ESCOLA POLITÉCNICA DA UNIVERSIDADE DE SÃO PAULO

Sensors: Human body and BioRobotics

Arturo Forner-Cordero
(aforner@usp.br)
Laboratorio de Biomecatrônica
Departamento de Engenharia Mecatrônica e Sistemas Mecânicos

Contents

Biomimetism

– Biomimetism: inspiration from Nature
  - Obtain “optimized” solution?
  - Optimization means minimization of a certain cost function.
  - Nature provides a solution “sufficient to survive”.

– Steps:
  - Observation
  - Understanding the mechanisms
  - Implementation with available technology

Bioinspiration: Biomimetism and bioimitation

- Bioinspiration (defined by ISO/TC266):
  - A design method based on the observation of biological systems.
  - This approach does not need to understand the goals and mechanisms of the biological system.
- Biomimetism does require a deep understanding of the biological system to solve a technological problem.
  - It uses models of biological systems in order to transfer these models to appropriate solutions

Research methodology: Biomimetism⇔Robotics

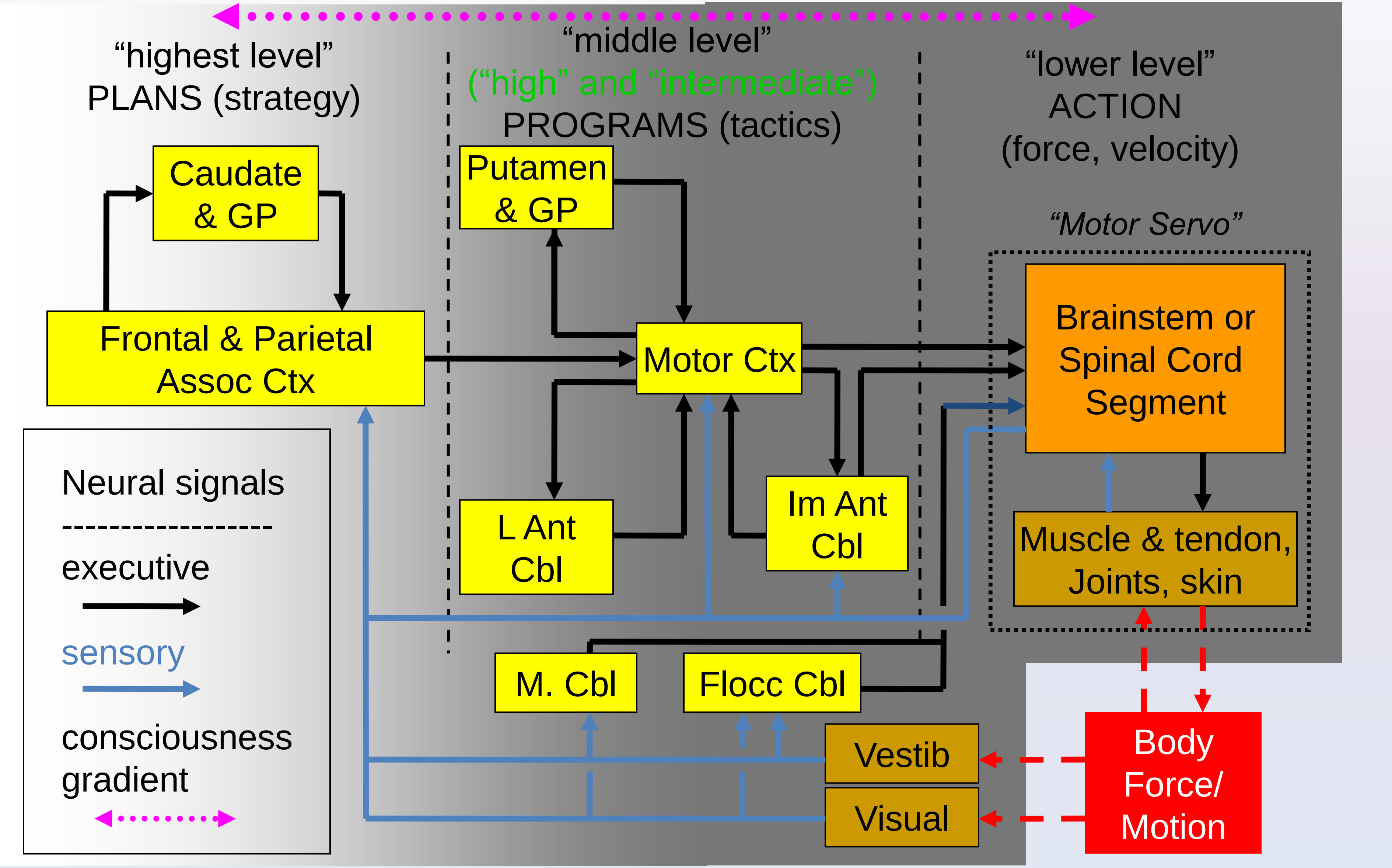
- Observation
- Concept model
- Mathematical model
  - Control theory
- Simulation
- Physical model construction

Biological motor control mechanisms

Model validation

Robot project

Human motor control

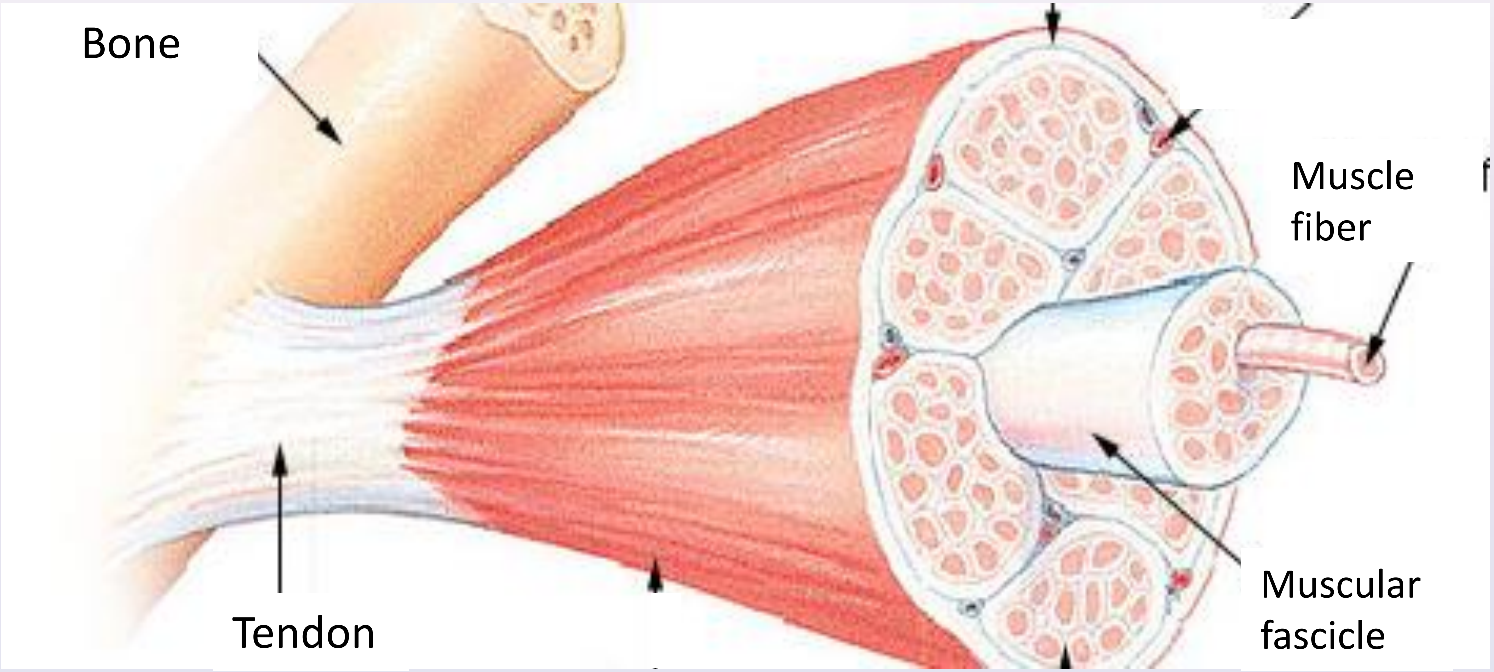


(adaptado de V Brooks, 1986)

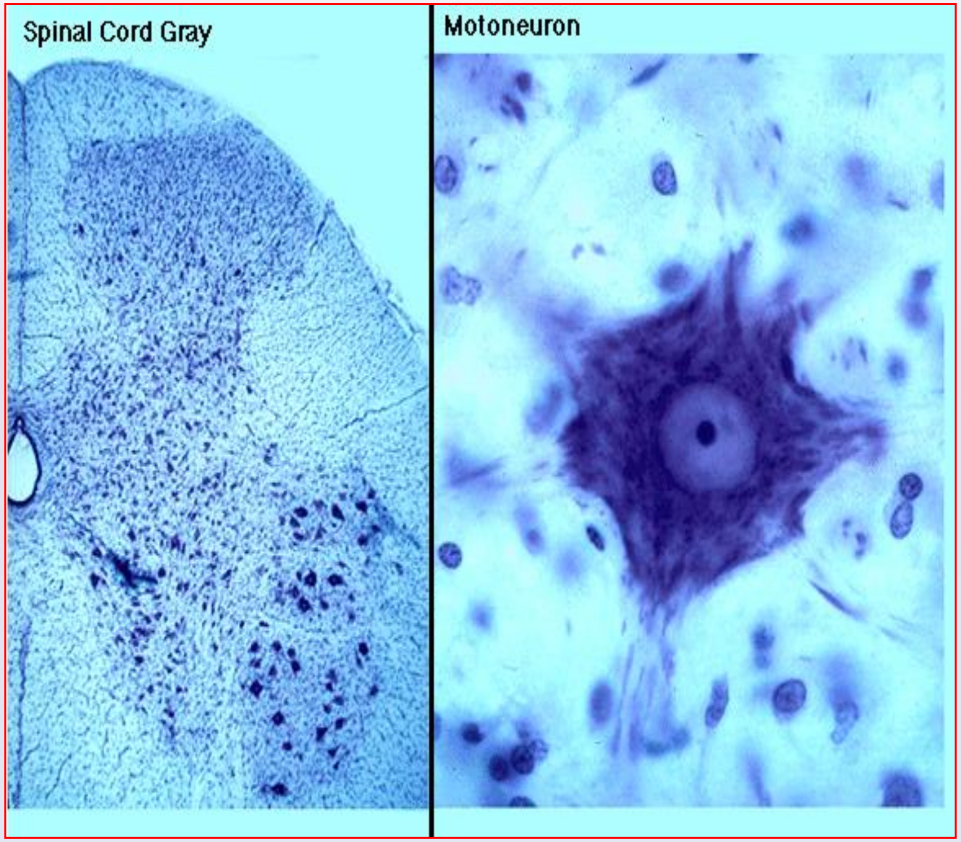
Comparison biological-artificial systems

	HUMAN	ARTIFICIAL
Energy cost	100 W	4000 W
Delays	30-160 ms	0.1-5 ms
N of sensors	17000	10-40
Actuators	639	20-40
Degrees of freedom	200	20-40

Sensors in the muscle



Motor-neurons



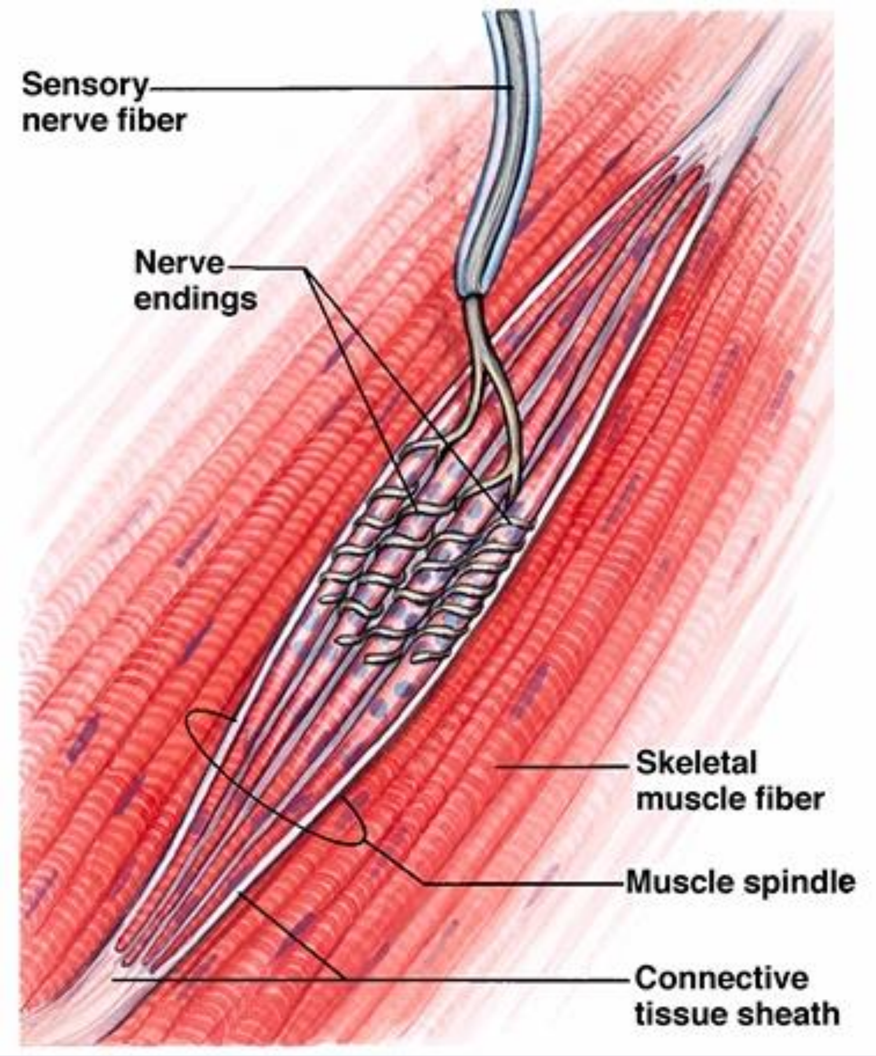
- alpha e gamma

- Alpha:
  - Extrafusal
  - 60-80 m/s
- Gamma:
  - Intrafusal
  - 25-60 m/s
- Motor unit: Motoneuron and the innervated muscle fibers

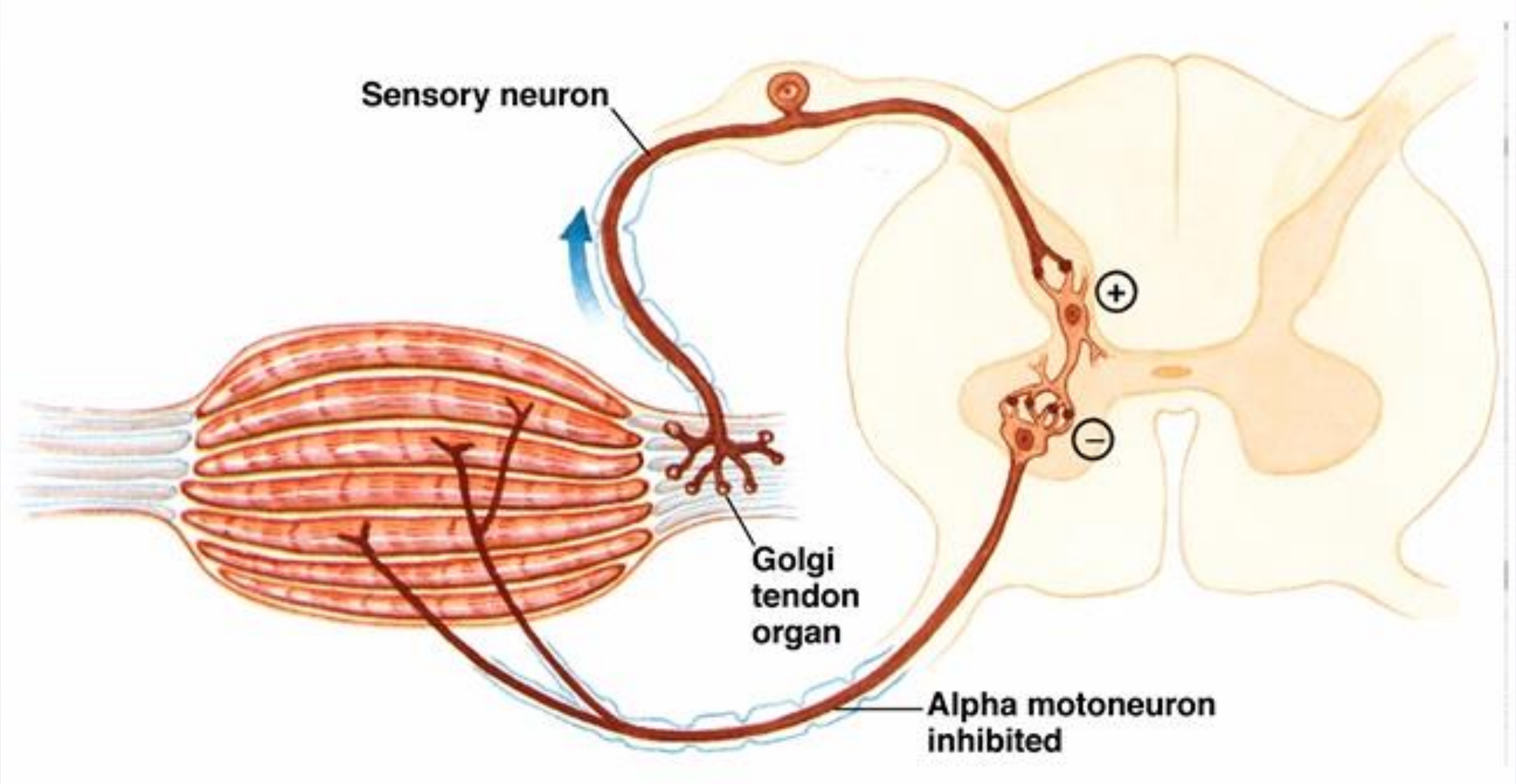
Sensors in the muscle

- Muscle spindle
  - Changes in muscle length
    - Static
    - Dynamic (speed)
  - Myotatic reflex (lengthening)
    - The lengthening of the muscle causes a reflex contraction
- Golgi Tendon Organ
  - Monitors muscle tension
  - Prevents damage due to excessive force
    - When stimulated: reflex muscle relaxation
    - Note: Role in Positive Force Feedback

Muscle spindle

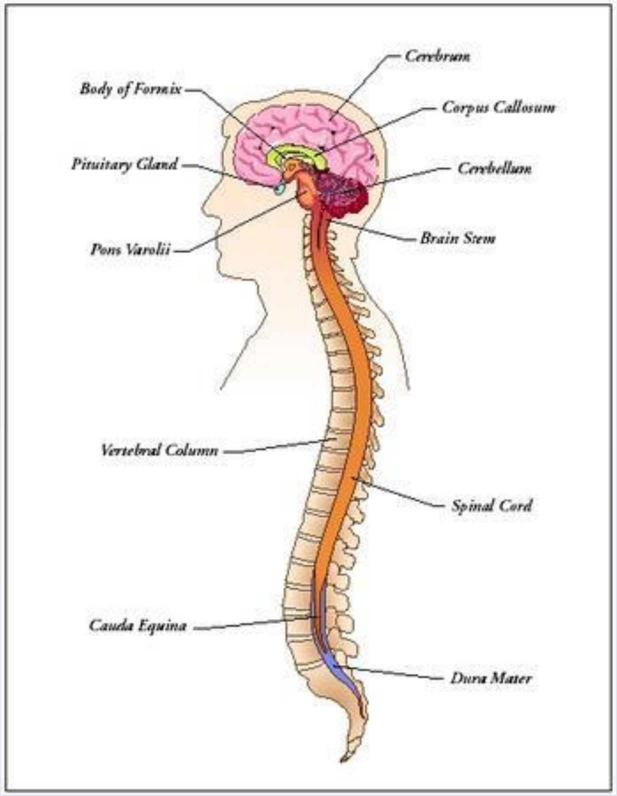


Golgi Tendon Organ



CONTROLLER: Nervous system

- Hierarchical structure
- Non-linear
- Control (low-level):
  - Feedforward
    - Motor commands
    - Reflex modulation
  - Feedback:
    - Reflexes
  - Sensor relevance



Kopp Illustration, Inc.

Contents

1. Introduction
   - Biorobotics
   - Biological motor control system
   - Proprioceptive biological sensors
2. Human biological sensors
   - Principles and organization:
     - Information coding
     - Receptors
   - Dermal sensors
   - Muscular system
3. Applications and future research
   - Bioinspired applications: Human bipedal gait
   - Ortheses e prostheses
   - Bioinspiration: Biomimetism and bioimitation

Sensory system

- Sensors:
  - Environment perception
  - Control motion
  - Regulate internal organs
  - Sleep-Wake cycles
  - Maintain activity

- Types of senses:
  - Vision
  - Hearing
  - Taste
  - Smell
  - Touch:
    - Touch
    - Pain
    - Thermal sensation
    - Proprioception

Human sensory system

- Localization
  - Exteroceptors
    - Stimuli on the body surface
  - Teleceptors
    - Distant stimuli
  - Proprioceptors
    - Body position and movement
  - Interoceptors
    - Internal organs information
- Nature of the stimulus:
  - Mechanoreceptors
  - Termoreceptors
  - Quimioreceptors
  - Fotoreceptors
  - Nociceptores
    - Noxious stimulus

Sensory systems in mammals

Table 20–1 Mammalian Sensory Systems

Modality	*Stimulus*	*Receptor Type*	*Specific Receptor*
Vision	Light	Photoreceptor	Rods, cones
Hearing	Air-pressure waves	Mechanoreceptor	Hair cells (cochlear)
Balance	Head motion	Mechanoreceptor	Hair cells (semicircular canals)
Touch	Mechanical, thermal, noxious (chemical)	Mechanoreceptor, thermoreceptor, nociceptor, chemoreceptor	Dorsal root ganglion neurons
Taste	Chemical	Chemoreceptor	Taste buds
Smell	Chemical	Chemoreceptor	Olfactory sensory neurons

Physiological images taken from: Medical Physiology, V.B. Mountcastle, 1980

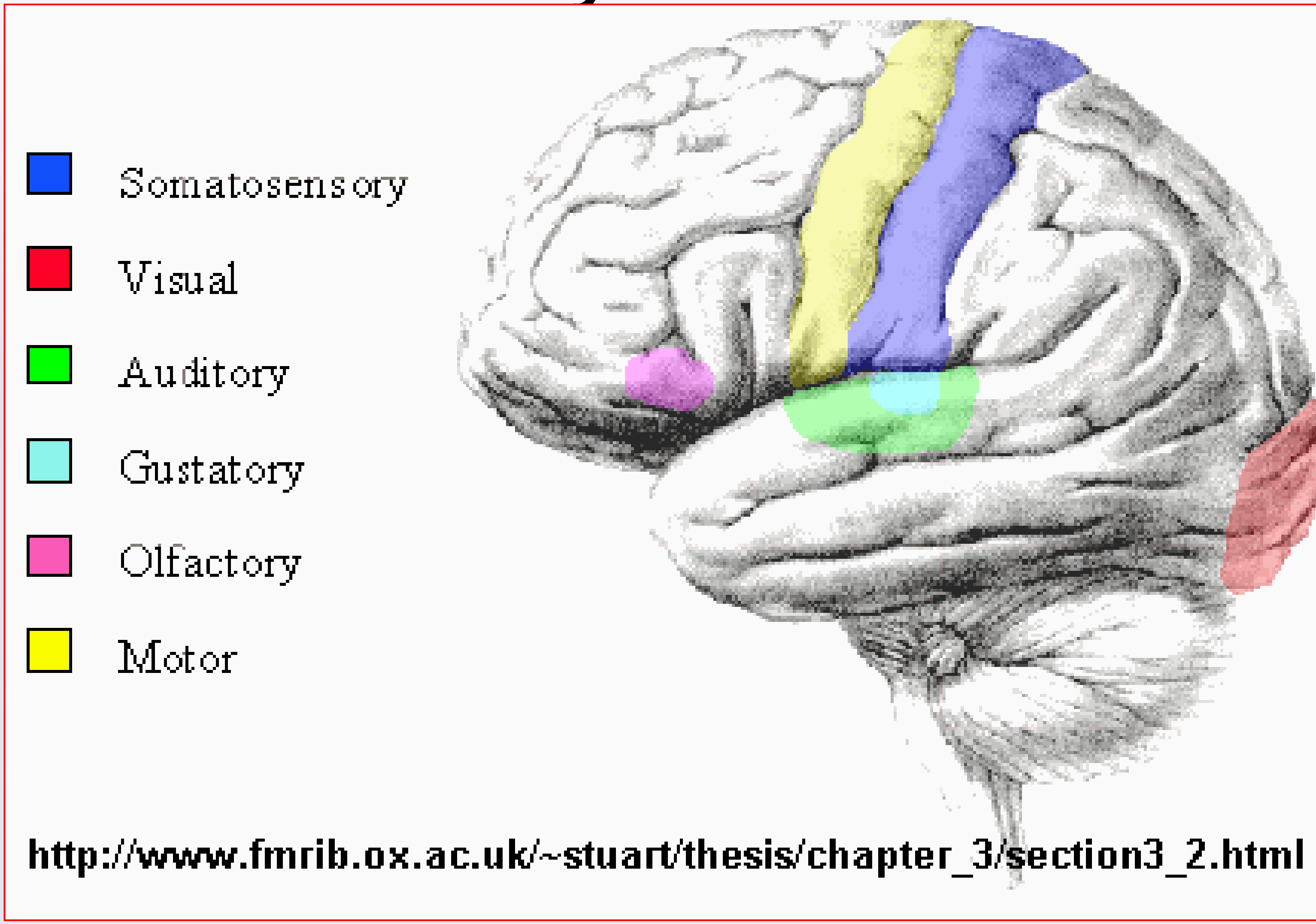
General principles of the sensory systems

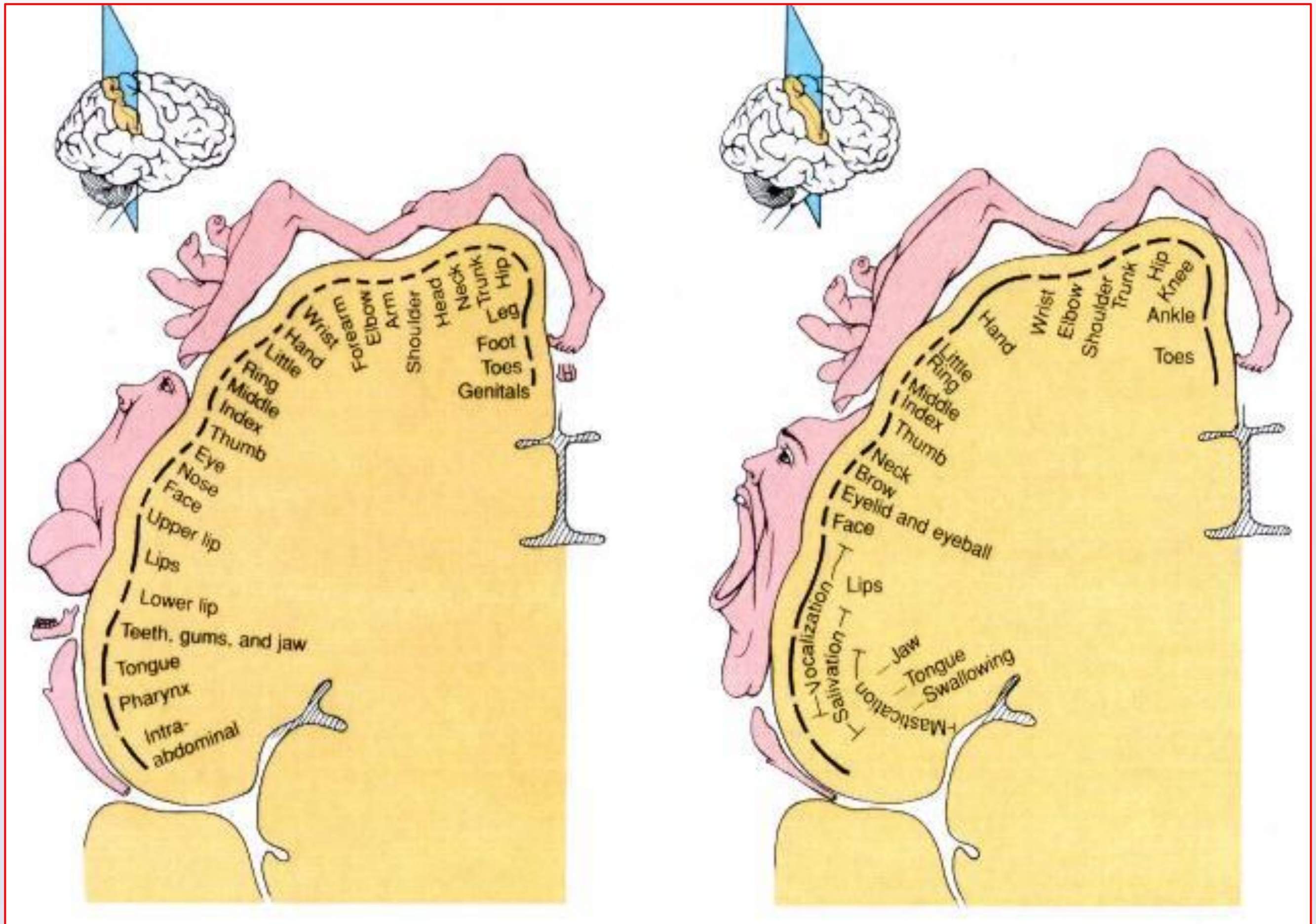
- Physical stimulus ► transduction ► sensation ► perception: combination of sensations
  - Sensory receptors
  - Transmission nuclei: Thalamus and brainstem
  - Cerebral cortex: Sensory area
  - Cerebral cortex: Associative area
- Codes modality (nature of the stimulus), spatial location, intensity and timing
- Johannes P. Muller, s. XIX: "Law of Specific Nerve Energies" – the modality of the stimulus is a property of the nerve fiber that carries the stimulus

General principles of the sensory systems

- Receptive field: spatial area that excites one sensory cell:
  - Processing is based on the transformation of receptive fields at different levels
- Half of the cortex => contralateral area
- Topological sensory organization
- The sensory space to neural space mapping is nonlinear
  - Receptors density determines the spatial resolution

Sensory cortex





(a) Somatosensory cortex in right cerebral hemisphere

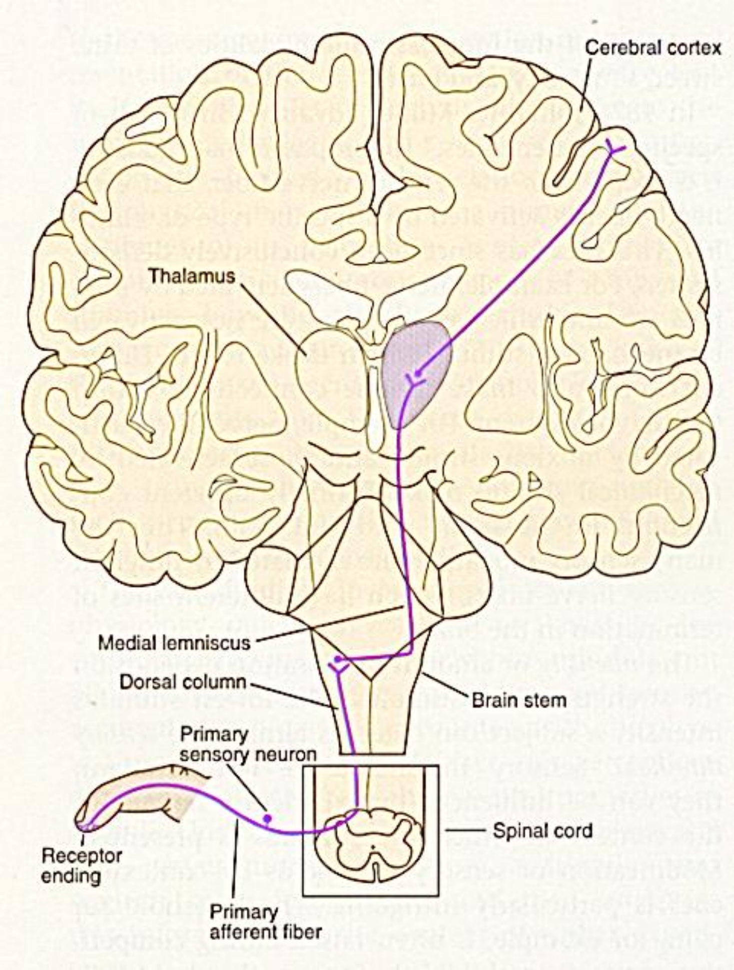
(b) Motor cortex in right cerebral hemisphere

Image taken from "Medical Physiology", VB. Mountcastle, 1980

psychlops.psy.uconn.edu/ eric/pics/homunc.gif

Human sensory system organization

- Receptive fields
- Transmission relays
- Interneurons
- Parallel pathways
- Hierarchy
- Neuronal maps



Receptive fields

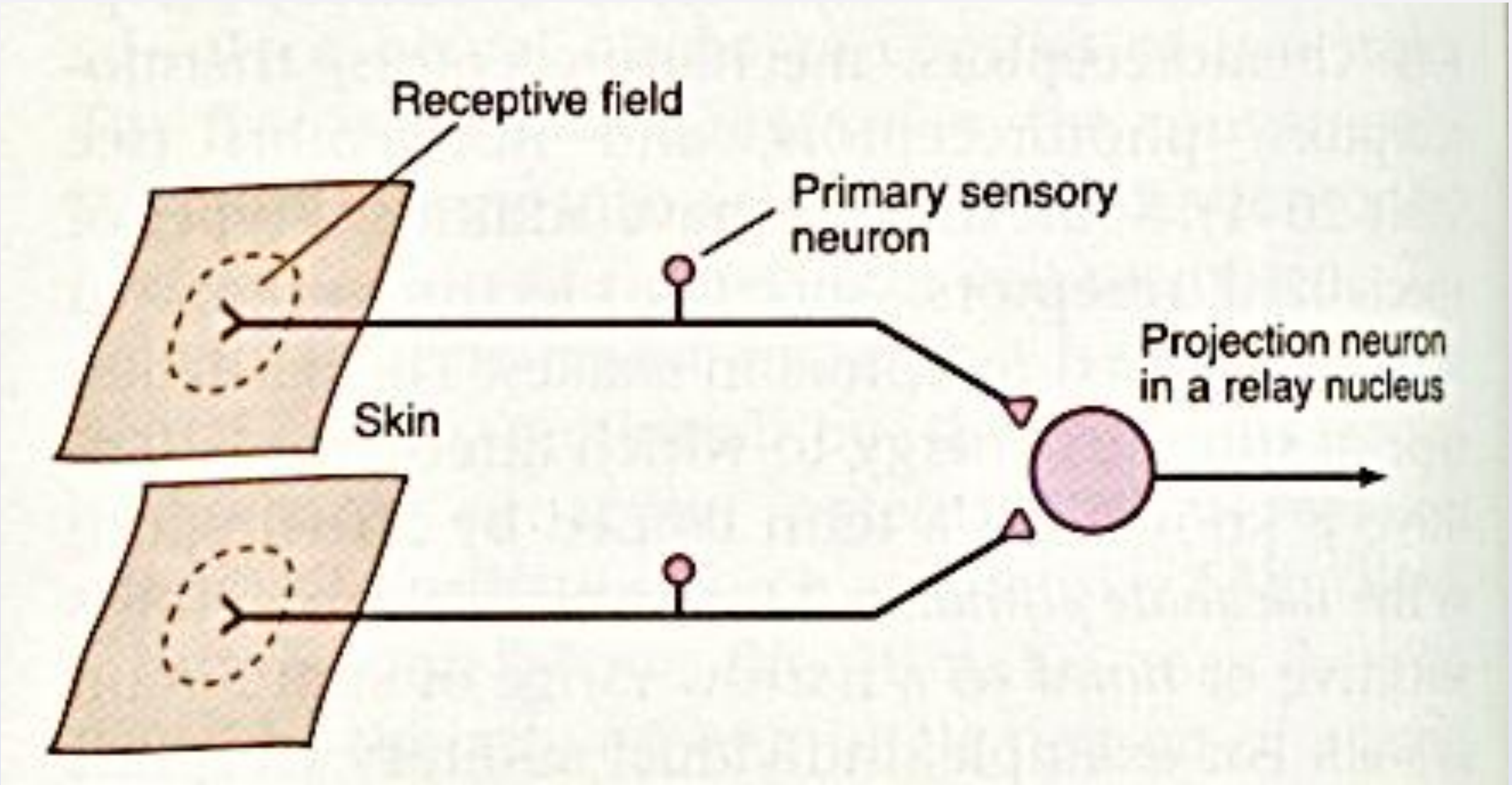


Image taken from "Medical Physiology", VB. Mountcastle, 1980

Stimulus specificity

Each sensor reacts to a certain stimulus

Example:

Auditive receptor with maximum sensibility at 2 KHz

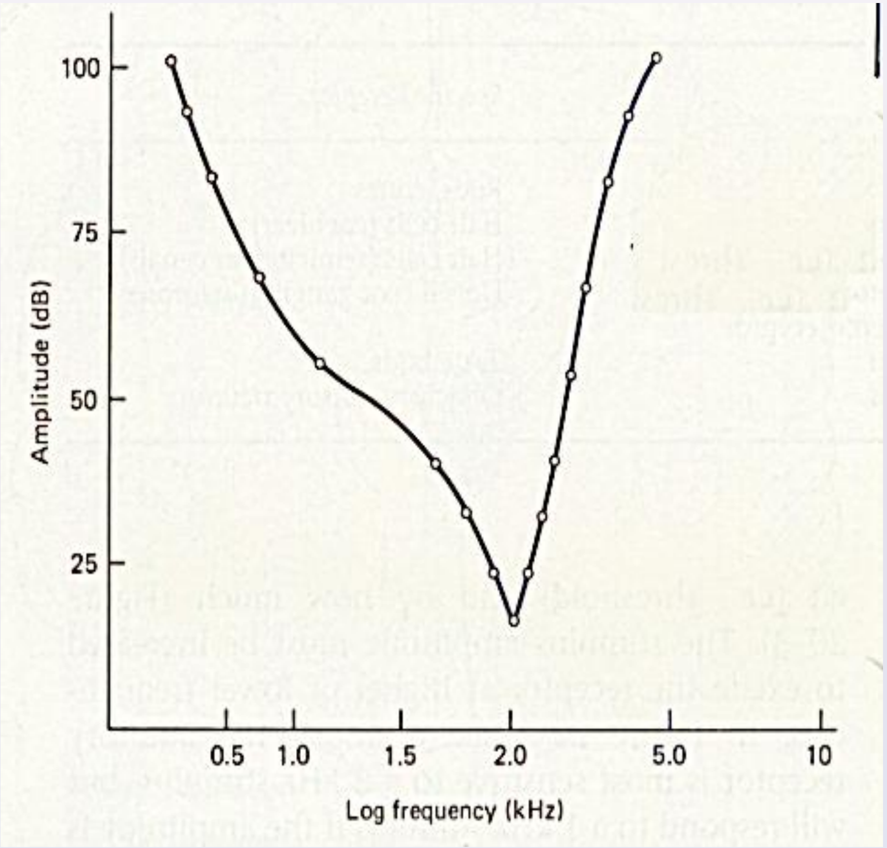


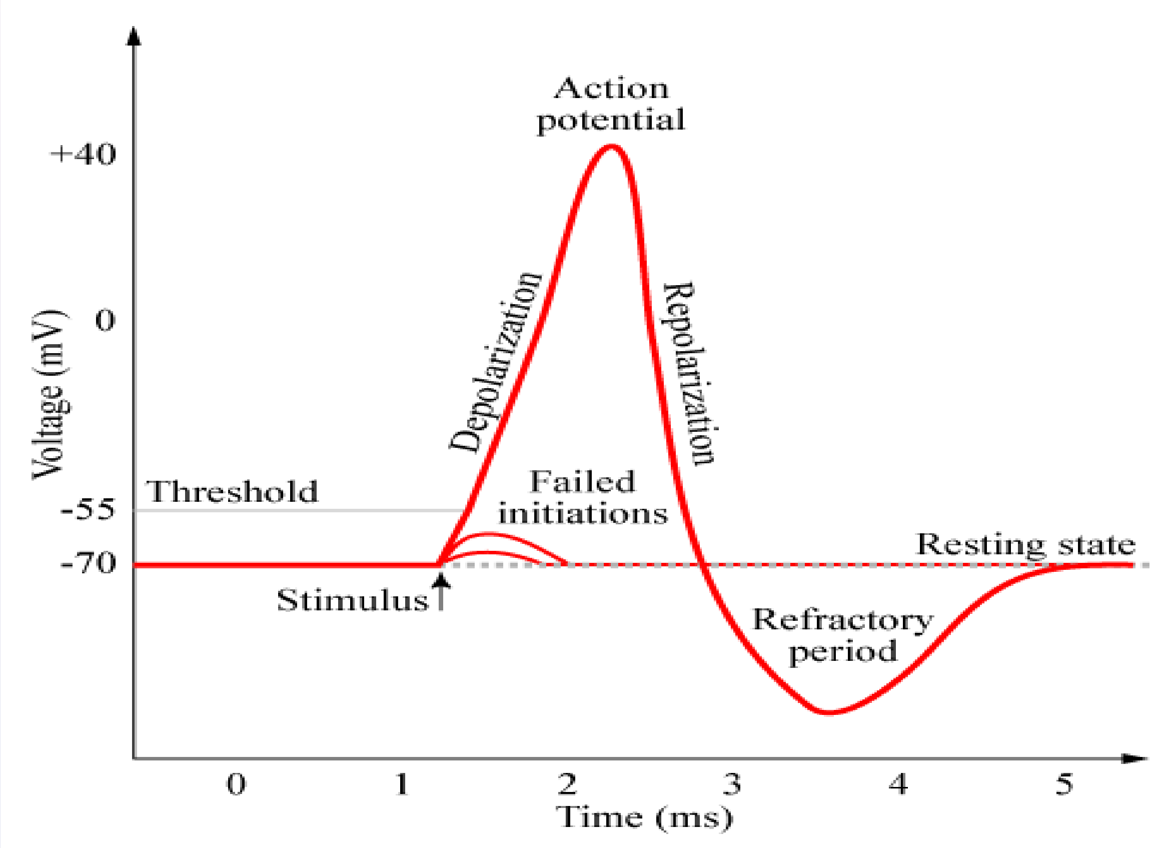
Image taken from "Medical Physiology", VB. Mountcastle, 1980

Basic features of the sensory system

- **Modality** – sense, what is the nature of the physical stimulus?
- **Intensity** – sensation threshold
  - Strength and discrimination
- **Duration** – adaptation
- **Situation** – where is it?
  (equivalent to detect in which part of the skin or what is the specific smell/flavour?)

Sensory coding

1. Neurons carry action potentials



Sensory coding

2. Each pathway codes and specific sense

3. Receptive fields determine spatial resolution

4. Convergence in the thalamus (except olfaction: temporal medial lobe)

Sensory coding

- Intensity:
  - Levels
  - Threshold
  - Levels vs discrimination
- Duration:
- Adaptation:
  - Sensation
  - Sensory receptor
- Localization

The stimulus must be coded with trains of electrical pulses

Sensory coding

- TRANSDUCTION

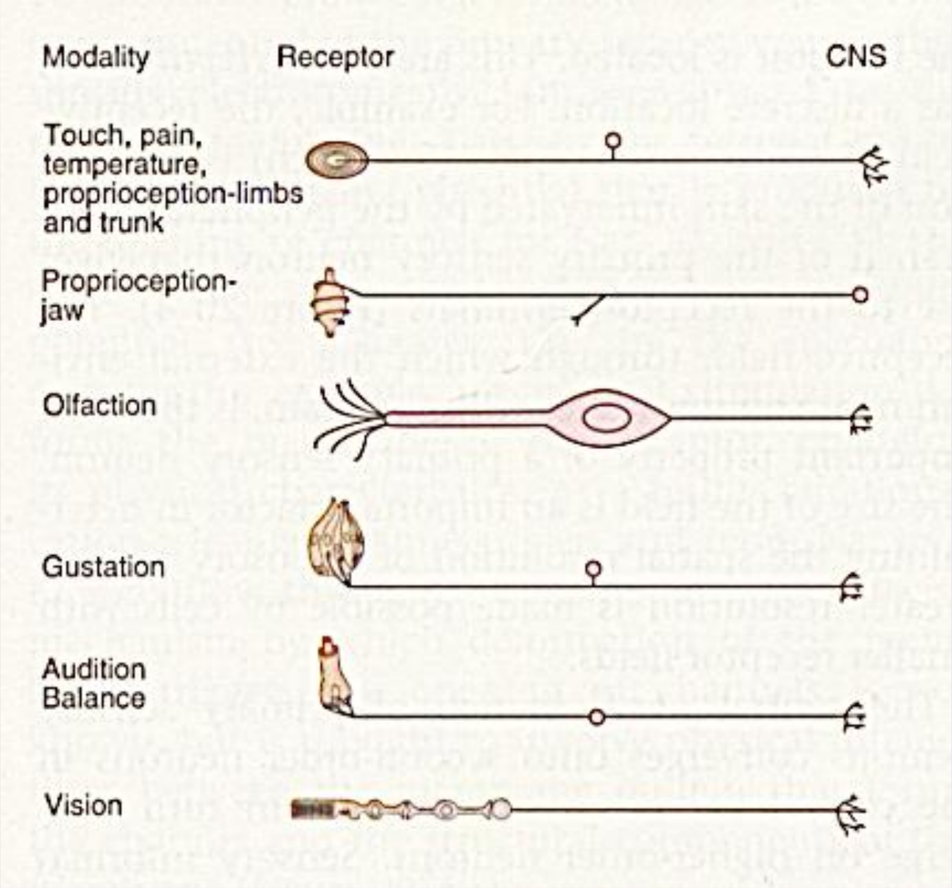
Physical stimulus energy => Electrochemical energy

- NEURAL CODING:

The characteristics of the stimulus are represented as nervous signals.
Action potentials:
  - Discharge frequency
  - Number of receptors

- DISCRIMINATION: LATERAL INHIBITION:
Adjust the signals to obtain the maximal information.

Sensory receptors



Different sensory receptors

Image taken from "Medical Physiology", VB. Mountcastle, 1980

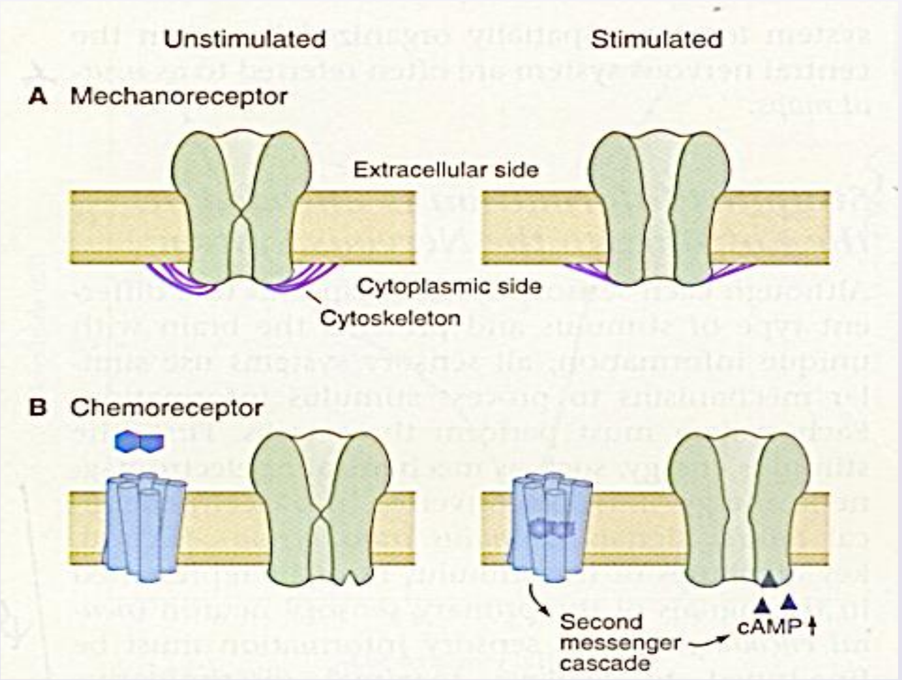
Sensory receptors

- Different structures
  - a. bare nerve endings surrounded by accessory tissues
    - Pacini corpuscle
  - b. ciliary structures – mechanical, olfactory, retina
  - c. electrical signaling - mechanical, olfactory
    - axons
  - d. chemical signaling – taste, retina -
    - (they can generate action potentials)

- The sensory cells react to specific stimulation

- Afferent and efferent information exchange in the sensory perception.

Types of receptors



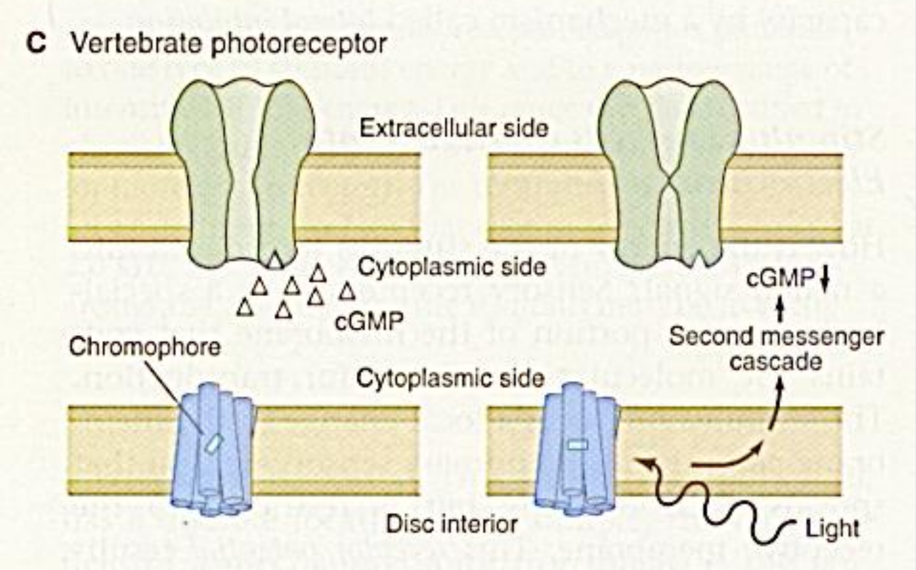
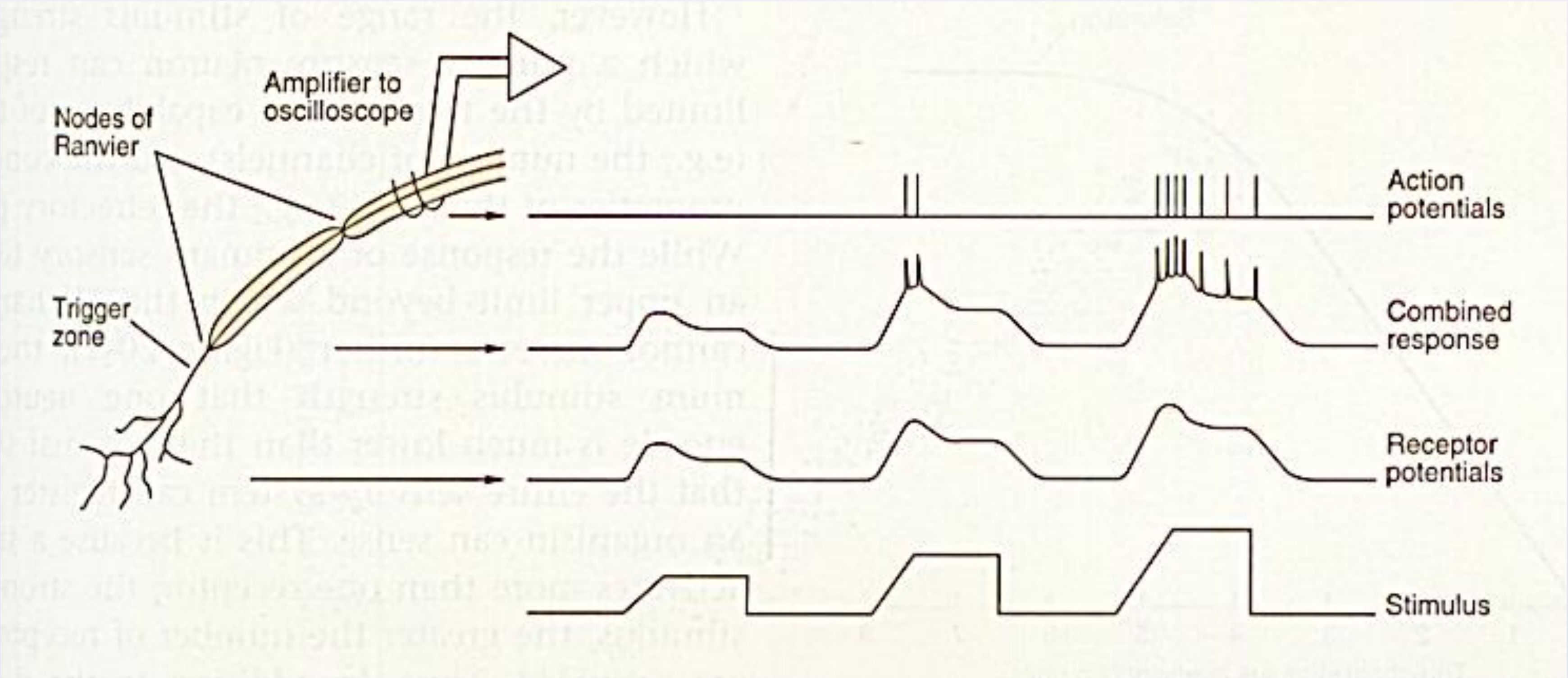


Image taken from "Medical Physiology", VB. Mountcastle, 1980

Types of receptors

- Mechanical sensors
  - Skin, muscles, ligaments
  - Channels activated by lengthening
- Light sensors
  - Eyes, (and similar structures)
  - Rhodopsin:
    - Photon=>Generation of action potentials
- Chemical sensors
  - Olfactive and gustatory
  - Specific chemical receptors
- Thermal and nociceptive sensors
  - Skin
  - Free nerve endings

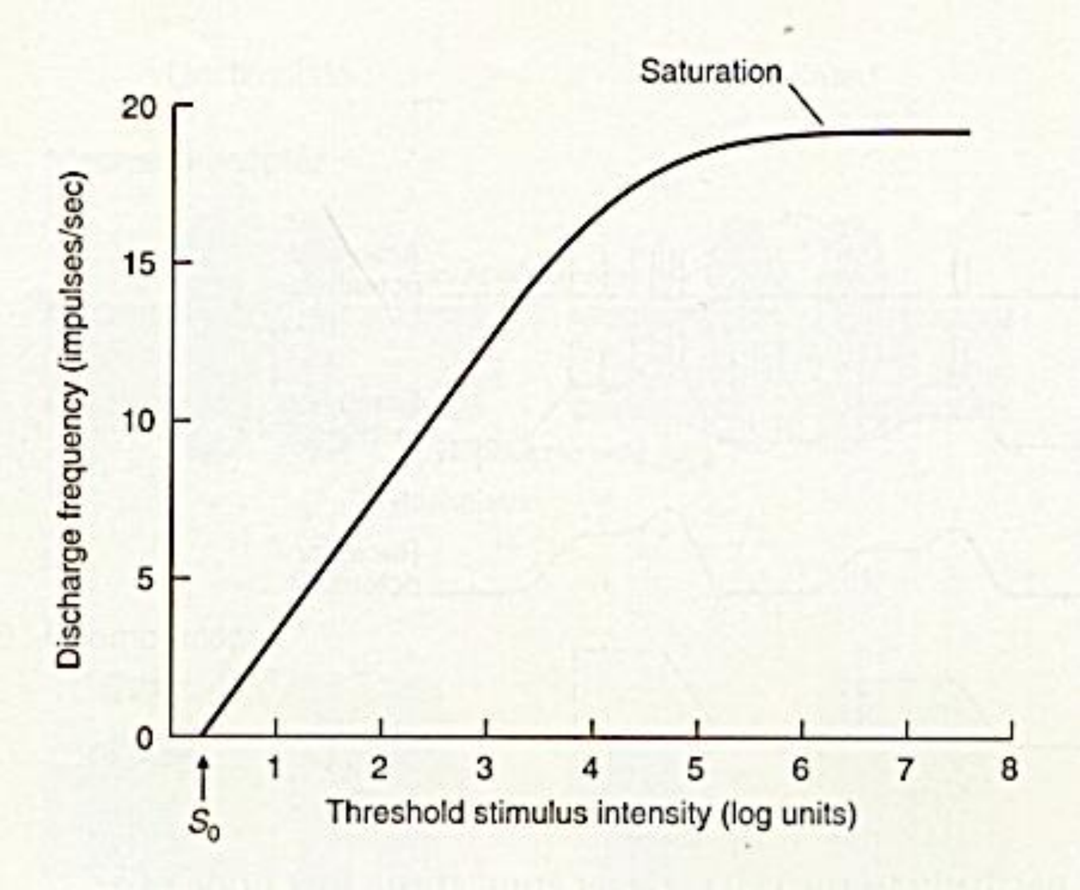
Generation of receptor potentials



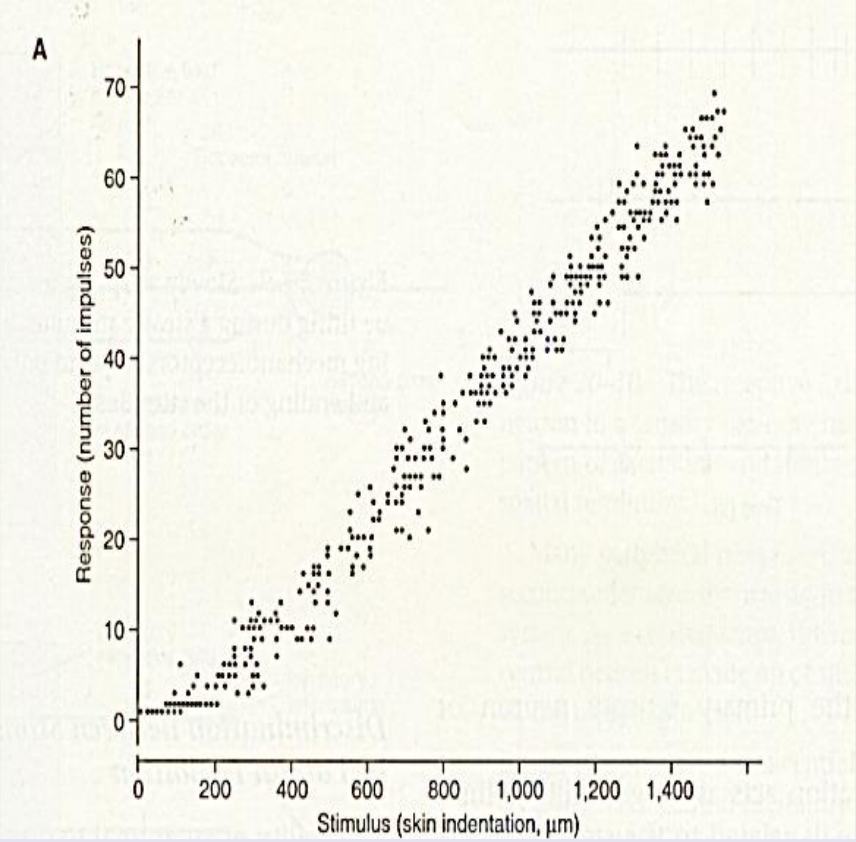
Coding of receptor potentials

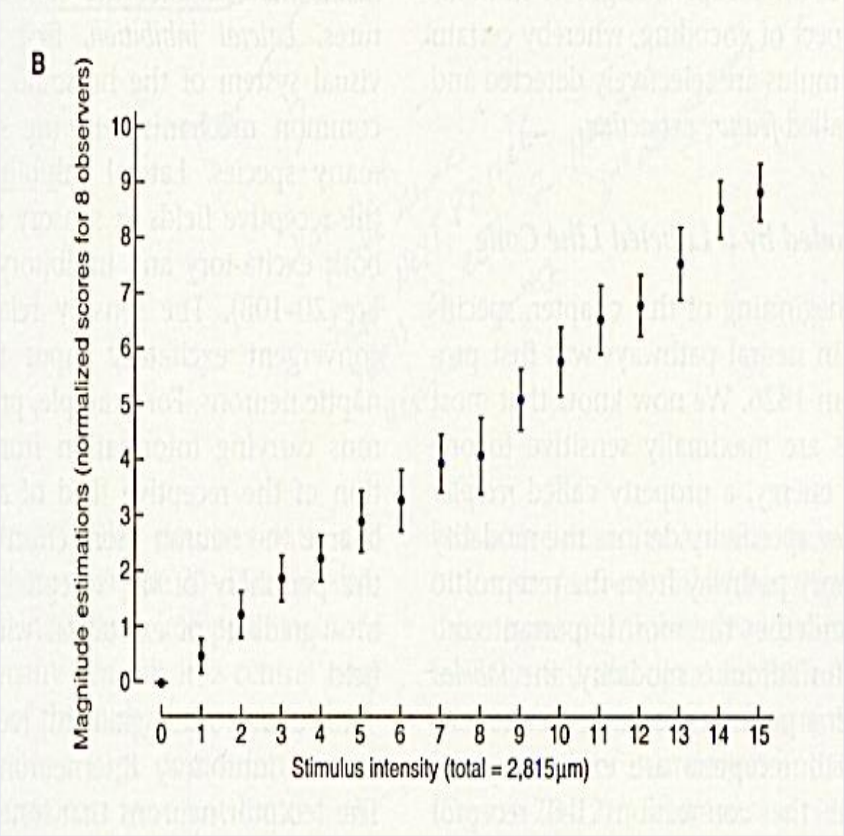
- Trigger patterns (action potential) codes the characteristics of the stimulus:
  - Intensity:
    - Codes based on frequency and neural population.
  - Duration:
    - Receptors discharge patterns with slow or fast adaptation.
  - Localization:
    - Stimulus discrimination.

Intensity
discharge frequency



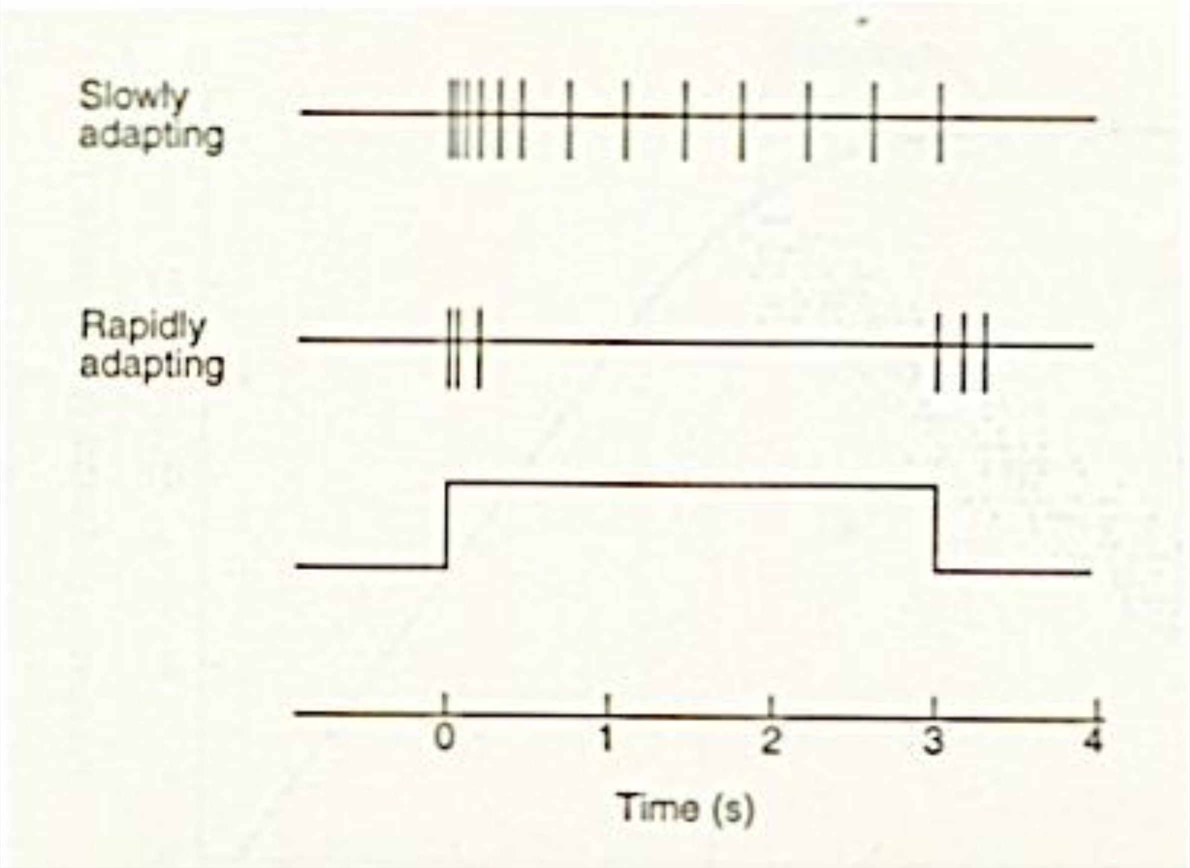
Codification of the intensity: discharge frequency





Stimulus duration

- The stimulus duration is coded by discharge patterns with slow and fast adaptation.



Localization: Stimulus discrimination

Inhibition in receptive fields:

1. Lateral inhibition

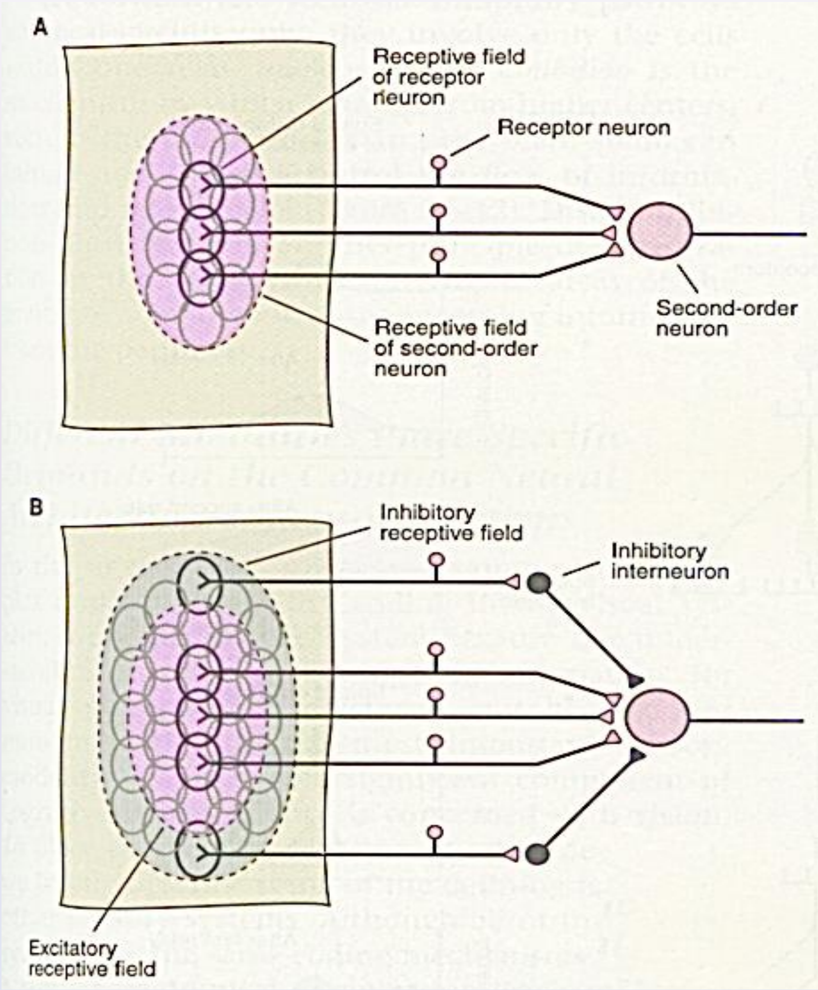
   in each synaptic relay the more active neurons inhibit the adjacent neurons more active

2. Forward inhibition

   The primary neurons inhibit directly the cells of the adjacent synaptic relay

3. Distal inhibition

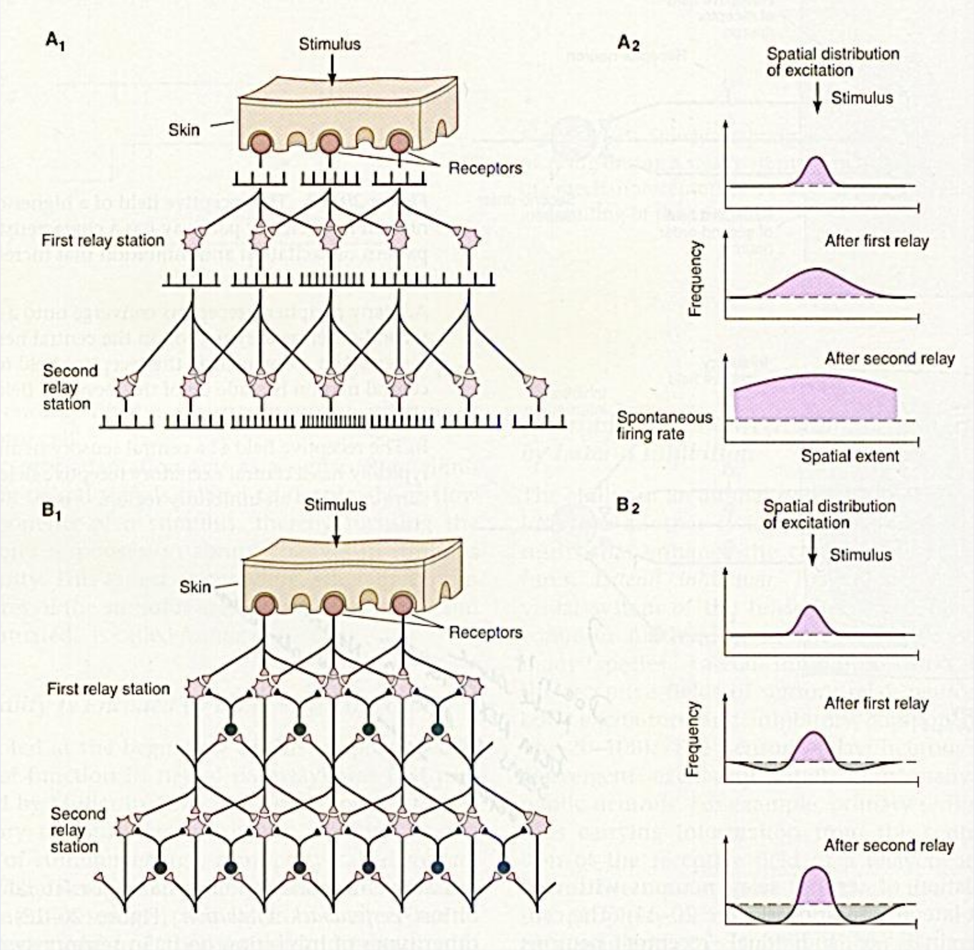
Receptive fields inhibitory or excitatory



Secondary neuron
Receptive field

Central neuron:
Excitatory field
Adjacent inibition region

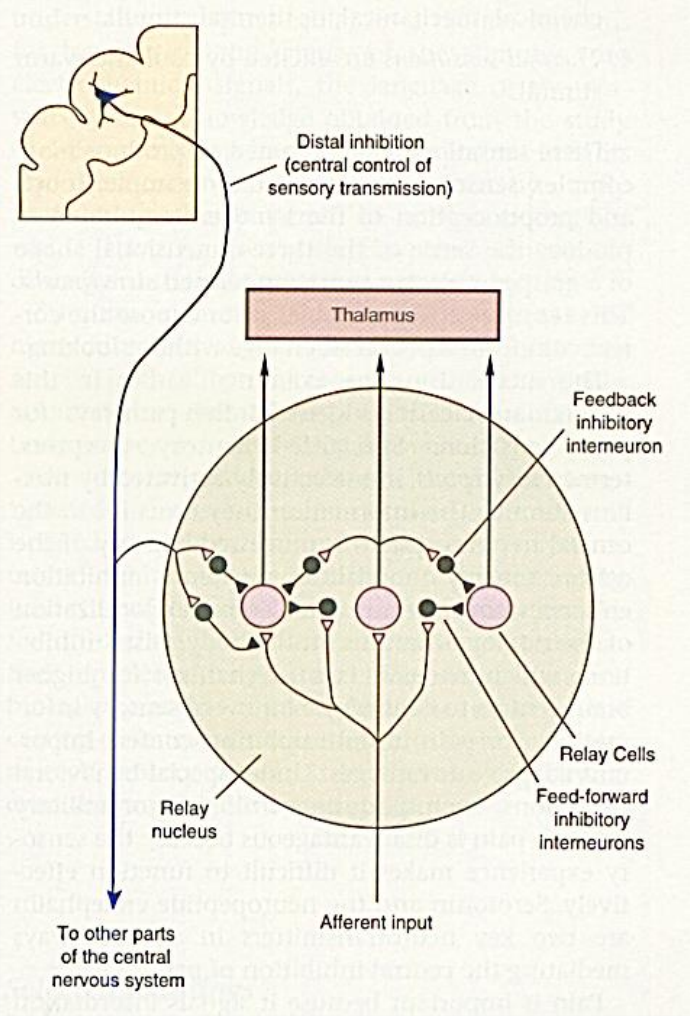
Lateral inhibition: Increases the stimulus contracts



Lateral inhibition:

Inhibits the afferent signals of neighbor receptors

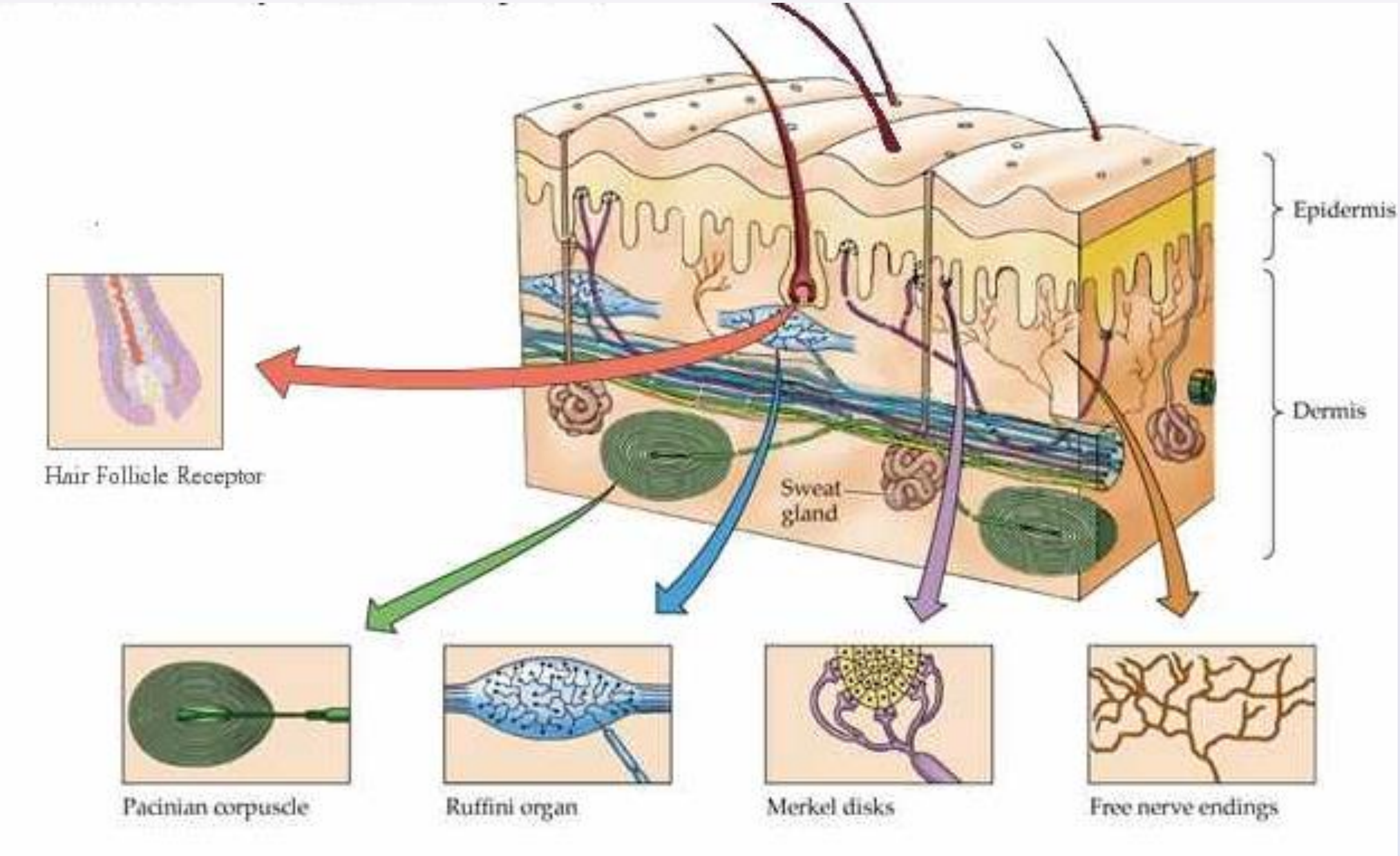
Inhibition types



Specific needs of each sensory system

- 1. Somato-sensory system:
  - Distributed in all the body:
    - Dermal sensors
  - Four sensations must be combined to form perceptions:
    - Mechanics: Pressure
    - Proprioception
    - Thermal
    - Nociceptive (noxious)
- 2. Smell and taste
  - Codification based in neural populations
  - Must identify smells and tests without prior experience
- 3. Auditory
  - Localization of sounds in space
  - Separate sounds in different frequencies (ICA)

Skin mechanoreceptors

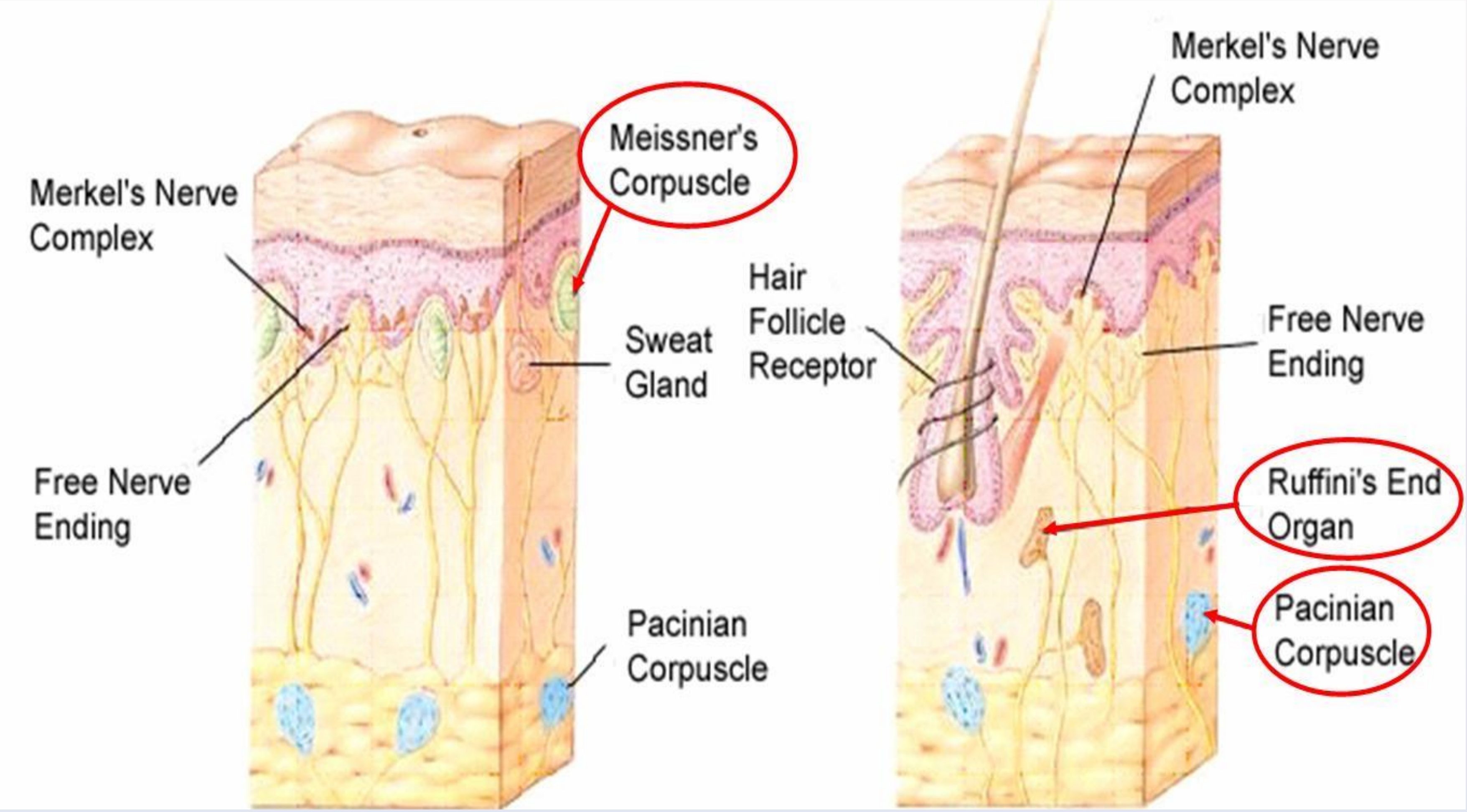


courtesy of http://www.hhp.uh.edu/clayne/6397/Unit4_files/image019.jpg

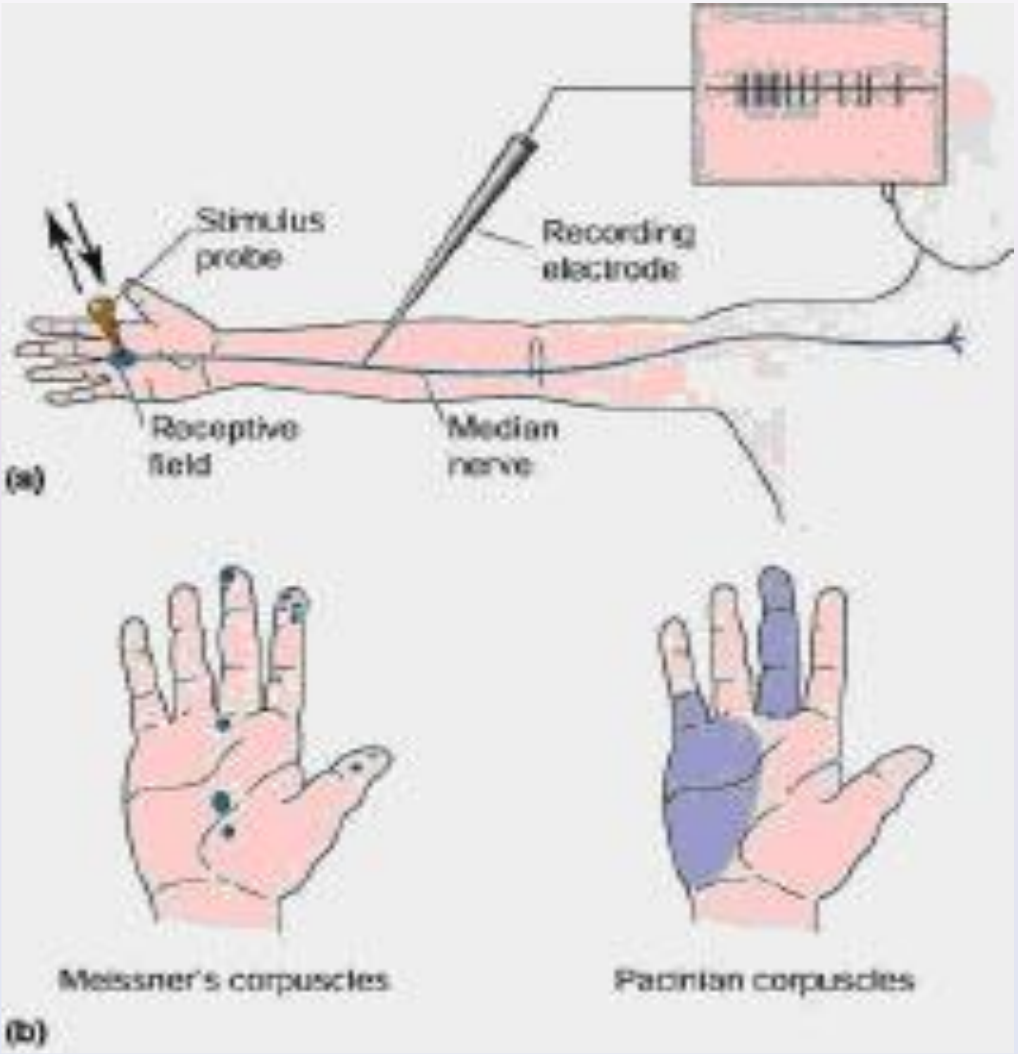
Skin mechanoreceptors

Receptor	Receptor Type	Field Diameter	Frequency Range	Sensed Parameter
Merkel Disks	SAI	3-4 mm	DC-30 Hz	Local skin curvature
Ruffini Endings	SAII	>10 mm	DC-15 Hz	Directional skin stretch
Meissner Corpuscles	FAI	3-4 mm	10-60 Hz	Skin stretch
Pacinian Corpuscles	FAII	>20 mm	50-1000 Hz	Unlocalized vibration

Skin mechanoreceptors



Skin mechanoreceptors



Summary

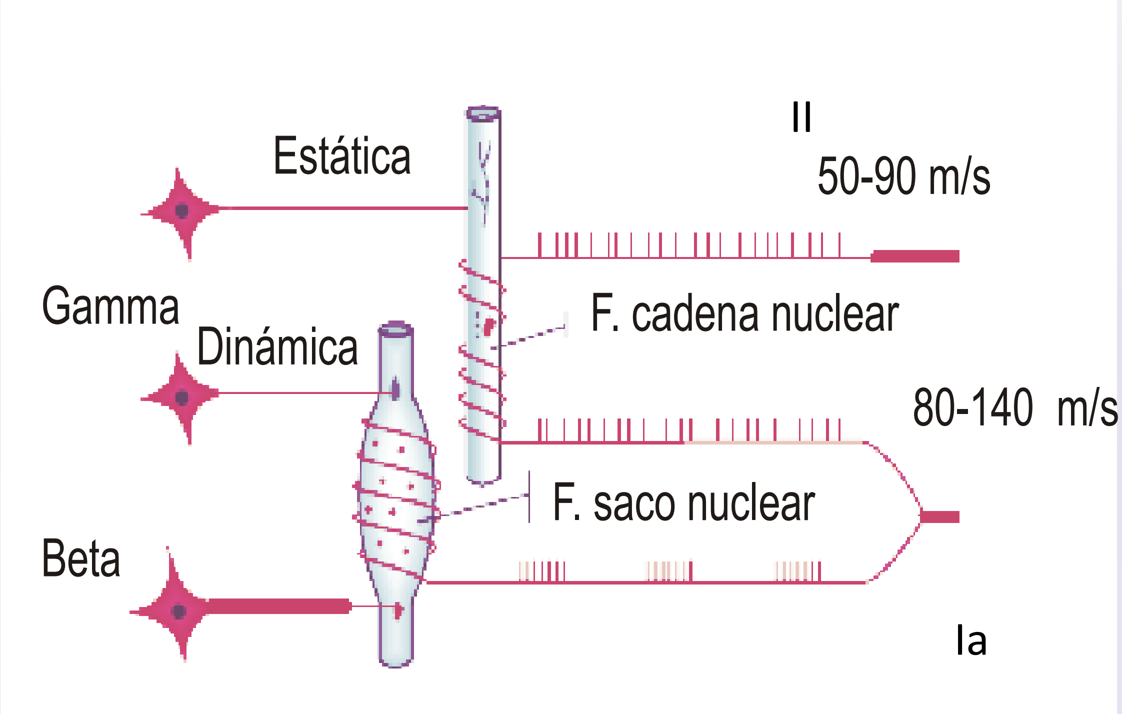
- Main functions of the sensory systems
- Outline of the organization
- Coding techniques:
  - Modality
  - Intensity
  - Duration
  - Localization

Muscle: proprioceptive feedback actuator

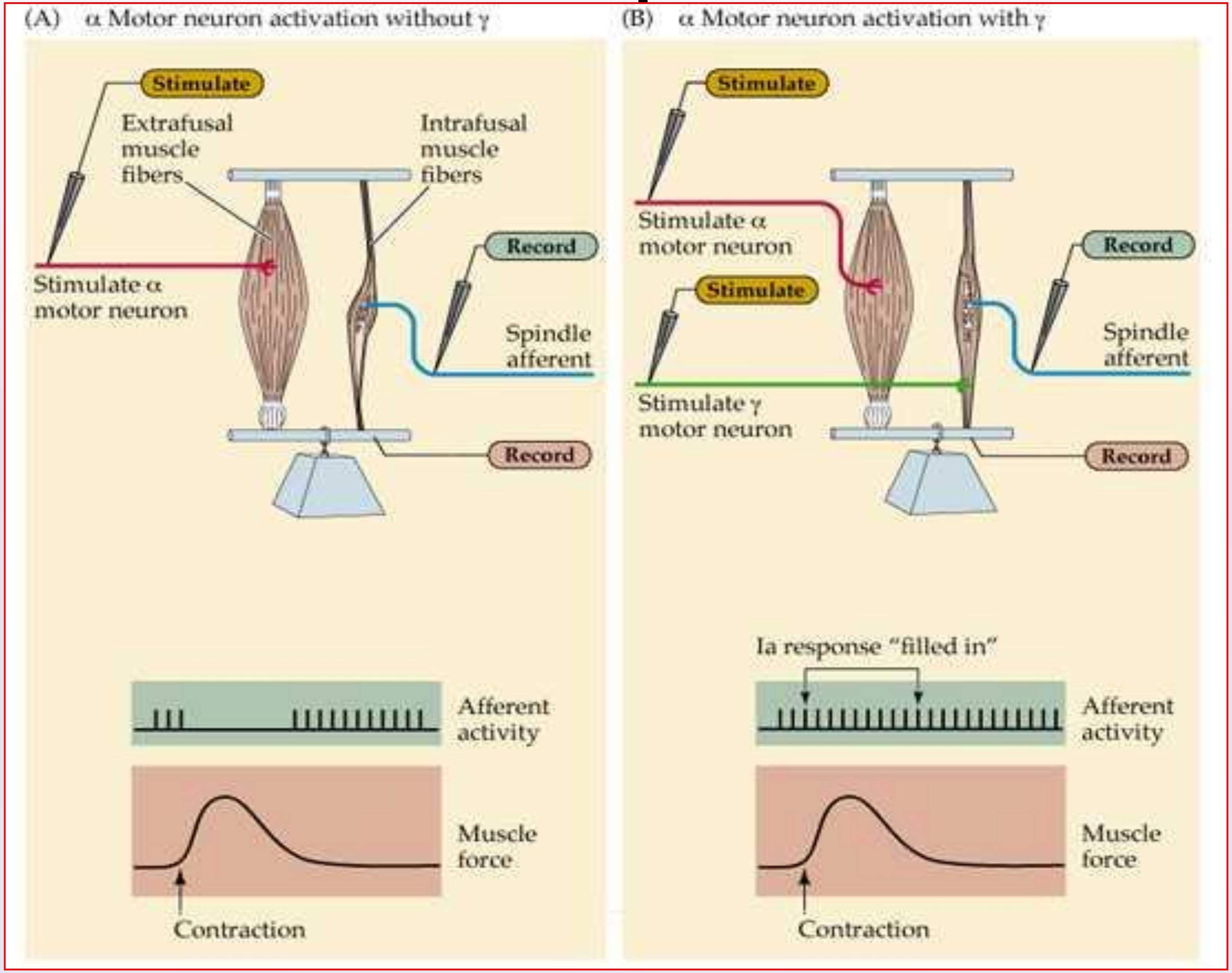
- Muscle: biological actuator
- Specialized sensors:
  - Muscle spindles
  - Golgi tendon organs (GTO)
- Includes a control structure that generates behaviors:
  - Reflexes
- The sensors (spindles) can be modulated from a higher control level:
  - Gamma motoneurons

Muscle sensors

- Muscle spindles
  - Length
  - Length change
- GTO
  - Force in the tendon
- Interneurons:
  - Reflexes at different levels



Muscle spindles

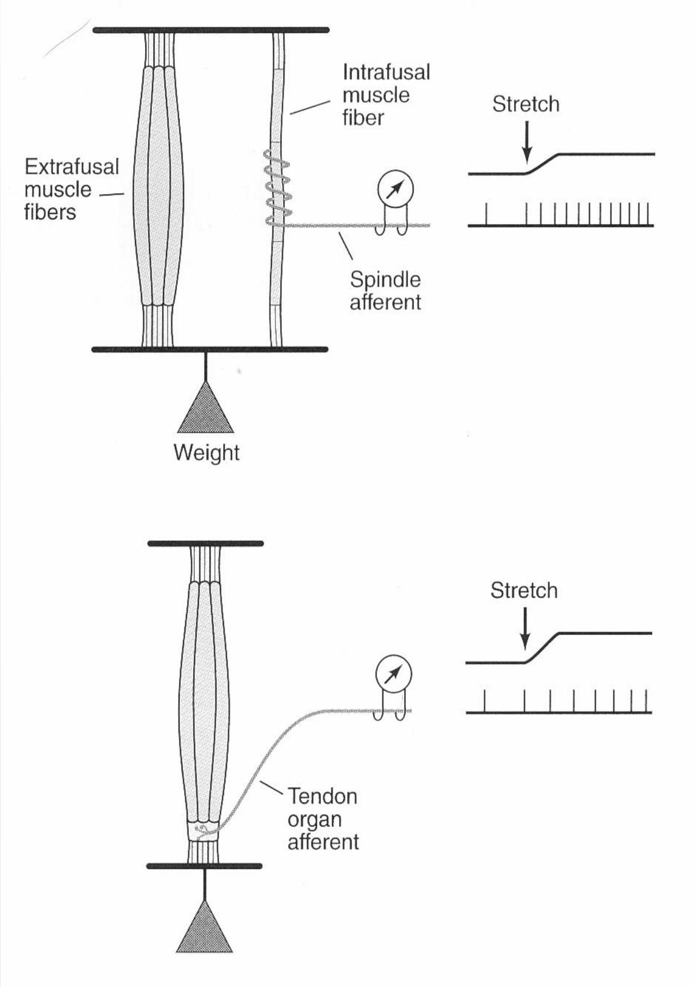


Lengthened muscle

Relaxed muscle:

The fibers are lenghtened

Not the tendon that is more rigid



Spindle response

GTO response

Contracted muscle

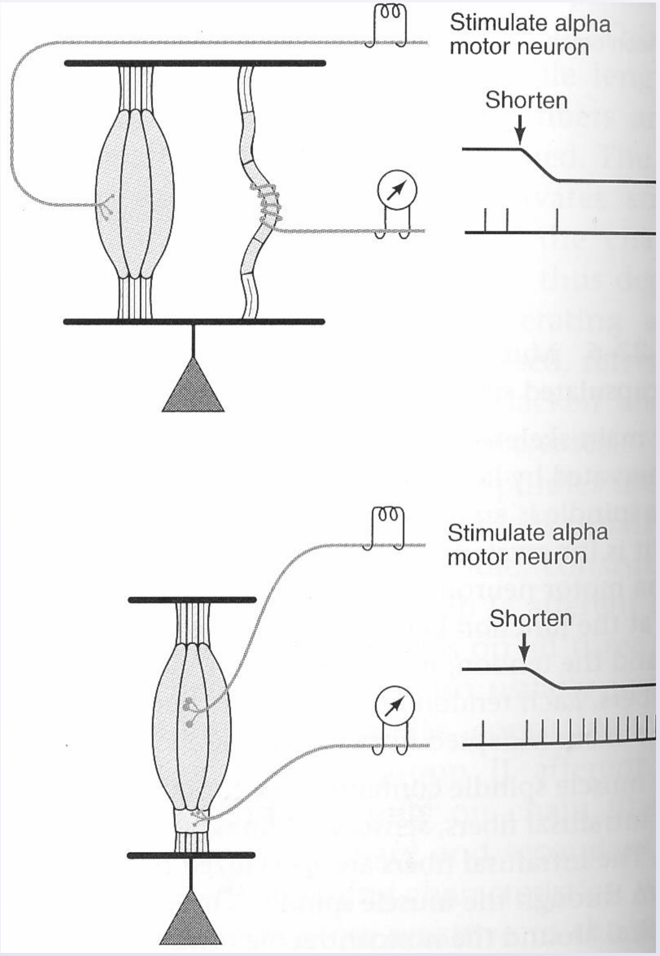
Contracted muscle:

- Muscle fibers are contracted.

- The tendon stretches.

- GTO activity

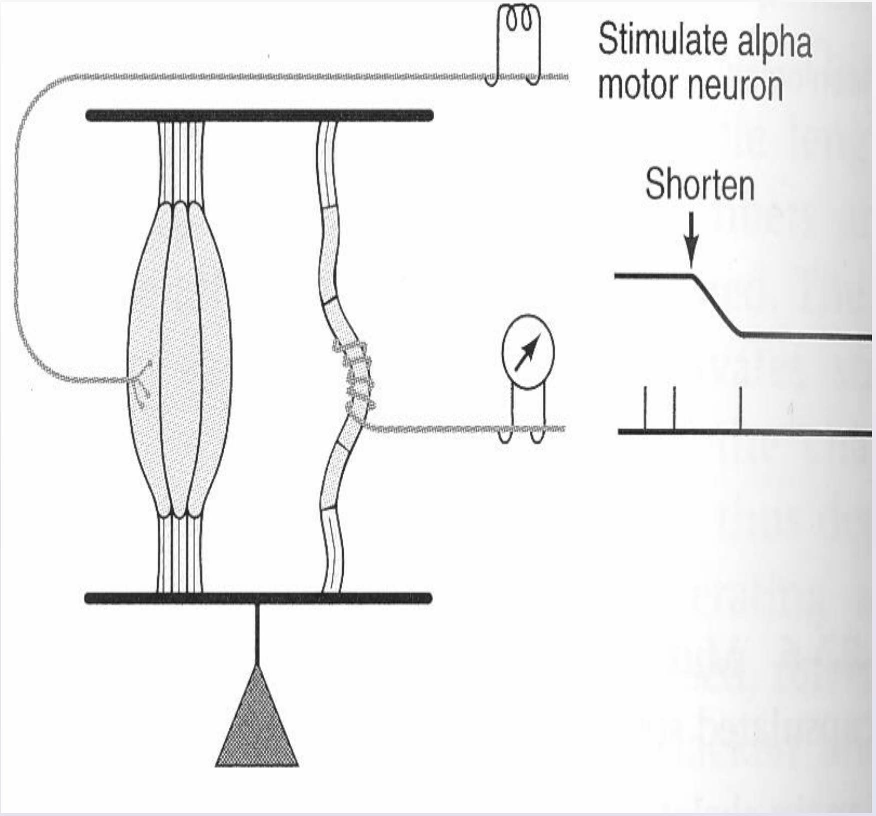
- Intrafusal fibers (spindles(are unloaded due to the extrafusal contraction.



Spindle response

GTO response

Contracted muscle



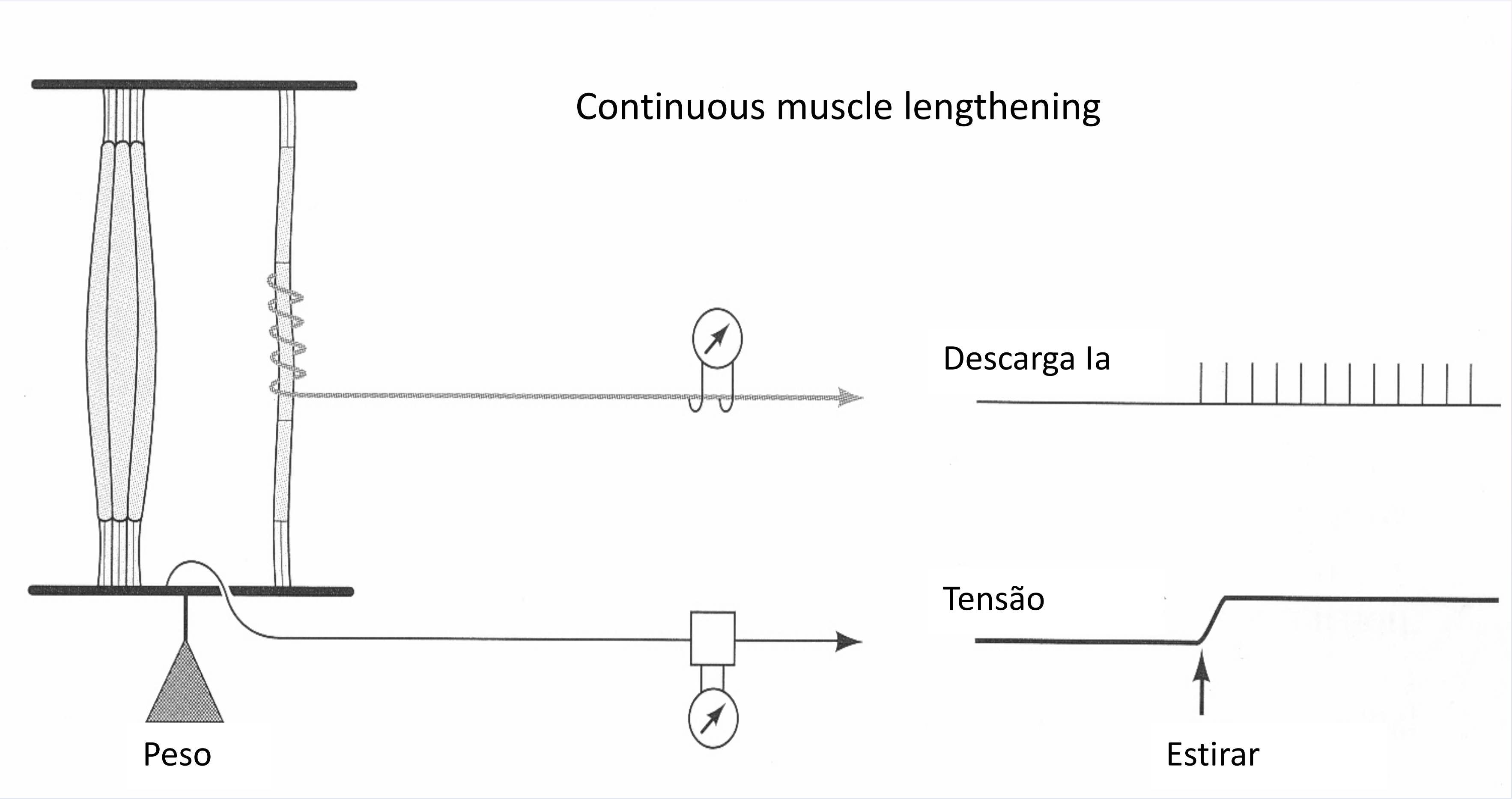
Spindle response

Intrafusal fibers are unloaded due to extrafusal contraction:

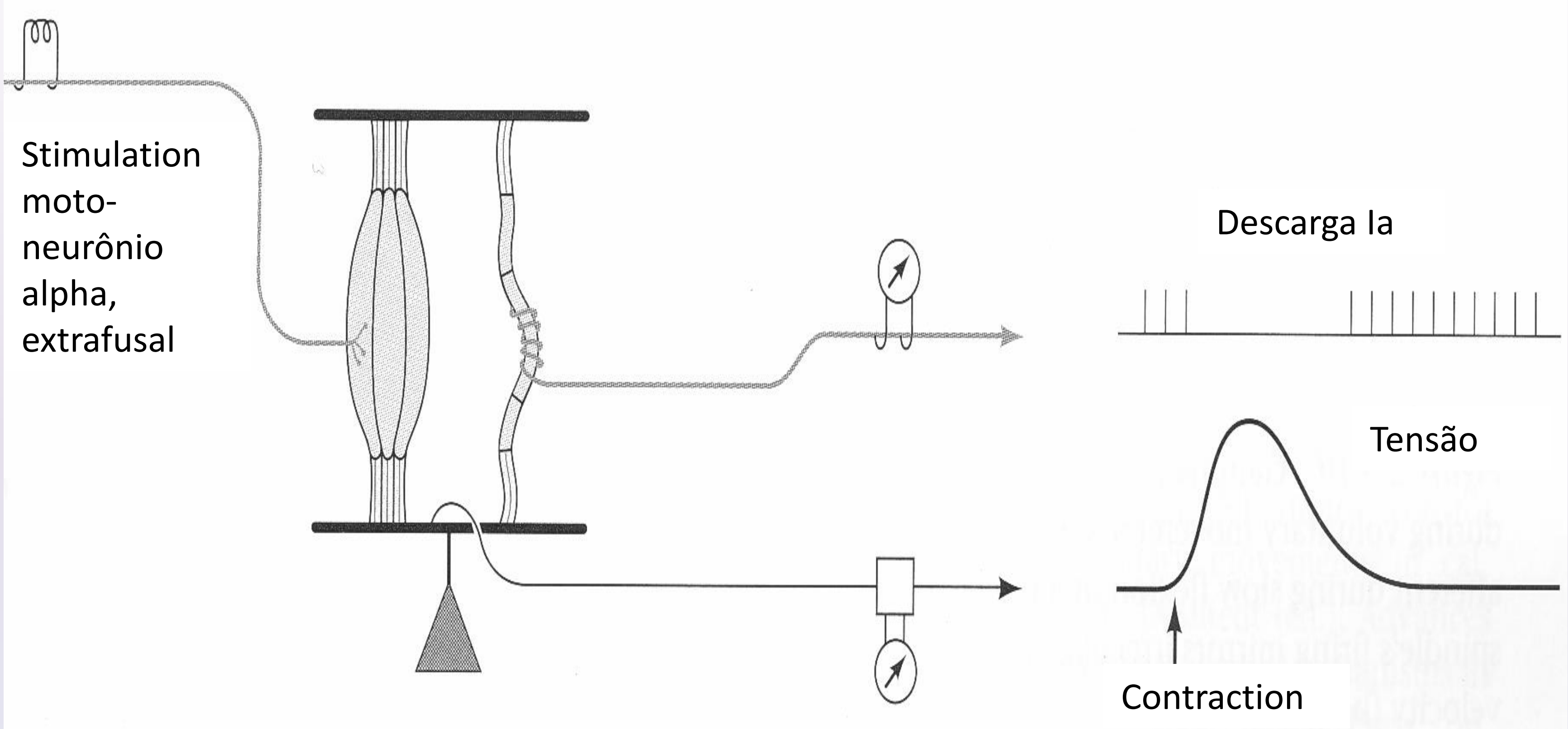
They cannot provide information during the shortening!

Is this correct?

Gamma stimulation

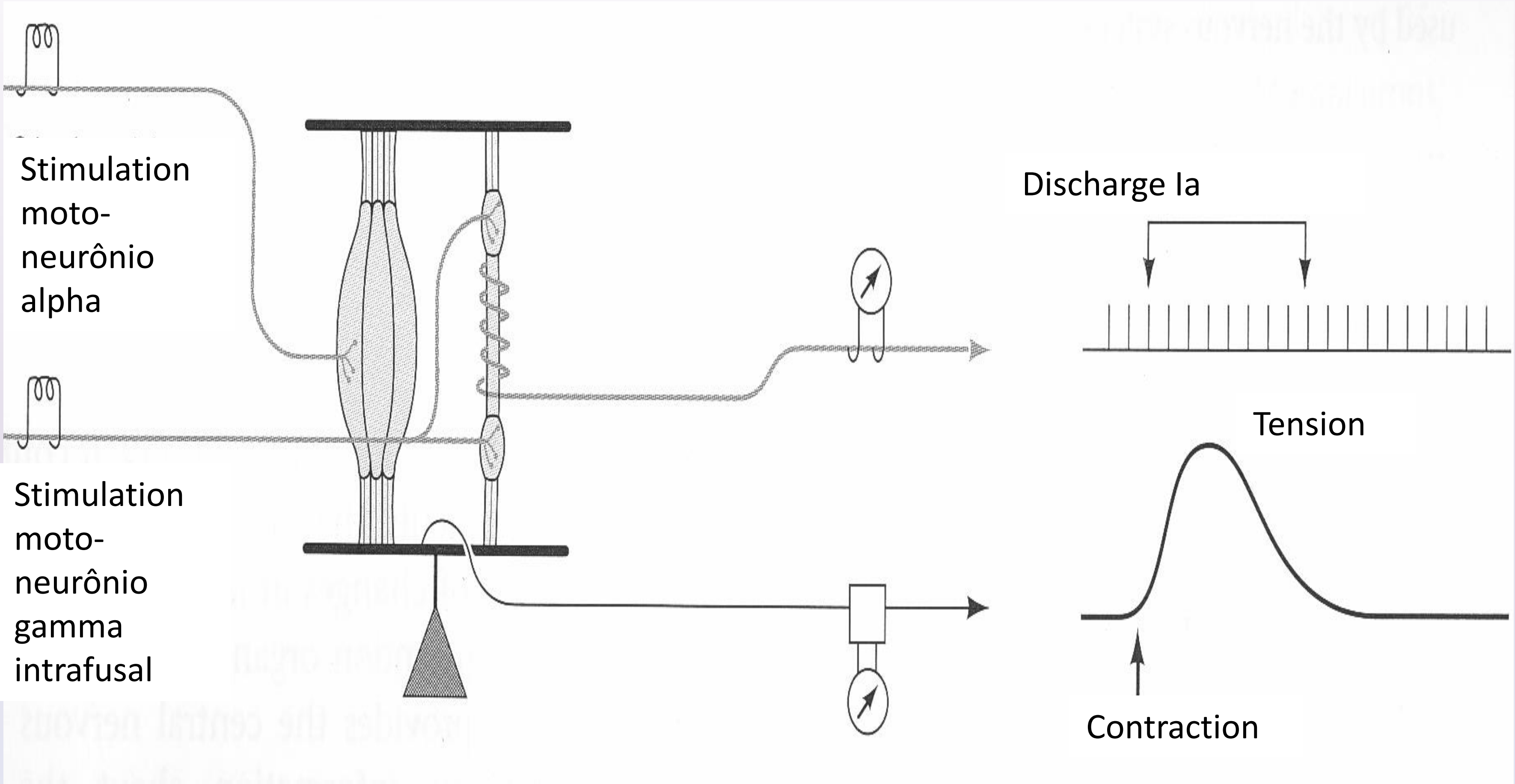


Gamma stimulation



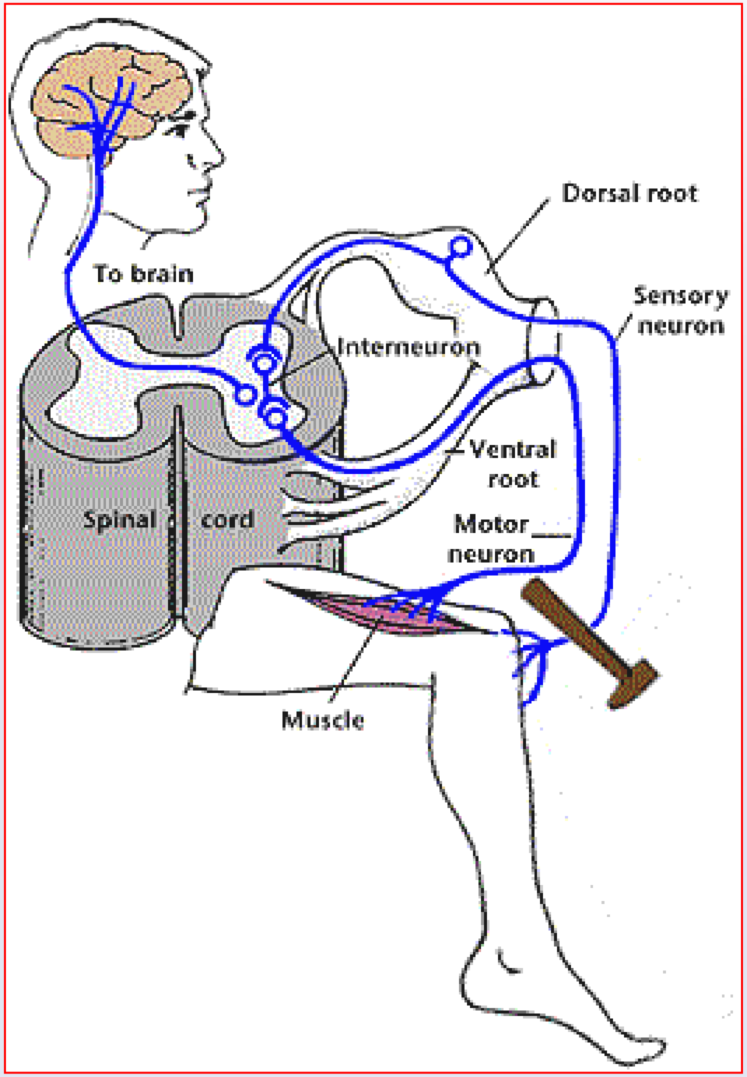
If the spindle is relaex during the contraction:
No information about muscle length

Gamma stimulation



Then, the spindle contracts independently during the extrafusal contraction :
information about muscle length!

Spinal reflex



- Reflex:

  Stereotyped pre-programmed reaction as a response to a stimulus

- Simple reflex:

  Monosynaptic myotatic reflex

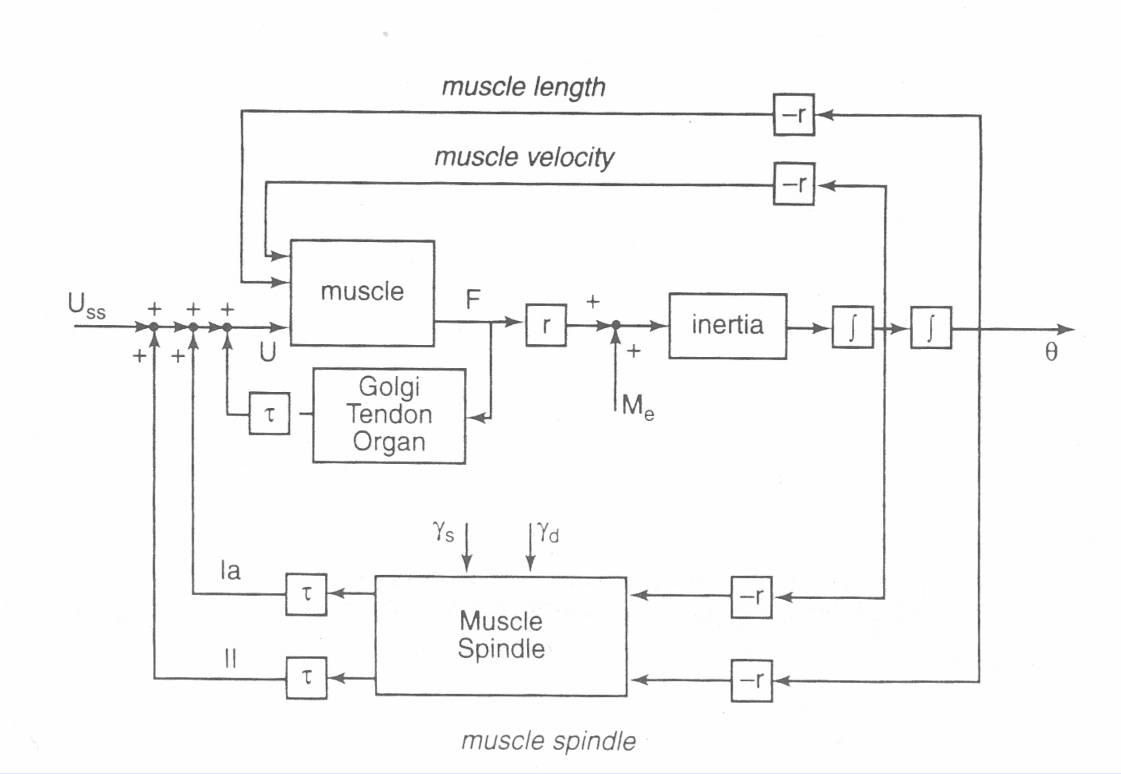
  (lengthening)

- Polysinaptic reflexes:

  Flexor (or withdrawal) reflex

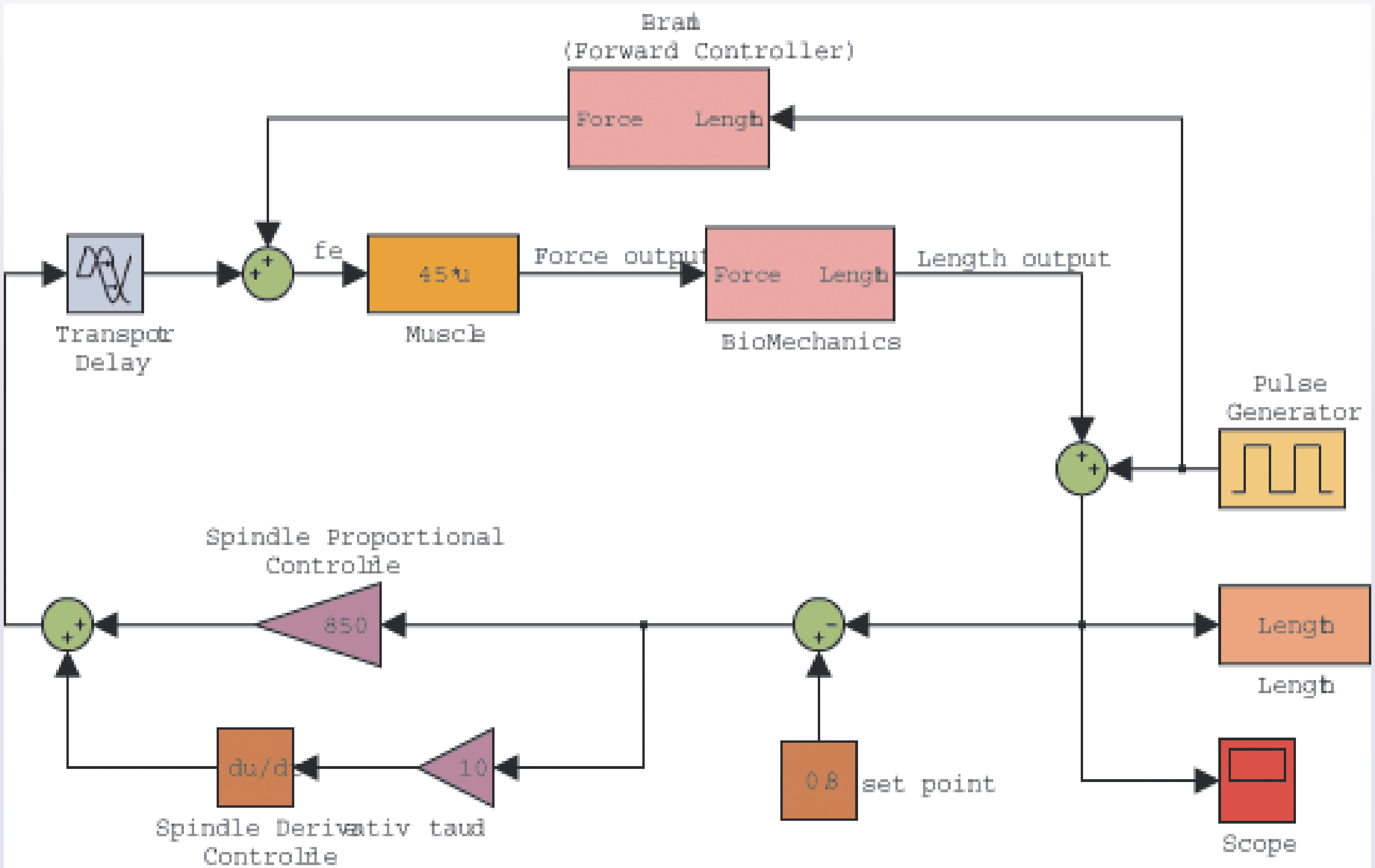
- Reflexes: modulated by higher centers

Model: muscle and myotatic reflex



Van der Helm FCT, Rozendaal LA (2000). Musculoskeletal systems with intrinsic and proprioceptive feedback. In: Winters JM, Crago P (Eds), Neural control of posture and movement, Springer Verlag, NY, 164-174

Model: muscle and myotatic reflex



ESCOLA POLITÉCNICA DA UNIVERSIDADE DE SÃO PAULO

Flexor reflex

Flexor reflex:

Leg withdrawal

Muscles:

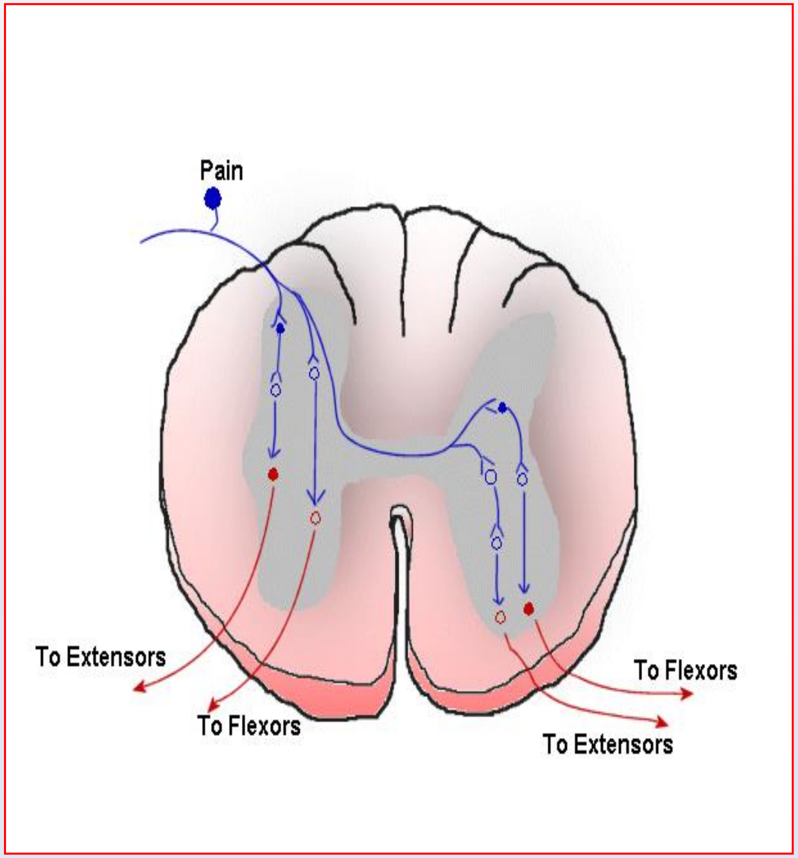
- Agonist
- Antagonist

Extensor reflex:

- Contralateral limb
- Postural support

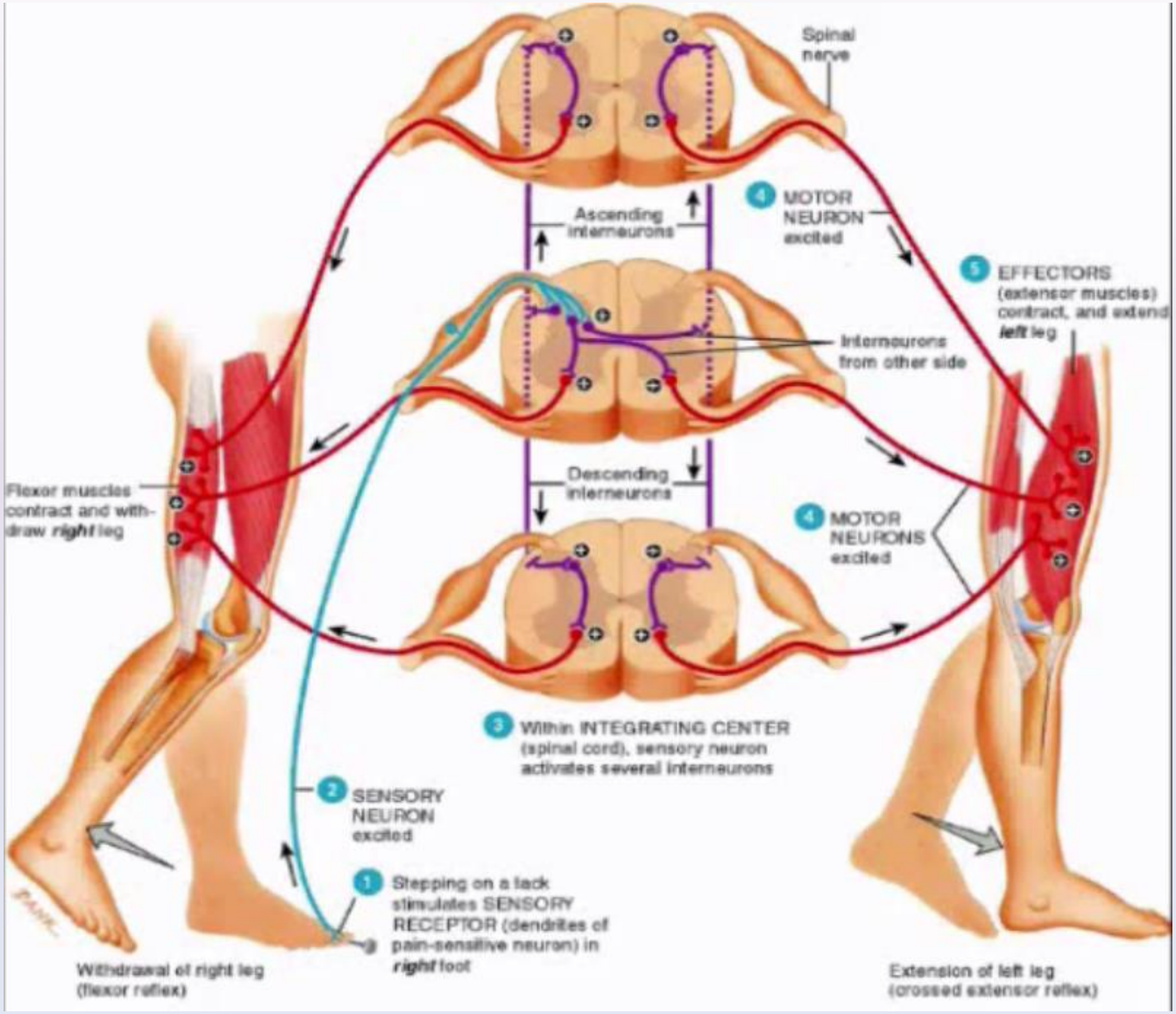
Multiple limbs:

Inhibition of motoneurons in the spinal cord




Today is a good day I think for more SECRETS of the MEDICAL PROFESSION!
Wooo!
Secrets!!
Dromiceiomimus, you know how doctors will hit your knee with a hammer to test your reflexes?
Indeed I do!
WELL! In some cases the patient will be too aware of what's going on, and the test won't work. In such cases the patient is asked to lock their hands together and pull them in opposite directions. This distraction allows the test to succeed!
I believe this is called the "Jendrassik Maneuver"!
That's a pretty sinister name!
You're telling me! What's neat about it, though, is that it's AUTOMATIC. Even if you're aware that it's a distraction, the Maneuver still works!
Really?
Yep! It's a neurological distraction affecting the pathways between the central nervous system and the motor neurons, dishibiting any tonic (i.e.: baseline) inhibition.
DOCTORS, huh?
(C) 2005 Ryan North
www.qwantz.com

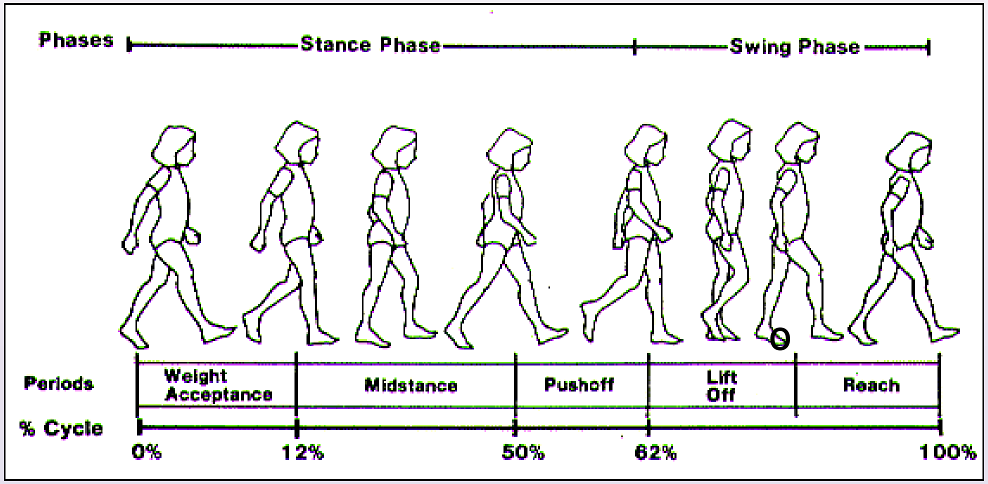
Crossed extensor reflex



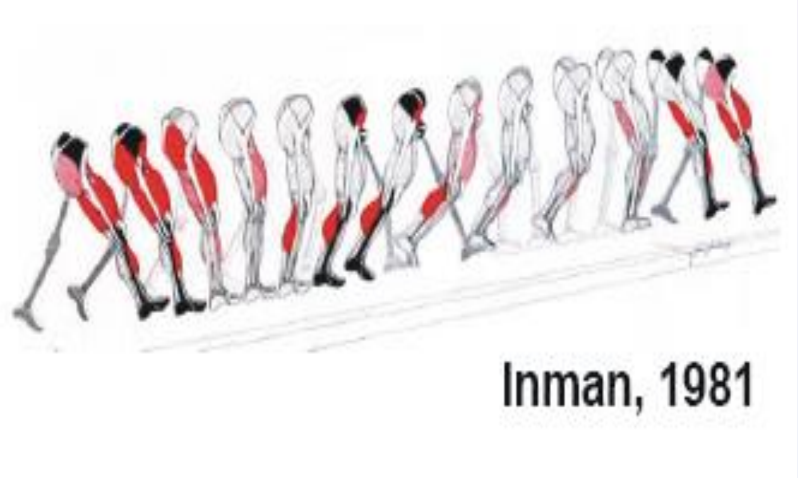
Contents

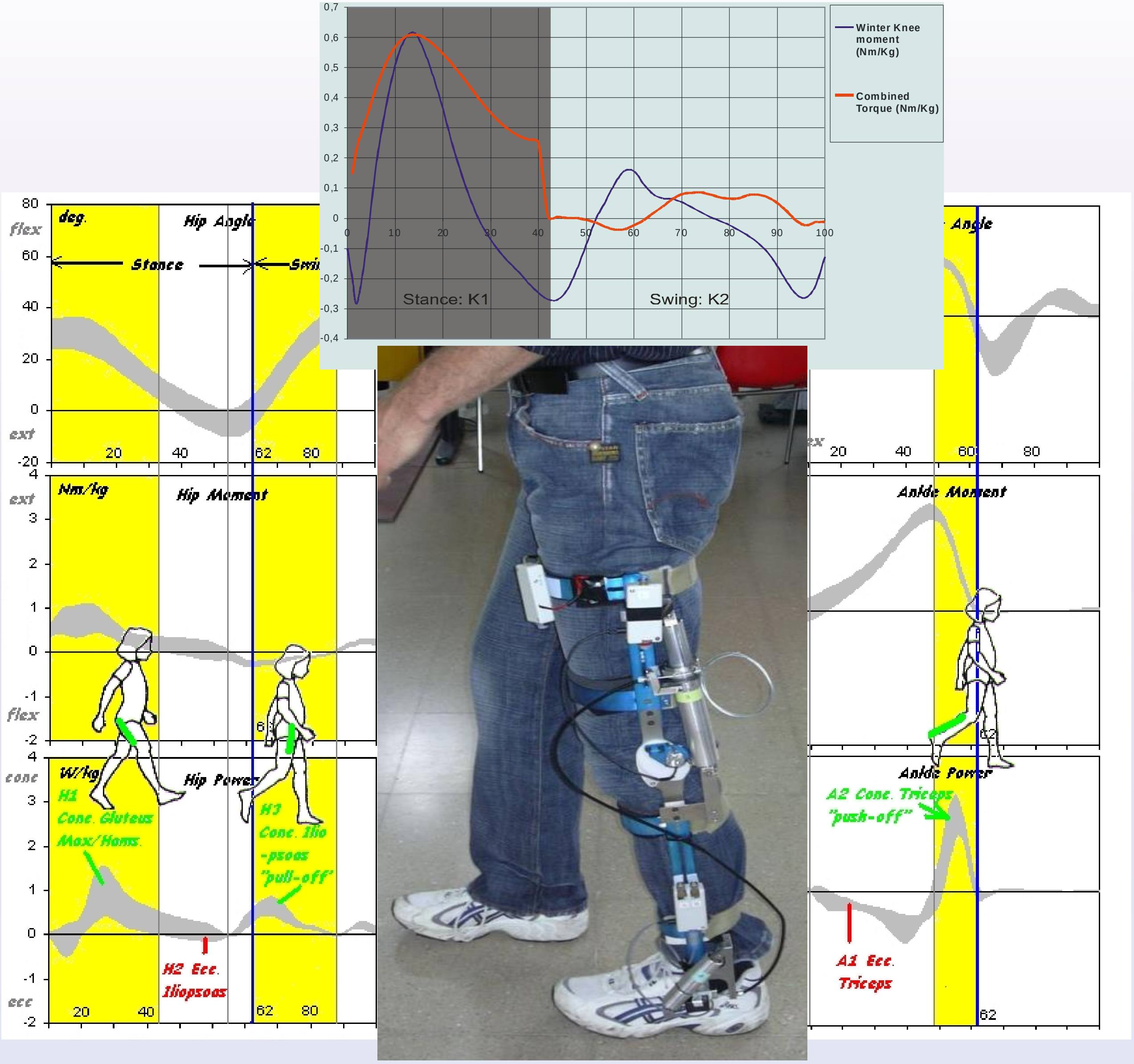
Human gait description

Phases of the gait cycle



Control: EMG



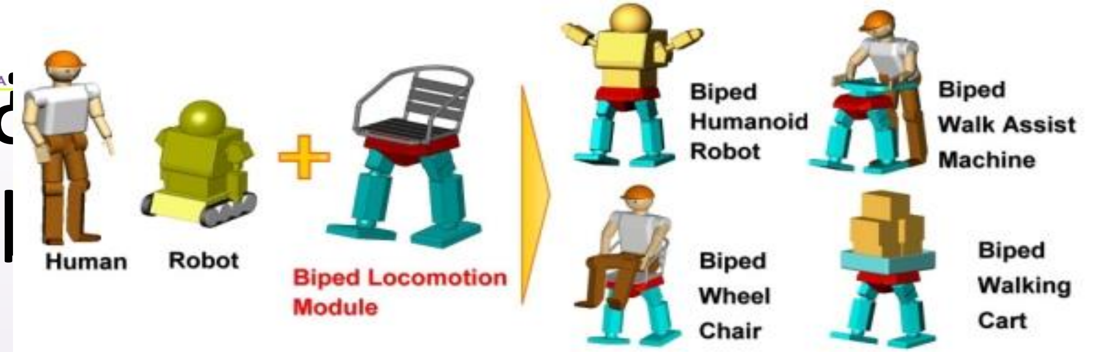

Winter Knee moment (Nm/Kg)
Combined Torque (Nm/Kg)
Stance: K1
Swing: K2
Hip Angle
deg.
flex
ext
Stance
Hip Moment
Nm/kg
Hip Power
W/kg
conc
ecc
H1 Conc. Gluteus Max/Hams.
H2 Ecc. Iliopsoas
H3 Conc. Ilio -psoas "pull-off"
Ankle Moment
Ankle Power
A1 Ecc. Triceps
A2 Conc. Triceps "push-off"

Is gait automatic?

- Attention and cognitive interference:
  - Alters gait in:
    - Elderly:
      - » The stopped walking to reply
    - Neurologic patients
  - Postural control is altered
- Hierarchical control
- High processing costs (discontinuous)

Lundin-Olsson L, Nyberg L, Gustafson e. "Stops walking when talking" as a predictor of falls in elderly people. Lancet1997;349:617.

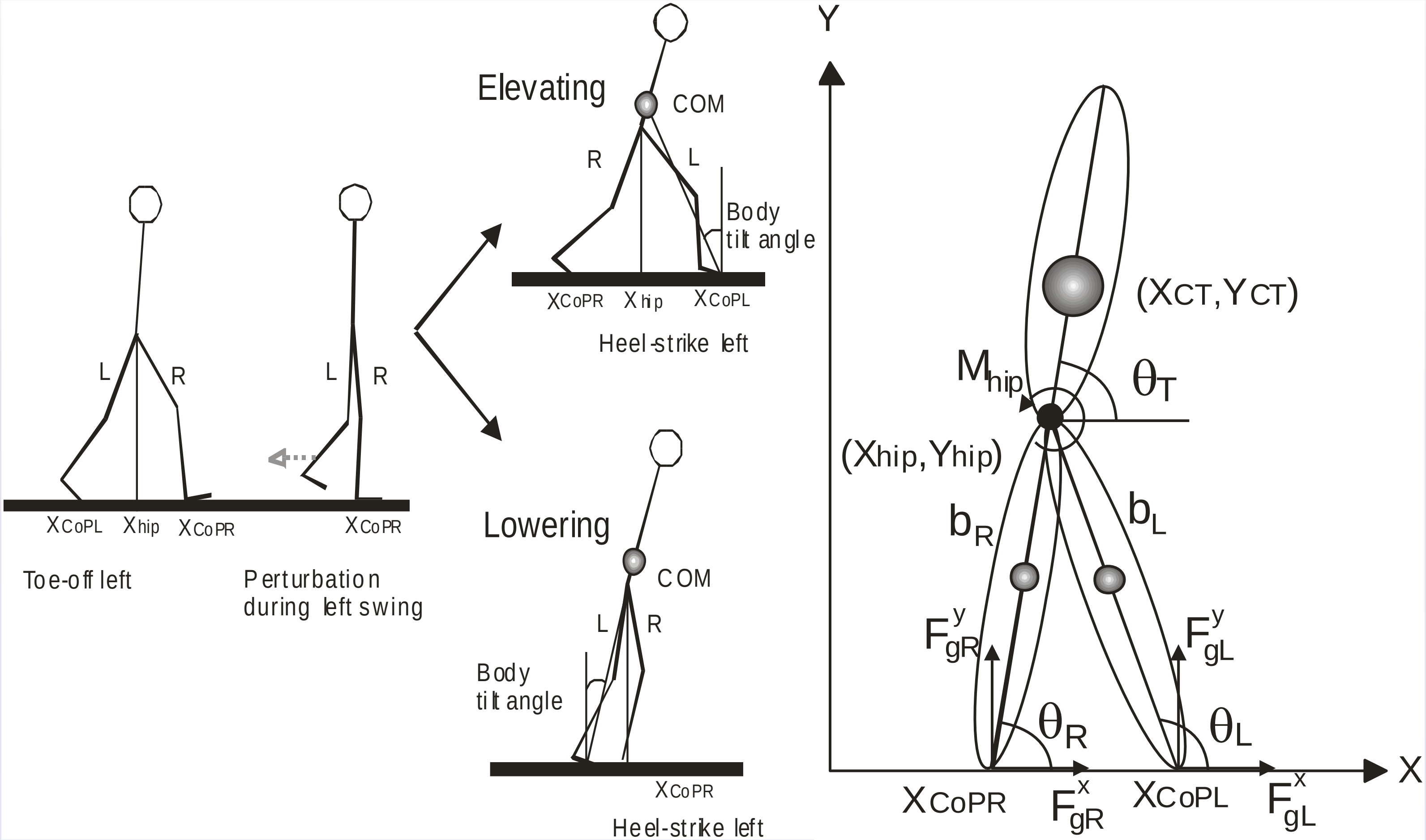
Forner Cordero, A.; Levin, O.; Li, e.; Swinnen, S.P. Posture control and complex arm coordination: Analysis of multijoint coordinative movements and the control of stance. J. of Motor Behavior (in press)



U. Waseda. F. Mechanical Engineering: WASEDA Biped. Takanishi Lab

- Challenges in stability control
- Human robot interaction
  - Anthropomorphic robot: replicate human behavior
- Disability: Assistive technologies
  - Robotic prostheses and orthoses

Minimal number of sensors to guarantee stable biped gait?



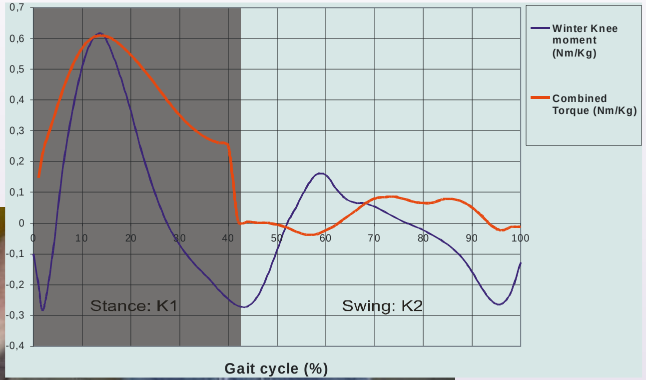
Forner Cordero, A.; Koopman H.F.J.M; van der Helm F.C.T. (2004). Mechanical Modo of the Recovery from Stumbling. Biological Cybernetics. 91(4) 212-22. 2004.

Biped gait sensors

- Minimal number of sensors:
  - Inertial (head or trunk):
    - Vestibular system (head)
  - Pressure, contact forces under the foot
    - Mecano-receptors
  - Hip, knee and ankle angles:
    - Muscle spindles
    - Joint proprioceptors
- Simple control structure: Limit cycle

Orthoses and prostheses

- GAIT
  - Orthosis with two springs that are switched between stance and swing.
- Inertial sensors:
  - Leg orientation
- Angular sensor:
  - Knee potentiometer (or encoder)
- Pressure sensors:
  - Pressure on the leg attachment



Orthoses and prostheses

Biomimetic control architectures: Hierarchy (MANUS)

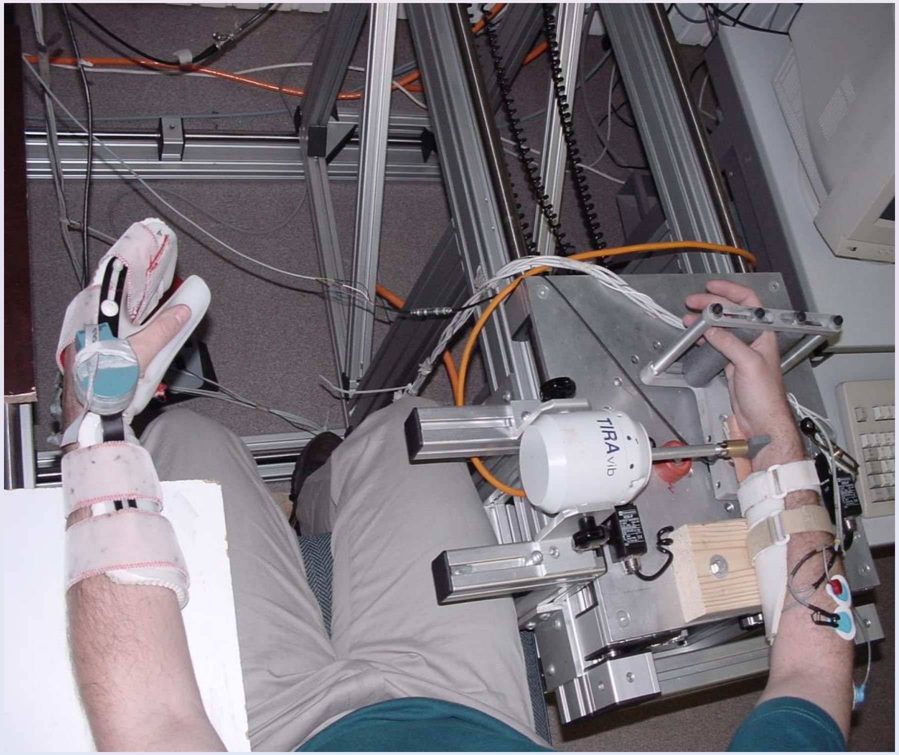
- Global: Gripping pattern selection
- Local: anti-slip reflexes

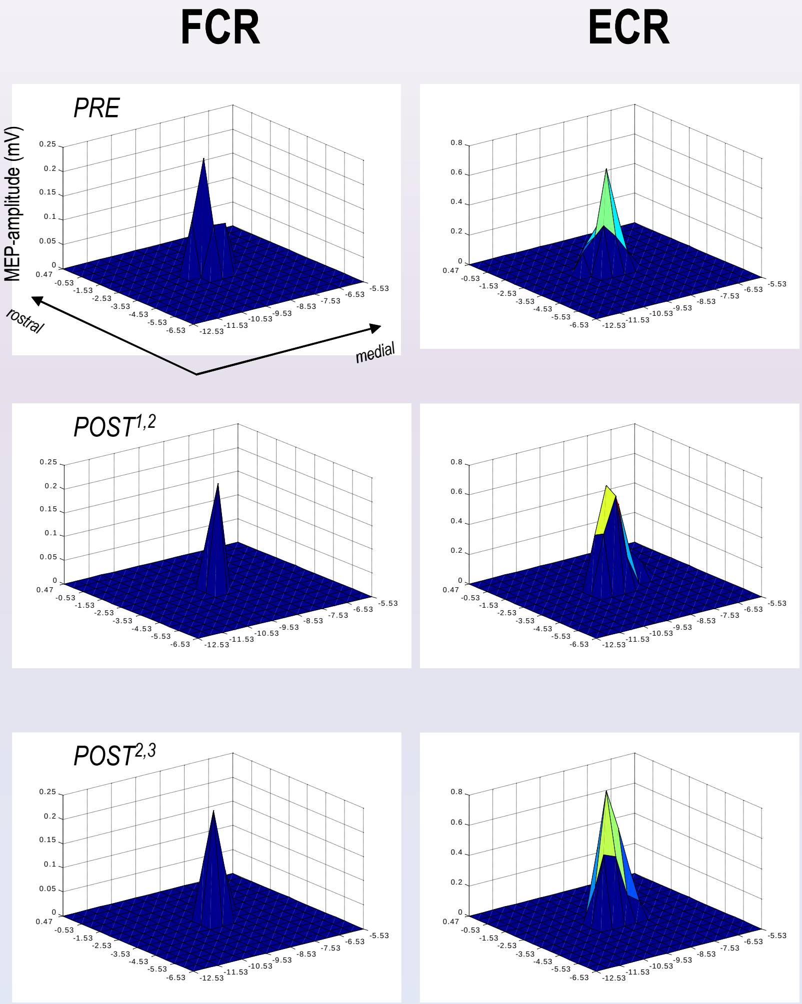
T. Kuiken. Rehabilitation Institute of Chicago (RIC).

Robotic arm controlled by nerve signals amplified by the muscles that are not used.

Robotic Neuro-Rehabilitation

- Experiments with Transcranial Magnetic Stimulation
  - Altered joint perception





Robotic Neuro-Rehabilitation

- New rehabilitation techniques based on neural reorganization:
  - Modification of the cortical motor maps with robotic sensory stimulation:
    - Muscle tendon vibration:
      - Excites Ia aferents: motion perception
    - Cyclical passive movements

- Publication:
  - A. Forner-Cordero et al. (2008). Changes in corticomotor excitability following prolonged muscle tendon vibration.
    Behav Brain Res, 190: 41-49.

Biomimetism=>Bioimitation

- Imitation levels:
  - Stimulus strengthening
  - Imitation of actions or structures without understanding
  - Imitation:
    1. Understand goals
    2. Models of behavior
    3. Combination of available actions/tools (technologies)
    4. Adapt to new situations
  - **Understand and model the biological mechanism**
  - **Translate these mechanisms to our context**
    - **E.g. Considering technological limitations**

Thank you