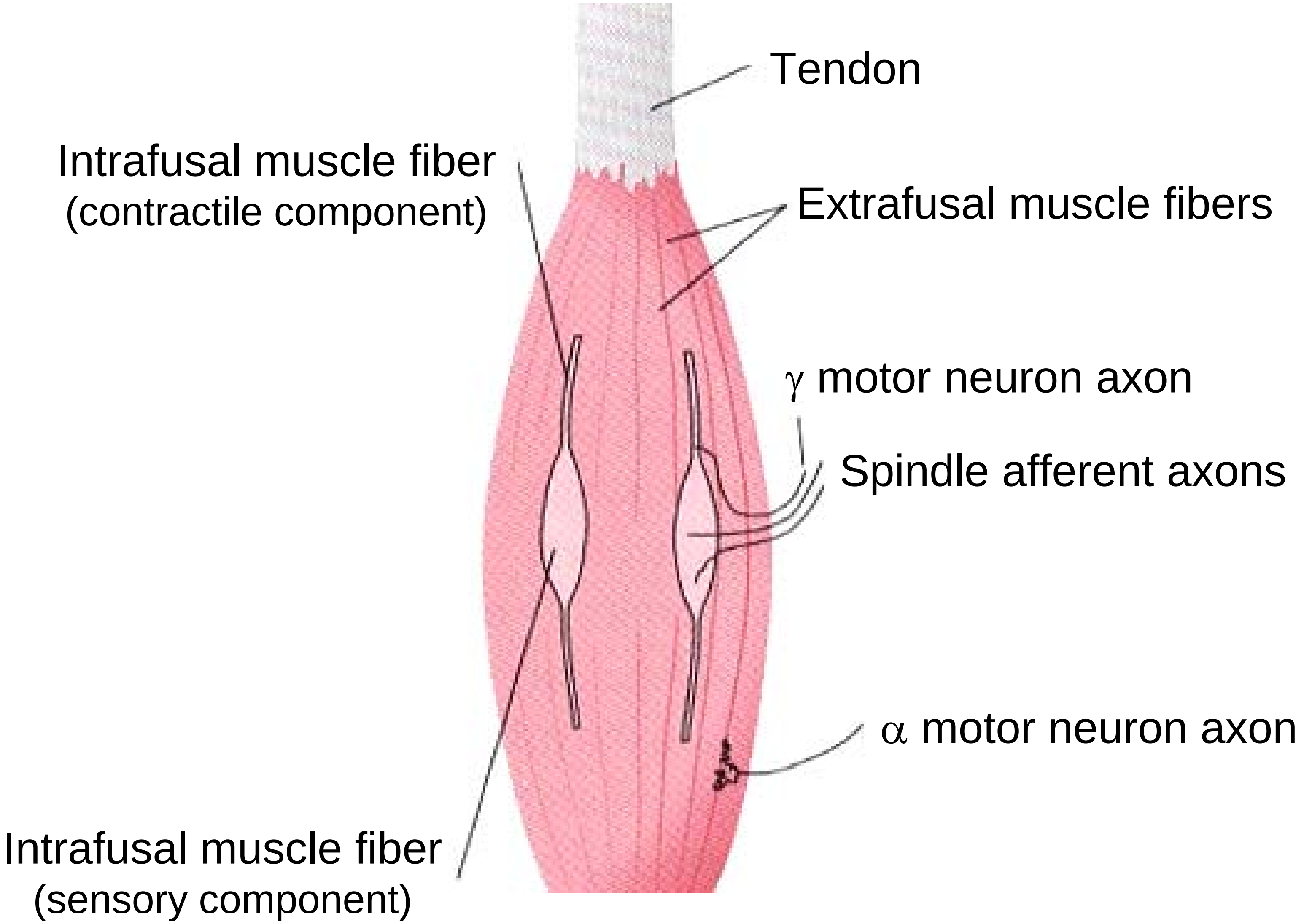




Motor stroke

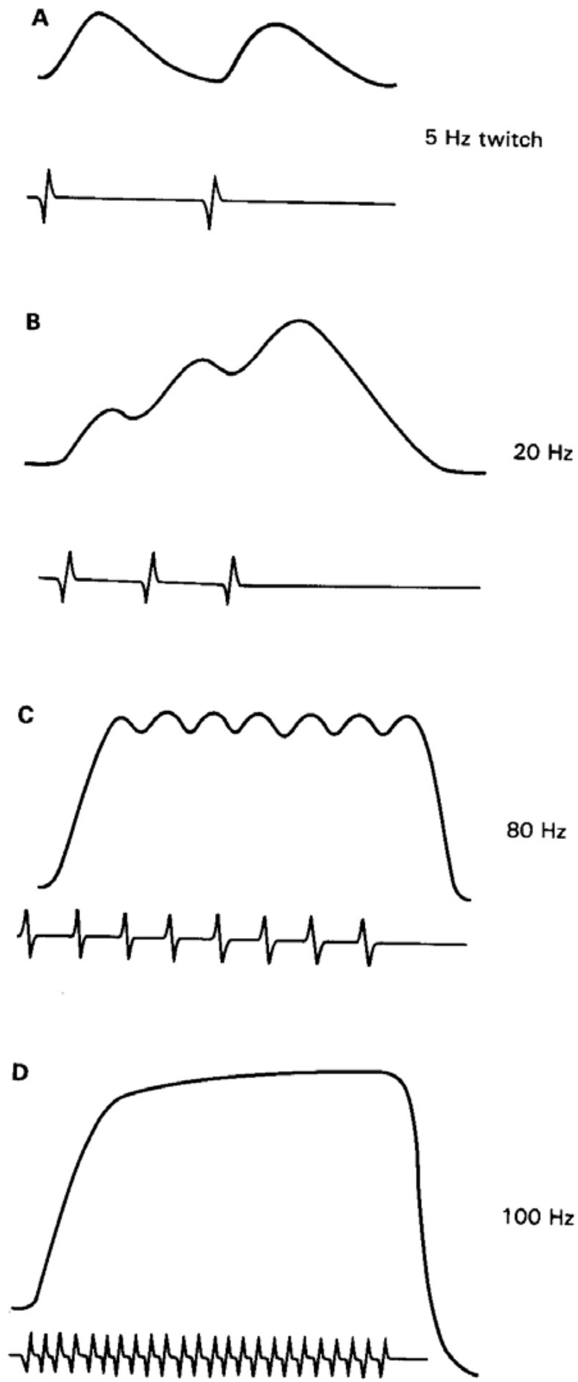
Damage to the brain causes loss of neurons that descend to the spinal cord. The resting discharge of motor neurons is severely reduced.

Halstead LS (1998) Sci Am 4:42-47



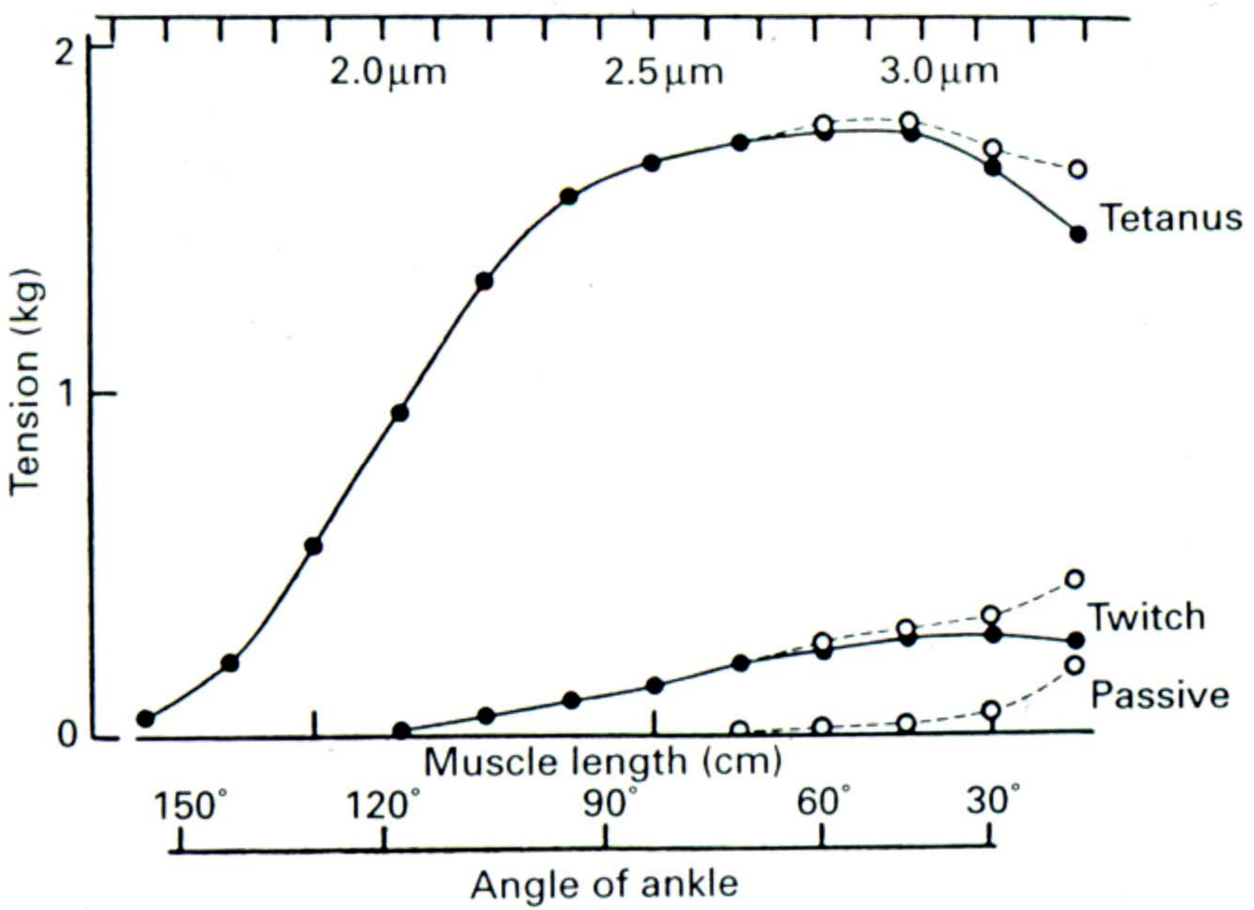
Tendon
Intrafusal muscle fiber
(contractile component)
Extrafusal muscle fibers
γ motor neuron axon
Spindle afferent axons
α motor neuron axon
Intrafusal muscle fiber
(sensory component)

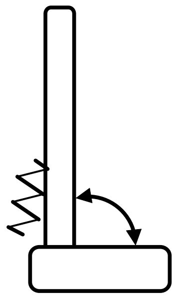
Force produced by a muscle depends on the **rate** of action potentials from the motor nerve.



Kandel ER et al. (1991)

Force produced by a muscle depends on its length

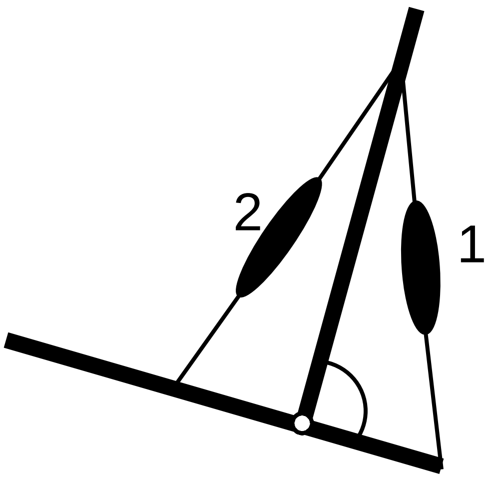


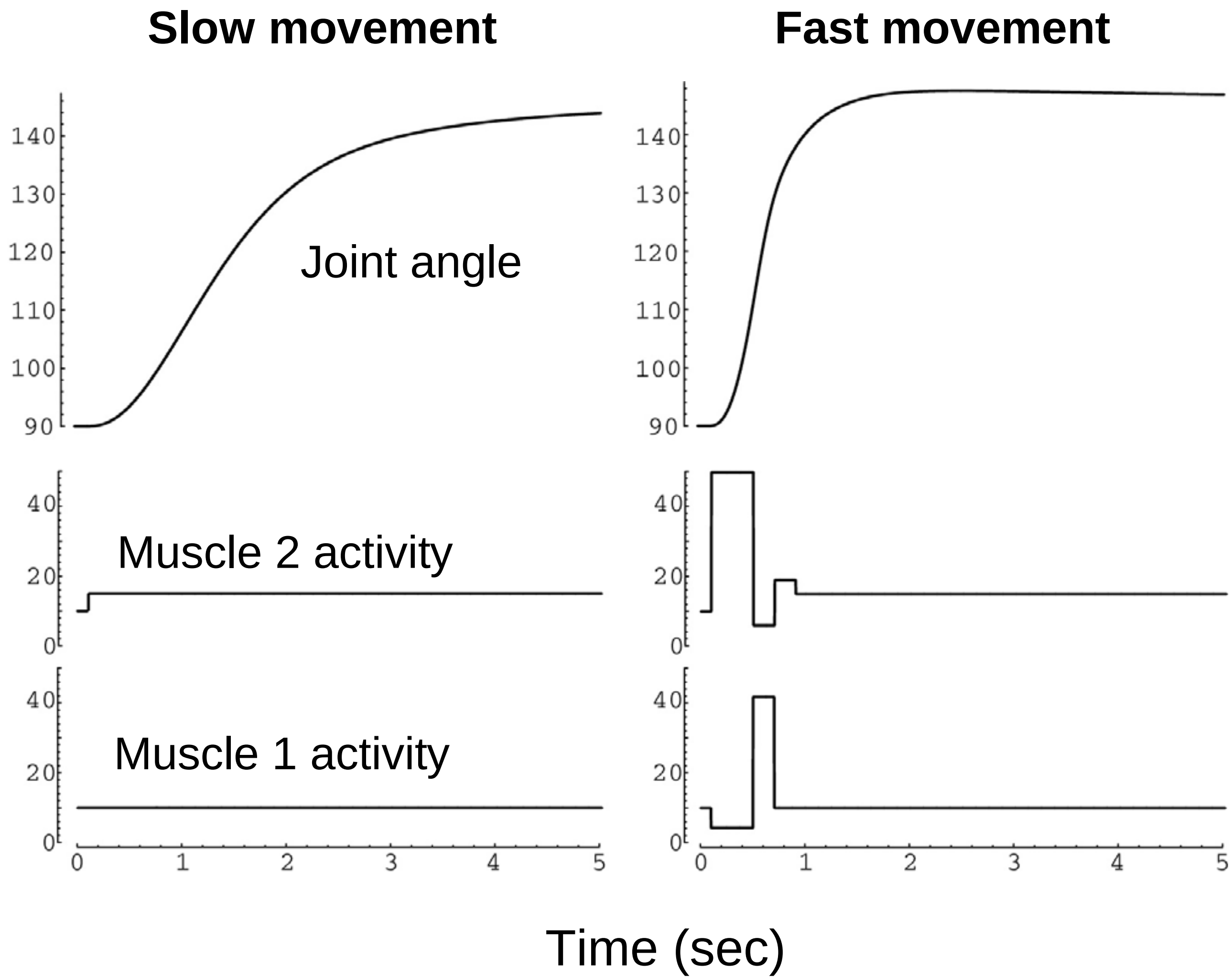


Force produced through direct electrical stimulation of the soleus muscle of a cat. This muscle's function is to extend the ankle.

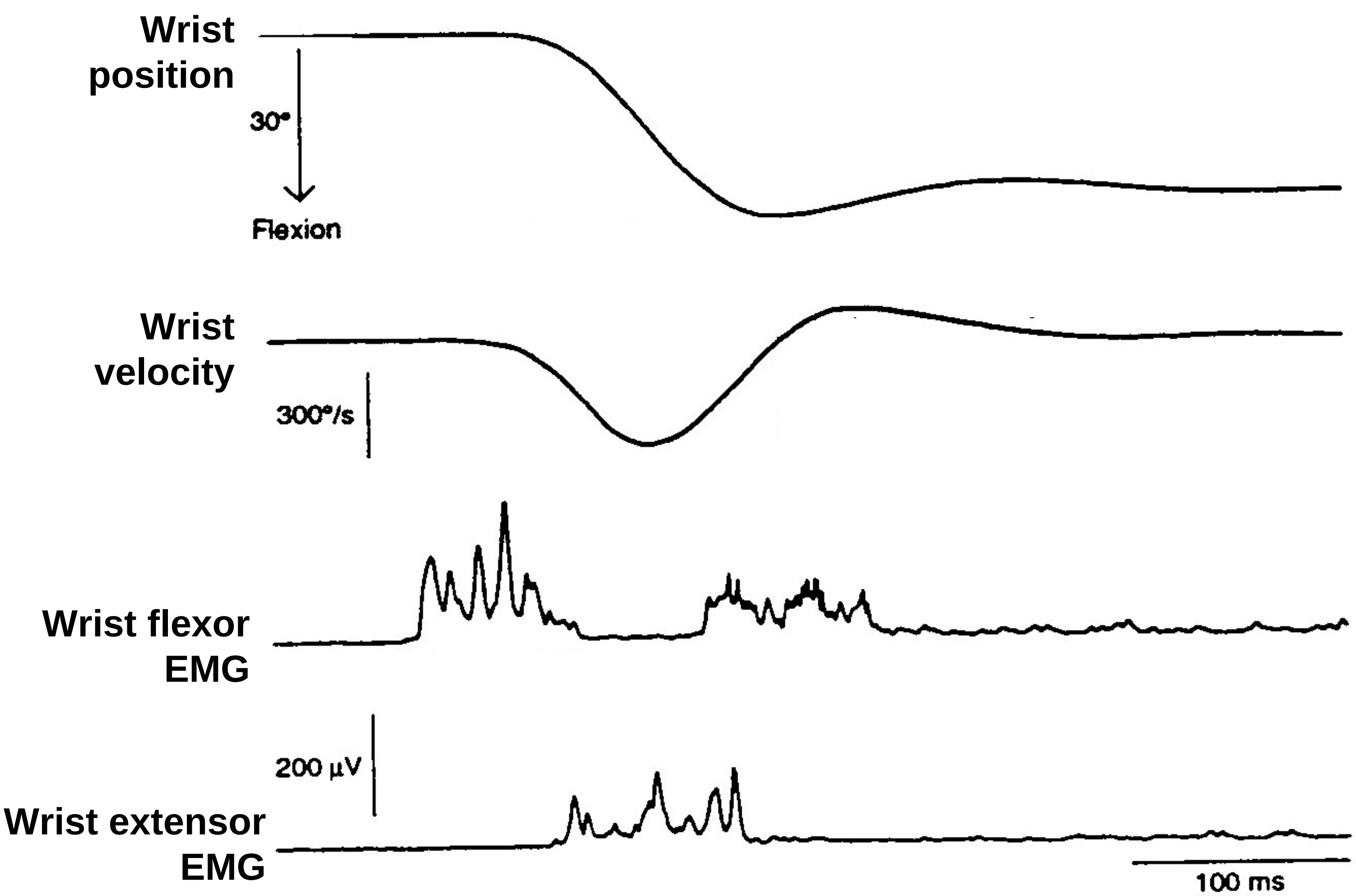
Muscles are organized in an “antagonistic” architecture

To rapidly move a limb, antagonist muscles are activated in sequence



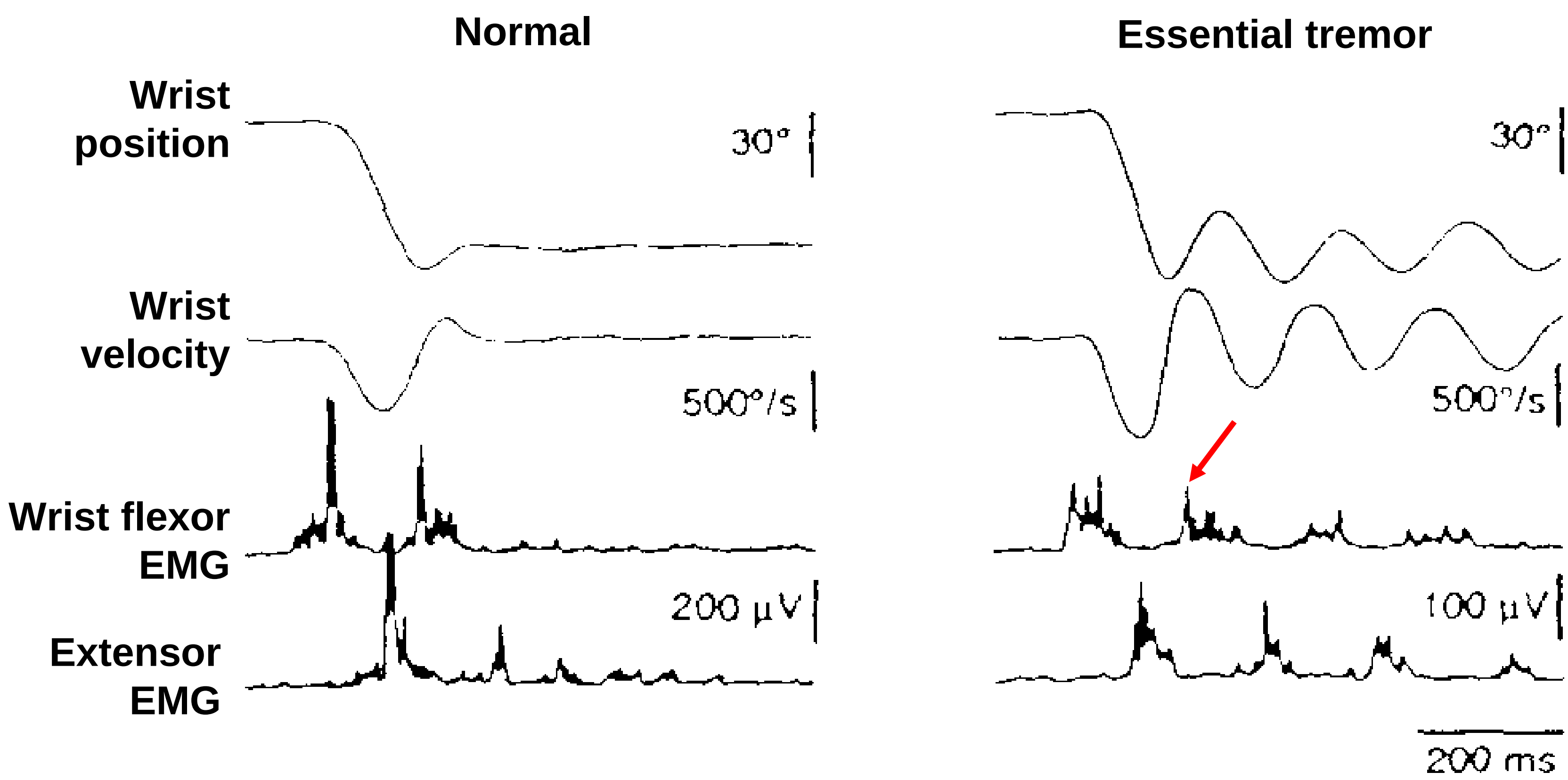


Rapid wrist flexion: agonist-antagonist-agonist activation pattern



Britton et al. 1994

Essential tremor: a cerebellar condition associated with delayed 2nd agonist burst



Britton et al. 1994

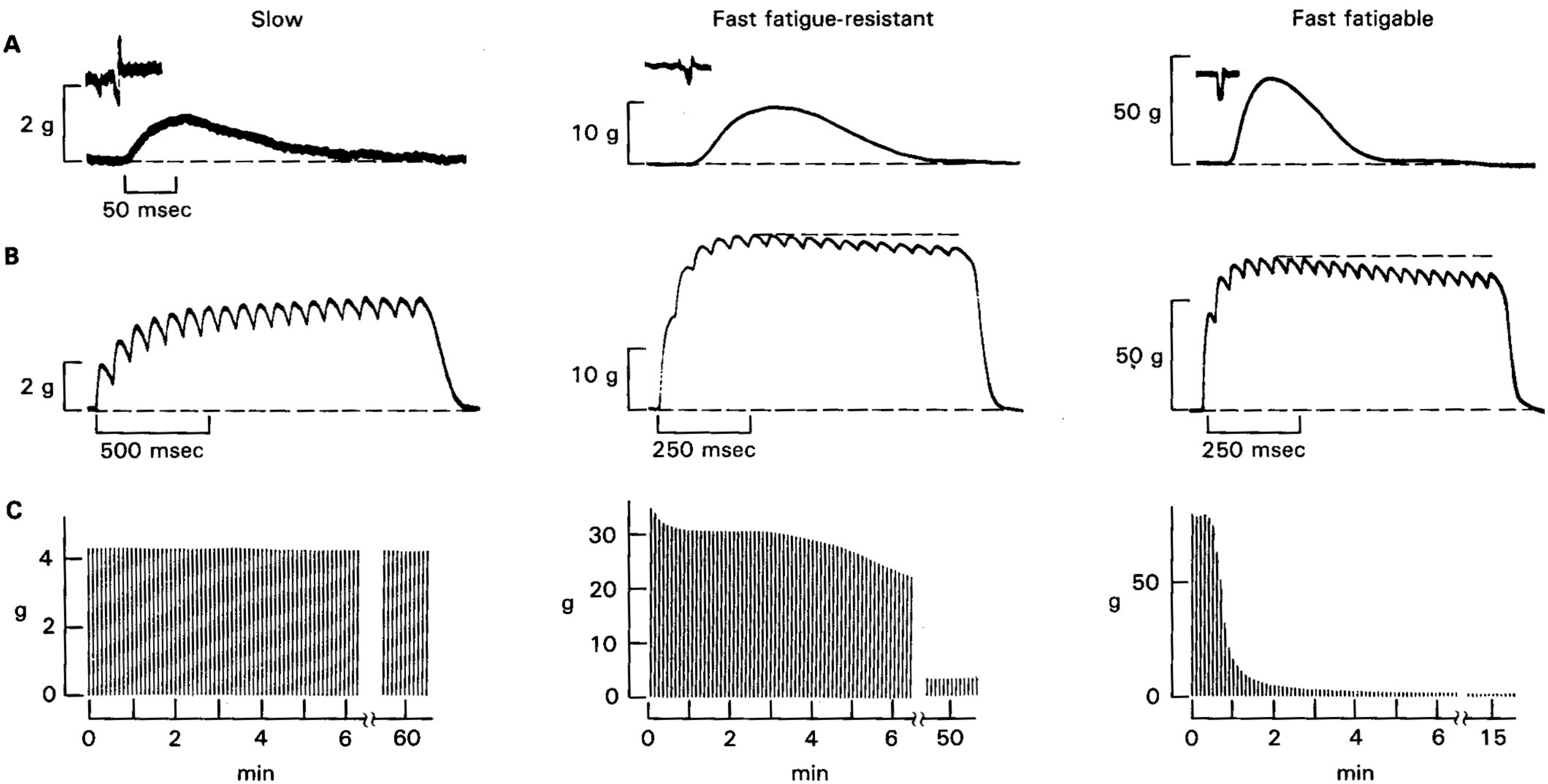
Types of Muscle Fibers

In adult humans, we find that a muscle may be made up of 3 distinct kinds of muscle fibers, where each fiber has a particular isoform of the myosin molecule.

- **Type I**: slow contracting fibers. Repeated stimulation results in little or no fatigue (loss of force).
- **Type II**: fast contracting fibers
    - Type IIa: fatigue resistant
    - Type IIx: easily fatigued

Composition of fiber types in a muscle depends on its function.

Types of Motor Units



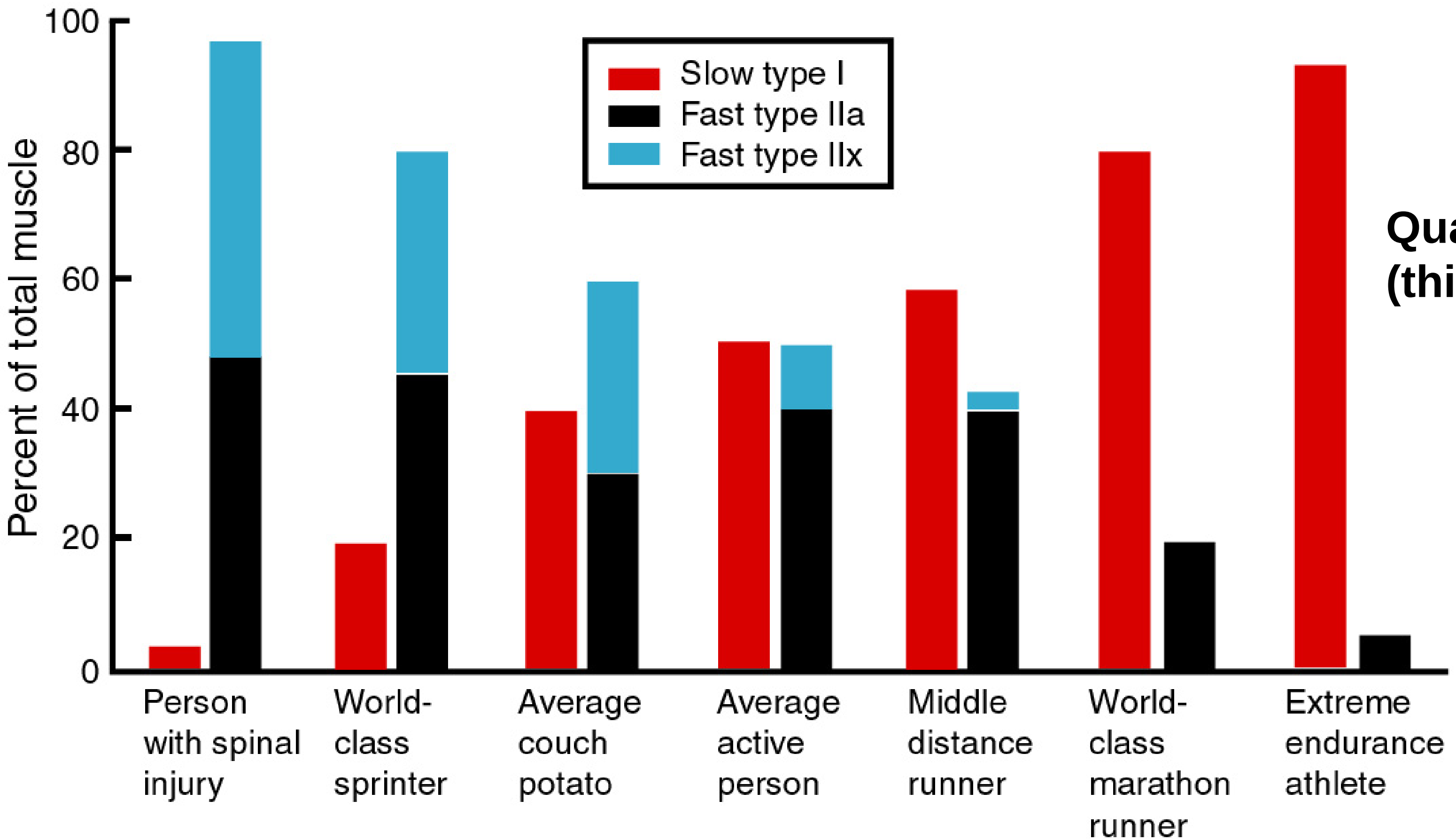
Three different motor neurons are stimulated intracellularly. A: Twitch response. B: Tetanic stimulation response. C: Tetanic stimulation for 330 msec, repeated every second.

RE Burke and P Tsairis, ANN NY ACAD SCI 228:145, 1974

Change in a Muscle: Spinal Cord Injury & Effect of Exercise

Strength training puts stress on tendons, signaling proteins to activate genes that make more myosin, resulting in the enlargement of muscle fiber. Type IIx fibers are slowly transformed into type IIa fibers.

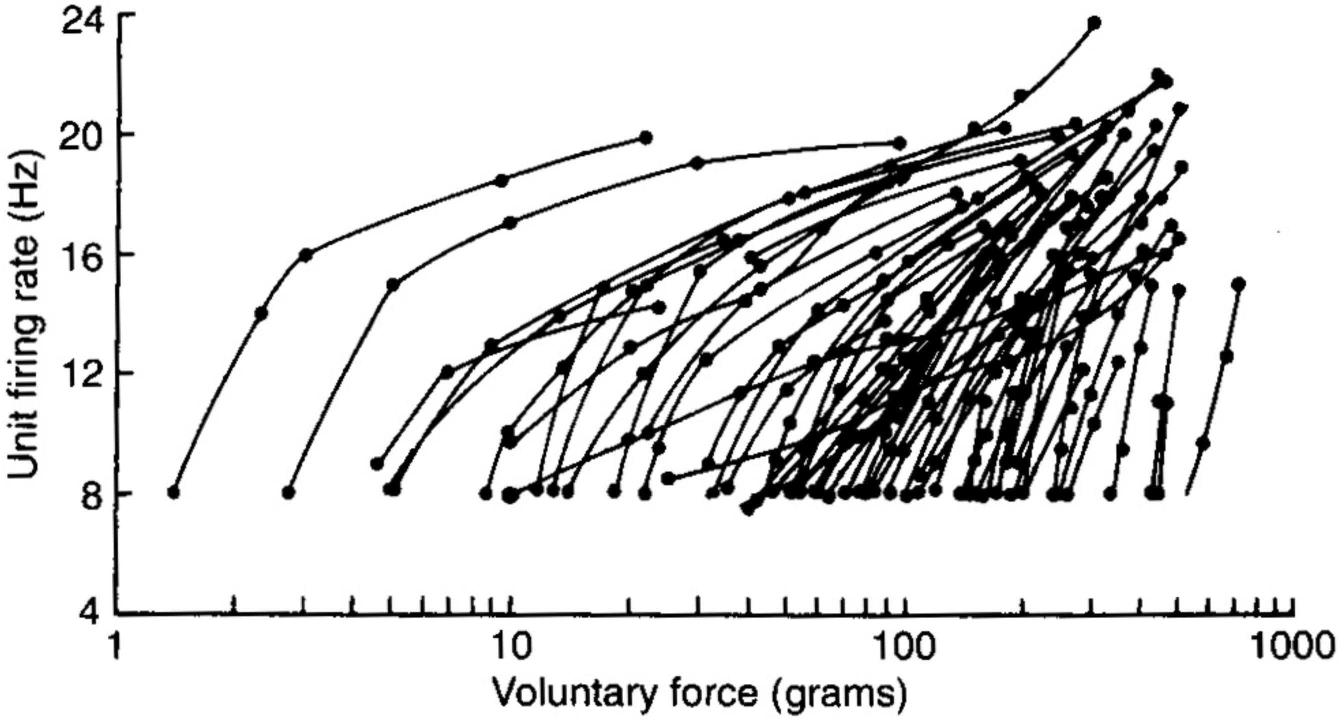
Paralysis: Transformation of type I fibers into type IIx.



Quadriceps (thigh muscle)

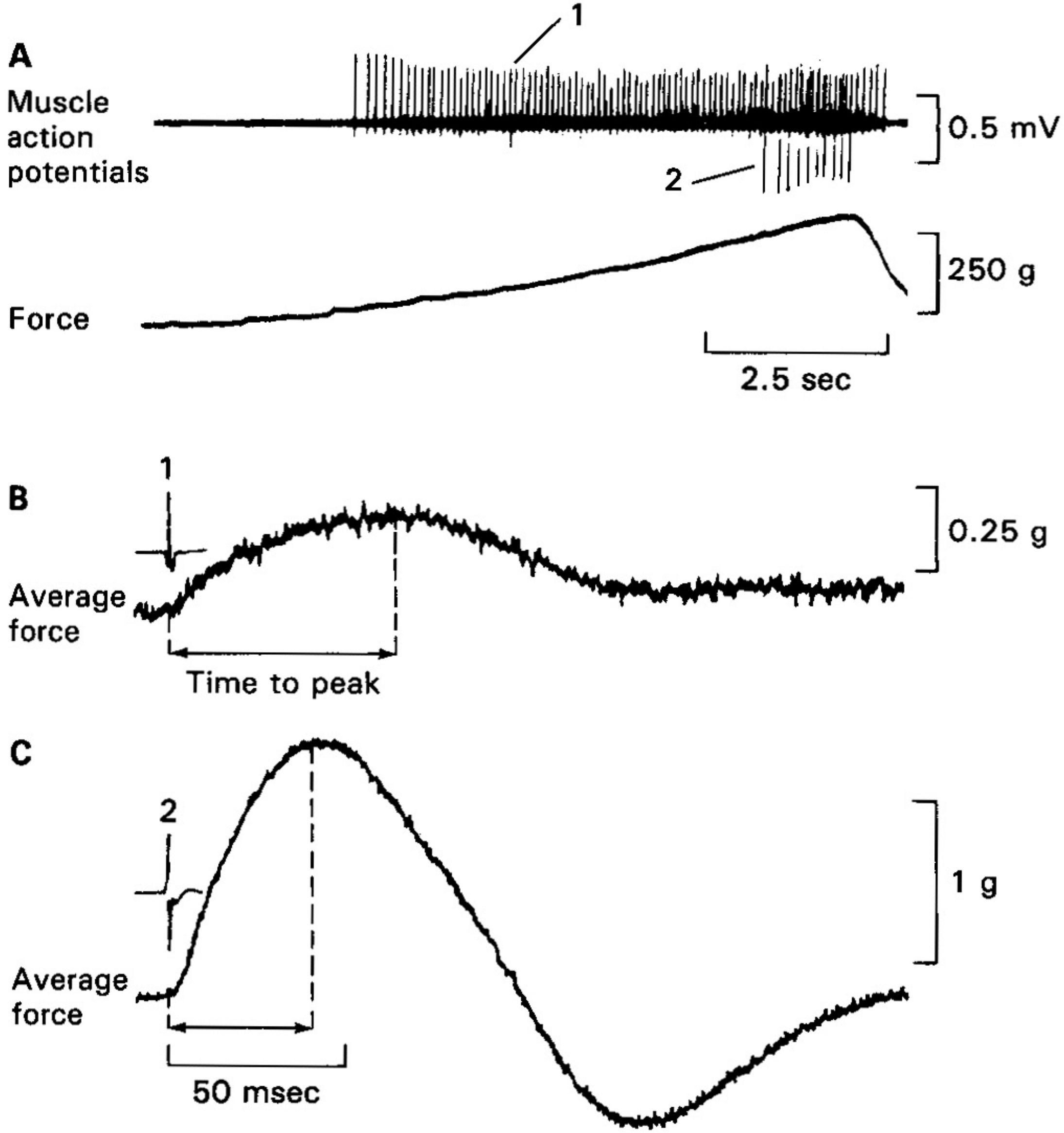
Control of Muscle Force

- As more force is need, more motor neurons are recruited.
- Frequency of activation of motor neurons is increased.



Monster AW & Chan H (1977) J Neurophysiol 40:1432

Motor units that are activated later tend to produce more force and have faster contraction time.



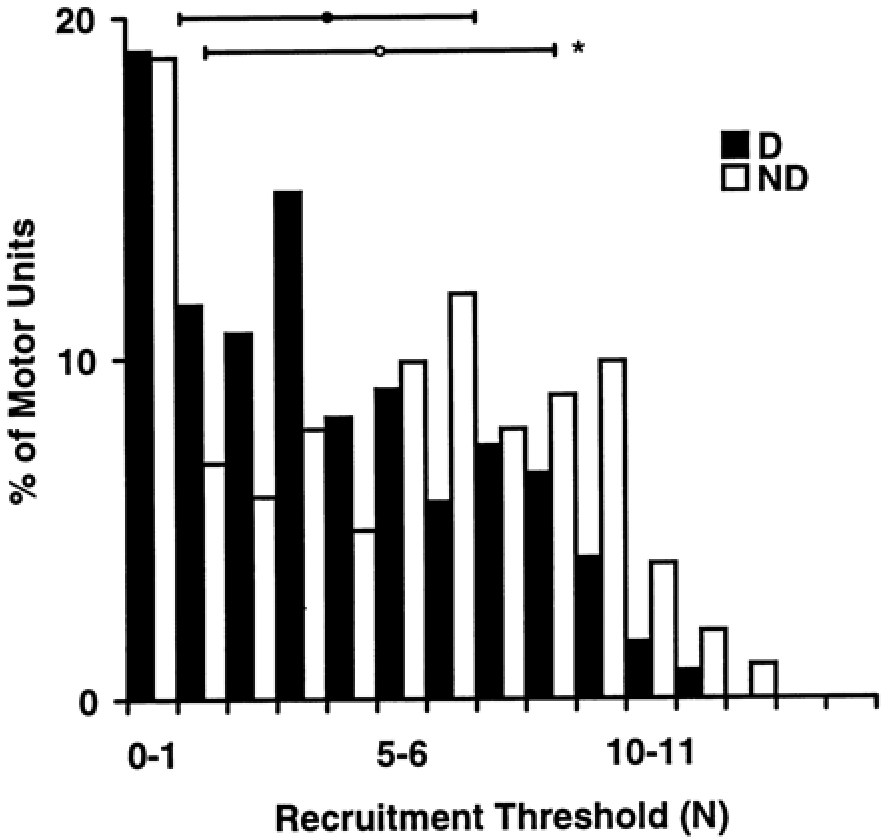
Motor unit 1

Motor unit 2

Desmedt JE & Godaux E (1977) Nature 267:717

Use dependent change in a motor unit recruitment: effect of handedness

Muscles of the dominant hand are used more, and so should have larger proportion of type I muscle fibers. To produce a given amount of force, a muscle that has a large number of type I muscle fibers will recruit a proportionally large number of motor units.



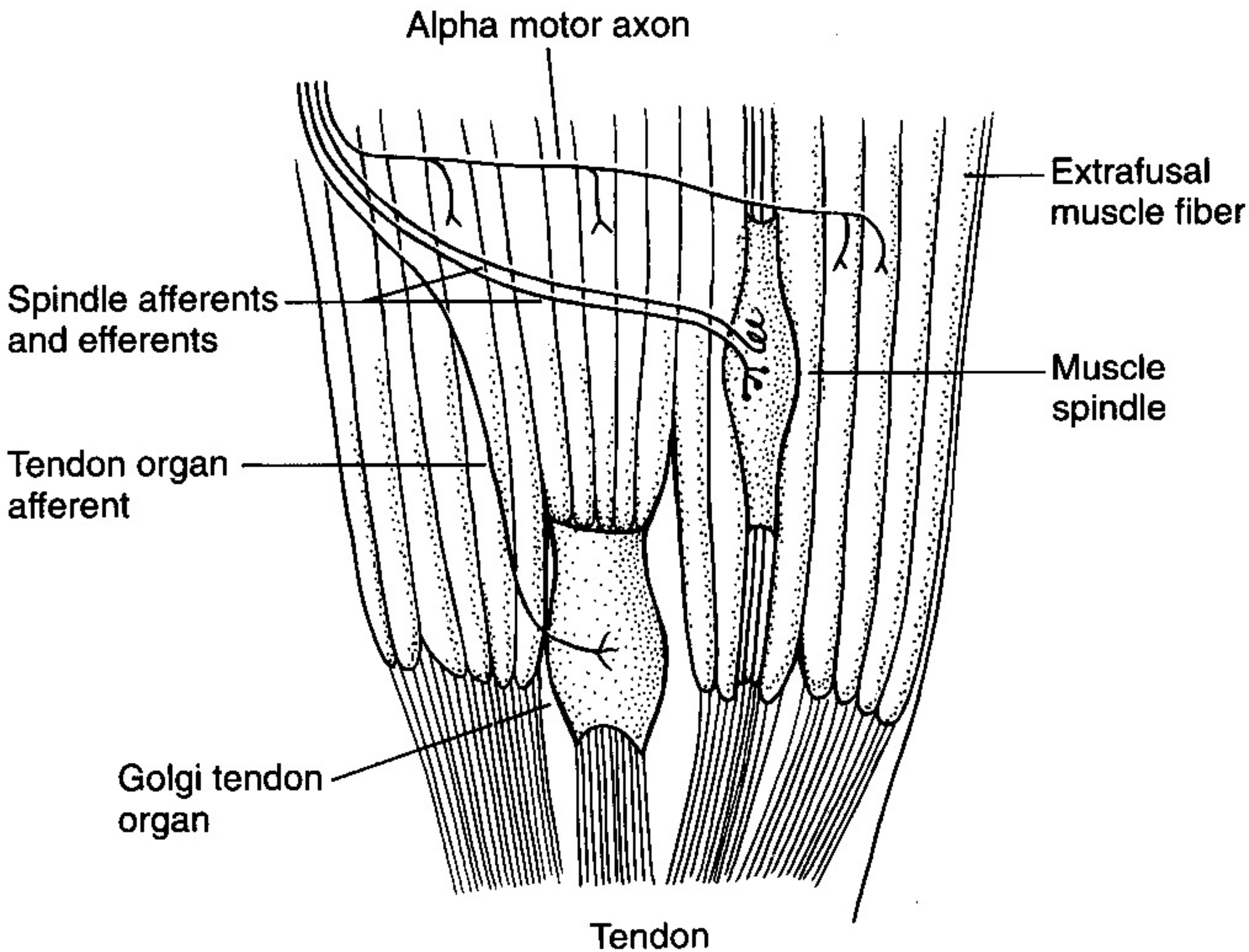
Distribution of motor unit recruitment threshold in dominant (D) and non-dominant (ND) hands. The task is isometric force production in the 1st dorsal interosseous muscle.

Adam, De Luca, Erim (1998) J. Neurophysiology 80:1373.

Muscle’s sensory system allows the CNS to measure force and length of the muscle

(Ia and II afferents)
(Gamma motor neuron)

(Ib afferents)

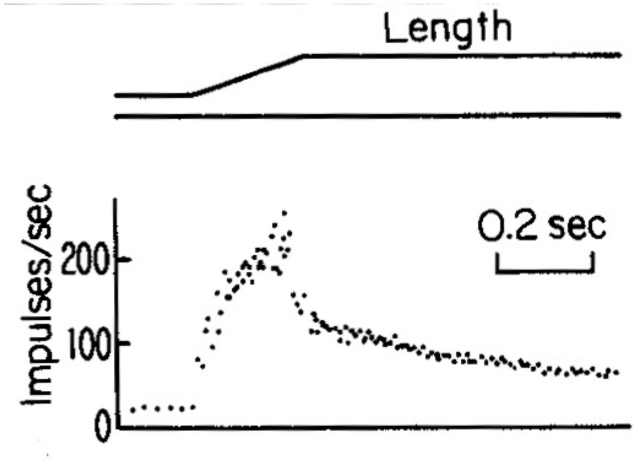


Houk et al. (1980)

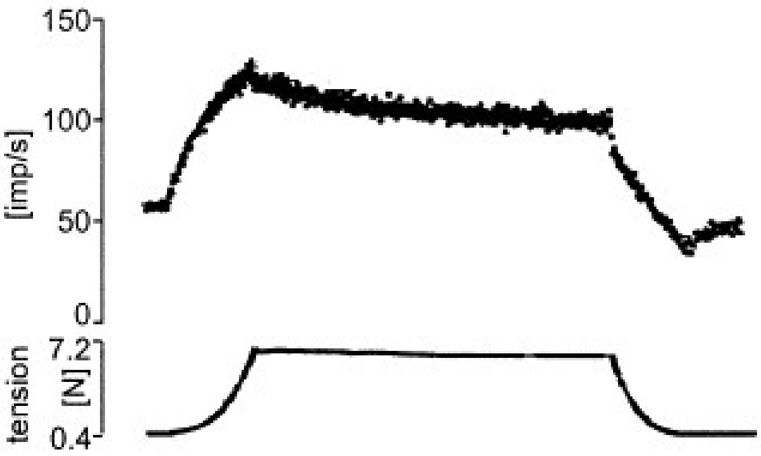
Spindle afferents signal length change in the muscle

Golgi tendon afferent signal force change in the muscle

Response of a muscle spindle afferent to an isotonic stretch

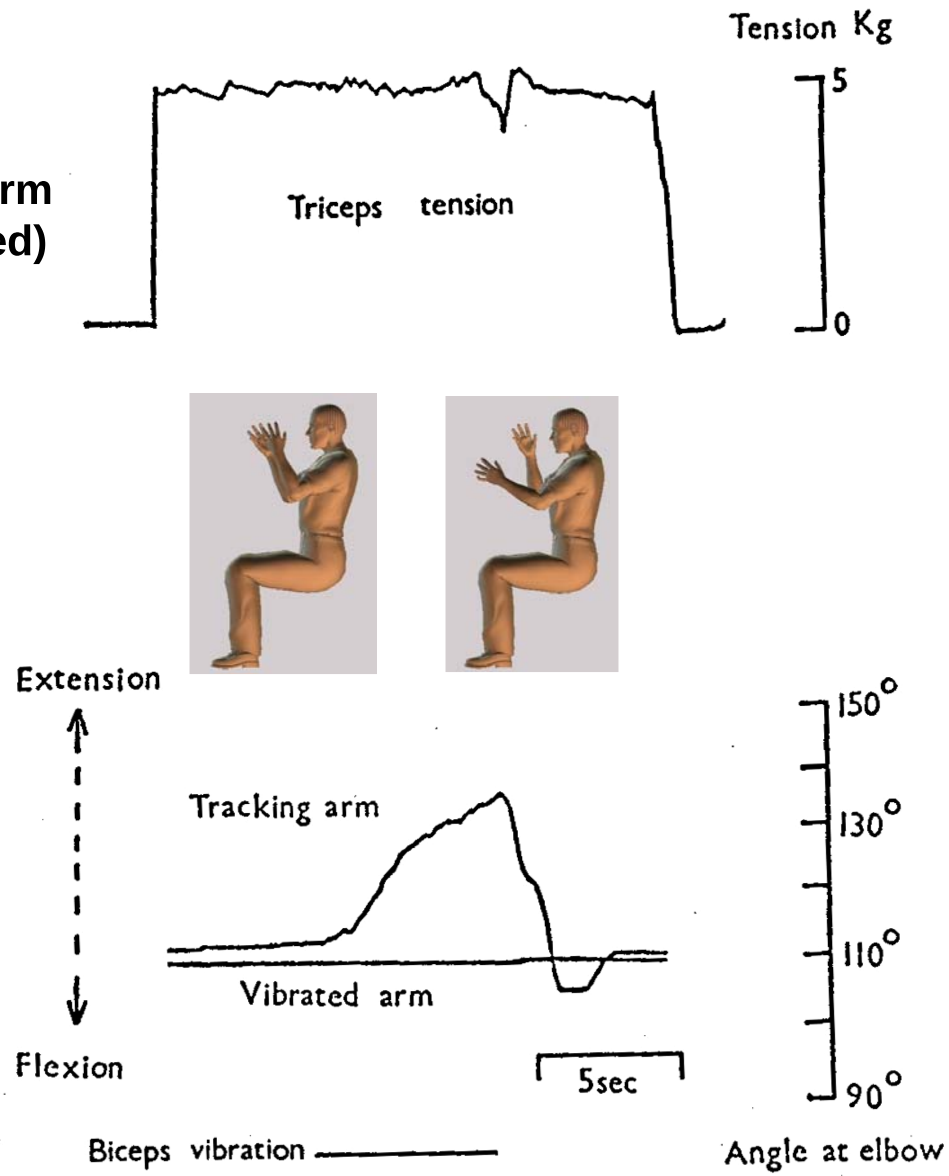


Response of a Golgi tendon afferent to an isometric increase in force



Our sense of limb position is via muscle spindles

Right arm (vibrated)



Elbows on a table, eyes closed. Right hand pulling a string attached to the ceiling. Task is to match position of the right arm with the left arm.

Right biceps is vibrated but remains stationary.

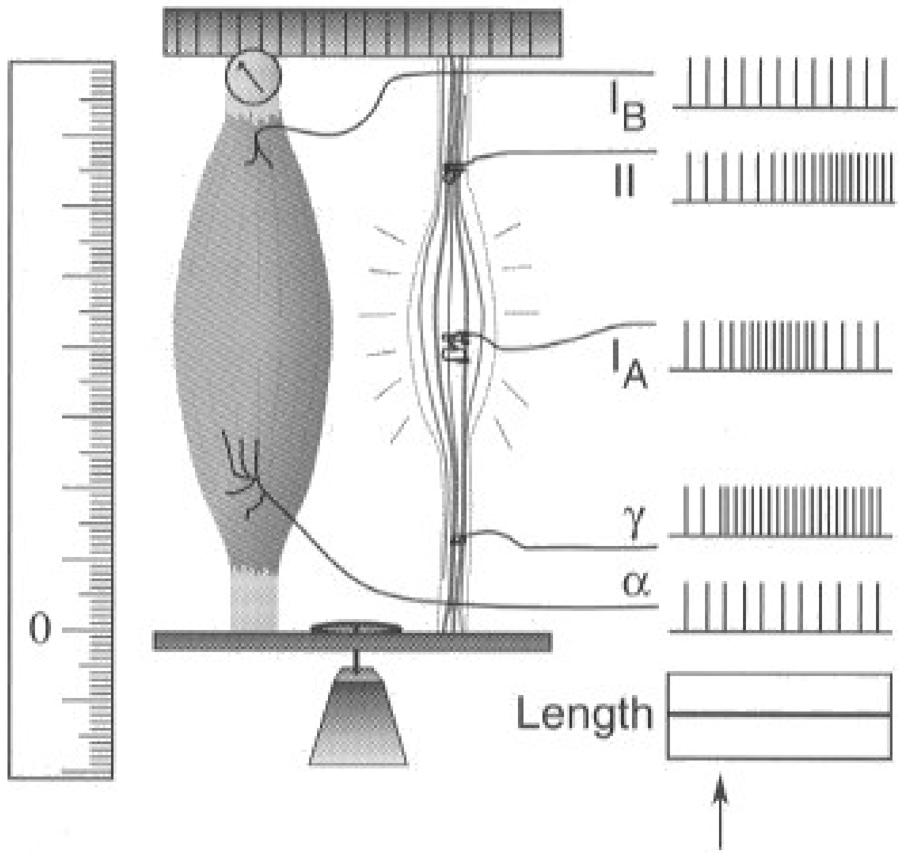
The tracking arm (left arm) becomes extended.

Gamma motor neurons control the sensitivity of the spindle afferents

Spindle is in parallel to the extrafusal muscle fibers

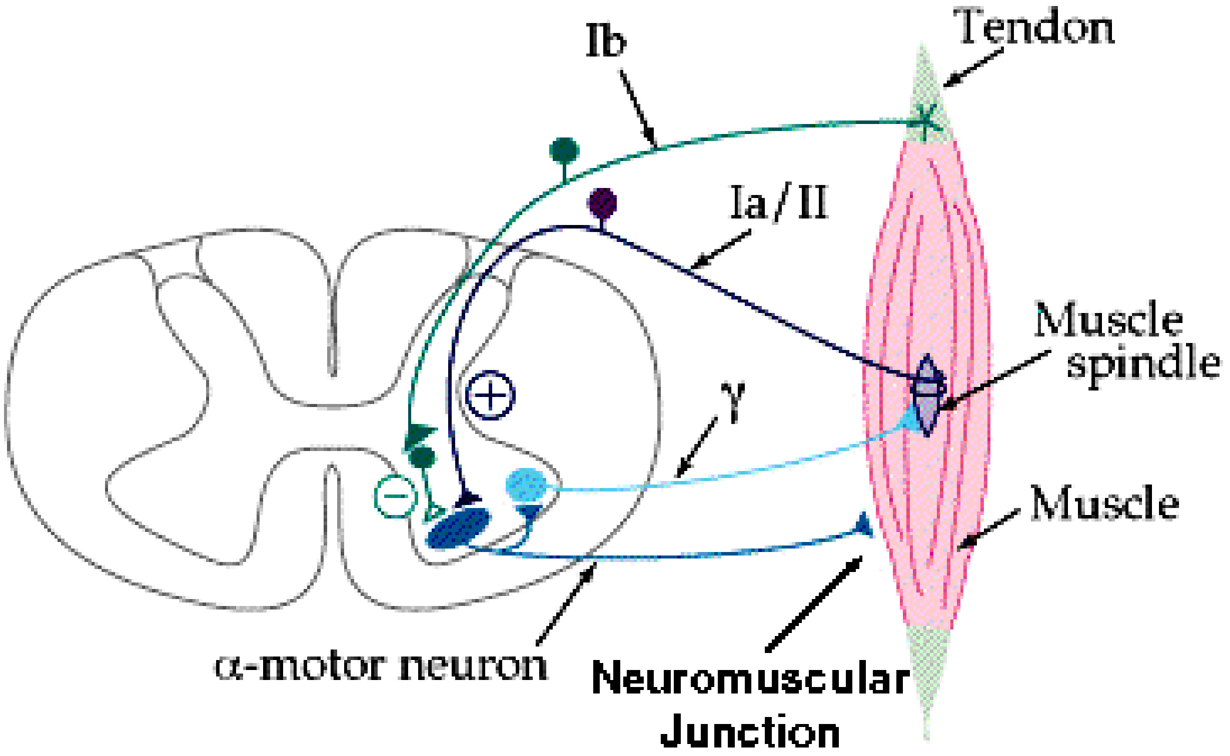
Stimulation of the γ-motor neuron shortens the spindle. This results in increased firing in the spindle afferent.

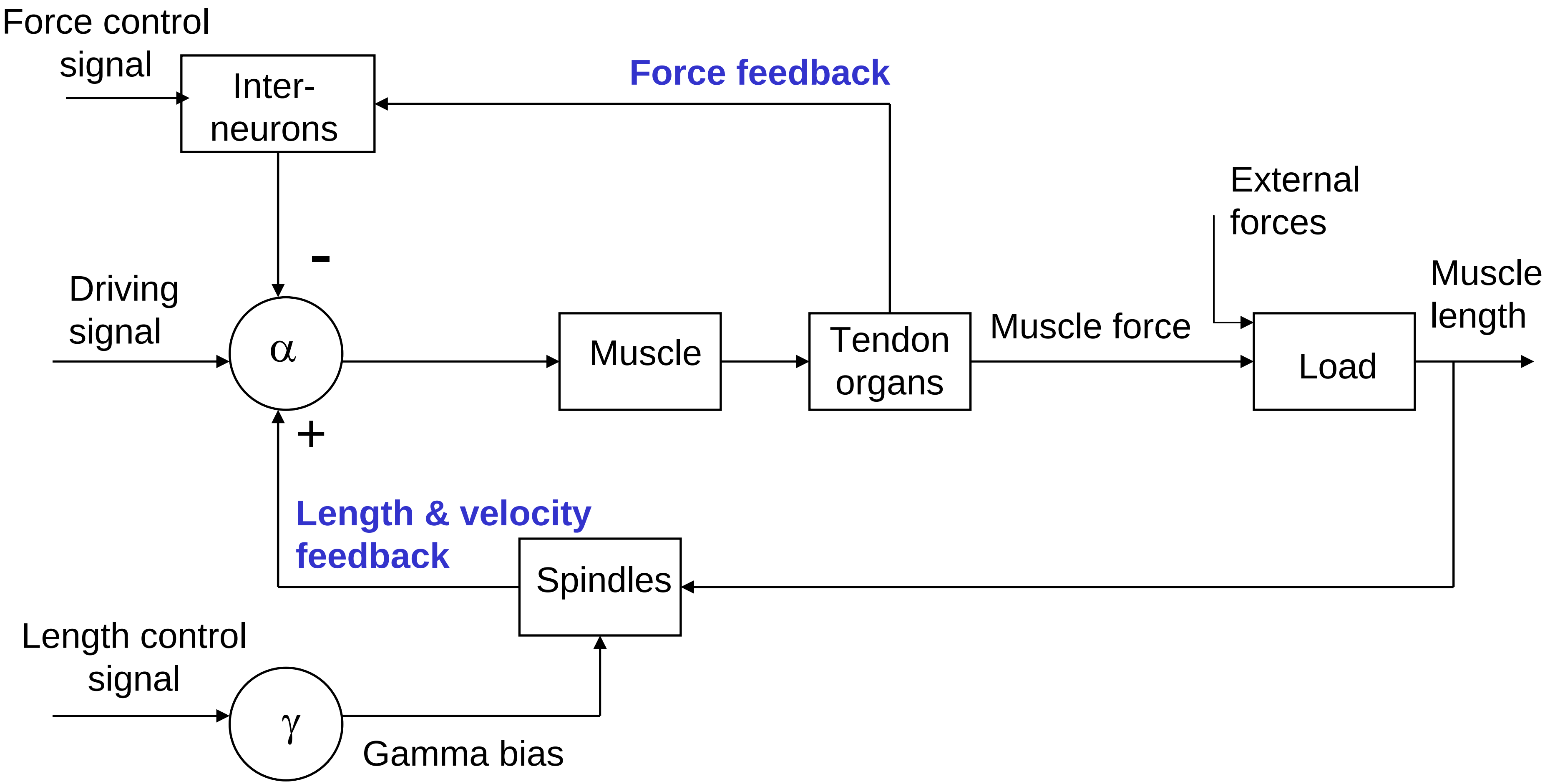
Spindle is sensitive to both γ-motor neuron input and the length of the extrafusal muscle.

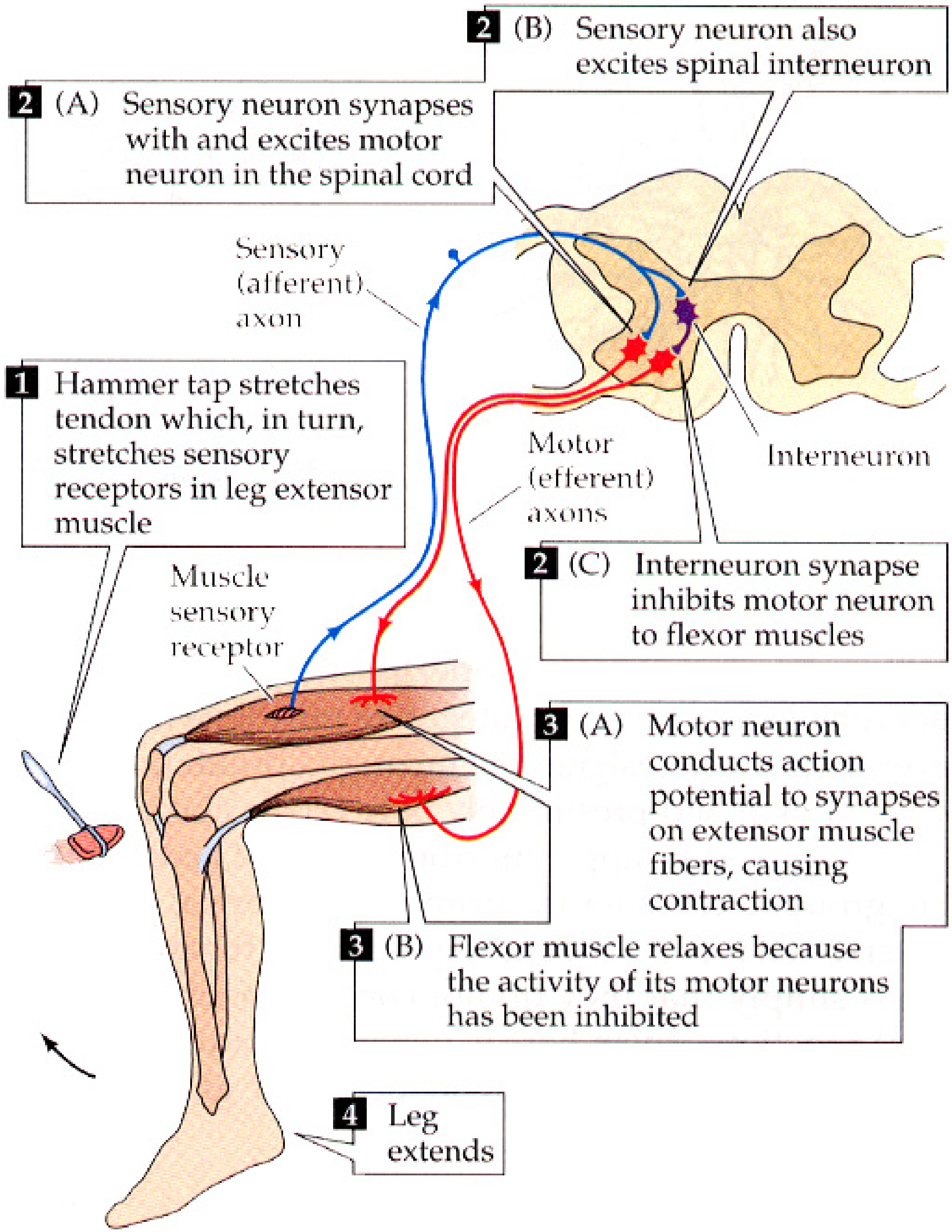


Spindle afferents excite α-motor neurons of the same muscle

Golgi tendon afferents inhibit (via inter-neurons) α-motor neurons of the same muscle

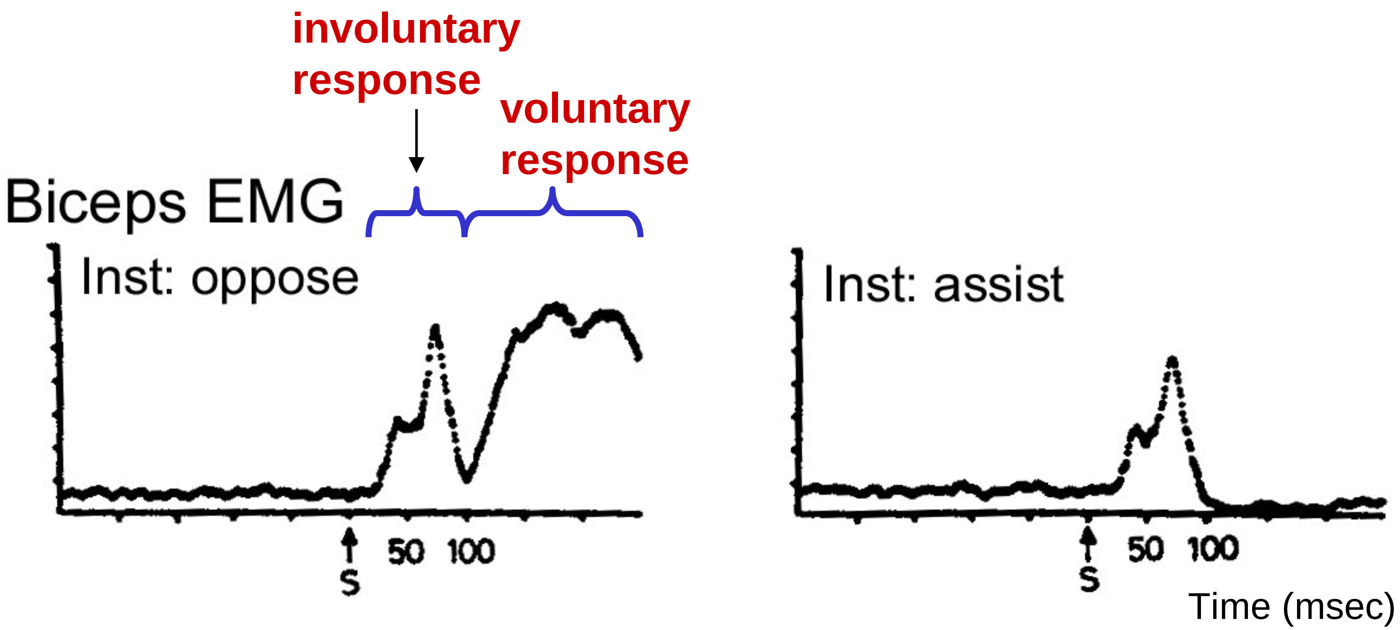



Force control signal
Inter-neurons
Force feedback
External forces
-
Driving signal
α
Muscle
Tendon organs
Muscle force
Load
Muscle length
+
Length & velocity feedback
Spindles
Length control signal
γ
Gamma bias



2 (B) Sensory neuron also excites spinal interneuron
2 (A) Sensory neuron synapses with and excites motor neuron in the spinal cord
Sensory (afferent) axon
1 Hammer tap stretches tendon which, in turn, stretches sensory receptors in leg extensor muscle
Motor (efferent) axons
Interneuron
2 (C) Interneuron synapse inhibits motor neuron to flexor muscles
Muscle sensory receptor
3 (A) Motor neuron conducts action potential to synapses on extensor muscle fibers, causing contraction
3 (B) Flexor muscle relaxes because the activity of its motor neurons has been inhibited
4 Leg extends

Time delay in the Reflex Loop Pathways

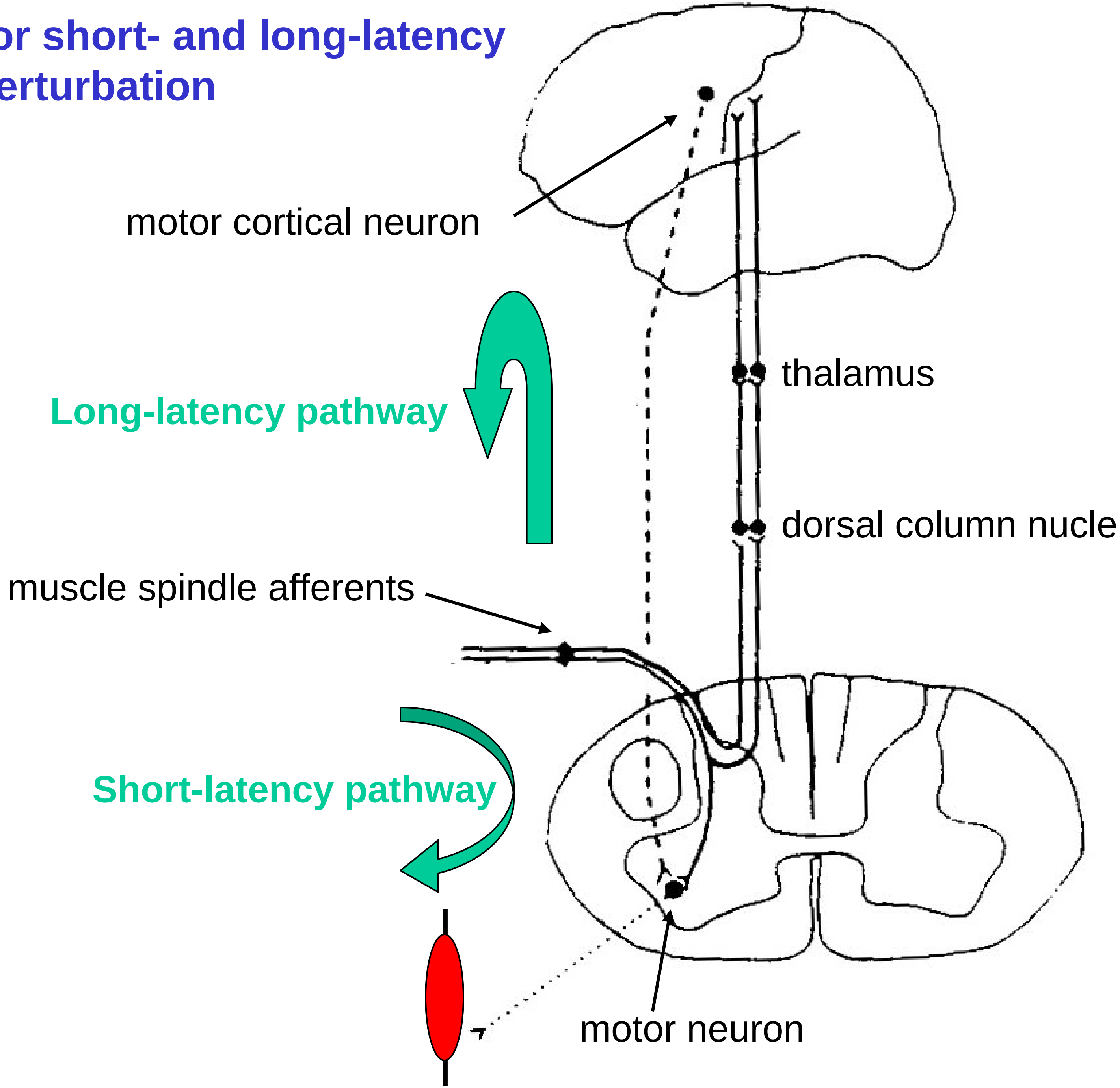


Task: biceps is suddenly stretched at time (S). Before the stretch, subject is instructed to either oppose the stretch (left), or assist it (right).

Delay in fastest reflexes is 30 msec.

Strick P (1978)

The pathways for short- and long-latency response to a perturbation



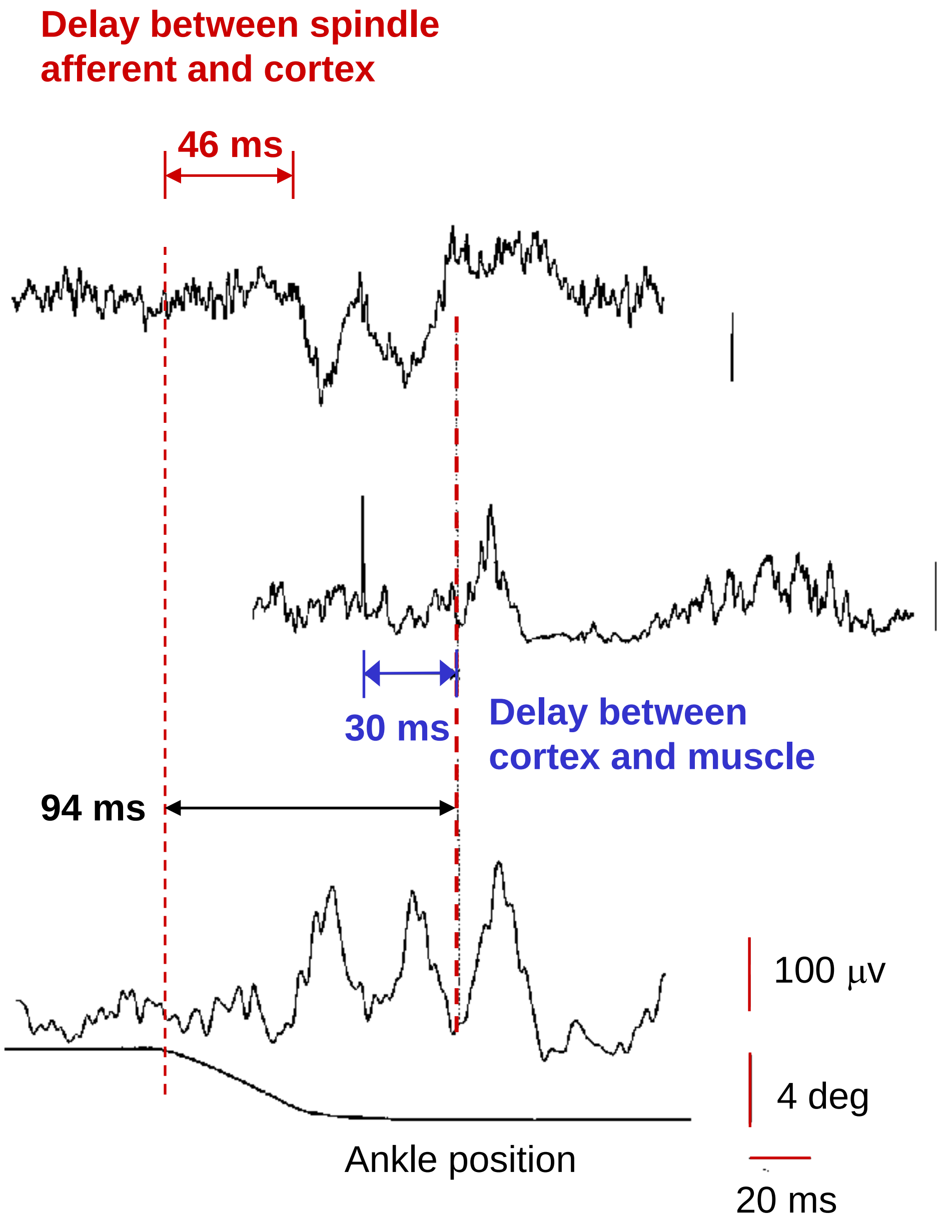
Time delays in the long latency reflexes

Ankle of a subject is suddenly stretched.

Evoked potential from somatosensory cortex (recorded by EEG electrode)

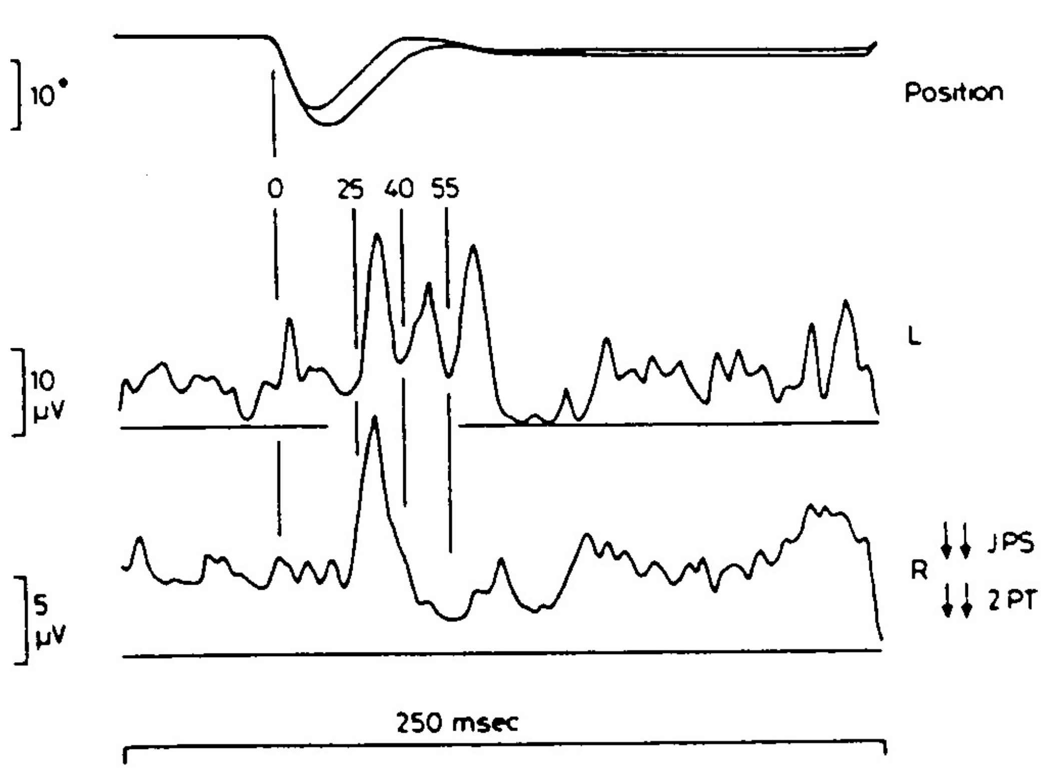
Evoked potential (recorded with EMG electrode from the ankle dorsiflexor muscle) when motor cortex of same subject is stimulated via magnetic stimulation

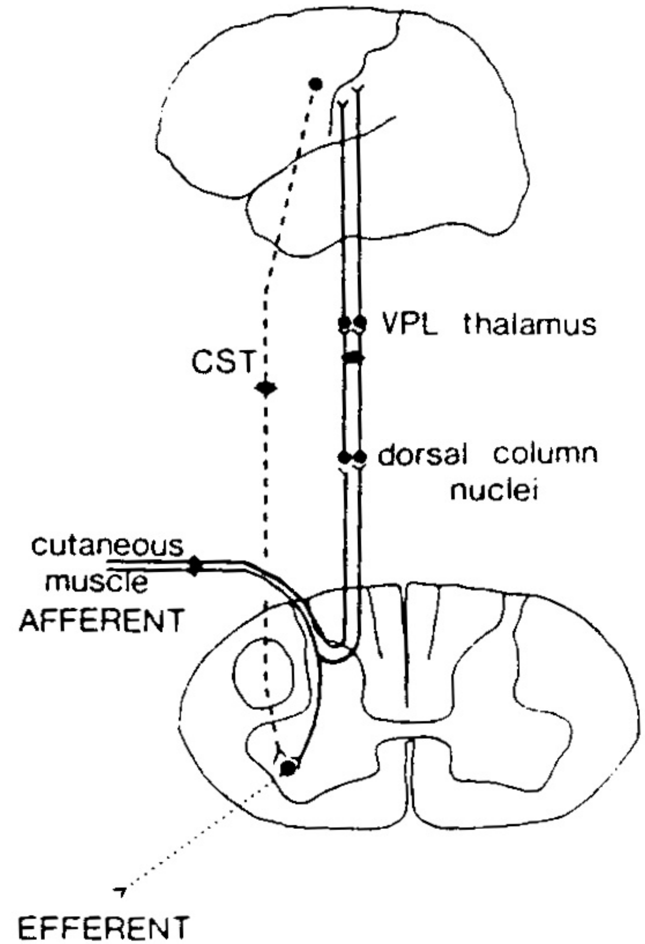
EMG recorded when ankle dorsiflexor muscle is suddenly stretched



Petersen et al. *J Physiol* 1998

Absence of long latency reflexes in a patient with right brainstem stroke

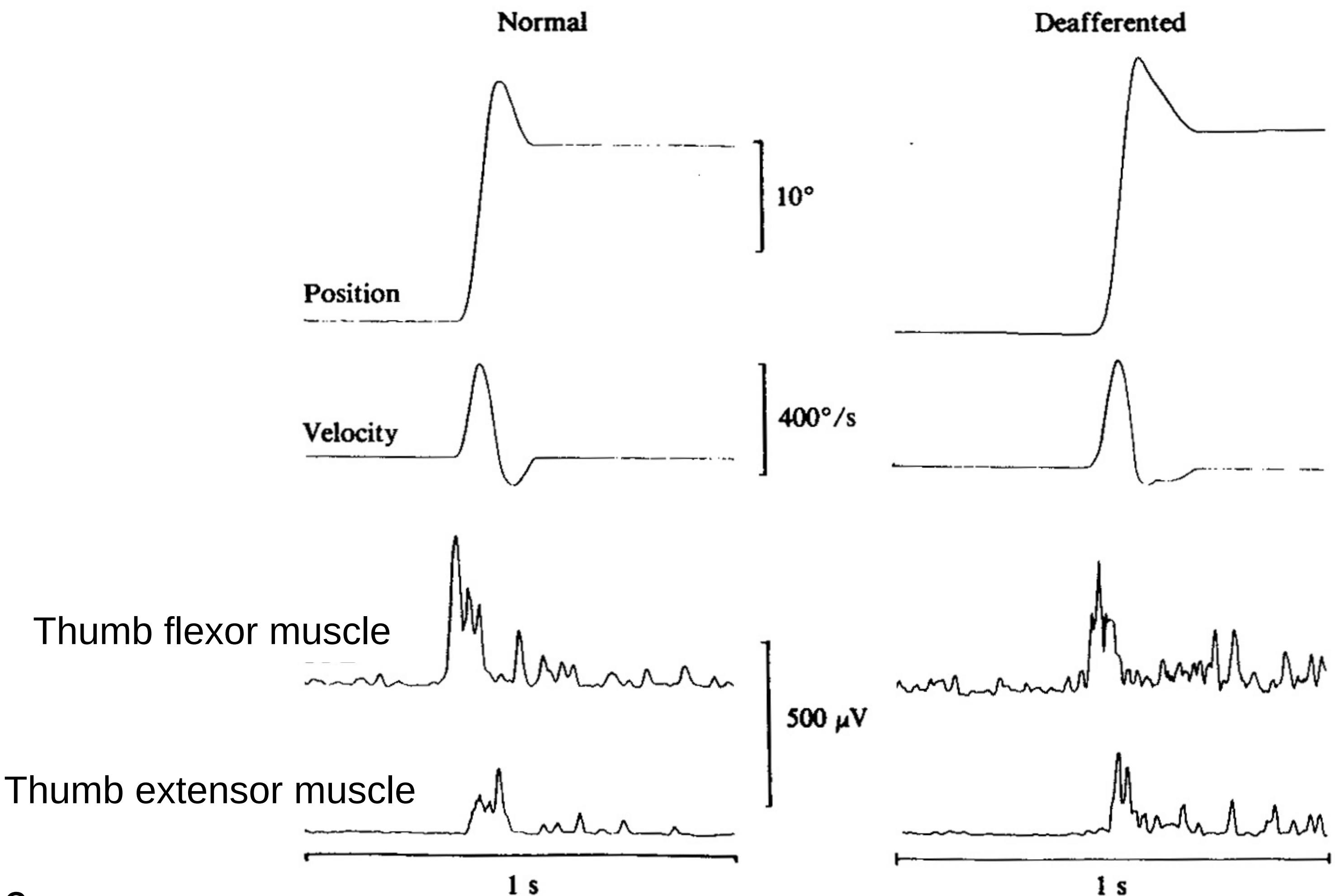




Brief stretch of thumb flexor muscle (at time zero) in a patient with lesion in the dorsal aspect of the right caudal medulla (stroke). Patient has no sense of position or two point discrimination on the right hand, but is normal on the left hand.

Patients without large fiber afferents can move their limbs

Rapid thumb flexion with visual feedback of the hand



Without afferents, vision is necessary to maintain limb posture

Rapid thumb flexion without visual feedback of the hand