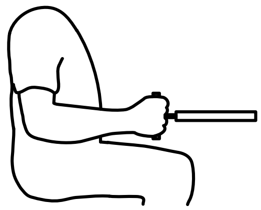
Human motion control

Intrinsic and reflexive feedback:



WB2407 2008-2009 / Lecture 7

June 23, 2009

Faculty of Mechanical Engineering
Department of Biomechanical Engineering
Laboratory for Neuromuscular Control

Contents

What is afferent feedback?

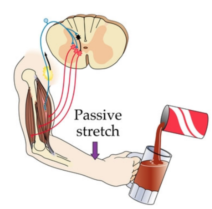
- Many different terms:
  Afferent feedback, proprioceptive feedback, reflexive feedback, stretch reflex, (spinal) reflexes, etc, etc

Definition used in this course:

- Functional contribution of proprioceptors to joint dynamics (primarily feedback from muscle spindles and Golgi tendon organs).

What is afferent feedback

- Joint dynamics comprise:
  - muscle visco-elasticity (co-contraction)
  - Afferent feedback from muscle spindles and Golgi tendon organs



Goal of this lecture

- Develop and analyze a (linear) neuromusculoskeletal model to get insight into how the different mechanisms (muscle/reflexes) contribute to the performance and interact with each other

=> Interaction exist between different structures and individual contribution is hard to recognize

Goal 1:

- Quantify/parameterize the intrinsic and reflexive contributions to human motor control from experiment (see also Lecture 8)

Goal 2:

- Analyze the theoretical contribution of reflexes to human motor control

Stability and admittance

- **Stability**: the system (joint, limb) will return to its position (trajectory) after a force perturbation.

- **Admittance** = position deviation / force deviation

- Or, the actual dynamic behavior of the system
- after a force perturbation, depending on:
  - stiffness
  - viscosity
  - inertia
  - other dynamic properties, e.g. feedback

Admittance of mass-spring-damper system

- Most simple model of a single joint is a mass-spring damper system

$$f(t) = M\frac{d^2x(t)}{dtdt} + B\frac{dx(t)}{dt} + K\left(x(t) - x_0\right)$$

- Laplace transform: d../dt => s (s=jω)

$$H_{adm}(s) = \frac{X(s)}{F(s)} = \frac{1}{Ms^2 + Bs + K}$$

Advantages of frequency domain

- Bode diagrams!
- Stability analysis
- Matlab demo

What is a linear system?

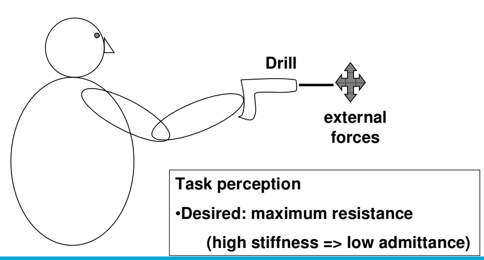
- Output is function of input:
  y(t) = f(u(t))
- Principle of *proportionality*, or *scaling property*
  c·y(t) = f(c·u(t))
- *Superposition* property
  $y_1(t) = f(u_1(t))$ & $y_2(t) = f(u_2(t))$
  $y_1(t) + y_2(t) = f(u_1(t) + u_2(t))$
- **Systems that obey both superposition and scaling property are said to be linear!**
- **=> Everything else is nonlinear**

Linearity vs. nonlinear

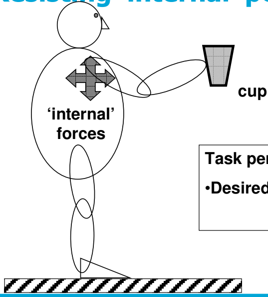
- Almost every course assumes linear systems (control theory, system identification, modeling)
- Almost every system on earth is nonlinear
- Why use linear techniques in a nonlinear world?
  Because you can use 'simple' mathematics (differential equations, Fourier transform, Bode, Nyquist, etc, etc)
- When is the use of linear techniques justified?

Contents

Postural control: Resisting external perturbations

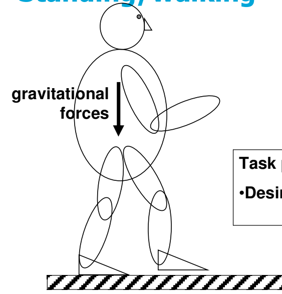


Postural control: Resisting ‘internal’ perturbations



Task perception
•Desired: minimum jerk (smooth) & oppose gravity

Postural control: Standing/walking



Task perception
•Desired: Do not fall
(Stabilize & ‘Minimum’ energy)

Postural strategies

- Position task (‘minimize displacements’)
  small displacements desired
  => high stiffness => low admittance

- Force task (‘keep force constant’)
  small force variations desired
  => low stiffness => high admittance

Strategies to decrease admittance

- Co-activation of muscles
  - Increased muscle stiffness & viscosity
  - Effective for large range of frequencies
  - Costs much metabolic energy

- Proprioceptive feedback
  - Length, velocity and force feedback
  - Energy efficient
  - Only effective for low frequent perturbations due to neural time delays and muscle activation dynamics
  - in nervous system

Task perception

Task perception depends on
- Goal
  - Minimum deviations
  - Don’t spoil coffee
  - Do not fall
- Disturbance
  - External/Internal
  - Gravity
  - slow/fast disturbances

Tasks and disturbances

Possible tasks
- maximum performance
- stabilize posture (stability with minimum energy)

General task descriptions
- Performance
- Stability
- Energy

Summary task perception

Performance
- analyzed with the admittance (closed-loop transfer function)
- Possible measure for performance: variance of the endpoint

$$E\{x^2\} = \sigma_x^2$$

Stability
- Property of the closed-loop
- Analyzed with open-loop(!) transfer function (Bode or Nyquist diagrams, phase/gain margin)

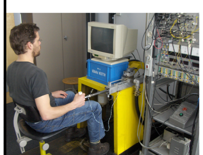
Energy
- is related with the muscle activation
- will not be analyzed in this lecture

Contents

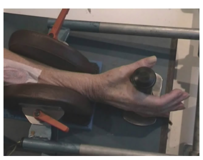
- Introduction
- Task perception
- Experimental setup
  - Manipulators
  - Perturbation type
  - Task instruction
- Linear model for human joint dynamics
- Summary & Conclusions
- Introduce assignment 3

Manipulators

- For system identification a perturbation is required
- In human joints: a manipulator is used to apply perturbations.
- Examples of manipulators:



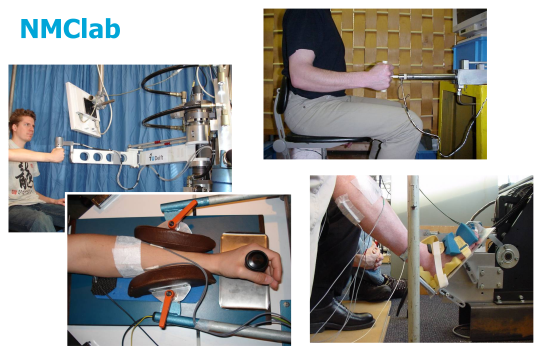
Proprio



PoPe

Armanda

NMClab

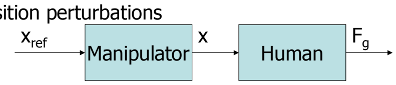


Perturbation type

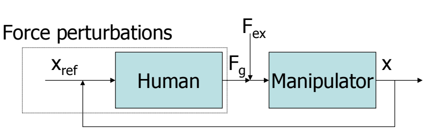
- How to control the manipulator:
  force-controlled vs. position-controlled manipulators
- Position-controlled manipulator acts as a position servo and dictates the position and the reaction force of the human is measured with a force sensor.
- With force controlled manipulator the human reaction force is measured and used to control the manipulator => interaction exist between human and manipulator

Block schemes

- Position perturbations



- Force perturbations



- Interaction => closed-loop system !

Force vs. position perturbations

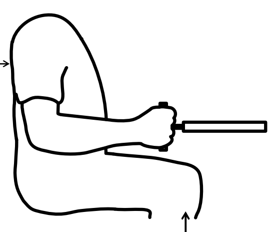
- Dictates manipulator design;
  position servo vs. force-controlled (=haptic) device
- Dictates identification scheme
  force perturbations require closed-loop algorithms
- Perturbation type directly influences the task instruction.
  - Position perturbation => force/emg task
  - Force perturbation => position task

Summary experimental setup

- Manipulator required to apply perturbations
- Perturbation type ⇔ Task instruction
- With force perturbations interaction exist between human and manipulator: => closed-loop identification
- Humans are adaptive: position perturbation results in unambiguous and natural task

Example: ident. of human arm dynamics

'Minimize Position'



Position (X)
Handforce (F_g)
EMG (A)

Disturbance (F_{ex})
30 sec multisine (1 - 20 Hz)

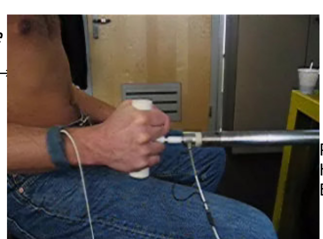
How to stiffen a joint

- Increase muscle co-contraction
- Increase muscle spindle feedback gain (proprioceptive reflexes / spinal reflexes)

=> Trade-off between muscle co-contraction and reflexive feedback

Example: ident. of human arm dynamics

'Minimize Position'



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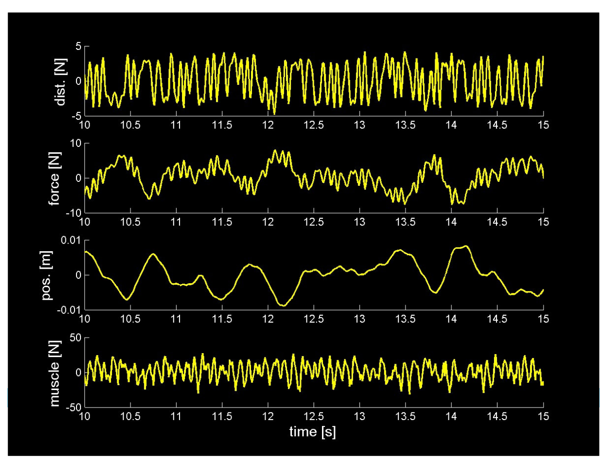
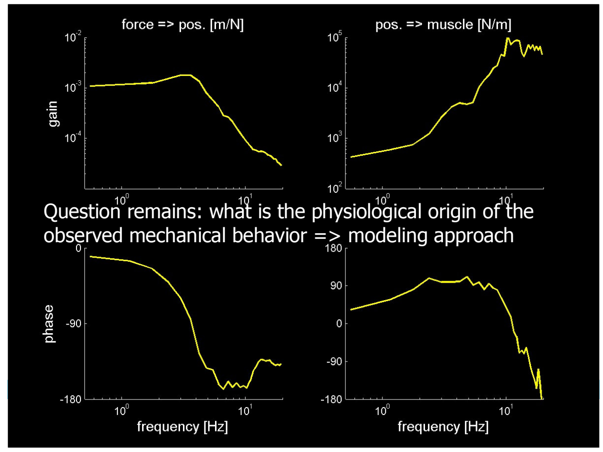


Frequency response functions

What can be measured form experiments

- Mechanical admittance
  - Joint translation/rotation as a result from external force/torque (as function of frequency)
- Reflexive impedance
  - Muscle activation (scaled in force/torque) as a result from joint translation/rotation

- 'minimize deviations' => decrease mechanical admittance



From behavior to parameters

Mechanical admittance gives limited information about the underlying structures.

Goal 1:

- Quantify/parameterize the intrinsic and reflexive contributions to human motor control from experiment

The 'why' question!

- Why do you want to know what the physiological origin of human movement?

- Curiosity: human motor control
  - functional contribution afferent feedback
  - adaptation of reflexive feedback
- Medical science
  - pathophysiology of movement disorders
  - effect drug treatment
  - disease progress
  - etcetera

Contents

- Introduction
- Task perception
- Experimental setup
- Linear model for human joint dynamics
  - Admittance
  - Neuromusculoskeletal (NMS) model
  - Analyzing the NMS model: NMClab
  - Performance of NMS
  - Stability of NMS
- Summary & Conclusions
- Introduce assignment 3

Admittance

Admittance = position deviation / force deviation

Or, the dynamic response after a (force) perturbation

Admittance depends on:

- Inertia of the limb
- Muscle properties (elasticity & viscosity)
- Proprioceptive feedback (muscle spindles, Golgi tendon organs)

Admittance of NMS model

Admittance:

With $H(\omega) = \dfrac{\theta(\omega)}{M_{EXT}(\omega)}$

$H(\omega)$	admittance
$M_{ext}(\omega)$	disturbance torque
$\theta(\omega)$	angle of the limb

All as a function of frequency ω [rad/s]

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Notes

- Model describes the human arm experiment, everything is expressed in 1 DoF (one lumped muscle) at grip/hand level (muscle length, muscle force, etc)
- Model structure is universal:
  different joint => different parameter values
  translations/rotations => different parameter units

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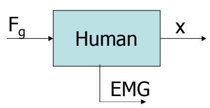
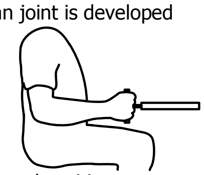
Basic model

- First the model for the human joint is developed





- Causal model: force as input and position as output

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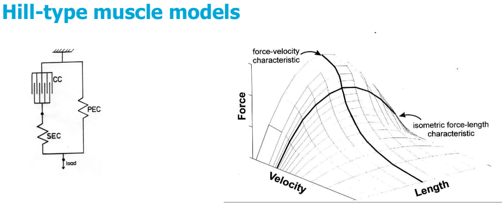
Hill-type muscle models



CC: Contractile component
(force-length-velocity characteristic of muscle fiber)
SEC: Series-Elastic component
(force-length characteristic of tendon & cross-bridges)
PEC: Parallel-Elastic component
(passive force-length characteristics of muscle)

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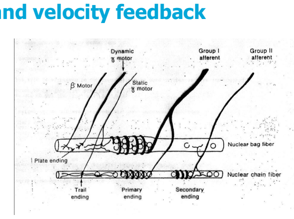
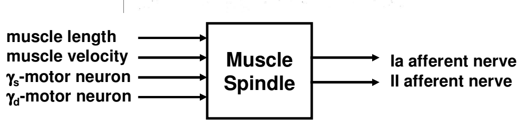
Muscle spindle:
Length and velocity feedback





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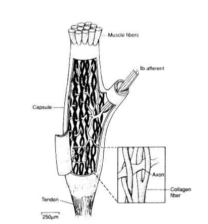
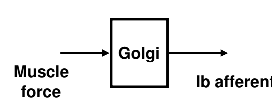
Muscle force feedback:
Golgi Tendon Organ





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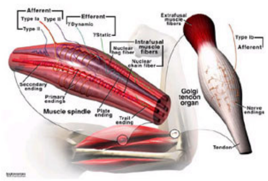
Proprioceptors

Muscle spindles (MS):
- Stretch (k_p)
- Stretch velocity (k_v)

Golgi Tendon Organ (GTO):
- Muscle force (k_f)

MS GTO



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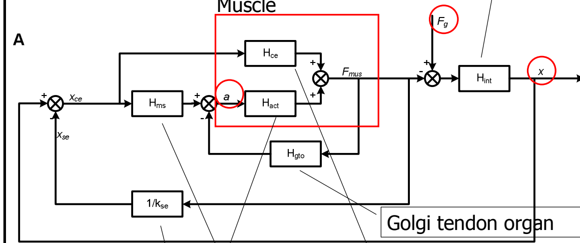

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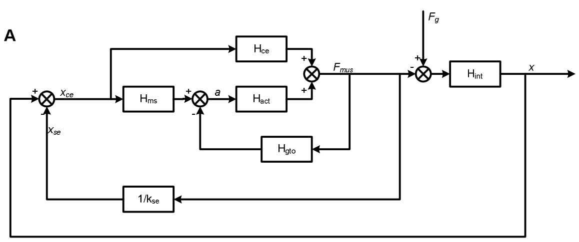

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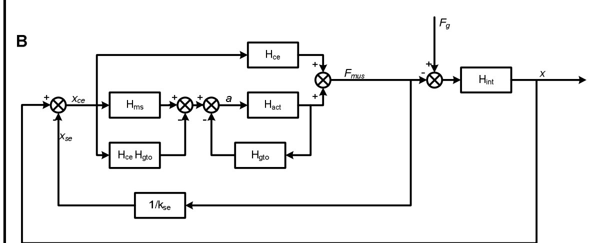

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Filtering effect of GTO feedback loop

- Golgi tendon organ senses the muscle force
- And acts as a feedback loop around the muscle activation dynamics
- As such GTO feedback increases the bandwidth of the muscle activation dynamics

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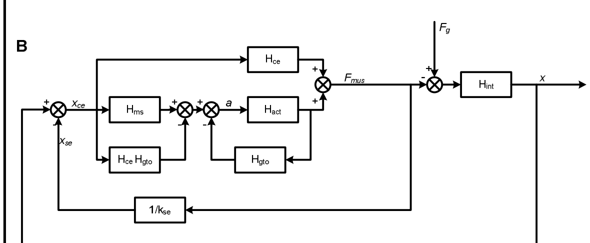

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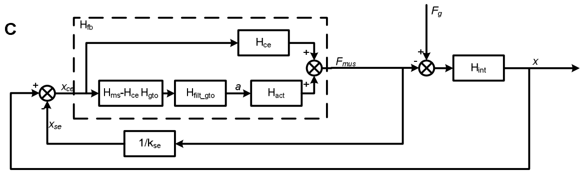
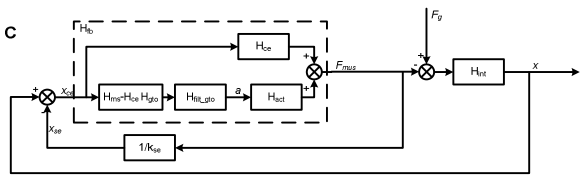


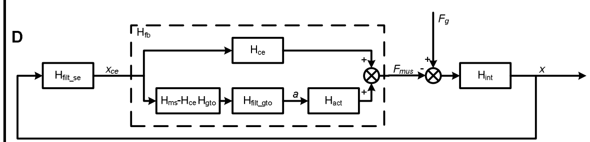
$$H_{filtgto} = \frac{1}{1 + H_{act} H_{gto}}$$

H_{fb} comprises intrinsic feedback (muscle properties) and reflexive feedback (muscle spindle and GTO)

Filtering effect of tendon elasticity

- As a result of tendon elasticity the muscle length is not proportional to the joint angle!
- $x = x_{ce} + x_{se}$
- This implicates the both the muscle visco-elasticity and muscle spindle feedback are affected!





$$H_{filtse} = \frac{1}{1 + \frac{H_{fb}}{k_{se}}} \quad ; if\ k_{se} = \infty \quad H_{filtse} = 1$$

Matlab: NMClab.m

General parameters from the arm:
(moment arms are omitted, i.e. r = 1)

Limb mass: M = 2 kg
Muscle viscosity: B_m = 30 Ns/m
Muscle stiffness: K_m = 600 N/m
H_{act}, critically second-order system:
2.2 Hz (β=0.7)
Neural delay: τ = 25 ms

Effect intrinsic parameters

- Admittance decreases with muscle stiffness & viscosity (K_m, B_m)

Notes

- energy demanding, as muscle are continuously activated!
- in normal muscle K_m and B_m are related and increase with activation level (u_0)

Effect muscle spindle feedback

- Admittance decreases with muscle spindle feedback

Notes:
- energy efficient as muscle are only (de-)activated in response to actual disturbances
- effectiveness is limited as instabilities can occur
- filtered by muscle activation dynamics

Effect Golgi tendon organ (GTO) feedback

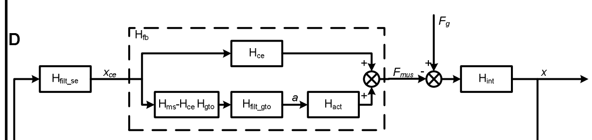
- Admittance increases with GTO feedback

Notes:
- GTO feedback increases admittance
- Muscle spindle feedback decreases admittance

Effect neural time-delay

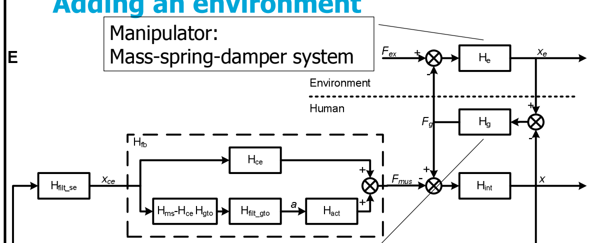
Notes
- neural-delay of monosynaptic (i.e. short latency) reflexes depends length of the pathways and conduction velocity
- Proximal joint have shorter time-delay than distal joints!

Adding an environment



Adding an environment

Manipulator:
Mass-spring-damper system



Grip dynamics:
Interface between the two mass-spring-damper systems

Effect Environment

- Behavior/performance now depends on the interaction between Human and Environment

Notes:
- Discussed in other Lecture

Good admittance?!

Desired: minimize deviations (low admittance)
(See Matlab Figure)

Which admittance is better?

Or,

How do judge the performance!

Performance

How do you judge the admittance

- Minimum deviations: minimum endpoint variance

$$E\{x^2\} = \sigma_x^{\,2} = \int_{-\infty}^{\infty} S_{xx}(f)\mathrm{d}f = \int_{-\infty}^{\infty} |H_{dx}(f)|^2 S_{dd}(f)\mathrm{d}f$$

Note: endpoint variance depends on:

- Force disturbance (S_{dd})
- Admittance (H_{dx})

=> Interplay between disturbance and admittance!

Performance

Properties of force disturbance are known:
Flat spectrum between lower and higher frequency

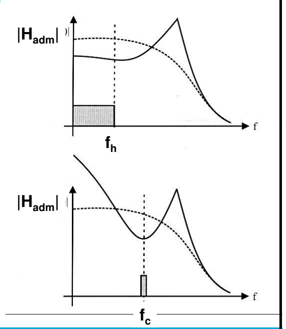
$$\text{if } S_{dd}(f) = C_1 \text{ between} f_l \text{ and } f_h :$$

$$E\{x^2\} = \sigma_x^{\,2} = \int_{-\infty}^{\infty} S_{xx}\mathrm{d}f = \int_{-\infty}^{\infty} |H_{dx}|^2 S_{dd}\mathrm{d}f = C_2 \int_{f_l}^{f_h} |H_{dx}|^2 \mathrm{d}f$$

Note: approximates the sum of the responses of all sine's within the bandwidth

Optimal admittance

$$\begin{aligned} J_x &= E\{x_e^T(t).x_e(t)\} \\ &= C_{xx}(0) \\ &= \int_{-\infty}^{\infty} S_{xx}(f).\mathrm{d}f \\ &= \int_{-\infty}^{\infty} H_{adm}(f).S_{dd}(f).H_{adm}(-f).\mathrm{d}f \\ &= \int_{-\infty}^{\infty} H_{adm}(f).S_{dd}(f).H_{adm}(-f).\mathrm{d}f \end{aligned}$$



- S_{dd}: Power spectrum disturbance signal
- H_{adm}: Admittance

Example performance

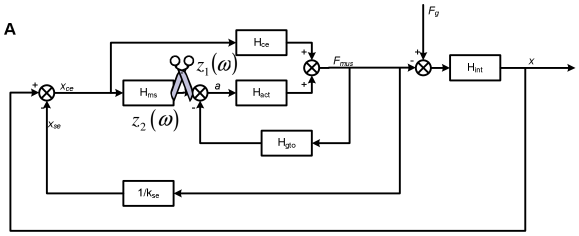
(See Matlab Figure)

How to analyze stability

Analyze open-loop transfer function

$$H_{CL} = \frac{Something}{1 + H_{OL}}$$

Unstable if H_{ol}=-1, i.e. amplitude = 1; angle = -180 degrees



$$H_{OL}(\omega) = \frac{z_2(\omega)}{z_1(\omega)}$$

Stability: Nyquist / Bode-diagram

Stable
- if gain is smaller than 1, where phase is -180 degrees

Or,
- If phase is less then -180 degrees, where gain is 1

Gain margin: inverse of the gain at -180 degrees
Phase margin: phase advance (cp. -180) at unity gain

Nyquist: not encircle (-1,0)

Strategies to decrease admittance

Goal 2:
- Analyze the theoretical contribution of reflexes to human motor control (complex interaction between physical structures)

- Co-activation of muscles
  - Increased muscle stiffness & viscosity
  - Effective for large range of frequencies
  - Costs much energy

- Proprioceptive feedback
  - Length, velocity and force feedback
  - Energy efficient
  - Only effective for low frequent perturbations due to time-delays in nervous system

Contents

Summary & Conclusion I

1. Mechanical admittance is a functional description of NMS system during posture control

2. The role of different feedback mechanisms (intrinsic, reflexive) can be assessed by displaying the admittance in Bode diagrams

3. The role of all control mechanisms is expressed in terms of performance (overall admittance => closed loop) and stability (open loop)

Summary & Conclusion II

Intrinsic and reflexive feedback:

- Co-contraction provides <u>instantaneous visco-elasticity</u> at the cost of <u>metabolic energy</u>

- Afferent feedback is <u>less energy</u> consuming, but <u>limited effective</u> due to the neural time-delay and muscle contraction dynamics

Summary & Conclusion III

Performance

- Admittance decreases with muscle activation
- Admittance decreases with muscle spindle feedback
- Admittance increases with GTO feedback

Stability

- Muscle co-activation is always stable
- Muscle spindle & GTO, too high gains => unstable (results from time-delay in feedback loop)

Energy

- Muscle activation is energy demanding

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Contents

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Assignment 3

- Goal: 'Play and feel ' with a NMS model and get insight into the functionalities of the relevant spinal cord physiology of human motor control
- Matlab and Simulink: NMClab.m & ArmSimulink.m

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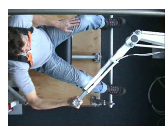
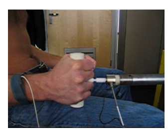
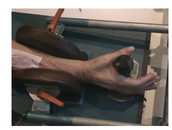
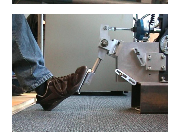
Different type of manipulators

- **Natural tasks**
- **Perturbations**
- **Closed-loop**
- **Interpretable parameters**

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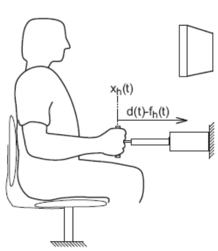
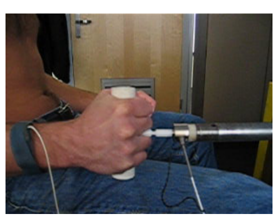
Hydraulic manipulator





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Experimental approach

- Open-loop system?
  - EMG ⇒ muscle force ⇒ motion ?
  - Motion ⇒ muscle spindles ⇒ CNS ⇒ EMG ?
  - No open-loop system identification methods !!
    - No cross-correlation methods !!
    - No linear regression methods !!
- Closed-loop system identification
  - Generate (known!) external perturbation signal of closed-loop feedback system
    - Perturbation forces
  - Estimate dynamic relation between external perturbation and internal signals
    - Hand position
    - Hand force
    - EMG
  - Estimate model parameters

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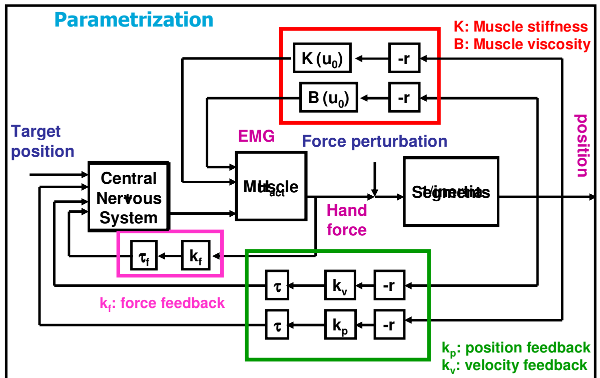
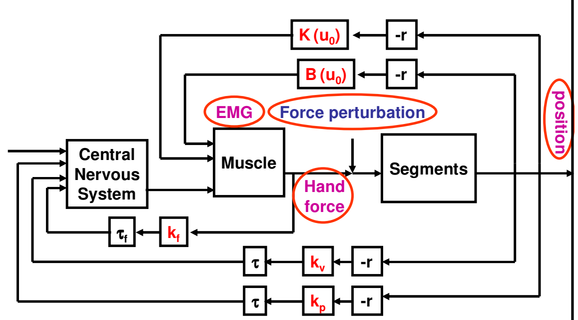
Robot manipulators

- Force-controlled manipulators
  - Admittance can be adjusted: Mass, viscosity, stiffness
  - Hydraulic and electrical manipulators
- Capable of high-frequency force perturbations
  - Necessary for system identification
  - Bandwidth
    - Shoulder: 33 Hz
    - Wrist: >50 Hz
    - Ankle: >50 Hz
    - 2 DOF (wrist, elbow, shoulder): 30 Hz

Parametrization



Signals measured



Data processing

- Dynamic transfer functions (ARMAX models):
  - Force perturbation ⇒ hand position
  - Force perturbation ⇒ hand force
  - Force perturbation ⇒ EMG
- Parameters fitted to the transfer functions:
  - Position feedback: k_p
  - Velocity feedback: k_v
  - Force feedback: k_f
  - Time-delay: τ
  - Intrinsic muscle stiffness: k_a
  - Intrinsic muscle viscosity: b_a

Estimation of transfer functions for closed-loop systems

•Using cross-spectral densities from force perturbation w(f), hand force f(f), hand position x(f) and EMG(f)

$$\hat{H}_{handforce2position}(f) = \frac{\hat{H}_{perturbation2position}(f)}{\hat{H}_{perturbation2force}(f)} = \frac{\hat{S}_{wx}(f)}{\hat{S}_{wf}(f)}$$

•Using time-domain estimates (ARMAX models)

$$\hat{H}_{handforce2position}(t) = \frac{\hat{H}_{perturbation2position}(t)}{\hat{H}_{perturbation2force}(t)} = \frac{\dfrac{B_{wx}(q^{-1})}{A_{wx}(q^{-1})}}{\dfrac{B_{wf}(q^{-1})}{A_{wf}(q^{-1})}}$$

Coherence of transfer functions

•Using cross-spectral densities from force perturbation w(f), hand force f(f), hand position x(f) and EMG(f)

$$\gamma^2_{handforce2position}(f) = \frac{\left|\hat{S}_{wx}(f)\right|^2}{\hat{S}_{ww}(f)\hat{S}_{xx}(f)}$$

$$\gamma^2_{perturbation2EMG}(f) = \frac{\left|\hat{S}_{wEMG}(f)\right|^2}{\hat{S}_{ww}(f)\hat{S}_{EMGEMG}(f)}$$

Estimation of physical model parameters

•Model fit in the frequency domain

$$L(p)=\sum_k \frac{1}{1+f_k}\left|\ln\left(\hat{H}_{handforce2position}(f_k)\right)-\ln\left(H_{\text{model\_f2p}}(f_k,p)\right)\right|^2 +$$

$$q.\sum_k \frac{1}{1+f_k}\left|\ln\left(\hat{H}_{position2EMG}(f_k)\right)-\ln\left(H_{\text{model\_p2EMG}}(f_k,p)\right)\right|^2$$

•Minimize L(p) with p = {K, B, k_p, k_v, k_f}

Experimental set-up

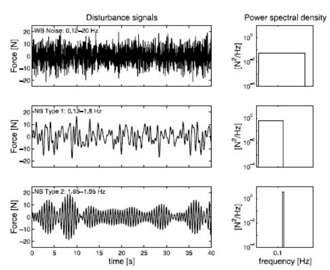
- Outcome measures:
  - Transfer functions
    - Human admittance $H_{admittance}(f)=\frac{X(f)}{F(f)}$
    - Reflexive impedance $H_{spindle}(f)=\frac{EMG(f)}{X(f)}$
  - Parameterized models
    - position, velocity and force feedback gains
    - time-delays reflex loop
    - Intrinsic muscle stiffness and viscosity
    - Muscle dynamics

External force perturbations with varying frequency content

White noise

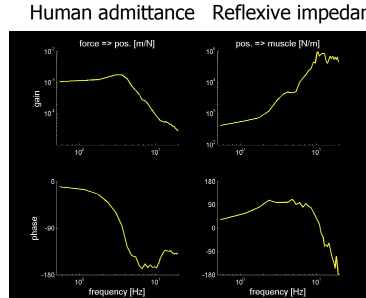
Narrow band noise I
0 – highest freq. f_h

Narrow band noise II
Center freq. $f_c \pm 0.15$ Hz



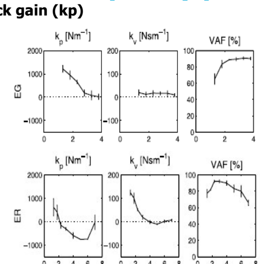
Transfer functions

Human admittance Reflexive impedance



Narrow-band frequency perturbations:

Position feedback gain (kp)
Velocity feedbac
(mean and stan

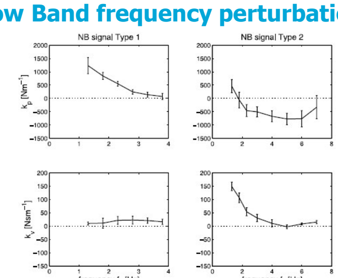


NB I:
0 – f_h Hz

NB II:
F_c ±0.15 Hz

Van der Helm et al., 2002

Narrow Band frequency perturbations



Mean 5 subjects

Conclusions
Reflexive control

- Reflex gains are task-dependent and rapidly modulated
- Neural control is more important for actuator properties than muscle properties!
- Is reflexive feedback optimal for disturbance rejection?

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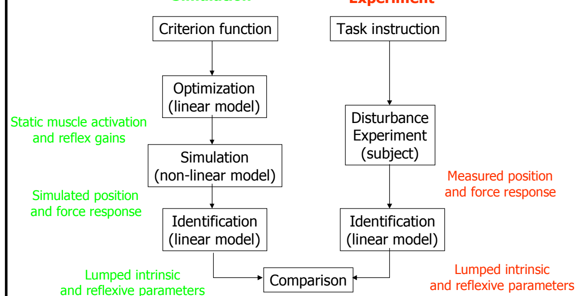
Optimal feedback gains
(Schouten et al., 2001)



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Criterion function

- $J = J_x + p.J_a$
  - J_x: minimize position deviations
  - J_a: minimize control effort (≈ muscle activation)
  - p: weighing factor
- Linear model
  - J_x and J_a formulated in the frequency domain
  - Stability constraints added
- Two-stage optimization
  - Constant muscle activation
  - Feedback gains

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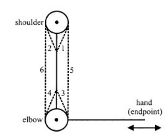
Musculoskeletal model



- 2 joints, 1 DOF
- 6 muscles, Hill-type
  - activation dynamics
  - force-length
  - force-velocity

- Linear feedback parameters
  - CE positive stretch
  - CE positive stretch velocity
- Settings derived from optimization
  - Muscle activation u_0
  - Feedback gains k_p and k_v

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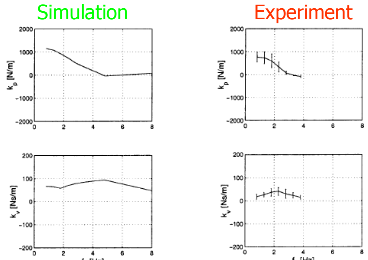
Results optimization
NB 1: Change of highest frequency (f_h)

Simulation | Experiment



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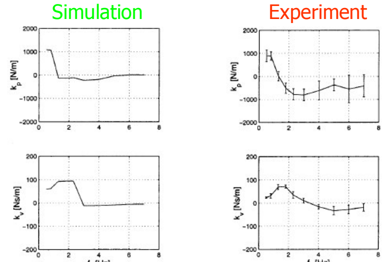
Results optimization
NB 1: Change of center frequency (f_c)

Simulation | Experiment



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Conclusions
Optimization of reflexive feedback

- Reflexive feedback seems to be (near) optimal for disturbance rejection
- Due to modulation of reflex gains

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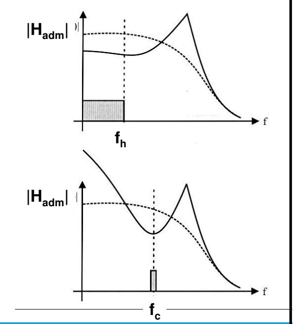
Optimal admittance

$$J_x = E\{x_e^T(t).x_e(t)\}$$
$$= C_{xx}(0)$$
$$= \int_{-\infty}^{\infty} S_{xx}(f).df$$
$$= \int_{-\infty}^{\infty} H_{adm}(f).S_{dd}(f).H_{adm}(-f).df$$
$$= \int_{-\infty}^{\infty} H_{adm}(f).S_{dd}(f).H_{adm}(-f).df$$

- S_{dd}: Power spectrum disturbance signal
- H_{adm}: Admittance



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Graphical User Interface
Neuromuscular model

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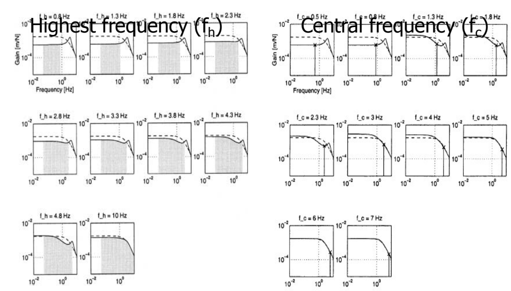
Frequency of disturbance signal



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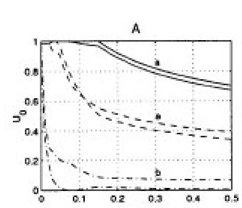
Effect of weighing effort vs. performance

- Increase of ρ:
  - effort is weighed more
  - less co-activation of bi-articular muscles, and also of elbow muscles



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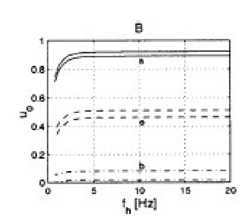
Effect of highest frequency on constant muscle activation

- No effect of frequencies in the perturbation signal on the constant muscle activation.



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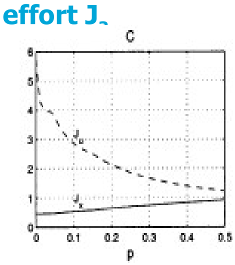
Effect of weight factor p on performance J_x and effort J_u

- Effort decreases dramatically with increased p, while performance (variance of position deviations) hardly detoriates.



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Conclusions
Optimization of reflexive control

- Reflexive feedback seems to be (near) optimal for disturbance rejection
  - Linear fit provides good estimates compared to experimental results
  - Effect of bandwidth perturbation signal is demonstrated
  - Energy weighing limits co-activation
- Hill-type muscle model results in poor estimates of intrinsic muscle properties
  - Muscle stiffness is underestimated (about 60%)
  - Muscle viscosity is overestimated (about 150%)

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Research goals

- Find objective measures which can quantify proprioceptive reflexes
  - Understand reflexive mechanisms, and the role of the Central Nervous System
    - **Negative and positive stiffness and damping**
    - **Force tasks vs. position tasks**

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Research goals

- Find objective measures which can quantify proprioceptive reflexes
  - Understand reflexive mechanisms, and the role of the Central Nervous System
    - **Force tasks vs. position tasks**

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Adaptation of reflex gains:

Positive and negative stiffness and damping in environment

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Methods

Five subjects (age: 20-24)

9 different condition applied 4 times for 30 seconds each
- External damping: -30, -15, 0, 15, 30 Ns/m
- External stiffness: -600, -300, 0, 300, 600 N/m

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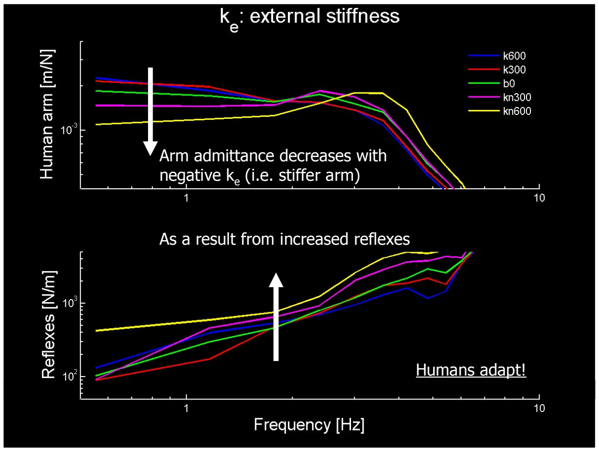

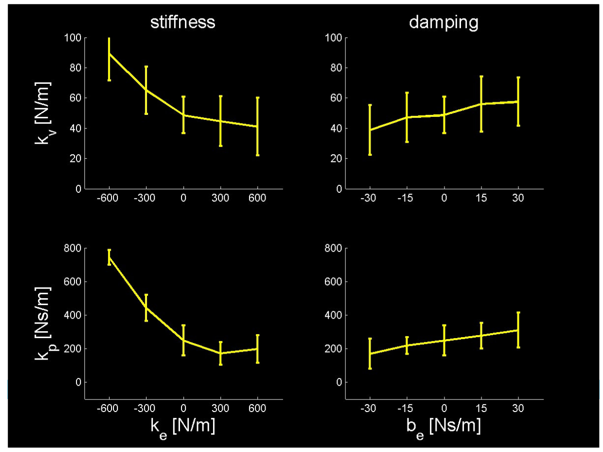

Adaptation of reflex gains:

Force and position task

Poster presentation Winfred Mugge

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Experimental set-up

10 subjects
- 20 – 28 years of age
- 5 male, 5 female

3 task instructions
- Force task
- Relax task
- Position task

3 disturbance bandwidths
- 0.01-0.7 Hz
- 0.01-1.2 Hz
- 0.01-2.0 Hz

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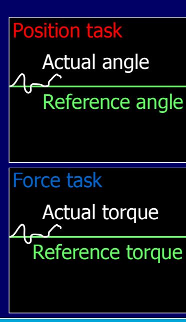
2. Experimental setup

- Actively force controlled gas pedal
- Monitor provides task related information



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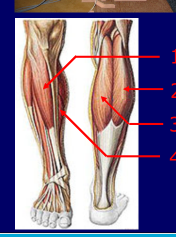
Experimental setup

Measured signals
- Gas pedal angular displacement
- Torque on the pedal

- EMG (Electric muscle activity)
  1. Tibialis Anterior
  2. Gastrocnemius Lateralis
  3. Gastrocnemius Medialis
  4. Soleus



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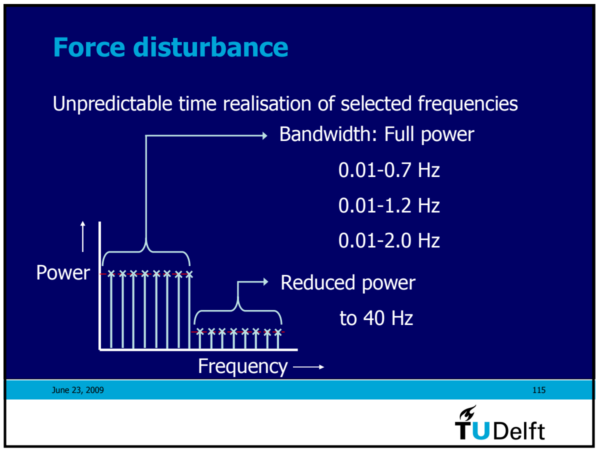
Force disturbance
Unpredictable time realisation of selected frequencies
Bandwidth: Full power
0.01-0.7 Hz
0.01-1.2 Hz
0.01-2.0 Hz
Power
Reduced power
to 40 Hz
Frequency
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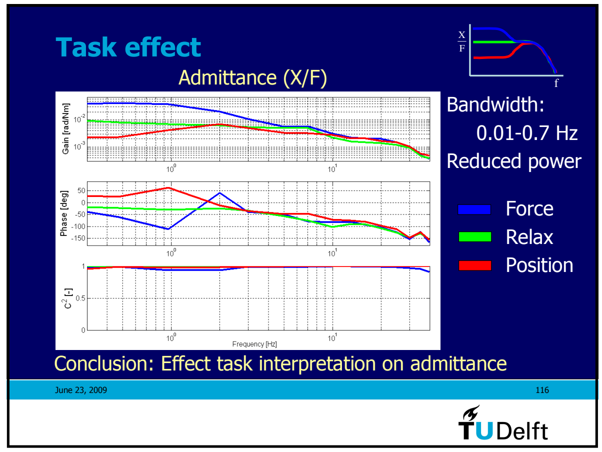
Task effect
Admittance (X/F)
Bandwidth:
0.01-0.7 Hz
Reduced power
Force
Relax
Position
Conclusion: Effect task interpretation on admittance
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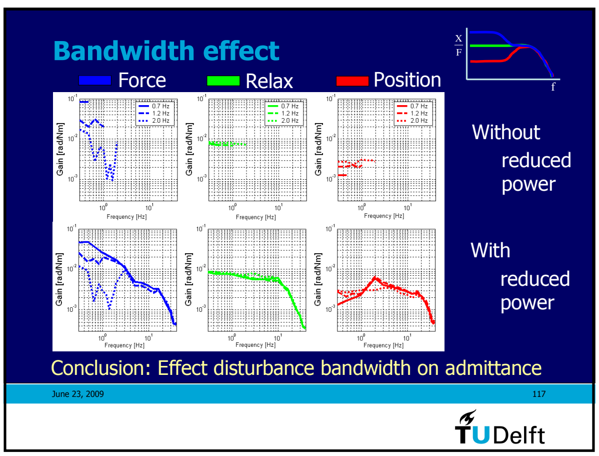
Bandwidth effect
Force
Relax
Position
Without
reduced
power
With
reduced
power
Conclusion: Effect disturbance bandwidth on admittance
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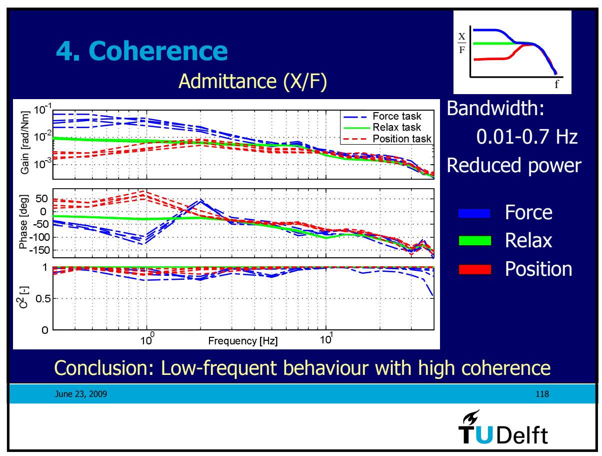
4. Coherence
Admittance (X/F)
Force task
Relax task
Position task
Frequency [Hz]
Bandwidth:
0.01-0.7 Hz
Reduced power
Force
Relax
Position
Conclusion: Low-frequent behaviour with high coherence
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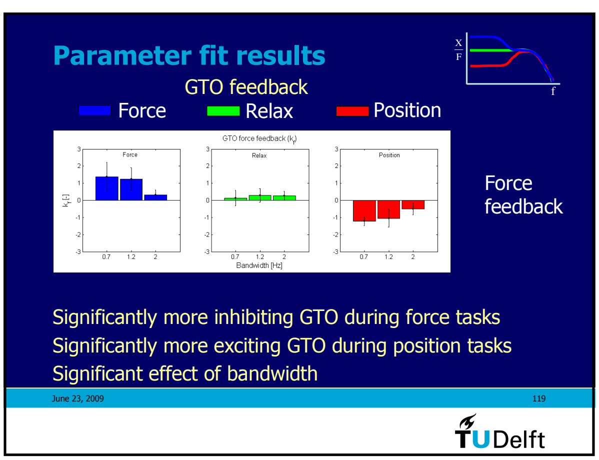
Parameter fit results
GTO feedback
Force
Relax
Position
Force
feedback
Significantly more inhibiting GTO during force tasks
Significantly more exciting GTO during position tasks
Significant effect of bandwidth
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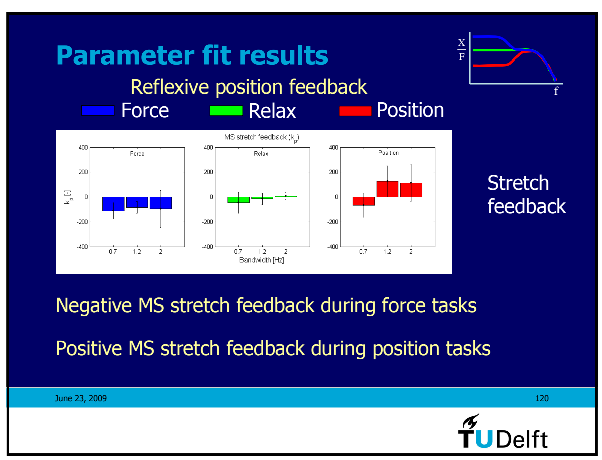
Parameter fit results
Reflexive position feedback
Force
Relax
Position
Stretch
feedback
Negative MS stretch feedback during force tasks
Positive MS stretch feedback during position tasks
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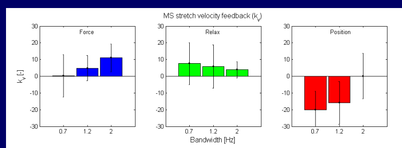
Parameter fit results

Reflexive velocity feedback

Force Relax Position



Stretch velocity feedback

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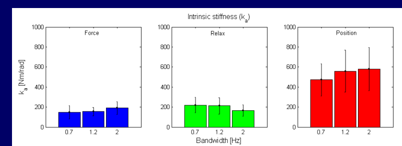
Parameter fit results

Intrinsic stiffness

Force Relax Position



Intrinsic feedback

Significantly higher intrinsic stiffness during postion tasks

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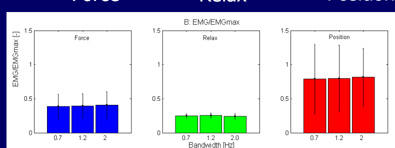
EMG results

Muscle activity

Force Relax Position



Muscle activity

Significantly more EMG during position tasks
Slightly, but significantly more EMG during force tasks

Corresponds to intrinsic stiffness results parameter fit

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Conclusions
force task vs. position taks

- Reflexive behaviour is task dependent
- During force task human admittance is higher than in relax task
  - Using reflexive system to 'give way'.
- Force feedback gains are modulated
  - from negative (position task) to positive (force task) values
- Position feedback gains are modulated
  - from positive (position task) to negative (force task)
- GTO feedback interacts with spindle feedback
  - should be simultaneously be assessed

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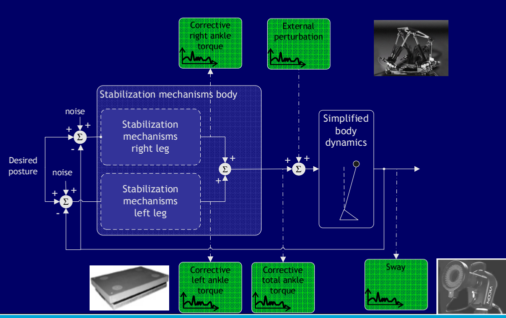
Balance model with 2 legs



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Two leg balance experiment

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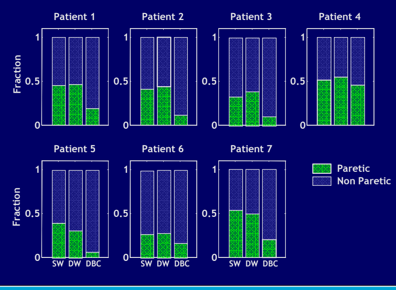
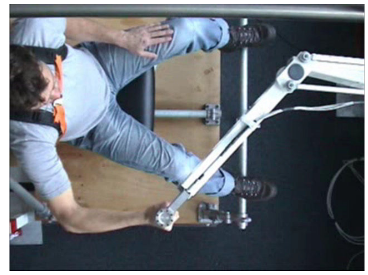
Results of stroke patients



2D manipulator (Armanda)



2D manipulator (Armanda)

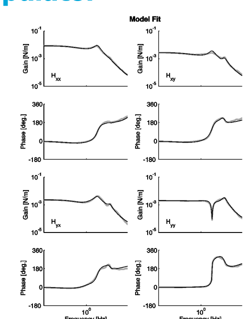
- 2 DOF manipulator, horizontal motions, elbow supported by rope
- 2 hydraulic actuators (500 Nm)
- Force controlled, force perturbations
- Motion range 0.8 m x 0.8 m
- Intrinsic stiffness and proprioceptive feedback parameters for wrist, elbow and shoulder:
  - Mono-articular muscles
  - Bi-articular muscles

Results 2-DOF manipulator*

* De Vlugt 2004 *PhD Thesis*

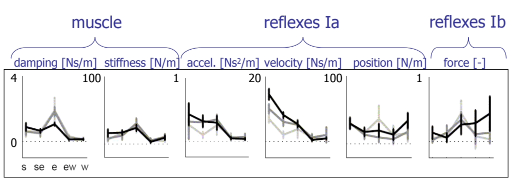
- healthy subjects (n=5)

Model
- 25th order
- VAF > 70%



Physical Model
Estimated Arm Admittance

Intrinsic and Reflexive Parameters



Remarks
- no clear difference with hand position
- muscle visco-elasticity
  - elbow joint > shoulder joint
- reflexive Ia (K_v, K_p)
  - elbow joint < shoulder joint

Hand position
Left
Central
Right

Research goals

- Find objective measures which can quantify proprioceptive reflexes
  - Understand reflexive mechanisms, and the role of the Central Nervous System
  - Understand movement disorders in patients with neurological dysfunction
    - **Stability measures for CVA patients**
    - **Parkinson's disease**
    - **Complex Regional Pain Syndrome**
      - **Use Biological Neural Network to mimic pathology**

Research goals

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      - **Use Biological Neural Network to mimic pathology**

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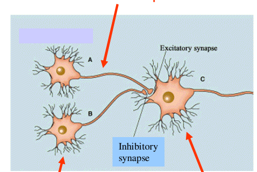
How are reflexes being modulated ?

- Pre-synaptic inhibition
- If inhibition fails, reflex gains will be too high
  - Parkinson: Failure of basal ganglia
  - Spinal cord lesions
  - Stroke
- Too high reflex gains
  - Oscillations
  - Spastic paralysis
- Tonic excitation of motor neurons
  - decreased threshold
  - increased reflex gains

Sensoric path



Supra-spinal inhibition

Alpha motor neuron

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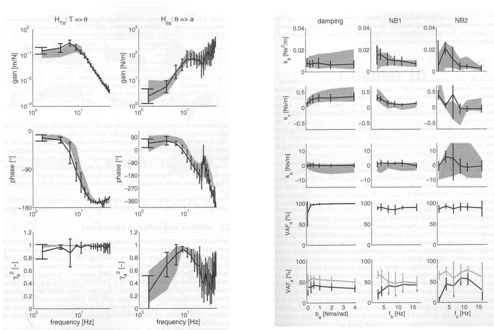
Parkinson's disease



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Parkinson's disease

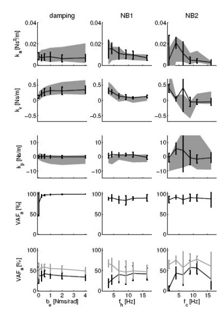
Acceleration feedback

Velocity feedback

Position feedback

Variance-Accounted-For (position)

Variance-Accounted-For (EMG)



Significant !!

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Parkinson's disease

- Significant differences
  - Position feedback is higher in PD
  - Neural time-delays are larger in PD
    - 54 vs 42 msec
  - Modulation is still possible
- Hypothesis:
  - Ia afferent system does not function any more
  - II afferent system is main feedback system
    - Mainly position feedback
    - Larger time-delays
    - Reason for oscillations?

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Complex Regional Pain Syndrome (CRPS)

- Symptoms
  - Severe pain
  - No direct traumatic cause
  - Motoric, sensoric and autonomic dysfunction
- Multi-factorial disease
- No proper diagnosis
- Related to whiplash and RSI?

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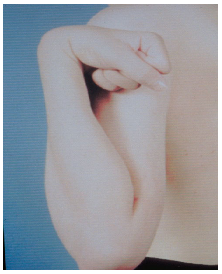
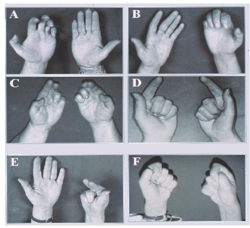
Dystonia in CRPS

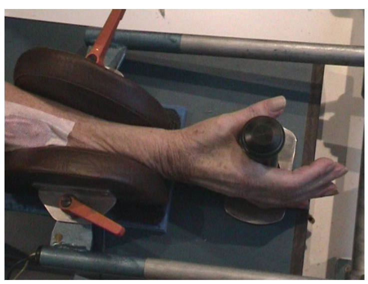




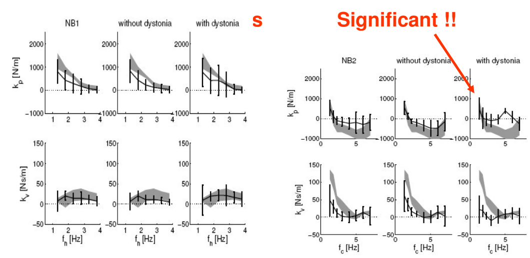
Schwartzman et al. Neurol 1990
van Hilten et al. Neurol 2000

Dystonia in CRPS

Wrist perturbator (PoPe)



CRPS patients
(Schouten et al., 2003)



0 hz – highest frequencies

Center frequencies

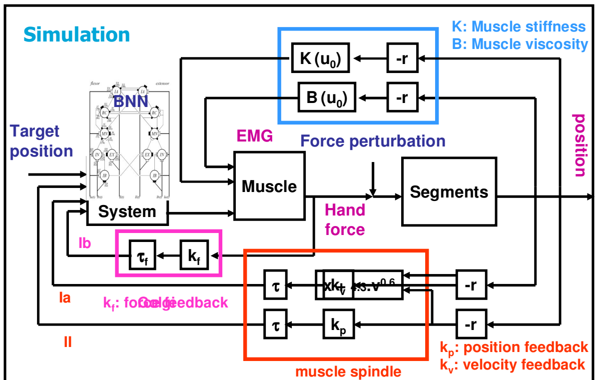
CRPS patients with dystonia

- Still able to modulate their reflex gains
- No negative feedback gains

Biological Neural Network
(Arno Stienen, Jasper Schuurmans)

- Goal:
  Derive physical parameters (interneural connections and synaps strength) in the Spinal Cord to explain the lumped parameters k_p, k_v and k_f.
- Biological Neural Network of spinal cord segment
  - 2298 Neurons
  - Good neuro-anatomical representation of connections

Simulation



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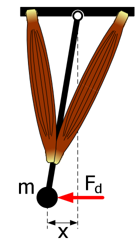
NeuroMusculoSkeletal model[1]

- 1 d.o.f. joint.
- Linear muscle model, innervated by motoneurons.
- Sensory feedback:
  - Golgi tendon organs[2] (force)
  - Muscle spindles[3] (stretch, velocity)
- Spinal neural network



[1]Stienen et al. (2006) cond. acc, Jnl. Comp. Neurosci.
[2]Crago et al. (1982) Jnl. Neurophys. 47.6, 1982
[3]Prochazka & Gorassini (1998) Jnl. Phys. 507.1

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Spinal neural network

- 2 x 6 identified populations[1]:
  - Motoneurons, Renshaw cells, Group Ia and Ib interneurons, excitatory and inhibitory interneurons
- Total: 2298 integrate-and-fire neurons[2]
- 4 states:
  - Membrane potential, potassium conductance, threshold, spike (disc.)
- Neural connections are kept "as is", no training whatsoever!

[1]Bashor (1998, Biol. Cyb. 78)
[2]MacGregor (1987, Neural & Brain Mod)

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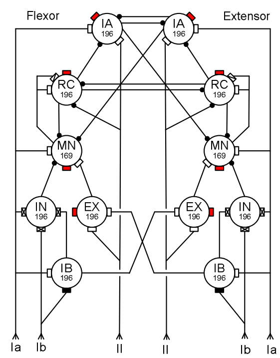
Spinal neural network



Legend:
X n — Population, *n* neurons type X

Synapses:
- Excitatory
- Double strength excit.
- Triple strength excit.
- Long time const. excit.
- Inhibitory
- Tonic supraspinal input

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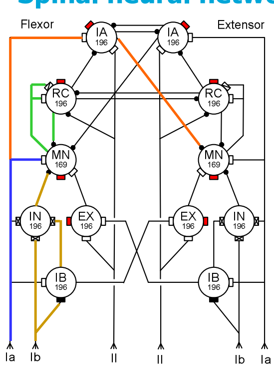
Spinal neural network



Some familiar pathways:

- Monosyn. stretch reflex
- Reciprocal inhibition
- Renshaw inhibition
- Golgi inhibition

Adjustment mechanisms:
- Pre-synaptic inhibition
- Tonic descending excitation

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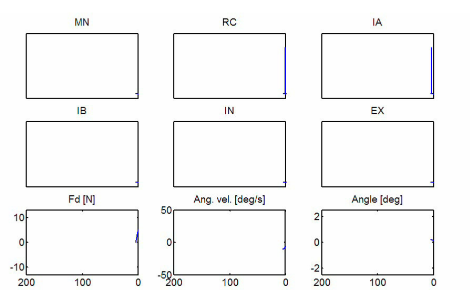
Simulation run (1)

- One neuron from each population
- Disturbance, joint velocity, joint angle



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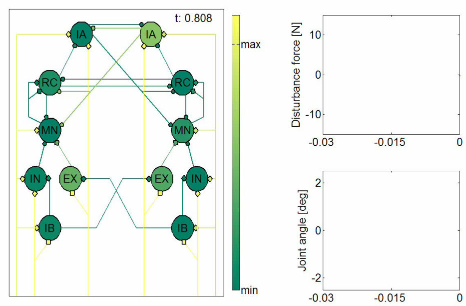
Simulation run (2)

- Summed output of populations
- Disturbance force, joint angle



Candidates for simulation of CRPS symptoms

- Symptoms of CRPS with dystonia
  - No negative feedback gains
  - Ability to modulate feedback gains
  - Sensitive to baclofen (replaces GABA inhibitory neurotransmitter): presumably inhibitory synaps involved
- Lack of pre-synaptic inhibition?
  - High feedback gains: oscillatory behaviour
  - No modulation of position, velocity and force feedback gains
- Alternative circuitry with inhibitory interneurons?

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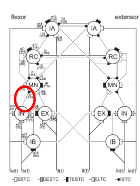
Alternative sensor input – motor neuron output connections

Aff.	Syn.	Nrn.	Syn.	Nrn.	Syn.	Nrn.	Stimulus
Monosynaptic Feedback Path							
Ia	$\xrightarrow{e5}$	MN					Positive
Disynaptic Feedback Paths							
Ia	$\xrightarrow{e14}$	IA	$\xRightarrow{i2}$	MN			Positive
Ia	$\xrightarrow{e20}$	IN	$\xrightarrow{i3}$	MN			Negative
Ib	$\xrightarrow{e21}$	IN	$\xrightarrow{i3}$	MN			Negative
II	$\xrightarrow{e15}$	IA	$\xRightarrow{i2}$	MN			Positive
II	$\xrightarrow{e23}$	EX	$\xrightarrow{e4}$	MN			Positive
Trisynaptic Feedback Paths							
Ia	$\xrightarrow{e14}$	IA	$\xRightarrow{i10}$	RC	$\xrightarrow{i1}$	MN	Negative
Ia	$\xrightarrow{e14}$	IA	$\xRightarrow{i13}$	IA	$\xRightarrow{i2}$	MN	Positive
Ia	$\xrightarrow{e17}$	IB	$\xrightarrow{e19}$	IN	$\xrightarrow{i3}$	MN	Negative
Ia	$\xrightarrow{e17}$	IB	$\xRightarrow{e22}$	EX	$\xrightarrow{e4}$	MN	Negative
Ib	$\xrightarrow{e18}$	IB	$\xrightarrow{e19}$	IN	$\xrightarrow{i3}$	MN	Negative
Ib	$\xrightarrow{e18}$	IB	$\xRightarrow{e22}$	EX	$\xrightarrow{e4}$	MN	Negative
II	$\xrightarrow{e15}$	IA	$\xRightarrow{i10}$	RC	$\xrightarrow{i1}$	MN	Negative
II	$\xrightarrow{e15}$	IA	$\xRightarrow{i13}$	IA	$\xRightarrow{i2}$	MN	Positive



- i3 synaptic connection is most likely candidate

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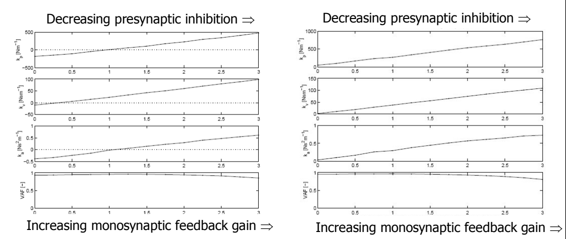
Results of synapse 'i3' knock-out



Normal situation

Without i3 synapse:
No negative feedback gains !
Still modulation !

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Conclusion simulations Biological neural network

- Results of lumped parameter model can be simulated by BNN
  - Presynaptic inhibition results in adaptation of reflex gains
  - Resulting reflexive feedback gains mimic experimental results
- Symptoms of CRPS patients can be simulated by knocking out one synaptic connection
  - No negative feedback gains
  - Still able to modulate feedback gains
- BNN is very promising for simulation of pathologic behaviour

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Experiment study: Reflex adaptation with unstable environments

- Additional environment influences total behavior/performance and such provokes reflex adaptation (humans adapt!)

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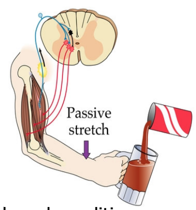
Introduction

- Joint dynamics comprise
  - muscle visco-elasticity (co-contraction)
  &
  - reflexes (muscle spindle feedback)



- Reflex strength varies with task and condition

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Introduction

Previous research[1] showed that reflex strength decreases with external stiffness as a result of decreased stability margins.

(and increases with external damping as a results of increased stability margins)

[1] De Vlugt et al. 2002 Biol Cybern

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Goal

- What are the limits of reflex adaptations
- Can humans adapt to unstable environments? (which are rarely seen and may feel unnatural)

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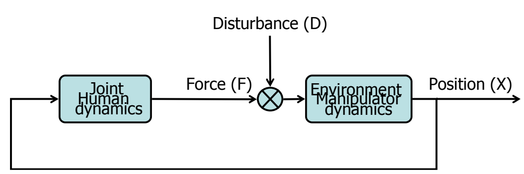
Human-Machine interaction



- Natural task: human controls the position
- Disturbance is needed to identify joint dynamics
- Joint dynamics comprise muscles and reflexes

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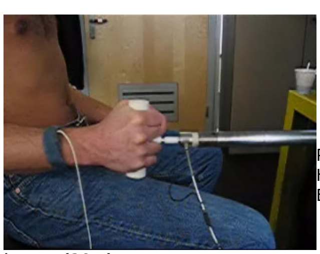
Quantifying reflexes: the 'Delft' method

'Minimize Position'



Position (X)
Handforce (F)
EMG

Disturbance (30 s)
External damping and stiffness (b_e, k_e)

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Analysis: Human motor control

Minimize deviations => decrease total admittance (X/D)

$$\frac{X}{D} = \frac{1}{m^* \cdot s^2 + b^* \cdot s + k^*} \quad [\mathrm{m/N}]$$

with

$$m^* = m_h + m_e + k_a \cdot e^{-s\tau_d} \cdot H_{act}$$
$$b^* = b_h + b_e + k_v \cdot e^{-s\tau_d} \cdot H_{act}$$
$$k^* = k_h + k_e + k_p \cdot e^{-s\tau_d} \cdot H_{act}$$

Muscle properties
Manipulator settings
Reflexive contribution

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Hypotheses

- Both reflexes and muscle co-activation decreases the admittance.
- Effectiveness of reflexes is limited as a result of neural time delays

1. *Negative external damping, reduces total damping, reduces stability margins and such allows smaller reflexive feedback gains*
2. *Negative external stiffness, reduces total stiffness, increases relative damping and such allows larger reflexive feedback gains*

Method

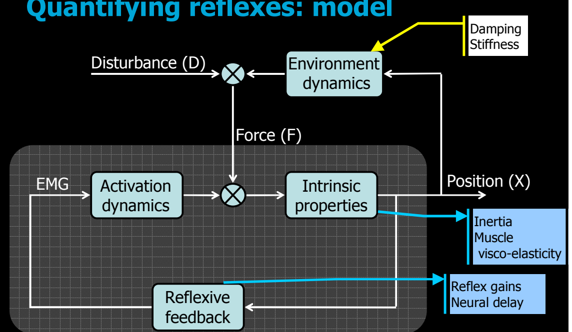
Five subjects (age: 20-24)

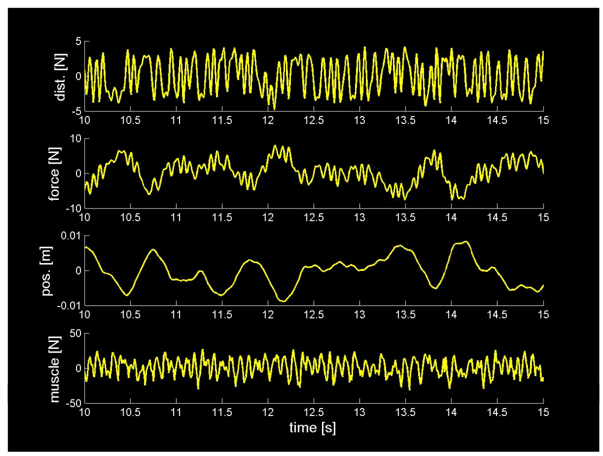
9 different condition applied 4 times for 30 seconds each

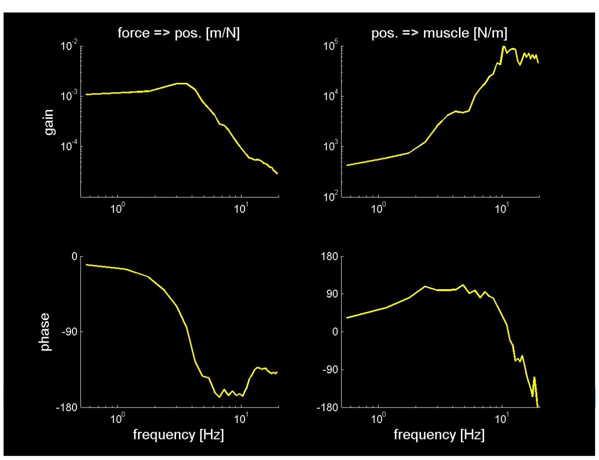
- External damping: -30, -15, 0, 15, 30 Ns/m
- External stiffness: -600, -300, 0, 300, 600 N/m

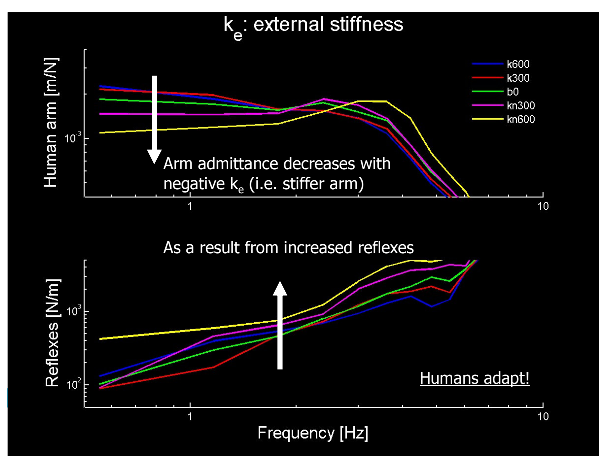
Note: human during MVC, ± 30 Ns/m & ± 600 N/m
=> Very demanding task!

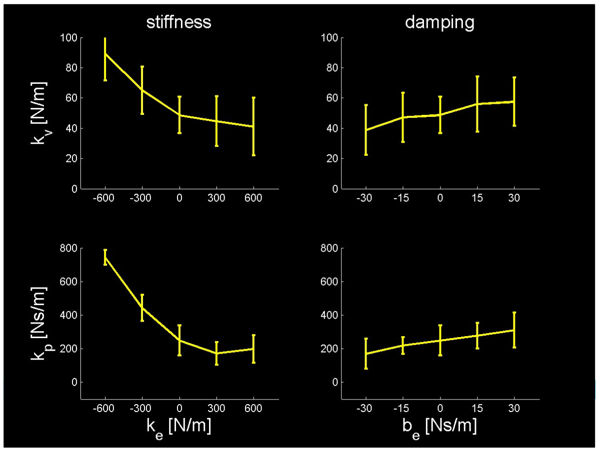
Quantifying reflexes: model











Experiments & optimizations

- Experiments show that human adapt
  But, is it optimal? (in the sense of performance)
- Matlab: NMClab.m
- Model optimization were performed.
  Given the external conditions and muscle properties, which reflexive feedback gains are optimal to minimize variance of hand position.

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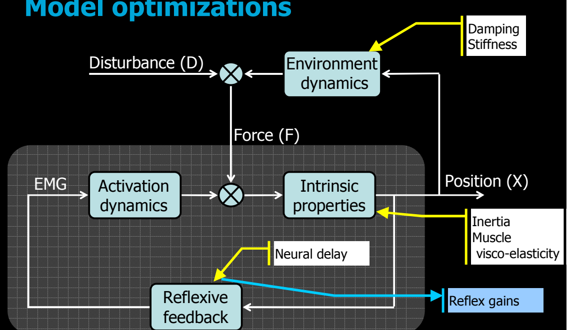
Model optimizations



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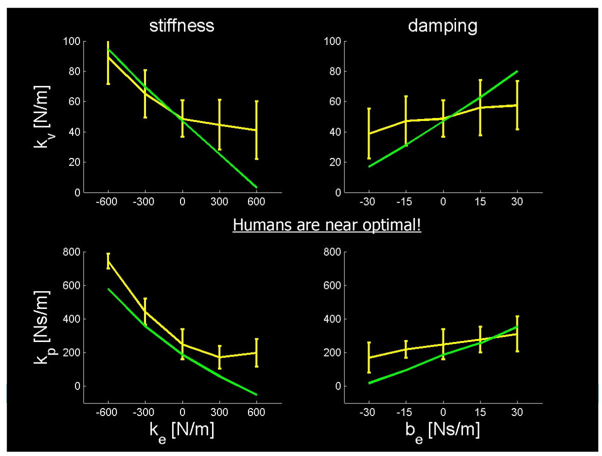

Conclusion & Discussion

1. Experiment: Humans adapt to unstable environments
2. Model study: Adaptations are optimal for performance

What is the nature of these adaptations?

- 'hardware' (muscle spindle property, non-linearity)
- 'software' (neural settings; presynaptic inhibition)
- combination (α-γ coupling; β-motoneurons)

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