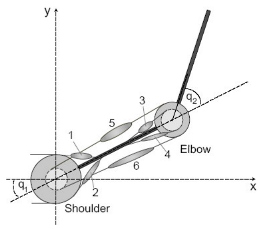
Arm Admittance
experimental approach
Wb2407 Lecture 8



Contents

- System definition
  - Causality: force vs position perturbations
- Experiment design
  - Perturbations, tasks, environment
- Data analysis
  - Input output description
  - Physical model parameterization
- Case studies
  - I: Ankle visco-elasticity and reflexes
  - II: Shoulder visco-elasticity and reflexes

System descriptions
causality

Only forces (F) can excite a system!

⇓

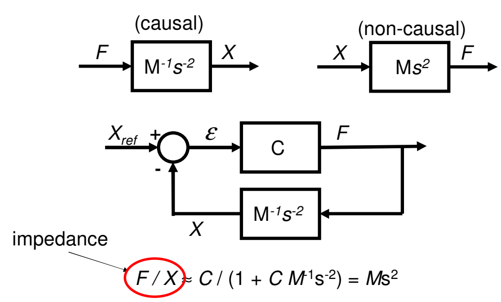
(Bio-)mechanical systems respond by a corresponding motion (X)

<u>as a consequence:</u>

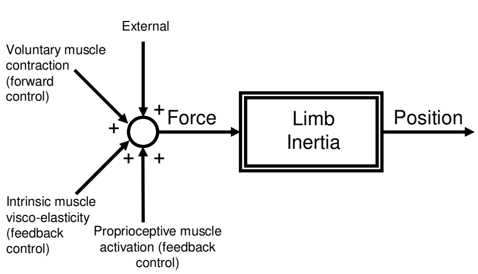
a mechanical system is properly described by its admittance ($=X/F$)

Force is the driving source

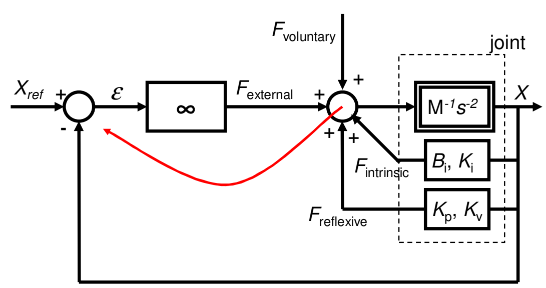
Motion of Mass



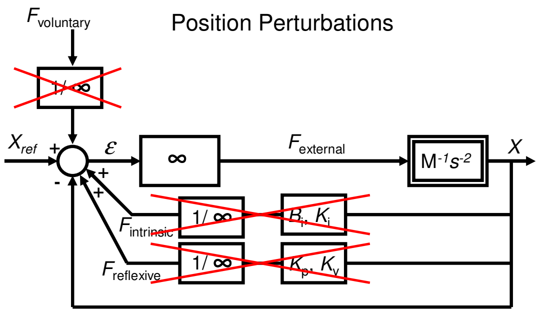
<u>Biomechanical Forces</u>



Position Perturbations



Position Perturbations

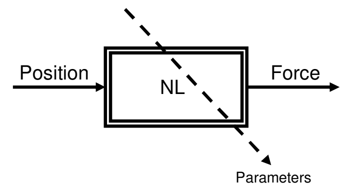


Intrinsic, reflexive and voluntary forces can be present (and measured) but have **no influence** on the motion.

Position perturbations

Conclusions

- Force and position are decoupled by the position servo: no mechanical interaction
- Open loop identification techniques can be used



Perturbations, Tasks and Applications

Force perturbations:

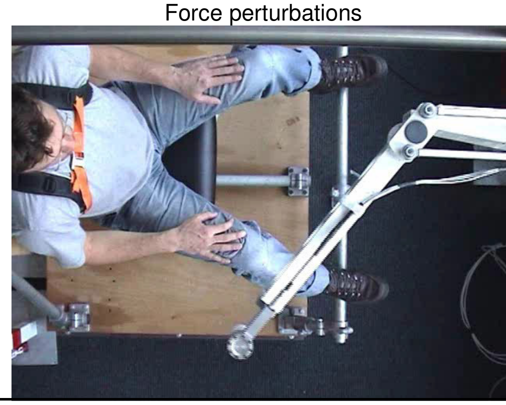
- identification of all force contributing mechanisms

  intrinsic + reflexive feedback

↓

Motion Control behaviour

Force perturbations



Tasks

- Force task
  - humans generate the appropriate muscle forces to obtain a desired contact force (or pressure) during posture maintenance or while moving
  - human motion control is represented as a mechanical impedance
- Position task
  - humans generate the appropriate muscle forces to obtain a desired motion (tracking) or maintain a posture (disturbance rejection)
  - human motion control is appropriately presented as a mechanical admittance

Perturbations, Tasks and Applications

General:

position perturbations → 'do not intervene' and/or 'maintain force level'
- integrity tests
- not functional to study neuro-muscular control properties

force perturbations → 'intervene' to obtain certain motions or maintain a posture
- functional assessment

Perturbations, Tasks and Applications

Applications

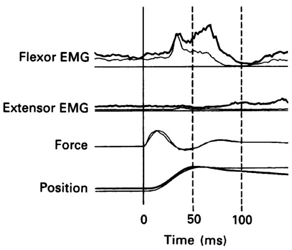
Task ↓ / Perturbation →	Position	Force
Position	useless	• intervene on position • motion feedback useful (muscle spindles) • what is the role of force feedback?
Force	• intervene on force • force feedback useful (Golgi tendon organs) • what is the role of muscle spindles?	• intervene on force • motion not relevant • force feedback useful ? • role of motion feedback ?

Combination of task and perturbation is determined by the experimental objective

Perturbations, Tasks and Applications

common applications

Task dependent muscle activity



Thick lines force perturbation - position task

Light lines position perturbation - force task

(Doemges and Rack, 1992)

Perturbations

Force perturbations: predictable or unpredictable ?

Predictable:

- humans tend to generate voluntary actions

Unpredictable:

- humans can not anticipate to the perturbation
- effective control only by intrinsic and/or reflexive feedback only

Perturbations

Force perturbations: continuous or transient ?

Transients:

- ***be at the mercy of the perturbation***

  stability and performance not relevant to the perturbation

Continuous:

- ***adaptation / interaction to the mechanical environment***

  stability and performance are relevant task properties

Time or Frequency domain?

Time domain:

- transient signals
- signal analyses easy by eye
- system dynamics hard to retrieve
- general applications

Frequency domain:

- continuous signals
- system dynamics can easily be visualized
- only for linear time invariant (LTI) systems

Endpoint vs Joint measurement

Multiple DOFs (linearized):

- Endpoint translation: $F = Ms^2 + Bs + K$

$$\frac{X}{F} = \frac{1}{Ms^2 + Bs + K}$$

- Joint rotation: $$\frac{\theta}{T} = \frac{1}{Is^2 + B_\theta s + K_\theta}$$

Endpoint vs Joint measurement

Transformation from joint to end-point coordinates.

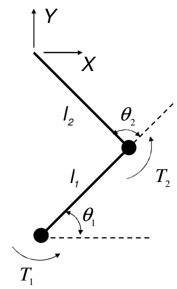
2 DOF example (non redundant):

$$x = l_1 cos(\theta_1) + l_2 cos(\theta_1 + \theta_2)$$
$$y = l_1 sin(\theta_1) + l_2 sin(\theta_1 + \theta_2)$$

$$dx = -l_1 s_1 d\theta_1 - l_2 s_{12}(d\theta_1 + d\theta_2)$$
$$dy = l_1 c_1 d\theta_1 + l_2 c_{12}(d\theta_1 + d\theta_2)$$

$$\begin{bmatrix} dx \\ dy \end{bmatrix} = \begin{bmatrix} -l_1 s_1 - l_2 s_{12} & -l_2 s_{12} \\ l_1 c_1 + l_2 c_{12} & l_2 c_{12} \end{bmatrix} \begin{bmatrix} d\theta_1 \\ d\theta_2 \end{bmatrix}$$

$$\boxed{\dot{X} = J\dot{\Theta}}$$



Endpoint vs Joint measurement

The redundant case: Jacobian is not square and can not be inverted ($DOF_\theta > DOF_x$)

Consequently, the joint admittance can not uniquely be derived from the measured endpoint admittance.

System Description

Different system descriptions:

- differential equations (equations of motion)
- state space equations
- impulse response functions (IRF)
- frequency response functions (FRF)

Nonlinear - chain of linear subsystems ?
- sophisticated techniques

Linear approach: - Fourier, Bode, Nyquist
- performance & stability analysis (pole-zero analyses)

Case study

Admittance Decomposition from Force Perturbations (Shoulder)

Posture Control at DUT

Objective: Posture maintenance

small deviations of state variables → linear approach justified

Hypotheses: all force contributing mechanisms (intrinsic and reflexive) are functional to the task

Goal: Quantification of reflexive feedback

Perturbations: Force perturbations

Task instruction: Minimize position deviations

Task instruction

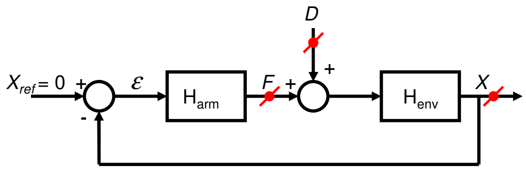
Task instruction: “Minimize position deviations”:

$$J_x = \sum_{f_l}^{f_h} X(f)df = \sum_{f_l}^{f_h} H_{arm}(f)D(f)df = C\sum_{f_l}^{f_h} H_{arm}(f)df$$

Functional: “Minimize arm admittance”

Measurement Scheme

posture control, force perturbation



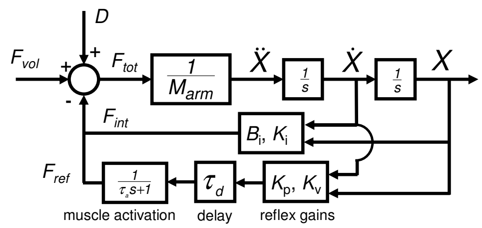
Measured signal

Closed-loop system identification:

estimate H_{arm} from measured signals

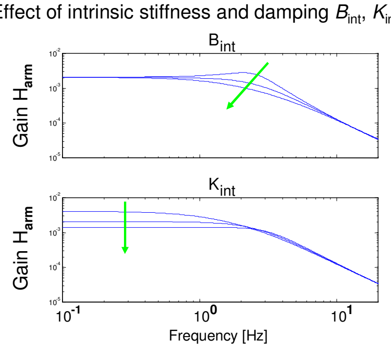
Hypotheses

Hypotheses: all force contributing mechanisms (intrinsic and reflexive) are relevant to the task



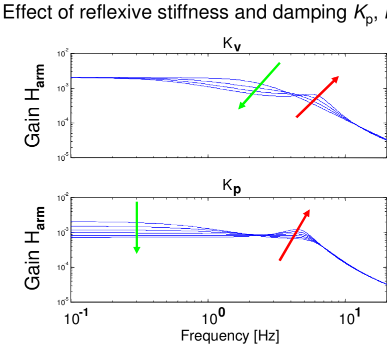
Intrinsic properties

Effect of intrinsic stiffness and damping B_{int}, K_{int}:



Reflexive feedback

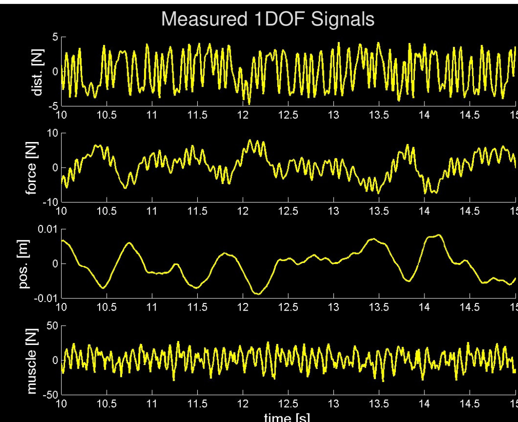
Effect of reflexive stiffness and damping K_p, K_v:



1DOF Shoulder Admittance

- linear movement of the hand
- continuous random force perturbations, position task

Measured 1DOF Signals



Data Processing

For estimating the transferfunction $H_{arm}(f)$, an <u>independent</u> signal is needed from <u>outside</u> the loop → take the <u>force disturbance signal</u>.

An estimation of $H_{arm}(f)$, i.e. $\hat{H}_{arm}(f)$, can be retrieved from spectral densities:

$$\hat{H}_{arm}(f) = \frac{\hat{G}_{dx}(f)}{\hat{G}_{df}(f)} \qquad \hat{\Gamma}(f) = \sqrt{\frac{\left|\hat{G}_{dx}(f)\right|^2}{\hat{G}_{xx}(f)\hat{G}_{dd}(f)}}$$

See De Vlugt 2002 and college *'System Identification'* for details.

Data Processing

Time signals are directly transformed to the frequency domain by the Fast Fourier Transform (FFT):

$$y(t) \xrightarrow{FFT} Y(f)$$

Spectral densities:

$$\hat{G}_{dy}(f) = Y(f)Z(\text{-}f)$$

$$\hat{G}_{yy}(f) = Y(f)Y(\text{-}f) = \left|Y(f)\right|^2$$

Data Processing

On the estimated transfer function

$$\hat{H}_{arm}(f)$$

A model:

$$H_{mod}(f)$$

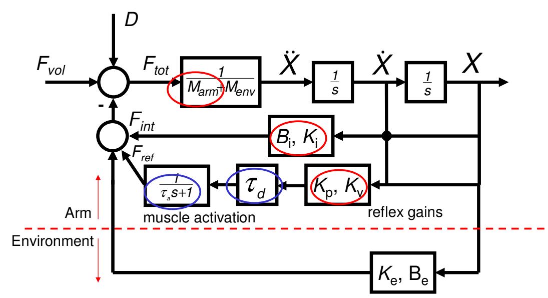
is fitted according to a least squares criterion:

$$crit = W\left|\hat{H}_{arm}(f) - H_{mod}(f)\right|^2$$

W is a weighting function

Data Processing

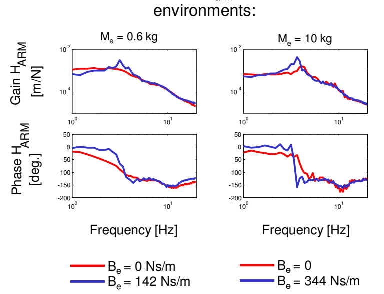
model



red circled are the obtained model parameters
blue are the fixed parameters

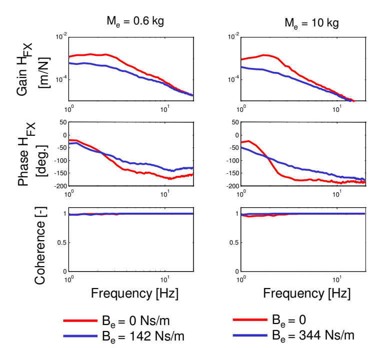
Results

Estimated transfer functions $\hat{H}_{arm}(f)$ of the arm for different environments:



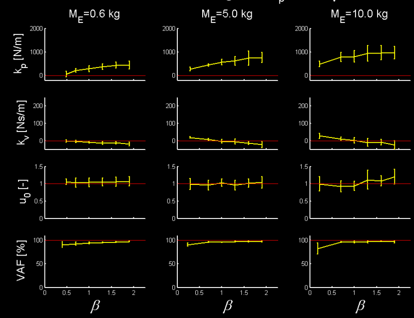
Results

Estimated transfer functions of total system (arm+environment):

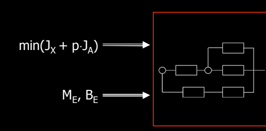


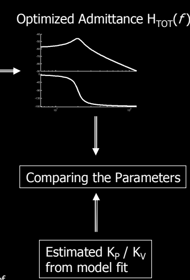
Results

Estimated reflex gains K_p and K_v:



Model Optimization





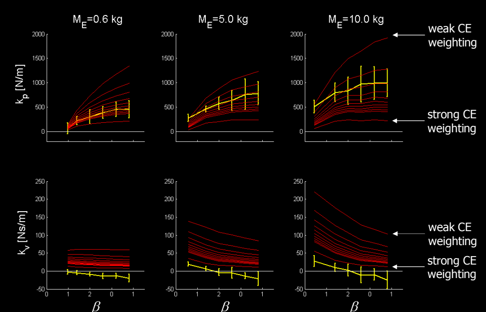
Control effort (CE) weighting:

$$J_{F_{ref}} = \sigma^2_{F_{ref}} = \int_{f_L}^{f_H} G_{F_{ref}F_{ref}}(f)\,df = p\int_{f_L}^{f_H} |H_{ACT}(f)|^2\,df$$

with Hact (in this case) the FRF from D => F_{ref}

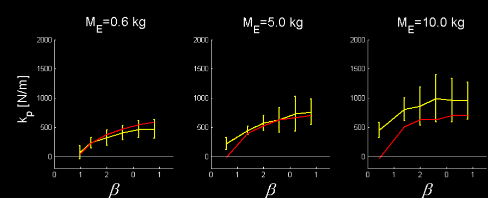
Note: intrinsic parameters were fixed at their estimated values

Optimized Reflex Gains



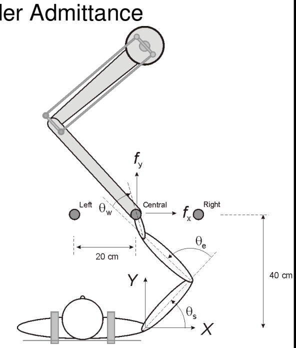
Optimized Length Feedback

- Only length feedback
- One CE weighing factor



2DOF Shoulder Admittance

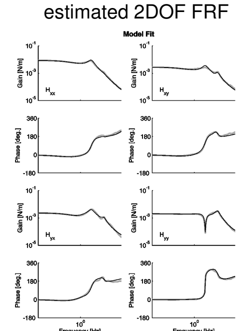
- 2dof measurements at hand level
- 3dof identification on joint level
- a redundancy problem!



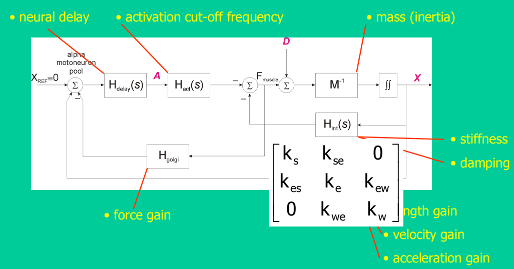
2DOF Shoulder Admittance

- 2dof measurements at hand level
- 3dof identification on joint level
- a redundancy problem!
- unique solution possible due to realistic model including only mono- and biarticular coupling

estimated 2DOF FRF



Physical (linear) Model $H_{mod}(f)$



Mono- and bi-articular muscles of shoulder-elbow-wrist

Conclusions Case study

- Monosynaptic reflex gains K_p and K_v vary with increasing damping and mass of the environment
- These reflex gains can be explained analytically using common control engineering techniques
- Model optimizations can determine whether the adjustments are optimal
- The combination force perturbations – position task is very appropriate to obtain knowledge of the control-ability of the central nervous system during natural movements