Neuromechanics of Human Motion

Sensory Feedback

Joshua Cashaback, Ph.D.

Recap — Dynamical Systems

1. Understand what is a dynamical system
2. Perform numerical integration by hand (Euler, RK4)
3. Program numerical integrators (Euler, RK4, odeint)
4. Convert nth order ODEs to n 1st order ODEs

Lecture Objectives — Sensory Feedback

1. Learn about different sensory organs
2. Focus on those related to human movement
   a. vision
   b. vestibular
   c. somatosensory (cutaneous, spindles, GTOs)
3. How sensory information travels to the Central Nervous System (CNS)
4. Understand the importance of sensory feedback and spinal reflexes

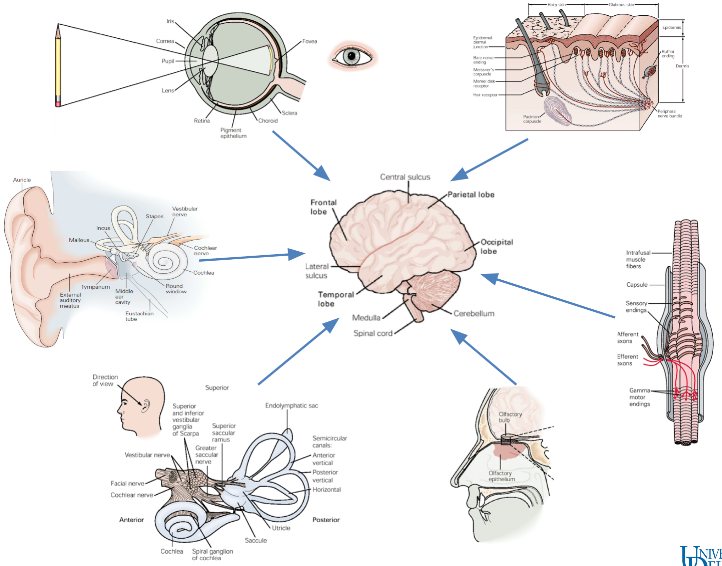
What are some technological feedback devices?

What are some technological feedback devices?

1. Position (video, mocap, goniometer, gyroscope), Acceleration (accelerometers)
2. Force (force transducers), Pressure (multiple force transducers)
3. Biological Systems have multiple sensors

Sensory Inputs are Critical for Motion

Multiple Sensory Organs



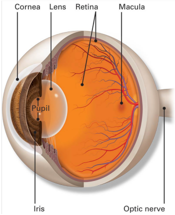
Classes of Sensory Organs

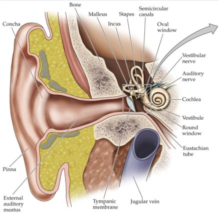
Table 21-1 Classification of Sensory Receptors

Sensory system	Modality	Stimulus	Receptor class	Receptor cells
Visual	Vision	Light (photons)	Photoreceptor	Rods and cones
Auditory	Hearing	Sound (pressure waves)	Mechanoreceptor	Hair cells in cochlea
Vestibular	Head motion	Gravity, acceleration, and head motion	Mechanoreceptor	Hair cells in vestibular labyrinths
Somatosensory				Cranial and dorsal root ganglion cells with receptors in:
	Touch	Skin deformation and motion	Mechanoreceptor	Skin
	Proprioception	Muscle length, muscle force, and joint angle	Mechanoreceptor	Muscle spindles and joint capsules
	Pain	Noxious stimuli (thermal, mechanical, and chemical stimuli)	Thermoreceptor, mechanoreceptor, and chemoreceptor	All tissues except central nervous system
	Itch	Histamine	Chemoreceptor	Skin
	Visceral (not painful)	Wide range (thermal, mechanical, and chemical stimuli)	Thermoreceptor, mechanoreceptor, and chemoreceptor	Gastrointestinal tract, urinary bladder, and lungs
Gustatory	Taste	Chemicals	Chemoreceptor	Taste buds
Olfactory	Smell	Odorants	Chemoreceptor	Olfactory sensory neurons

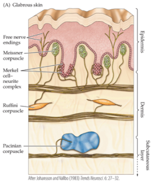
Classes of Sensory Organs

1. Visual
2. Vestibular
3. Somatosensory (body sense)
    - cutananeous
    - muscle spindles
    - golgi tendon organs





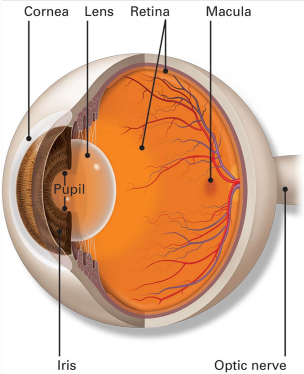
NEUROSCIENCE 6e, Figure 13.4 (Part 1)

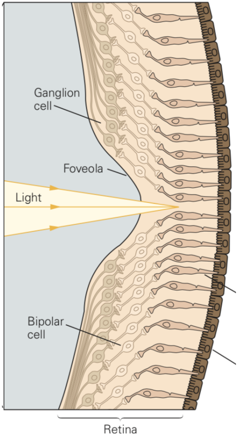


After Johansson and Vallbo (1983) *Trends Neurosci.* 6: 27–32.

NEUROSCIENCE 6e, Figure 9.5 (Part 1)

Visual System





photons hit the retina, cones and rods relay light information to the optic nerve (cranial nerve II)

Rods and Cones

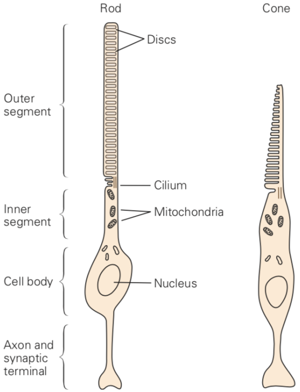


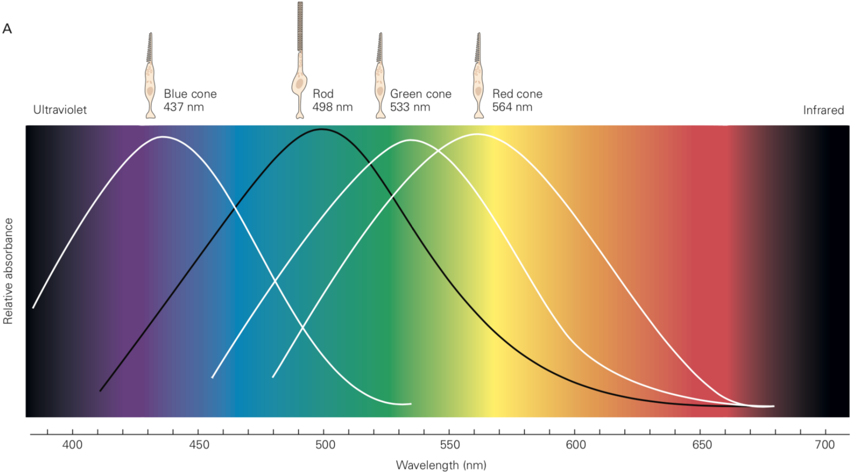
Figure 26–5 Rod and cone photoreceptors have similar structures.

Phototransduction - proteins (photopigment rhodopsin) in outer segment sensitive to certain light frequencies.

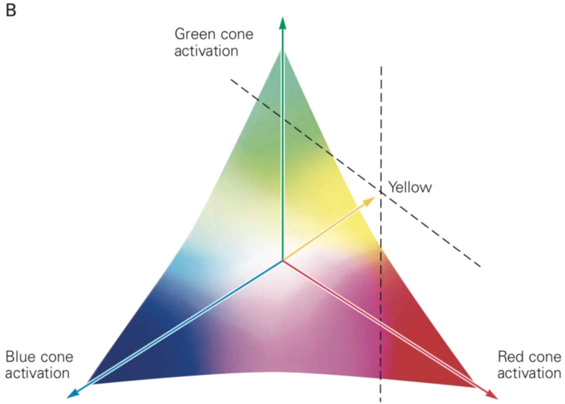
Spectrum Sensitivity

1. rods - low brightness
2. cones - high brightness
   a. S-cones: short-wavelengths (blue)
   b. M-cones: medium-wavelengths (green)
   c. L-cones: long-wavelengths (red)

Spectrum Sensitivity



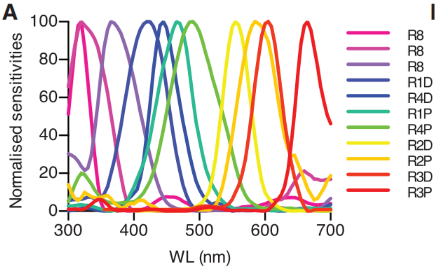
Color Perception



Vector Approach

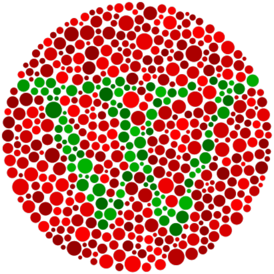
Cone Variation Across Species

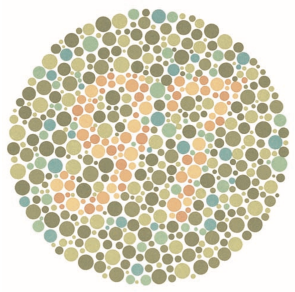
1. Trichromatic vision (3 cones) - humans and monkeys
2. Tetrachromacy vision (4 cones) - birds and fish
3. 12 cones! - shrimp
    a but poor at colour discrimination tasks (circuit dependent)
    b integrate colours over time like satellite scanners (sparse light)



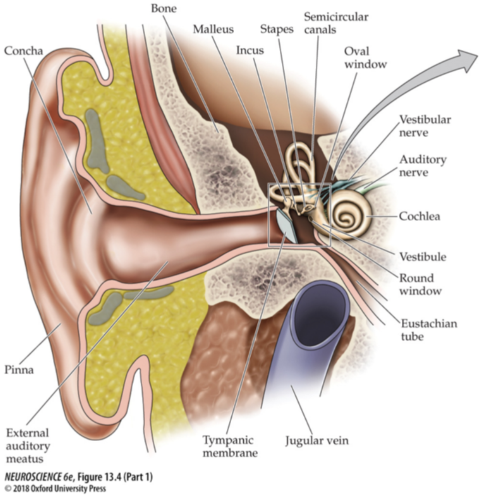
Cone Variation Within Species

1. Colorblindness - dichromacy (2 cones)



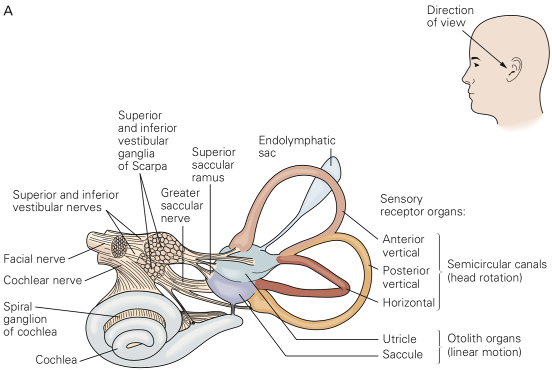


Vestibular System



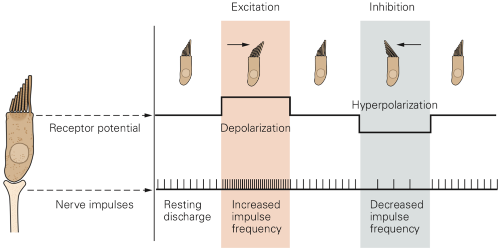
Inner ear

Vestibular System



1. Otolith Organs - linear motion
2. Semicircular Canals - rotational motion
    a. orthogonality, gyroscopes, gimbal

Otolith and Semicircular Canal Hair cells



1. No motion - still release of neurotransmitters (resting DR)
2. Gelatinous mixture
3. Mechanoreceptors (Δ DR important)
    a. Bending short stereocilla opens ion channels
    b. Bending long stereocilla closes ion channels
4. Cranial nerve VIII (vestibulocochlear nerve)

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Why Both Linear and Rotational Sensors?

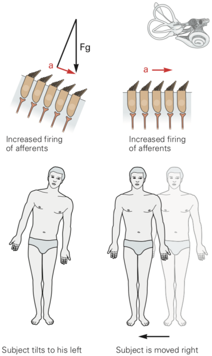
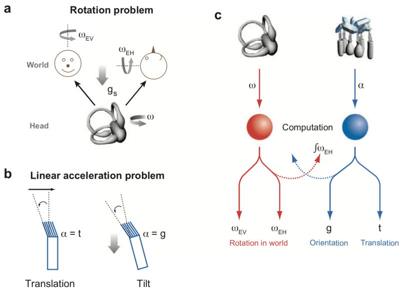


Figure 40–7 Vestibular inputs signalling body posture and motion can be ambiguous. The postural system cannot distinguish between tilt and linear acceleration of the body based on otolithic inputs alone. The same shearing force acting on vestibular hair cells can result from tilting of the head (**left**), which exposes the hair cells to a portion of the acceleration (**a**) owing to gravity (**Fg**), or from horizontal linear acceleration of the body (**right**).

Computation via Neural Circuitry



earth vertical (EV) = not influence by g (yaw)
earth horizontal (EH) = influenced by g (pitch, roll) AP, ML sway
ω input takes in g estimate to decompose into EV and EH
α input takes in $\int \omega_{EH}$ input to decompose g and t
e.g., $\int \omega_{EH} \approx g$; thus $\alpha - \int \omega_{EH} = t$

1. Integrate angular velocity (e.g., tilt)
2. Combine position estimate with otolith to estimate g and t

Vestibular Computational Model

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF NEURAL ENGINEERING

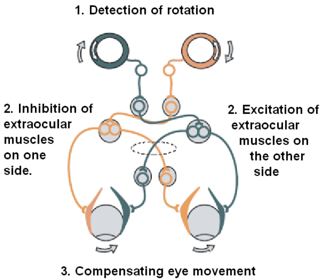
J. Neural Eng. **2** (2005) S164–S179 doi:10.1088/1741-2560/2/3/S02

Sensory vestibular contributions to constructing internal models of self-motion

Andrea M Green, Aasef G Shaikh and Dora E Angelaki

UNIVERSITY OF DELAWARE

Vestibular Reflexes



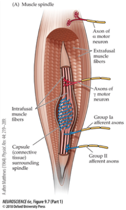
1. Vestibulo-ocular reflexes - stabilize images on the retina
2. Vestibulo-spinal reflexes - maintain balance

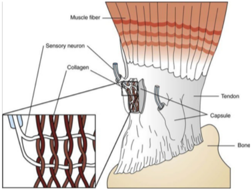
Example of Vestibular Ocular Reflex

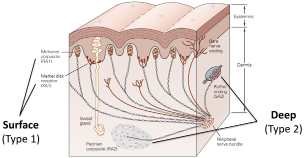
https://www.youtube.com/watch?v=LEGZ7hGaMNI

Vestibular Disruption

Somatosensory System

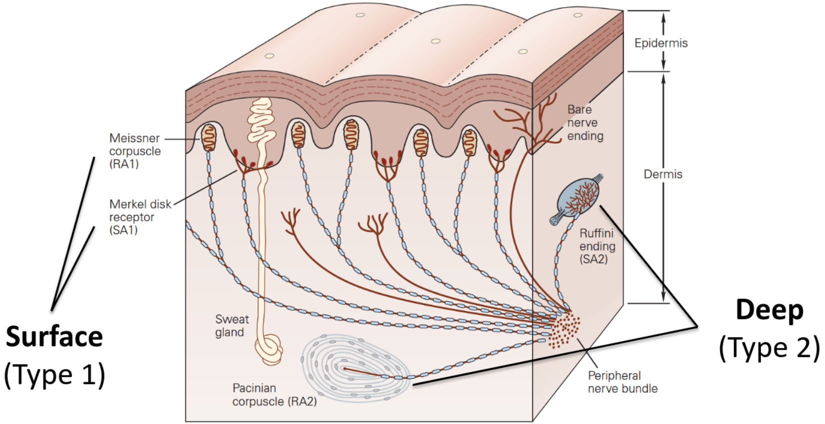






Type	Axon	Receptor	Sensitive to
Ia	12–20 μm myelinated	Primary spindle ending	Muscle length and rate of change of length
Ib	12–20 μm myelinated	Golgi tendon organ	Muscle tension
II	6–12 μm myelinated	Secondary spindle ending	Muscle length (little rate sensitivity)
II	6–12 μm myelinated	Nonspindle endings	Deep pressure
III	2–6 μm myelinated	Free nerve endings	Pain, chemical stimuli, and temperature (important for physiological responses to exercise)
IV	0.5–2 μm nonmyelinated	Free nerve endings	Pain, chemical stimuli, and temperature

Cutaneous System



- mechanoreceptors (skin deformation and motion)
- pain, itch

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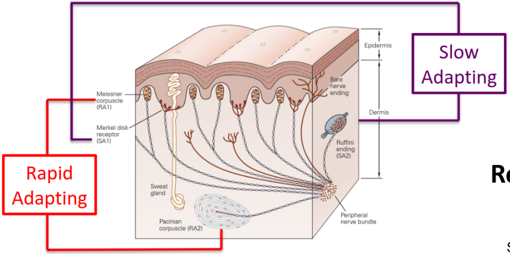
Shallow and Deep Receptors



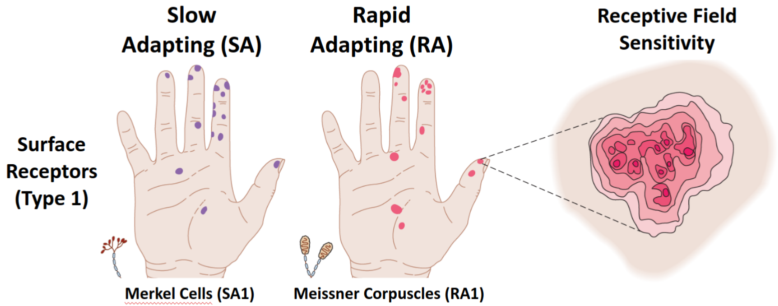
Summary of Receptor Properties

Adapting Rate

Stimulus Properties: Vibration frequency	Slow	Rapid
Low	Merkel receptors (SA1)	Meissner receptors (RA1)
High	Ruffini (SA2)	Pacinian corpuscle (RA2)

- rapid = transient changes in force
- slow = force magnitude

Surface — Slow and Rapid Adapting



- fingertip forces
- fine forms
- edge contours
- texture

- Δ fingertip forces
- fine forms
- moving stimuli
- friction

Properties of Surface Receptors

1. Small, complex receptive field
2. Multiple 'hot spots'

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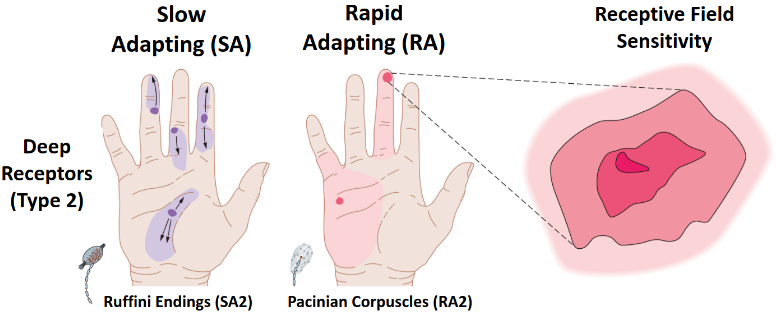
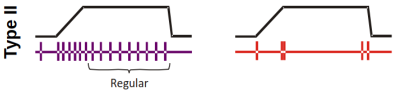
Deep — Slow and Rapid Adapting





- tissue strain

- transient events
- vibration

Properties of Deep Receptors

1. Large, simple receptive field
2. Single ’hot spot’

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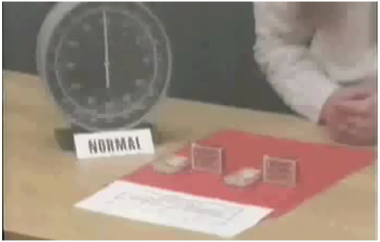
Critical for Function

Normal Sensibility, Full Vision



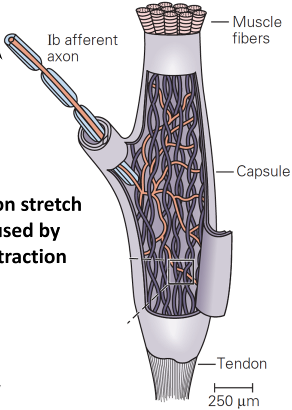
Normal hand function

Fingertip Anesthesia, Full Vision

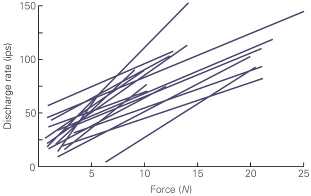
Difficulty with object manipulation

Golgi Tendon Organs

Tendon stretch caused by contraction



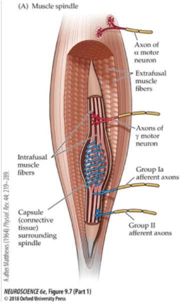
GTO Discharge Rate



GTO discharge is **directly proportional** to the **force** of **muscle contraction.**

Ib sensory fibers = sense force

Muscle Spindle



1. Ia sensory fibers = muscle fiber length and velocity
2. II sensory fibers = muscle fiber length
3. α motor neurons activate extrafusal fibers = contraction
4. γ motor neurons keep intrafusal fibers taut / regulated by CNS (cortex) to increase spindle sensitivity

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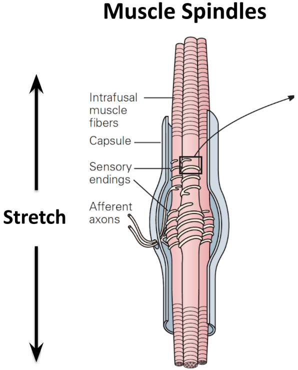
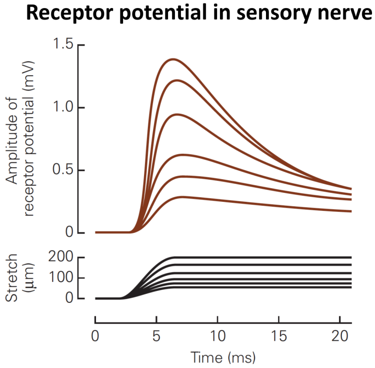
Muscle Spindle





Stretch Reflex

1. tendon tap
2. resists muscle lengthening (protective)
3. monosynaptic spinal reflex (fast - 20-50ms)

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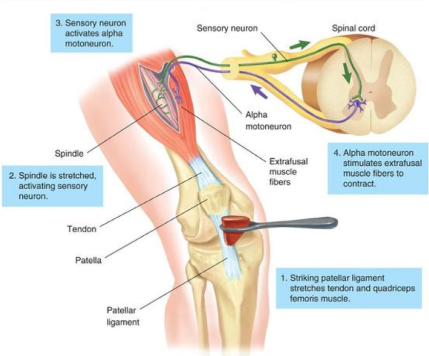
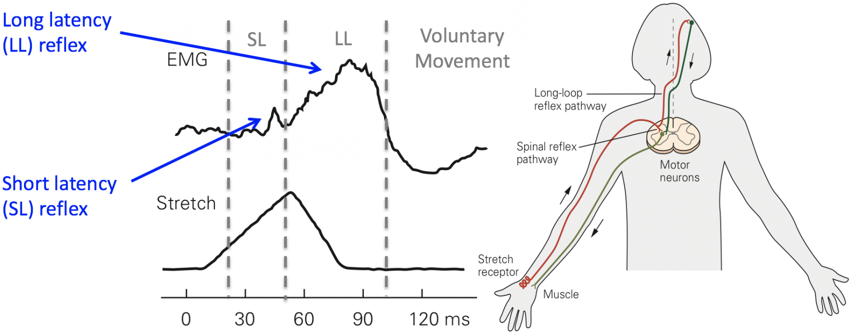
Stretch Reflex

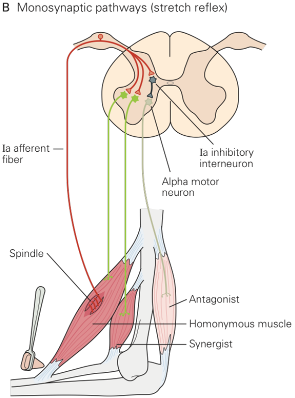


1. stretch muscle
2. spindles (Ia) fire travel up dorsal root (back)
3. synapse / excite α motor neuron
4. α motor neuron travels down ventral root (front)
5. stretched muscle contracts
6. kicking motion

Stretch Reflex



Reciprical Inhibition



1. stretch muscle
2. spindles (Ia) fire travel up dorsal root
3. synapse / excite inhibitory interneuron
4. inhibits antagonist α motor neuron
5. antagonist muscle relaxes
6. does not resist kicking motion

Protective Mechanisms

1. How would the stretch (short-latency) response of protect the muscle-tendon unit from getting damaged by very rapid stretching? (Hint: think about how a muscle contraction can change the length of a muscle)

Protective Mechanisms

1. How would the stretch (short-latency) response of protect the muscle-tendon unit from getting damaged by very rapid stretching? (Hint: think about how a muscle contraction can change the length of a muscle)
2. How does reciprocal inhibition aid the short-latency (stretch) reflex in protecting from rapid stretching of the agonist?

Proprioceptive Models

Golgi Tendon Organ Model

J Neurophysiol 96: 1789–1802, 2006.
First published May 3, 2006; doi:10.1152/jn.00869.2005.

Mathematical Models of Proprioceptors. II. Structure and Function of the Golgi Tendon Organ

Milana P. Mileusnic and Gerald E. Loeb
Department of Biomedical Engineering, Alfred E. Mann Institute for Biomedical Engineering, University of Southern California, Los Angeles, California

Muscle Spindle Model

J Neurophysiol 96: 1772–1788, 2006.
First published May 3, 2006; doi:10.1152/jn.00868.2005.

Mathematical Models of Proprioceptors. I. Control and Transduction in the Muscle Spindle

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Muscle Spindle and Muscle Mechanics Model

Diverse and complex muscle spindle afferent firing properties emerge from multiscale muscle mechanics

Kyle P Blum, Kenneth S Campbell, Brian C Horslen, Paul Nardelli, Stephen N Housley, Timothy C Cope, Lena H Ting

What is the muscle-tendon length?

For example, during a concentric (shortening) contraction:

1. muscle fibers shorten (spindles)
2. tendons lengthen (GTOs)
3. combining information from both can give an estimate of muscle-tendon length (and joint position)

J Neurophysiol 109: 1126–1139, 2013.
First published October 24, 2012; doi:10.1152/jn.00751.2012.

Control of position and movement is simplified by combined muscle spindle and Golgi tendon organ feedback

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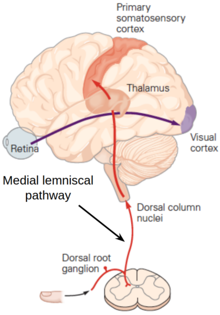
Somatosensory Signals — Spinal Cord



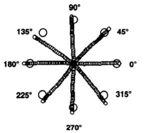
1. Individual afferent neurons travel in bundles (peripheral nerves) to the spinal cord
2. Medial lemniscal pathway (spinal cord) consists of large diameter fibers that carry touch and proprioception information
3. Spinal cord information sent to the brain (Neural Basis lecture)

Somatosensory Deafferentation
Patient GL

1. Deafferentation - somatosensory inputs to the spinal cord no longer function or have been severed
2. Patient GL - neuropathy (no cutaneous or proprioception)

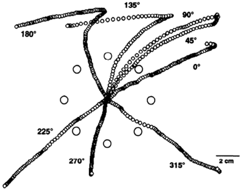
Somatosensory Deafferentation
Patient GL

Control MFG



Intact proprioceptive system

Patient GL

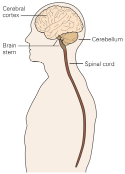


Deafferented

Gordon J et al. (1995) J Neurophysiol

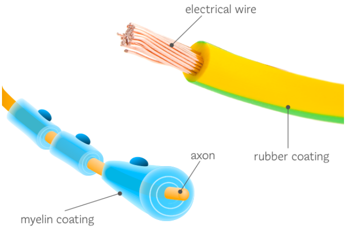
1. Deafferentation - somatosensory inputs to the spinal cord no longer function or have been severed
2. Patient GL - neuropathy (no cutaneous or proprioception)

Hierarchy of Control



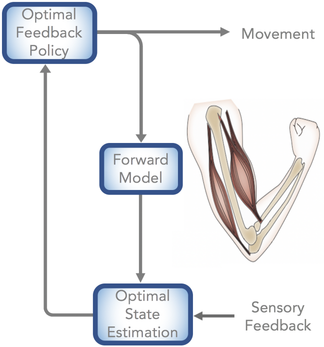
1. Cerebral Cortex - select, plan, execute goal-directed movement (highly adaptable)
2. Cortical-Spinal reflexes: contain both simple reflexes and goal-directed actions (moderate adaptation)
3. Spinal reflexes: simple reflexes (little or no adaptation)

Importance of Spinal Reflexes



1. nerves are relatively slow
2. time delays bad for control
3. reflexes mitigate time delays and correct errors

Voluntary Control
Optimal Feedback Control



Multiple Sensory Modalities Critical for Correcting Movement Errors and Generating Successful Actions

Summary

1. Should know about the visual, vestibular, somatosensory organs
2. Know the pathways to the central nervous system (e.g., spinal cord, cranial nerves)
3. Know some common sensory reflexes
4. Understand why sensory feedback is important (and what happens without it)

QUESTIONS???

Next Class

1. Introduction to Action Potentials
2. Hodgkin-Huxley Model

Acknowledgements

Michael Carter