Bio-mecha-tronics

Course 2008 (wb 2432)

Lecture 2

Human Motion Control

Erwin de Vlugt

Research at

Neuro-Muscular Control Lab (NMC)

www.3me.tudelft.nl/nmc

NMC: The People

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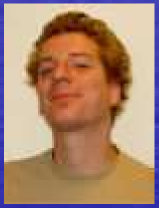
Dirk-Jan
Associate

Herman
Associate

Alfred
Assistant

Erwin
Assistant

Riender
Assistant



David
Postdoc

Winfred
PhD student

Jasper
PhD student

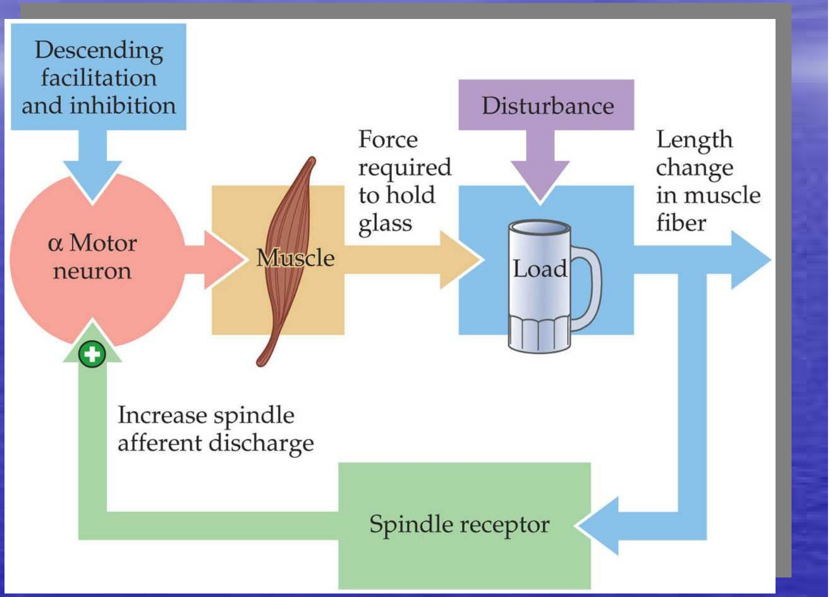
Per year:
5 – 10 Masters
8 – 12 Bachelors

Contents

- Intro: Feedback control (Propriocepsis)
- Postural & motion control
- Stability and admittance
- Feedback model:
  - intrinsic muscle properties
  - force feedback
  - velocity feedback
  - length feedback

Human motor system

- Human motor system
  - feedforward control
  - feedback control
- Focus on the spinal reflexes
  - Corrective motor action
  - Energy efficient
  - Fast (spinal pathways)
  - Adaptive



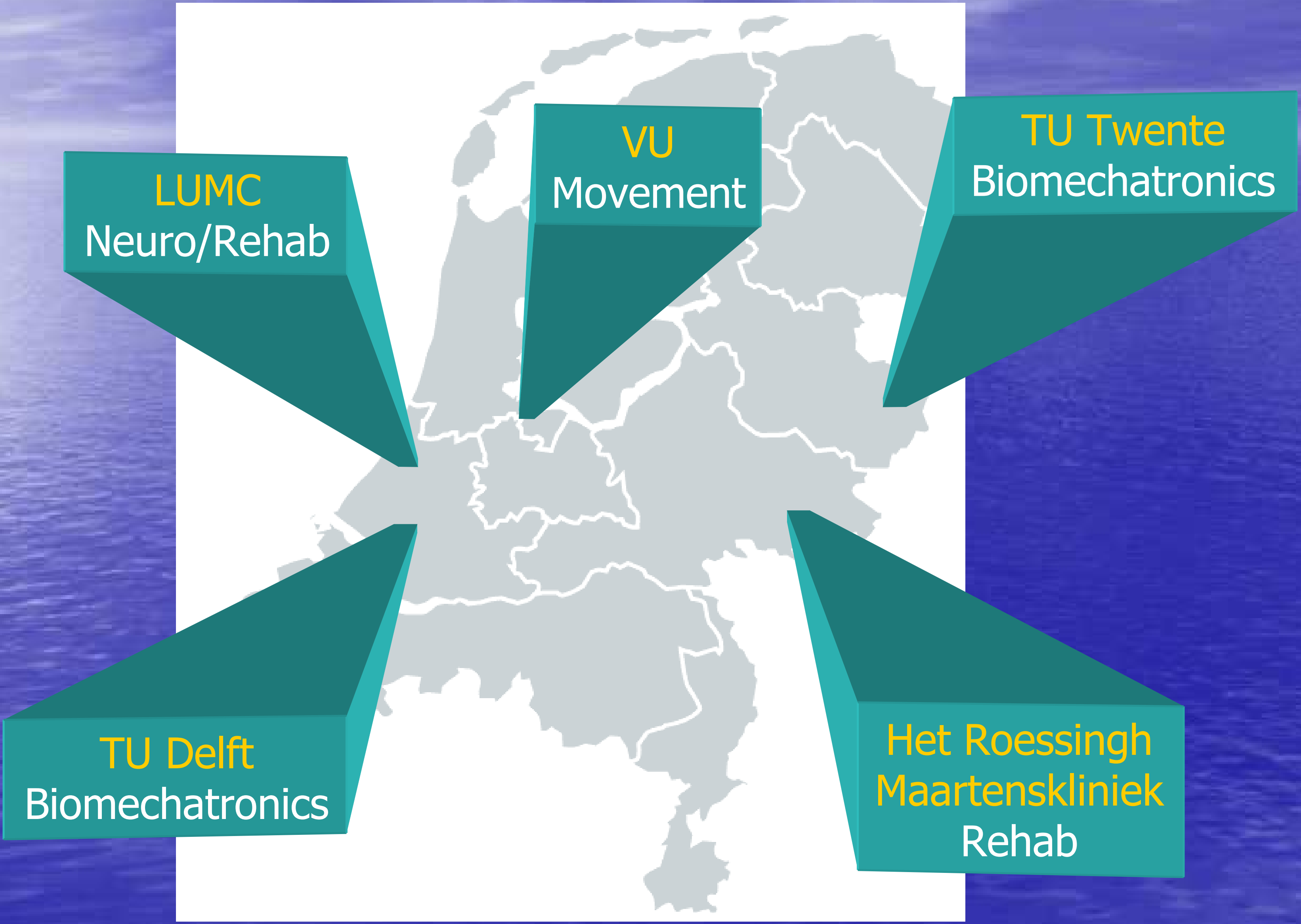
Motoric diseases

- NMC Lab
  - fundamental research: how does the system work?
  - clinical application: what causes the motoric disfunction?
- Motor disorders:
  - loss of motion dexterity
  - difficult to start a movement
  - spastic (uncontrolled) motions
- Motoric diseases (e.g. stroke, Parkinson, Multiple Sclerosis) affects:
  - neural control
  - the muscles

The man who lost his body

- BBC documentary

Research in NL



LUMC
Neuro/Rehab

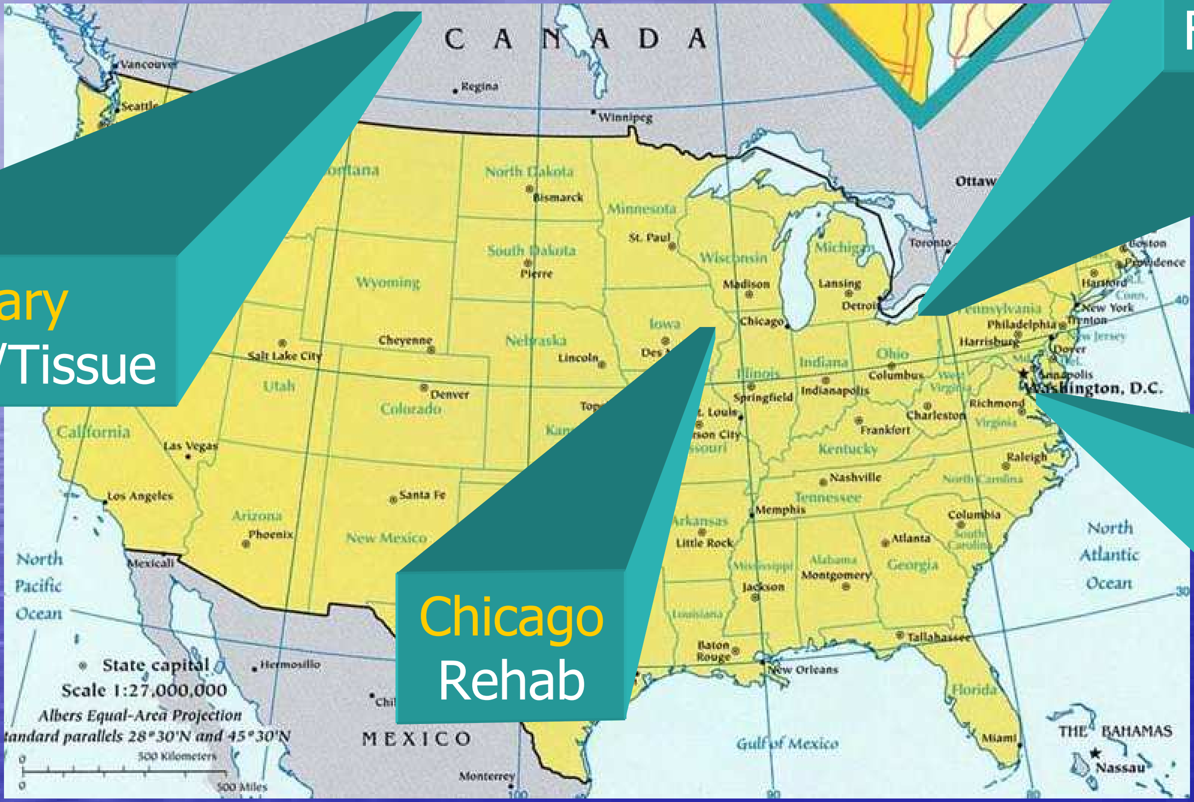
VU
Movement

TU Twente
Biomechatronics

TU Delft
Biomechatronics

Het Roessingh
Maartenskliniek
Rehab

Research in the US



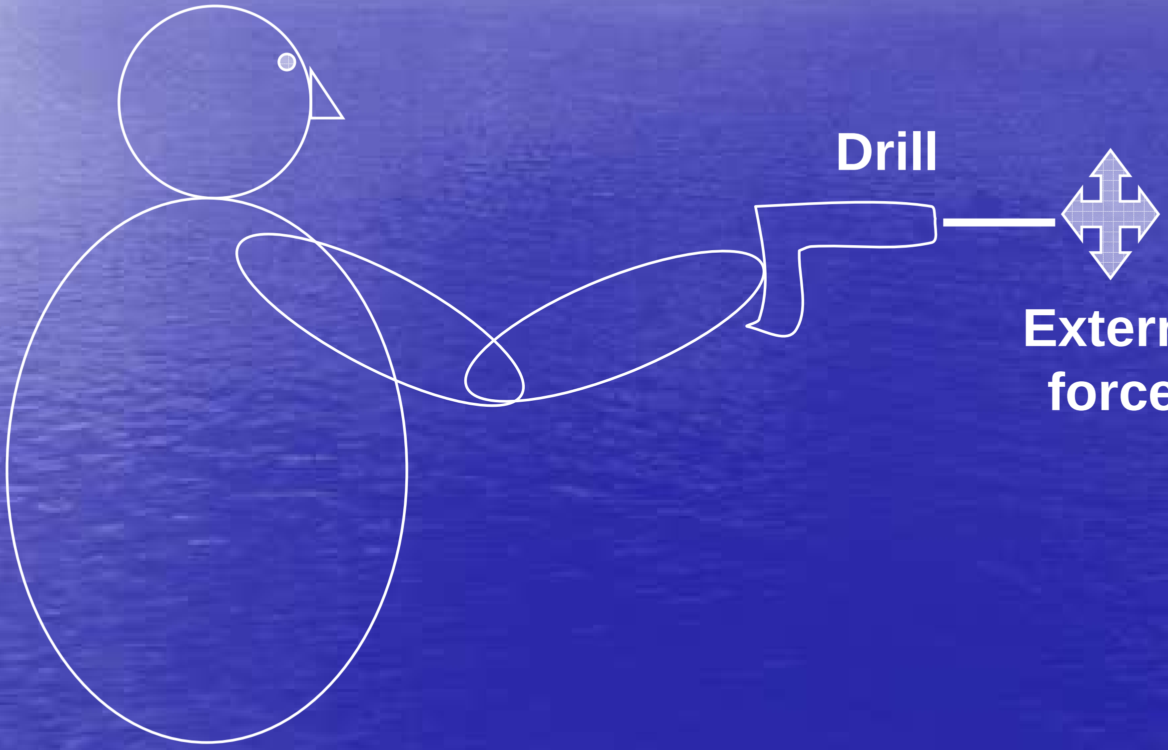
Cleveland
FES / Shoulder

Calgary
Muscles/Tissue

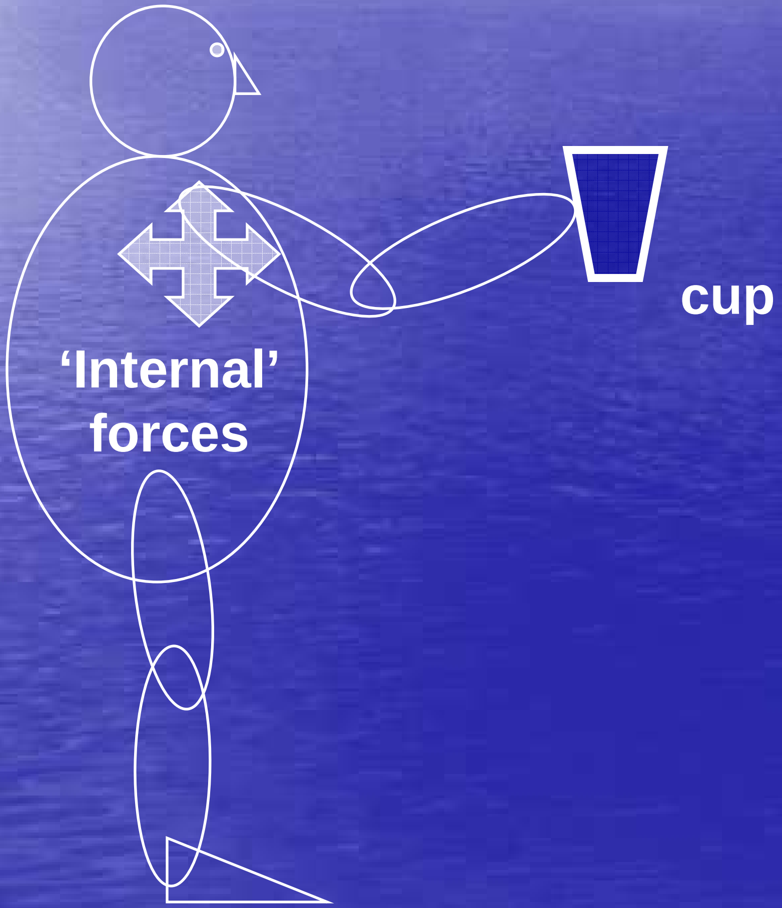
Chicago
Rehab

Washington
Rehab

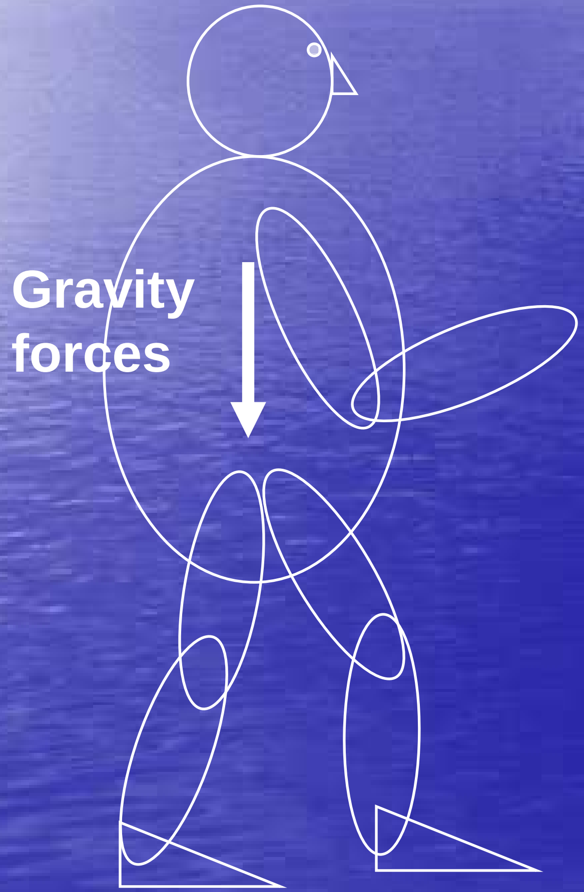
Postural control:
Resisting external perturbations



Postural control:
Resisting ‘internal’ perturbations



Postural control: Standing/walking

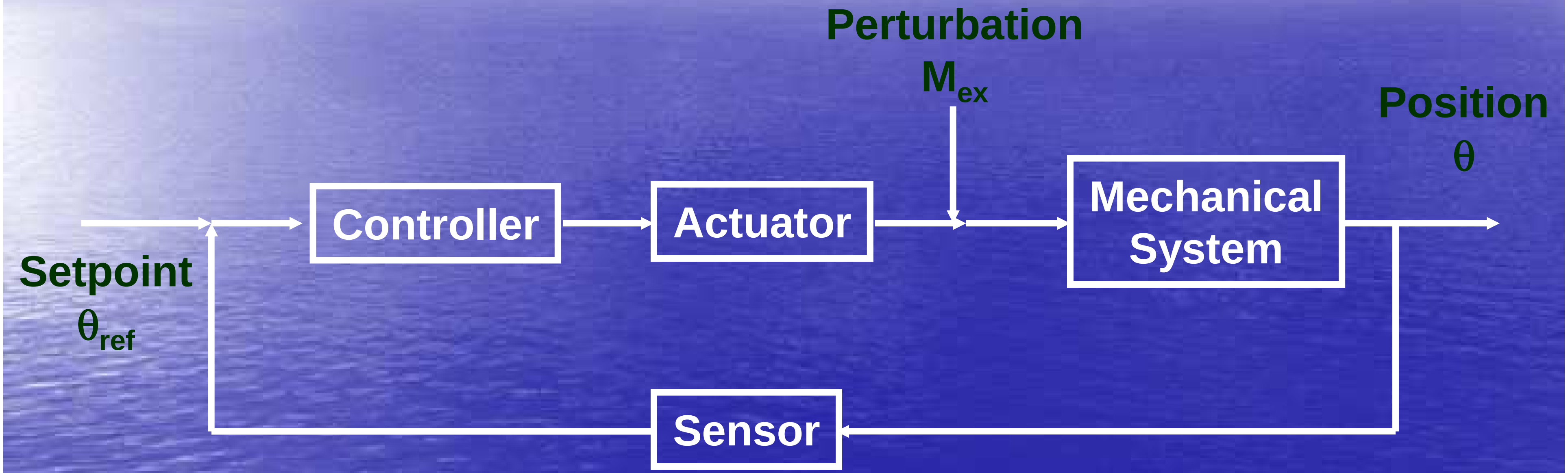


Motion Control

- Goal-directed motions
- Cyclic motions
- Postural motions

Postural Motions or Posture Control

Posture control



Stability & admittance

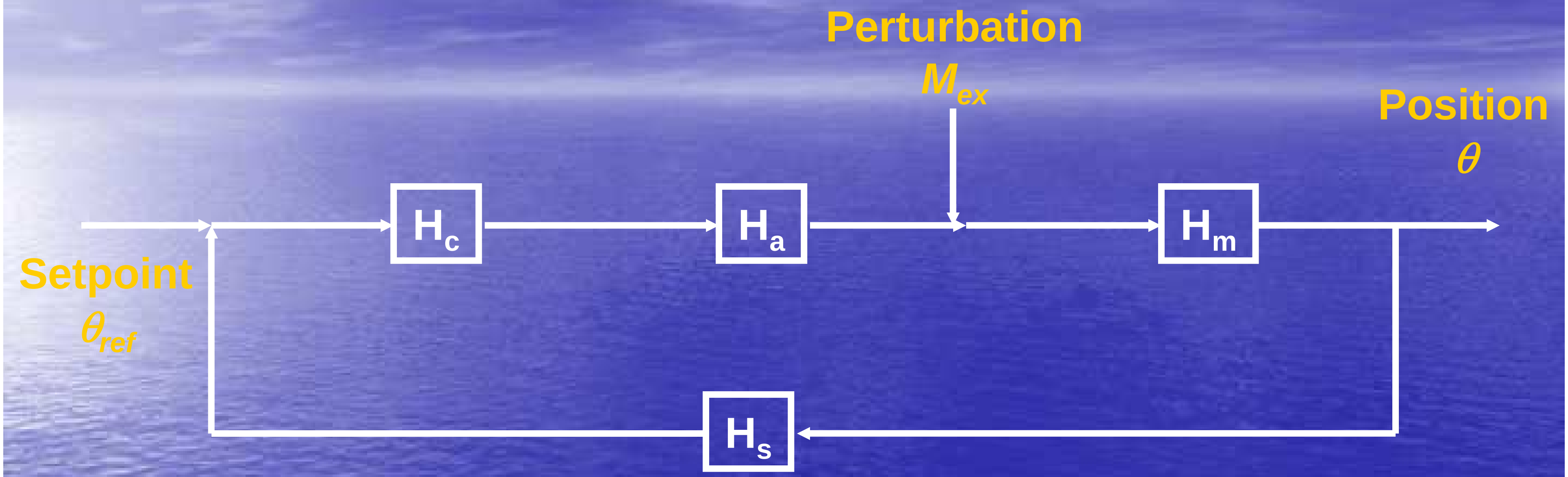
Stability: The arm will return to its position (trajectory) after a force perturbation

Admittance (reciprocal of impedance):

The dynamic behaviour of the arm depends on:

- stiffness
- viscosity } adjustable by muscle activation
- inertia } adjustable by configuration
- neural feedback } adjustable by neural modulation

Posture control and admittance



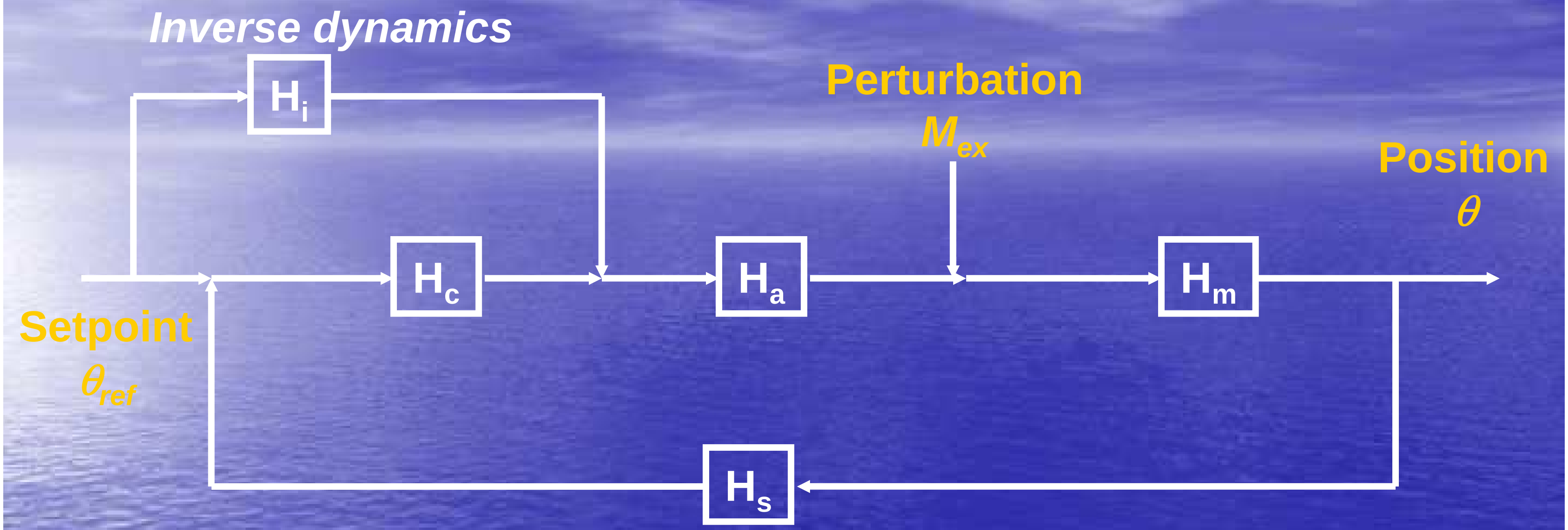
Feedback Control: $$H_{fb} = \frac{\theta}{\theta_{ref}} = \frac{H_c.H_a.H_m}{1+H_c.H_a.H_m.H_s}$$

Admittance: $$H_{adm} = \frac{\theta}{M_{ex}} = \frac{H_m}{1+H_c.H_a.H_m.H_s}$$

Admittance

- Humans are well capable in adjusting their endpoint admittance to deal with different environments (hard/soft surfaces, unexpected forces)

Feedforward & Feedback control



Feedback Control: $$H_{fb} = \frac{\theta}{\theta_{ref}} = \frac{H_c.H_a.H_m}{1 + H_c.H_a.H_m.H_s}$$

Feedforward Control: $$H_{ff} = \frac{\theta}{\theta_{ref}} = \frac{H_i.H_a.H_m}{1 + H_c.H_a.H_m.H_s}$$

Feedforward control

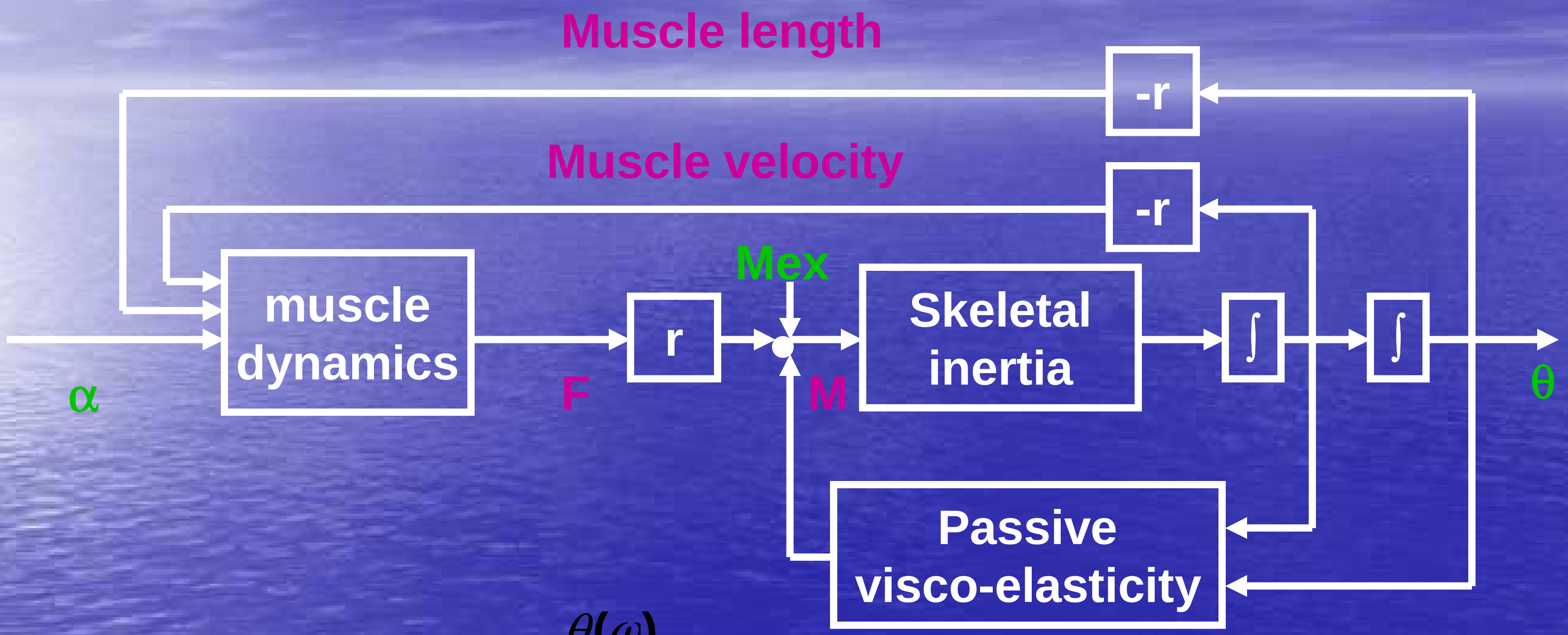
$$\boxed{H_{ff} = \frac{\theta}{\theta_{ref}} = \frac{H_i.H_a.H_m}{1 + H_c.H_a.H_m.H_s}}$$

- $H_i = (H_a.H_m)^{-1} \quad \Rightarrow \quad \theta \approx \theta_{ref}$ if
  $H_c = 0 \Rightarrow H_{c.}\, H_a.H_m.H_s = 0$ (no feedback)
- No feedback implies that unexpected perturbations are not compensated !
- Motion control is mix of feedback and feedforward control:
  - Fast motions: Feedforward control (all feedback gains will tend to zero)
  - Slow motions: Also feedback control
  - Posture: Only feedback control

Control Strategies

- (Co-)activation of muscles
  - Produces motion
  - Increase muscle stiffness & viscosity
    - Effective for large range of frequencies
    - Costs much energy
- Proprioceptive feedback
  - Length, velocity and force feedback for ‘automatic’ control
    - Energy efficient
    - Only effective for low frequent perturbations due to time-delays in nervous system

Models



Muscle length

-r

Muscle velocity

-r

Mex

muscle dynamics

r

Skeletal inertia

∫

∫

α

F

M

θ

Passive visco-elasticity

Admittance depends on:

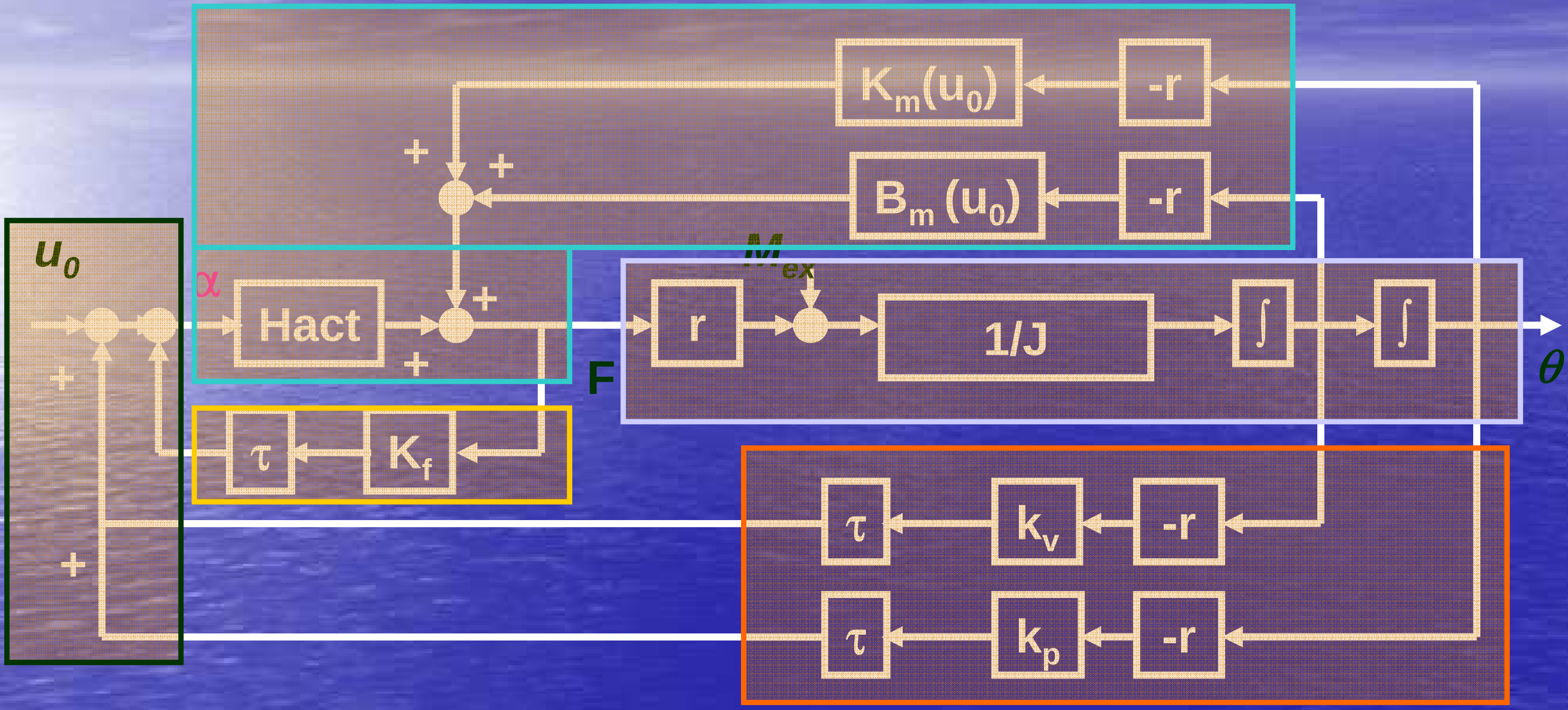
$$H_{adm}(\omega) = \frac{\theta(\omega)}{M_{ex}(\omega)} \quad ,$$

- Inertia, passive visco-elasticity
- intrinsic muscle properties:
  length & velocity dependency muscle

Models

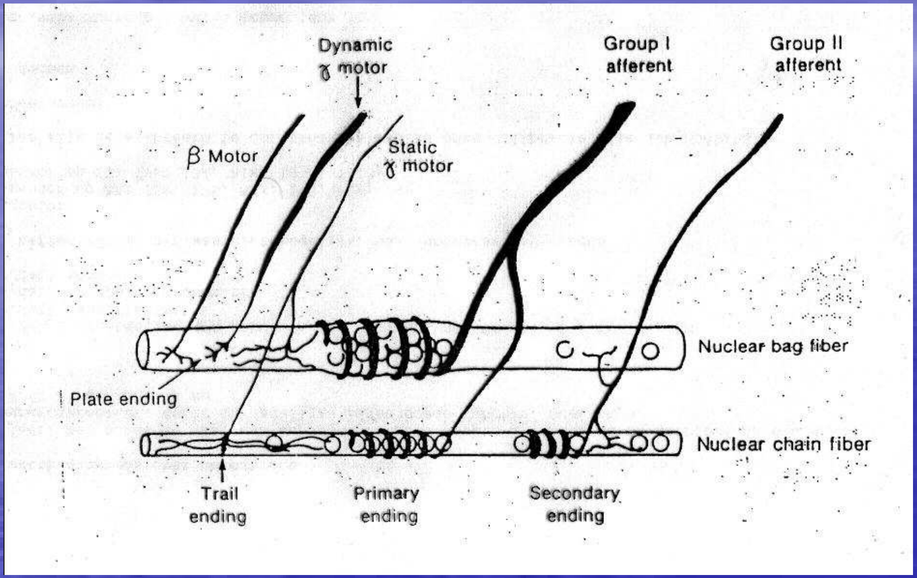
- The neuromuscular system is highly nonlinear
  - the Delft Shoulder and Elbow Model (DSEM) is a large scale nonlinear model based on cadaver studies (Van der Helm)
  - contributions of different muscles to certain movements can be studied
  - e.g. application for tendon transpositions for pre-operative prediction of the (improved) range of motion
- For small amplitude movements, a linear model is a good description of the mechanical behavior at endpoint.
  - recent posture control studies of the NMC Lab

Linear model



Muscle spindle:

Length and velocity feedback



Matthews P.B.C. (1964) Muscle spindles and their motion control. Physiological Reviews, Vol. 44, p. 219 – 288

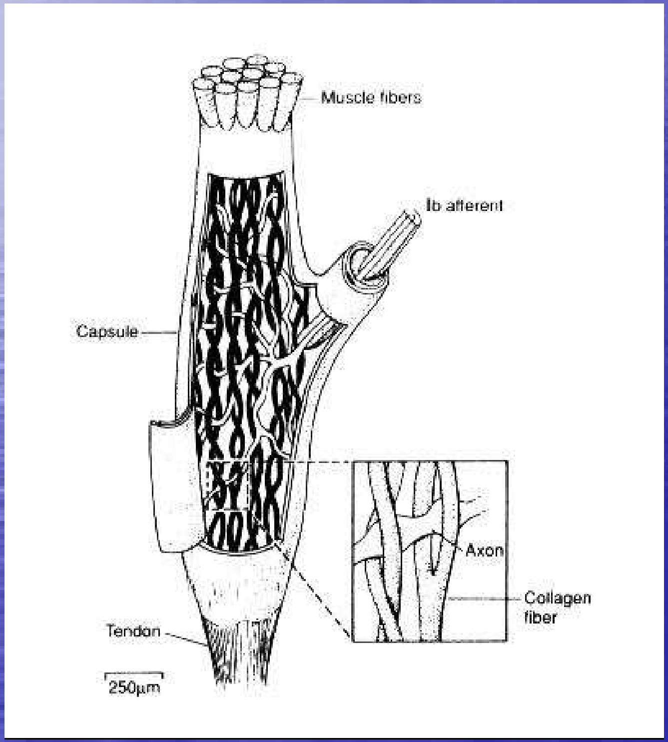
muscle length
muscle velocity
γ_s-motor neuron
γ_d-motor neuron

Muscle Spindle

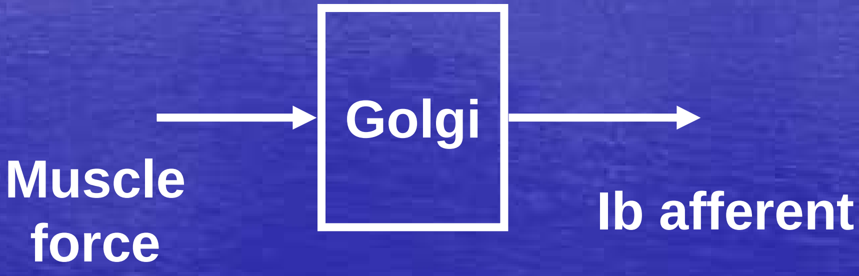
Ia afferent nerve
II afferent nerve

Muscle force feedback:

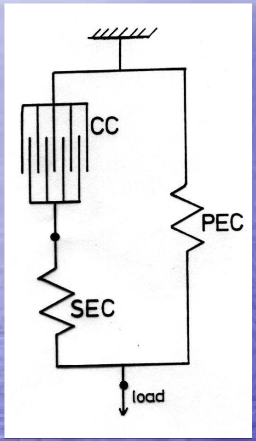
Golgi Tendon Organ

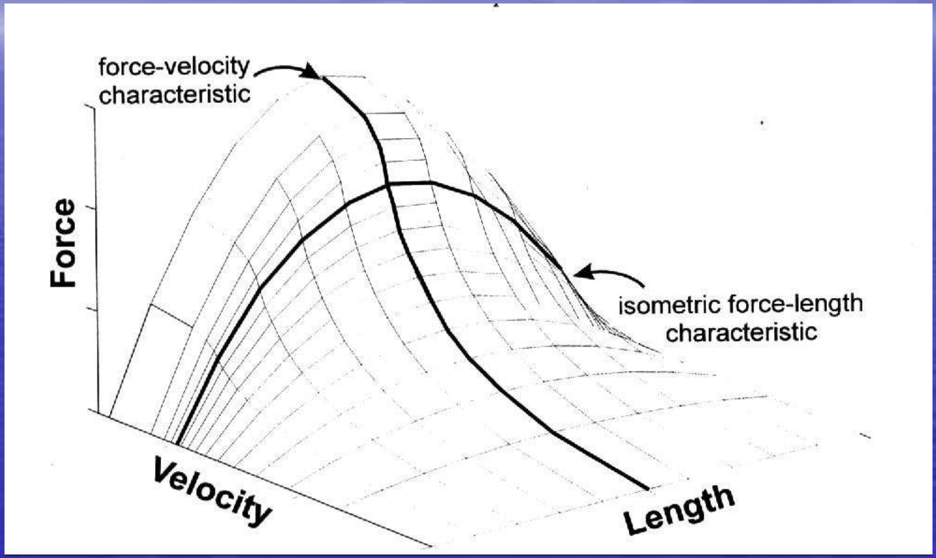


Kandel E.R., Schwartz J.H. and Jessel T.M. (2000), Principles of Neuroscience, 4th Edition, McGraw-Hill, New York, USA



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

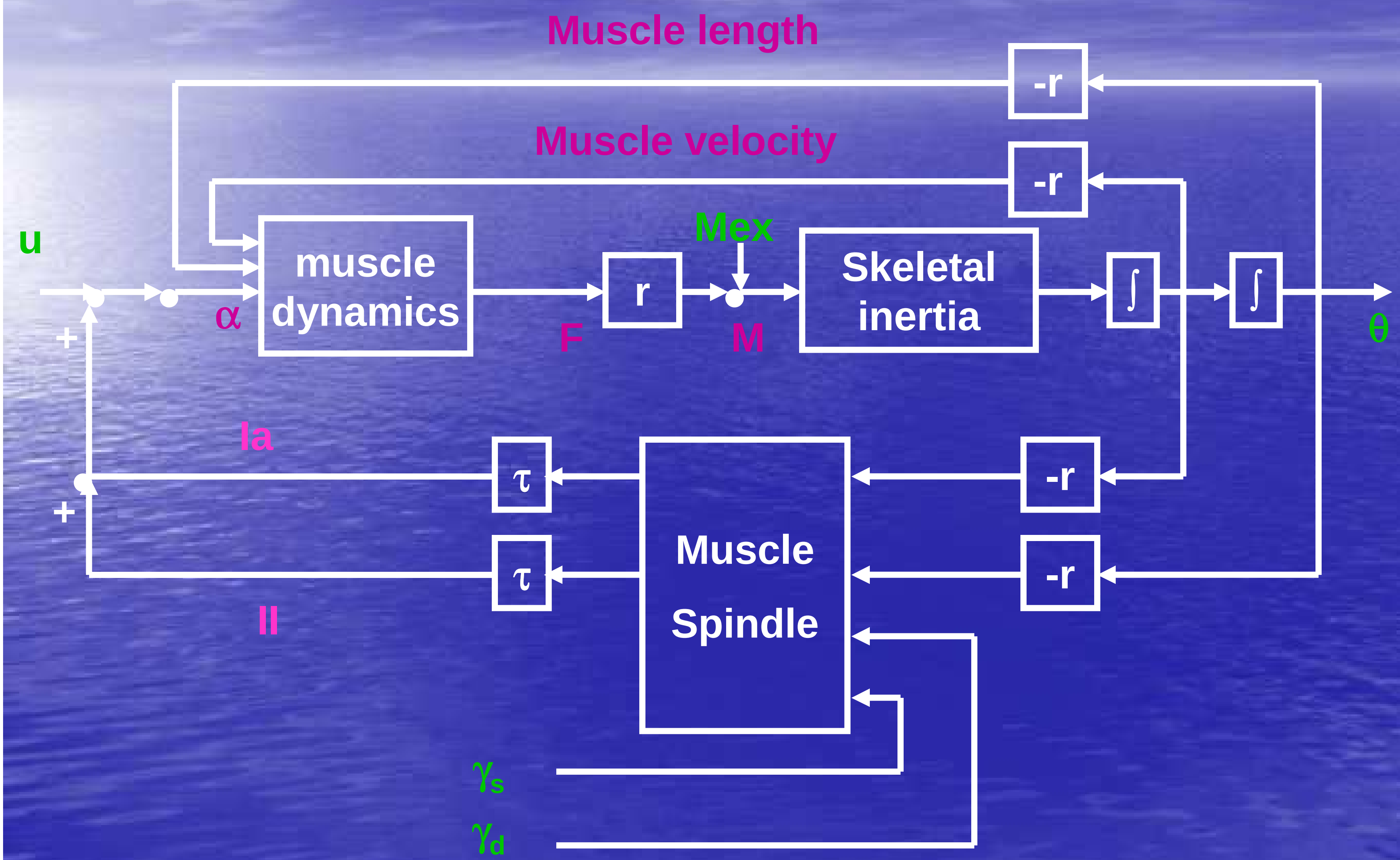
PEC: Parallel-Elastic component

(passive force-length characteristics of muscle)

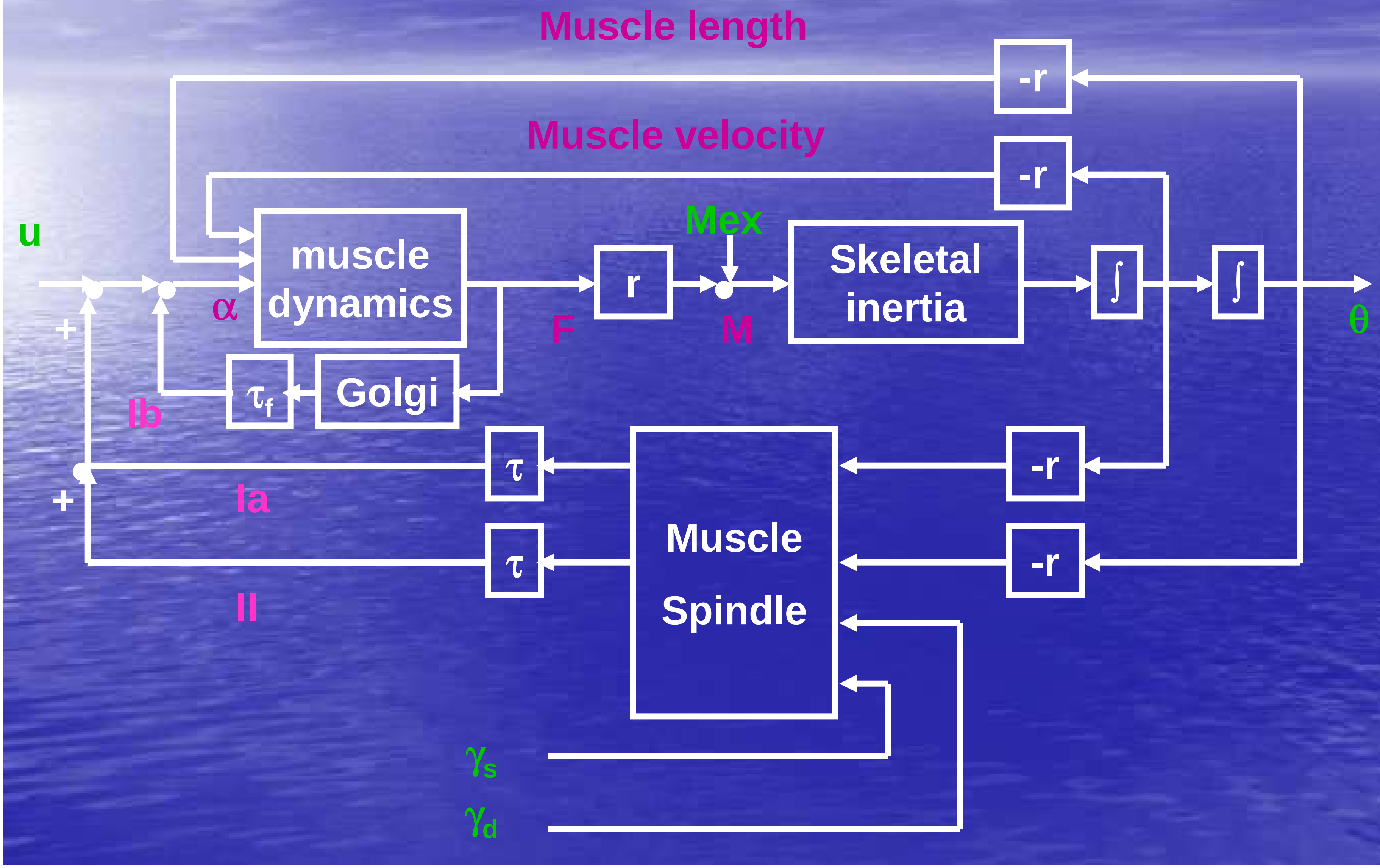
Feedback loops

- Intrinsic feedback
  - Muscle visco-elasticity: Muscle force depends on muscle length and contraction velocity
- Reflexive feedback
  - Length and velocity feedback through muscle spindles
    - Increase muscle stiffness and viscosity
  - Force feedback by GTOs
    - Decreases intrinsic feedback !!
    - Changes the bandwidth of the activation dynamics (force controller)

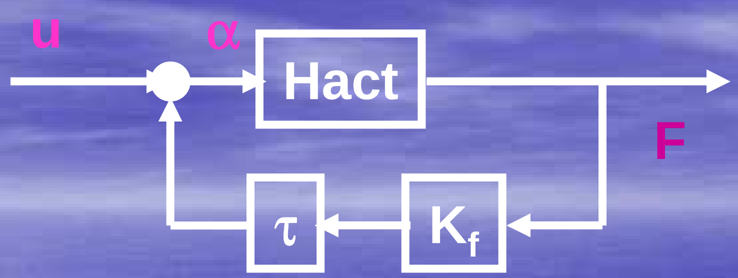
Musculoskeletal models
with length & velocity feedback

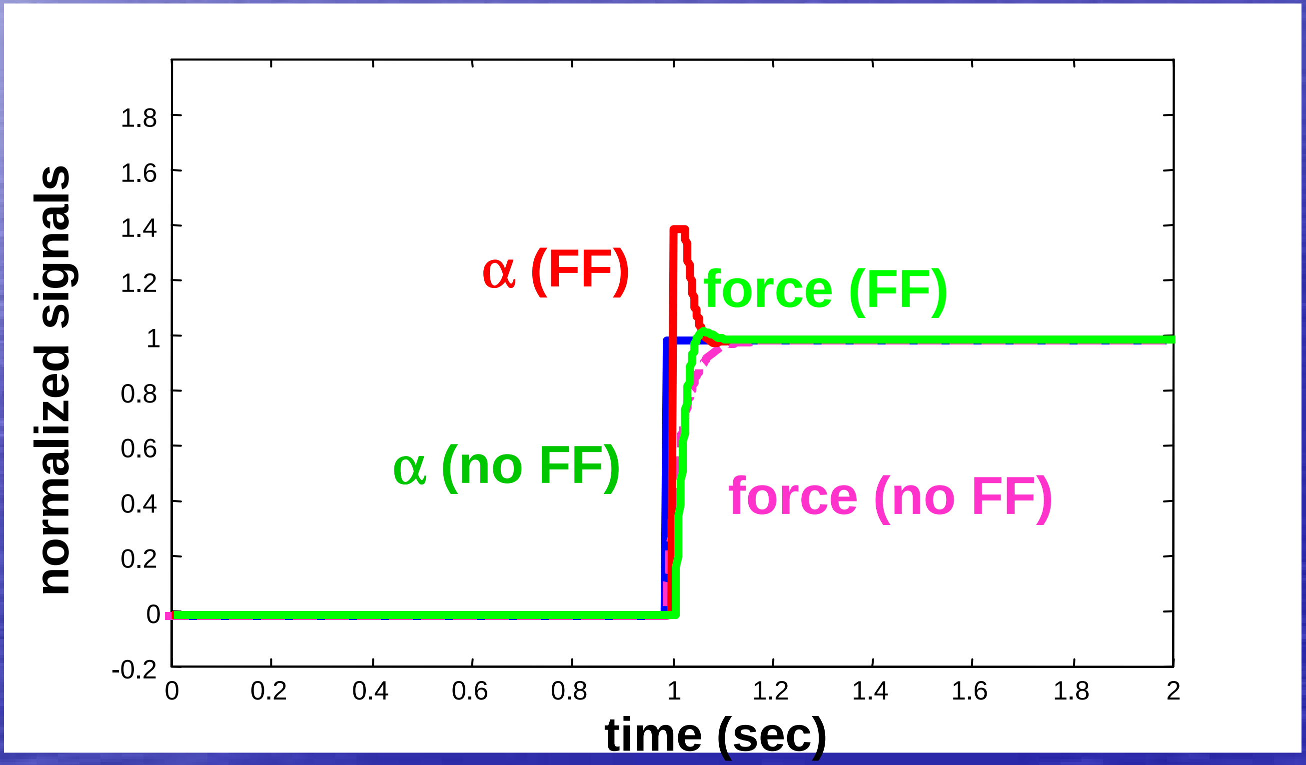


Musculoskeletal models
with length, velocity & force feedback

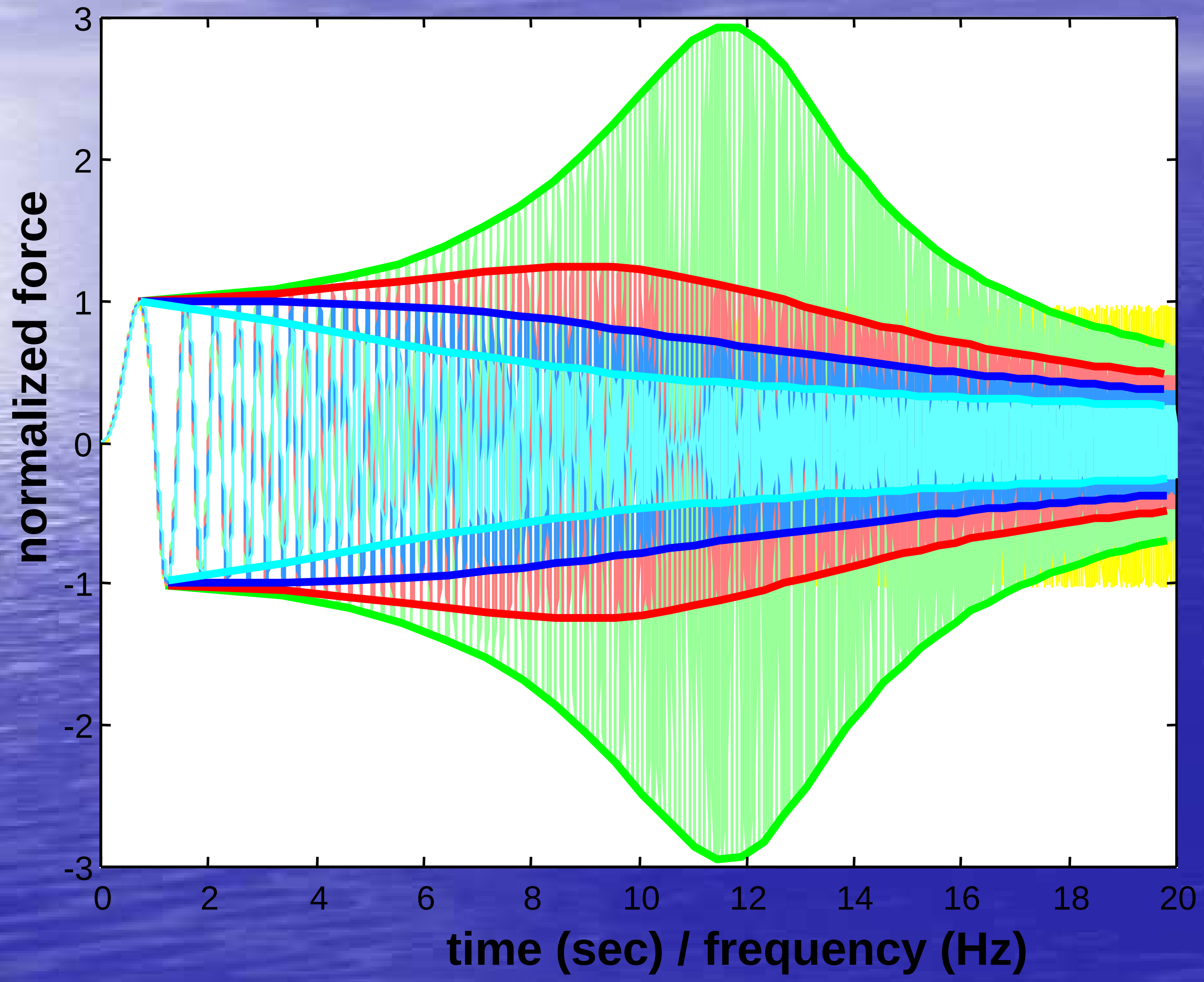


α - motor neuron activity & force





Effect of force feedback



Force feedback:

Neural input

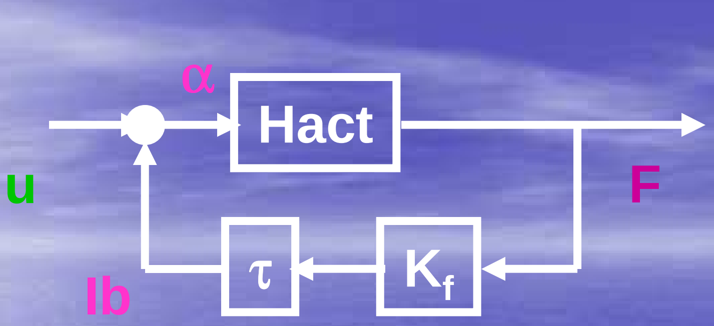
No force feedback

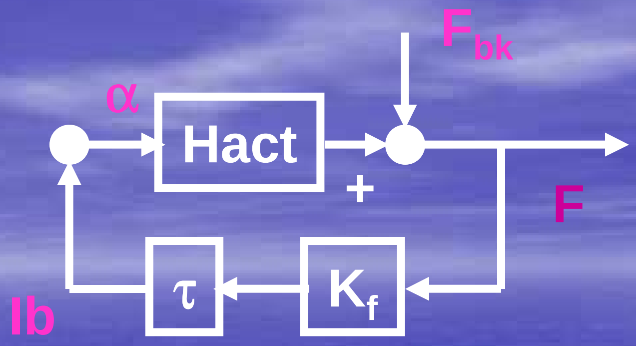
Loop gain = 0.4

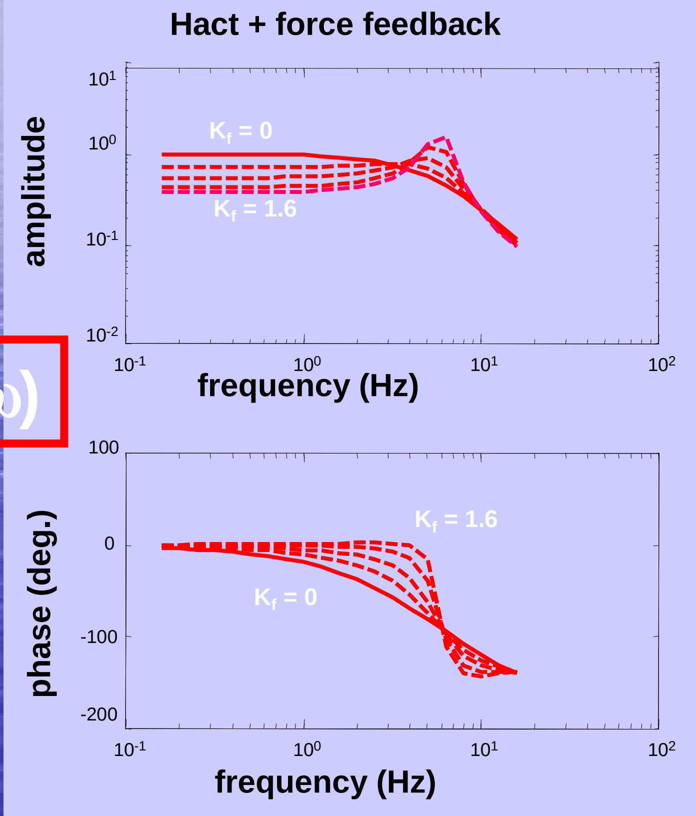
Loop gain = 0.8

Loop gain = 1.6

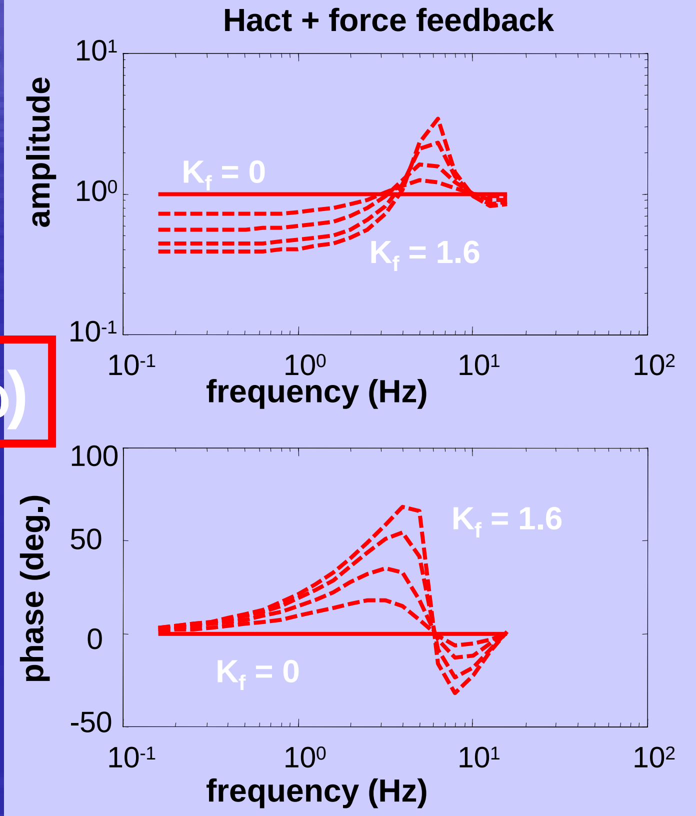
Activation dynamics with force feedback







$H^{*}_{act}(\omega)$



$H^{**}_{act}(\omega)$

Combined
Intrinsic and reflexive feedback

Overall impedance:

$$\frac{\theta(\omega)}{M_{ex}(\omega)} = \frac{1}{J.(j\omega)^2 + (H_{act}^{**}(\omega).B_m.r^2 + H_{act}^{*}(\omega).k_v.r^2.e^{-j\omega\tau}).j\omega + (H_{act}^{**}(\omega).K_m.r^2 + H_{act}^{*}(\omega).k_p.r^2.e^{-j\omega\tau})}$$

$$= \frac{1}{J.(j\omega)^2 + (H_{act}^{**}(\omega).B_{\mathrm{int}\,rinsic} + H_{act}^{*}(\omega).B_{reflexive}).j\omega + (H_{act}^{**}(\omega).K_{\mathrm{int}\,rinsic} + H_{act}^{*}(\omega).K_{reflexive})}$$

- feedback gains k_p and k_v represent γ_s and γ_d efferent stimulation
- no interaction between length and velocity signals
- bi-directional length and velocity feedback
- only short-latency monosynaptic reflexes
- (no cross-reflexes between muscles)

Stability of closed-loop system

- Analyze the open-loop transfer function:
  - Phase margin
  - Amplitude margin

$$\frac{\theta(\omega)}{M_{ex}(\omega)} = \frac{1}{J.(j\omega)^2 + (H_{act}^{**}(\omega).B_m.r^2 + H_{act}^{*}(\omega).k_v.r^2.e^{-j\omega\tau}).j\omega + (H_{act}^{**}(\omega).K_m.r^2 + H_{act}^{*}(\omega).k_p.r^2.e^{-j\omega\tau})}$$

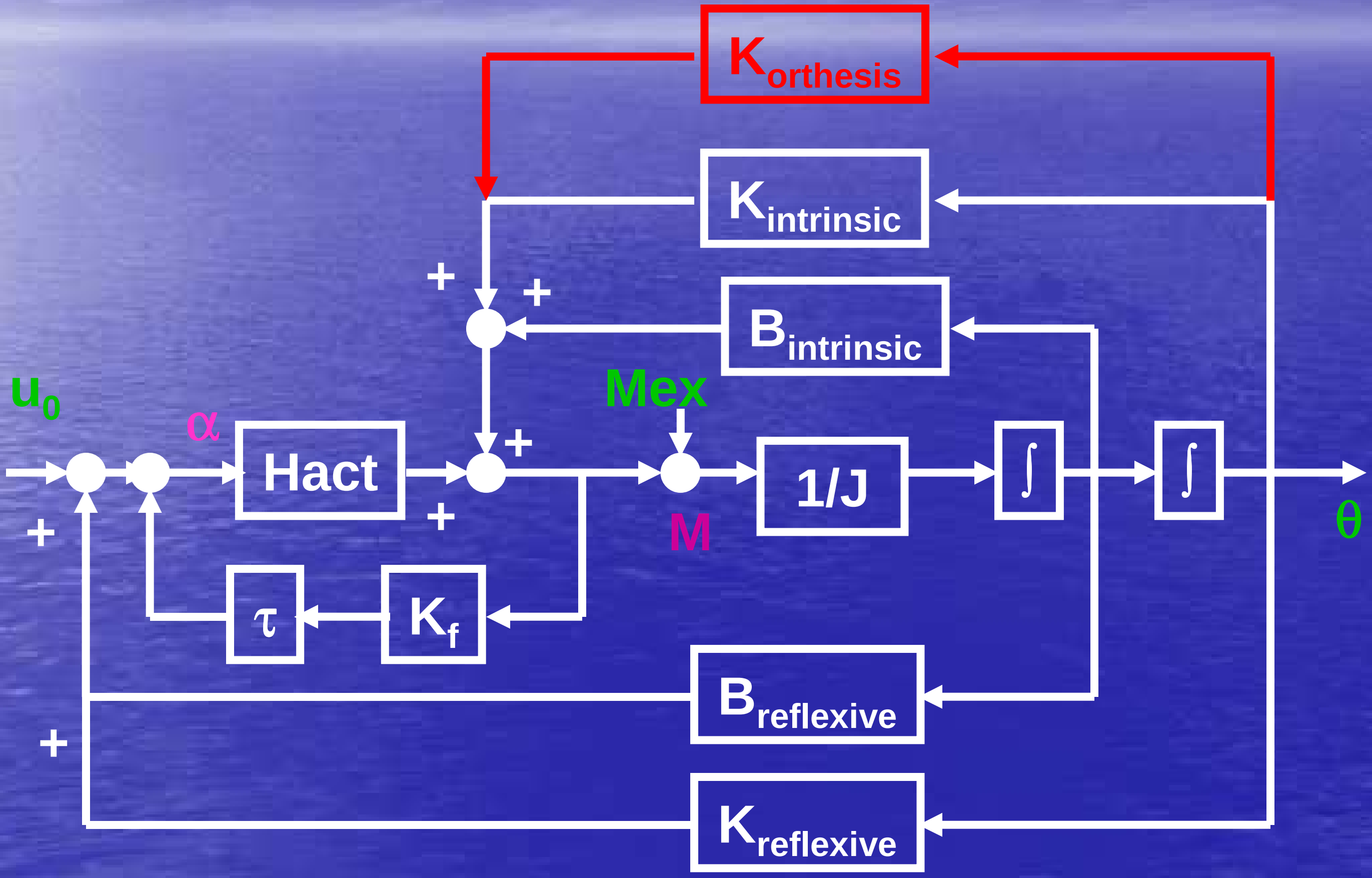
$$= \frac{\dfrac{1}{J.(j\omega)^2}}{1 + \dfrac{(H_{act}^{**}(\omega).B_m.r^2 + H_{act}^{*}(\omega).k_v.r^2.e^{-j\omega\tau}).j\omega + (H_{act}^{**}(\omega).K_m.r^2 + H_{act}^{*}(\omega).k_p.r^2.e^{-j\omega\tau})}{J.(j\omega)^2}}$$

$$H_{open\_loop}(\omega) = \frac{(H_{act}^{**}(\omega).B_m.r^2 + H_{act}^{*}(\omega).k_v.r^2.e^{-j\omega\tau}).j\omega + (H_{act}^{**}(\omega).K_m.r^2 + H_{act}^{*}(\omega).k_p.r^2.e^{-j\omega\tau})}{J.(j\omega)^2}$$

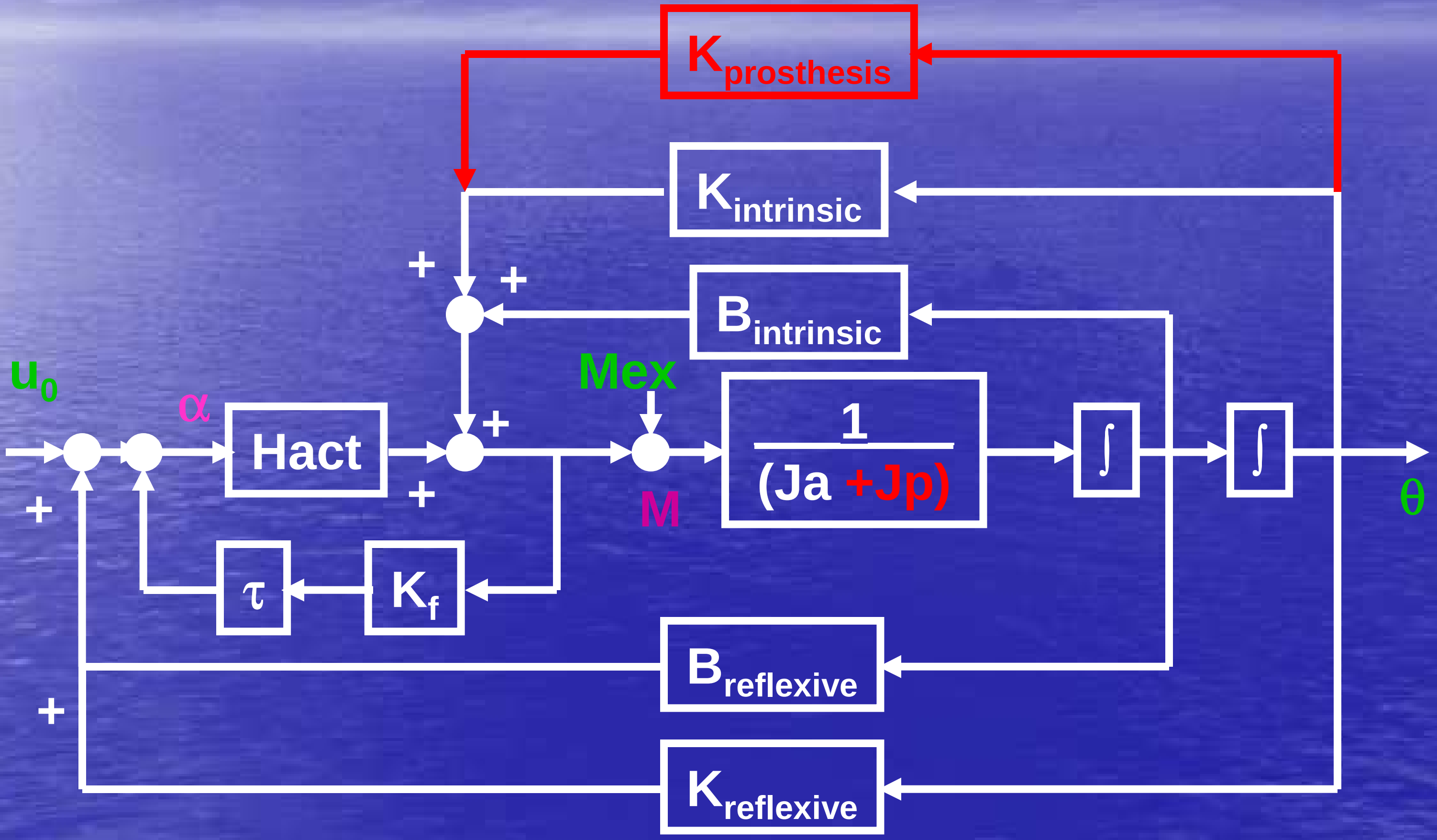
NMClab Demo

the Matlab GUI for linear analysis

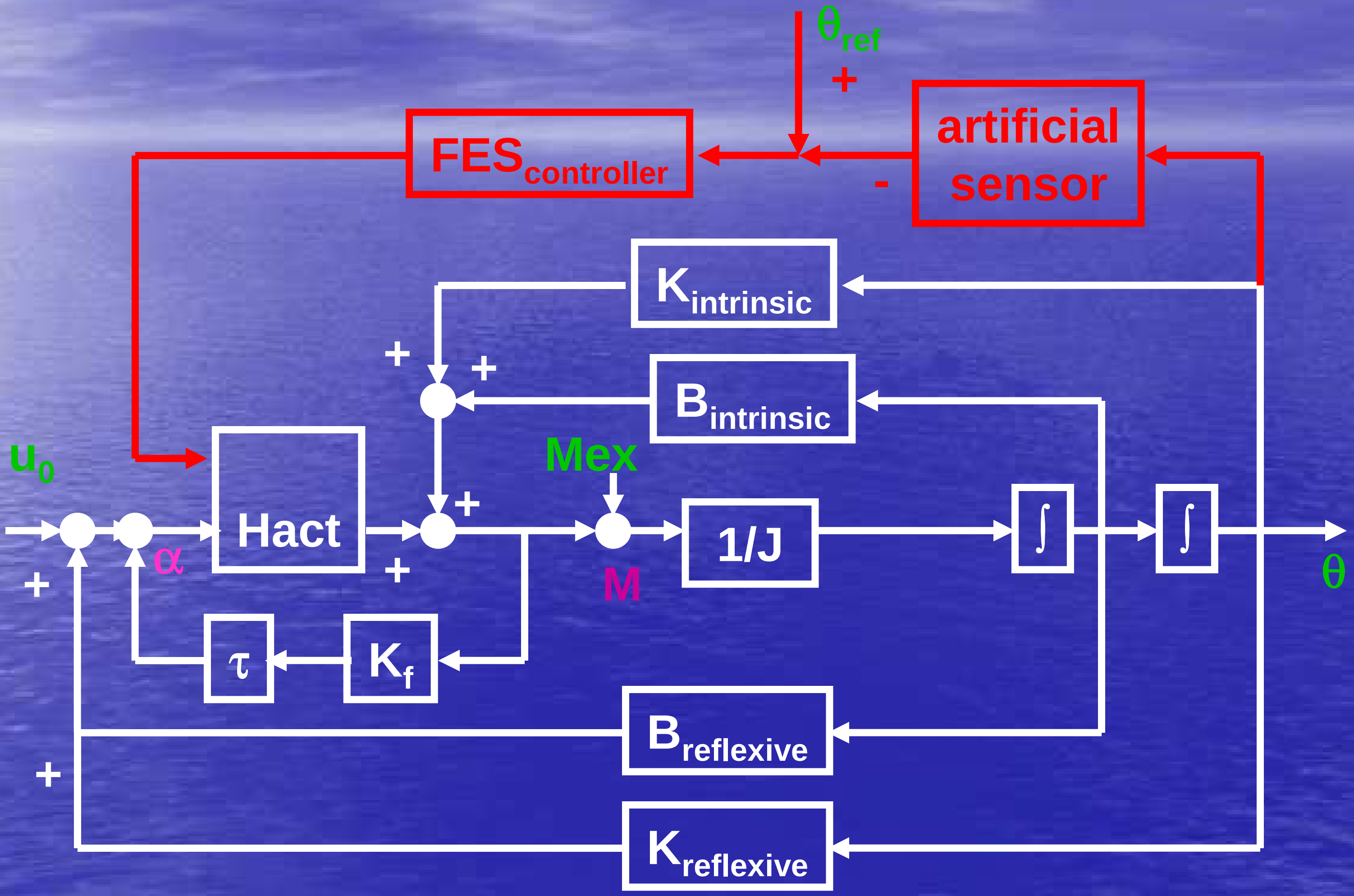
Motion control of orthosis



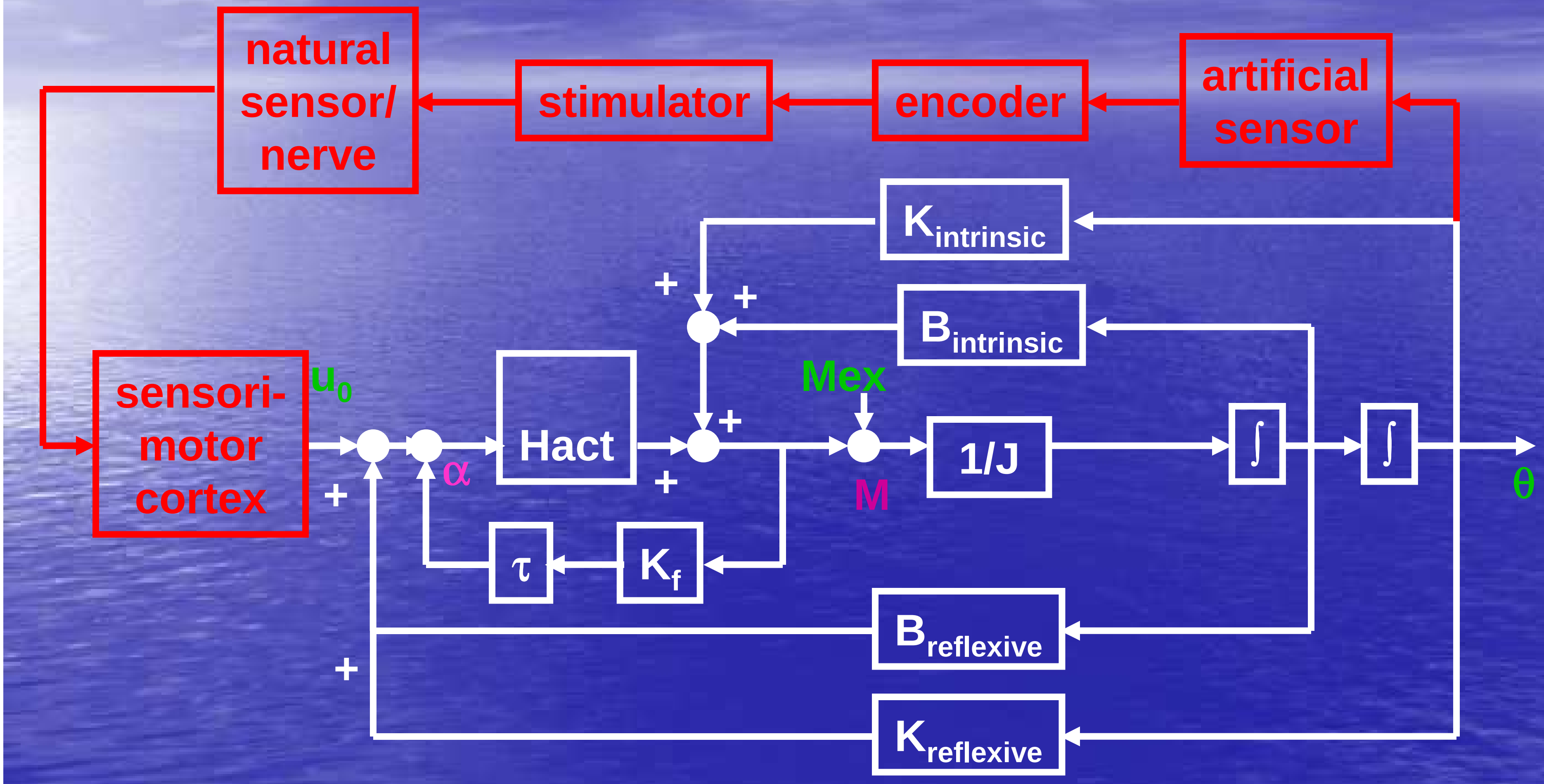
Motion control of prosthesis



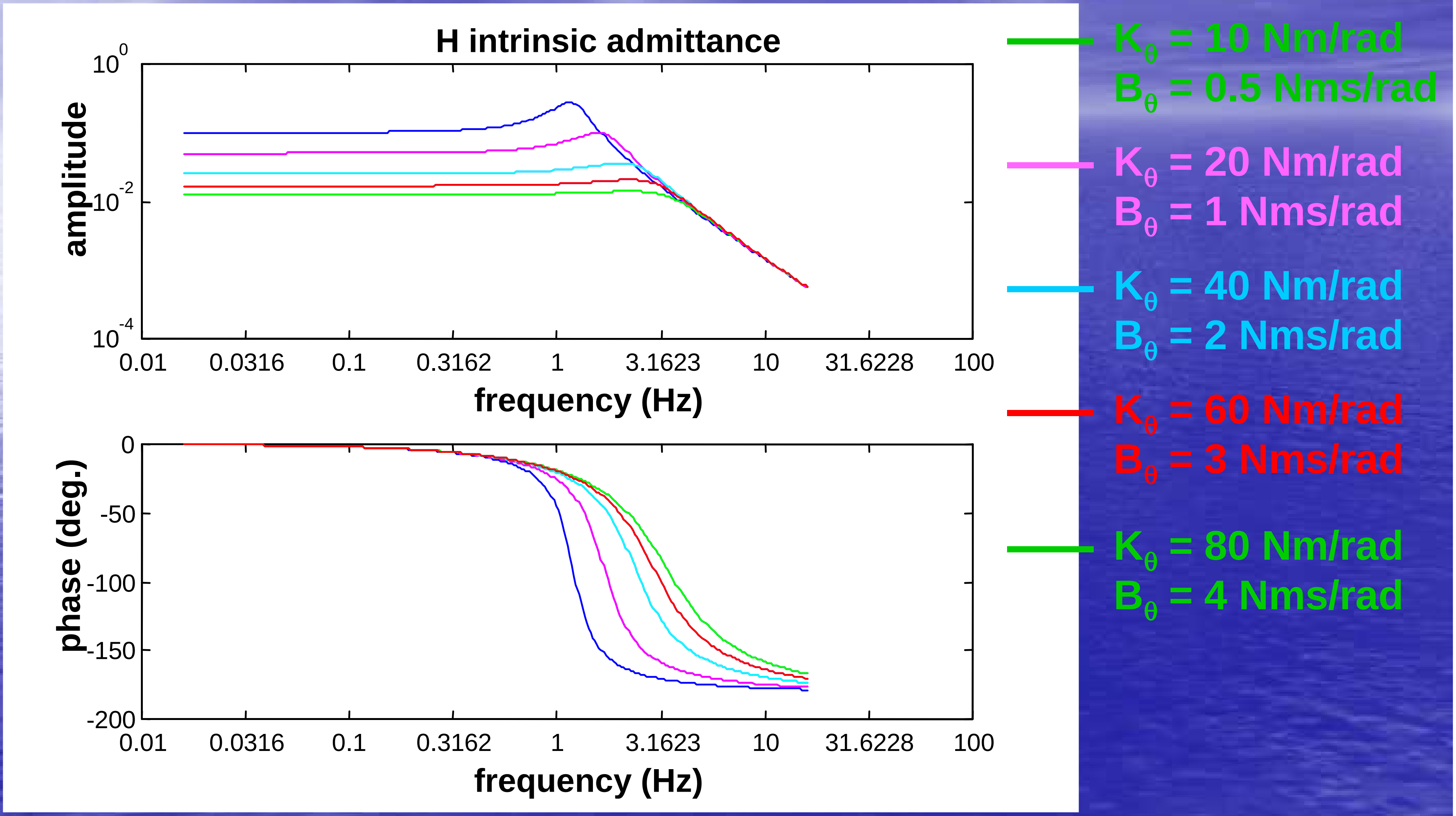
Motion control of FES



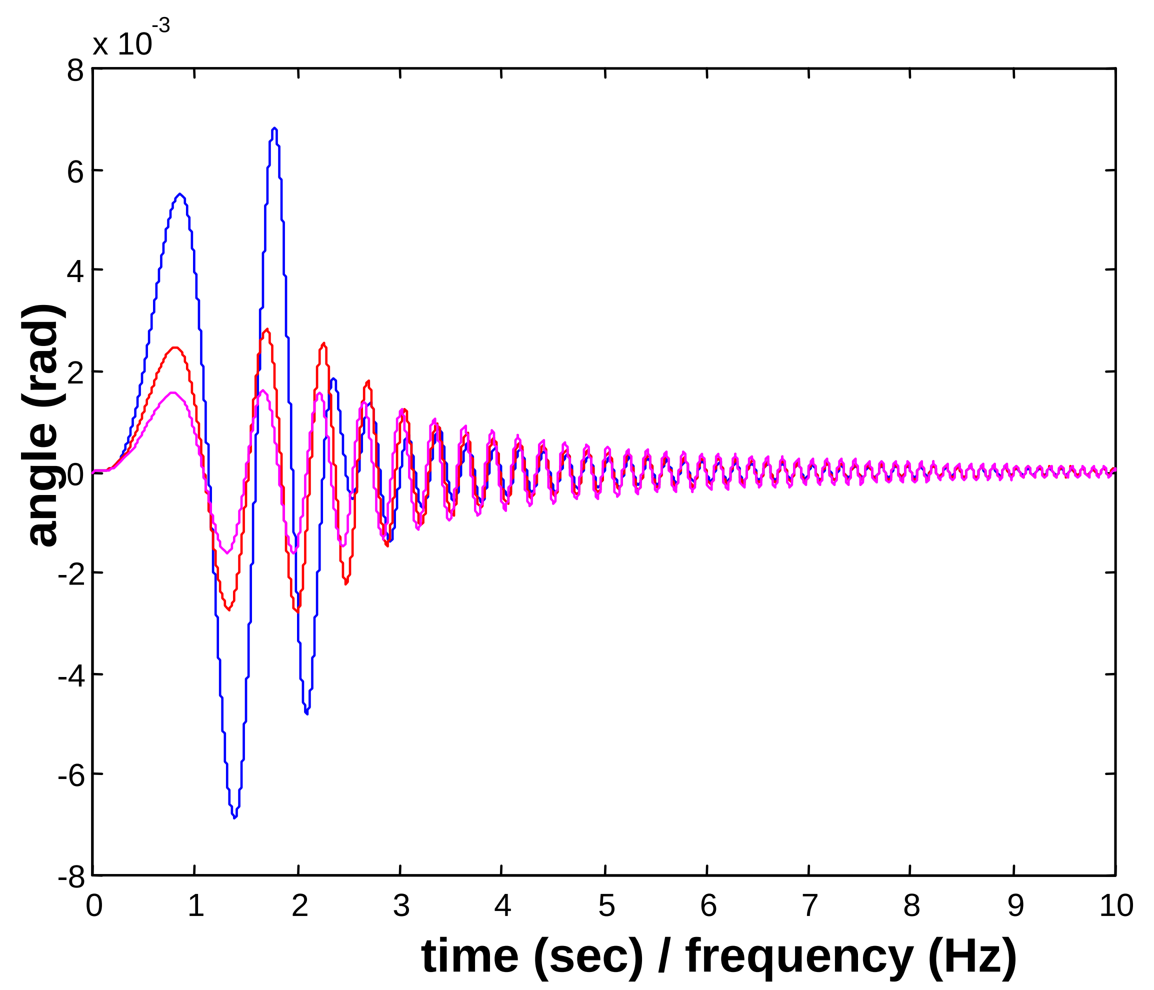
Motion control of artificial sensor



Intrinsic admittance (shoulder)



Effect of length & velocity feedback



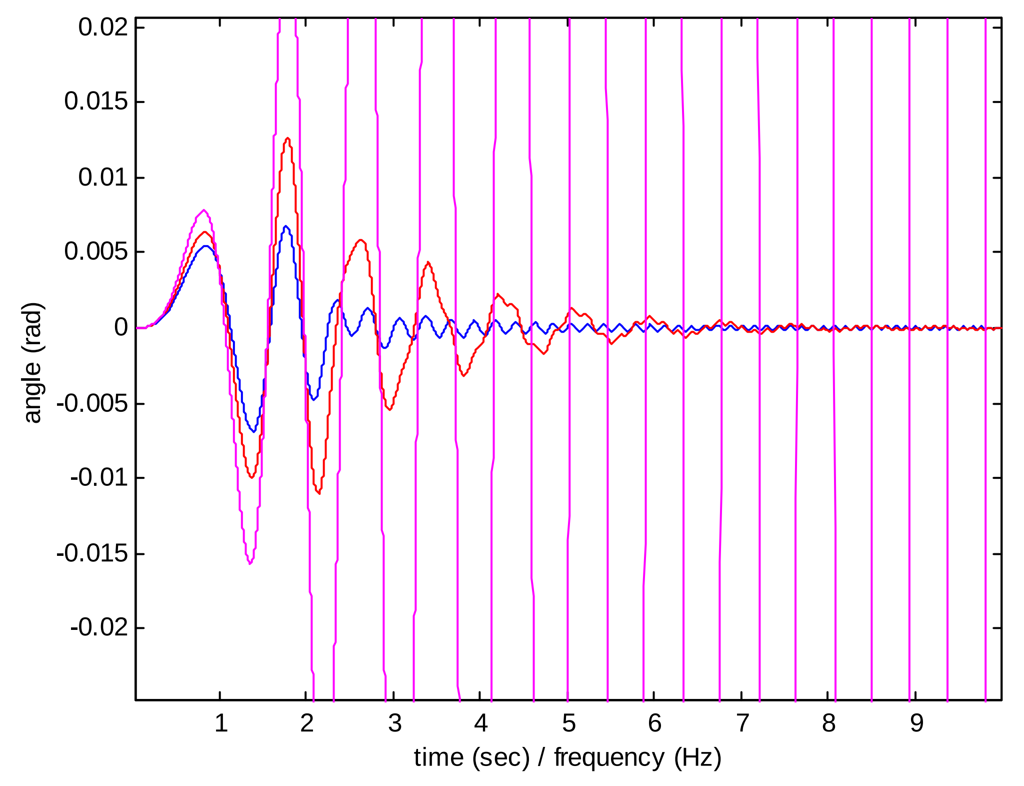
K_θ = 40 Nm/rad
B_θ = 2 Nms/rad

Kp = 300, Kv = 30

Kp = 600, Kv = 60

Kp = 900, Kv = 90

Effect of velocity feedback



K_θ = 40 Nm/rad
B_θ = 2 Nms/rad

Kp = 300, Kv = 30

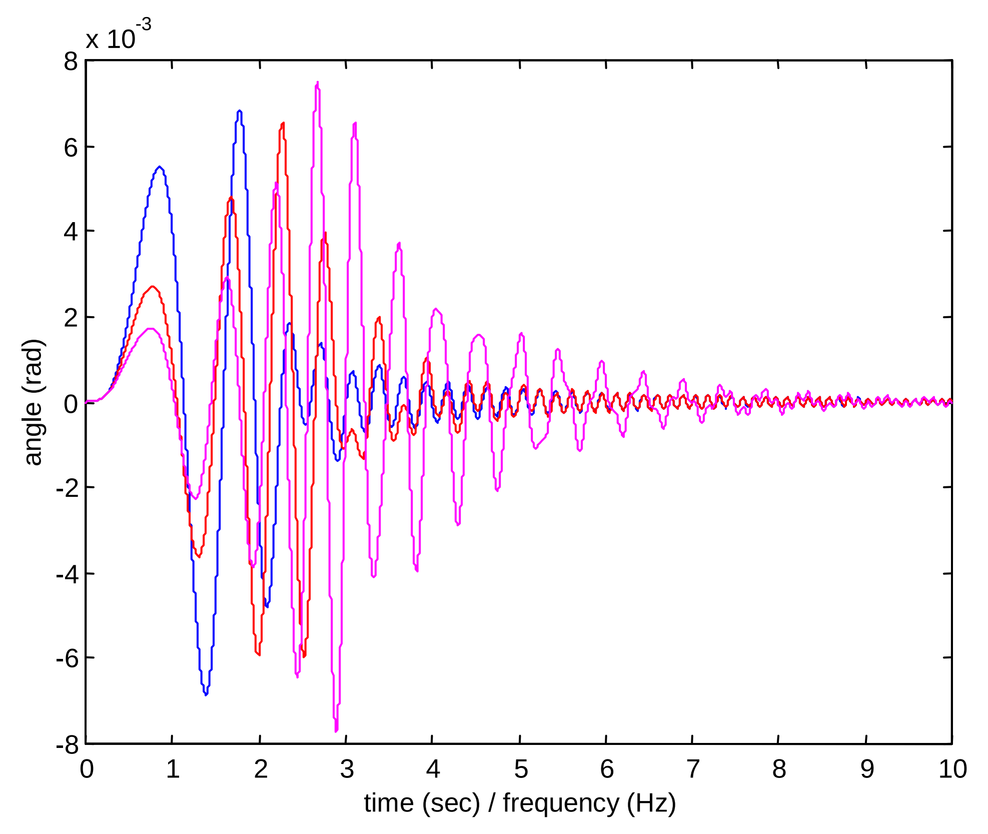
Kp = 300, Kv = 15

Kp = 300, Kv = 0

⇒ Instability !!

Effect of length feedback

K_θ = 40 Nm/rad
B_θ = 2 Nms/rad



Kp = 300, Kv = 30

Kp = 600, Kv = 30

Kp = 900, Kv = 30

Effect of length feedback

- Decrease of low frequency admittance (increase of 'stiffness')
- Oscillation frequency becomes higher:

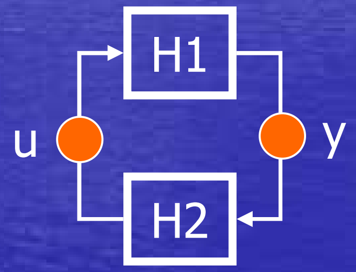
$$\omega_o = \sqrt{\frac{K}{J}}$$

- relative damping becomes lower:

$$\beta = \frac{B}{2\sqrt{K.J}}$$

Experimental approach

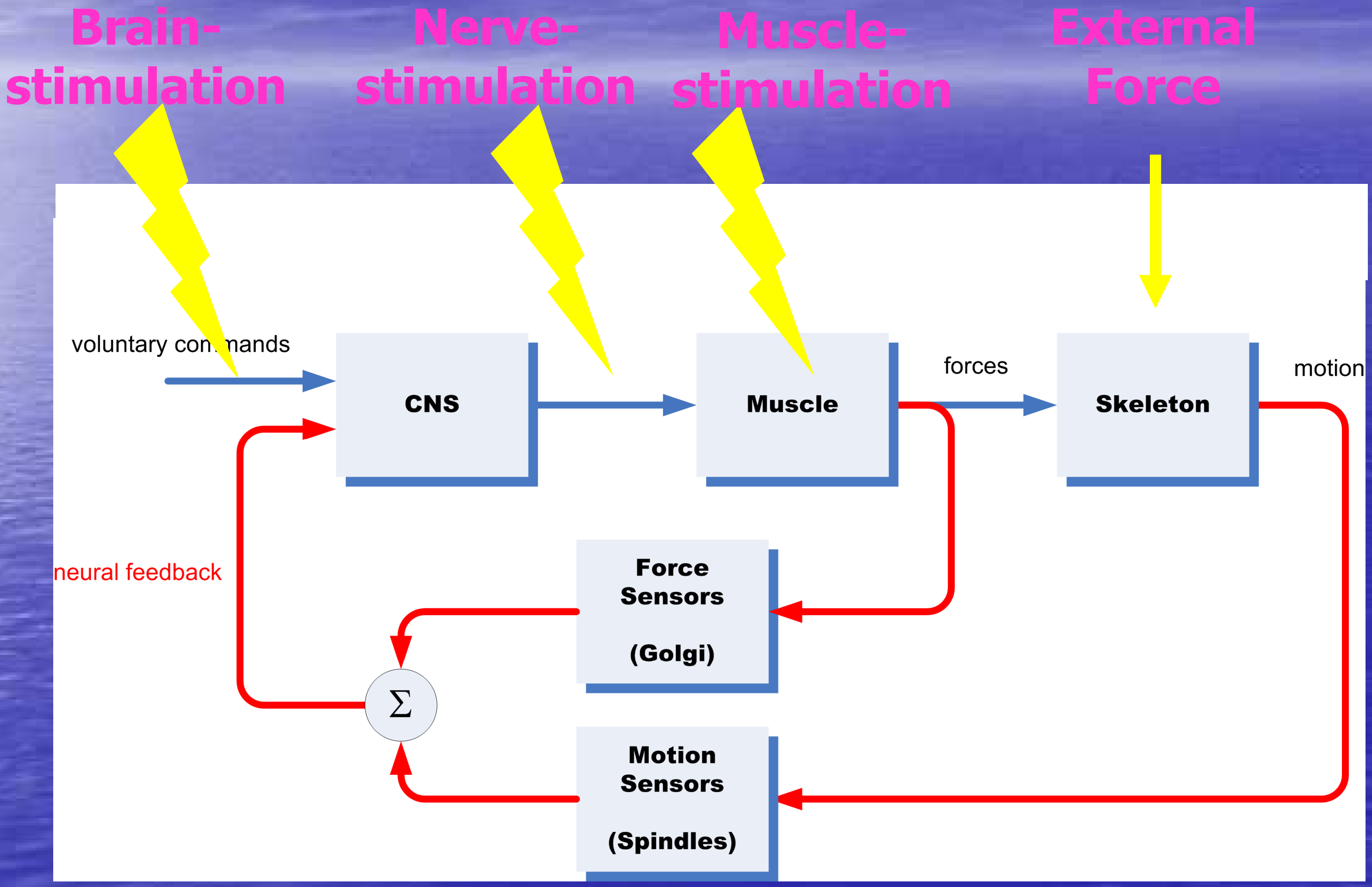
- Closed-loop system
  - causality problem: cause and effect can not be separated in a straightforward manner



$u/y = H2 = H1^{-1}$

- Solve the problem by using an external (perturbation) signal (Course SIPE wb2301)

Stimulus-Response Approach



External force is most natural stimulus !

Input signals

- Use ***manipulable*** or ***measurable external*** input signal
- Frequency content
- Duration of trial
- Number of repetitions per trial
- (Quasi-)stochastic: Prevent feedforward responses
- Task instructions:
  - "Do not intervene": Low impedance
  - "Minimize position perturbations": High impedance

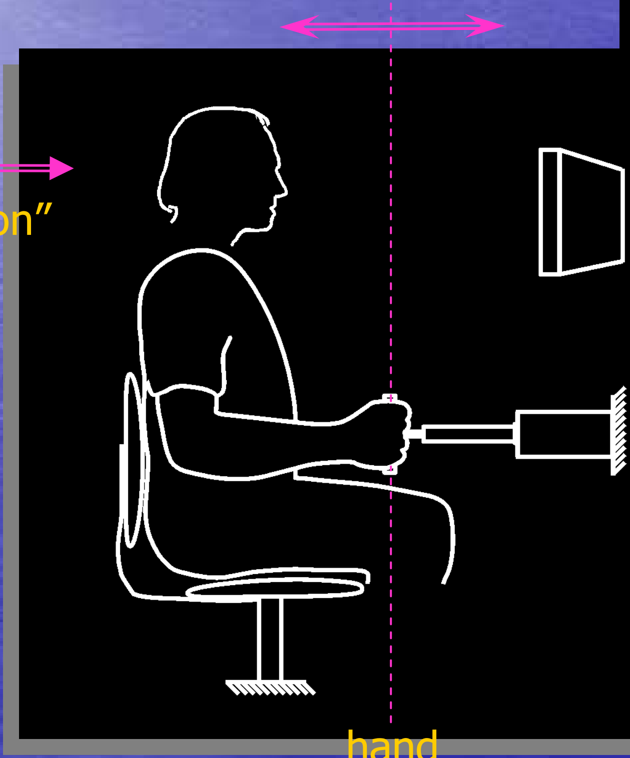
Experiments with upper and lower extremities (1998-now NMC Lab TUDelft and LUMC)

main goal: quanification of intrinsic and reflexive properties

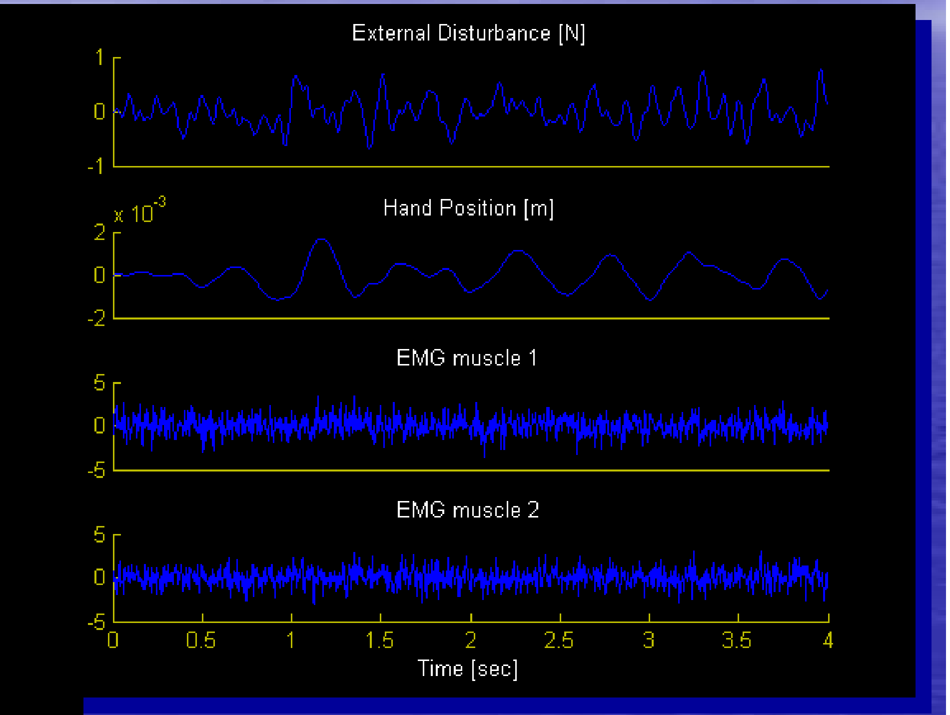
Force Perturbations – Position Task

unpredictable external
force disturbances

task:
"maintain position"



hand
position

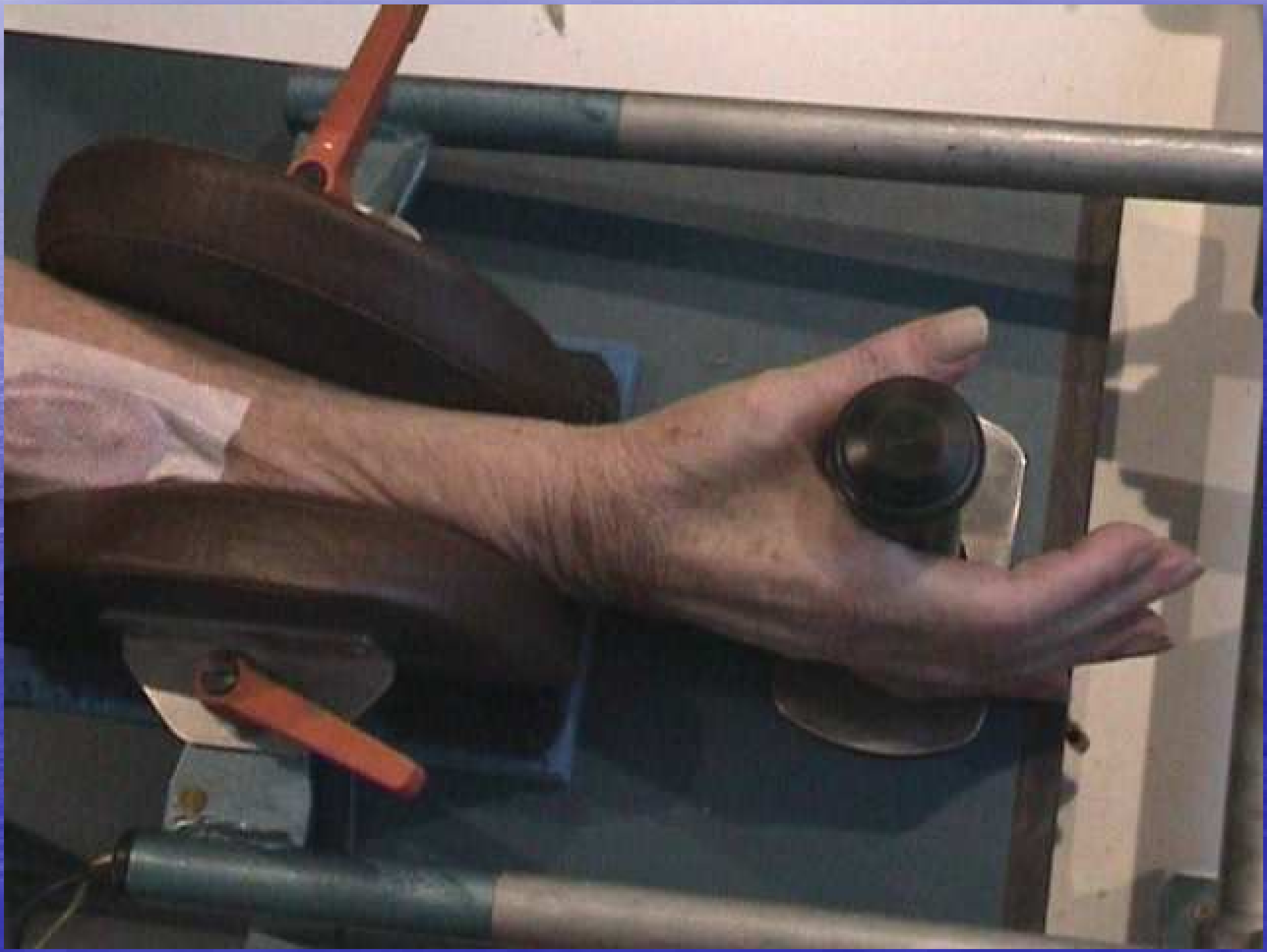


Posture Control: 1D Arm Motions
"Proprio" Robot

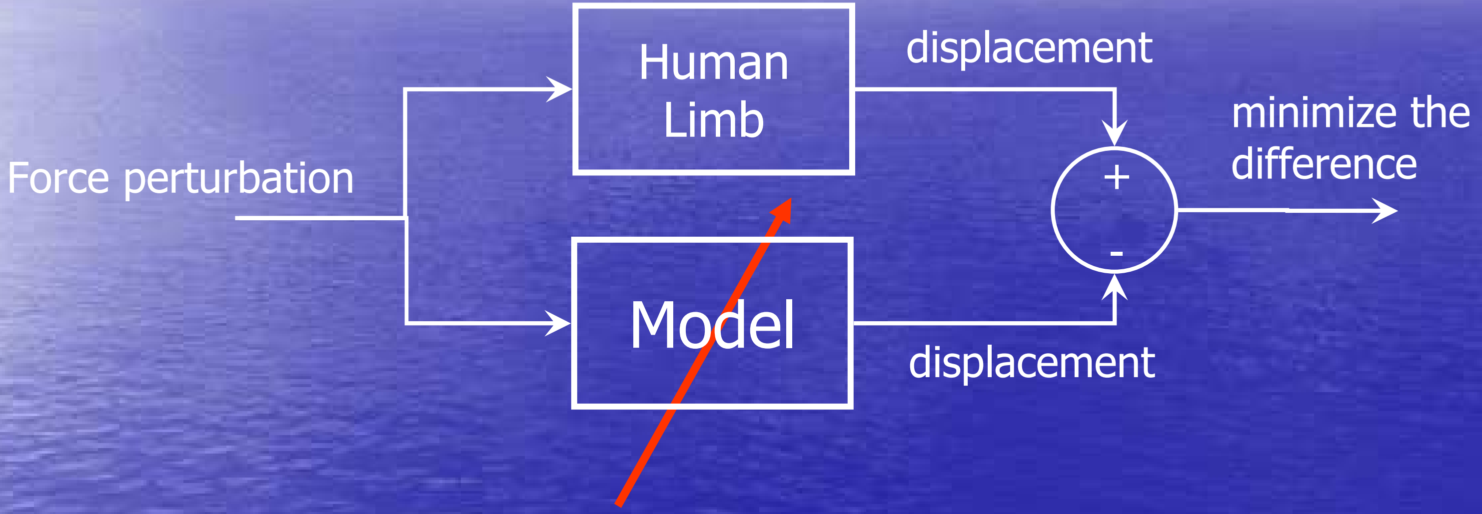
Posture Control: 2D Arm Motions “ARMANDA” Robot

minimize my hand displacement

Patient Studies 1D Wrist Motion
“Pope” Robot



Parameterization of models

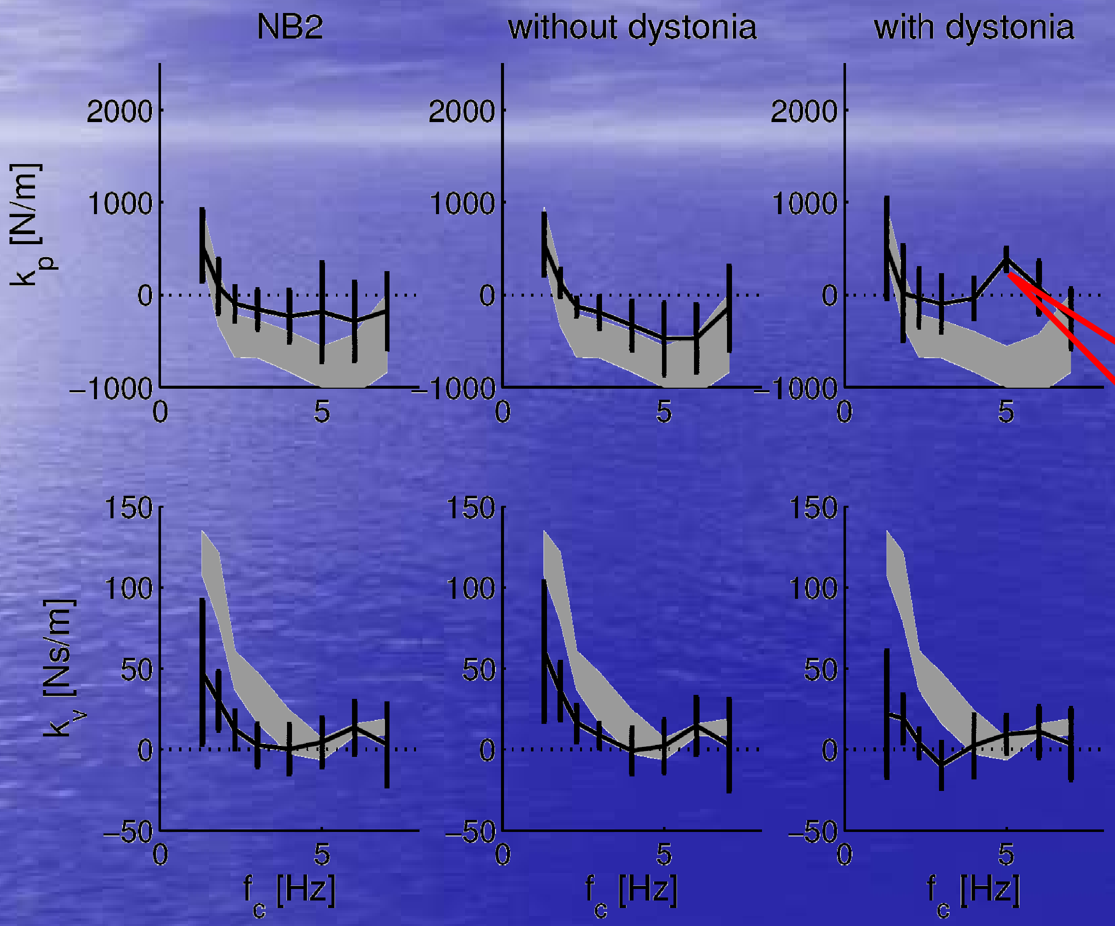


adjust the model parameters until
difference is at a minimum

Two ways of parameterization

1. analytical using transferfunctions
2. simulation

Results from CRPS Study



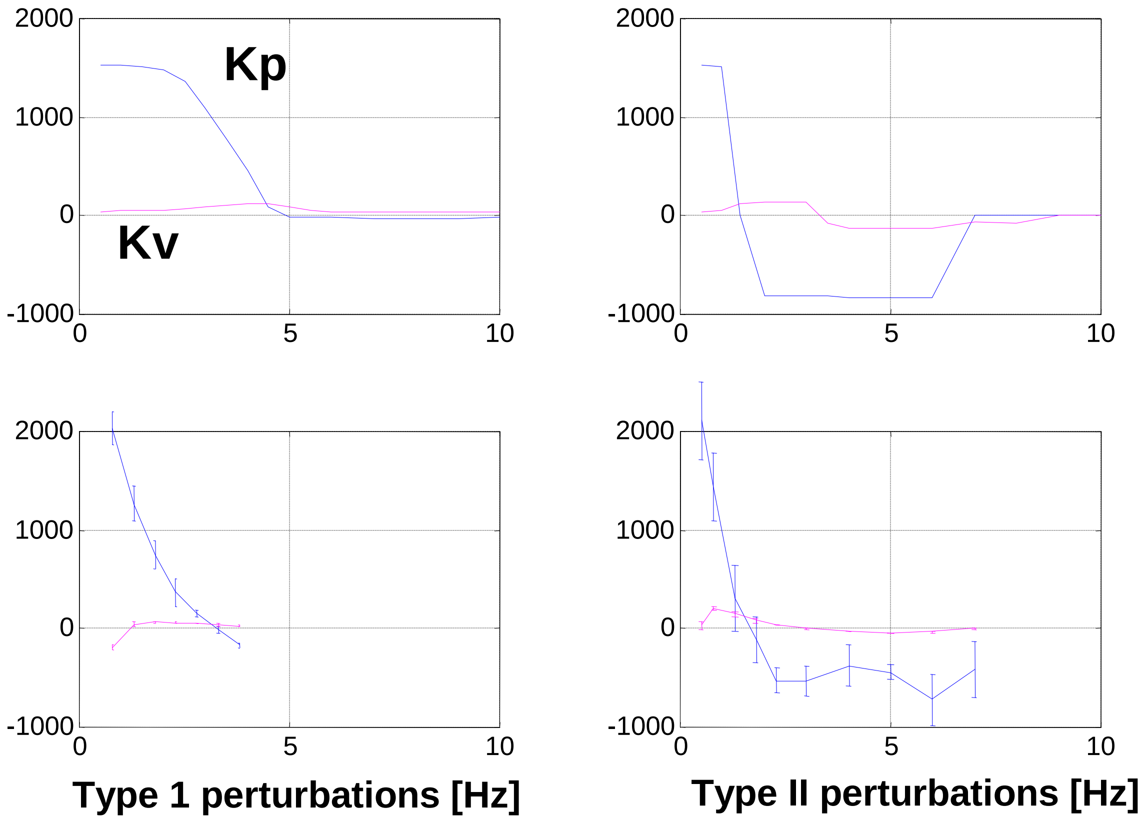
CRPS with dystonia:
No negative gains!

Figure 3.2: *Mean reflexive parameters for NB2 disturbance. Left: CRPS patients (n = 12); middle: CRPS patients without a tonic dystonia (n = 8); right: CRPS patients with a tonic dystonia (n = 4). The error bars denotes the means ± SD. The grey area denotes the mean ± SD of healthy subjects.*

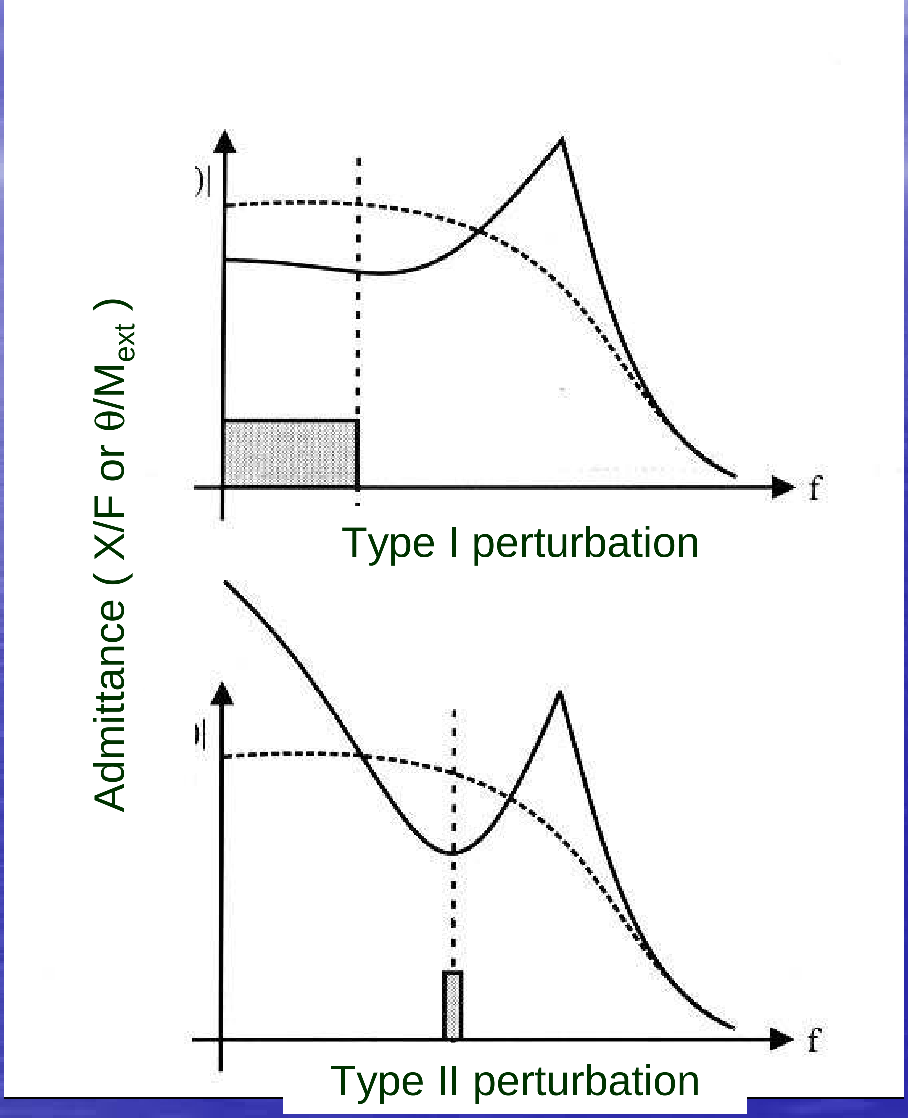
Optimized vs. recorded feedback gains k_p and k_v

Optimized

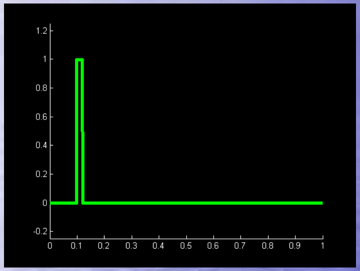
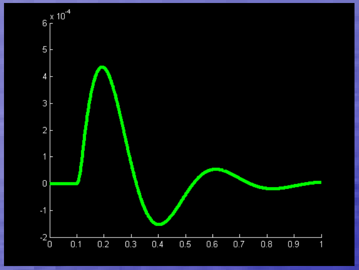
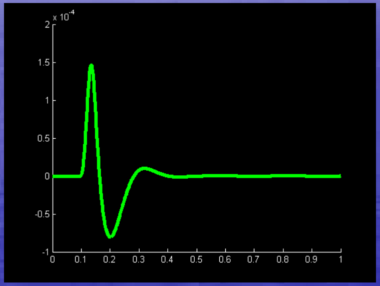
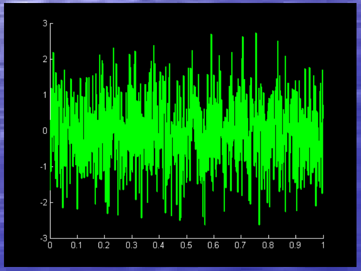
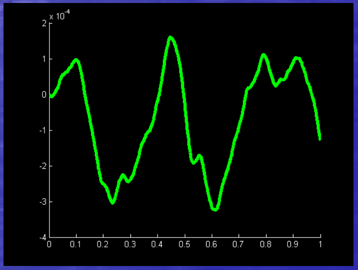
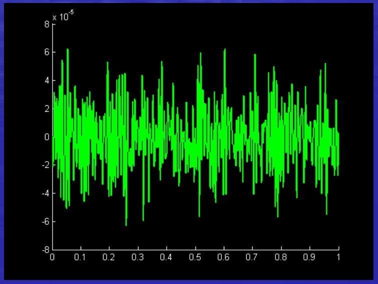
Measured



Concept of posture control: Optimal admittance



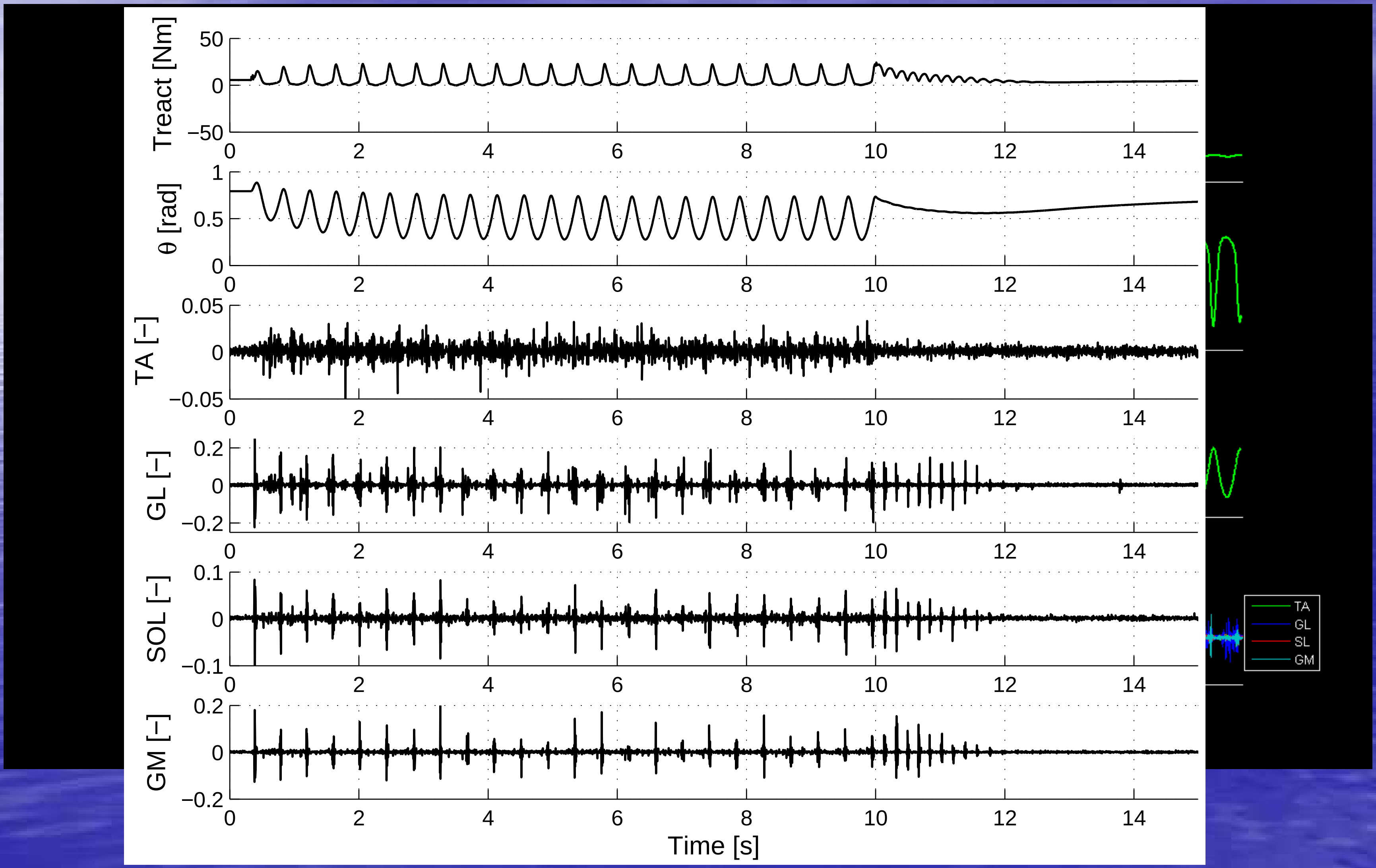
Force perturbations

External force	*Joint angle*	*EMG*	*Application*
transients 			- estimates the state just before the stimulus - time domain analysis - NMC studies (2005 - …)
colored noise 			- closed loop correllation techniques required - appropriate for linear system behavior - e.g. posture tasks - NMC studies (1998 - …)

Clonus (Stroke)

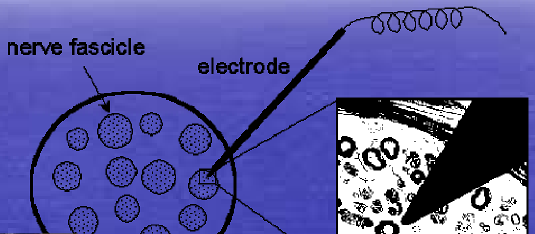
movie

Clonus (Stroke)



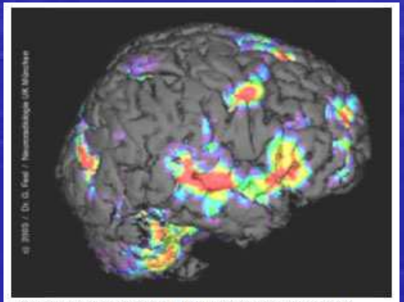
Upcoming research

- Identification of Time-Varying Reflexes during Movement
- Microneurography (Direct nerve measurements)



- EEG-EMG (Correlation brain-muscles)

- EEG-fMRI-Motion (Brain locations)



Aktivierung der Hirnoberfläche bei einer Sprachaufgabe

- Nonlinear models including motorneuron properties

Conclusions

- Reflexes have very large effect on the joint dynamics
- Proprioceptive feedback system is adaptive
- Reflex gains are different in patients
- Robotic identification techniques provide detailed insight in the human motion system:
  - fundamental knowledge
  - clinical applications