HUMAN ROBOTICS

- muscle mechanics and control
- single-joint neuromechanics
- multi-joint multi-muscle kinematics
- multi-joint dynamics and control
- motor learning and memory
- interaction control
- motion planning and online control
- integration and control of sensory feedback
- applications in neurorehabilitation and robotics

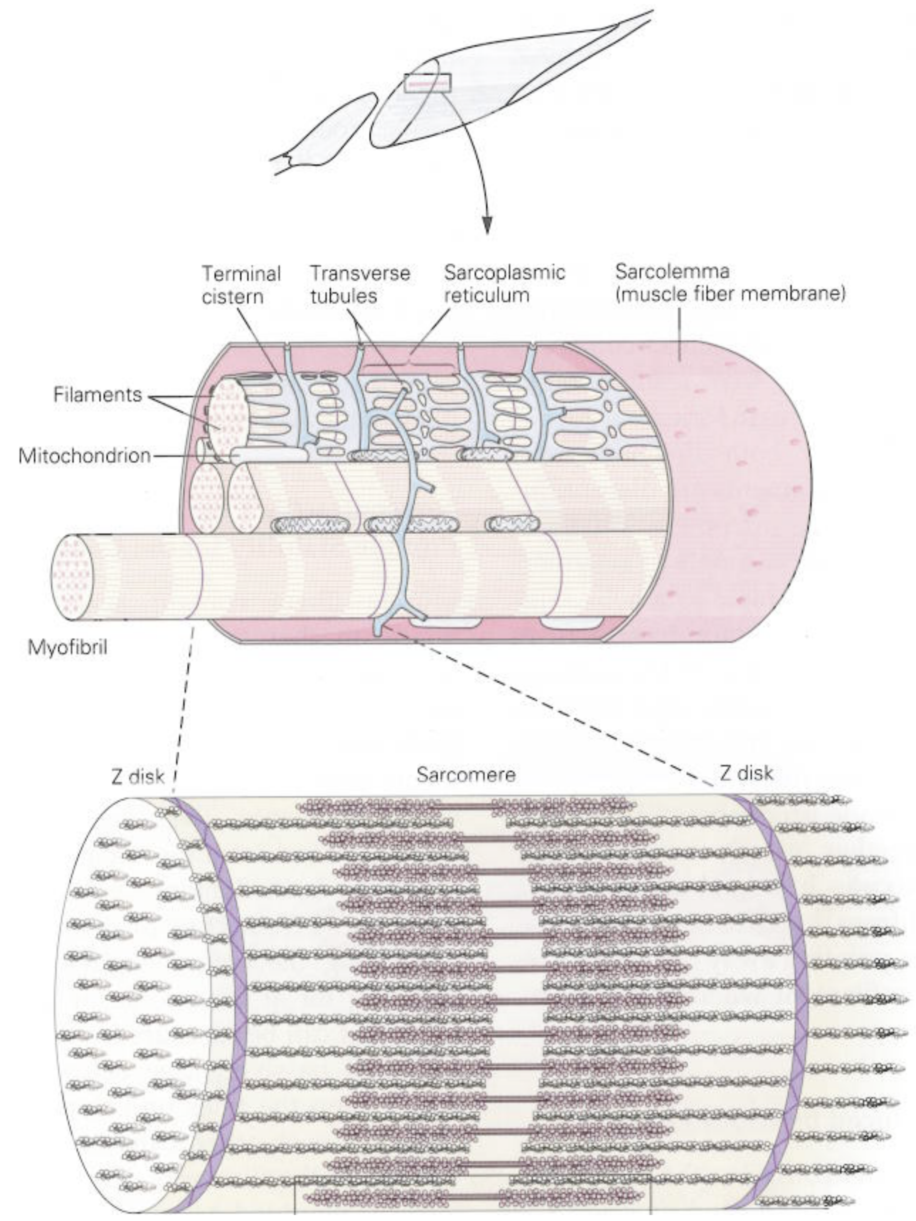
MUSCLES TYPES

- the major consequence of the information processing that takes place in the (animal) brain is the contraction of skeletal muscles

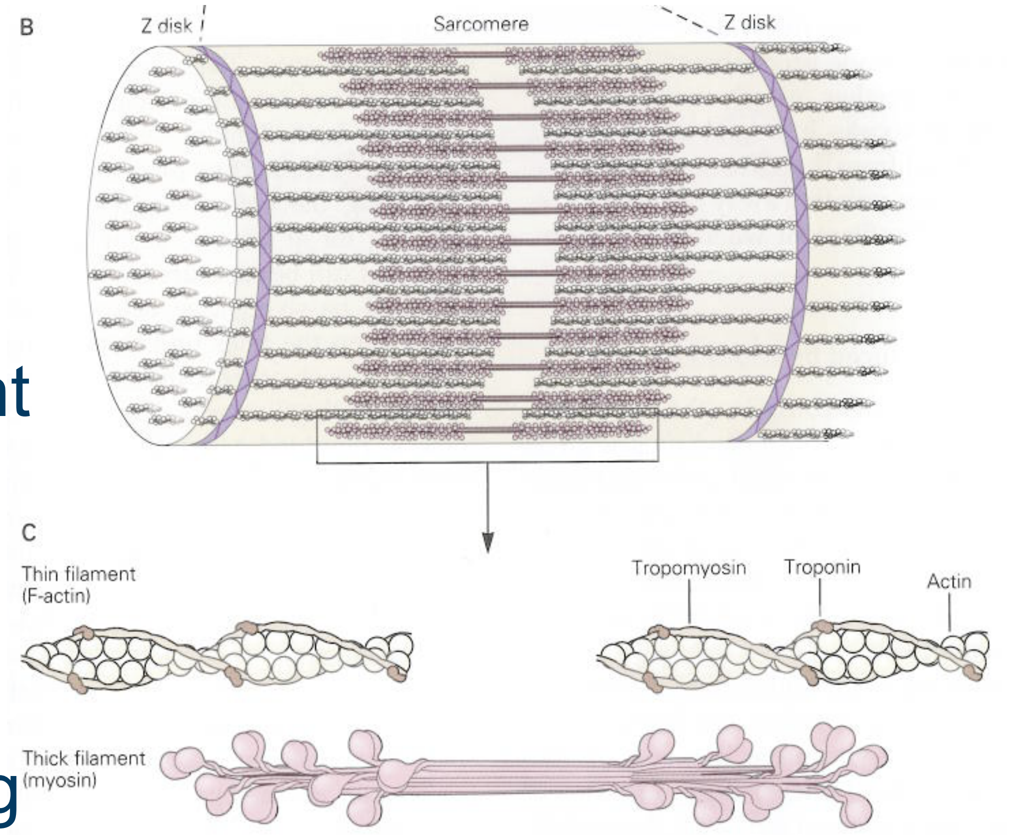
- there are three types of muscles:
  - smooth muscles (gut and blood flow control)
  - cardiac muscle
  - skeletal muscles to move the bones and flesh

MUSCLES FIBERS

- a typical muscle consists of many thousands of muscle fibers working in parallel
- motor unit: one or several fibers activated by one motor neuron
- a single muscle fiber contains several myofibrils, made of sarcomere sections separated by Z disks



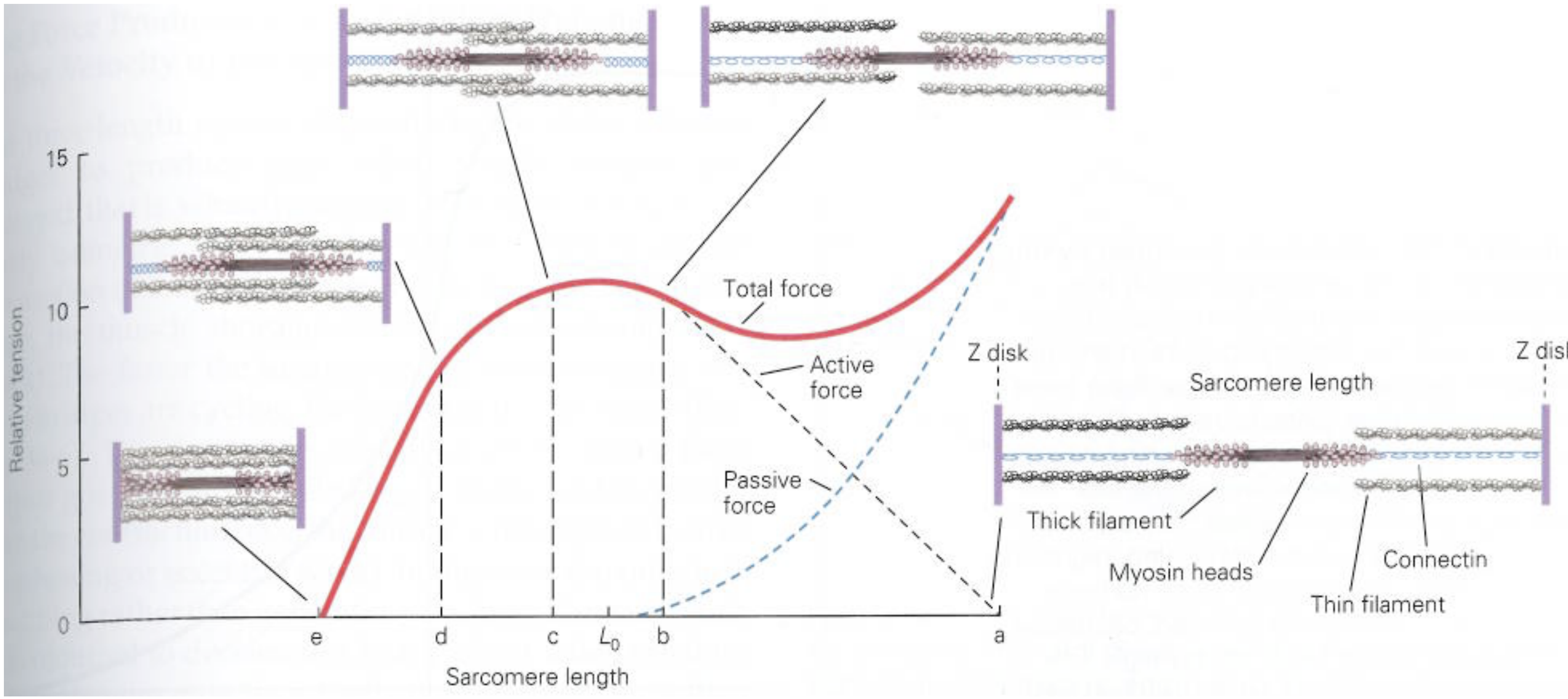
CROSS BRIDGES



- actin (thin) and myosin (thick) filaments are arranged in hexagonal lattice: 1 thick filament interacts with 6 thin filaments
- cross-bridges linking actin and myosin pull towards center of sarcomere ⇒ muscle shortening

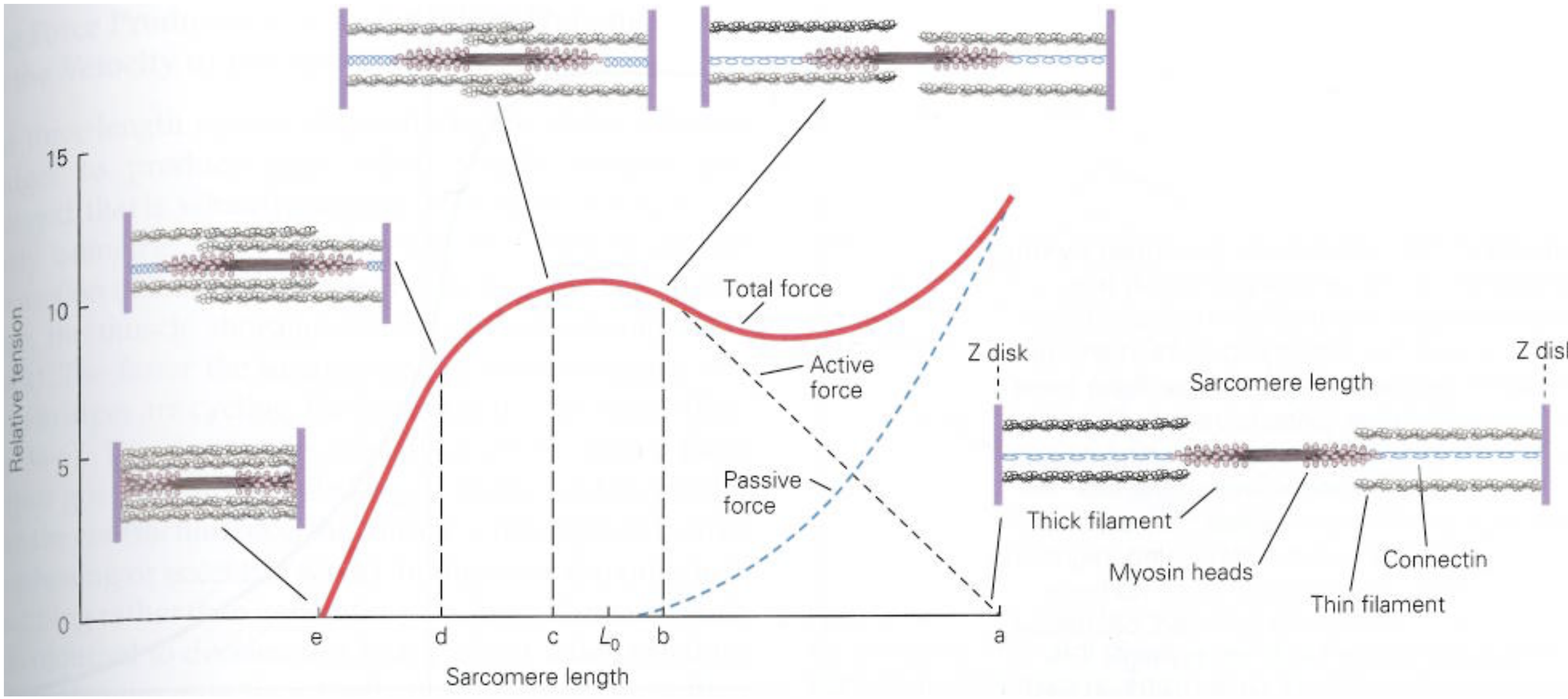
- actin and myosin filaments slide by repeated attachment and detachment of cross-bridges (AF Huxley et al. 1950)
- if muscle shortening is prevented isometric tension develops

SARCOMERE FORCE VS LENGTH



- active force declines at long lengths as filament overlap is reduced
  $\Rightarrow$ fewer actin sites available for myosin binding
- active force declines at short lengths because filaments interfere

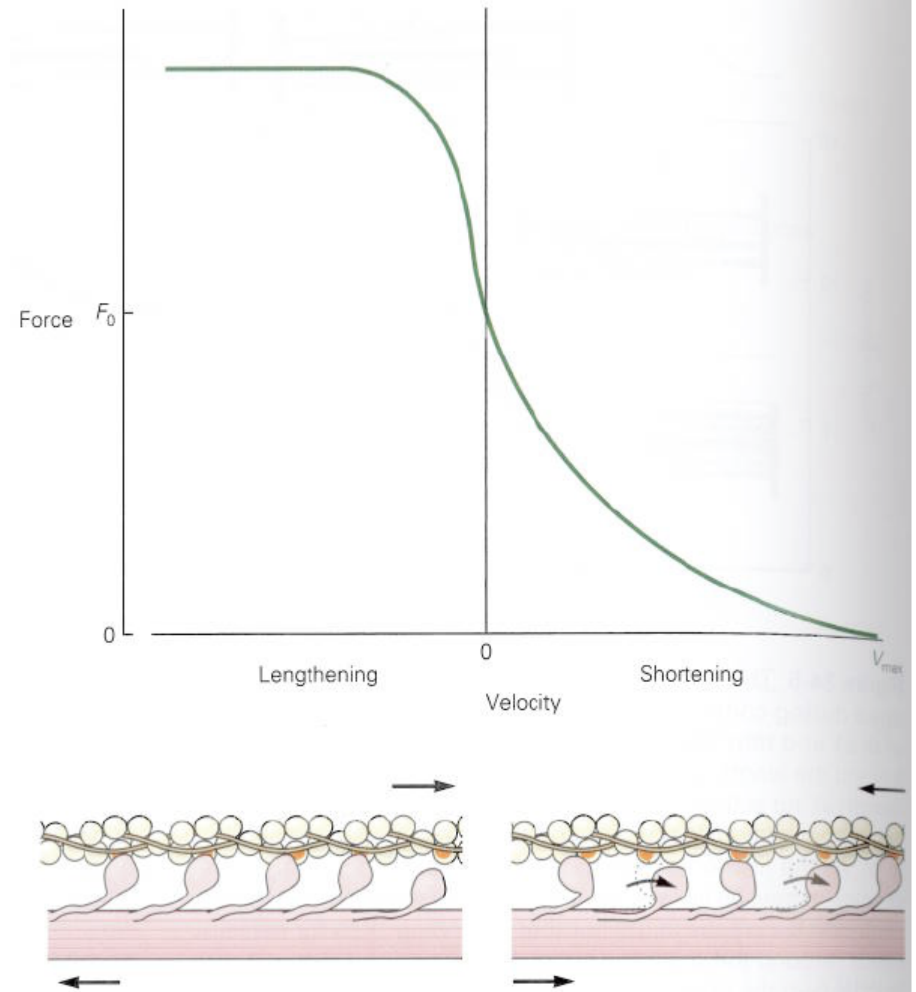
SARCOMERE FORCE VS LENGTH



- sarcomere force and stiffness vary with muscle length in proportion to number of cross bridges
- passive force increases at long lengths as structural proteins and myofilaments are stretched

SARCOMERE FORCE VS VELOCITY

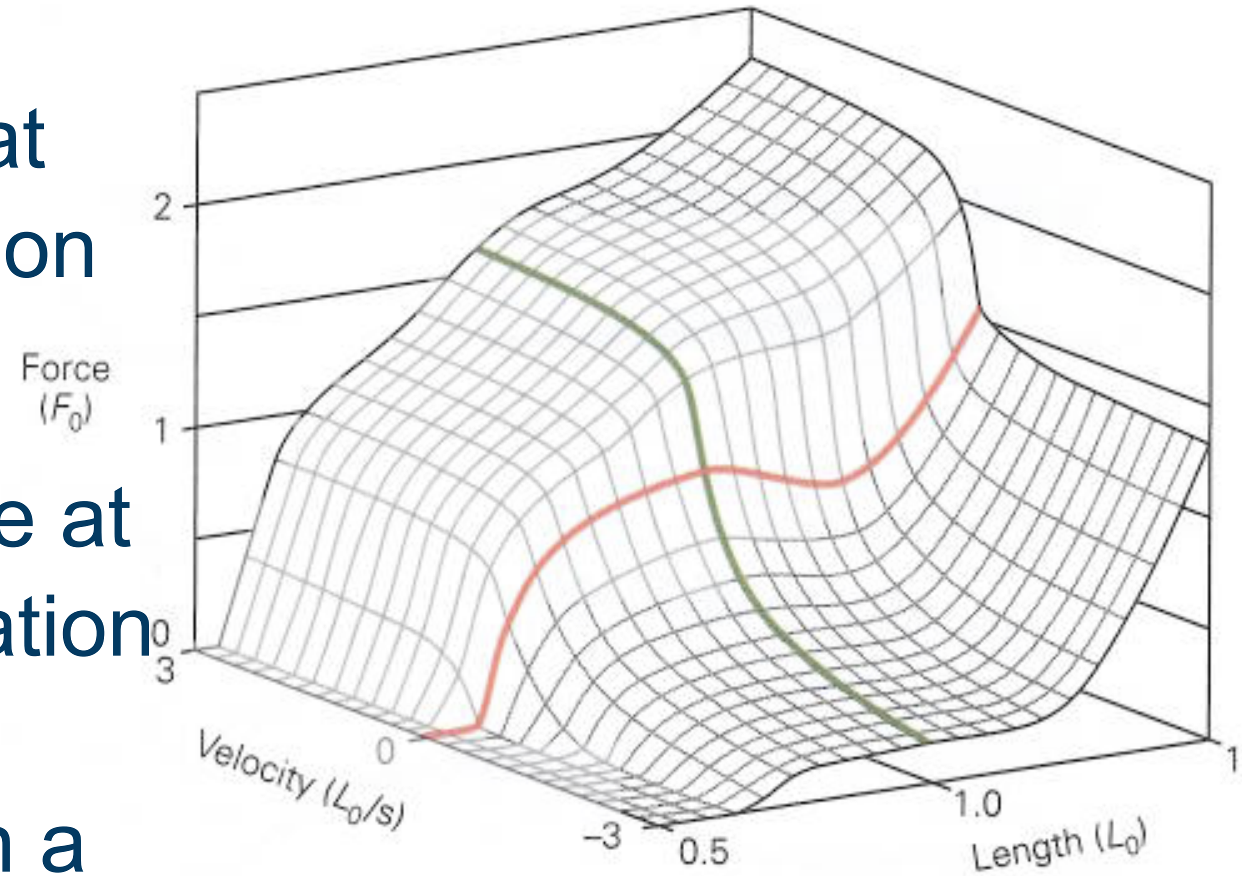
- sarcomere force increases by 20-50% at negative velocities
- detaching and reattaching causes the myosin heads to spend more time near the end of their power stroke by shortening



- this results in decreasing ability to generate force

FORCE VS LENGTH AND VELOCITY

- soleus muscle of a cat during tetanic activation
- passive+active force produced by a muscle at a given level of activation depends both on its length and velocity, in a nearly independent way

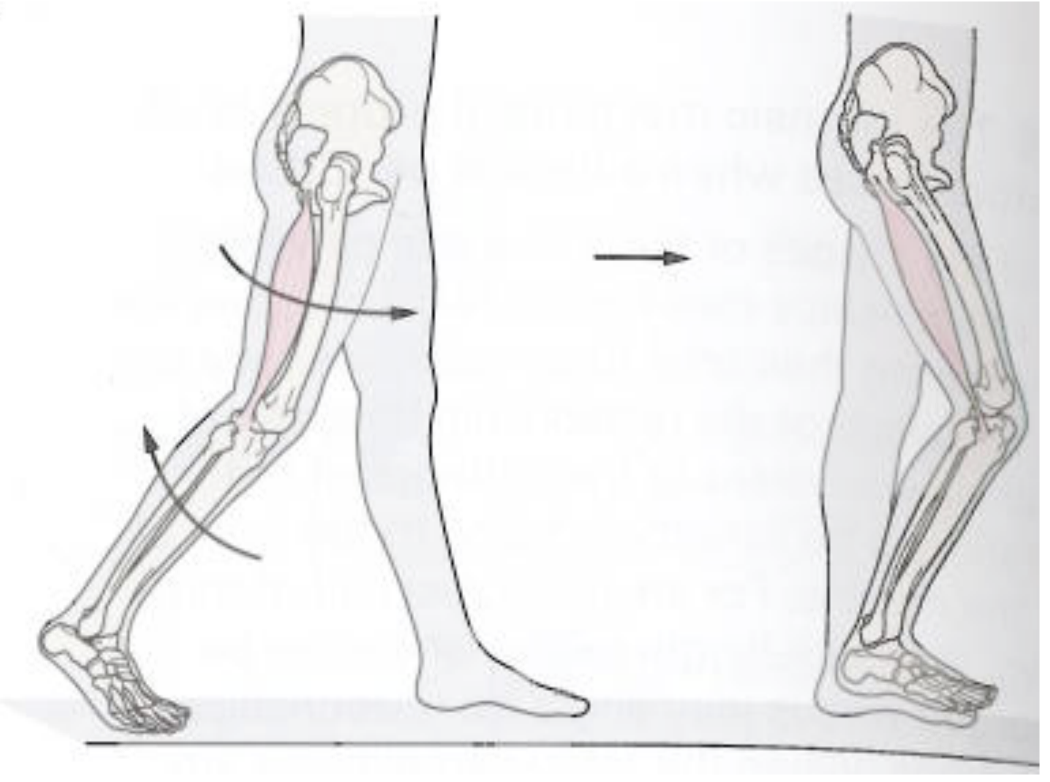


[Brown, Scott, Loeb, J Muscle Res Cell Motil 1996]

- small changes in velocity around zero create particularly large changes in force

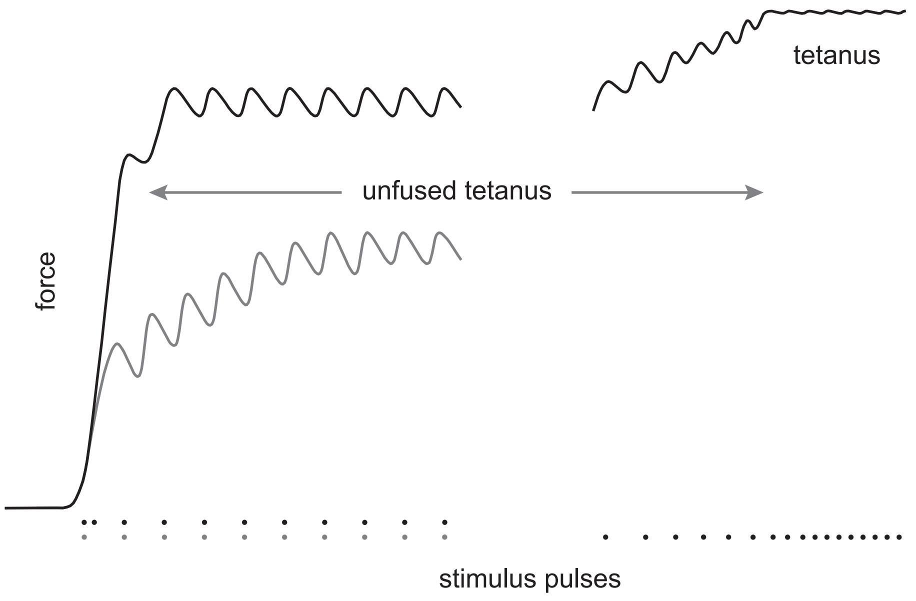
THE CNS CAN USE MECHANICAL MUSCLE PROPERTIES

- in the swing phase the knee is flexed thus tends to shorten the (biarticular) hamstrings while hip is also flexed thus tends to lengthen it



- monoarticular knee muscles would have to consume much energy to achieve the necessary force while shortening
- the hip extension by the hamstrings also help decelerating the leg by elasticity

FORCE REGULATION BY FIRING RATE

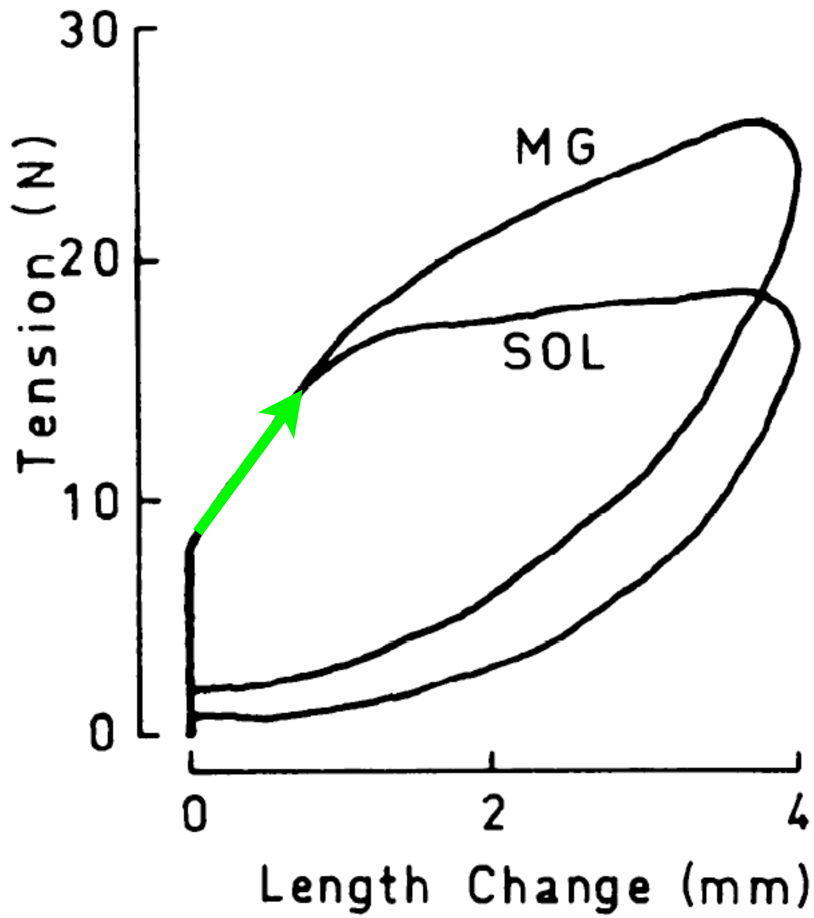


- at low firing rates muscle fiber tension relaxes between action potentials
- at high firing rates the number of cross-bridges remains relatively constant and force does not fluctuate much (tetanus)

ELASTIC ENERGY STORAGE

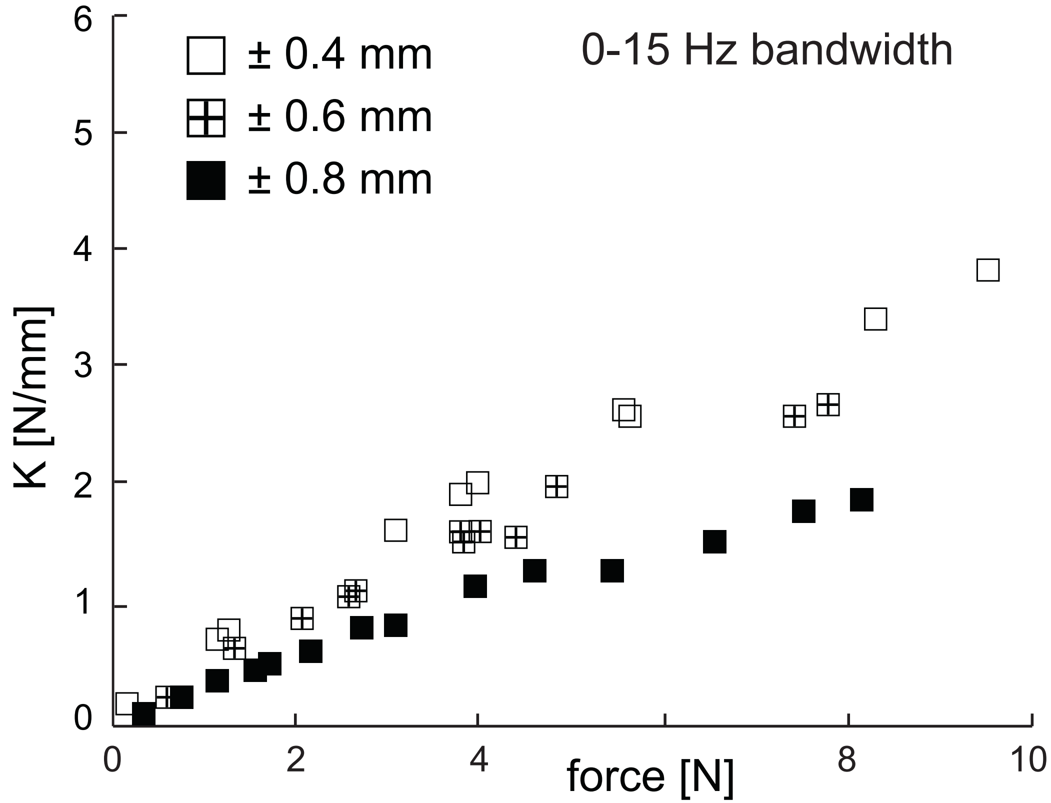
- cat medial gatrocnemius (MG) and soleus (SOL) muscles in the same hindlimb are cut, then gradually stretched and shortened while force is measured

- there is a large hysteresis, i.e. an elastic energy loss, when a muscle is lengthened and then shortened



[Walmsley and Proske J of Neurophysiology 1981]

MUSCLE STIFFNESS

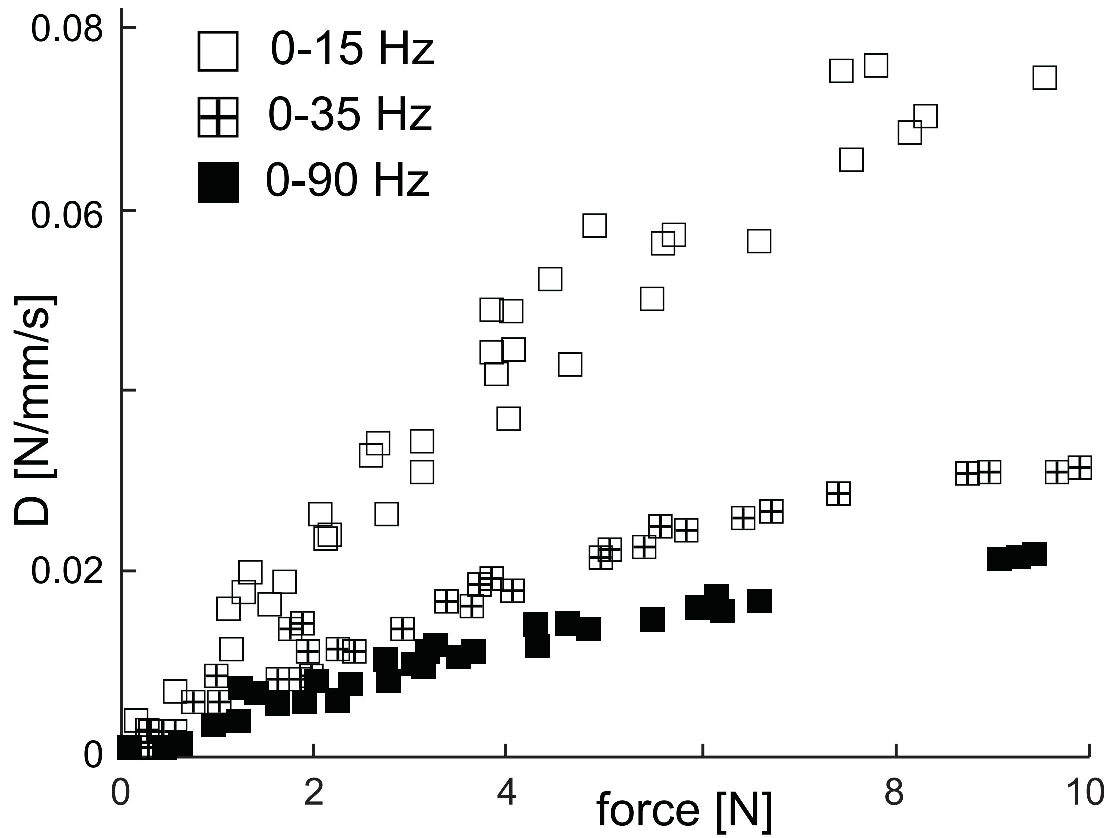


- random position perturbation with controlled frequency range on deafferented cat muscle
- stiffness and damping identified from the measured force

- muscle stiffness increases linearly with muscle force
- stiffness decreases with larger displacements
- stiffness tends to increase at higher frequencies

[Kirsch et al. IEEE Trans on Biomedical Engineering 1994]

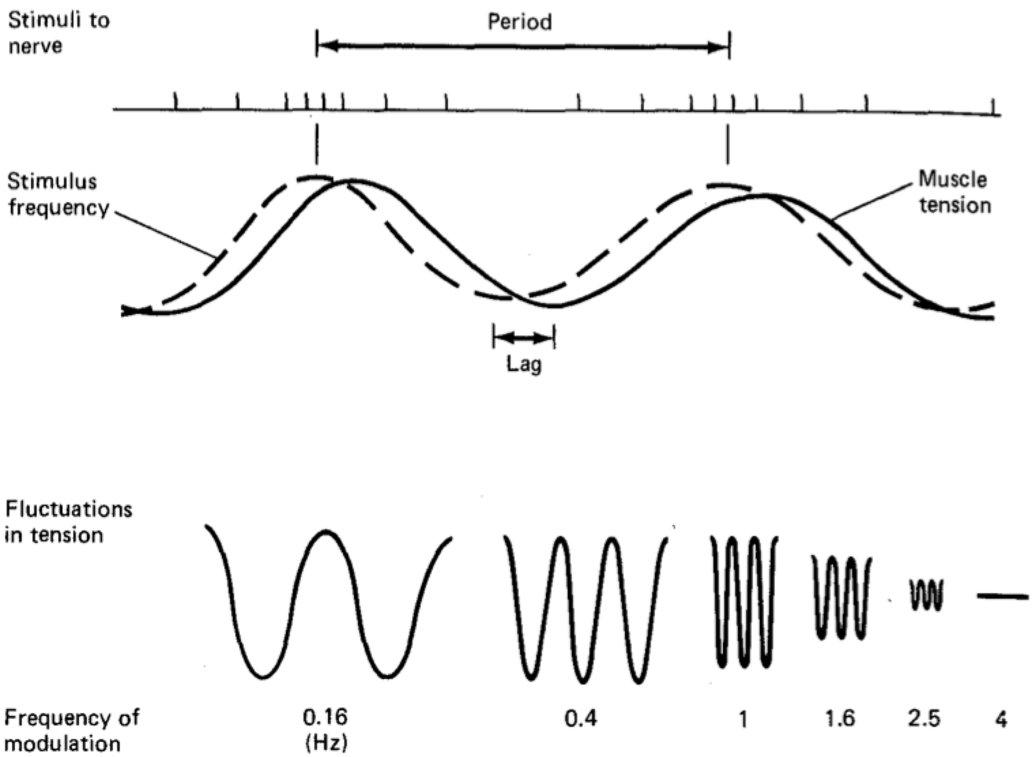
MUSCLE DAMPING

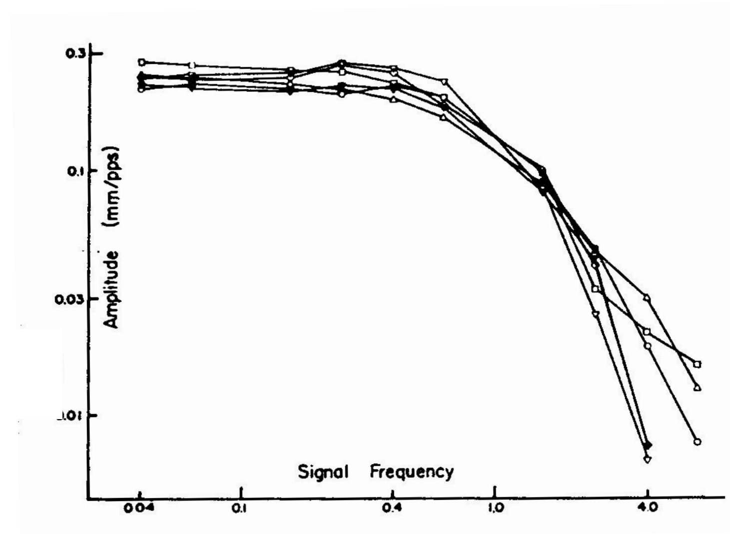


- damping increases with muscle force
- damping decreases at higher frequencies (i.e. with higher velocity)

[Kirsch et al. IEEE Trans on Biomedical Engineering 1994]

MECHANICAL FILTERING





- amplitude of muscle force modulation decreases as the action potential firing rate and phase-lag increase
- muscle acts like a low-pass filter with a cutoff frequency around 1-2*Hz* for action potential frequency modulation

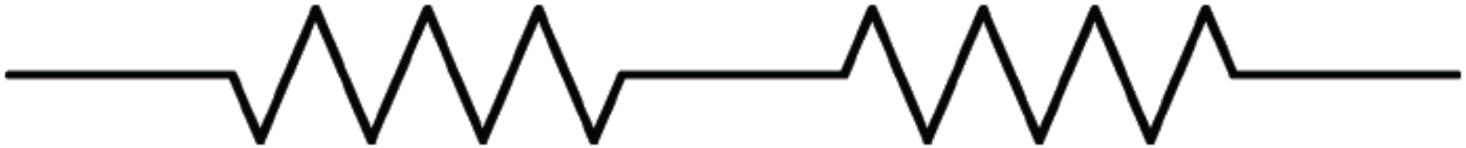
[Partridge American Journal of Physiology 1994]

SUMMARY OF MUSCLES MECHANICS

- muscle tension increases with stretch and activation
- tension depends on both length and velocity
- muscle acts like a low-pass filter with a cutoff frequency around 1-2*Hz* for action potential frequency modulation
- muscle have a spring-like properties
- stiffness and damping increase with activation

MUSCLE TENDON SYSTEM

- stiffness $K \equiv \frac{dF}{dx}$ compliance $C \equiv \frac{dx}{dF} = \frac{1}{K}$
- elastic elements in series:



$$dx = dx_1 + dx_2 \qquad F = F_1 = F_2$$

$$C = \frac{dx}{dF} = \frac{dx_1}{dF} + \frac{dx_2}{dF} = \frac{dx_1}{dF_1} + \frac{dx_2}{dF_2} = C_1 + C_2$$

- for example: muscle attached to the bone with tendon

SENSORY RECEPTORS

exteroception detects external stimuli

- vision, hearing, smell, taste, touch, temperature, pain
- via sensory receptors in the eyes, ears, nose, tongue, skin

proprioception detects output of the motor system

- senses limb position and movement
- via mechanoreceptors in muscle, joints and skin

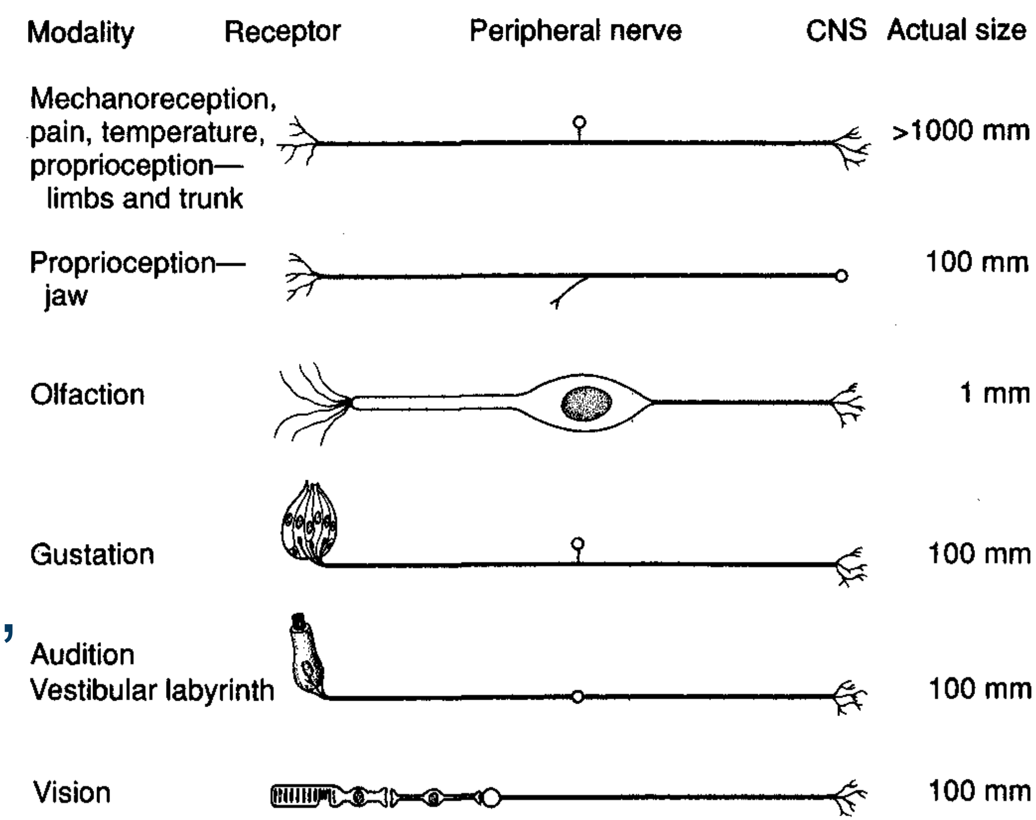
(haptic sensation: touch and force requires both extero- and proprioception)

SENSORY RECEPTORS

transform energy

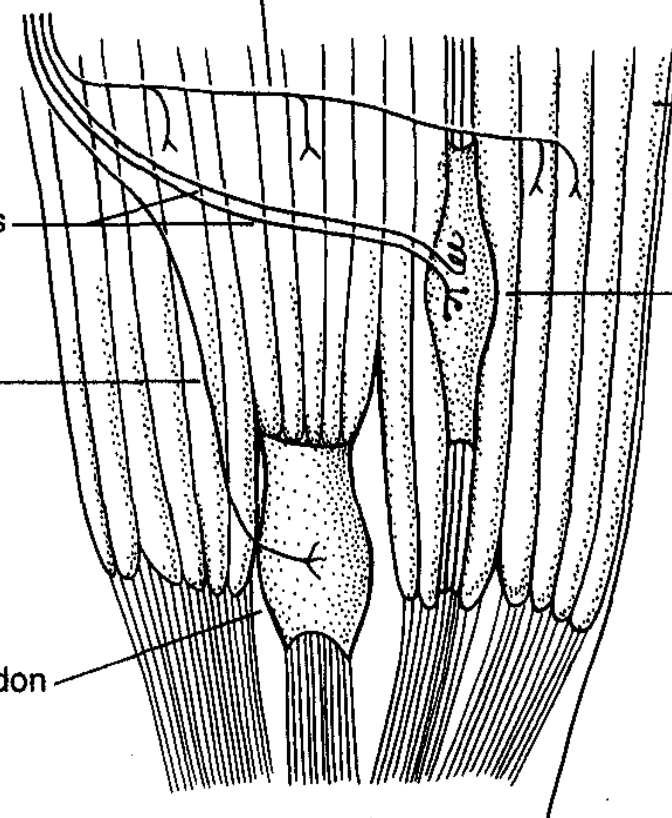
- light: photoreceptors
- mechanical: nociceptors, mechanoreceptors
- thermal: thermoreceptors
- chemical: chemoreceptors, nociceptors

into changes in membrane potential



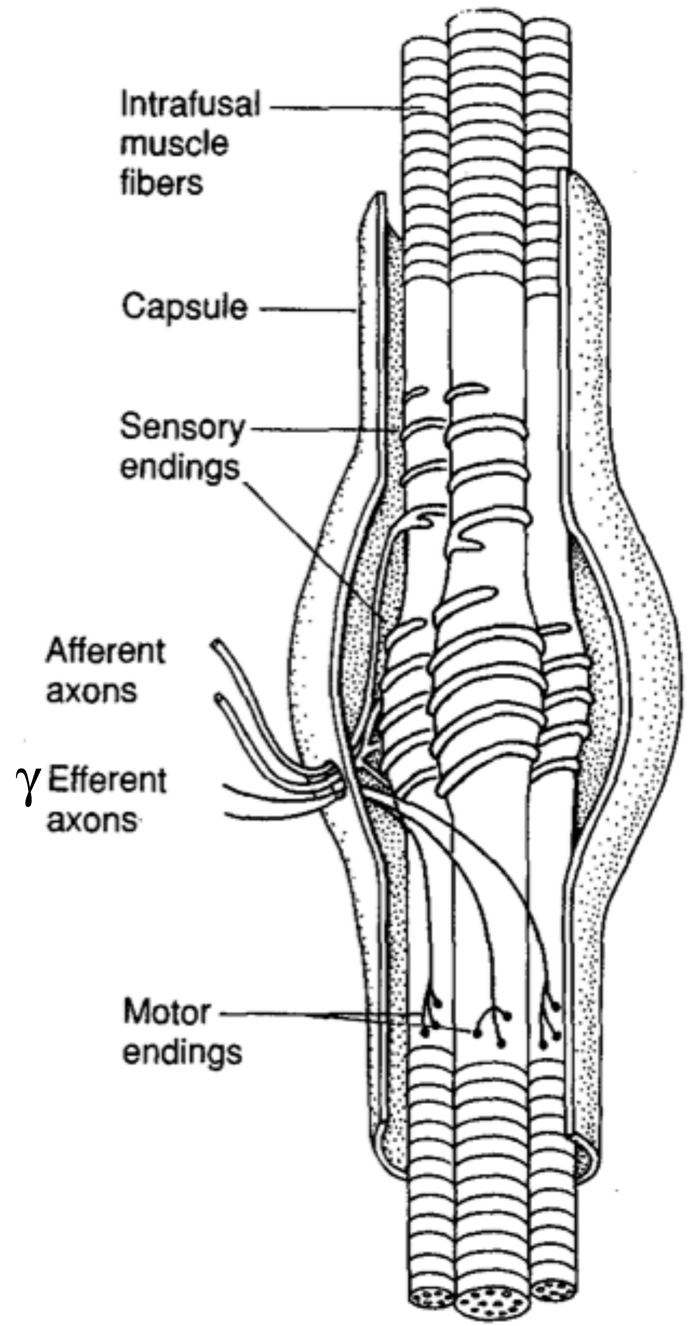
MUSCLE SENSORY RECEPTORS

- skeletal muscles are richly supplied with a variety of receptors
- muscle spindles and Golgi tendon organs are particularly important for motor control
- sense changes in muscle length and force

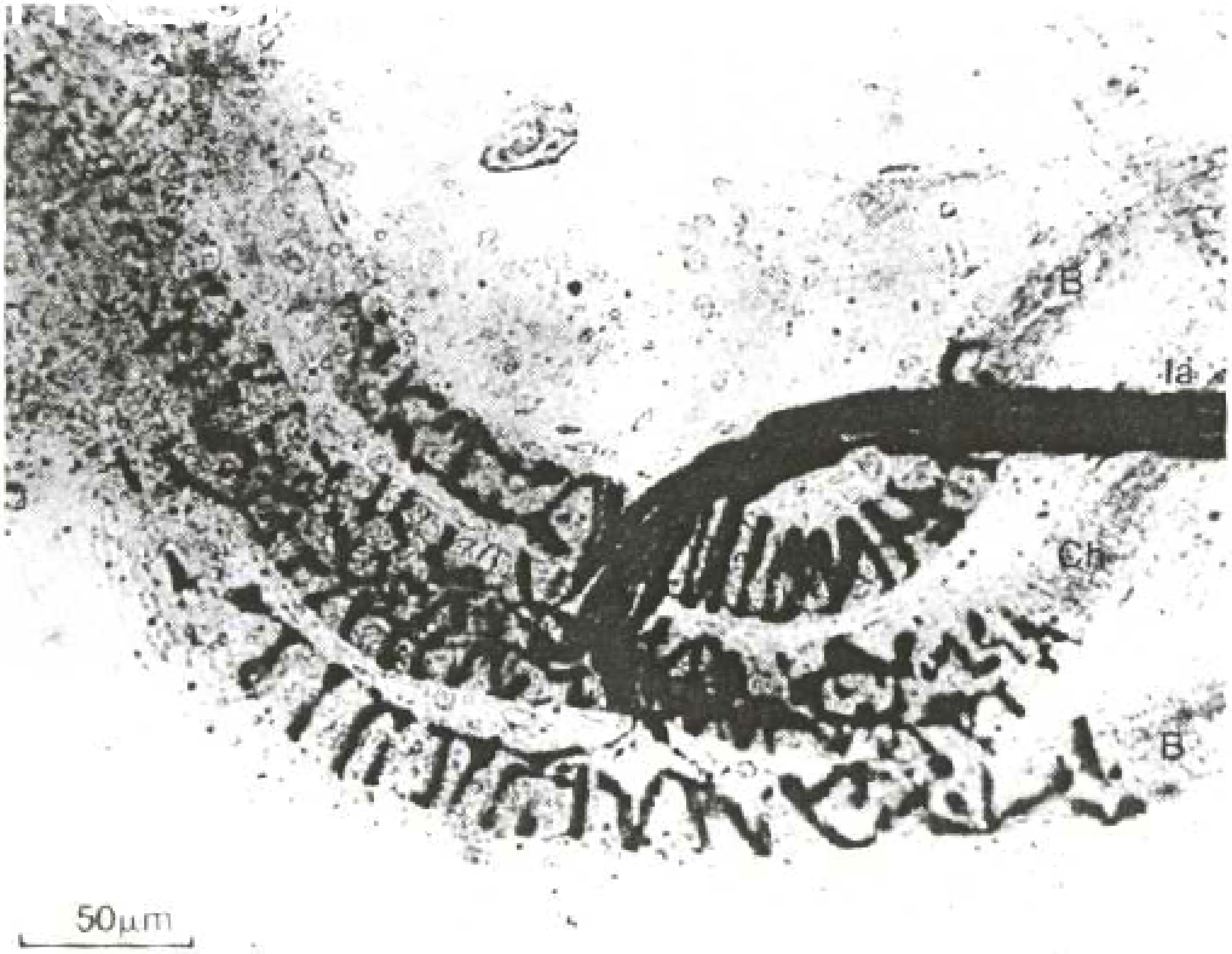


MUSCLE SPINDLE

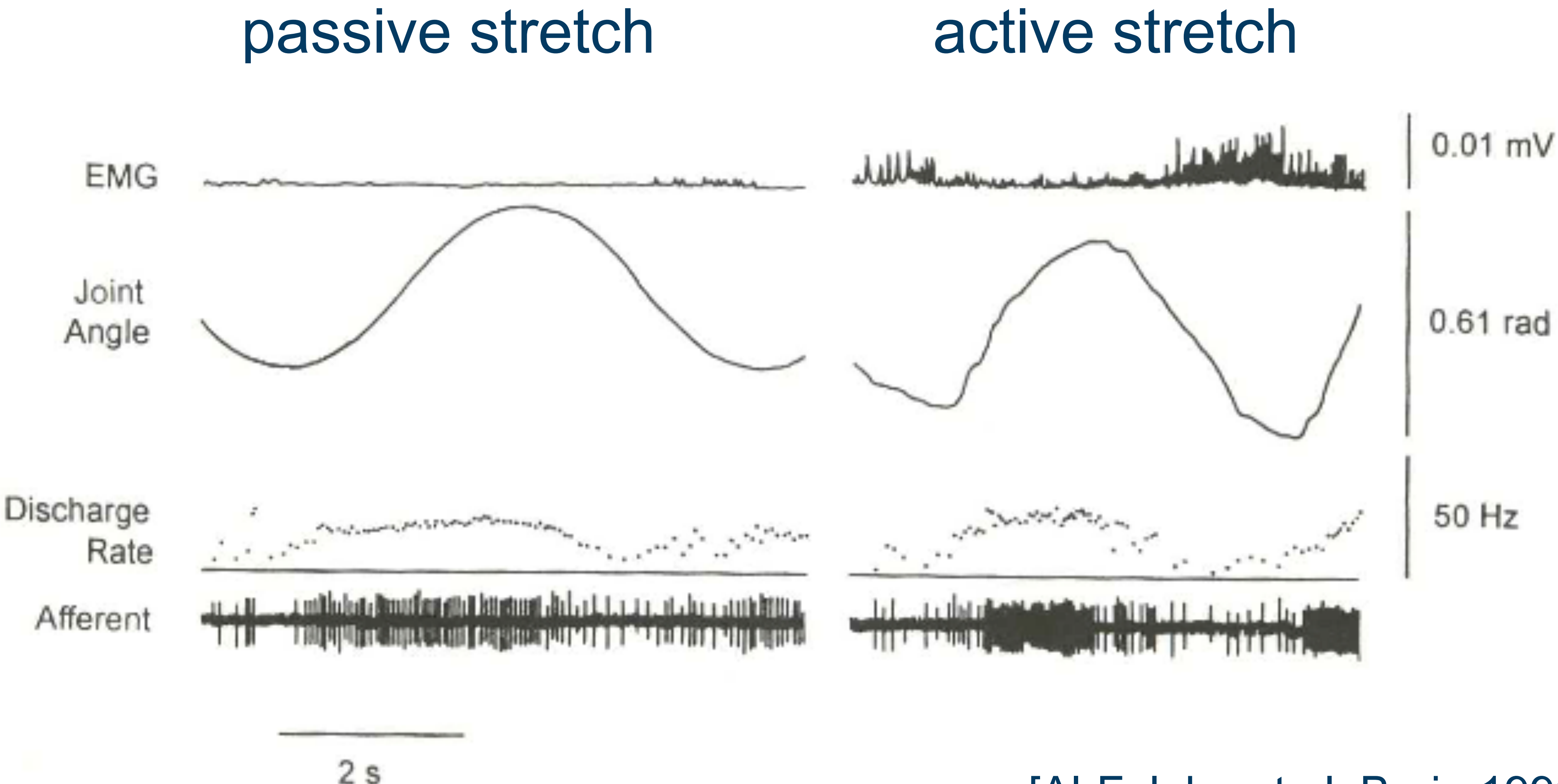
- encapsulated structure, 4-10*mm* long
- muscle fibers dedicated to sensing length changes: *intrafusal fibers*
- intrafusal fibers have a smaller width than normal *extrafusal fibers* thus are more compliant to stretch
- sensory axons terminate near center of intrafusal fibers
- stretch causes compression of the sensory endings and firing
- γ-motoneuron activation increases sensitivity of muscle spindle



MUSCLE SPINDLE



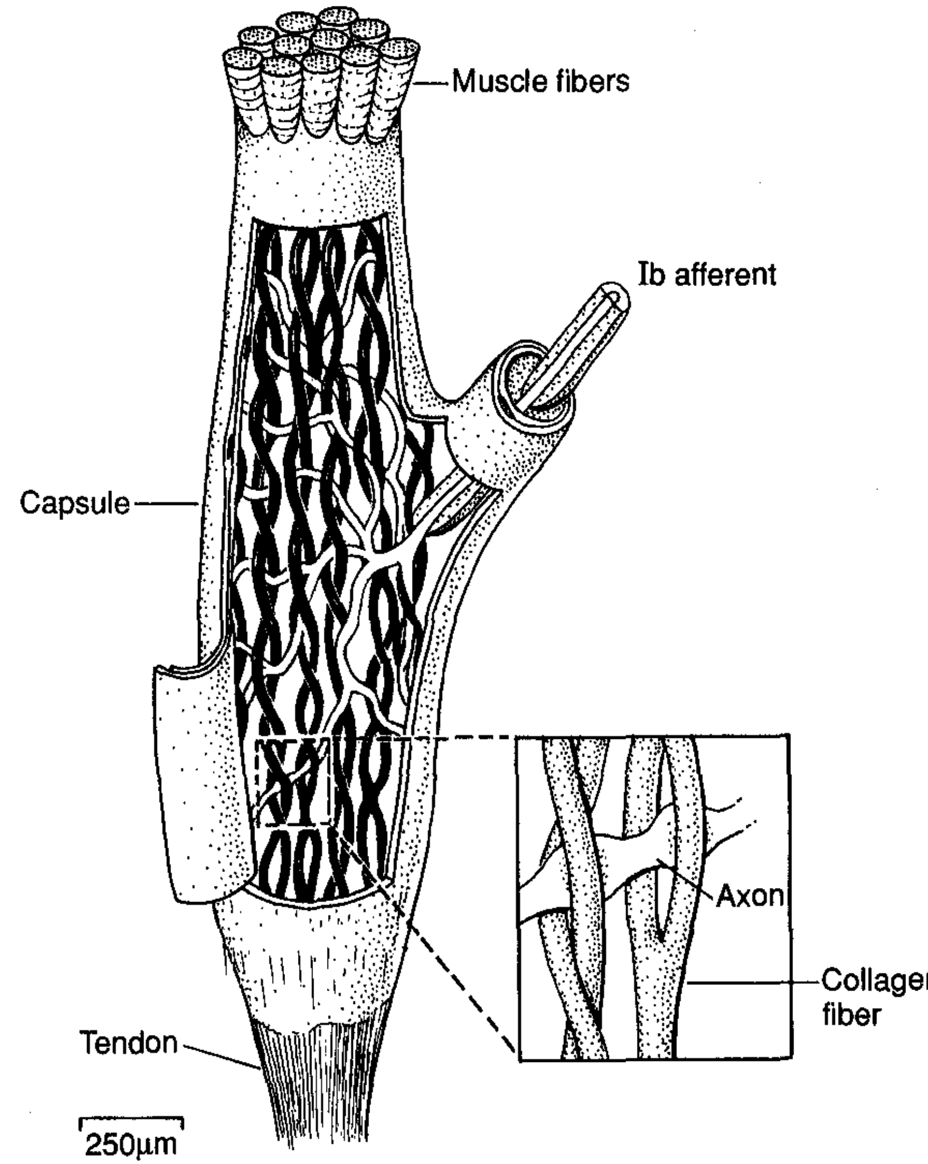
MUSCLE SPINDLES SENSE STRETCH



[Al-Falahe et al. Brain 1990]

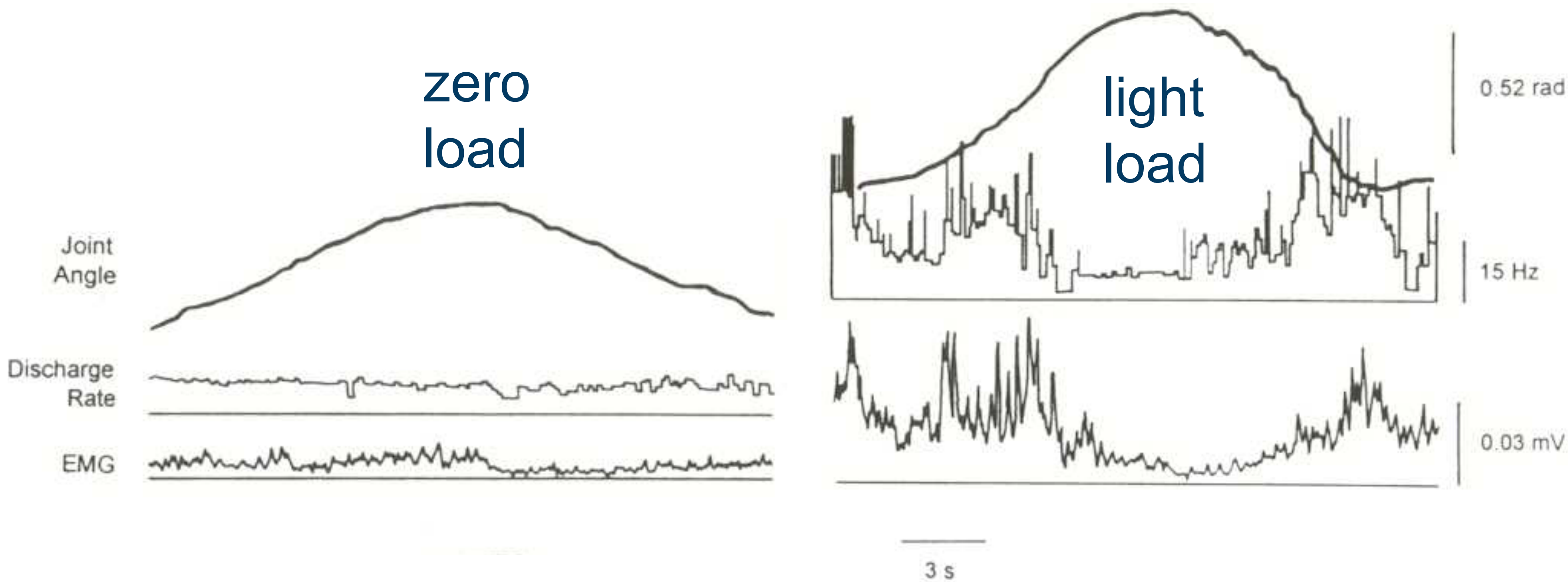
GOLGI TENDON ORGAN

- encapsulated structure about 1*mm* in length
- located at the junction of muscle and tendon
- afferent axons intertwine among collagen fascicles
- stretching of the ending organ straightens the collagen fibers, which deforms nerve endings, causing them to fire



GOLGI TENDON ORGAN DURING FINGER MOVEMENT

finger
movement



[Al-Falahe et al. Brain 1990]