ESCOLA POLITÉCNICA DA UNIVERSIDADE DE SÃO PAULO

Biological Motor Control

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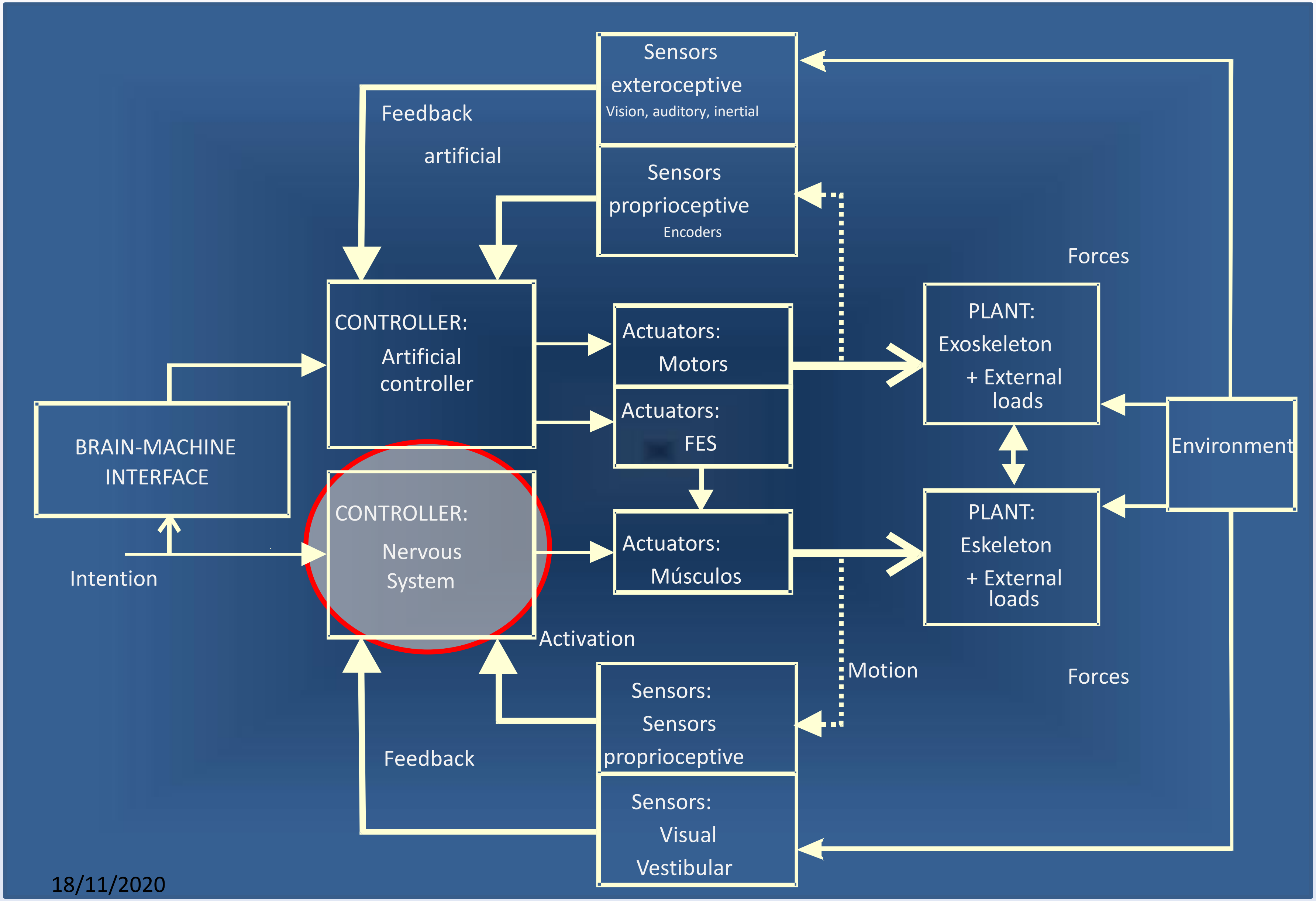
Contents

Introduction

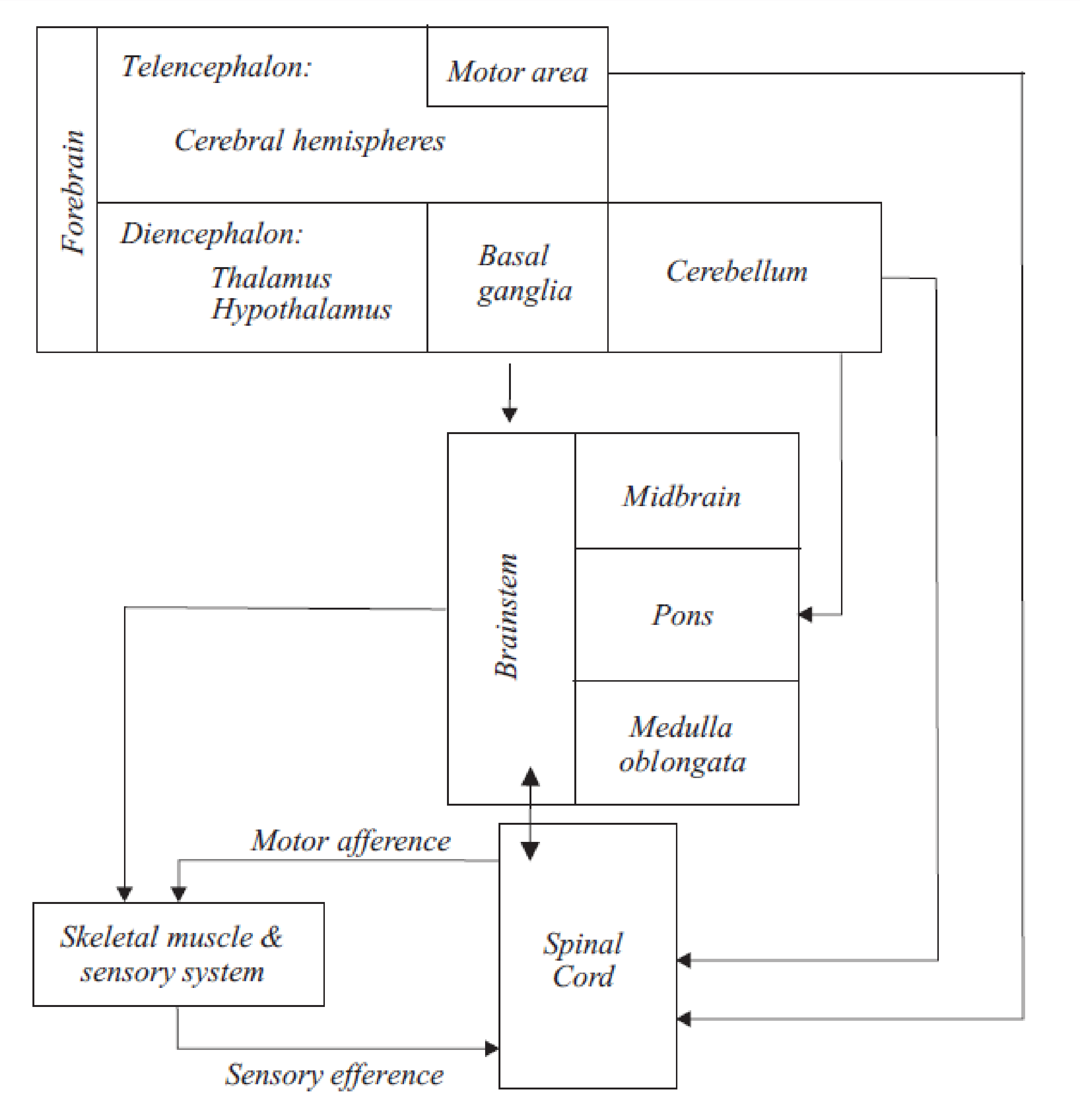
- Motivation
  - Understanding the system
  - Intervention:
    - Rehabilitation
    - Training
  - Functional compensation
  - Functional electrical stimulation
  - Development of bioinspired control systems

Motor compensation



Goals

- Introduce the Nervous system as a controller:
  - Hierarchical structure
  - Reflexes and modulation
  - “Optimal” interaction with the environment
- Controversies in the biological motor control:
  - Equilibrium-point theories
  - Internal models theories
- Motor control problems:
  - Motor control disturbances cause disabilities
  - Summary of the motor disturbances



Chapter 2. Basis for Bioinspiration and Biomimetism in Wearable Robots. Forner-Cordero,et al. Wearable Robots: Biomechatronic Exoskeletons. Editor: J. L. Pons (2008) John Wiley & Sons, Ltd.

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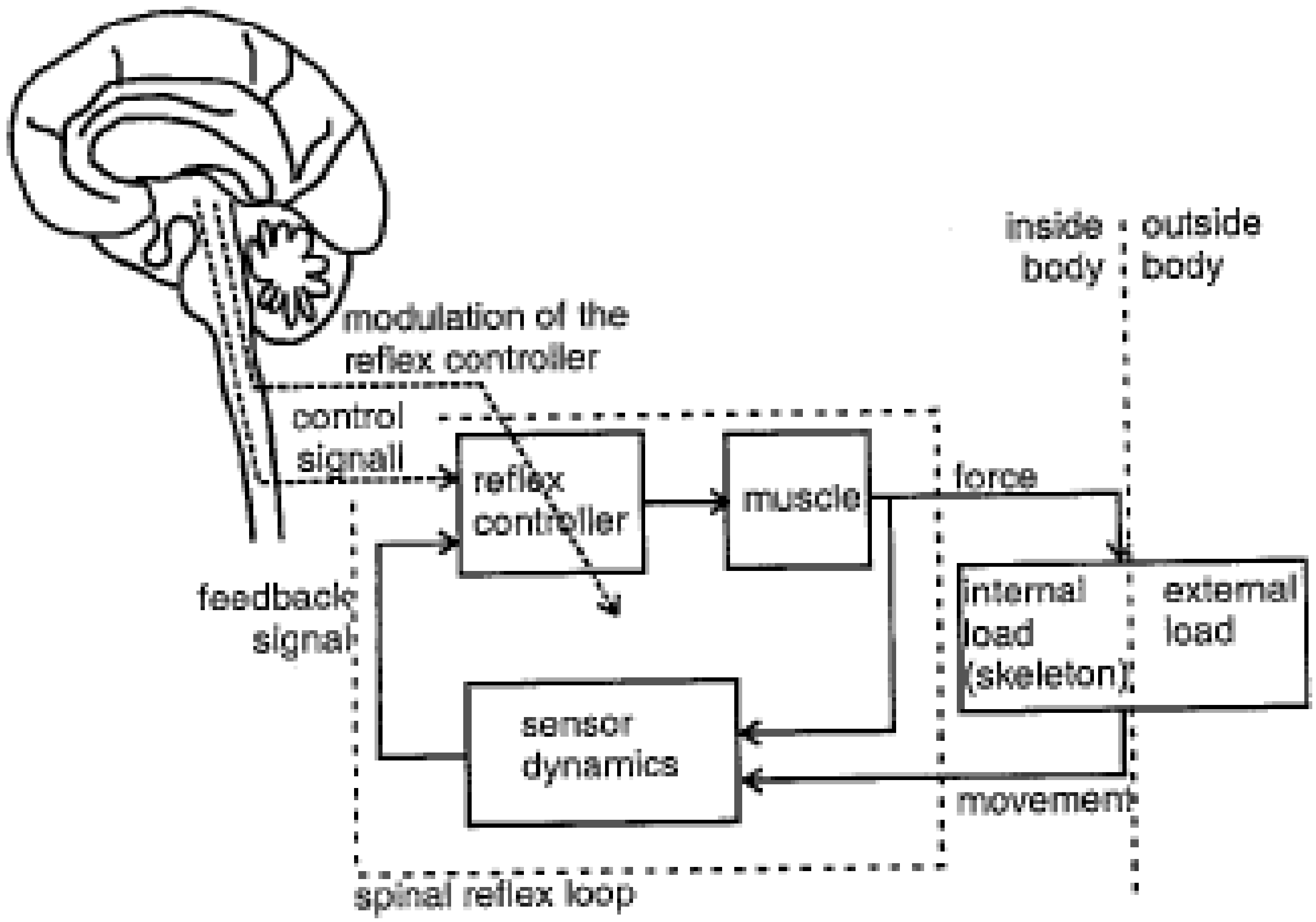
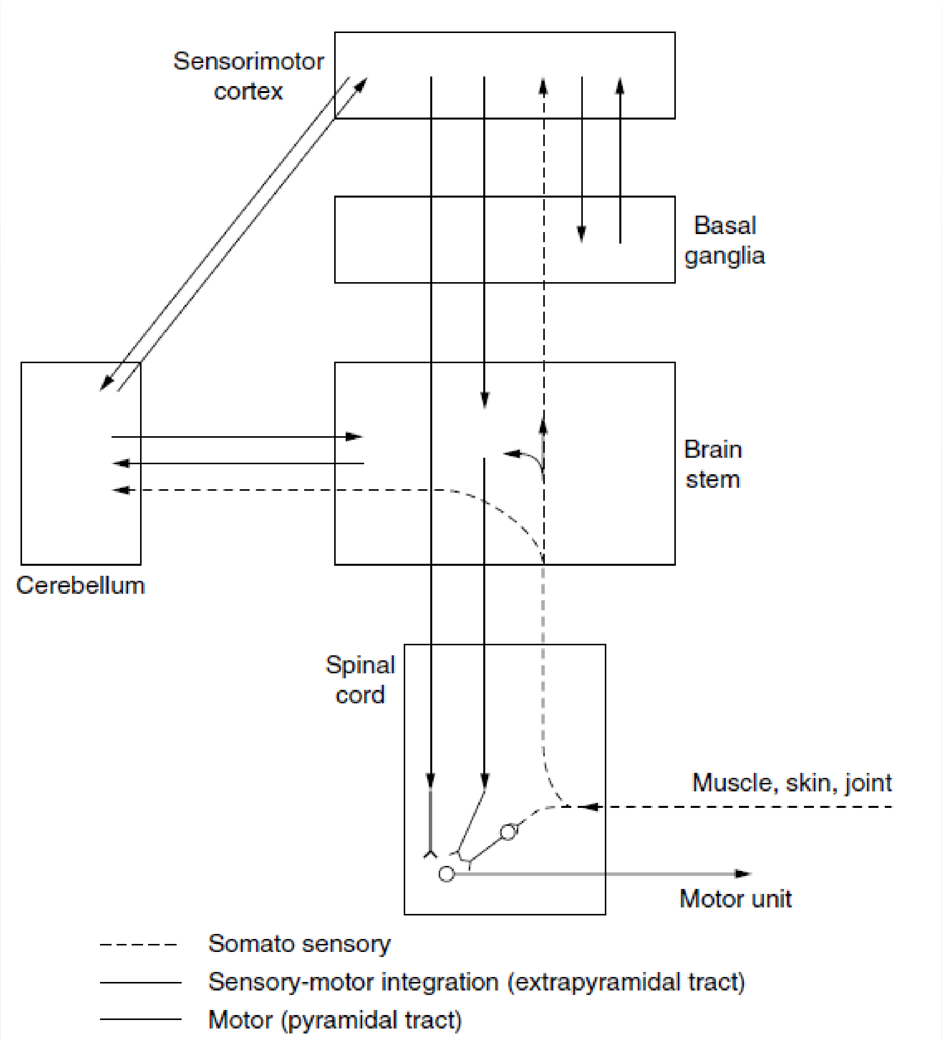
1. Introduction: Motivation and goals
2. Reflex control
   - Low-level control
   - Reflex modulation
3. Impedance control
   - Theoretical foundations (Hogan, 1985)
   - Equilibrium-point models
4. Internal model
   - Principles of operation
   - Robot control example
5. Pathological motor control
   - International classification of disabilities
   - Motor disturbances:
     - » Spasticity, CVA, Parkinson, CP, ...

Biomechatronics (Notes)

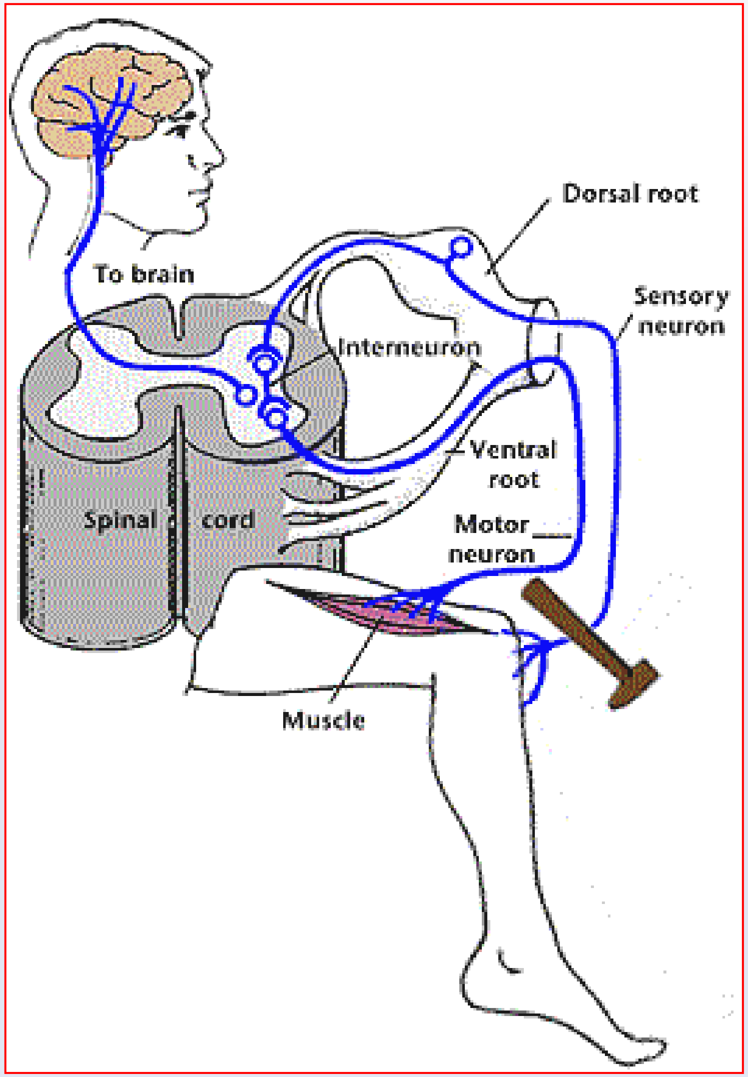


Muscle control structure



Adaptado de McMahon, 1984. Muscles, Reflexes and Locomotion.

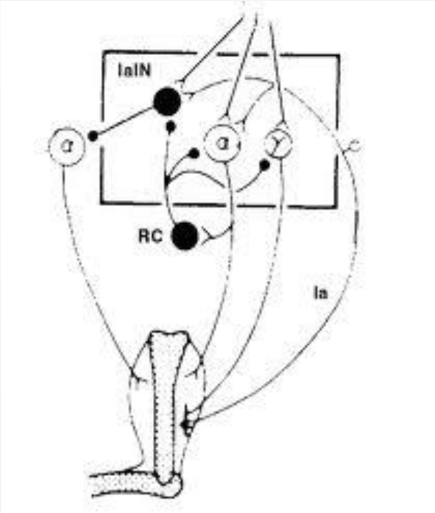
Low-level reflex control

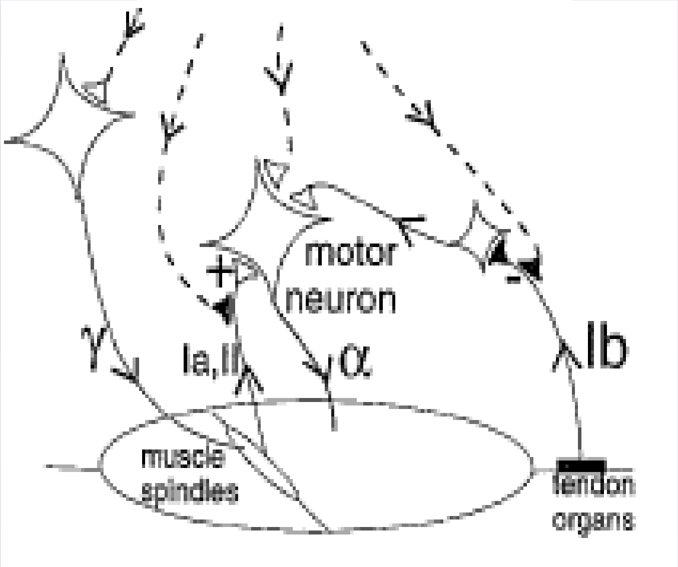


- Reflection:
- Stereotyped preprogrammed reaction as a response to a stimulus
- Simple reflex:
- Myostatic monosynatic reflex (stretching)
- Polyinate reflexes:
- Reflex flexor the withdrawal
- Reflexes: modulated by higher levels
-

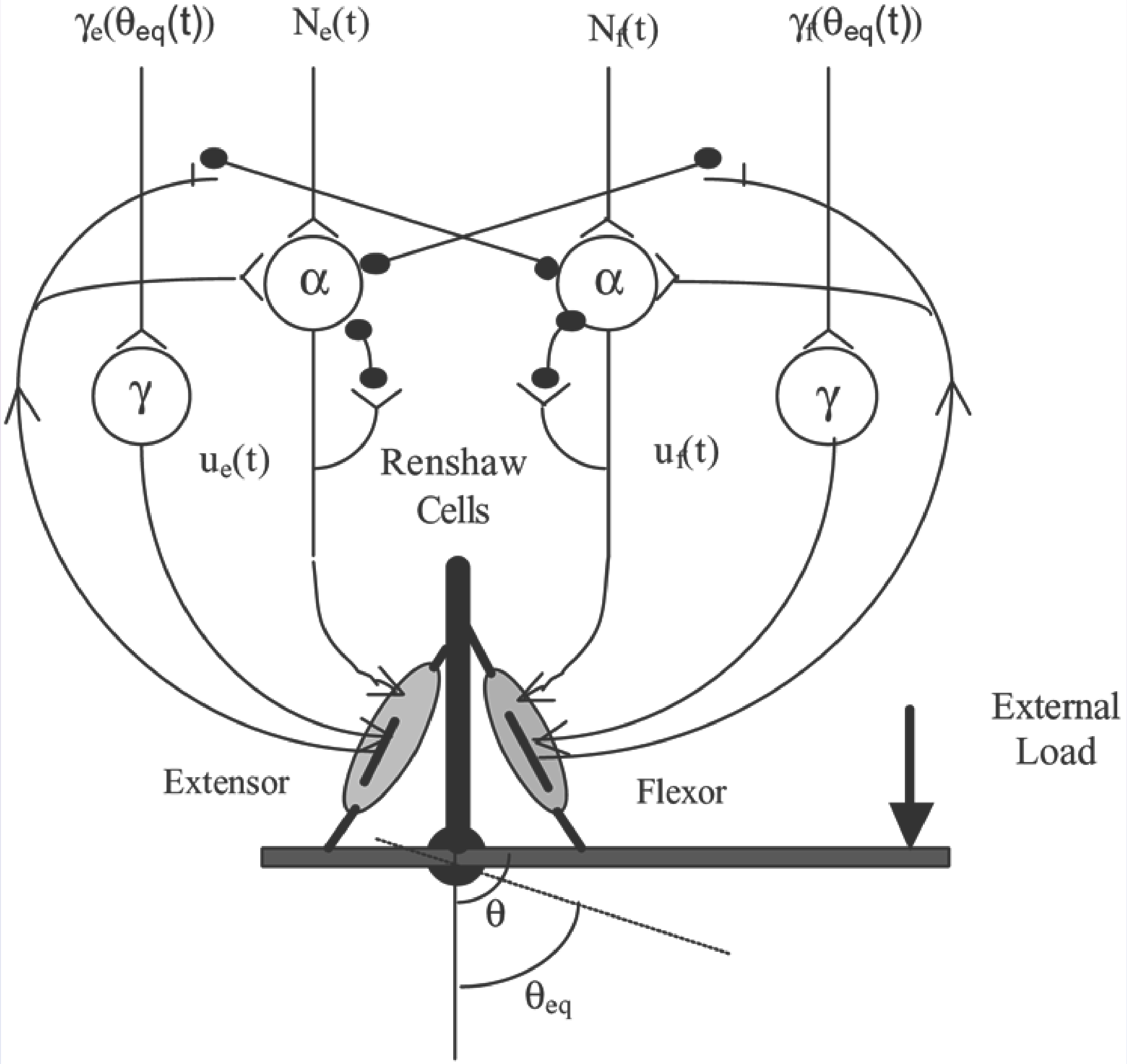
Low-level reflex control

- Motorneurons-α
  - Efferent signals
  - Afferent signals
    - Spindles, GTO
  - Feedback system
- Reflexes:
  - Delay: 60 ms for the leg
- Motorneurons-γ
  - Muscle spindles



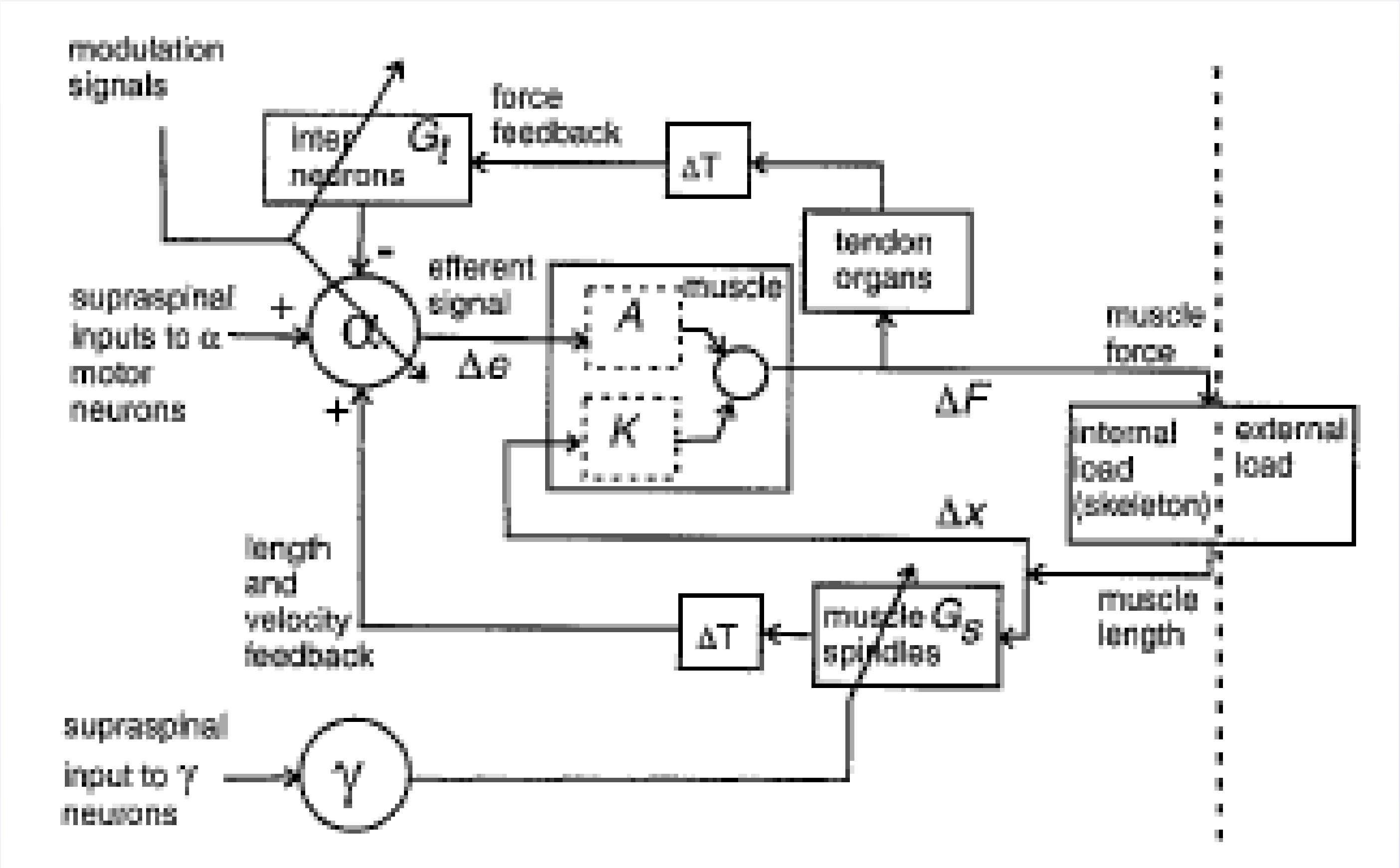


Low-level reflex control



Lan et al, 2005

Low-level reflex control



Adaptado de Houk, 1974

Low-level reflex control

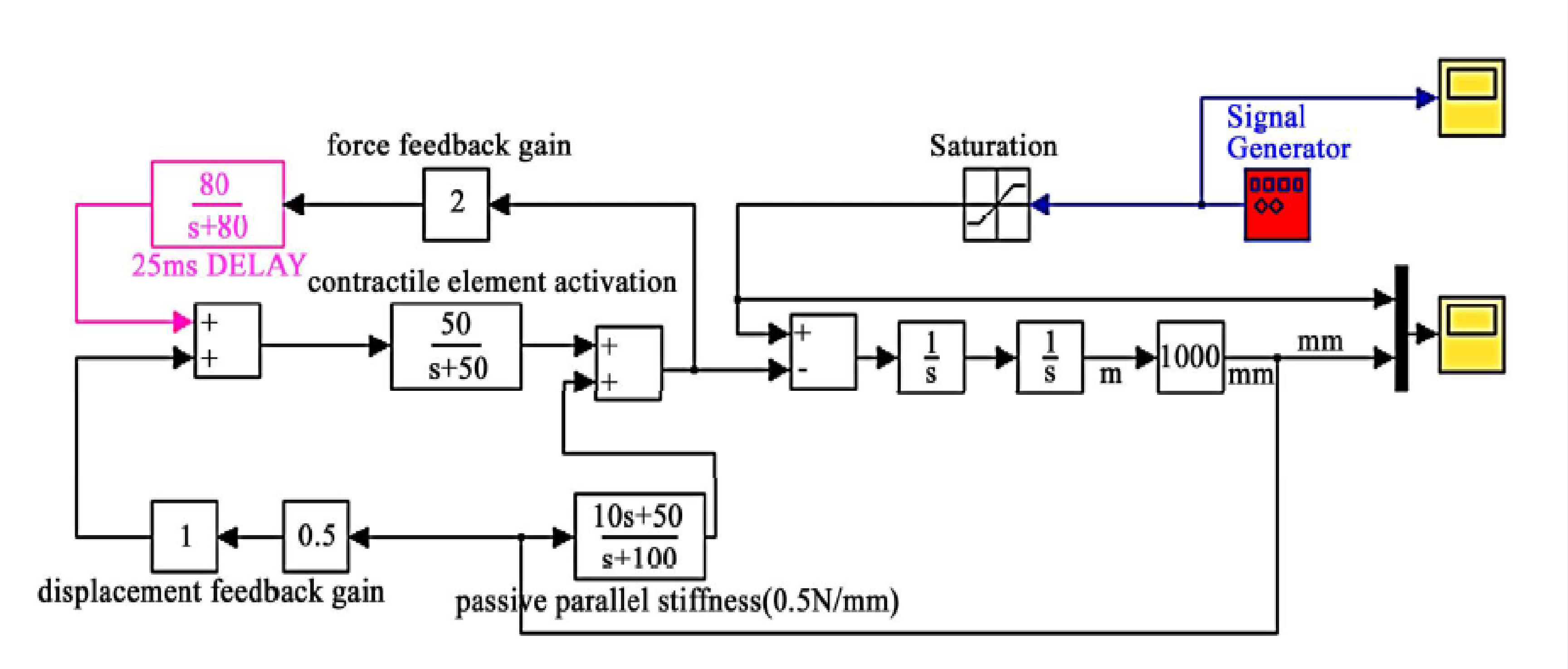
- Central efference:
  - Motoneurons
  - Pre e post synaptic inhibition on sensory afferent
  - Interneurons
- Impedance control:
  - Gain changes:
    - High or low stiffness

Example. Linear model

Condições estáticas

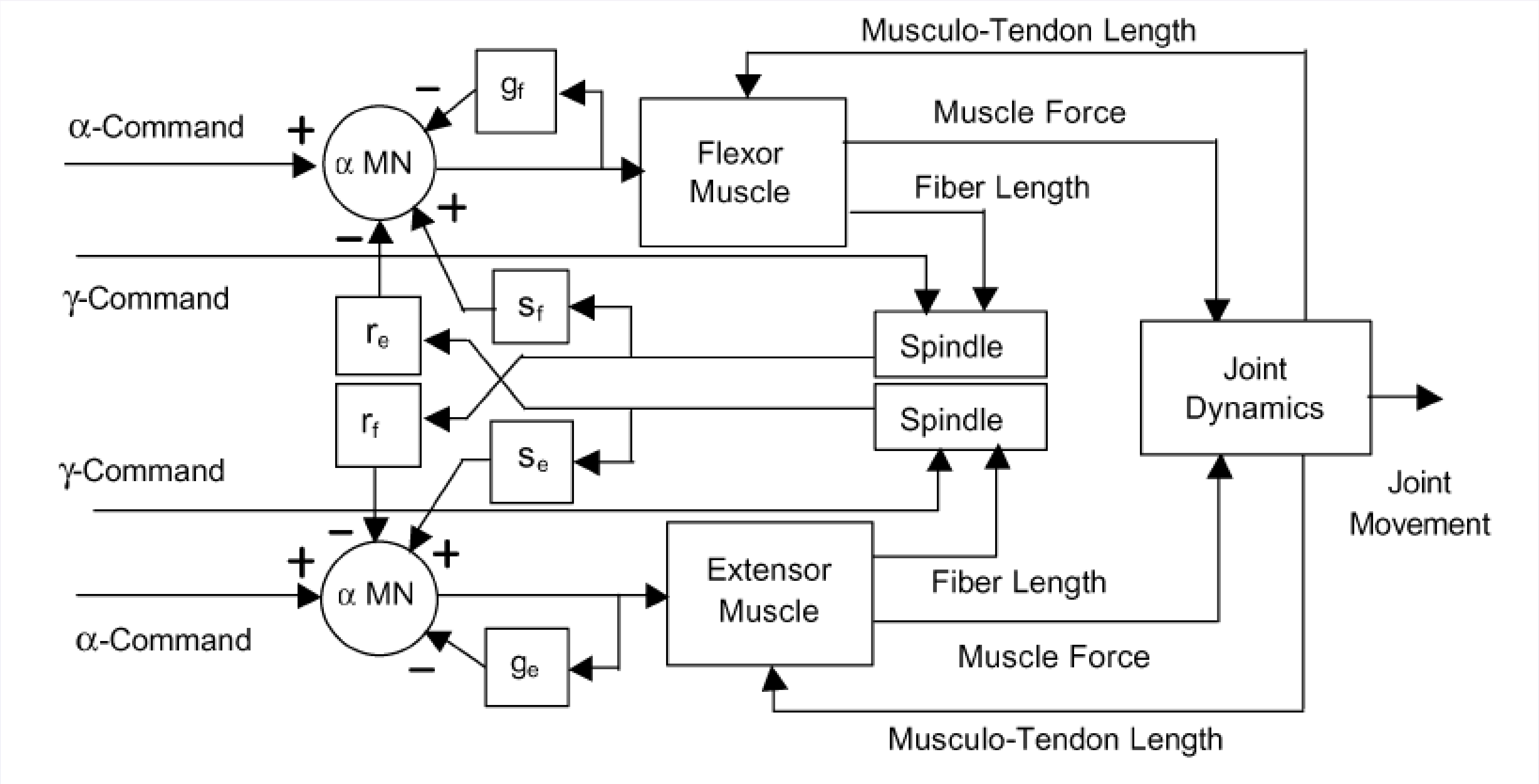
- Linearity assumption: $\Delta ef = Gs\Delta x - Gt\Delta F$
- Force depends on efference e and muscle stretching x: $\Delta F = A\Delta ef + K\Delta x$
- Muscle stiffness: $\Delta F/\Delta x = (K+AGs)/(1+AGt)$
  - $Gs \ll K/A$ e $Gt \ll 1/A$ => Stiffness= K (intrinsic)
  - $Gt \ll 1/A$ => Stiffness = K+AGs
  - $AGs \gg K$ e $AGt \gg 1$ => Stiffness = Gs/Gt

Example. Simulink model



Behbahani&Jafari, 2009

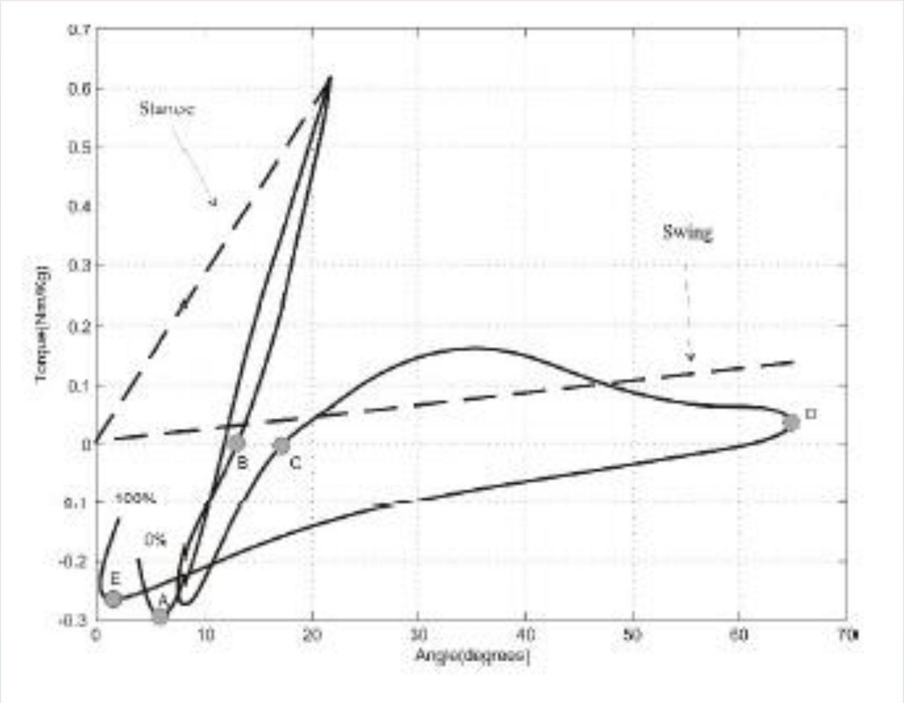
Example. Cocontraction model



Lan et al, 2005

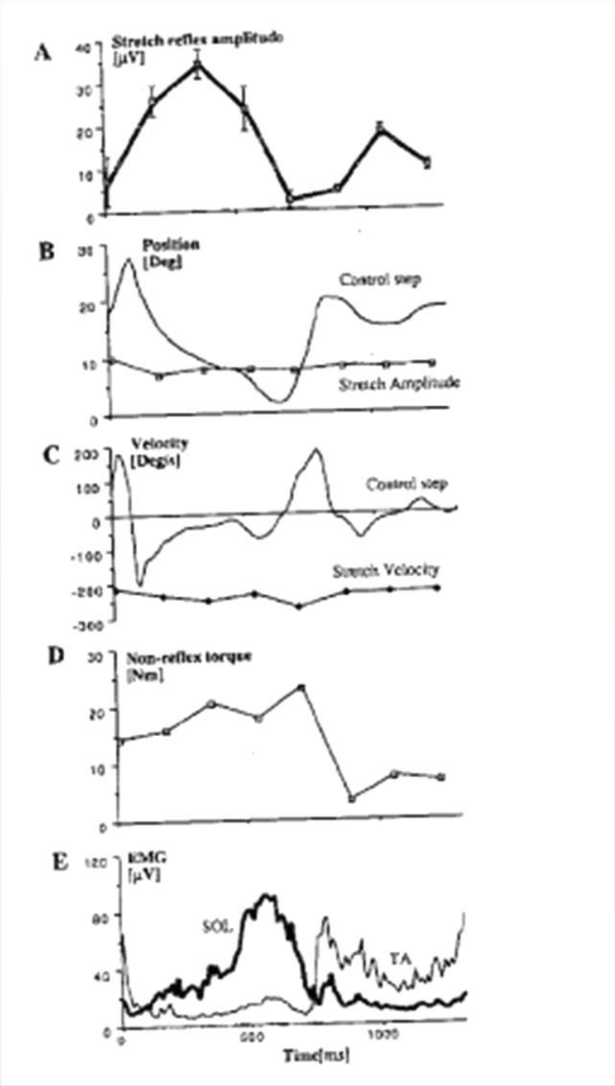
Reflex modulation

- Central modulation of sensory feedback signals
- Varies during the task
- Modulation during the cycle of travel:
- Support: high load. High stiffness
- Oscillation: low stiffness



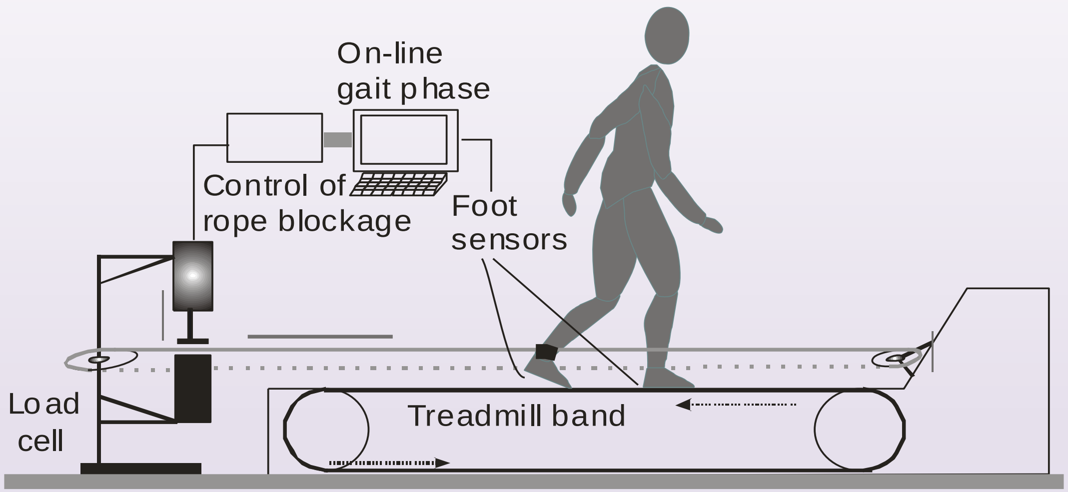
Adapted from Cullell et al, 2008

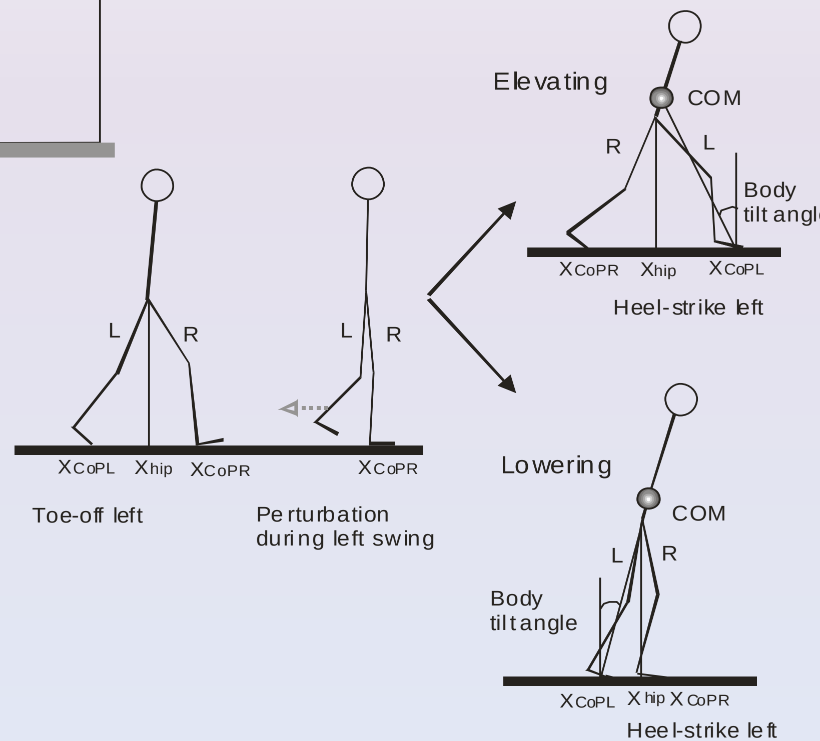
Reflex modulation



Adapted from Sinkjaer, 1996

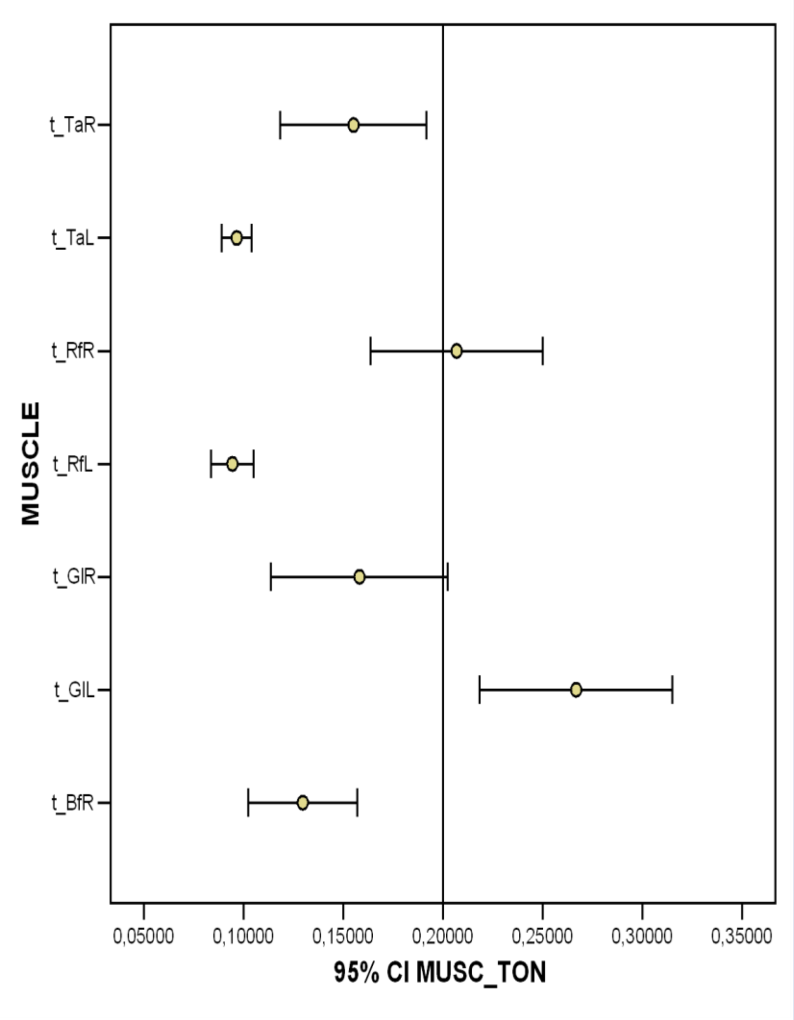
Reflex modulation?





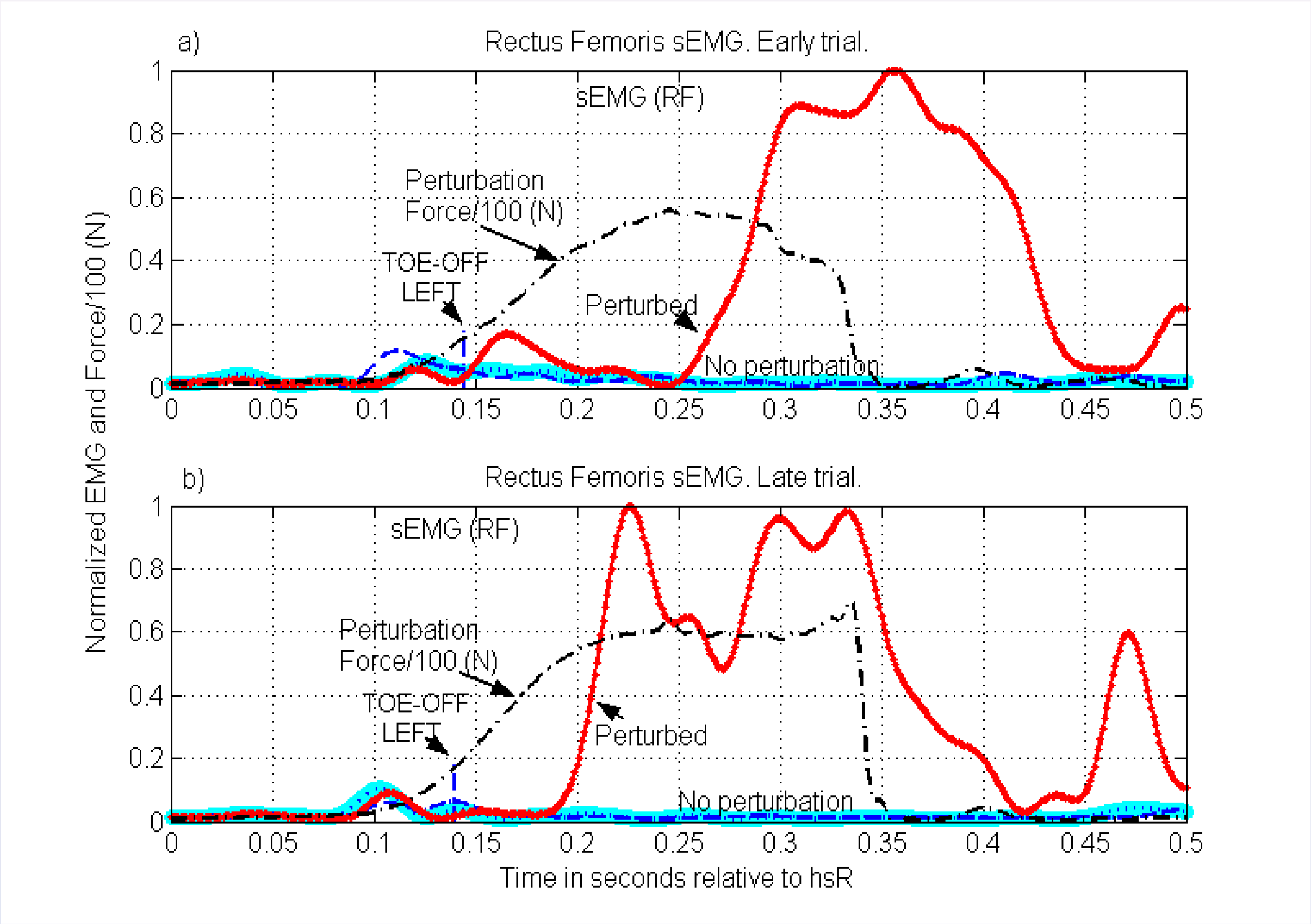
Adapted from Forner-Cordero et al, 2003

Reflex modulation?



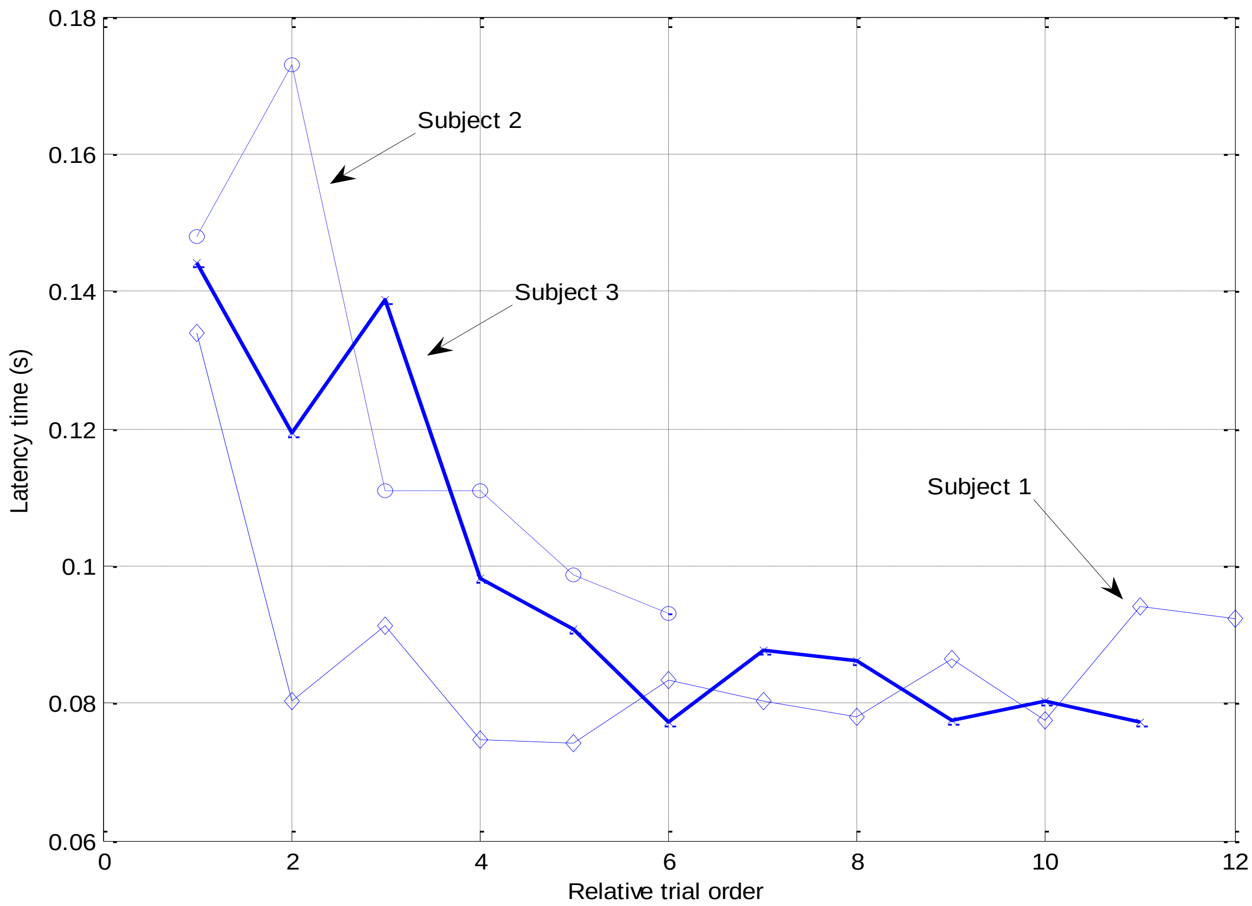
Forner-Cordero et al, 2015

Reflex modulation?



Forner-Cordero et al, 2007

Reflex modulation?



Forner-Cordero et al, 2015

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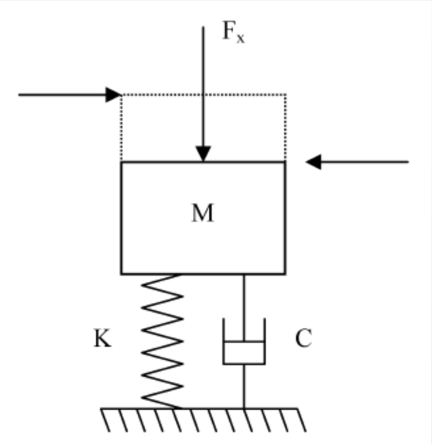
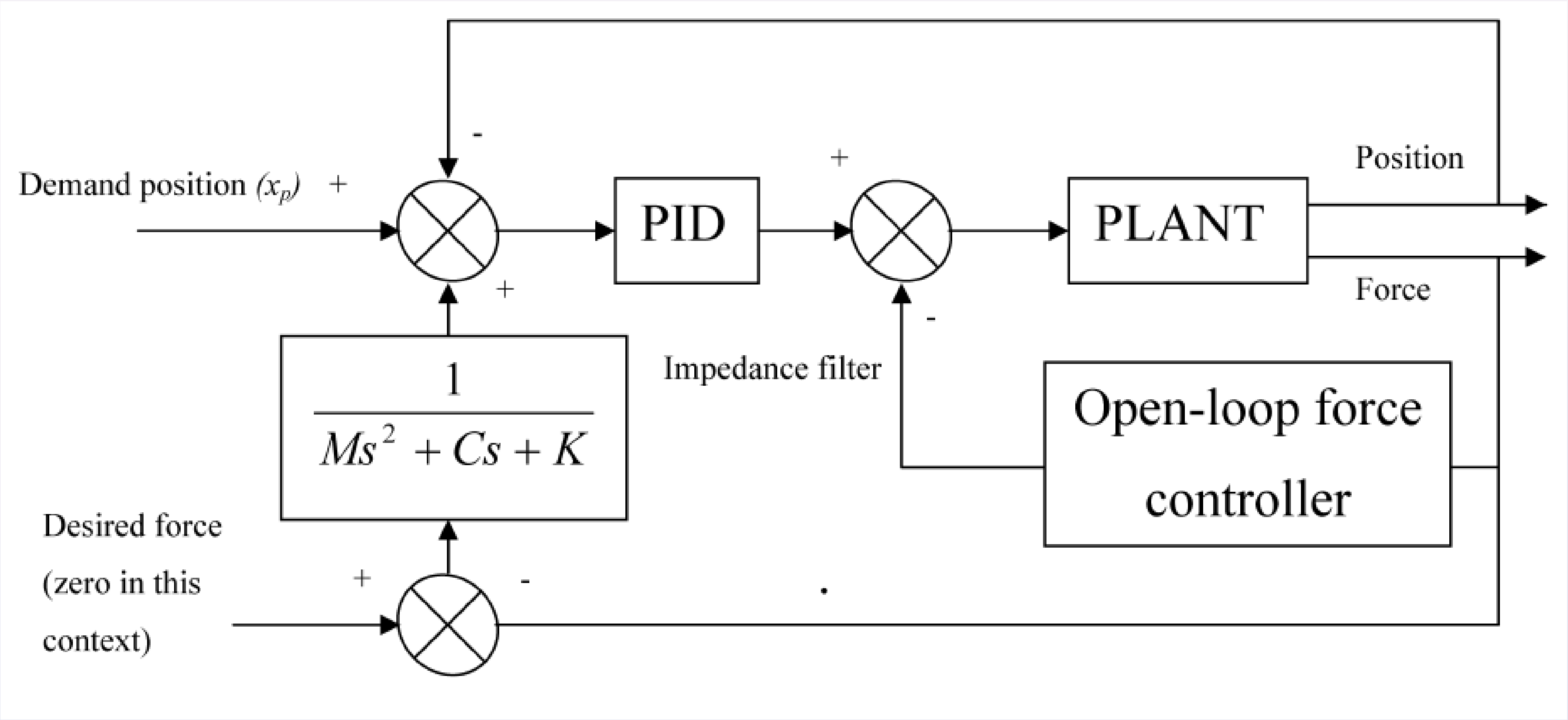
Impedance control

- Control:
  - Position
  - Force
  - Mechanical impedance:
    - Fixes the relation between forces and displacements

$$\frac{x_i}{F_x} = \frac{1}{Ms^2 + Cs + K}$$



Impedance control



Richardson et al, 2006

Example: HAL-3 e HAL-5

Modelo da perna: pendulo

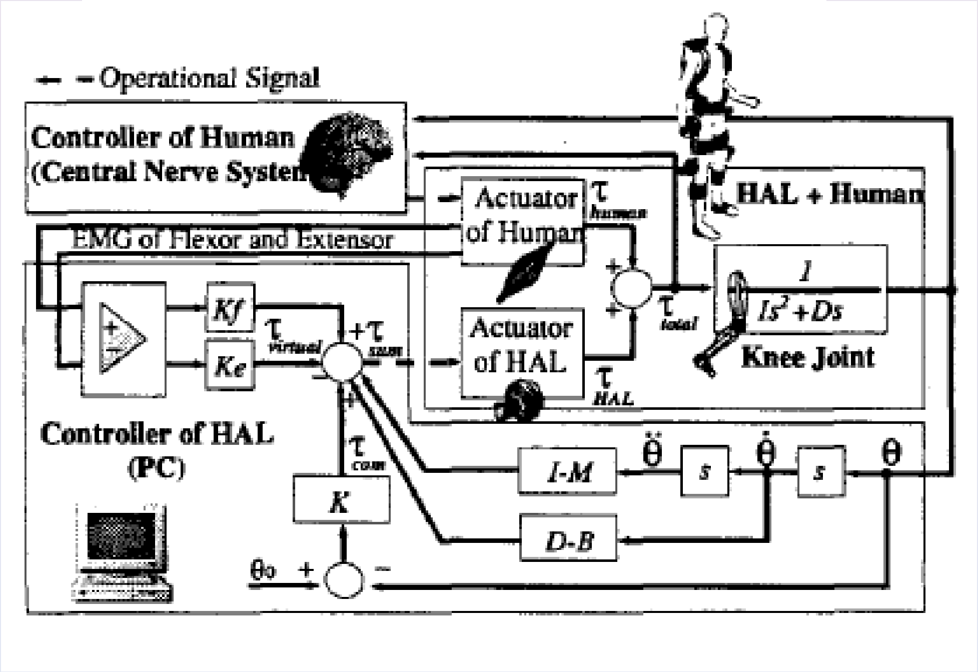
$$I\frac{d^2\theta}{dt^2} + D\frac{d\theta}{dt} + C\left(\theta, \frac{d\theta}{dt}\right) = \tau + J^T F_e$$

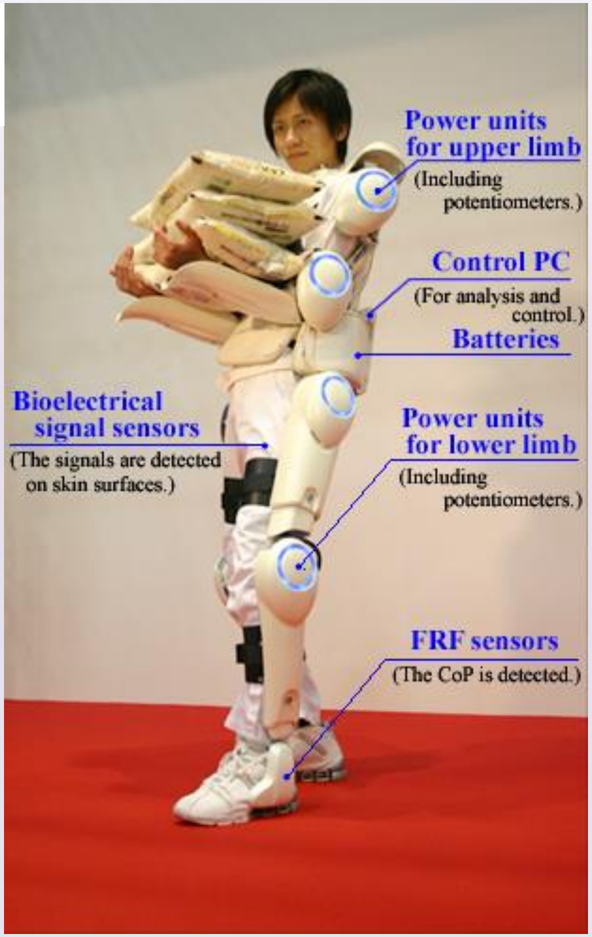
M, B, K Impedância desejada

$$J^T F_e = M\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} + K(\theta - \theta_0)$$

O torque de compensação:

$$\tau_{com} = (I - M)\frac{d^2\theta}{dt^2} + (D - B)\frac{d\theta}{dt} + K(\theta_0 - \theta) + C\left(\theta, \frac{d\theta}{dt}\right)$$

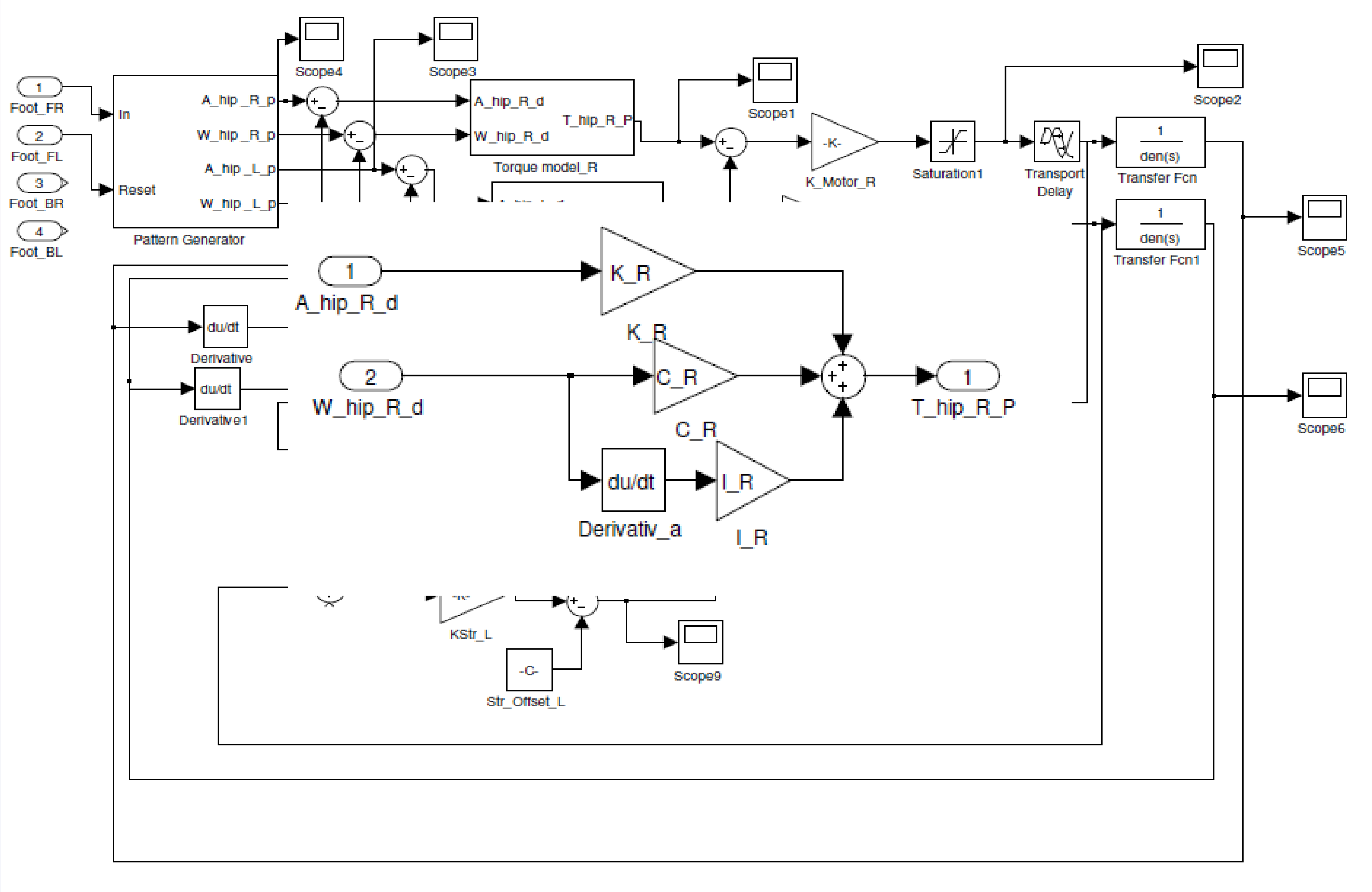




Lee & Sankai, 2002, 2003

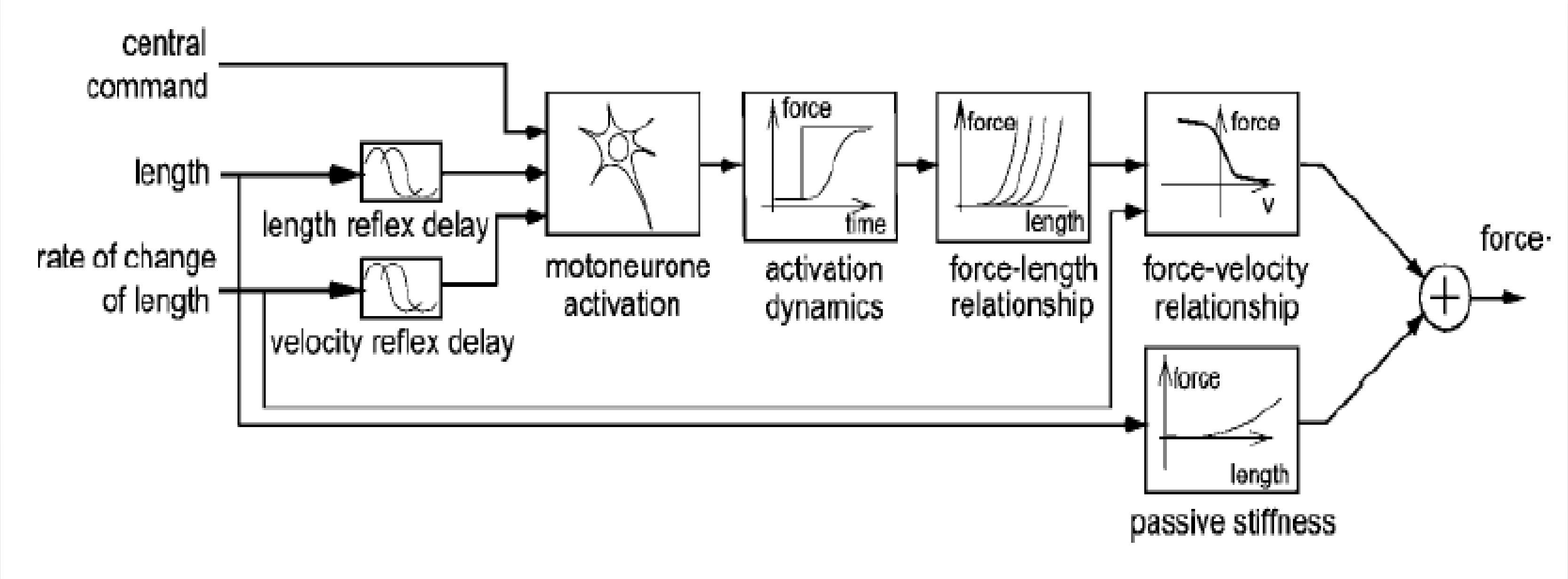
Exoskeleton HAL

Example



Foot_FR
Foot_FL
Foot_BR
Foot_BL
In
Reset
A_hip _R_p
W_hip _R_p
A_hip _L_p
W_hip _L_p
Pattern Generator
Scope4
Scope3
A_hip_R_d
W_hip_R_d
T_hip_R_P
Torque model_R
Scope1
-K-
K_Motor_R
Saturation1
Transport Delay
Scope2
den(s)
Transfer Fcn
Transfer Fcn1
Scope5
Scope6
du/dt
Derivative
Derivative1
A_hip_R_d
W_hip_R_d
K_R
C_R
I_R
Derivativ_a
T_hip_R_P
KStr_L
-C-
Str_Offset_L
Scope9

Equilibrium point models



Feldman, 1986

Equilibrium point models

Threshold muscle length:

$$\lambda^* = \lambda - \mu v + \rho + \varepsilon(t)$$

Muscle is active if the current muscle length (x) exceeds the threshold length, λ^*:

$$x - \lambda^* > 0$$

Muscle activation is proportional to

$$A = [x - \lambda^*]^+$$

Muscle force:

$$F = f(A, v, t)$$

Motor action results from the tendency to diminish the gap between x and λ^*, i.e., reach a

$$\min A$$

The range of λ regulation, $[\lambda_-, \lambda_+]$, is greater than the biomechanical range of changes in the muscle length, $[x_-, x_+]$.

Feldman, 2009

Level	Control form
A single motoneuron or muscle	threshold muscle length, λ
Muscles spanning a single joint	threshold joint angle
Several joints of the arm	threshold configuration of the hand
	threshold aperture of fingers
	threshold arm configuration
All skeletal muscles	threshold or referent body configuration
Effectors or whole body in the environment	threshold localization of effectors or whole body in the environment

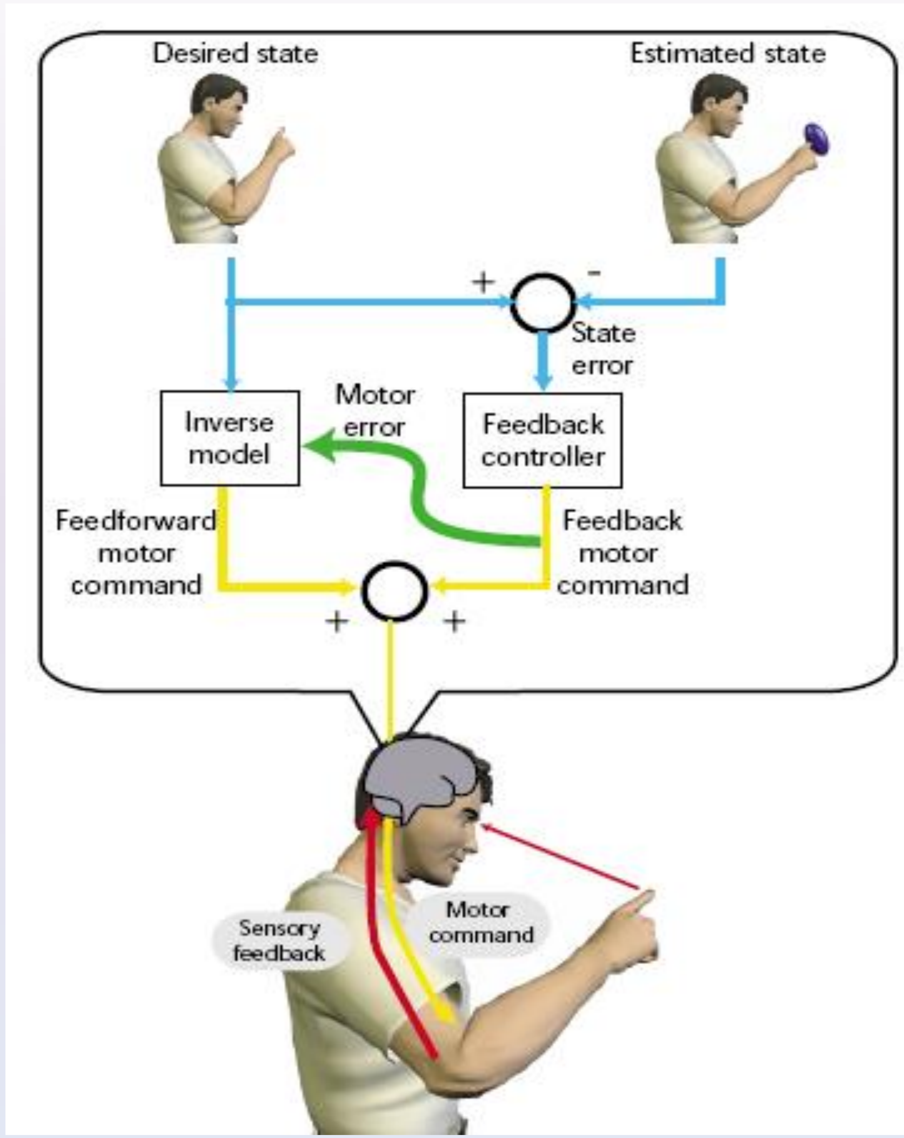
Contents

Internal model

- Neural processes:
  - Replicate the dynamics of the body and its surroundings
  - Predict the sensory consequences of motor action
  - They compare prediction and measurement
  - Robustness:
    - Delays and
    - Noise in sensors
  - Learning:
  - Model update

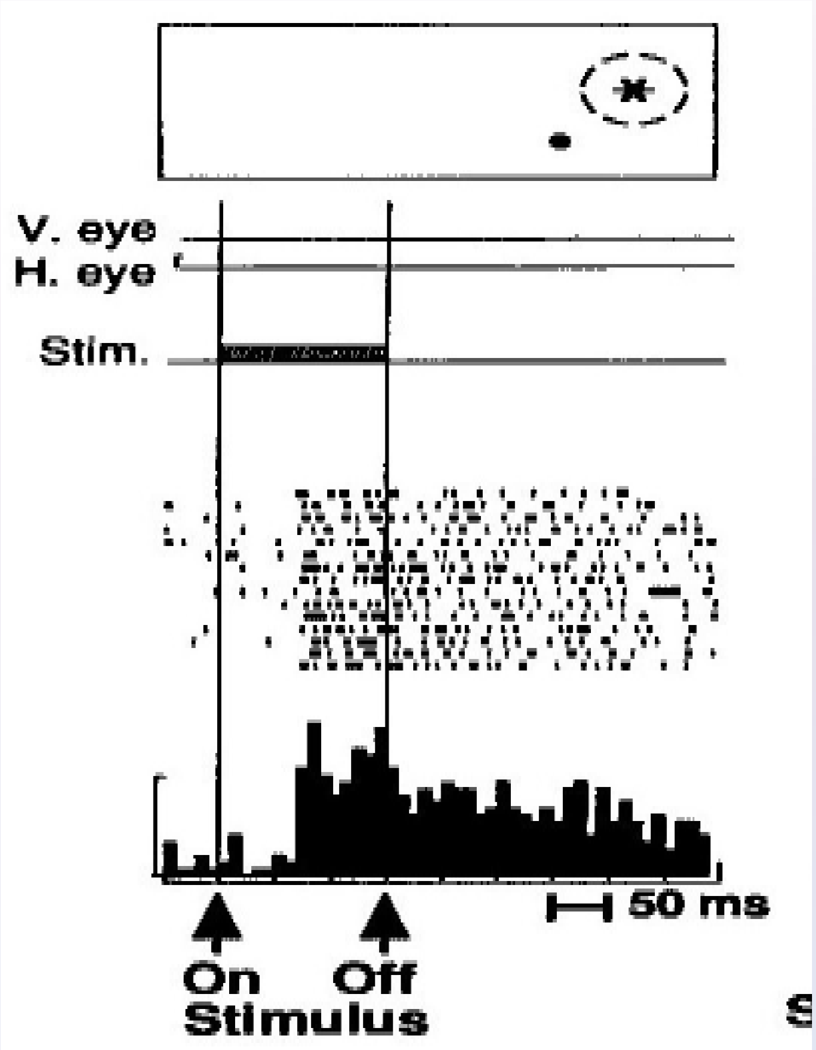
- Where and how are they implemented?

Internal model



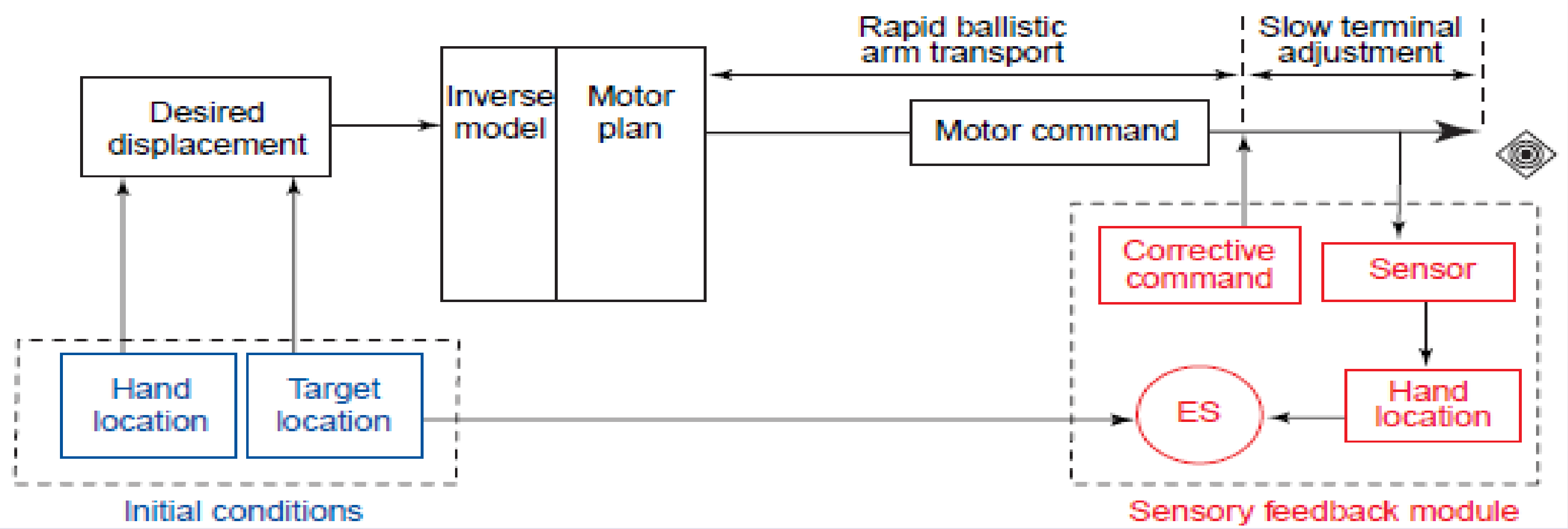
Wolpert and Ghahramani, Nat Neurosci. 2003

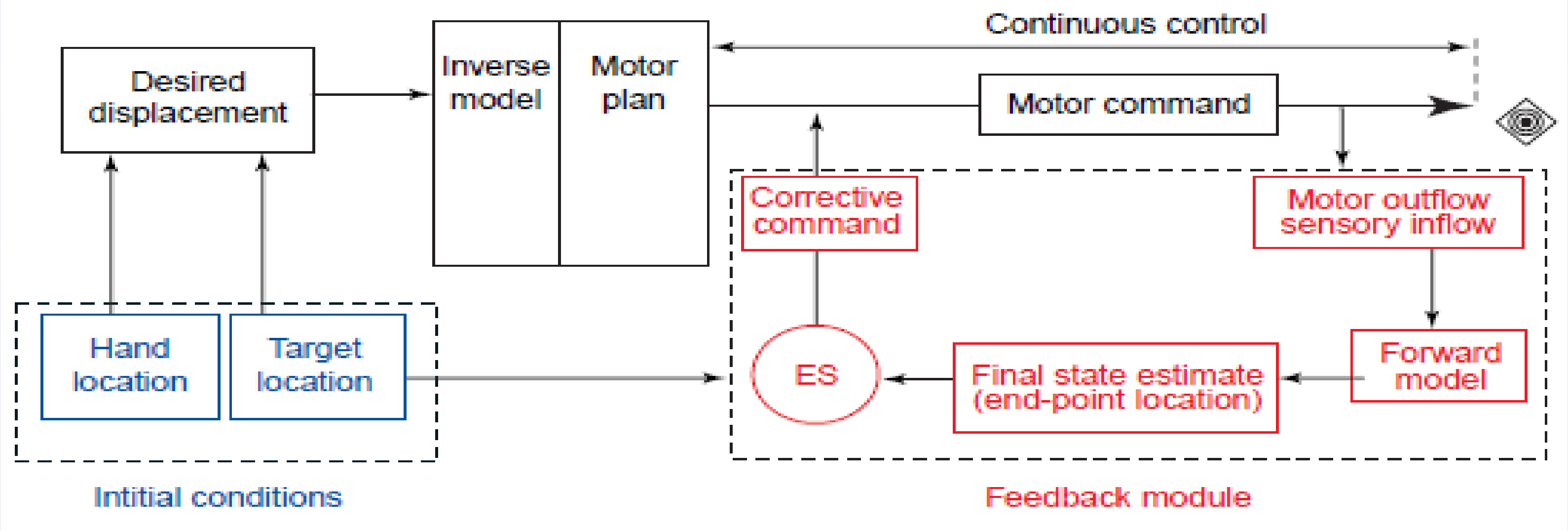
Internal model. Evidence



Duhamel, 1992

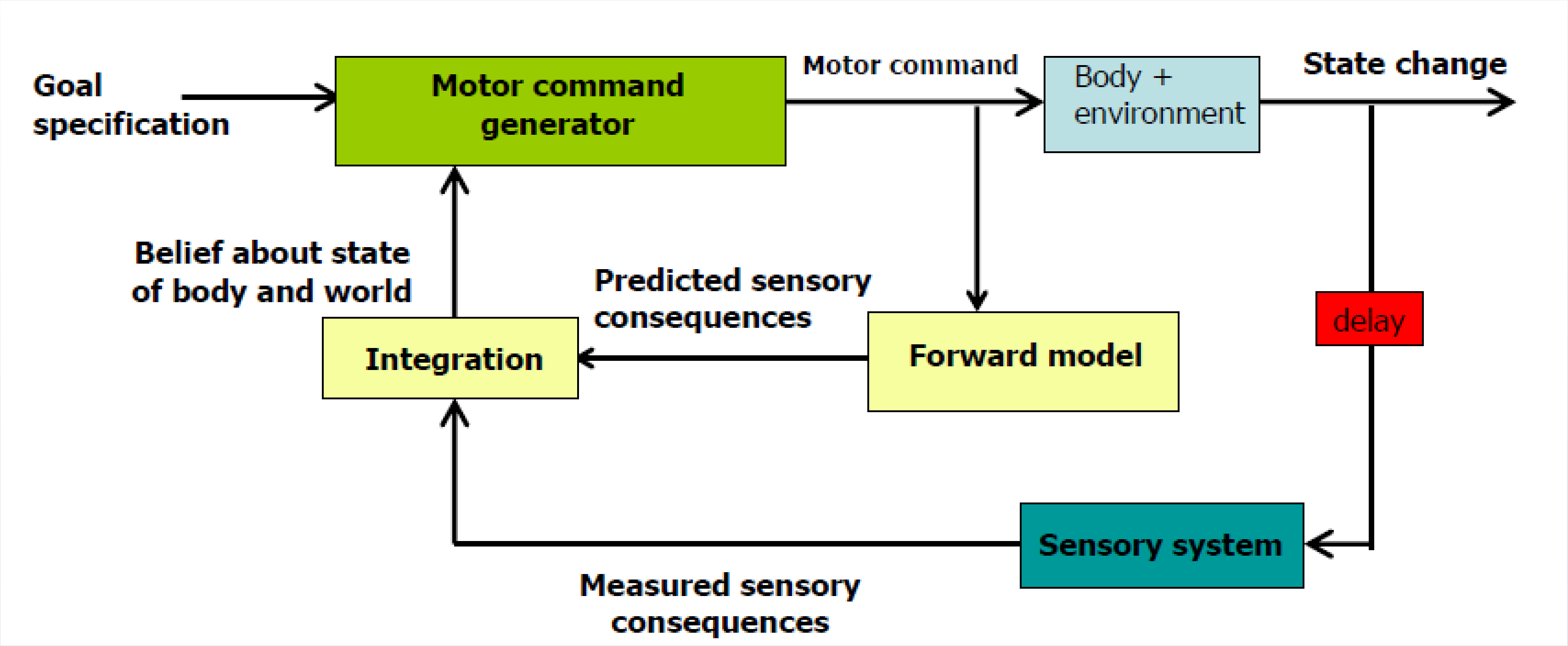
Internal model





Desmurget and Grafton, 2000

Internal model. Usefulness



Shadmehr, Lecture Notes

- Improves perception of the surroundings
- Avoids the problem of delays

Internal model. Optimal control

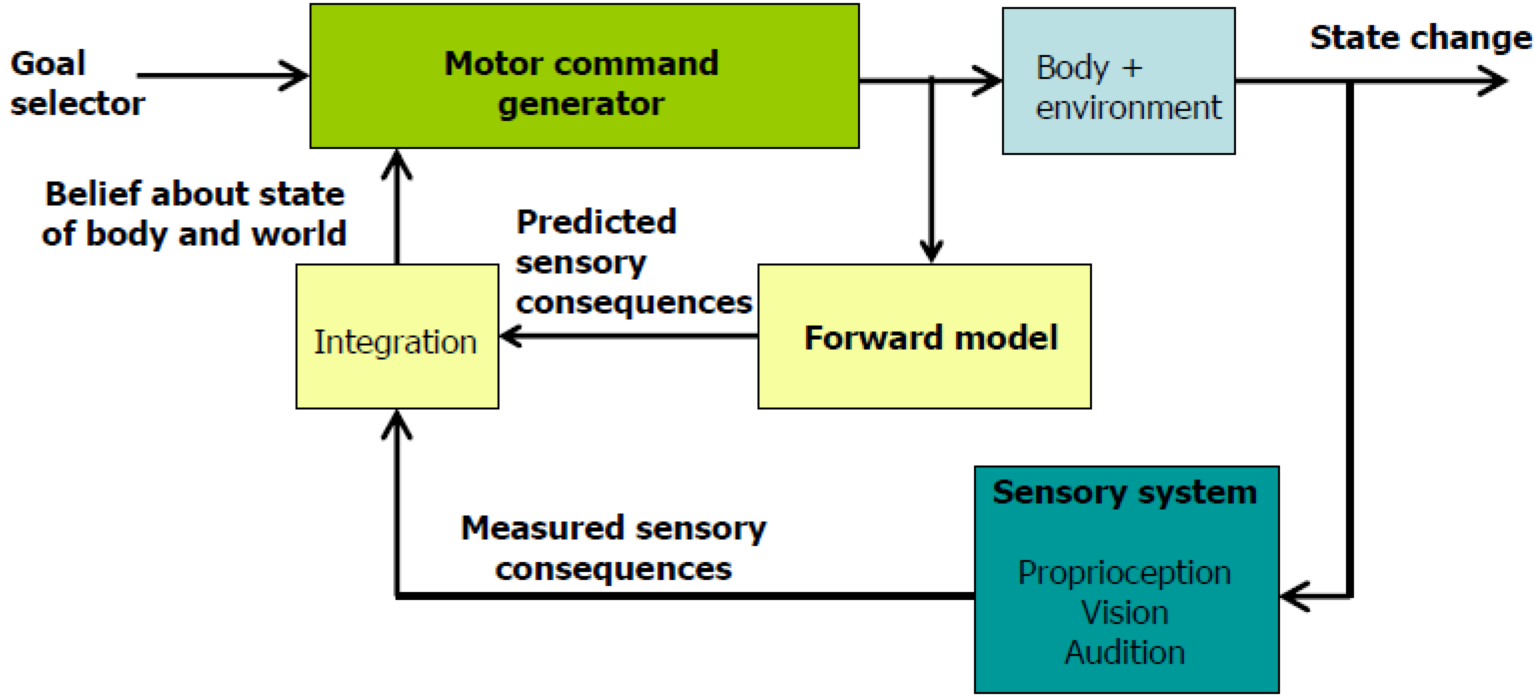
Motor command generator as a stochastic optimal controller

Todorov (2005)

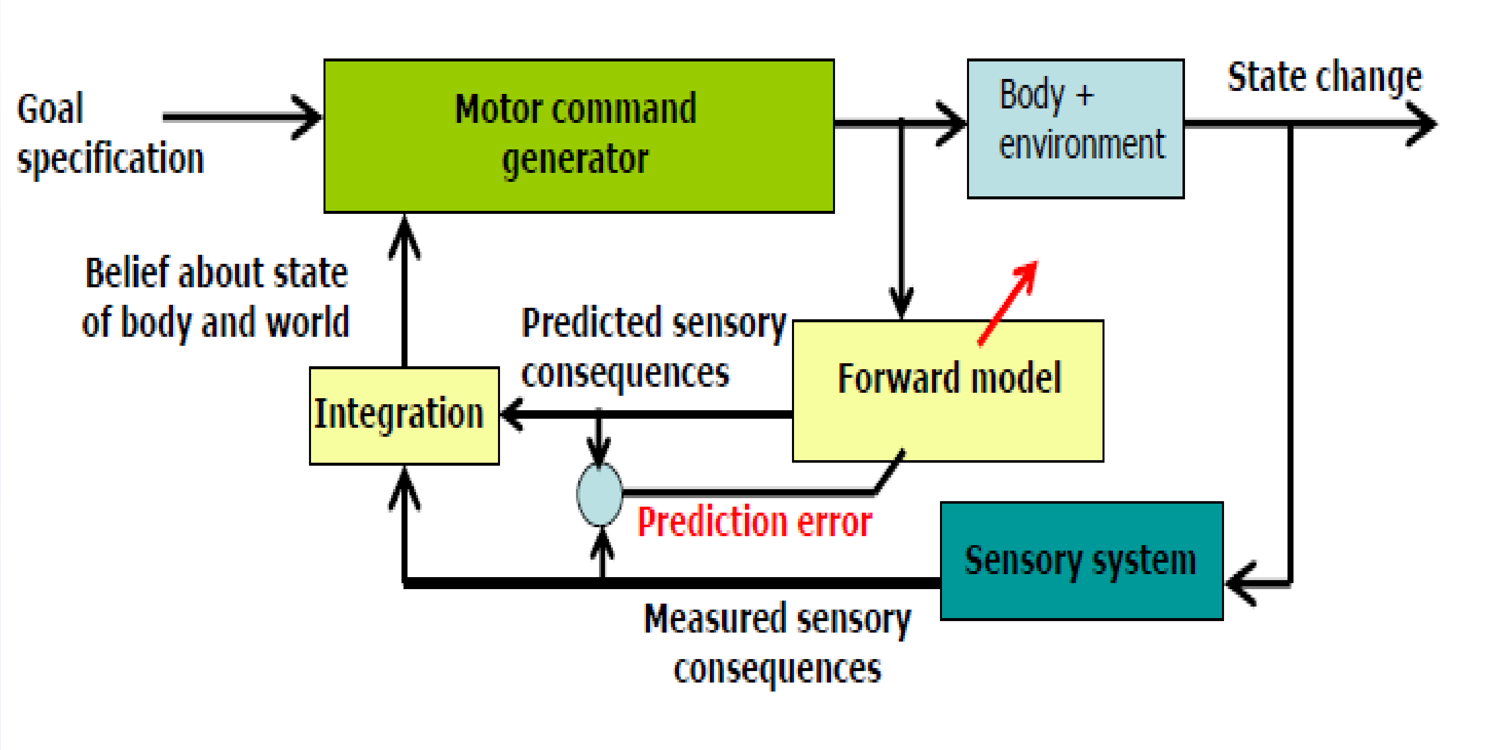
Actual state of the system (eye state, target state, etc.)

Signal dependent motor noise

$$\mathbf{x}^{(k+1)} = A\mathbf{x}^{(k)} + C\left(\mathbf{u}^{(k)} + \boldsymbol{\varepsilon}_u^{(k)}\right)$$



Internal model. Learning



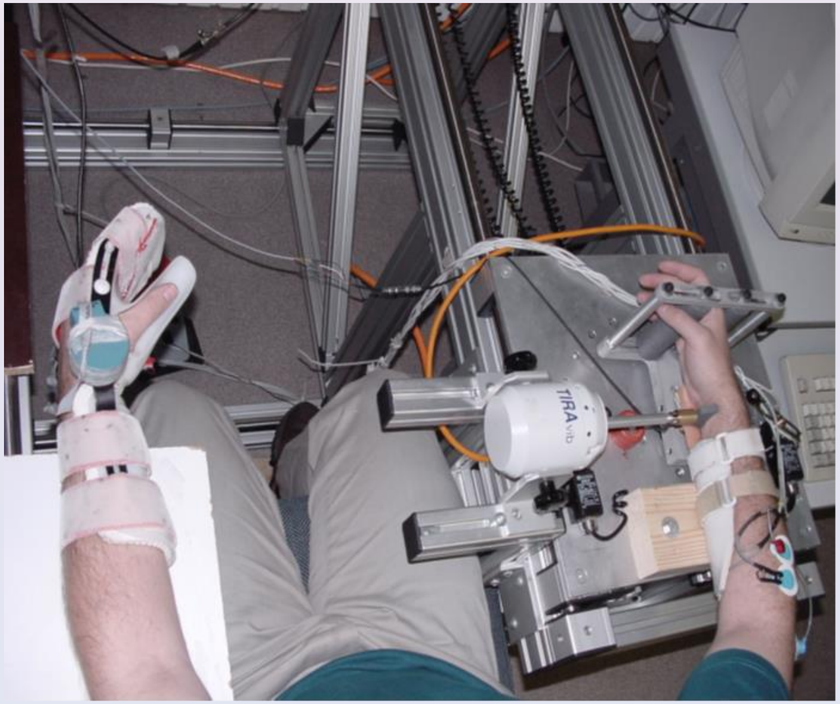
Shadmehr, Lecture Notes

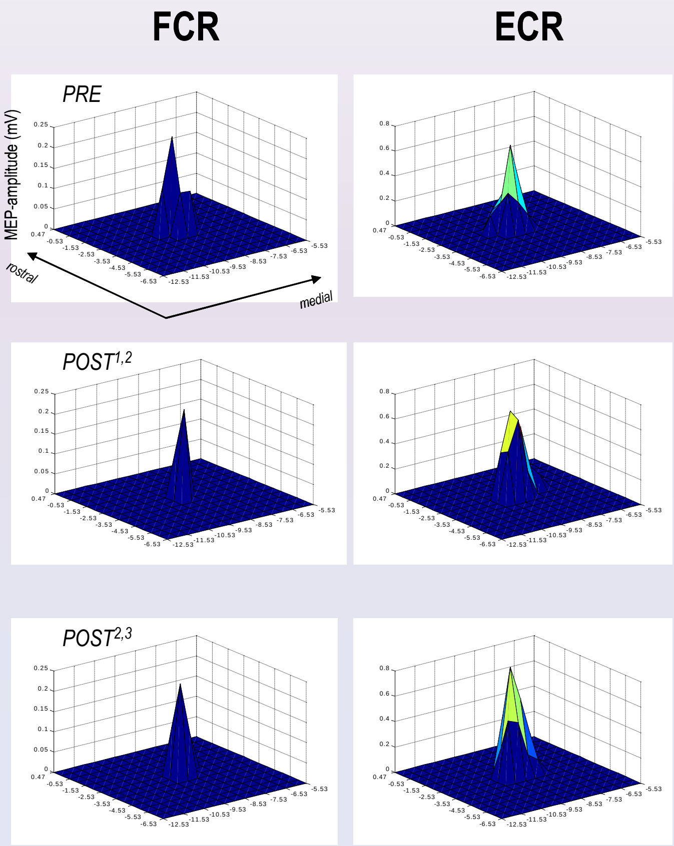
Motor control neurophysiology

Experiments with Transcranial Magnetic Stimulation

Modification of the motor maps of the cerebral cortex by vibrating the muscular tendon:

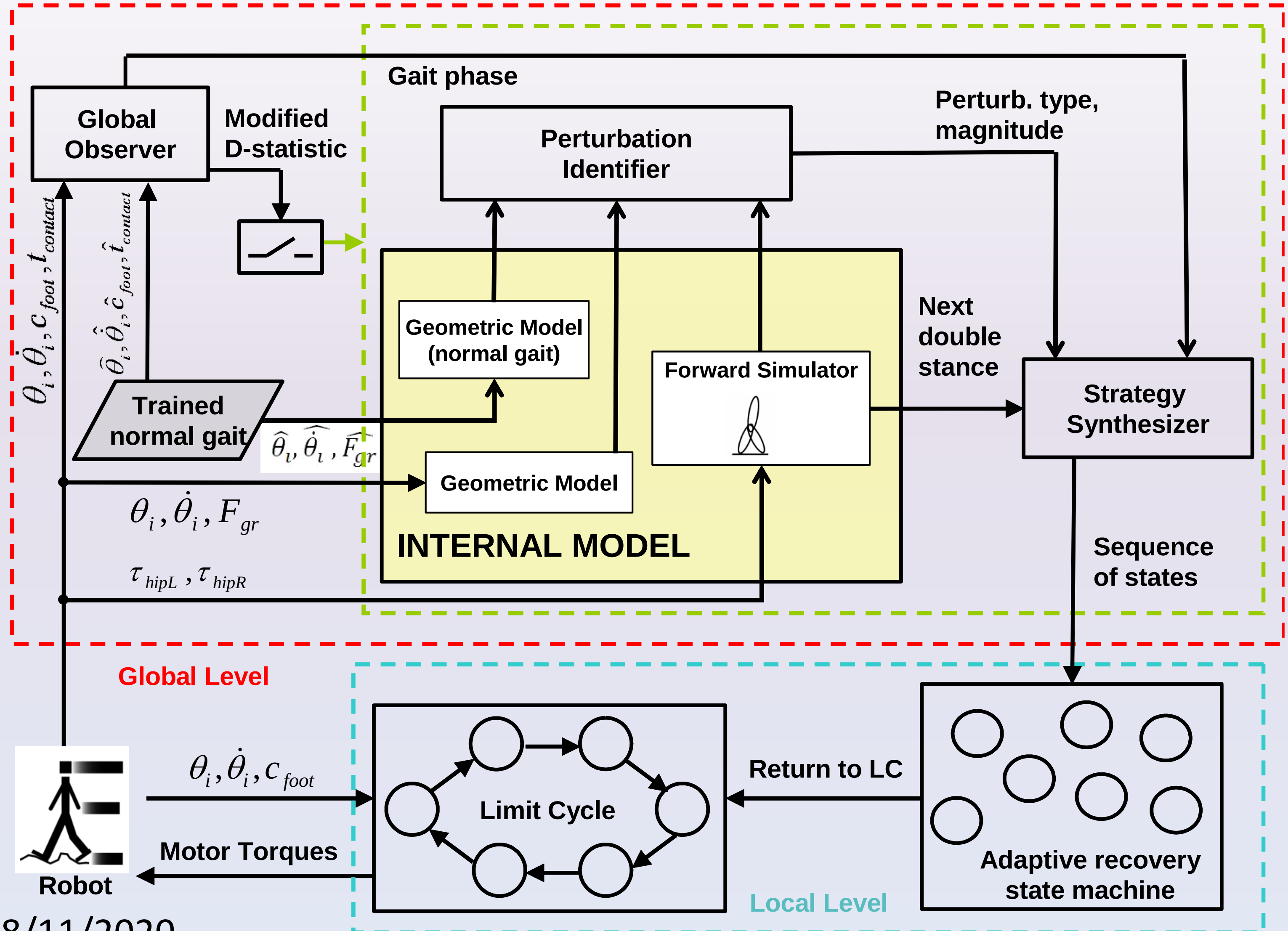
Proprioceptive illusion!





Forner-Cordero et al, 2008

ESBiRRobot control architecture



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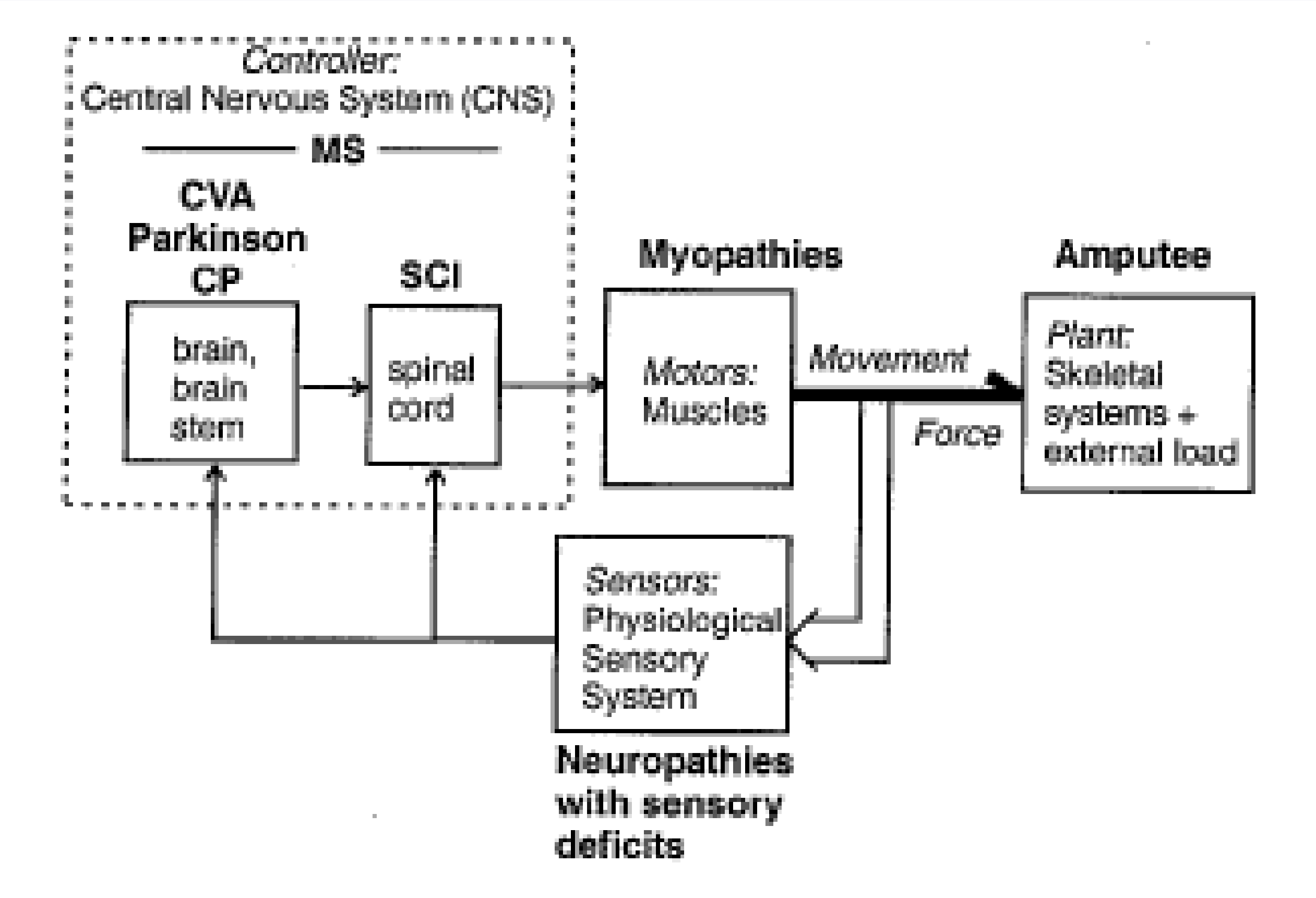
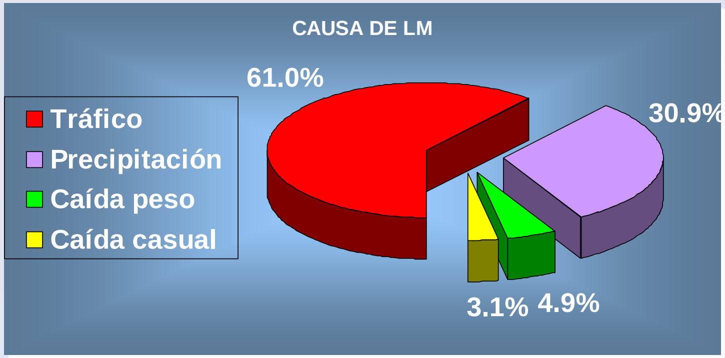
Pathological motor control

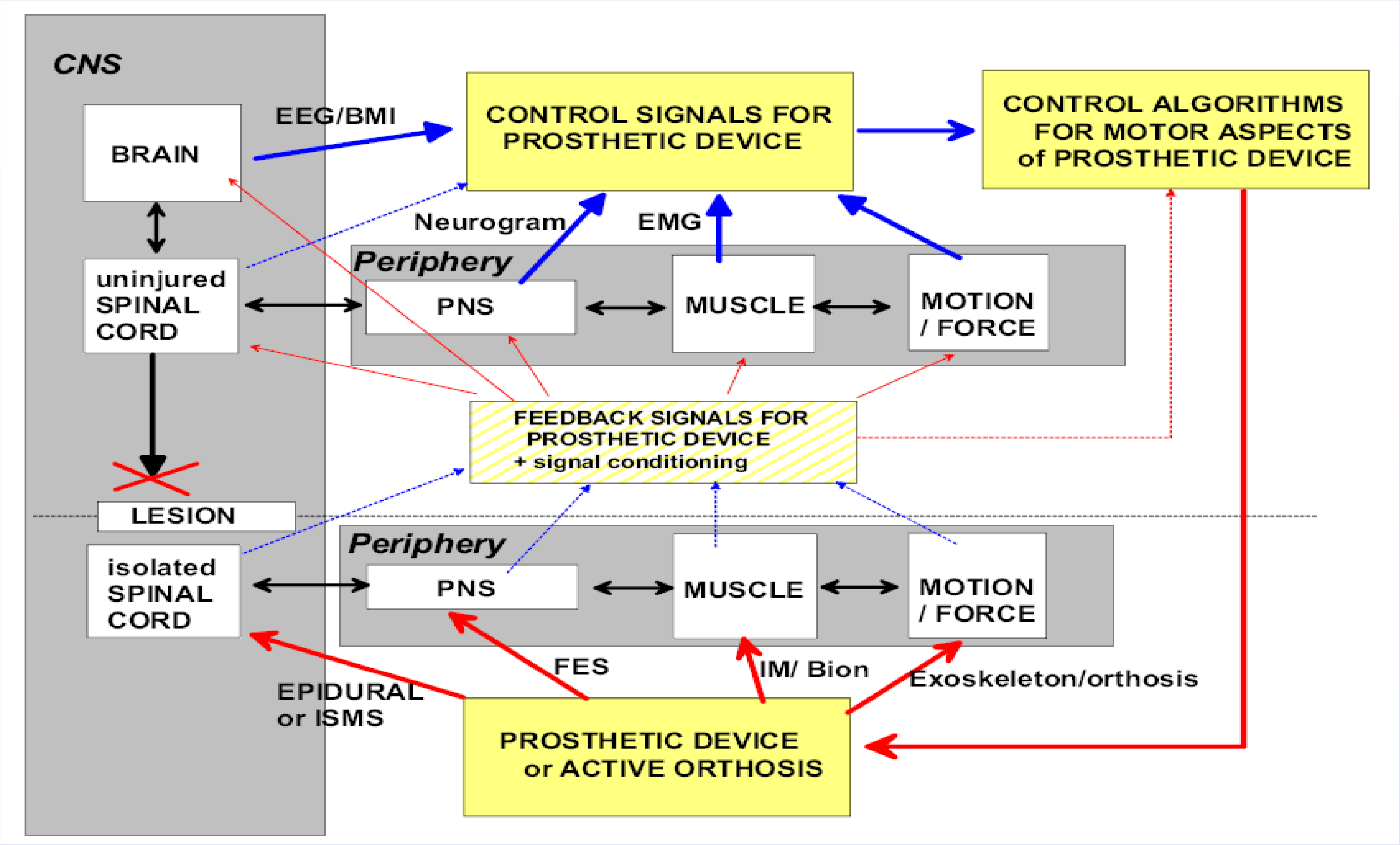


Motor pathologies

- Cerebro-vascular Accident (CVA)
  - Disturbance in the vascular flow. Cortex injury.
    - Hemiplegia/paresia upper and lower limbs
- Cerebral Palsy (CP):
  - Cortical injury congenital
    - Hemiplegia/paresia upper and lower limbs
- Spinal Cord Injury (SCI):
  - Section of the medula
    - Paraplegia / Tetraplegia



Motor disturbances

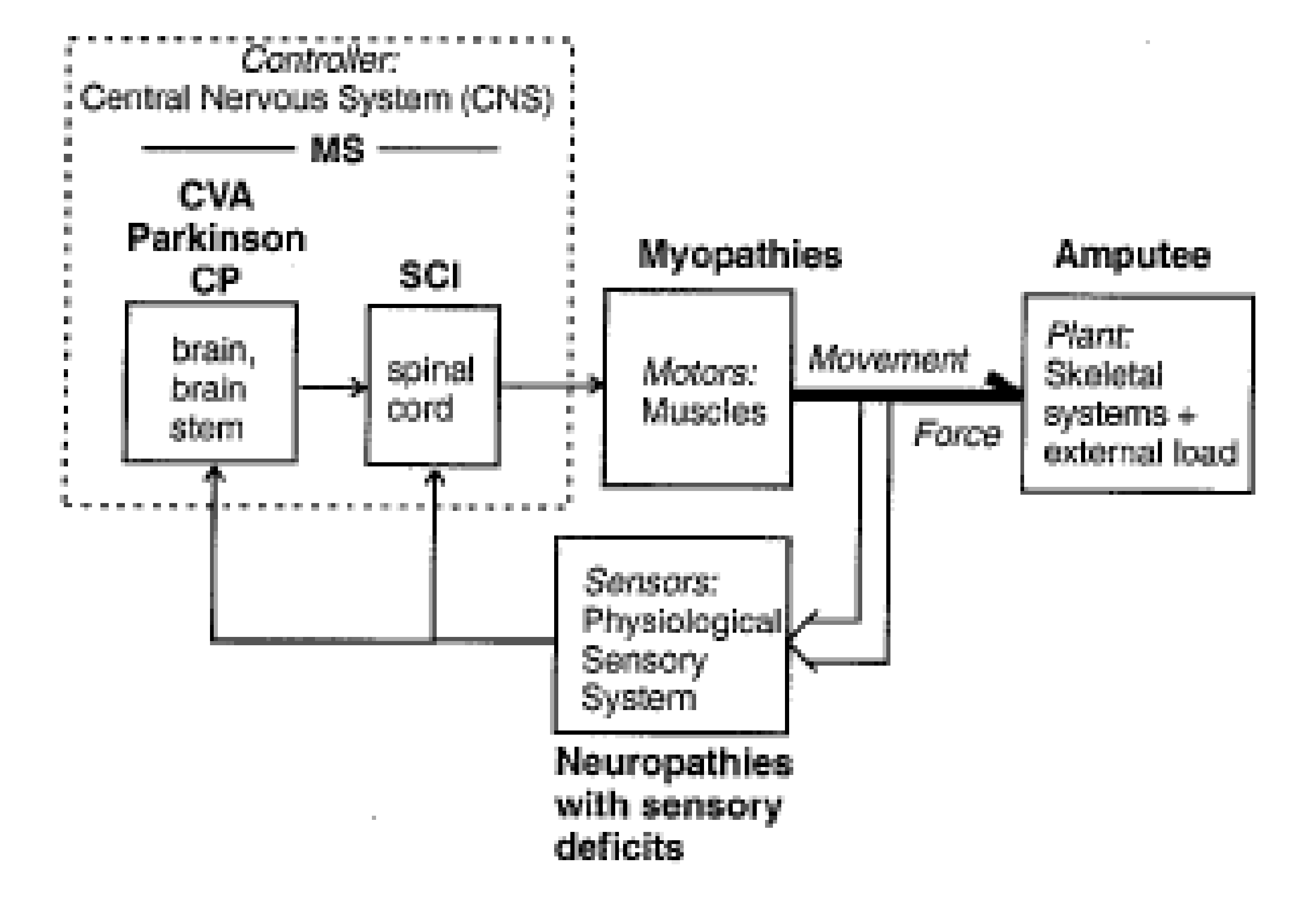
- 

Giszter, 2008. Neurotherapeutics

WHO: Impairment and disability

- Impairment: abnormalities in organs and systems and body structures;
- Disability: consequences of deficiency from the point of view of:
  - functional performance, or
  - performance of activities
- Handicap (*desvantagem*) is the adaptation of the individual to the environment resulting from disability and disability

Motor disturbances



Spasticity

- Spastic hypertonia
- Increased muscle tone dependent on la speed
- Hyperexcitability of the stretching reflex:
  - Threshold modification
  - Increased gain
- Upper motoneuron injury

CVA

- Neurological injury:
  - Loss of motor control
  - Changing sensations
  - Cognitive or language impairments
- Caused by altered blood flow:
  - Obstructive
  - Hemorrhagic
- Deficiency:
  - Depends on the place of injury
  - Hemiplegia
- Disability: Activities of Daily Life

Paralisia Cerebral

- Non-progressive lesion of the imaduro brain
- Posture and movement disorders
- Deficiencies:
  - Neuromuscular control
  - Muscle weakness
  - Abnormal muscle tone: Contracture and deformities
- Disabilities:
  - Limitations of independence
  - Lack of mobility

Parkinson

- Neurodegenerative disease
  - Idiopathic
  - Dopaminergic neurons (base ganglios)
- Deficiencies:
  - Motor: Akinesia, Hypokinesia, Bradikinesia
  - Tremor and Stiffness
  - Altered posture
- Disabilities:
  - Gait:
    - difficulty to start, stop or change direction
    - stop before lines on the ground (freezing)

Spinal Cord Injury

- Disability:
  - Traumatic injury of the spinal medulla
  - Level:
  - Thoracic ou lumbar: Paraplegia
  - Cervical: Tetraplegia
  - Complete or incomplete
  - Inability:
  - Paraplegia: Mobility
  - Full tetraplegia: High dependency

Multiple Sclerosis

- Destruction of myelin sheaths that cover and isolate nerve fibers:
- Neuronal transmission delay:
- Neural activity desynchronization
- Weakness, paresthesia, gait difficulties, ataxia

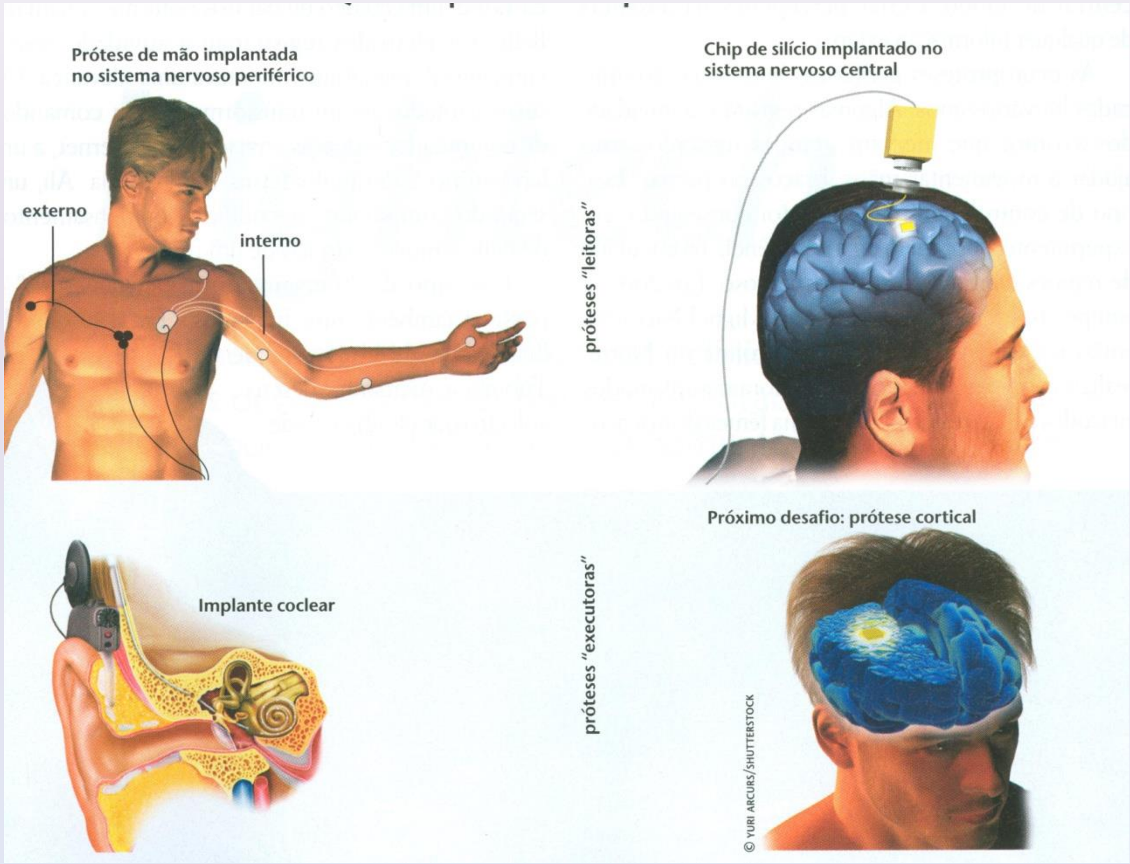
Cognitive interaction

- Human =>robot:
- EMG, EEG
- NCCI Interfaces
- Robot=>Human
- Electrical stimulation
- EEF. Biomechanical models
- Epidural
- Mechanical stimulation
- Sensory feedback
- Nervous Sist Physiology

Nicolelis&Lebedev, 2009 Nat. Rev. Neurosci.

Future rehabilitation robots

- Neuroprostheses



DARPA

Nicolelis, Mente e Cerebro, 2009

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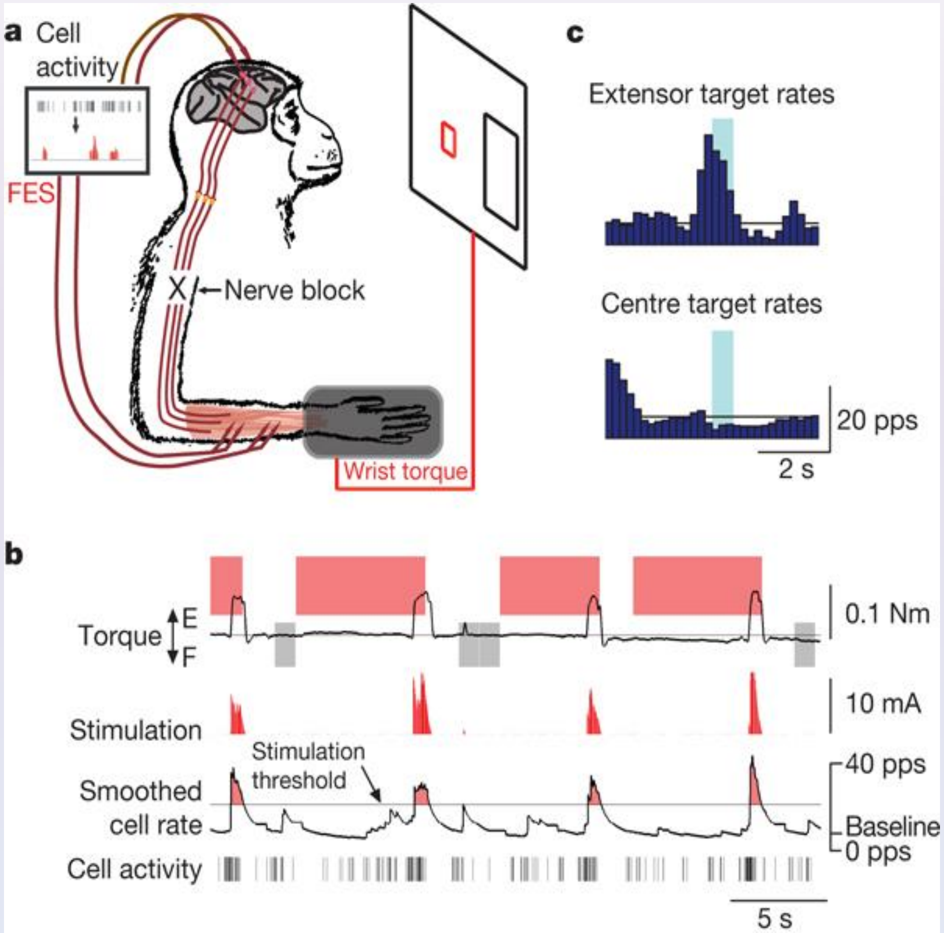
Future rehabilitation robots

- Motor control⇔BNCI
  - Artificial connection brain-muscle:
    - Multiple electrodes?
    - Assigning arbitrary electrode-Muscle?
  - Biomimetic solution



CT Moritz *et al.* *Nature* **2008**, 1-4 (2008) doi:10.1038/nature07418

Muito Obrigado