Human Motion Control

Dept. of Mechanical Engineering
Course 2008 - 2009
(Wb 2407)

Lecture 9
Theories on motor control
Effect of non-linearities

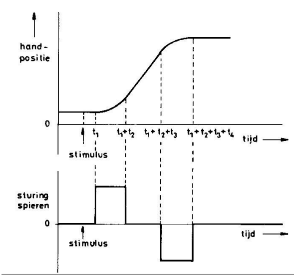
Delft University of Technology

Contents

- Goal-directed, cyclic and explosive tasks
- Planning and execution of motions
  - Equilibrium Point hypothesis & Force Fields
  - Feedforward planning, inverse dynamics
- Short, medium & long latency reflexes
- Adaptation

Goal-directed task

- Bang-bang control
  - acceleration phase
  - movement phase
  - homing-in phase
- Combination of motion control and position control



Cyclic motions

- Examples: Walking, running, cycling, rowing
- Exact motion trajectory is not important
- Walking motion is generated in ballistic way:
  - Natural swing of segments: Distribution of mass & stiffness
  - Energy efficient
  - Stable: Reflexes add to increased 'stiffness'

Explosive motions

- Goal is maximal energy production
- Examples: Jumping, throwing, kicking, …
- Exact motion trajectory is not important
- Borderline stable: Stability costs energy!

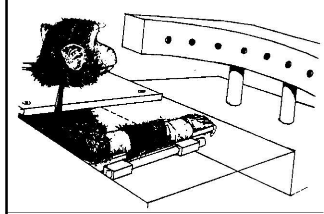
Question for planning and execution of motion

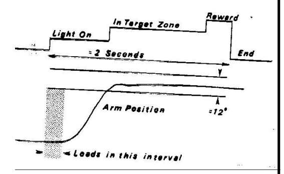
- How can the CNS plan every (unknown?) motion in advance?
- How can the CNS control every single muscle?
- Distributed properties: Intrinsic muscle properties and reflexive properties guide the limb to the end position
- Role of feedback?

Theories for human motion control

- Feedback controlled motions
  - Equilibrium point hypothesis
  - primitives
- Use of internal representation
  - Feedforward and feedback model
  - Adaptive feedback model
  - Combined model (neural network)

De-afferented monkey (Bizzi, 1973)



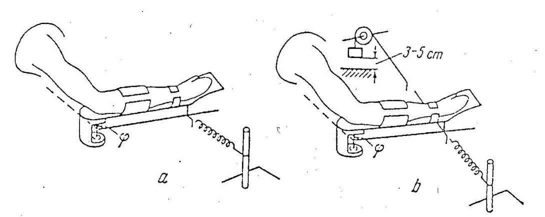


De-afferented monkey (Bizzi)

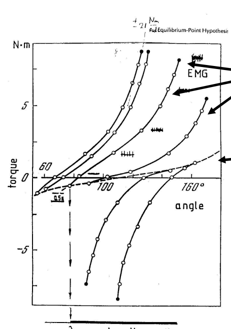
- All dorsal roots are cut: No sensory pathways
- Vision is blocked
- Still able to reach its goal
- Still able to reach its goal when perturbed !!
- After perturbation the limb returns to the trajectory, not to the endpoint !!
- Stiffness is result of activity α-motor neuron

- Conclusion: Monkeys (humans) control their motions by controlling an equilibrium point
- During motions the equilibrium point moves: Virtual trajectory

Quick release (Fel'dman, 1966)



Quick release (Fel'dman)



Release points

Passive line (zero offset)

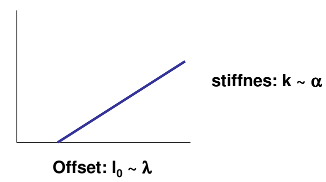
Feldman:

- Task: "Do not intervene"
- Control of limb system: Non-linear spring with variable offset and constant stiffness.
- Controlled variable: offset ~ Equilibrium point: λ
- Stiffness is result of intrinsic muscle properties and reflexive feedback
- Controlled parameter λ is set by supraspinal neural input

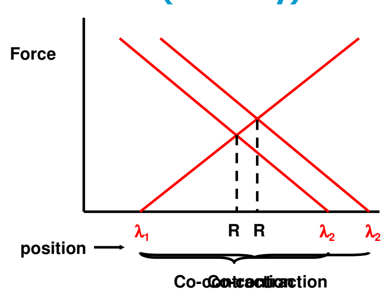
‘Equilibrium Point’ Theory

- One of the major theories in motion control
  - λ-theory : Fel’dman (1966; ….), Latash (1993)
  - α-theory : Bizzi (1983), Hogan
- λ is setpoint (threshold) for muscle length
- R: resulting equilibrium point from all λ’s
- C: defines amount of co-contraction
- Muscle ≈ spring with variable offset and constant stiffness (+ velocity term):
  - Activation = $(l(t - \tau) - \lambda(t) + \mu(t).\ (t - \tau))$
  - Conventional feedback control! (PD controller)

‘Equilibrium Point’ Theory



‘Equilibrium Point’ Theory (λ-theory)

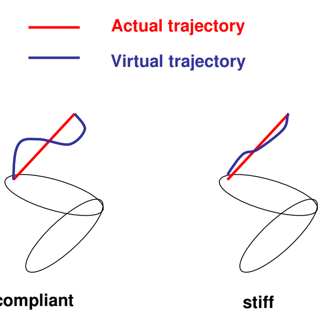


Virtual Trajectory

- Virtual trajectory is a sequence of equilibrium points
- Kinematic planning of motion trajectory
- Sufficient stiffness is necessary for smooth pursuit

- Equilibrium hypothesis predicts high stiffness during motion!

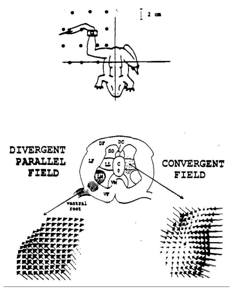
Virtual trajectory



Primitives

- Background hypothesis
  - In the CNS are clusters of neurons dedicated to a certain task
  - Complex task is a concatenation of these clusters
  - For motion control a stiffness (position) cluster (force field) and maybe a viscosity (velocity) cluster can be distinguished
  - Stiffness cluster is in accordance with Equilibrium Point Hypothesis

Force Fields



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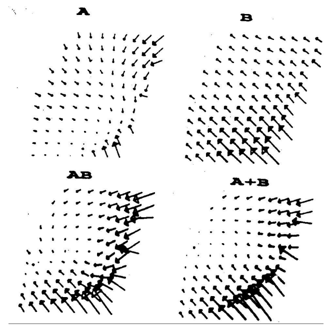
Force Fields



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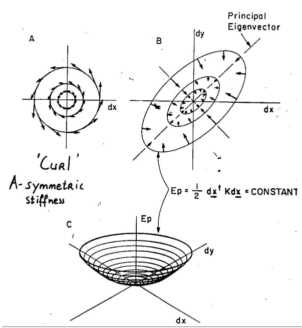
Stiffness ellips



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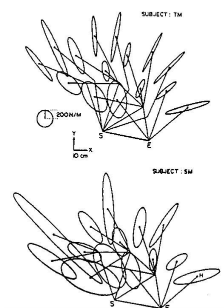
Endpoint stiffness



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Force Fields

- Force field is the result of a stiffness field and a displacement
- Any force field can be generated by combining 'primitive' force fields
- In a force field intrinsic and reflexive properties are incorporated
- Static approach! All time-delays and other dynamics are neglected!
- Velocity field has not yet been shown.

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Equilibrium hypothesis

- Feedback controller with limited bandwidth, only low frequency motions can be executed
- EP would predict high stiffness for fast motions

<u>Against Equilibrium hypothesis</u>
- Feedforward control is necessary for fast motions
- Optimal feedforward control is inverse dynamic system (actuator + plant)
- Equilibrium point hypothesis uses only kinematic information
- Low stiffness and no feedback is predicted by feedforward models, in accordance with recordings

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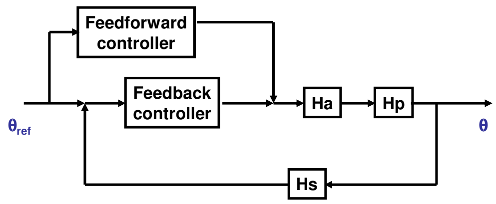
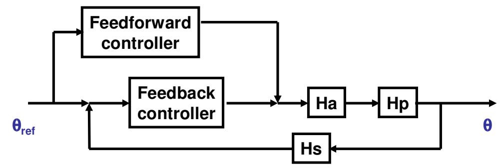
Role of feedback control



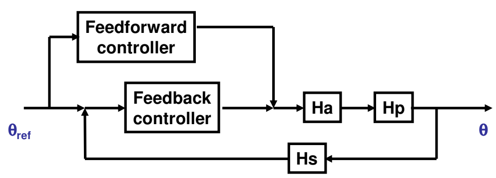
- Feedback control: $H = \frac{Hfc.Ha.Hp}{1 + Hfc.Ha.Hp.Hs}$
- Optimal if |Hfc.Ha.Hp| >> 1 and |Hs| = 1
- Bandwidth Hfc.Ha.Hp is limited, no high frequencies

Role of feedforward control



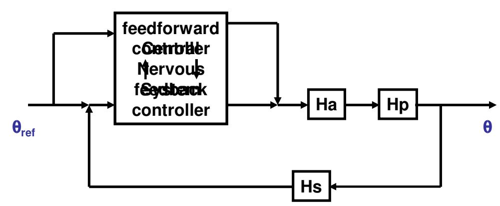
- Feedforward control: $H = \frac{Hff.Ha.Hp}{1 + Hfc.Ha.Hp.Hs}$
- Optimal if |Hff.Ha.Hp| = 1 and |Hfc.Ha.Hp.Hs| << 1
- Hff = $(Ha.Hp)^{-1}$ and Hfc = 0 !
- Optimal feedforward: Intern model is inverse dynamic model & Feedback gains are zero!

Internal model



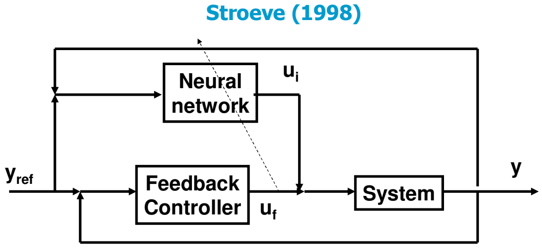
- Intern model used by feedforward controller: Anticipation
- Optimal feedforward: Intern model is inverse dynamic model & Feedback gains are zero!
- **Adaptation** of intern model by evaluation of feedback signals!

Central Nervous System



- Central Nervous system represented by Artificial Neural Network
- Non-linear feedforward and feedback
- Trained by examples

Feedback & FeedForward Controller Stroeve (1998)

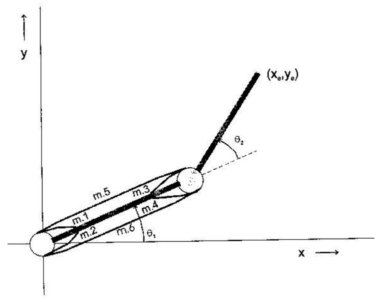


- If feedback error is minimal, neural network will be inverse of system -> optimal **feedforward** controller!!
- Neural network takes over feedback and feedforward control

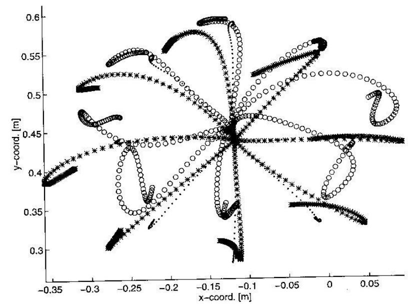
Combined feedback & feedforward controller

- Applied to 2 DOF, 6 muscle arm model
- Two layer NN model, 32 hidden nodes
  - Non-linear feedback controller
  - Gains set by input signal
- Backpropagation-Through-Time (BTT) learning algorithm
- Can adapt to new environmental impedance
- Accounts for time-delays

Musculoskeletal model

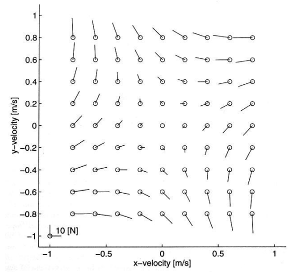


Learning with/without FF or FB

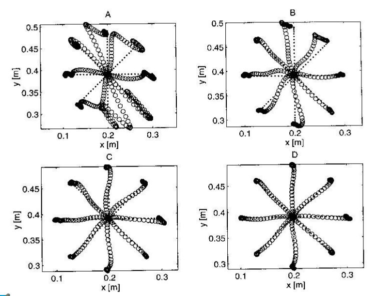


….. With FF & FB
ooo Without FF
*** Without FB

Nonlinear environmental impedance: Viscosity force field



Learning with non-linear viscosity force field

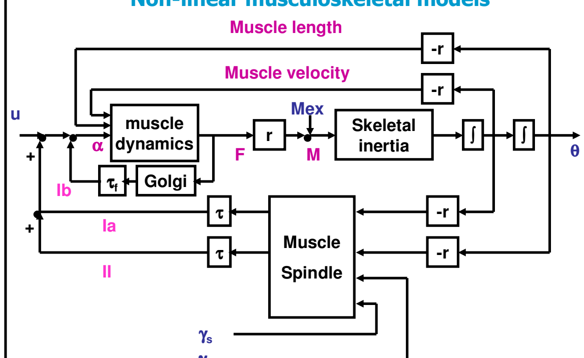


A: Before learning
B: after 100 trials
C: after 500 trials
D: after 100000 trials

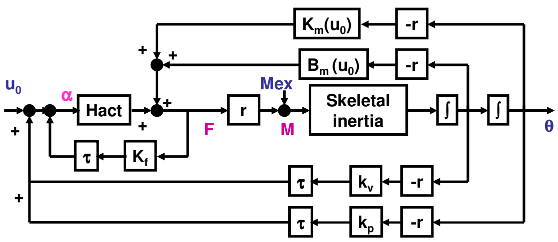
Effect of non-linearities

- Any system is outside certain limits non-linear, linearity is an assumption
- A musculoskeletal system is highly non-linear
- Non-linear properties are distributed over all parts of the musculoskeletal system, and are functional

Non-linear musculoskeletal models



Linearized musculoskeletal models



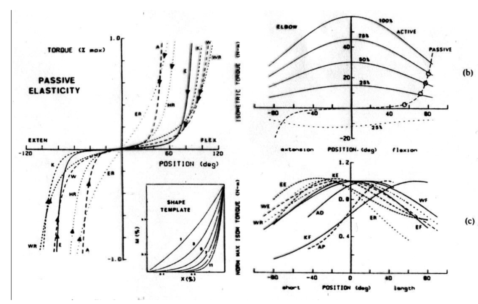
Linearization

- Linearization feasible in a working point
- Only appropriate for postural control
- 'Hard' non-linearities can (strictly) not be linearized:
  - Uni-directional force generation
  - Uni-directional sensor sensitivity
  - Calcium in- and outflow
- Analysis of motion control: Simulation with non-linear models
- Range of working points: Non-linear properties become important

Non-linear properties

- Skeletal model
  - Passive joint stiffness
- Muscle
  - Moment arms
  - Calcium dynamics
  - Independency activation & contraction dynamics
  - Force-length relationship
  - stiffness
  - Force-velocity relationship
- Muscle spindle
  - Stiction
  - Competitive contribution to Ia afferent fiber
- CNS
  - Sensory integration center

Passive joint stiffness



Passive joint stiffness

- Towards the last 20 degrees of Range-of-Motion, the passive forces increase
- High (agonistic muscle) forces needed to get into this range
- Advantage
  - Motion will be stopped even without proper muscle coordination
  - Forward dynamic simulations will not get out-of-bounds

Muscle

- Moment arms
- Calcium dynamics
- Independency activation & contraction dynamics
- Force-length relationship
- stiffness
- Force-velocity relationship

Moment arm m. biceps

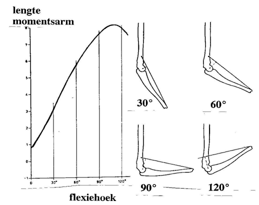
•Change of moment generated by muscle

•Determines length range:

$$\Delta l_m = \frac{\partial l_m}{\partial \theta}.\Delta\theta$$

•Determines contraction velocity:

$$\dot{l}_m = \frac{\partial l_m}{\partial \theta}.\dot{\theta}$$



Moment arm & apparent joint stiffness

- Apparent stiffness: Change of joint stiffness as function of muscle stiffness and change of moment arm:

$$M = r.F_m = \frac{dl_m}{d\theta}.F_m$$

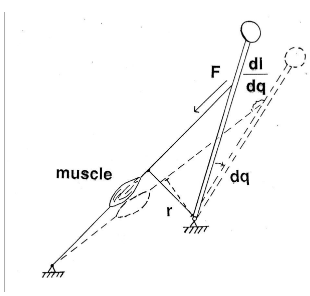
$$\frac{dM}{d\theta} = r.\frac{dF_m}{d\theta} + \frac{dr}{d\theta}.F_m$$

$$= r.\frac{dF_m}{dl_m}.\frac{dl_m}{d\theta} + \frac{dr}{d\theta}.F_m$$

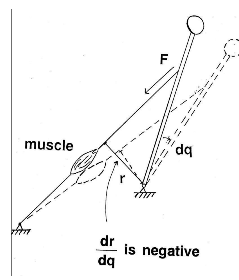
$$= r^2.K_m + \frac{dr}{d\theta}.F_m$$

- 'Stiffness-related' and 'Force-related' joint stiffness

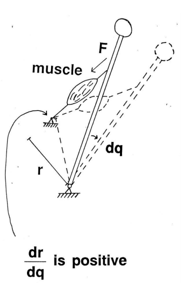
Change of muscle length



Change of moment arm

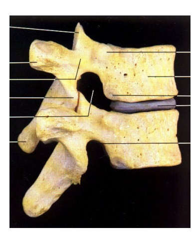


Change of moment arm

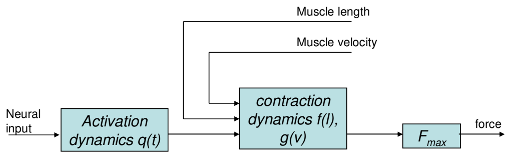


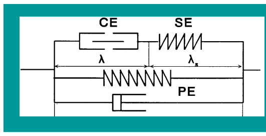
Apparent joint stiffness

- Most often change of moment arm is destabilizing!
- Sometimes change of moment arm is stabilizing: Spinal column!



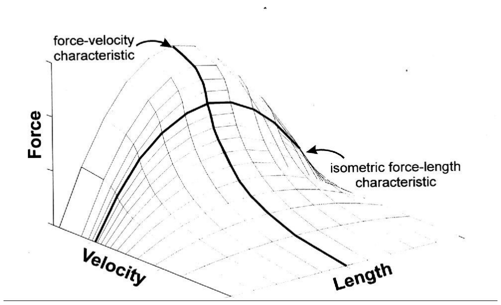
Muscle models



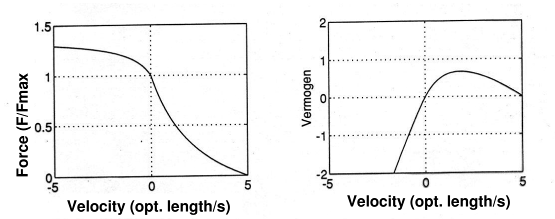


$$F_{mus} = \frac{F_{SE}}{\cos\alpha} + F_{PE} + F_{PV}$$
$$F_{SE} = F_{CE}$$
$$F_{CE} = F_{\max} \cdot q(t) \cdot f(l) \cdot g(v)$$

Muscle force-length-velocity relation



Power vs. velocity

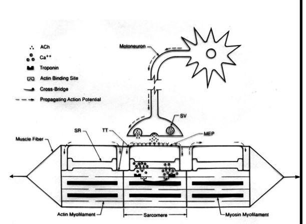


Efficiency

- Muscles are most efficient around 30% V_{max}
- Maximal single muscle efficiency:
  Work output/ metabolic energy input ~36%
- Efficiency of gross motor tasks:
  - Walking: ±20%
  - Cycling: ± 25%
  - Skating: ± 15%
  - Wheelchair: ±8%
- During motion striving for optimal muscle velocity

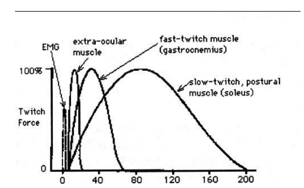
Calcium in- & outflow

- Calcium 'pump' cost about 30% of energy consumption of muscle!
- Energy is spend for the ability of very fast initiation of motion.
- Survival of the Fittest !?

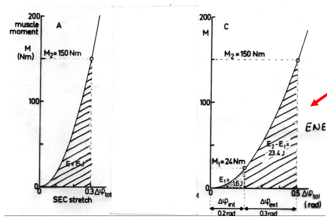


Fast & slow twitch muscles

- Most muscles are mix of slow & fast twitch fiber
- Fast twitch fibers ('white fibers'):
  - High and rapid force generation
  - Fast metabolism, rapid depletion of stored energy
  - Not much blood supply
  - Fatigueing!
- Slow twitch fibers ('red fibers'):
  - Postural muscles, slow force generation
  - Much blood supply
  - Not easily fatigued



Energy storage in series-elastic element



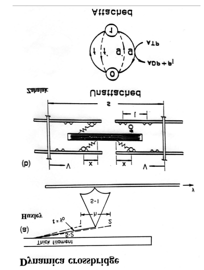
Energy stored:

$$E_{stored} = \int F.dx = \int K.x dx = 0.5 K x^2$$

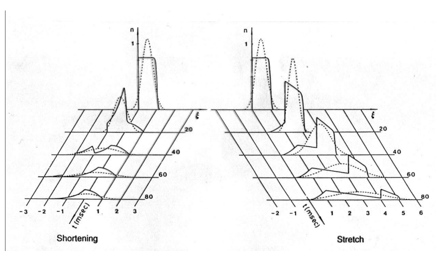
Compliant tendons can store more energy for the same force !

Cross-bridge dynamics

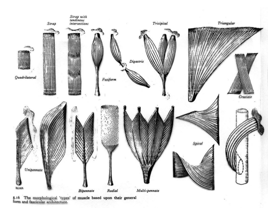
- •Account for rapid dynamic effects
- •Determines the force-velocity relation:
- •Higher muscle stiffness than expected from force-length curve
- •Determines energy consumption due to contraction dynamics



Cross-bridge dynamics: Amount of coupled cross-bridges



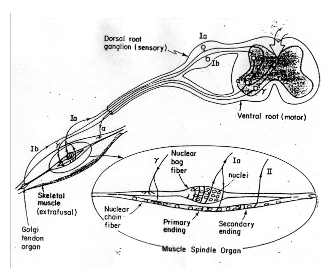
Muscle shape



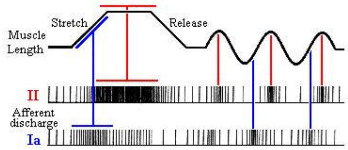
Pennation angle

- Change of force-length curve of muscle
  - High pennation angle results in small length range and high maximal force
- Change of force-velocity curve of muscle
  - High pennation angle results in higher contraction velocity: change of pennation angle during shortening
- Change of force:
  - Smaller force due to angle between muscle fiber and muscle line-of-action

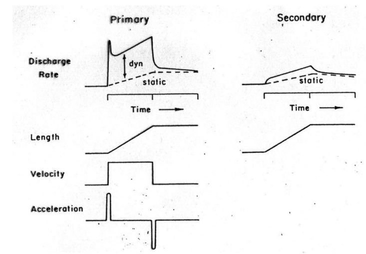
Muscle spindle



Muscle spindle response

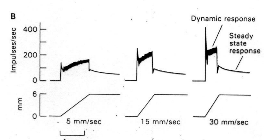


Muscle spindle transient responses



Muscle spindle transient responses

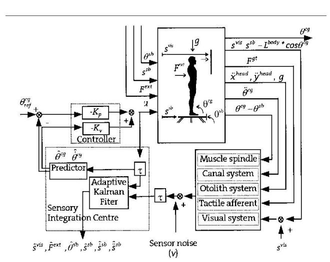
- Stiction effect, not acceleration
- For small length changes higher afferent output
- Higher efferent output, higher forces
- Muscle seems stiffer for small length changes!



Competitive summation Ia afferent nerve fibers

- Connection of nerve from nuclear chain and nuclear bag, without synaps
- Spike trains do not merge
- ‘Winner takes all’:
  - Nerve ending with highest frequency extincts competitors by ‘anti-drome inhibition’
  - Max-operation
- During posture: Length information
- During motion: Velocity information

Sensory Integration Center



Sensory Integration Center

- Multiple sensors and sensor types provide ‘redundant’ information
- State variables are ‘reconstructed’: Sensory Information Center (SIC)
- Sensor input is weighed with expected information and sensor noise
- In case of sensor malfunction, other sensors take over ⇒ Adaptation of SIC

Effect of non-linearities distributed system

- Non-linearities set bounds to the motion dynamics and range
- Intrinsic and geometric muscle properties help the CNS for easier control
- For non-linear controller like the CNS, non-linearities in the mechanical linkage system or environment only play a minor role