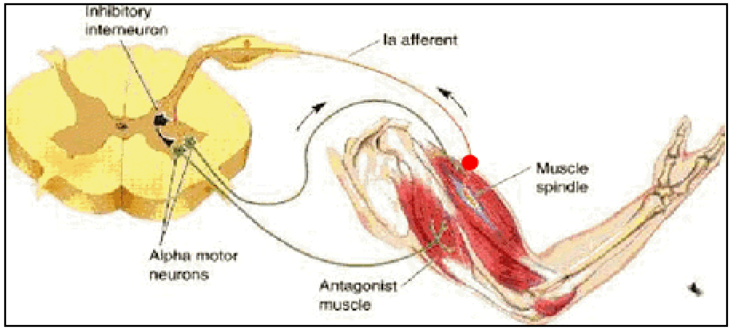
The Human Controller
Class 3. …to action

While computers are capable of sometimes beating the world's best (human) chess masters, states Wolpert, "when it comes to dexterity, a five-year-old child could beat any machine being made."
- Wolpert's TEDx Lecture



Teacher:

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- BioMechanical Engineering, Delft University of Technology, The Netherlands

Learning Goals Lecture 2

After this lecture, you will be able to:

1. Reproduce the human sensors
    1. Basics of anatomy, functionality of haptics (tactile & kinesthetic)

2. Apply methods to determine limitations of haptic perception

1. Apply the concept of admittance to explain neuromuscular feedback

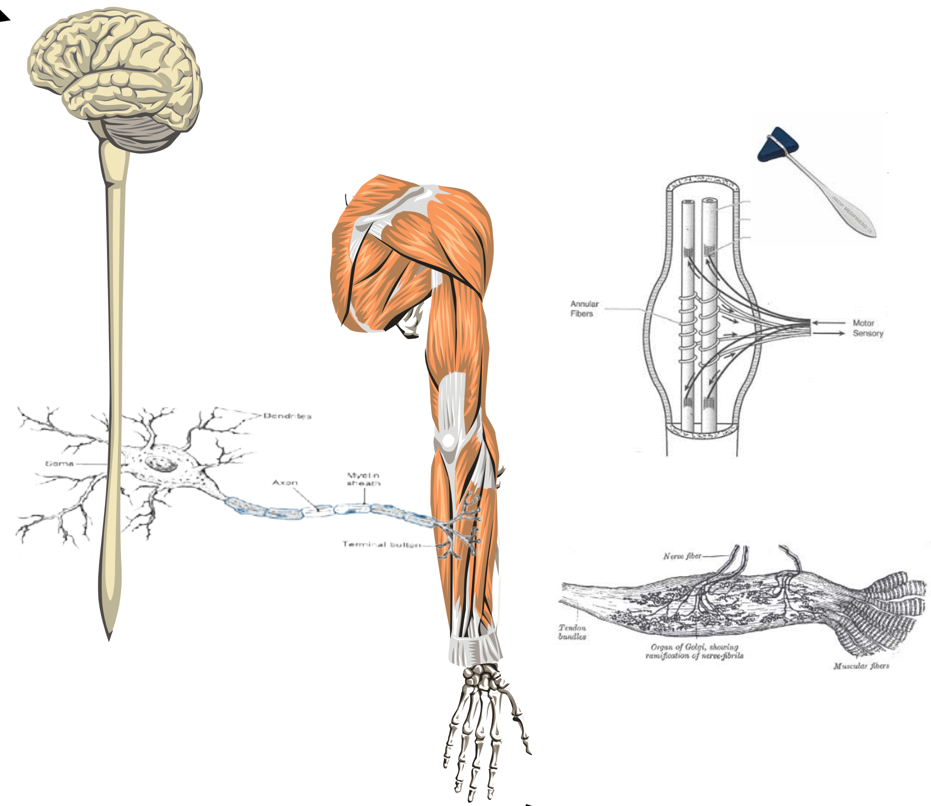
1. Critically reflect on feedforward and feedback control

2. Critically reflect on the role of the neuromuscular system while performing a visual/vestibular tracking task

The Neuromuscular System

- Linkage (skeleton)
- Actuators (muscles)
- Sensory system
  - muscle spindles (pos/vel feedback)
  - Golgi tendon organs (force feedback)
- Controller (Central nervous system, posterior parietal cortex)
- Wires (neurons)

$X_{desired}$



$X_{realized}$

The Neuromuscular System

- Linkage (skeleton)
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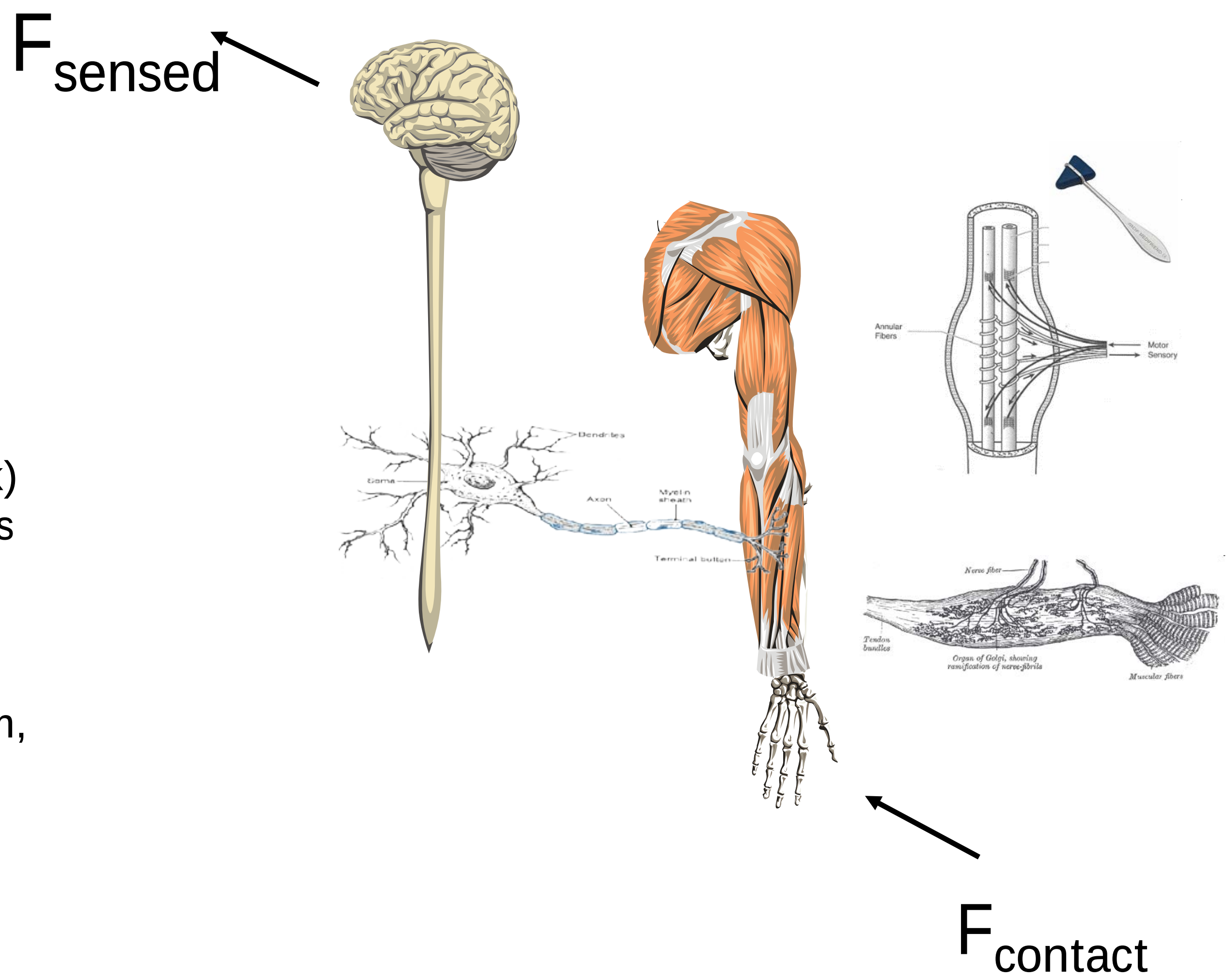
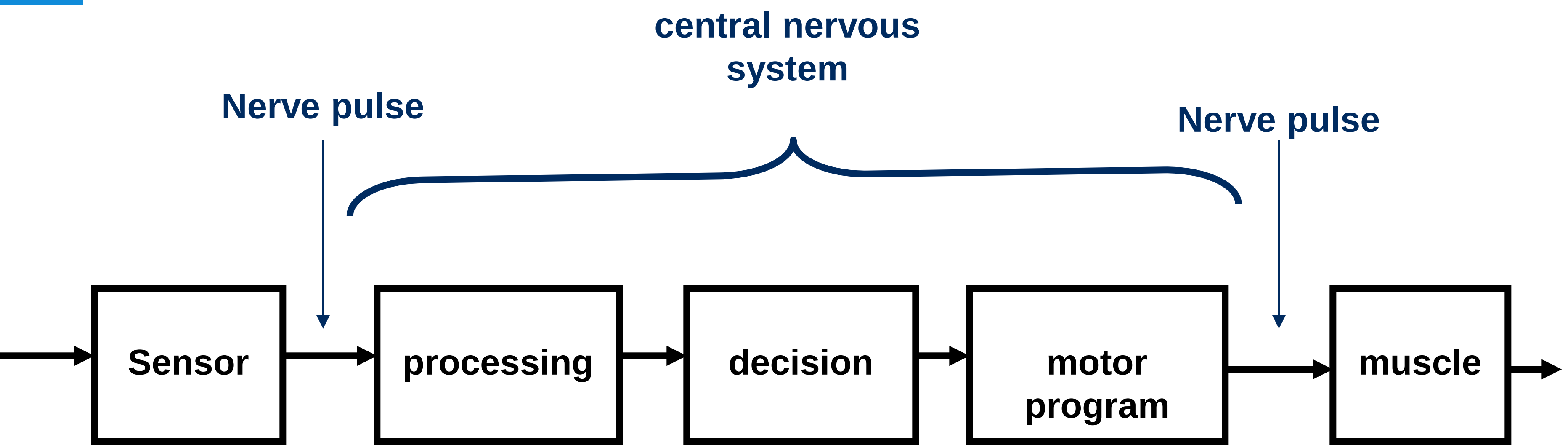
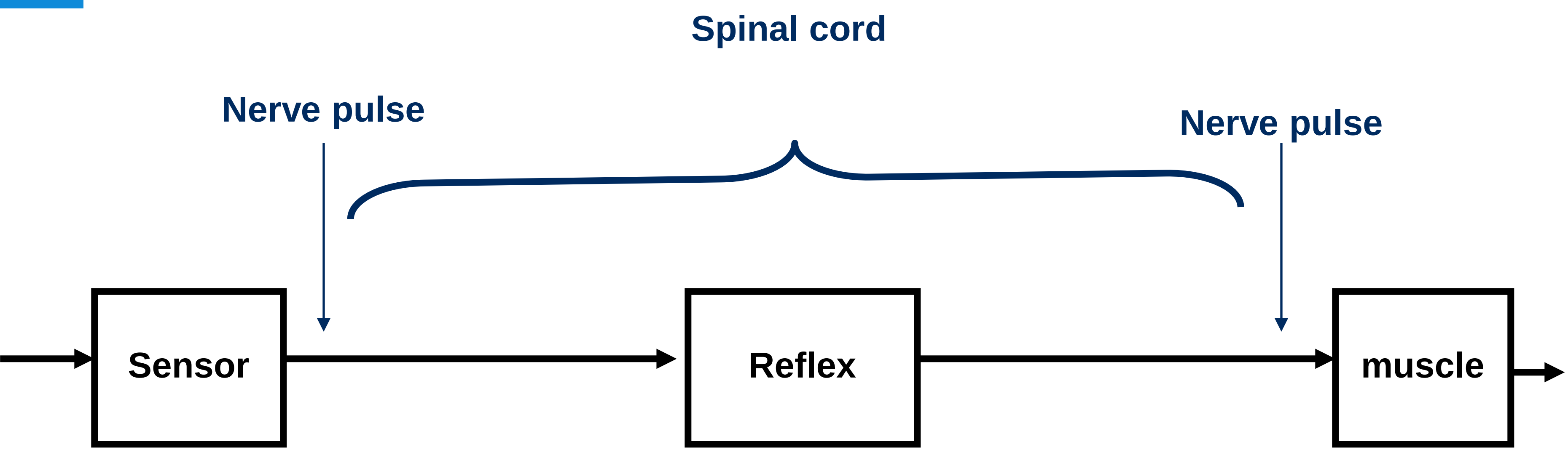


Information Processing: cognition



Information Processing: ‘reflex’



Haptic sensing (feeling):
Tactile and Proprioceptive sensors

Function of haptic perception

- Gathering information
  - Interaction with outside world
  - About forces, movements and orientation of limbs

- Human-machine interaction
  - Haptic Displays
    - Vibrations (cell phone)
    - Forces (assistance, simulation)

Two kinds of haptic perception

1. **Kinaesthetic/Proprioceptive:**

force and displacement

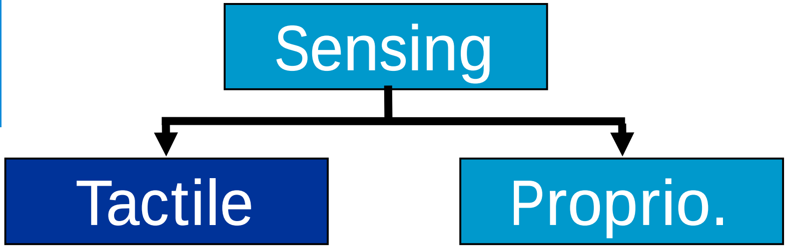
from tendon force, muscle stretch and stretch velocities

1. **Tactile:**

“everything else” :
vibrations, temperature, pain, tickles, surface roughness, shear stress etc.

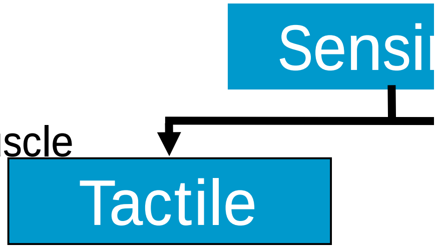
from receptors in the skin

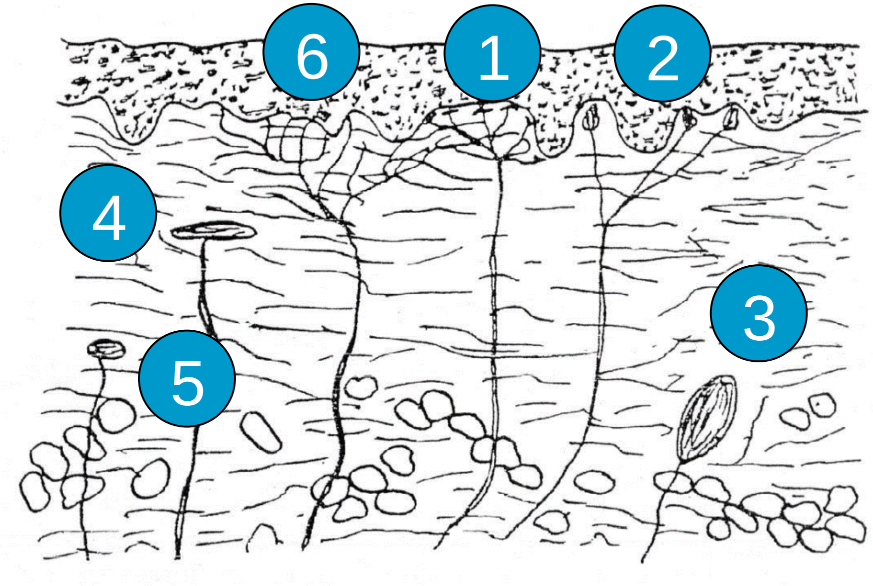
Anatomy: tactile



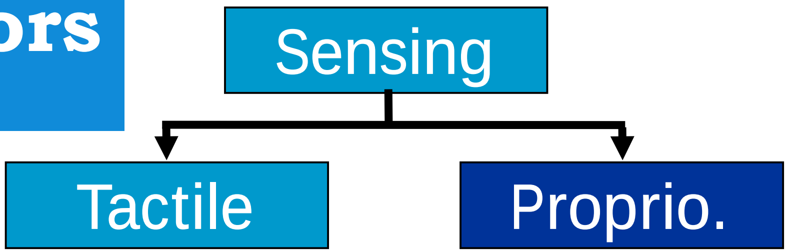
Tactile sensors

1. Merkel disk receptor
2. Meissner corpuscle
3. Pacinian corpuscle
4. Ruffini ending
5. Golgi-Mazzoni corpuscle
6. Free nerve ending
7. Hair tylotrich, hair-guard
8. Hair-down
9. Field

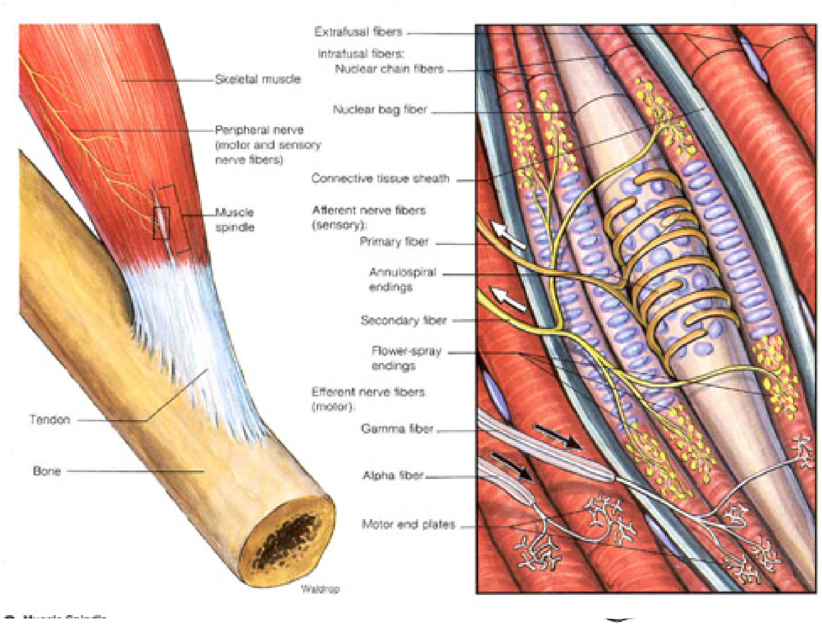


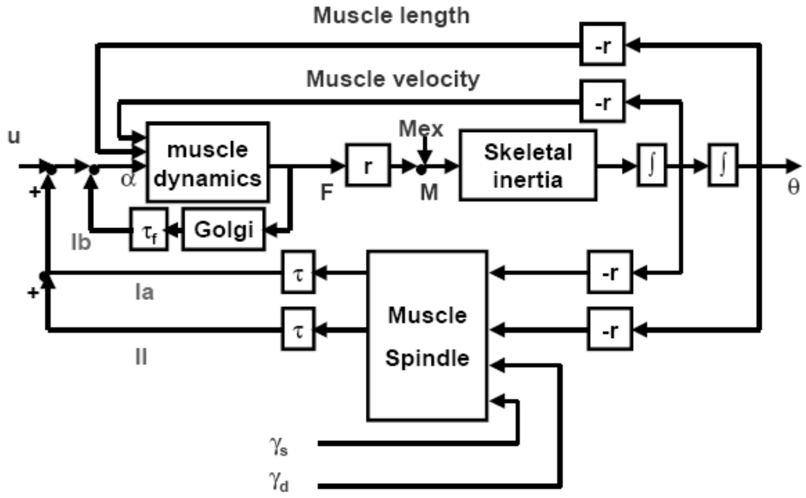


Anatomy: proprioceptors



Golgi Tendon Organ: force
Muscle Spindles: position and velocity





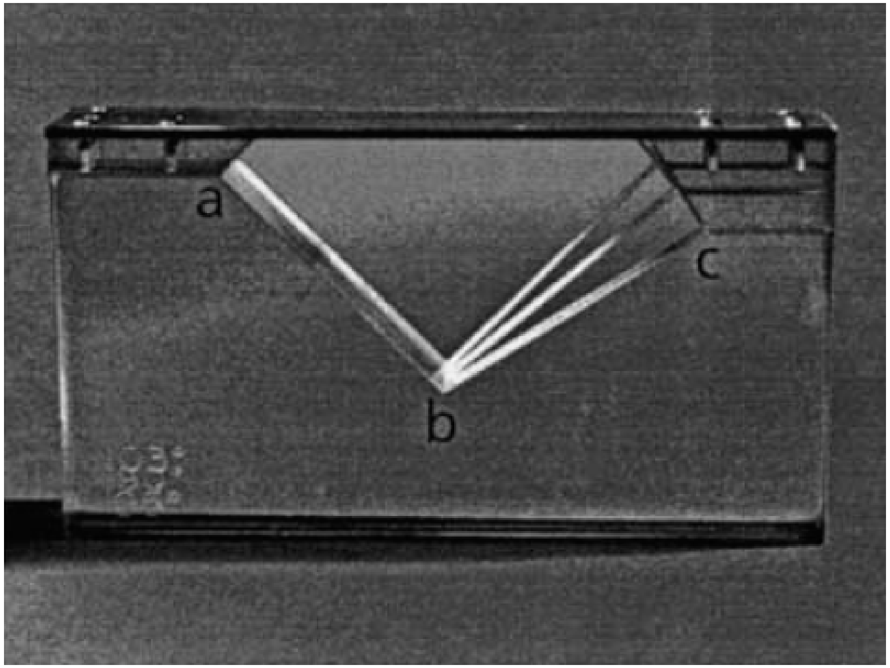
Proprioceptive and tactile contributions to haptic perception

Experiment set-up

2D angle discrimination

Index finger positioned at ‘a’

Single to-and-fro movement (a-b-c-b-a)



Subjects identify the larger of two angles (2AFC)

Voisin, 2002

Proprioceptive and tactile contributions to haptic perception

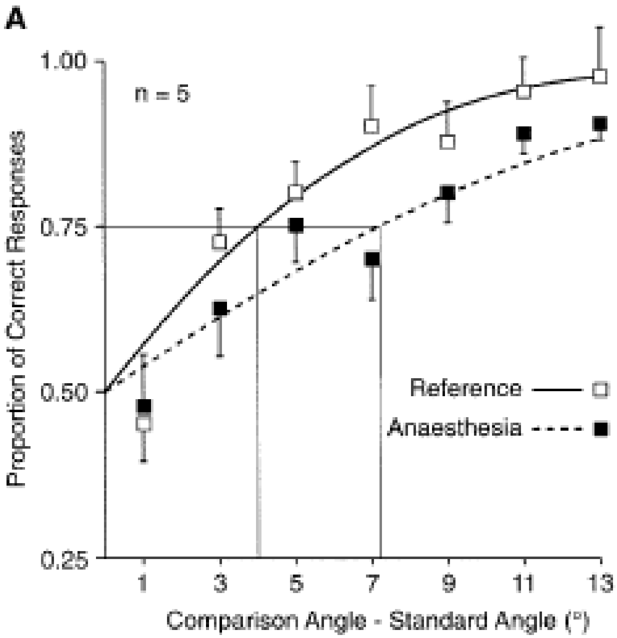
Experiment conditions

	Tactile feedback	No tactile feedback
Proprioceptive feedback	Active touch, both present (reference)	Active touch with finger anaesthesia, only proprioceptive
No proprioceptive feedback	Passive touch, only tactile	Passive touch with digital anaesthesia, neither

Voisin, 2002

Proprioceptive and tactile contributions to haptic perception

Experiment results



	Tactile feedback	No tactile feedback
Proprio-ceptive feedback	4.0°	7.2°
No proprio-ceptive feedback	8.7°	Chance (>13°)

Voisin, 2002

Sensory Noise

- ... research on the computational principles of motor control can help us understand everyday occurrences like fights between your kids in the back seat of the family car. A few years ago, Wolpert set out to understand why these battles escalated. Each of his daughters, then age 9 and 12, would always claim that the other one had hit her harder, so they would continue and hit harder each turn. He figured that sensory filtering was at work here, as in tickling: "Whenever you are getting sensations based on your own movements, you will subtract some of that from your own perception. Tit-for-tat actually escalates." He confirmed the hypothesis with a tapping (not slugging) experiment, finding that the force of the taps increased 40% at each exchange.

Sensory Weighting (Mugge et al., 2009)

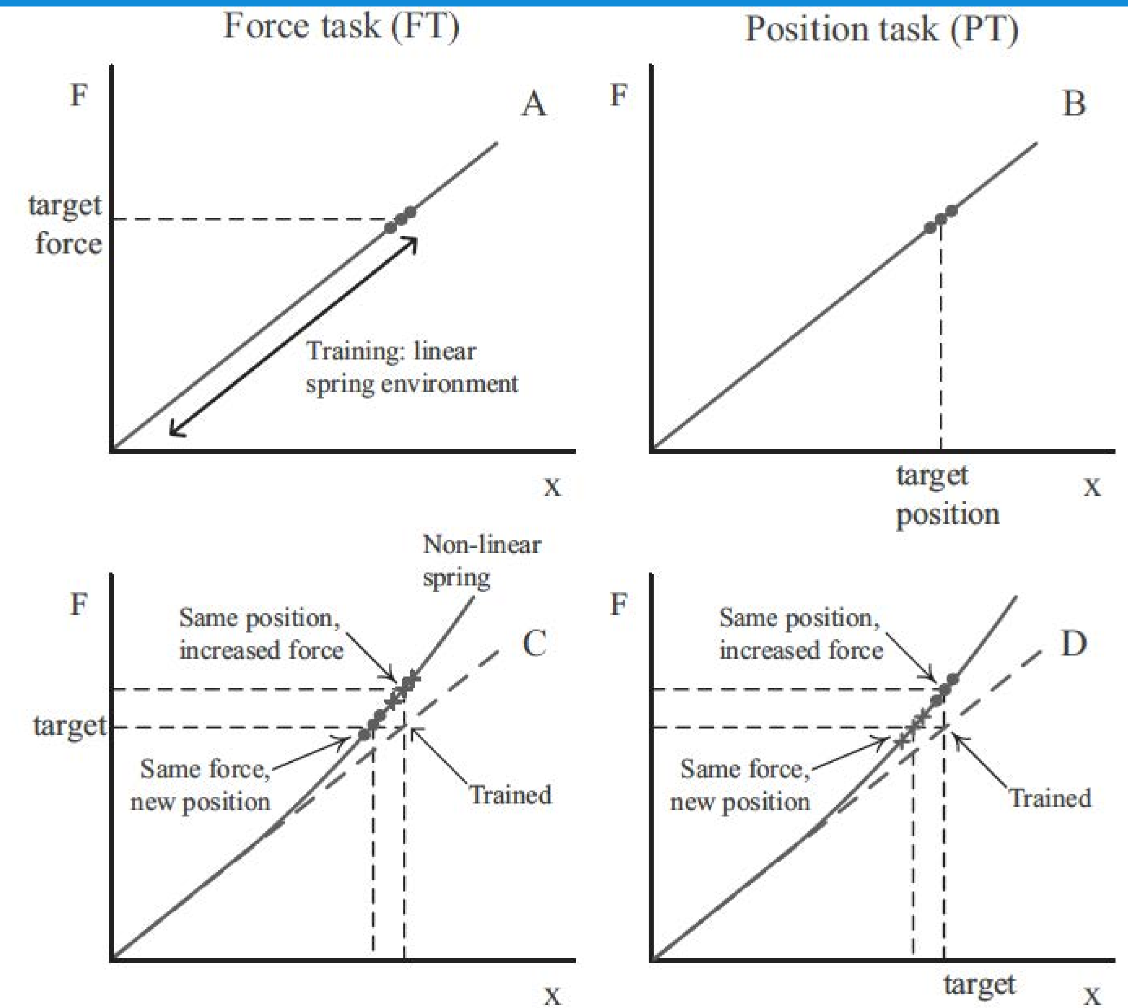


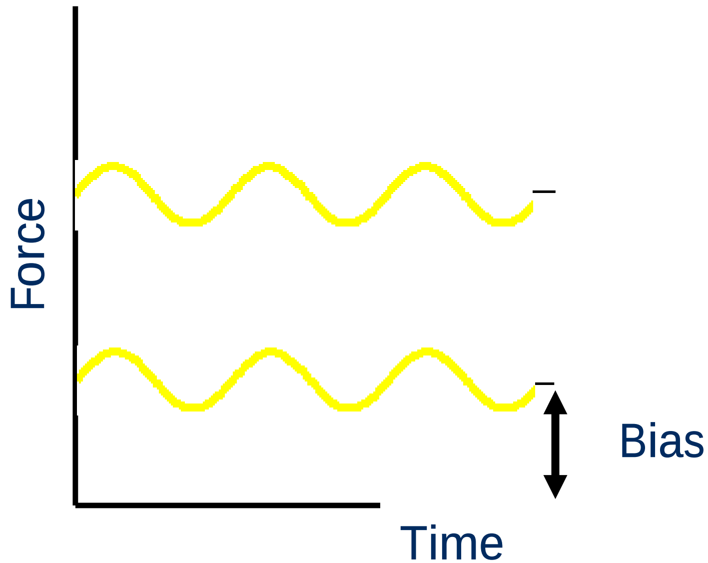
Figure 1. Subjects were trained to blindly reproduce either a target force (*A*) or a target position (*B*) against a linear spring. During catch trials the characteristic of the spring is covertly altered to determine how the subject weights force and position feedback during task execution (*C*, *D*).

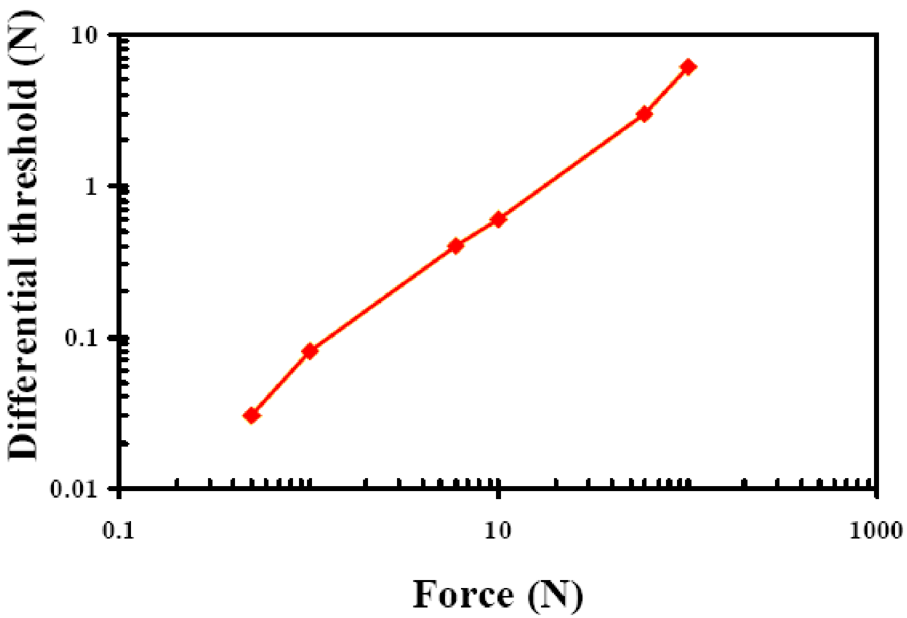
Influences on Haptic Perception

- What do you expect to influence whether you perceive a force or not?

Influences on Haptic Perception

Bias force



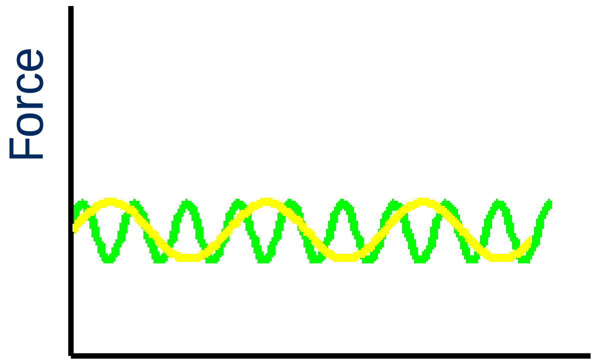


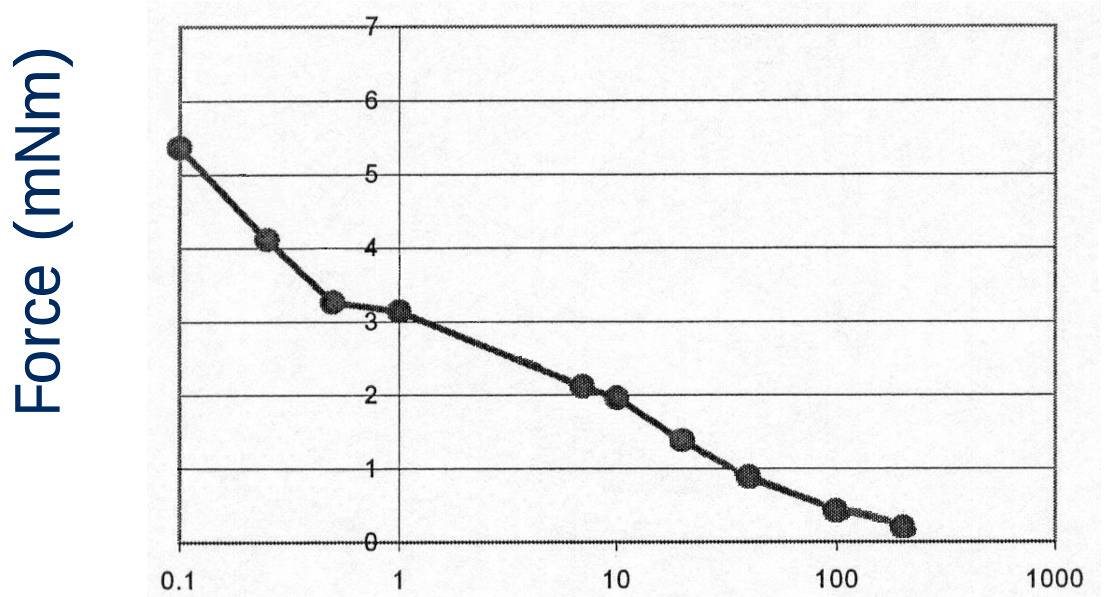
Increase in bias force increases Just-Noticeable Difference proportionally

Jones, 2002

Influences on Haptic Perception

Frequency:





Higher frequencies (up to 250 Hz) are easier to detect

Enriquez, 2002; Jones, 2002

Influences on Haptic Perception

Body location, shape and size of stimulator

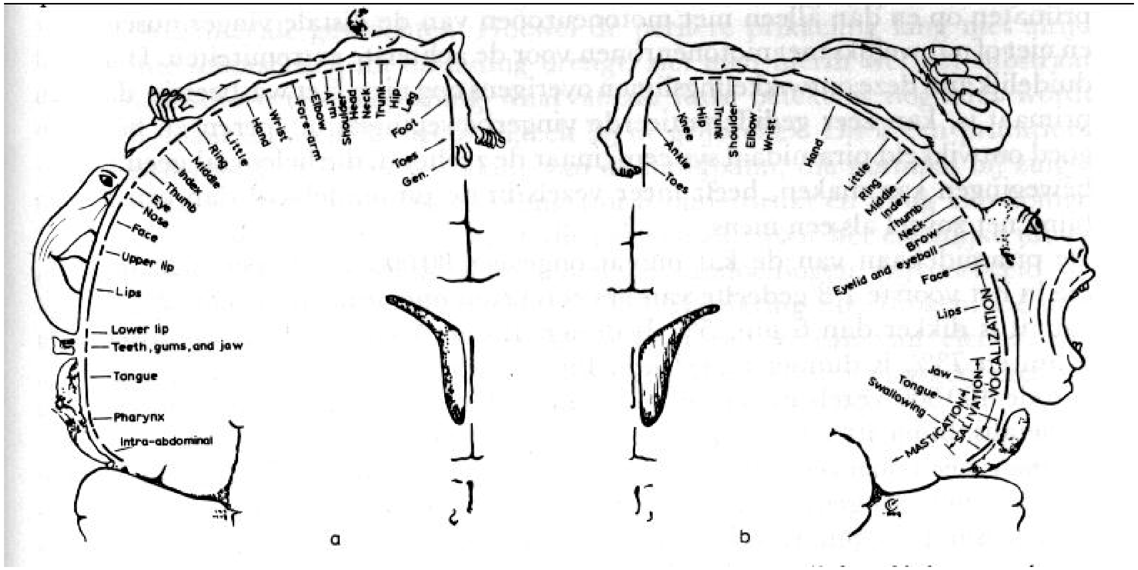
Density of receptors in body parts is different

For example density of corpuscles of Meissner:

Fingertips: 23 per mm^2

Forearm: 1 per 36 mm^2

Ratio: 800 to 1



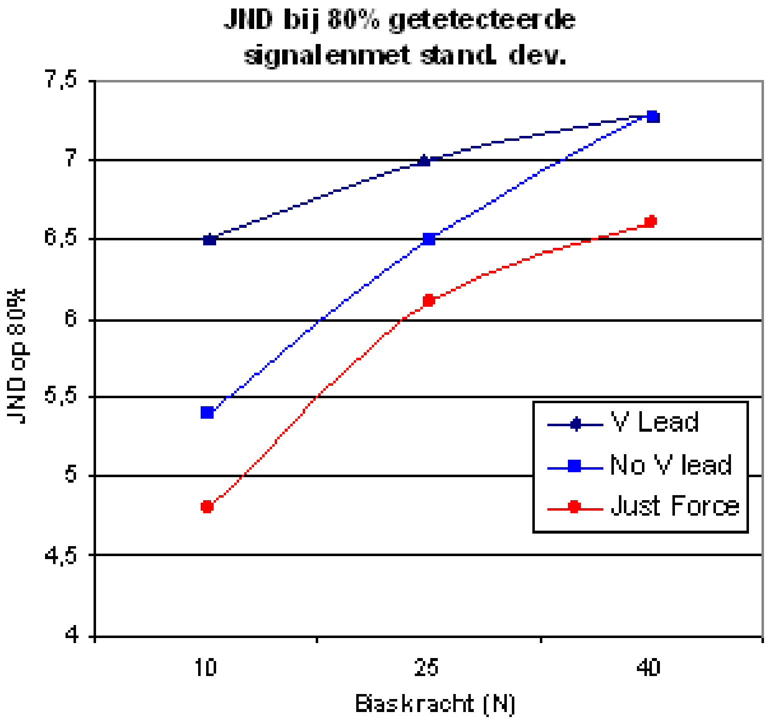
Greater amount of affected mechanoreceptors are easier to detect

Van Lunteren & Stassen, 1970

Influences on Haptic Perception

Distraction

BSc research:
Determination JND
at three different task
complexities

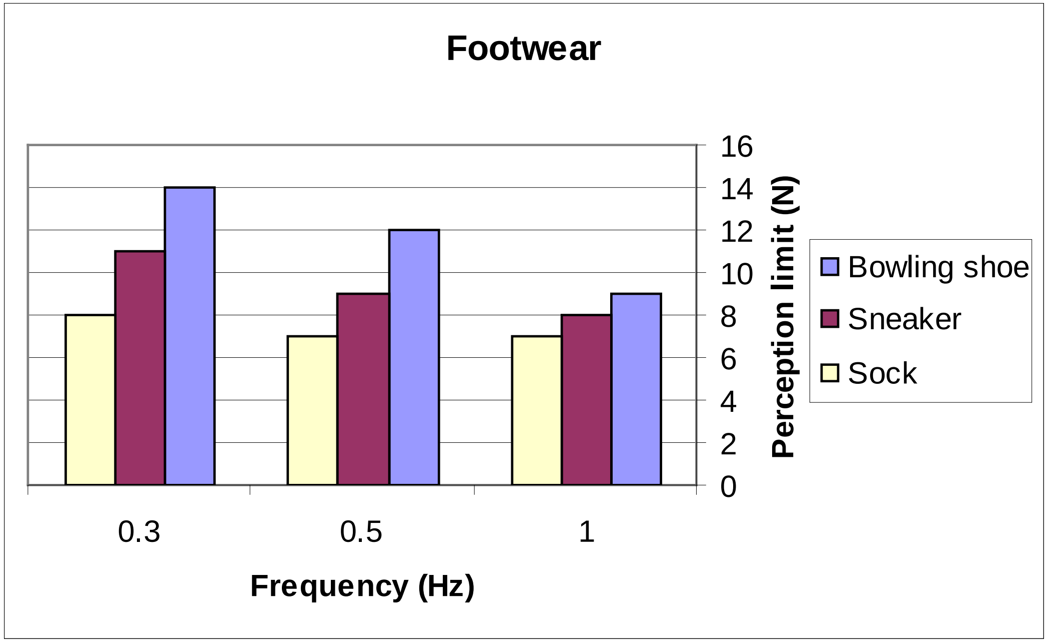


Additional task deteriorates performance on haptic perception

Influences on Haptic Perception

Covering of the skin (gloves, shoes)

Determination perception limits with different types of footwear



Footwear deteriorates haptic perception

Altena & De Gier, 2004

Influences on Haptic Perception

Conflicting sensory input

In general vision is dominant over other modalities when conflicting information is presented

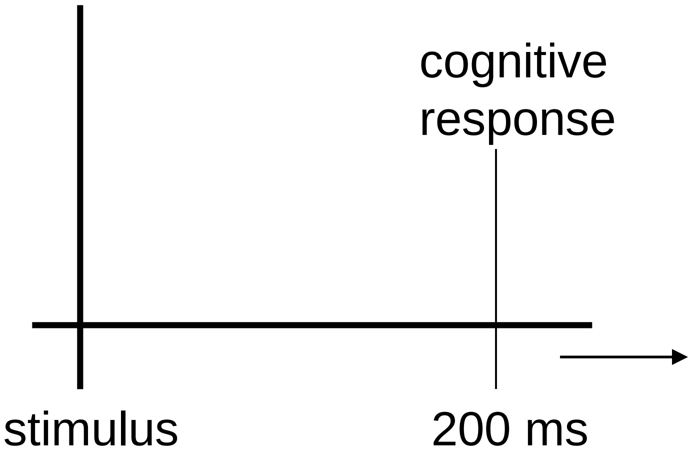
e.g. larger objects of the same weight are perceived heavier

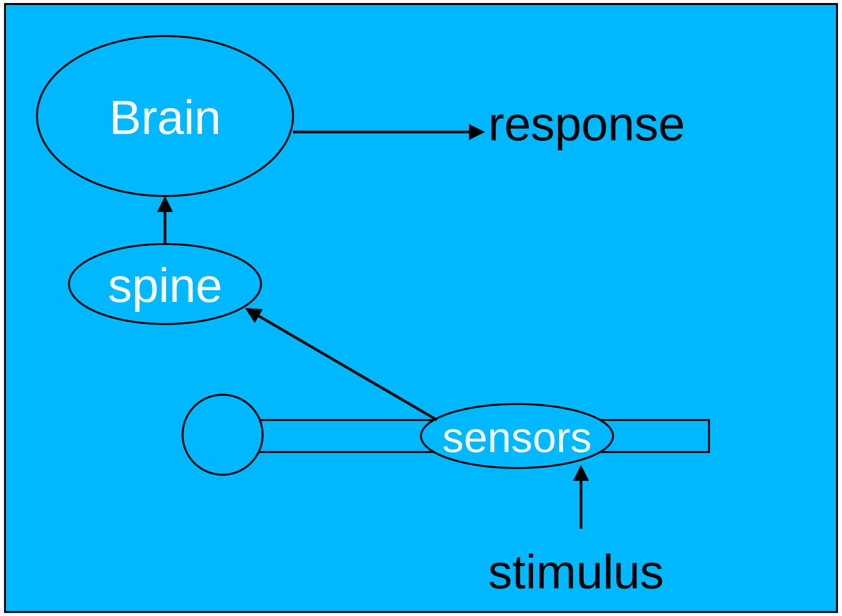
Nevertheless when more precise judgements are required the response modality dominates

Heller, 1999

From Perception to Action

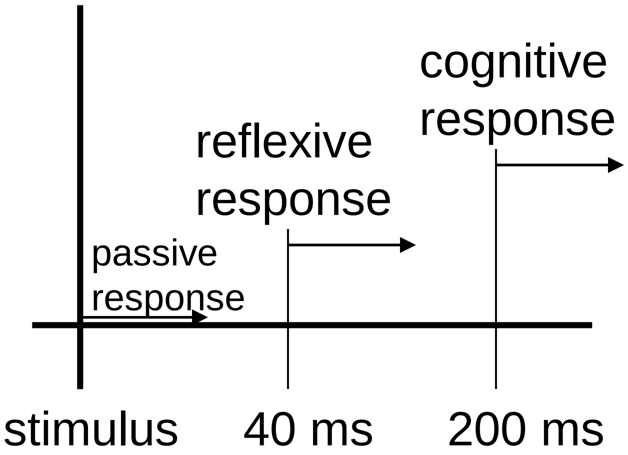
How do you respond to a signal?

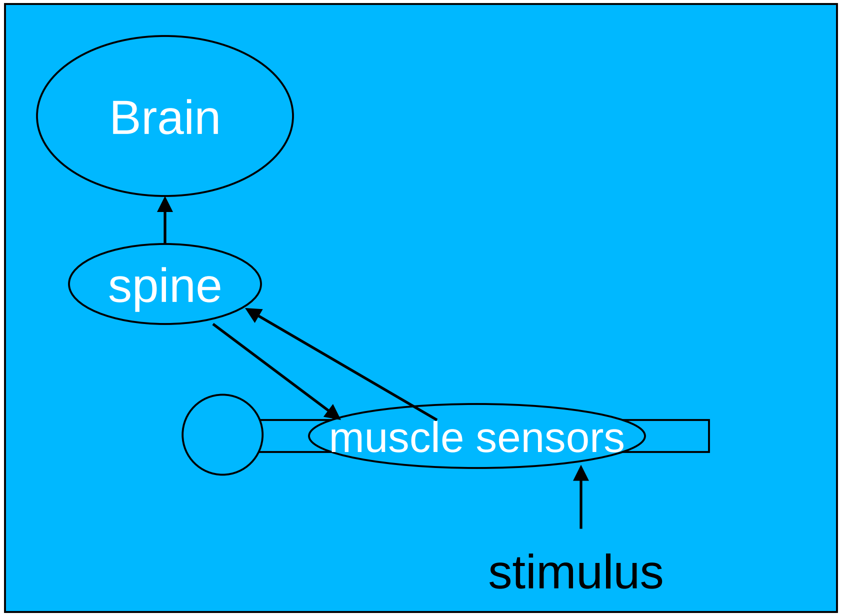




From Perception to Action

How do you respond to a signal?

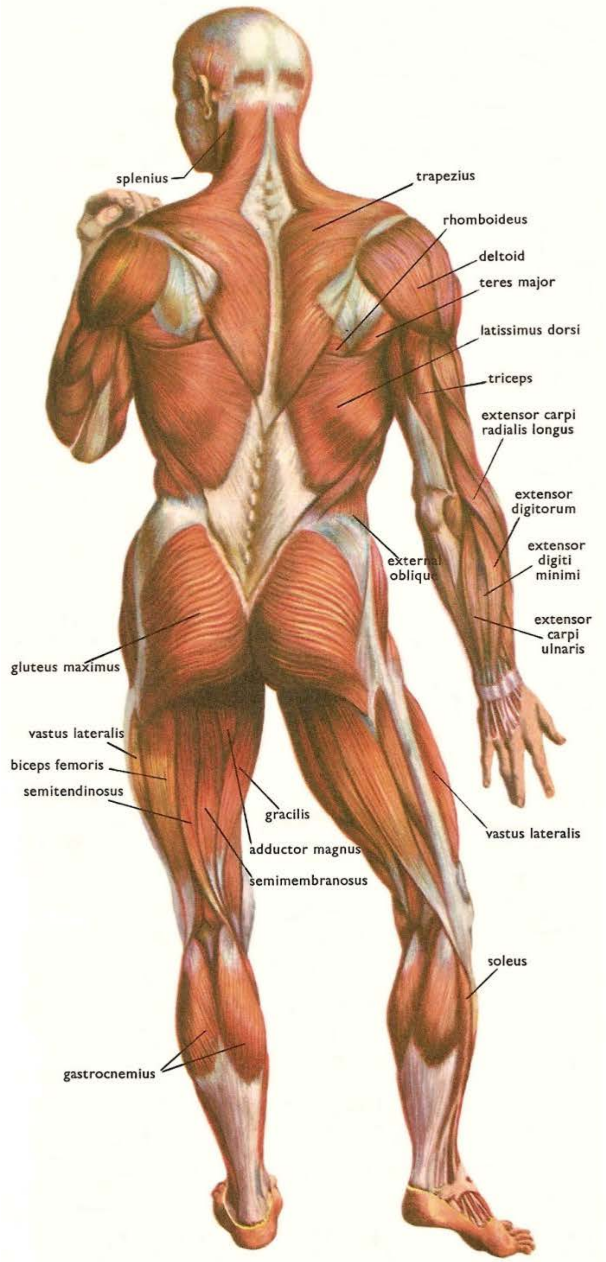




Haptic Applications (more in class 7-9)

1. Re-constructing Reality
   - Tele-operation: restoring natural force feedback
   - Over distance / in scale
2. Simulating Reality
   - Training difficult manual tasks
3. Enhancing reality
   - Games, Fun and Gadgets
   - Art & Music
   - Communication / Alerts/ Warnings
   - Improving Manual Control
     - Shared Control

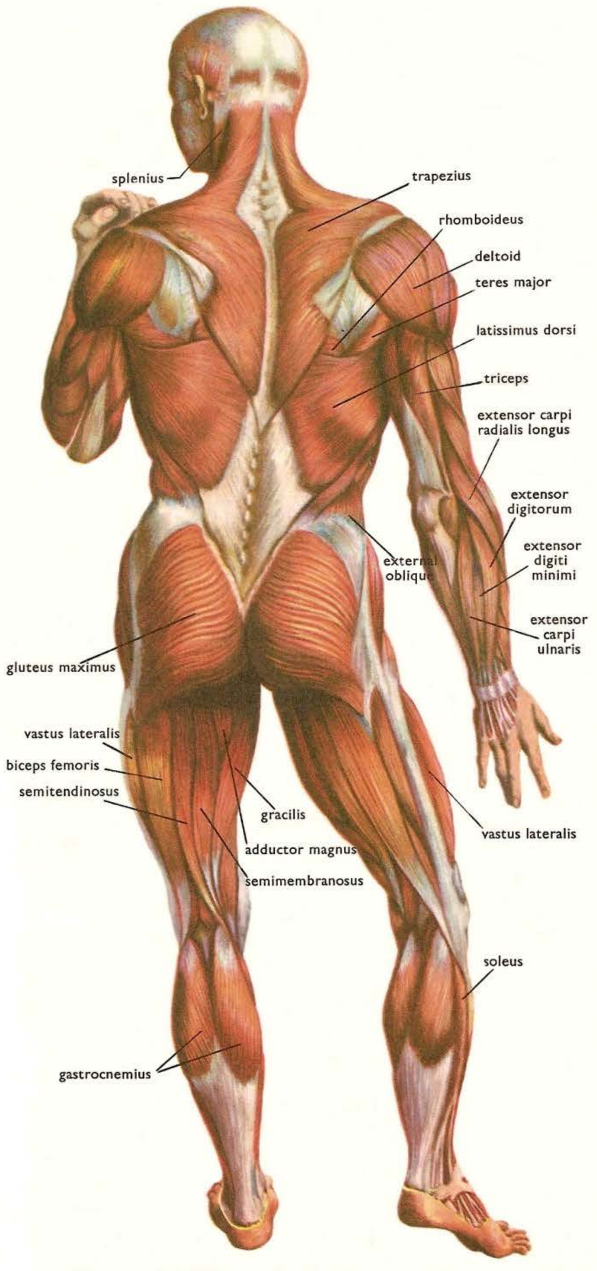
Neuromuscular System - generating force



How do we generate force?

Physiological and anatomical aspects

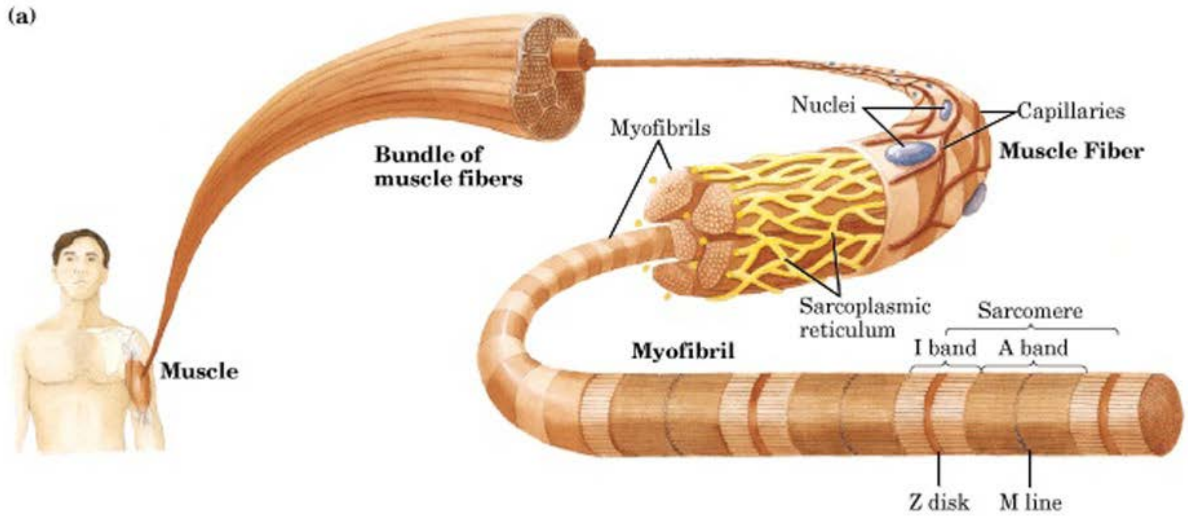
- Humans generate force by **contracting skeletal muscles**
- Skeletal muscles consist of muscle fibers
- Muscle fibers are built up from myofibrils, the basic force generating unit of muscles
- Muscles can **only contract actively**; extension is passive



Anatomy

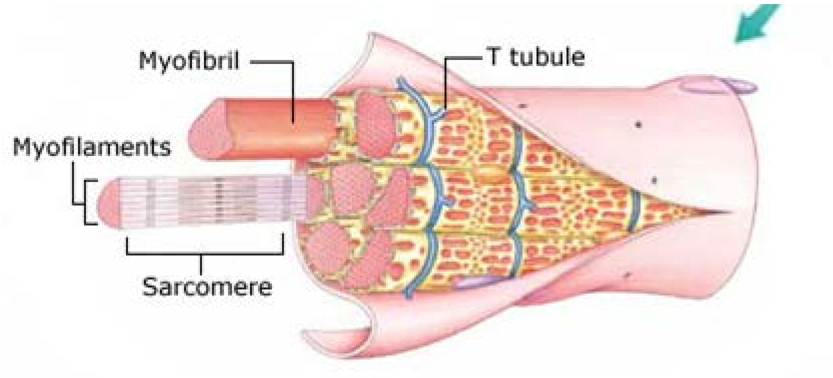
Physiological and anatomical aspects

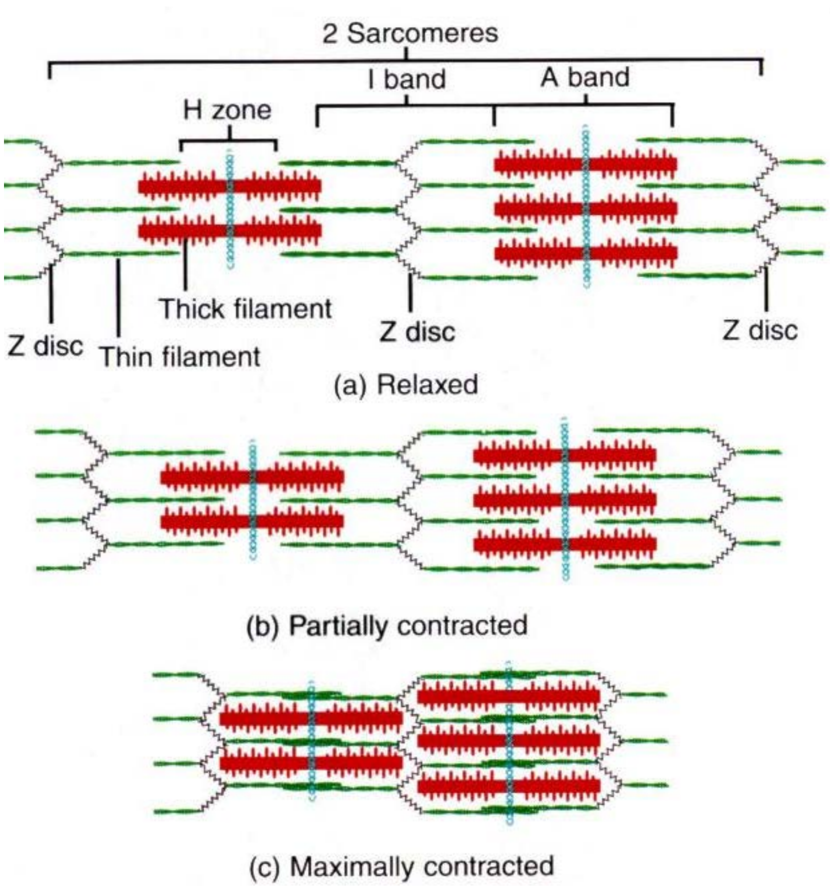
Structure of skeletal muscle



Anatomy

Physiological and anatomical aspects



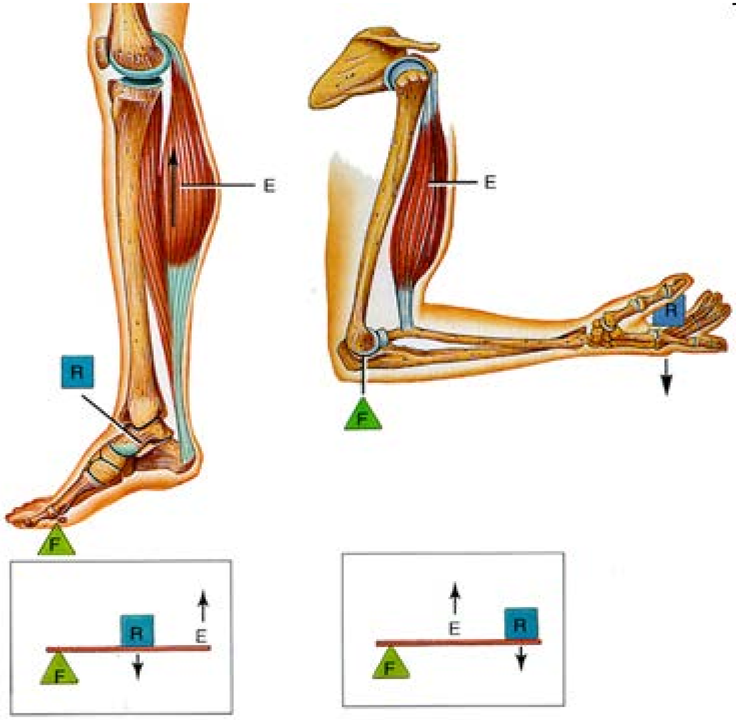


- Muscles can only contract actively due to chemical structure of the myofibrils
- Muscles cannot, therefore, actively extend

Transfering muscle force to skeleton

Limb movement

- Skeletal muscles are connected to bones via tendons
- Force, speed and unidirectional of movement of limbs is achieved via levers of bone-muscle attachments



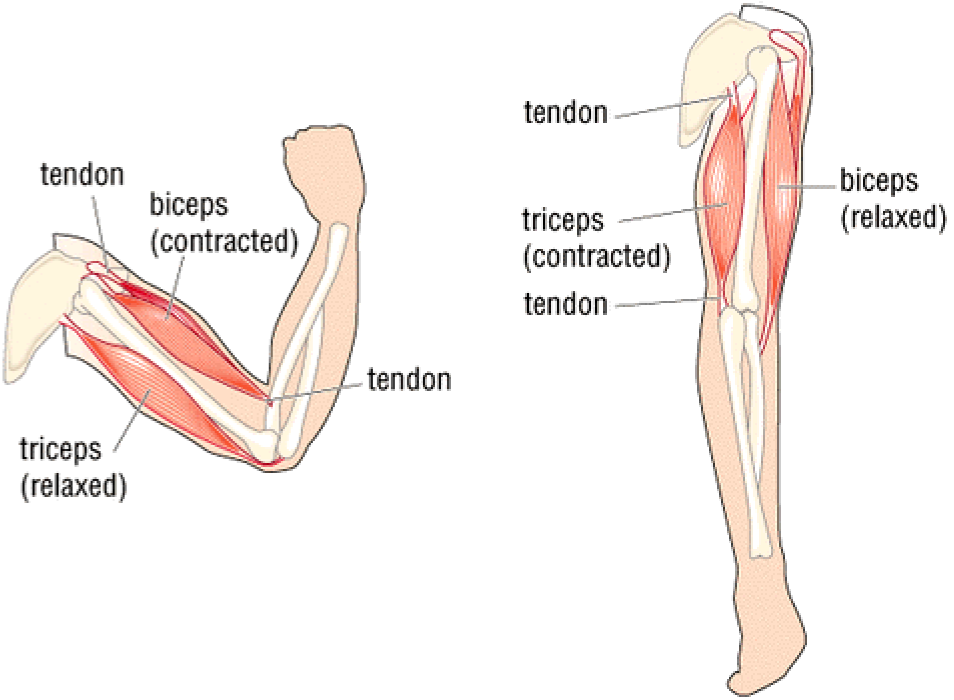
(b) Second-class lever

(c) Third-class lever

Moving a joint – muscle pairs

Limb movement

- Bidirectional movement of limbs is achieved through a combinations of antagonistic muscle pairs



Information flow to and from muscles

Control of muscle force and limb movement

- Afferent neurons carry signals from the muscles to the spinal chord and the brain
- Efferent neurons carry signals form the brain and spinal chord to the muscle fibres

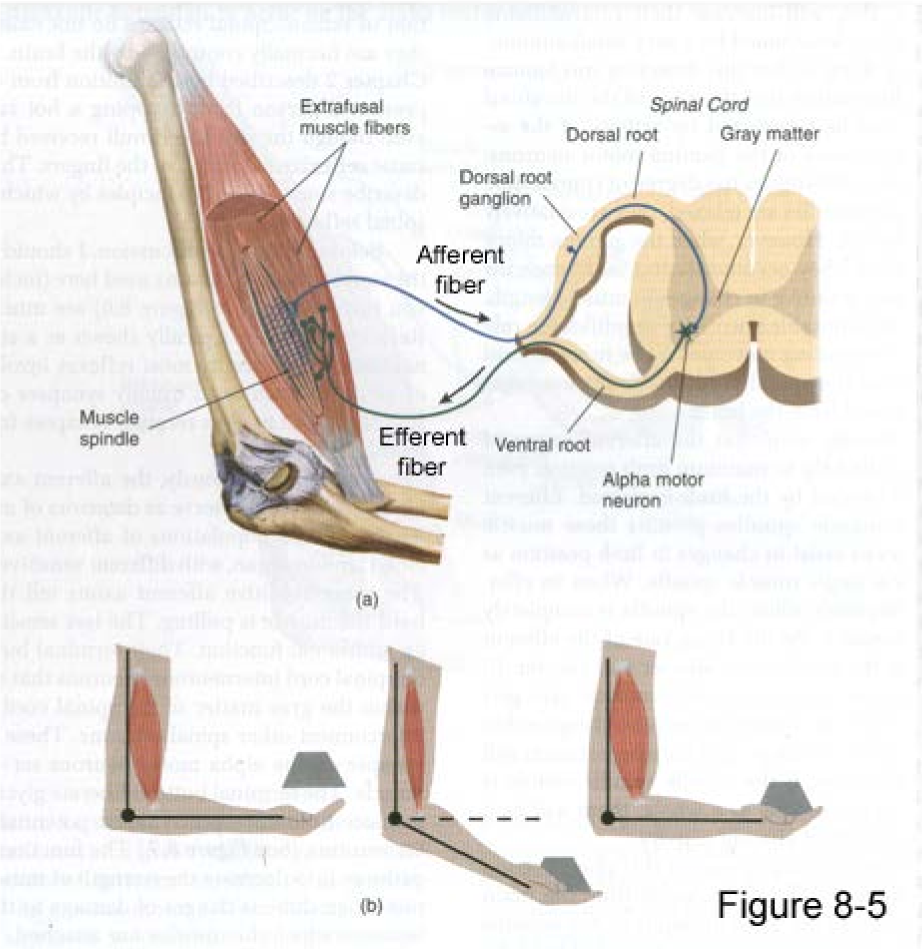
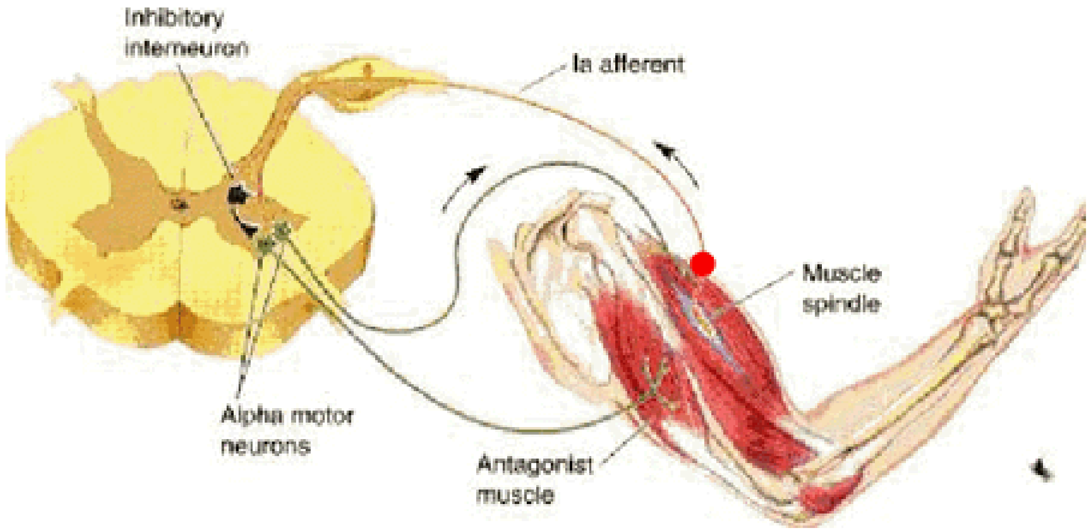


Figure 8-5

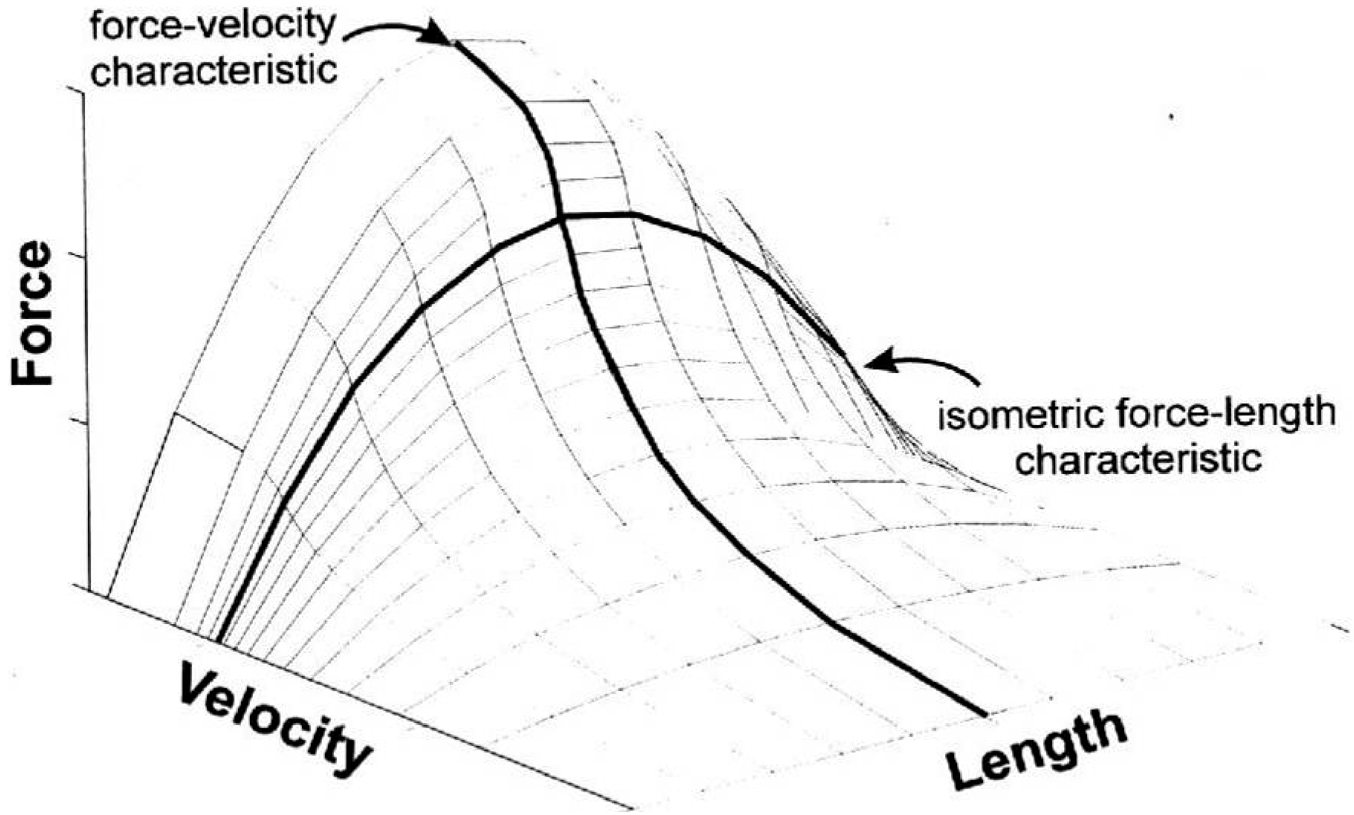
Central Nervous System and Muscles

Control of muscle force and limb movement

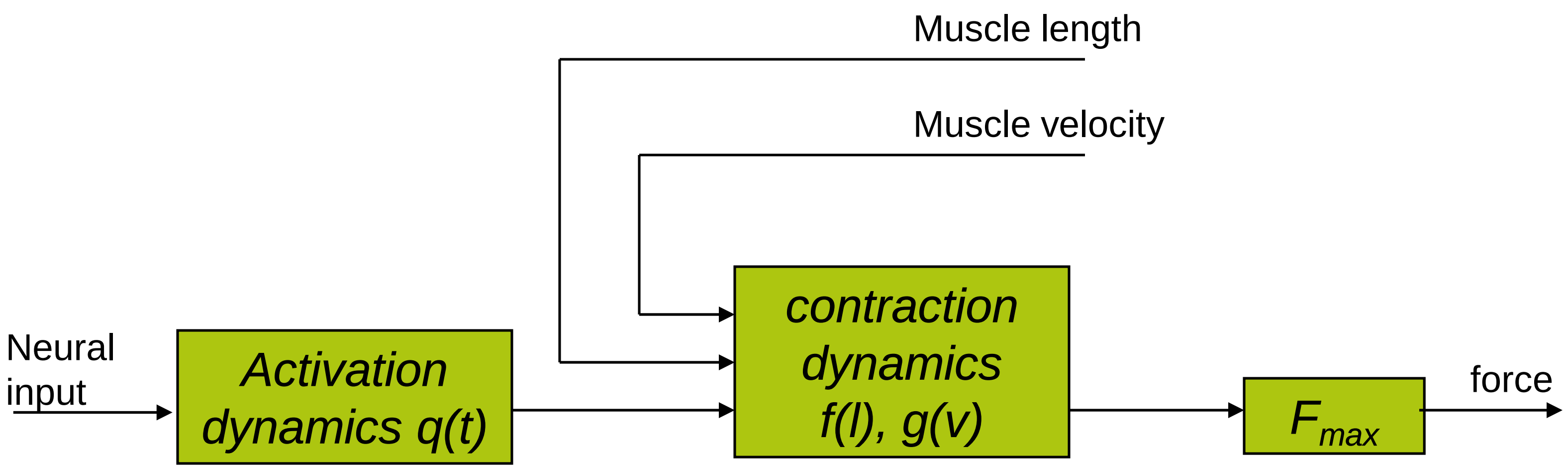
- Conscious control requires input from the brain
- Limb movement is the result of automatic inhibition of antagonist muscle upon activation of agonist muscle



Muscle Force depends on: velocity and length



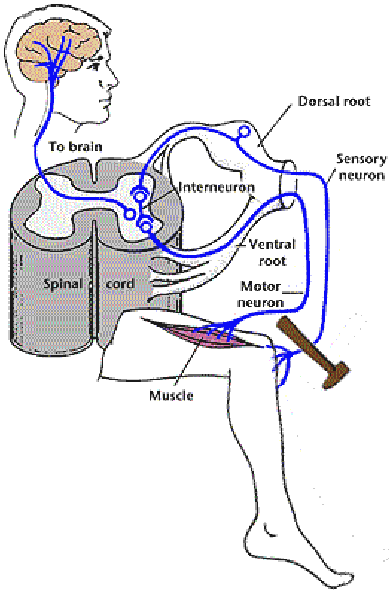
Modeling Muscle Force Generation: Hill



$$F = F_0 \cdot q(t) \cdot f(l) \cdot g(v)$$

Motor Noise

- Force build-up is not perfectly smooth:
  - motor noise
- Motor noise depends on
  - Type of muscle
  - Fatigue
- Can be reduced



Neuromuscular System

- motor control
- experiments & modeling

Motor Control – two types

Feed-forward control

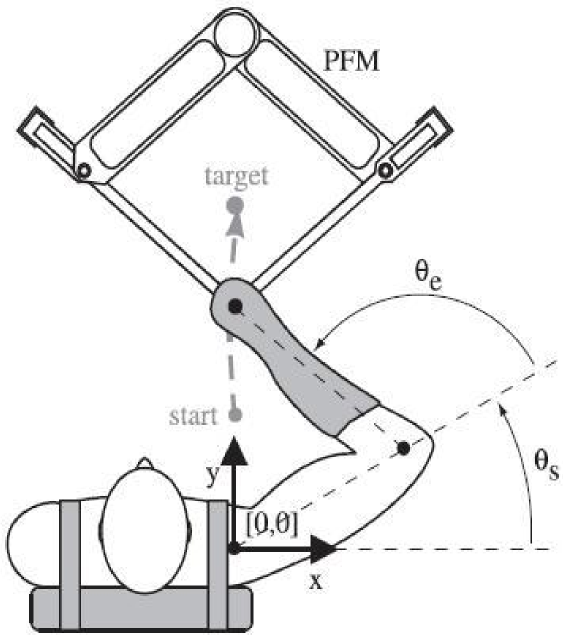
- Requires: Good internal model of interaction
- Most used: No perturbations
  Fast goal-directed movements

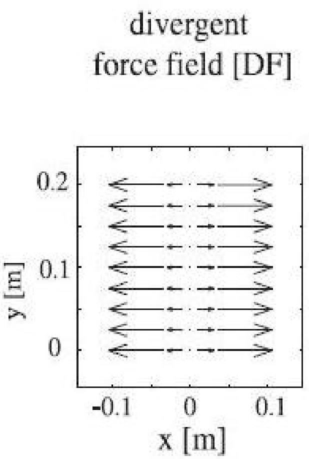
Feedback control (impedance control)

- Requires: sensory information
- Most used: disturbance rejection

Experimental study

- Hogan: “Impedance control can be used to stabilize the arm”
- To what extent can impedance control be modified?





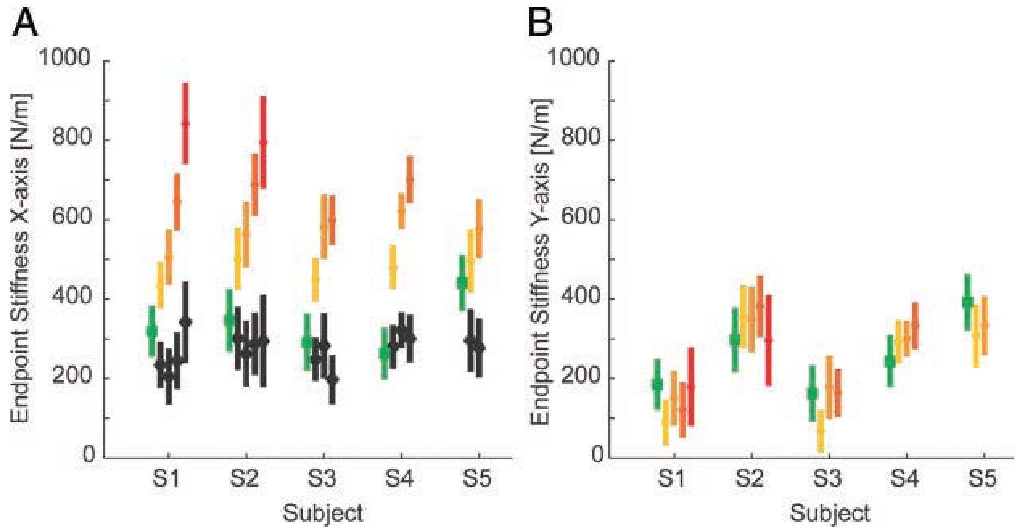
Procedure

1. Learn trajectories in normal field
2. Perform in divergent force fields (4 strengths)
3. Randomly do stiffness measurements during some DF-trials

Franklin et al (2004) - Impedance Control Balances Stability With Metabolically Costly Muscle Activation. Journal of NeuroPhysiology

Results

- Subjects learn to generate smooth trajectories in each unstable environment
- Subjects adapted their endpoint stiffness to each unstable environment: the stronger the field, the larger the stiffness
- Overall stiffness (of manipulator + human) remained similar



All of this suggests that metabolic energy and stability margins are balanced during motion control

Controlling posture or forces: how?

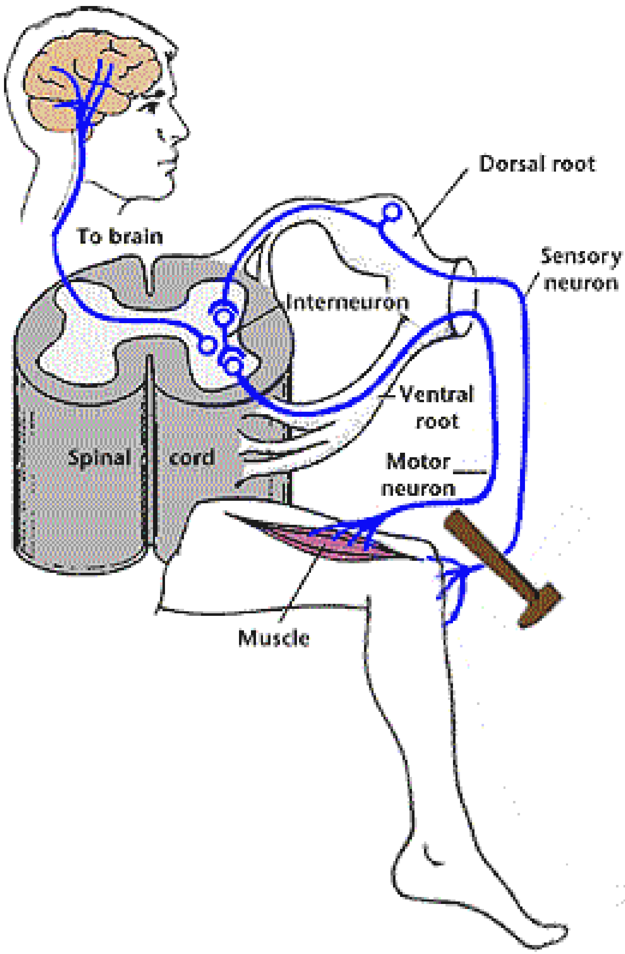
- How do humans control posture?
  - What is the role of motor reflexes?
  - How effective is intrinsic joint stiffness (resulting from pretension of antagonist muscles)?

- Motivation
  - Aircraft control (stability issues)
  - Automotive control (steering, haptic gas pedal)
  - Medical, understand & diagnose motor disorders

Spinal Reflexes

Control of muscle force and limb movement

- Reflexive behaviour is regulated via the spinal chord and does not require conscious control
- But: conscious control can influence the strength and nature of the response!
- Reflexive behaviour is fast and also automatically inhibits the antagonistic muscle to allow movement of the excited muscle

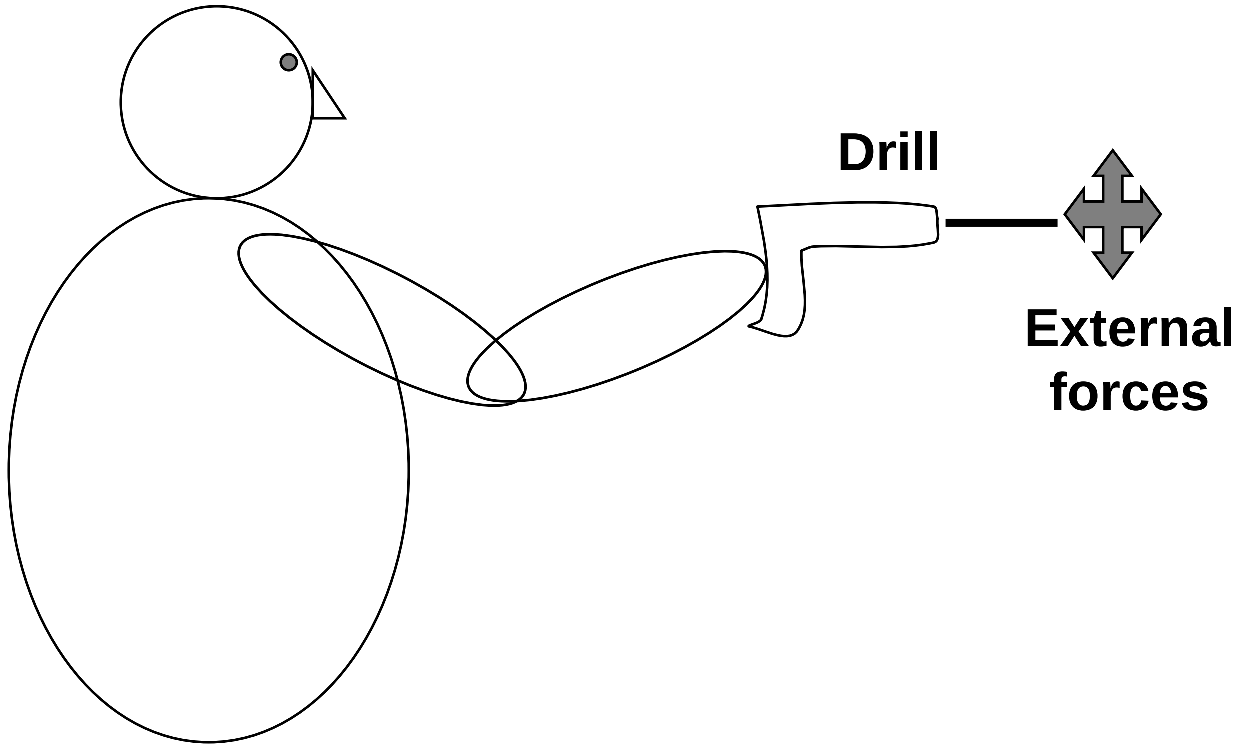


Two strategies to resist perturbations

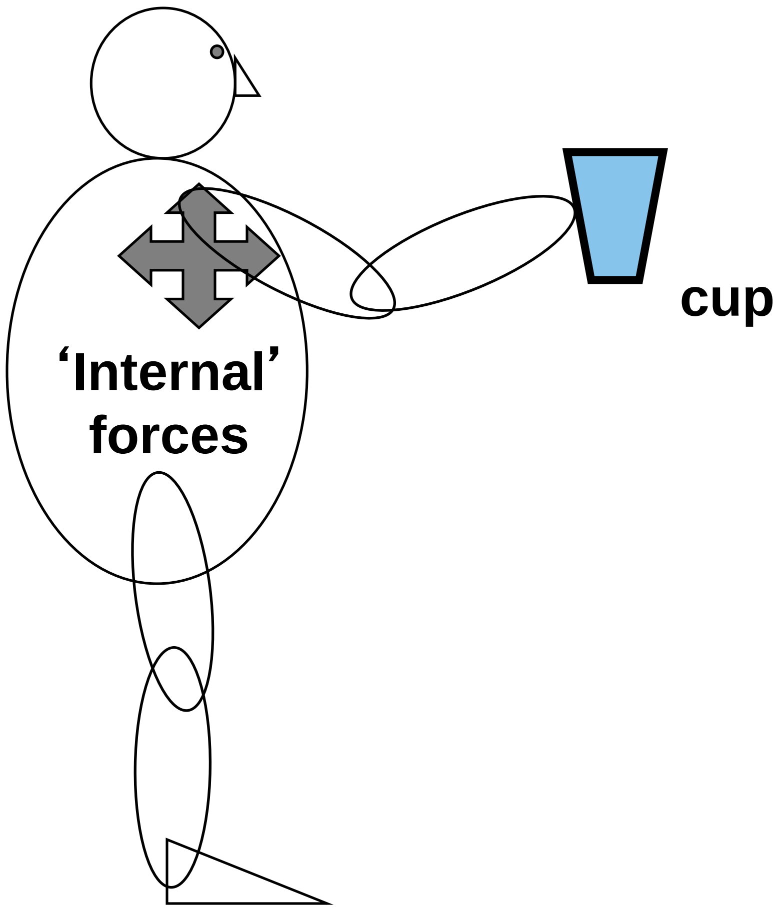
- Co-activation of muscles (co-contraction):
  - Increased muscle stiffness & viscosity
  - Effective for large range of frequencies
  - Costs much energy

- Proprioceptive feedback:
  - Length, velocity and force feedback
  - Energy efficient, only active if perturbations are present
  - Only effective for low frequency perturbations due to time-delays in nervous system

Postural control:
Resisting external perturbations



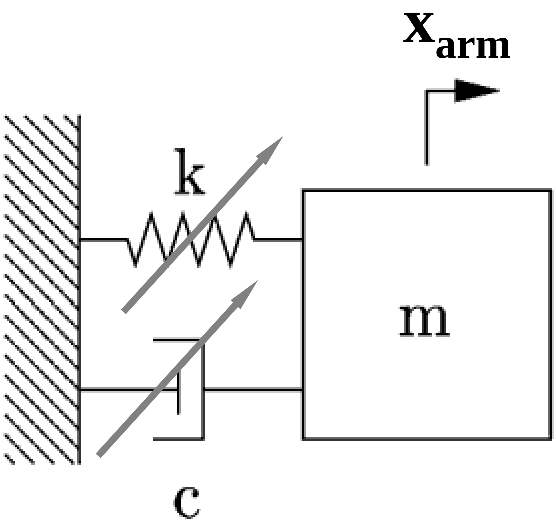
Postural control: Resisting ‘internal’ perturbations



Simple Modeling of the Neuromuscular System

Physical mass-spring-damper model

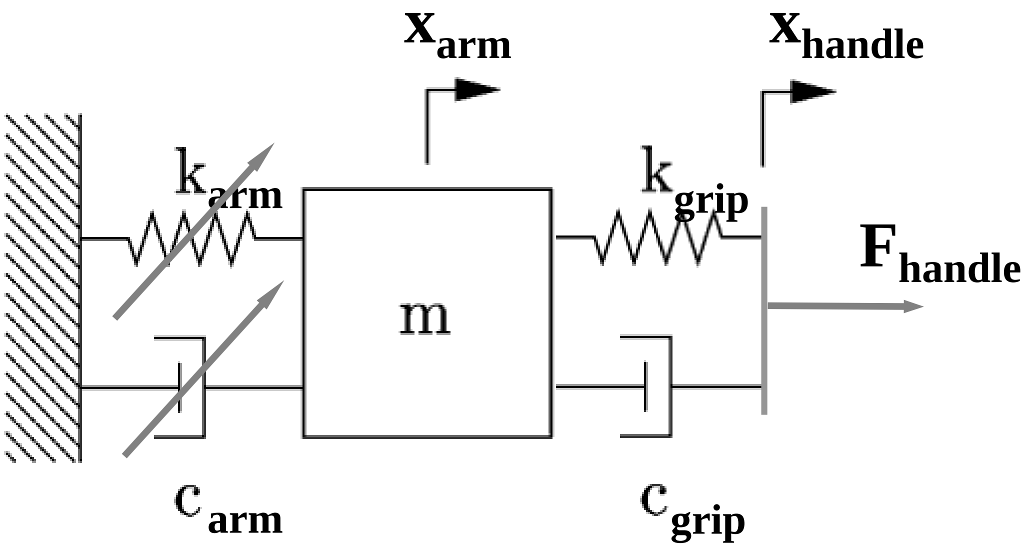
- The neuromusculoskeletal system is modeled as a mass-spring-damper system
- Humans can actively control the stiffness of the muscles



Simple Modeling of the Neuromuscular System

Physical mass-spring damper model

- When in contact with objects, the grip is modeled as a very stiff system with some damping and no mass.



Adaptability of Neuromuscular Feedback

Response to perturbations is highly adaptive

Stretch amplitude & muscle activation
(e.g., Cathers, 1999; Kearney and Hunter, 1983)

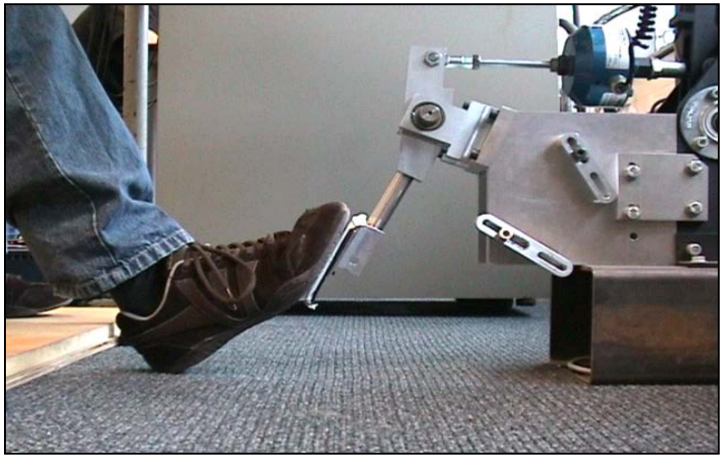
Frequency content of perturbation
(e.g., Van Der Helm et al., 2002)

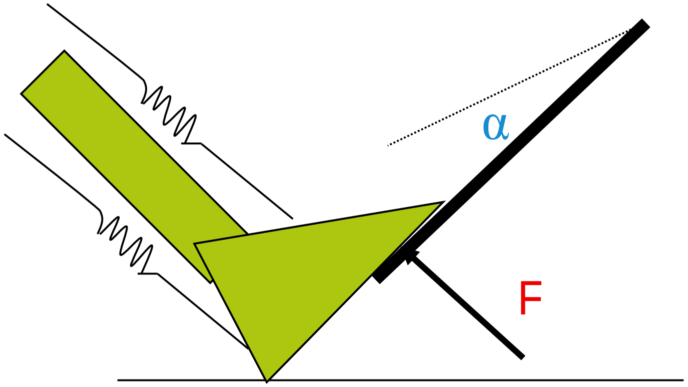
Dynamics of environment (stiffness, damping)
(e.g., Schouten et al. 2004, 2008b, Abbink et al. 2004)

Task instruction (transient response)
(e.g., Doemges & Rack 1992a,b; Abbink et al. 2004, 2009)

Measuring Neuromuscular Feedback

1. Impose Force Perturbation
2. Task Instruction
3. Measure Signals
   - Pedal Force
   - Pedal Displacement
   - Force Perturbation
4. Estimate Admittance





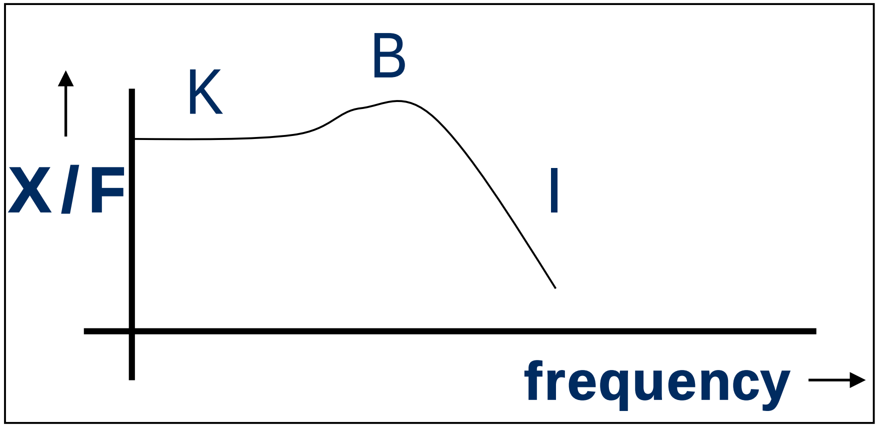
Measuring Neuromuscular Feedback

Admittance:

can be estimated as frequency response function

input force/torque
output position/rotation

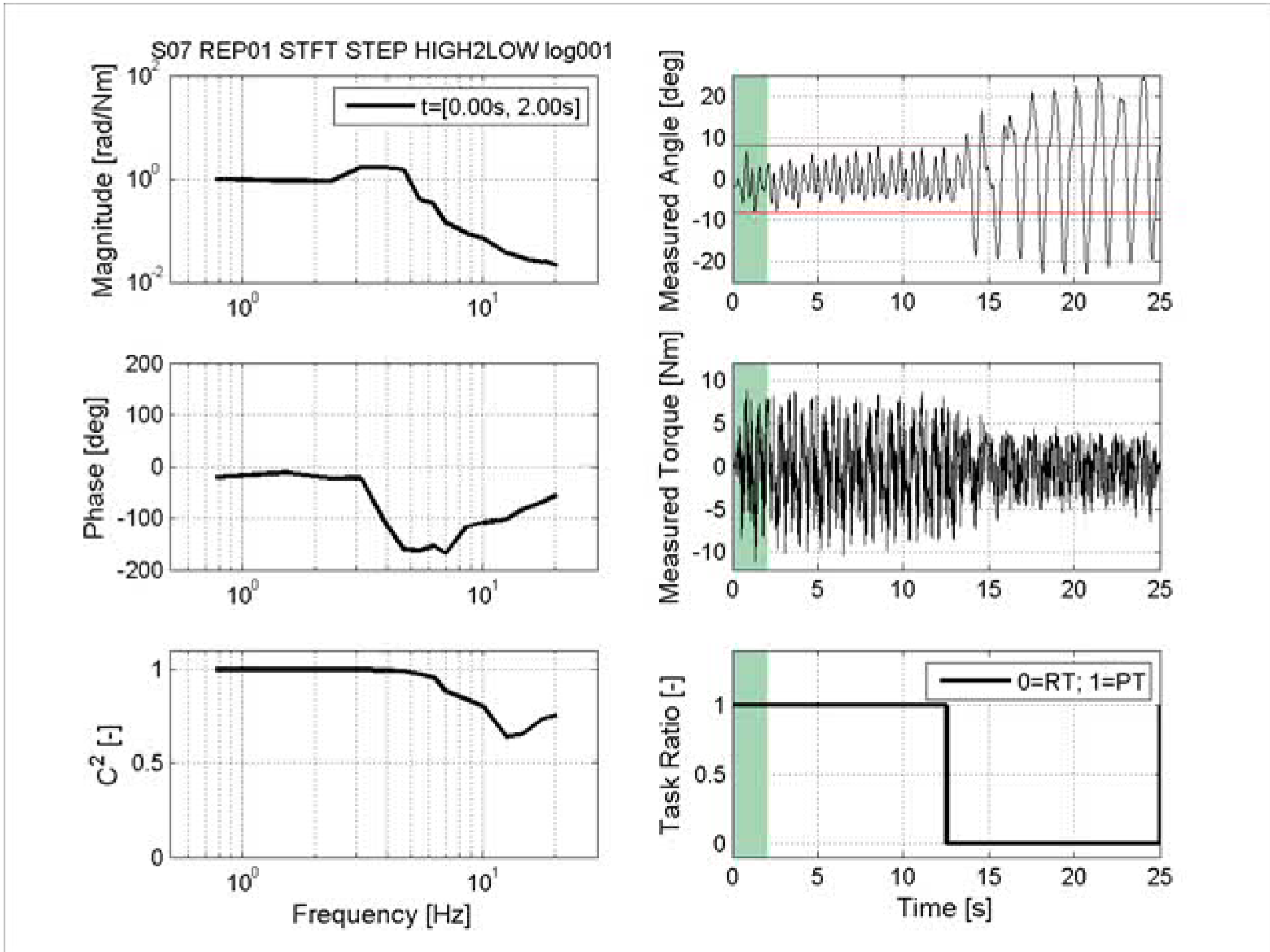
captures **causal** dynamic response of a human to interaction forces with the environment



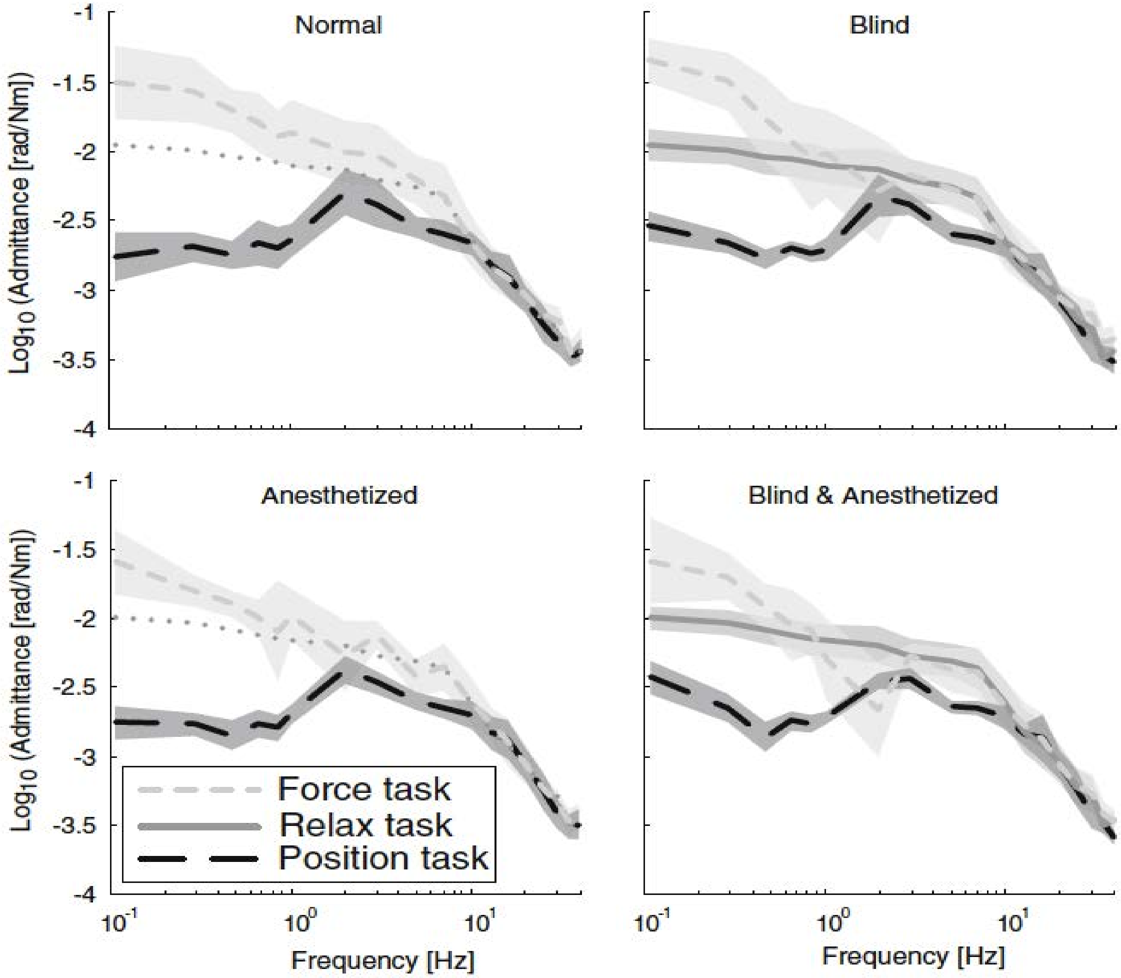
Roughly resembles 2nd order system

Highly adaptive!

Time-variance in admittance (Abbink et al.)



Tactile and kinesthetic contributions to admittance (Mugge & Abbink 2013)



Conclusions about the Neuromuscular System

- Skeletal muscle is strongly non-linear (Hill)
  - Non-linearity is essential in human motion
  - Linearization is successful for control tasks with small amplitudes

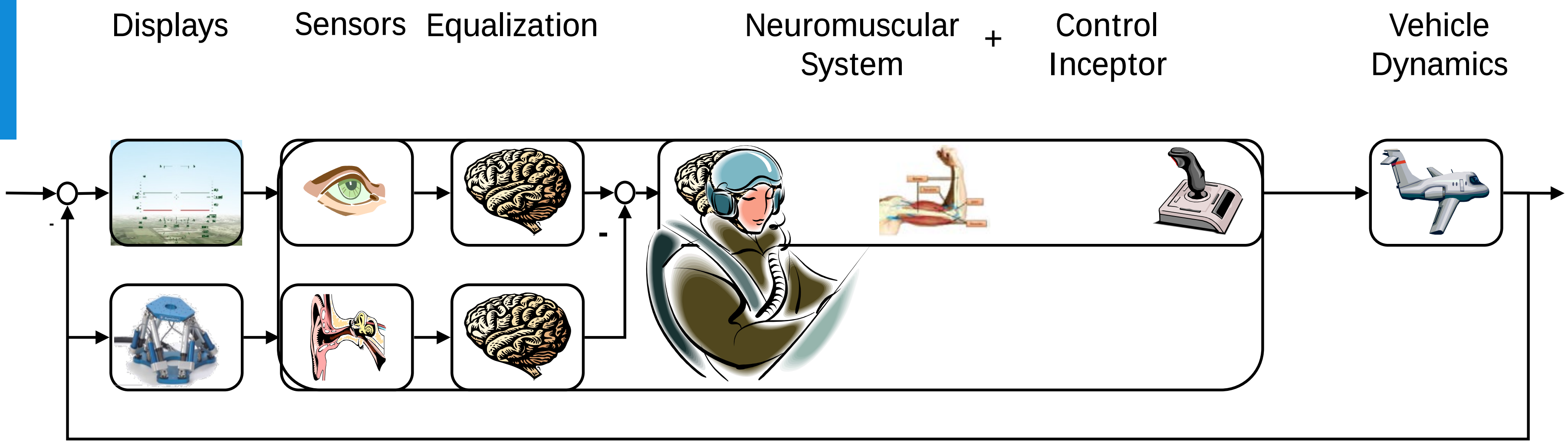
- Reflexive feedback gains are very important for the behaviour of neuro-musculoskeletal systems
  - Position feedback
  - Velocity feedback
  - Force feedback

- Co-contraction and Reflexive feedback gains are continuously adapted, near-optimal
  - task instructions, environment, perturbations

- Endpoint behaviour can be captured by admittance

The Role of the Neuromuscular System in visual / vestibular control loops

The Lumped Neuromuscular System

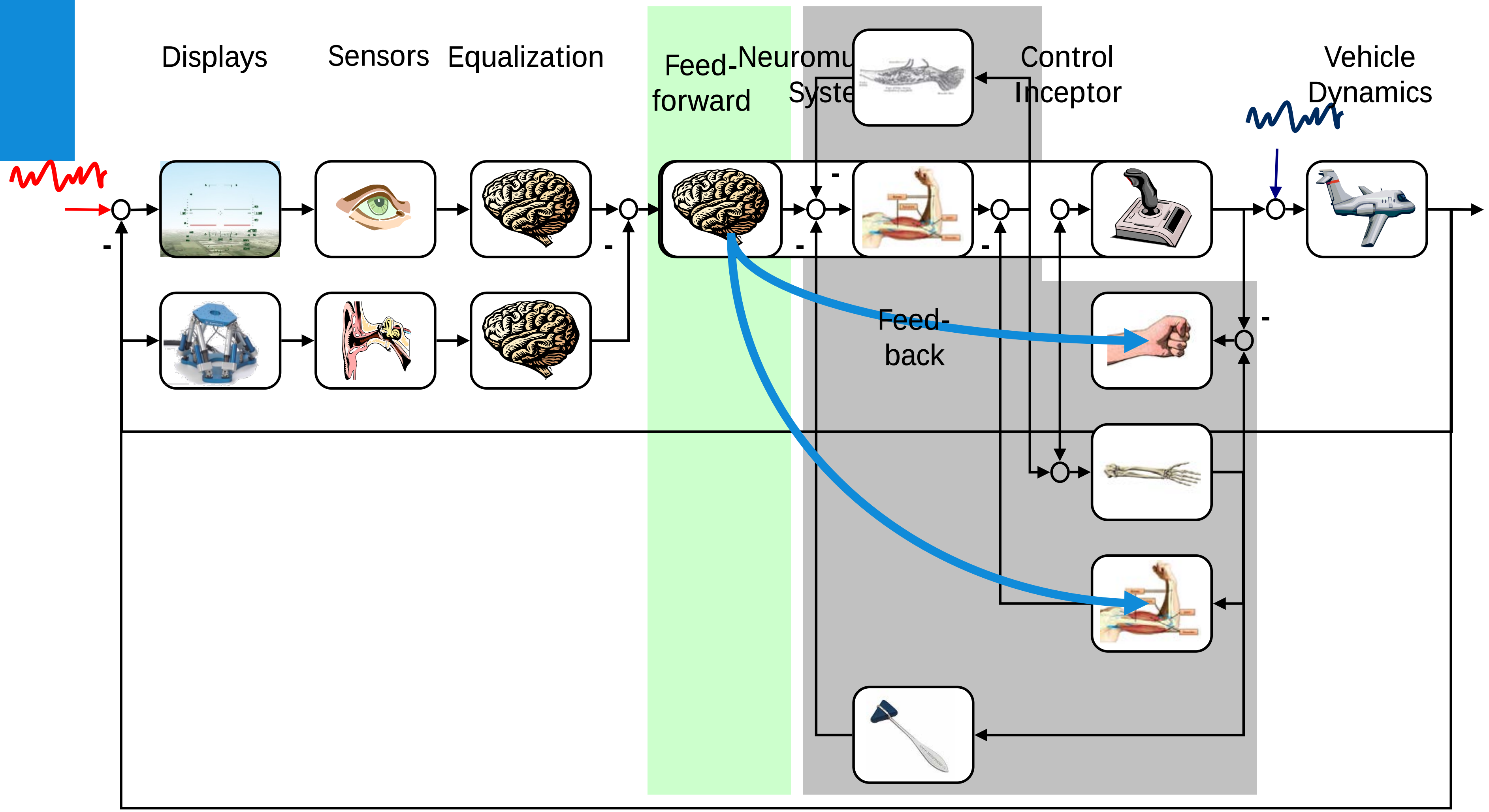


The neuromuscular system is usually considered as a limitation, and can be seen as a controller-actuator system between $u_{desired}$ and $u_{realized}$

The neuromuscular system can be modeled as a first or second-order low-pass filter: **Lumped neuromuscular system**.

$$H_{lumped} = \frac{\omega_{nm}^2}{\omega_{nm}^2 + 2\zeta_{nm}\omega_{nm}s + s^2}$$

The Neuromuscular System



Take Home Message

Today you have learned:

1. About two kinds of haptic perception
   1. Tactile
   2. Proprioceptive

2. About Human Motion Control (muscles and reflexes)
   1. Feedforward
      1. Learn smooth movements over time
      2. Motor noise
   2. Feedback
      1. stiff through co-contraction and reflexive activity
      2. compliant through relaxed muscles and reflexive activity
      3. Endpoint feedback properties can be captured by admittance