Human Motion Control

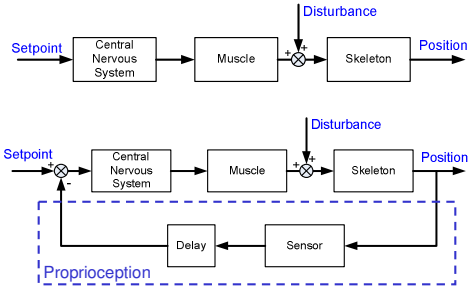
2008-2009

Proprioception

Proprioception

- Introduction
  - Musculoskeletal system with proprioceptive feedback
  - Role of sensors
- Nervous system
  - Central nervous system
  - Peripheral nervous system
  - Sensors and neurons
- Information Processing
  - Organization & reflexes
- Sensors in motor pathways
  - Joint capsule sensors
  - Muscle spindles
  - Golgi Tendon Organs

Open and closed loop control



Proprioception

from *proprius* Latin for “one’s own” and *perception*.

The body's awareness of position, posture, movement and changes in equilibrium

Proprioception

Have you ever said any of the following?

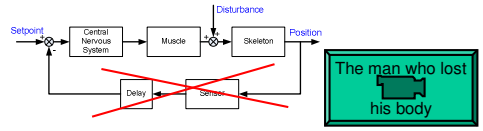
- “I think I smell gas!”
- “Did you hear that sound?”
- “I have a headache.”
- “I just noticed my elbow is slightly flexed and my hand is approximately 30 centimeters away from my face.”

Proprioception happens unconsciously.

Loss of proprioception

Example loss of proprioception: Ian Waterman

- No sensory feedback below the neck
- Not paralyzed!
- One of only 10 patients in the world.



Sensors

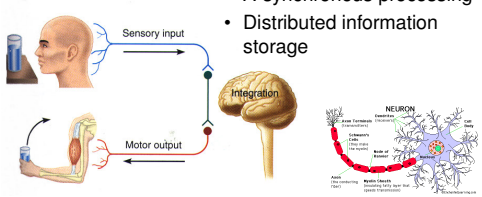
- Vestibulary system: Translational and rotational **accelerations** of the head
- Visual system: **Position** and **velocity** information
- Tactile system: **External force** information
- Joint capsule receptors: **Joint angle**

- *Muscle spindles*: Muscle **length** and **contractile velocity**
- *Golgi tendon organs*: Muscle **Force**

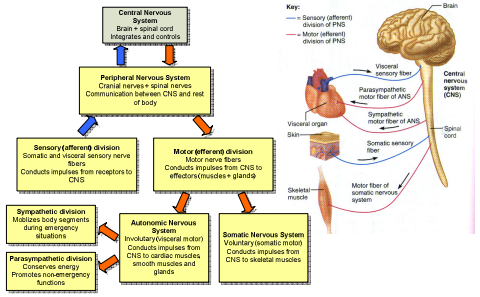
Sensory integration $\Rightarrow$ **Central Nervous System**

Central Nervous System (CNS)

- 10^{11} neurons
- 10^{4} synapses per neuron: 10^{15} synapses
- A-synchronous processing
- Distributed information storage

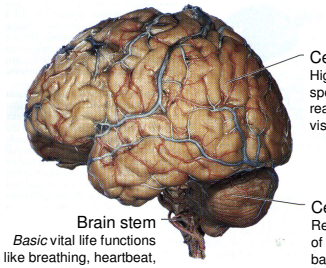


Structure of the CNS



CNS

The Brain

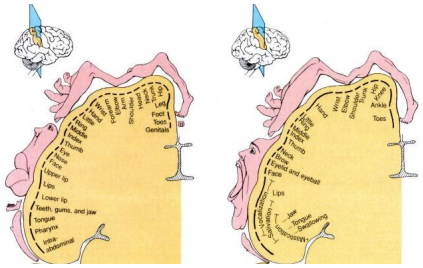


Cerebrum
Higher brain functions like: speech, emotions, reasoning, movements, vision, memory, etc…

Cerebellum
Regulation and coordination of movement, posture and balance.

Brain stem
Basic vital life functions like breathing, heartbeat, blood pressure.

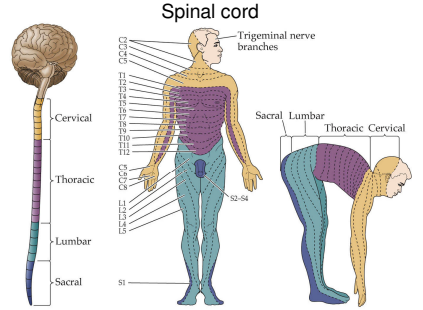
Sensory and motor projections in the cortex



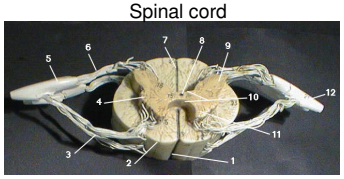
Sensory and motor projections in the cortex

Sensory system **Motor system**

CNS
Spinal cord



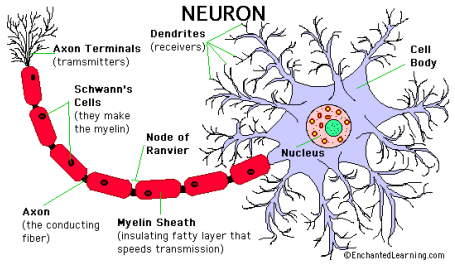
CNS
Spinal cord



3. Ventral root: motor output to muscles
5. Dorsal root ganglia: contains cell bodies of sensory neurons
6. Dorsal root: sensory input to spinal cord
9. Posterior horn: spinal interneurons
10. Anterior horn: alpha motoneurons

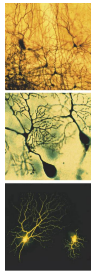
2. White matter: myelinated axons
4. Grey matter: nerve cell bodies

Building block of the CNS: the neuron



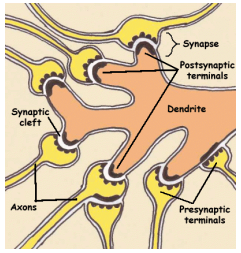
Connections between CNS and PNS:
Neurons

- Neuron also called “nerve cell”
- Dendrites
  - receive incoming spikes.
  - diffusely branched
  - one neuron generally has many dendrites.
- Axon
  - transmits information.
  - one neuron has one axon.
  - length up to one meter.
- Axon terminals
  - communicate output to other neurons (or muscles).
  - One axon generally has multiple terminals

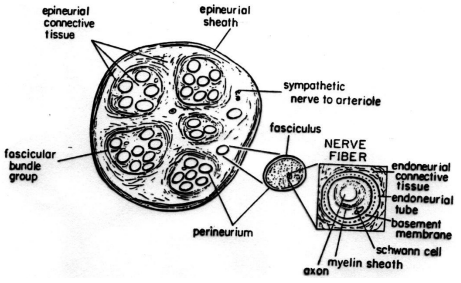


Connections between neurons: synapses

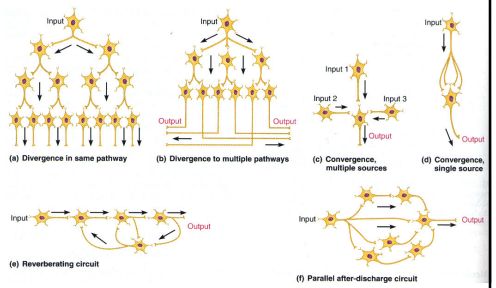
- Junction between two neurons or between neuron and effector
- Between 1,000 - 10,000 synapses per neuron
- Electrical (few) or chemical (most)



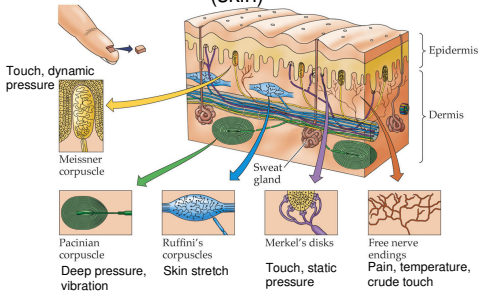
Organisation of neurons:
nerve fibers



Neural integration: neuronal pools



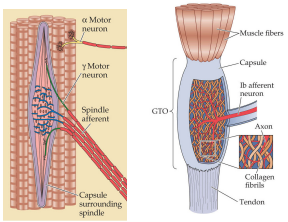
Types of somatic sensory nerve endings (skin)



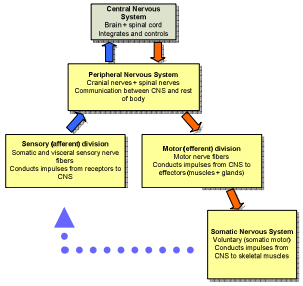
Types of somatic sensory nerve endings (musculoskeletal system)

Muscle spindle
muscle stretch and stretch velocity

Golgi tendon organ
tendon force

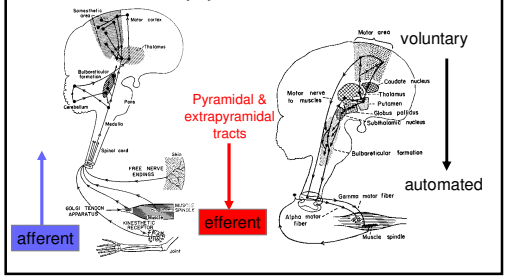


Simplified structure of the CNS

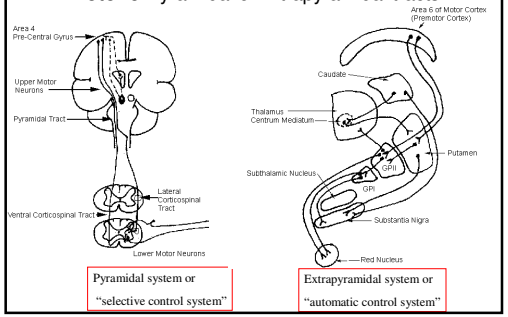


Neural integration
(CNS and PNS)

- The somatic sensory system
- the motor division



Neural integration:
Motoric Pyramidal & Extrapyramidal tracts



Pyramidal system or "selective control system"

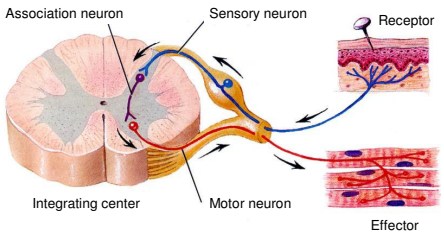
Extrapyramidal system or "automatic control system"

Information processing

- Cortex
  - motor control
- Lower brain
  - subconscious activities, coordinate functions
  - medulla, pons, cerebellum, basal ganglia
- Spinal cord
  - reflexes

complex → basic

Reflexes

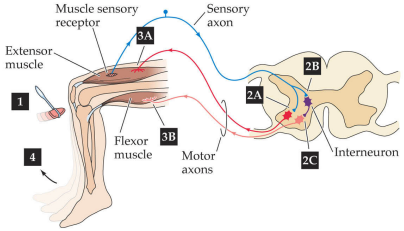


Reflex: involuntary response to a stimulus.
Response is initiated before the subject is aware of it.

Reflex loops

- Short latency reflexes (about 50 ms):
  - Spinal cord
  - Monosynaptic (excitation of same muscle that received stimulus)
  - Act like delayed 'stiffness' and 'viscosity' (position and velocity feedback)
- Medium latency reflexes (about 70 - 100 ms)
  - Spinal cord / Brain stem
  - Coordinated reflex between antagonistic muscle pairs
  - Adequate response to perturbation
- Long latency reflexes
  - Cerebellum
  - Well-coordinated reflex responses for muscle system of one limb

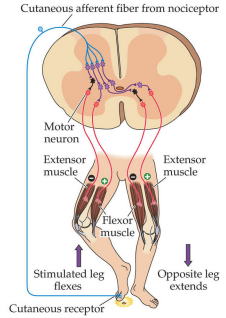
Monosynaptic reflex: patellar reflex



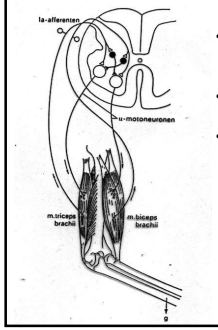
1. Hammer tap stretches tendon → muscle sensors stretch.
2. Sensory neuron excites spinal motor neuron of extensor.
3. Sensory neuron inhibits flexor motor neuron through interneuron/

Multisynaptic reflex: withdrawal reflex

1. Subject steps on tack.
2. Leg flexes as response to pain.
3. Opposite leg extends for weight support.

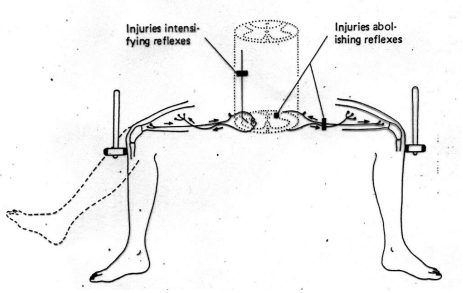


Reciprocal inhibition



- Antagonist muscle is inhibited when agonist muscle is excited.
- Increases effectiveness
- Increases efficiency.

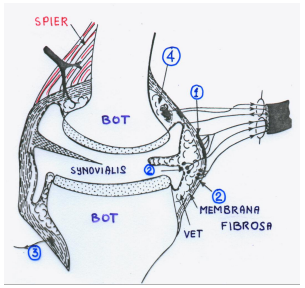
Injuries to the CNS & PNS affecting reflexes



Sensors in motor pathways

- Joints
  - Stretch receptors
- Muscles
  - Golgi tendon organ
  - Muscle spindle

Sensors in the joint capsule



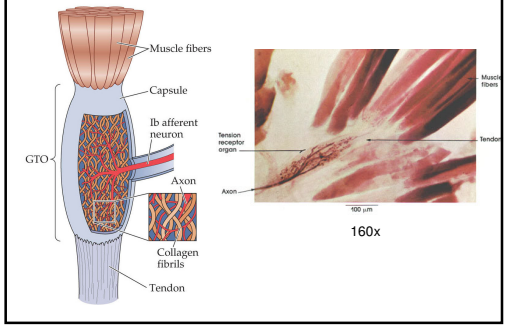
Sensors in the joint capsule

- Mainly stretch receptors in ligaments
- Only signaling towards outer position of the joint
- Not appropriate for proportional control of joint angle
- Slow adaptation
- Presumed to have role in error signaling for learning

Sensors in the muscles

- Golgi Tendon Organs:
  - In series with the muscle fibers
  - strain in tendon = **force** in muscle
- Muscle spindles:
  - parallel to muscle fibers
  - sensitive to **length** and **contraction velocity**
  - *active* 'intra-fusal' muscle fibers, *passive* sensory part
  - innervated by γ motor neurons

Golgi Tendon Organ



160x

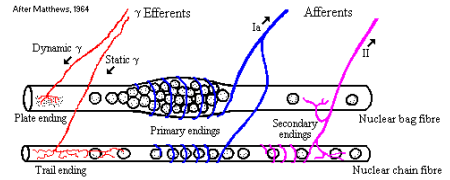
Golgi Tendon Organ

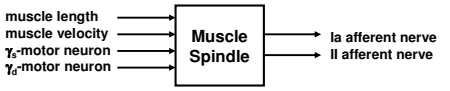
- Strain in tendon ⇒ force
- Ib afferent nerve fiber
- About 50 GTOs per muscle
- Sensitive to a few motor-units (active force)
- Less sensitive to passive muscle stretch
- Contribution to position feedback: Compensates (slow) muscle dynamics
- Comparable with pressure feedback in hydraulic actuators

demo

Muscle spindle

Muscle spindle:
Length and velocity feedback

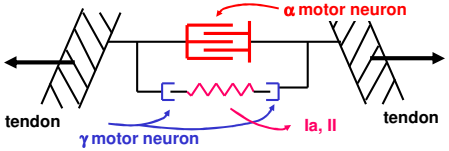




Muscle spindle sensory part

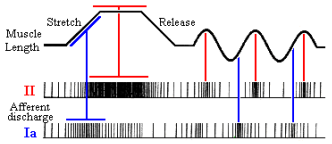
- Nuclear bag fiber:
  - length: 7-8 mm
  - senses **velocity**
- Nuclear chain fiber:
  - length: 3-4 mm
  - senses **length**

Mechanical equivalent of spindle



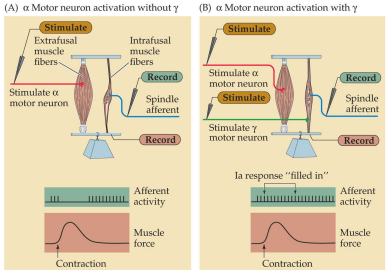
- Extra-fusal fibers innervated by: α motor neurons
- Intra-fusal fibers innervated by: γ motor neurons
- Sensor is sensitive to
  - stretch: II afferents
  - stretch and stretch velocity: Ia afferents
- Goal of gamma-activation: keep muscle spindle pre-tensed and regulate sensor gain.

Response muscle spindle



stretch: II afferents
stretch & stretch velocity: Ia afferents

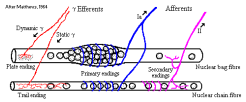
Function γ-activation



- Adjustment of operating point (optimal sensitivity)
- Adjustment feedback gain of reflex loop

demo

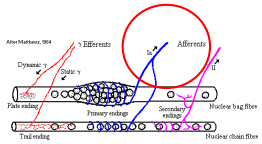
- Type Ia afferent
  - sensory information from the central annulospiral endings of all the intrafusal fibres
    - excitatory effect (mono- or polysynaptic) on the alpha motorneurons of the same muscle (and its synergists)
    - inhibitory effects (via interneurons) on antagonist alpha motorneurons



- Type II afferent
  - sensory information from the secondary endings, mainly associated with chain fibres.
    - excites alpha motorneurons of the same muscle via polysynaptic pathways.

Competitive summation in Ia fibers

- Connection of nerve from nuclear chain and nuclear bag has no synapse.
- Spike trains do not merge.
- 'Winner takes all':
  - Nerve ending with highest frequency overrules competitors by 'antidromic inhibition'
  - Max-operation
- During posture: Length information
- During motion: Velocity information



Summary Muscle spindle

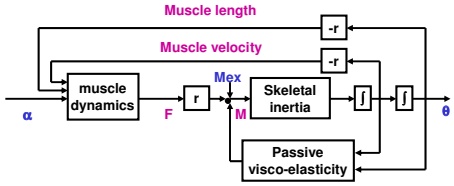
- Length and contraction velocity information
- γ-activation: Reflex gain, sensor sensitivity
- Length feedback: Contributes to additional 'stiffness' of muscle
- Velocity feedback: Contributes to additional 'viscosity' of muscle
- Time-delays in nervous system results in additional dynamic behavior

Transmission speeds of neurons

(measured in cat, humans about 20% slower)

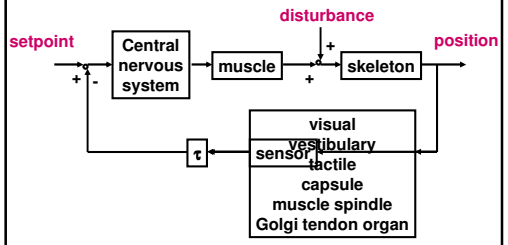
Group	*Diameter (μm)*	*Transmission speed (m/s)*	*Sensor*	*Stimulus*
Ia	12 – 20	70 – 100	muscle spindle	length & velocity
Ib	12 – 20	70 – 100	Golgi tendon organ	force
II	6 – 12	35 – 70	muscle spindle	length
	2 – 5	12 - 30	Pacini sensors	pressure
	0.5 – 2	0.5 – 2.5	free nerve endings	nociceptive

'Open-loop' musculoskeletal models

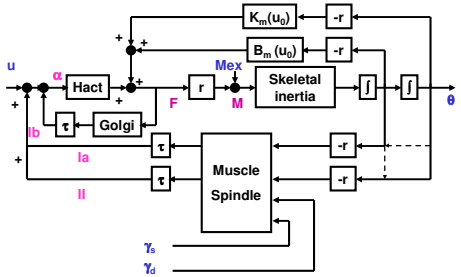


Result depends on:
•Inertia, passive visco-elasticity
•Intrinsic muscle properties:
length & velocity dependency muscle

Closed loop control



Closed loop musculoskeletal models



Conclusion

- Musculoskeletal system needs feedback
- Human nervous system comprises integrated feedback systems
  - Reflex loops at different levels of organization
  - some sensors are also feedback systems
- Feedback sensors
  - muscle spindles
  - golgi tendon organis
  - joint capsule stretch sensors