Neural control of movement

Redundancy of the motor system

- Biomechanical level

  extra number of degrees of freedom $\Rightarrow$ interjoint coordination

- Muscular level

  extra number of muscles $\Rightarrow$ interjoint coordination

- Neural level

  extra number of motor units $\Rightarrow$ motor unit recruitment

Il “problema dei gradi di libertà”
Nikolai Bernstein (1896-1966)

Come John Hughlings Jackson, Bernstein ritiene che il sistema nervoso sia organizzato in modo gerarchico, per renderne gestibile la complessità,

ma diversamente da Jackson si rende conto che il movimento non è determinato univocamente dal **cervello** (i comandi efferenti) ma dall’interazione tra questi e la dinamica del **corpo** e dell’**ambiente**

inventore del termine “Biomeccanica” intesa in senso lato

N. Bernstein (1967) The co-ordination and regulation of movements. Oxford: Pergamon Press.

Il “problema dei gradi di libertà” Nikolai Bernstein (1896-1966)

Il problema dei gradi di libertà è il cuore della Cibernetica (N. Wiener, *Cybernetics,* 1947)

Il corpo è troppo complicato perché il cervello lo possa controllare in modo diretto

La dinamica complessiva corpo-ambiente crea delle opportunità (Affordances : J.J. Gibson 1950) che il cervello deve imparare a cogliere

N. Bernstein (1967) The co-ordination and regulation of movements. Oxford: Pergamon Press.

Dal problema dei gradi di libertà alla **teoria del punto di equilibrio**

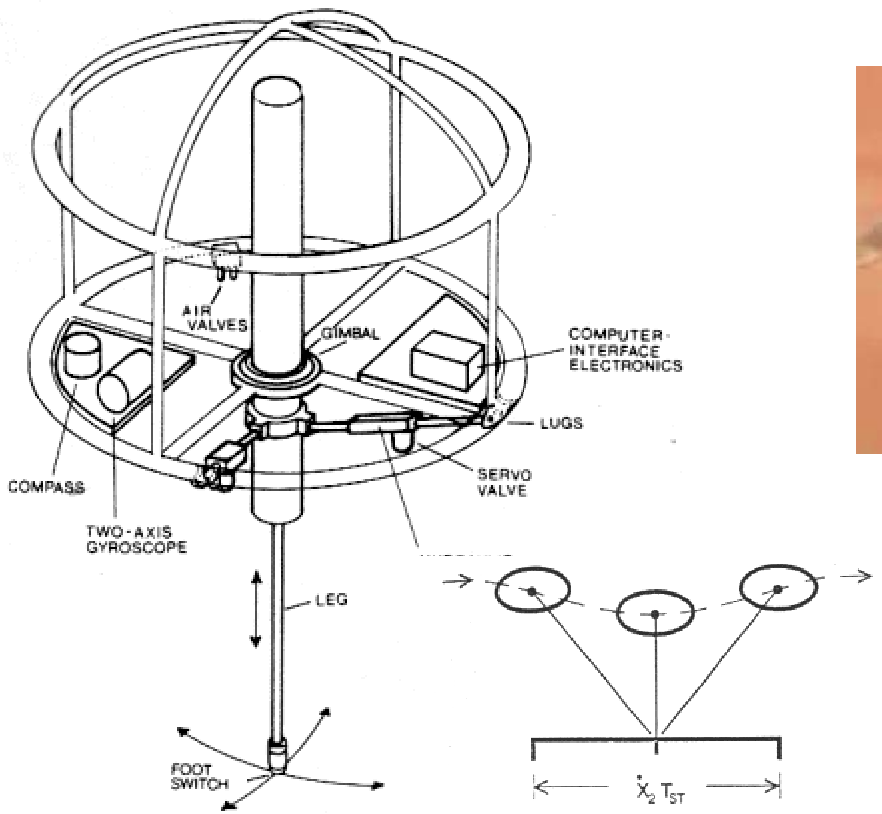
- La postura non è controllata esplicitamente in modo dettagliato ma è la "conseguenza biomeccanica" dell'equilibrio delle forze muscolari e delle forze dell'ambiente
- Il movimento è la conseguenza della "rottura dell'equilibrio", ovvero è la transizione da un equilibri ad un altro
- Il meccanismo funziona perché i muscoli non sono puri generatori di forza ma sono in grado di immagazzinare e restituire energia meccanica ⇒ il controllo del movimento equivale a controllare il flusso dell'energia meccanica

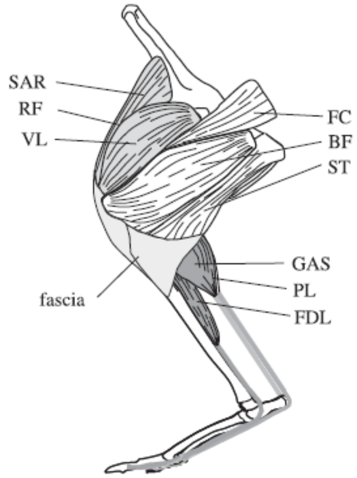
Asatryan DG, Feldman AG (1965) Functional tuning of the nervous system with control of movements or maintenance of a steady posture. *Biophysics* 10:925–935.

Bizzi E, Polit A, Morasso P (1976) Mechanisms underlying recovery of final head position. *J Neurophysiol* 39: 435-444.

Energetic efficiency in locomotion

During movements, a huge amount of energy can be stored passively in the biomechanics of the muscle system. Controlling such a system in a way that takes advantage of the stored energy has lead to the Equilibrium-point hypothesis (EPH).





As kangaroos hop faster over level ground, their rate of metabolic energy consumption remains nearly the same. This phenomenon has been attributed to efficient elastic energy storage and recovery via long compliant tendons in the legs.

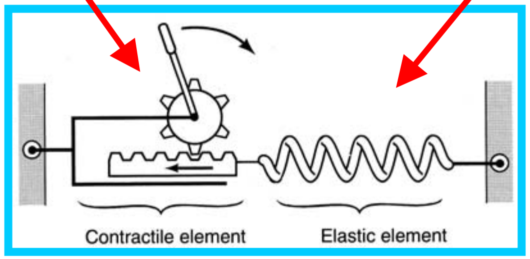
Raibert MH (1990) Trotting, pacing and bounding by a quadruped robot. J Biomech 23:79-98.

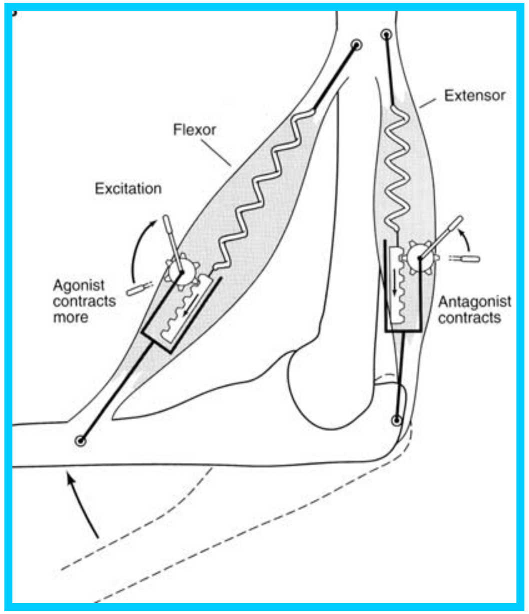
Alexander RMcN, Vernon A (1975) The mechanics of hopping by kangaroos (Macropodidae). *J Zool (Lond)* 177, 265–303.

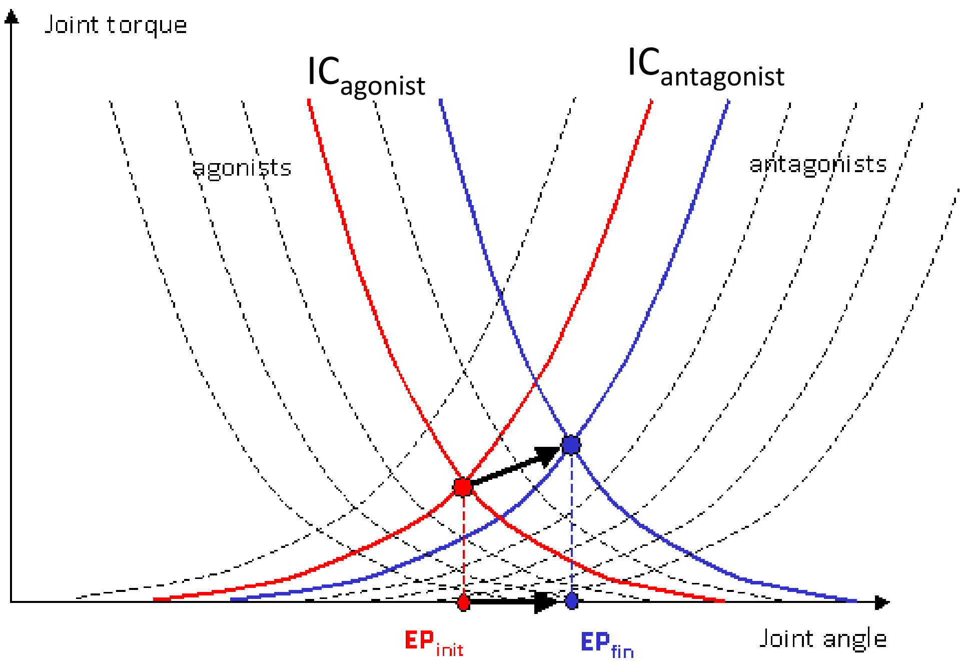
Postural stability

λ : soglia del riflesso di stiramento (variabile di controllo)

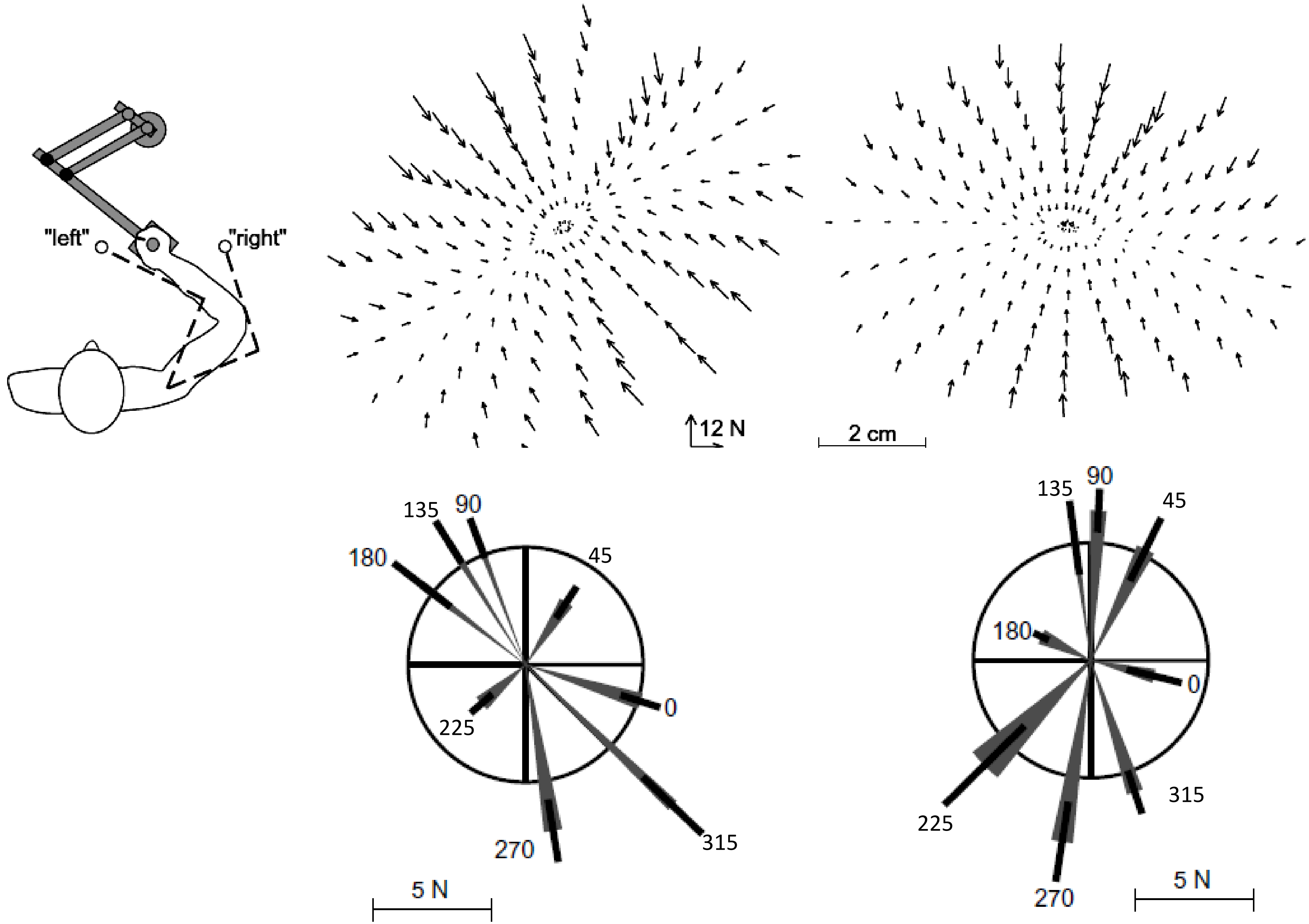
energia potenziale (non linear stiffness)



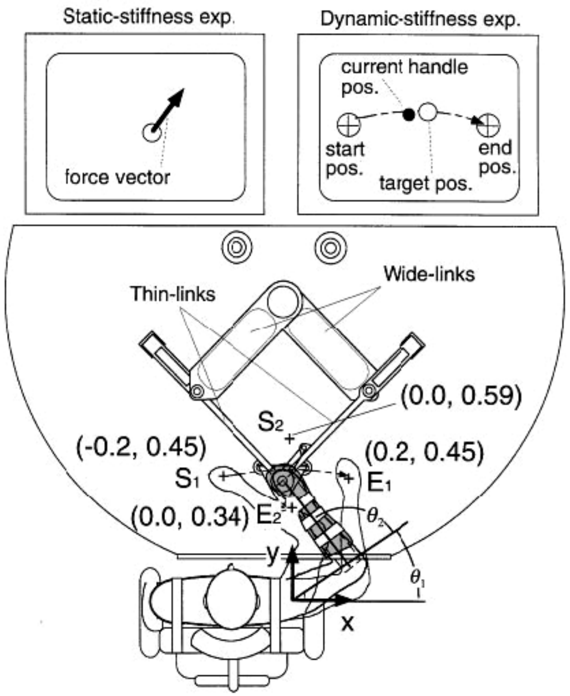




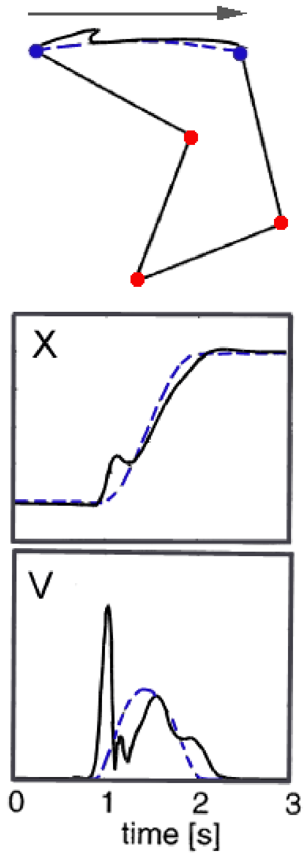
Feldman AG (1986) Once more on the equilibrium-point hypothesis (lambda model) for motor control. *J Mot Behav* 18:17-54.

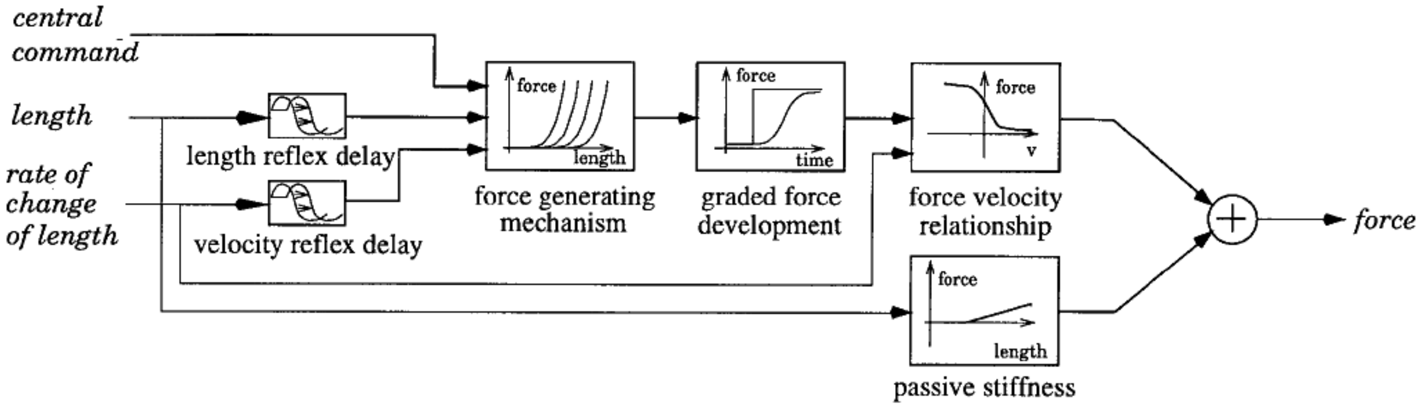


Shadmehr, R., Mussa-Ivaldi, F. A., and Bizzi, E., 1993, Postural force fields of the human arm and their role in generating multi-joint movements, J. Neurosci., 13:45-62.



Gomi H, Kawato M (1996) Equilibrium-point control hypothesis examined by measured arm stiffness during multijoint movement. *Science* 272: 117–120.





Gribble PL, Ostry DJ, Sanguineti V, Laboissiere R (1998) Are complex control signals required for human arm movement? *J Neurophysiol*, 79, 1409-24.

Dal controllo neurale del movimento alla riabilitazione motoria

La riabilitazione neuromotoria è un intervento complesso e multifattoriale

↓

C’è bisogno di una **base teorica** al di là di approcci puramente empirici

Derick Wade (2009) Control in rehabilitation research (Editorial). Clinical Rehabilitation 2009; 23: 675–680.

Elementi essenziali per una base teorica

- Neurofisiologia di base: Reclutamento della Plasticità Neurale (Nudo e coll.)
- Neurofisiologia del controllo motorio: Teoria del punto di equilibrio (Feldman, Bizzi)
- Neuropsicologia dell'apprendimento di task: Schema Theory (Schmidt)

Beyond the time-dependent spontaneous neurological recovery, the principal process responsible for functional recovery is the <u>use-dependent reorganization</u> of neural mechanisms made possible by <u>neural plasticity</u>.

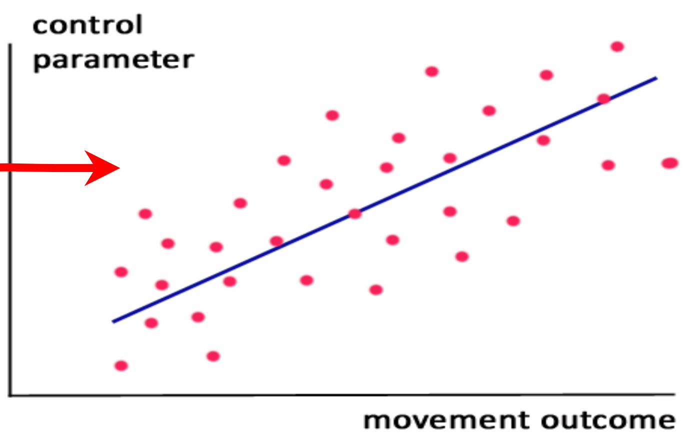
Nudo RJ (2006) Mechanisms for recovery of motor function following cortical damage. *Current Opinion in Neurobiology,* 16:638–644.

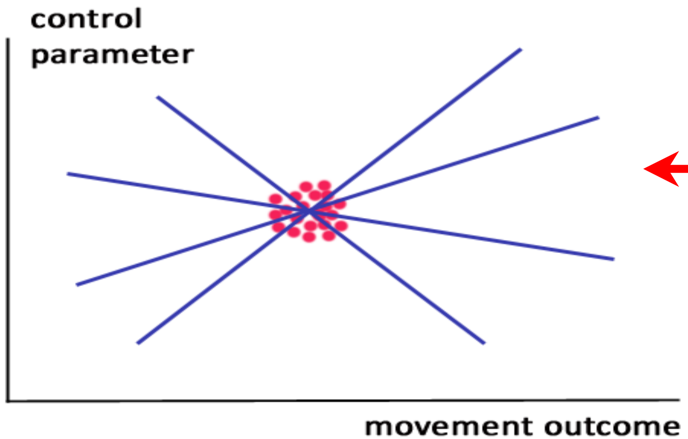
Nudo RJ (2007) Postinfarct cortical plasticity and behavioral recovery. *Stroke* 38:840-5.

Cumberland Consensus Working Group (2009) The future of restorative neurosciences in stroke: driving the translational research pipeline from basic science to rehabilitation of people after stroke. *Neurorehabil Neural Repair* 23:97-107

Schema Theory of Motor Leraning: Rehabilitation techniques can be efficient if they can promote increasing levels of motor skill

People don't learn specific movements. Instead, they construct Generalized Motor Programs (GMP), that relate Control Parameters to Movement Outcome, during training





- **People will more quickly learn the relationship between parameters and a desired movement outcome if they practice a task in wide variety of situations, and experience errors in the process.**
- **Practice that lacks variety, but is instead repetitive, will not provide enough information for learning the rules that underlie the GMP.**

Schmidt (1975). A schema theory of discrete motor skill learning. *Psychol Review, 82,* 225-260.

Schmidt (1991). Motor learning principles for physical therapy. In: Foundation for Physical Therapy. *Contemporary Management of Motor Control Problems: Proceed II-STEP Conference.* Alexandria, VA, USA.

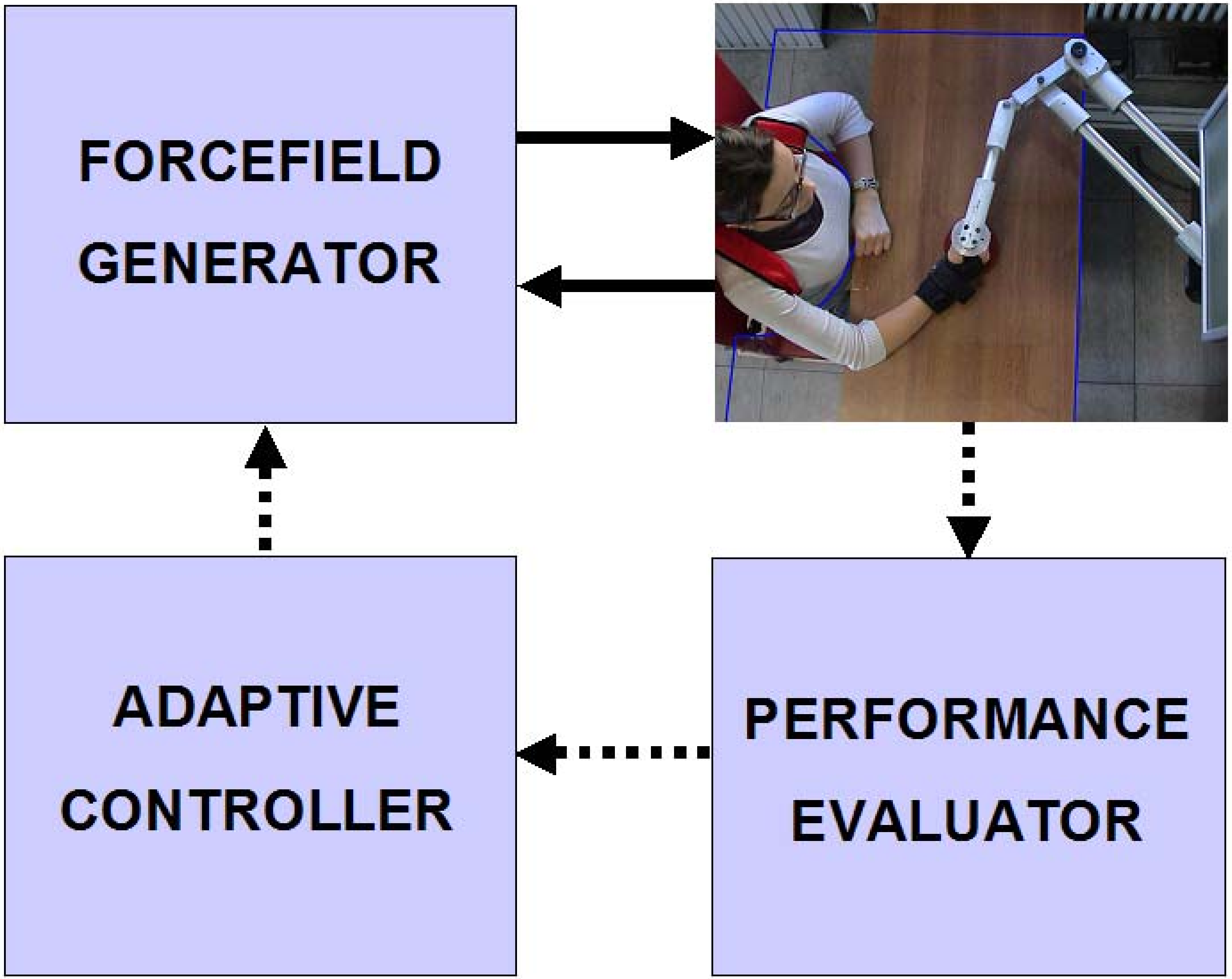
Schema Theory ⇒ Optimal regulation of "Robot Assistance"

$$P = f(A + C)$$

Performance (Outcome) — Assistance — (voluntary) Control

The assistance force should be

- Large enough to allow the subject to complete the task, although in an imprecise and/or slow manner (in order to avoid frustration).
- Small enough to motivate the subject to contribute as much as possible to the outcome (in order to avoid laziness)
- The assistance force should be reduced from trial to trial as performance improves (in order to promote the emergence of control).
- The assistance force should be boosted at the beginning of each session (non-monotonic modulation in order to allow memory consolidation)


FORCEFIELD
GENERATOR
ADAPTIVE
CONTROLLER
PERFORMANCE
EVALUATOR

In cosa consiste la "**Robot Assistance**"?

Essenzialmente consiste nella generazione di "**Campi di Forza**" capaci di insegnare al sistema nervoso centrale dei "**Modelli Interni**" di controllo.

Perché dovremmo aspettarci che la "**Robot Assistance**" possa essere efficace come strumento di training?

Perché ci sono evidenze sperimentali che il cervello comprenda il "**linguaggio dei campi di forza**"

- **Teoria del punto di equilibrio**
- **Motor imagery**

Teoria del Punto di Equilibrio

- La postura non è controllata esplicitamente in modo dettagliato ma è la “conseguenza biomeccanica” dell’equilibrio delle forze muscolari e delle forze dell’ambiente
- Il movimento è la conseguenza della “rottura dell’equilibrio”, ovvero è la transizione da un equilibrio ad un altro

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Bizzi E, Polit A, Morasso P (1976) Mechanisms underlying recovery of final head position. *J Neurophysiol* 39: 435-444.

Motor imagery

Motor imagery is a specific type of mental imagery = mental rehearsal of a motor act in the absence of overt motor output (Crammond, 1997).

Experimental results (in terms of EEG, fMRI, PET, NIRS) generally support the idea of common underlying functional networks subserving both the preparation for execution and imagery of movements.

They also provide a broader context for this notion by revealing similarities in cognitive components associated with the movement tasks (Kranczioch et al, 2009; Munzert at al 2009).

Decety, J., 1996. Do imagined and executed actions share the same neural substrate? Brain. Res. Cogn. Brain Res. 3, 87–93.

Crammond, D.J., 1997. Motor imagery: never in your wildest dream. Trends Neurosci. 20, 54–57.

Kranczioch C, Mathews S, Dean JA, Sterr A (2009) On the Equivalence of Executed and Imagined Movements. Human Brain Mapping.

Munzert J, Lorey B, Zentgraf K (2009) Cognitive motor processes: the role of motor imagery in the study of motor representations. Brain Res Reviews 60:306-26.

Mental Simulation Theory (M. Jeannerod 2001)

MST stresses that cognitive motor processes such as motor imagery, movement observation, action planning & verbalization **share the same representations** with motor execution.

MST views motor images as being based on neural processes for motor execution that are inhibited at a certain stage of processing.

This activation includes not only premotor and motor areas such as PMC, SMA, and M1 but also subcortical areas of the cerebellum and the basal ganglia.

⇓

Internal models of control involved in motor imagery are the same at play in actual movement ⇒ **I.M. can be trained by means of force fields**

Jeannerod, M., 2001. Neural simulation of action: a unifying mechanism for motor cognition. NeuroImage 14, 103–109.
Lotze M, Montoya, P et al (1999) Activation of cortical and cerebellar motor areas during executed and imagined hand movements: an fMRI study. J Cogn Neurosci 11: 491–501.
Bonda E, Petrides M et al (1995) Neural correlates of mental transformations of the body-in-space. PNAS 92:11180–84.

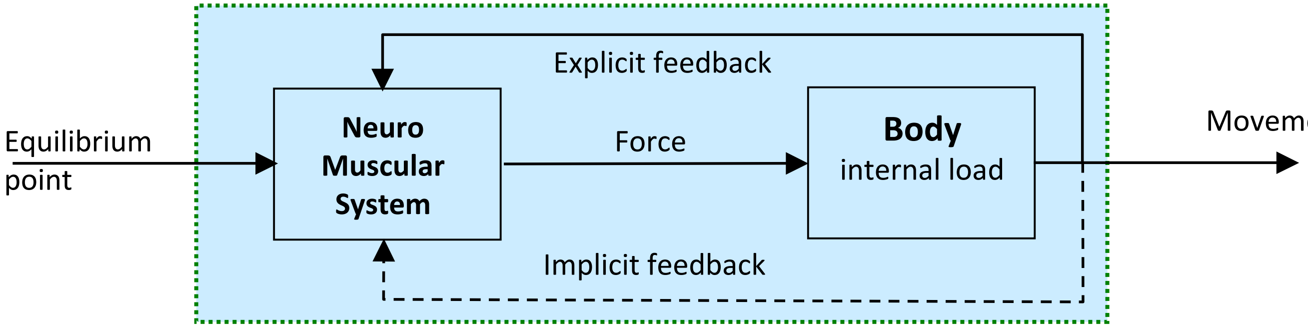
EPH is a general language for describing motor control in humans and humanoid robots.

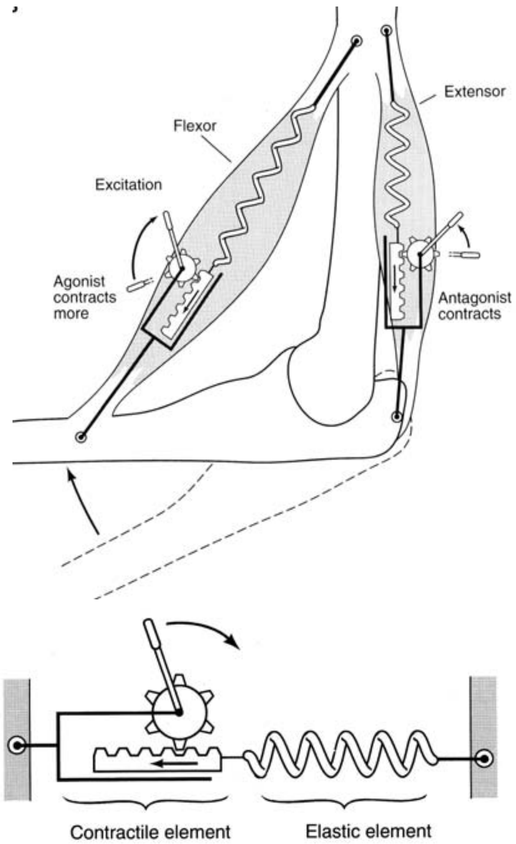
But it is a language with many dialects.

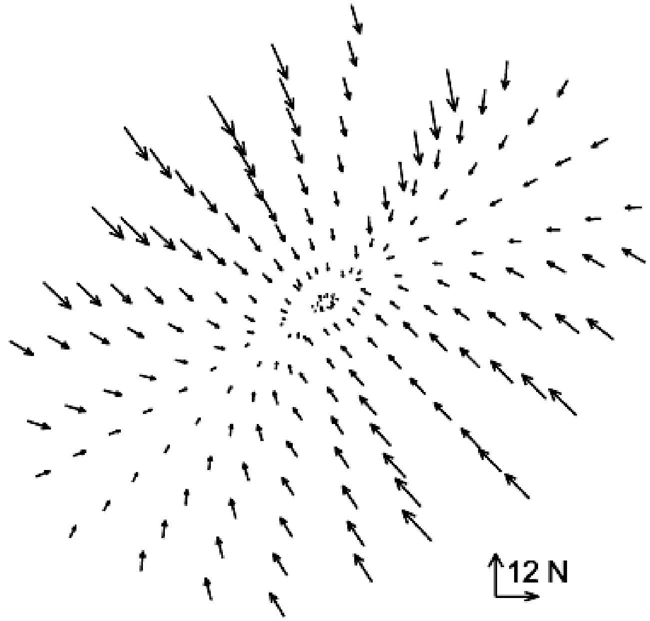
Its power comes from the ability to solve the "degrees of freedom problem" as formulated by Nikolai Bernstein

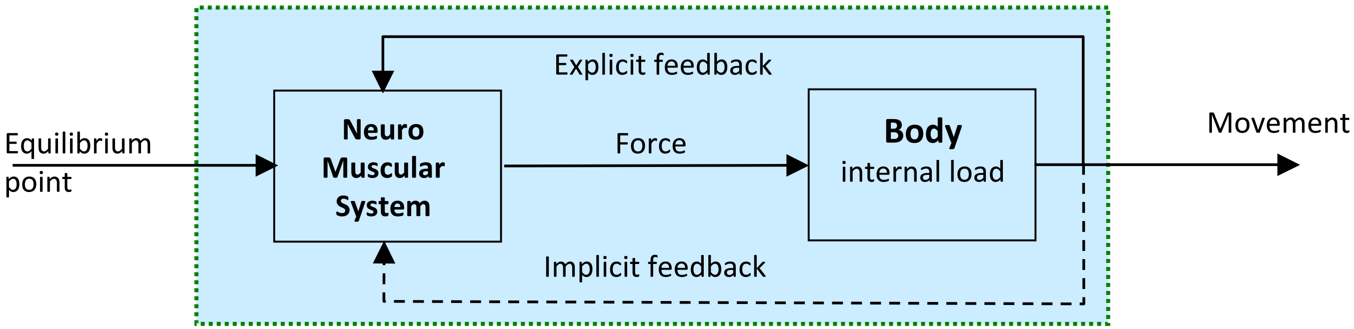
Equilibrium ⇔ Energy function ⇔ Force fields

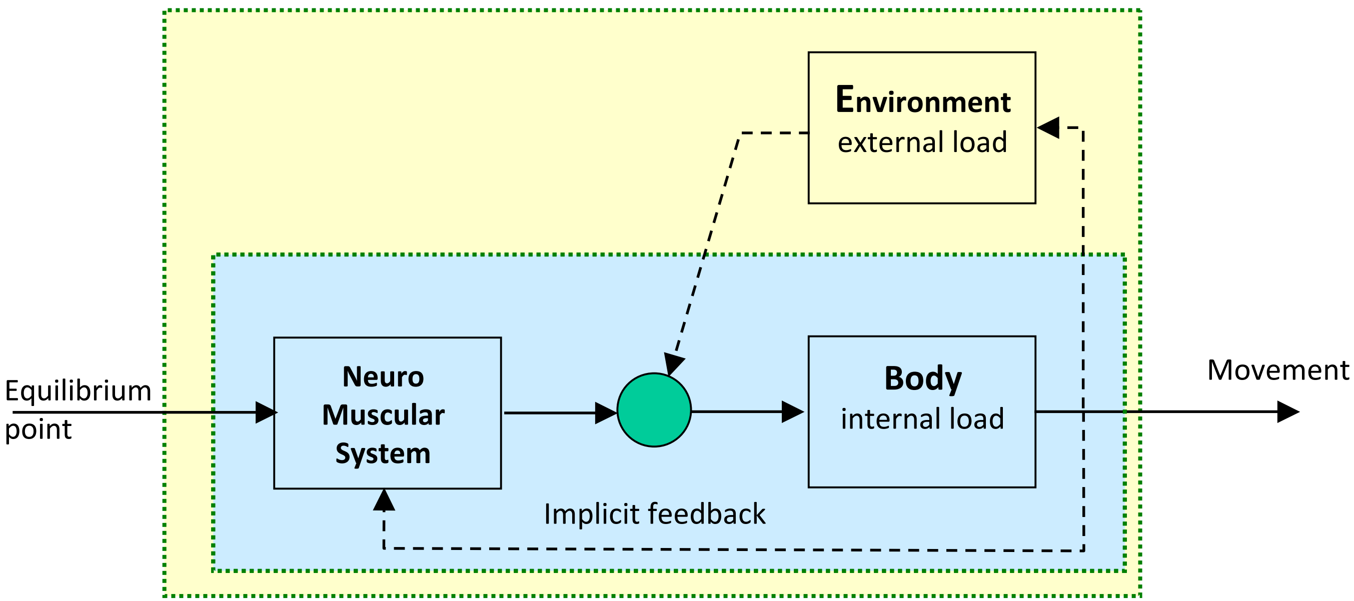
- Physical force fields
  - muscle properties
- Virtual force fields
  - attractor dynamics of cortical maps / motor imagery
- Physical force fields
  - haptic robots / haptic interaction in physiotherapy


Explicit feedback
Neuro
Muscular
System
Force
Body
internal load
Equilibrium
point
Movement
Implicit feedback

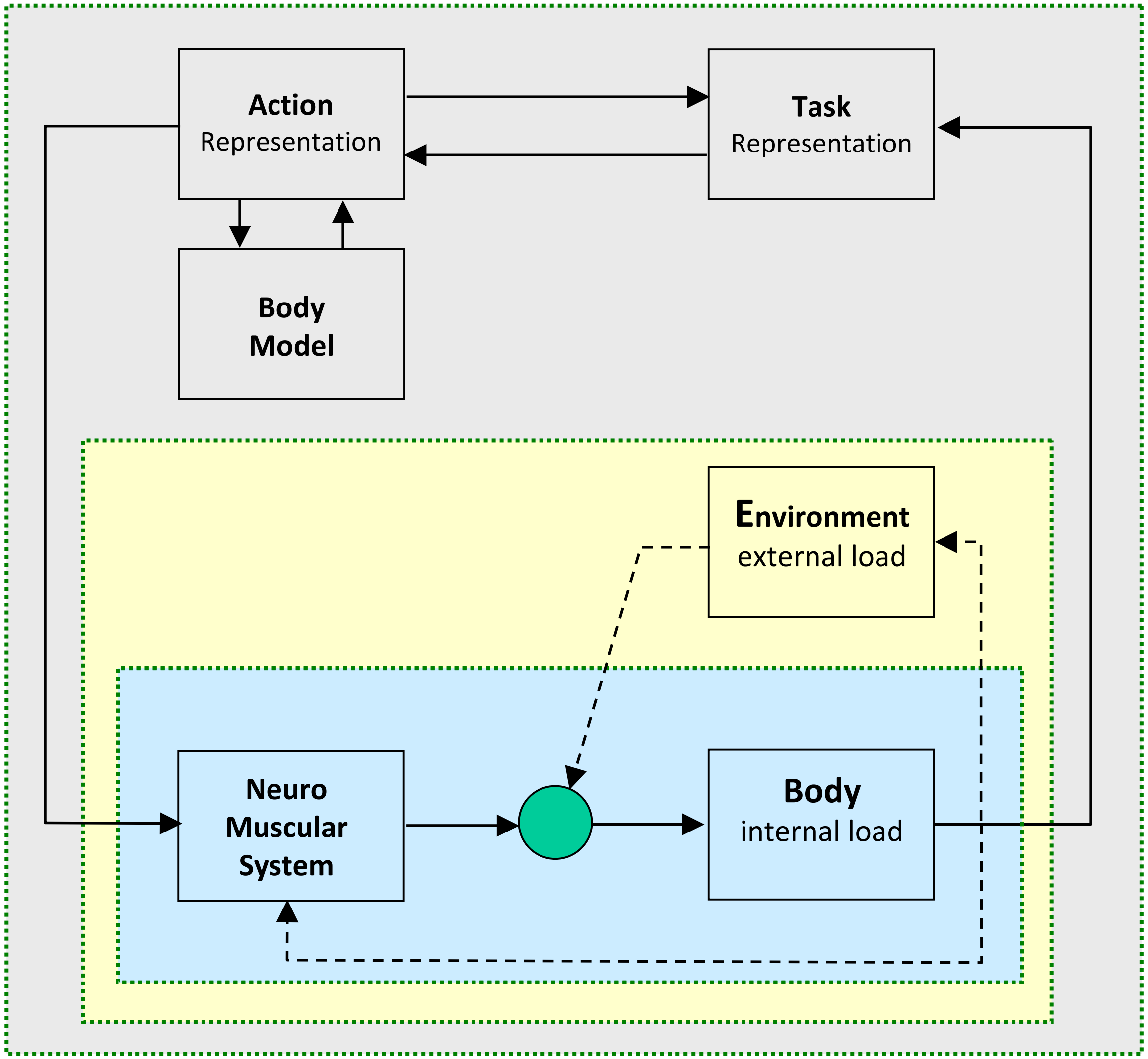

Flexor
Extensor
Excitation
Agonist contracts more
Antagonist contracts
Contractile element
Elastic element

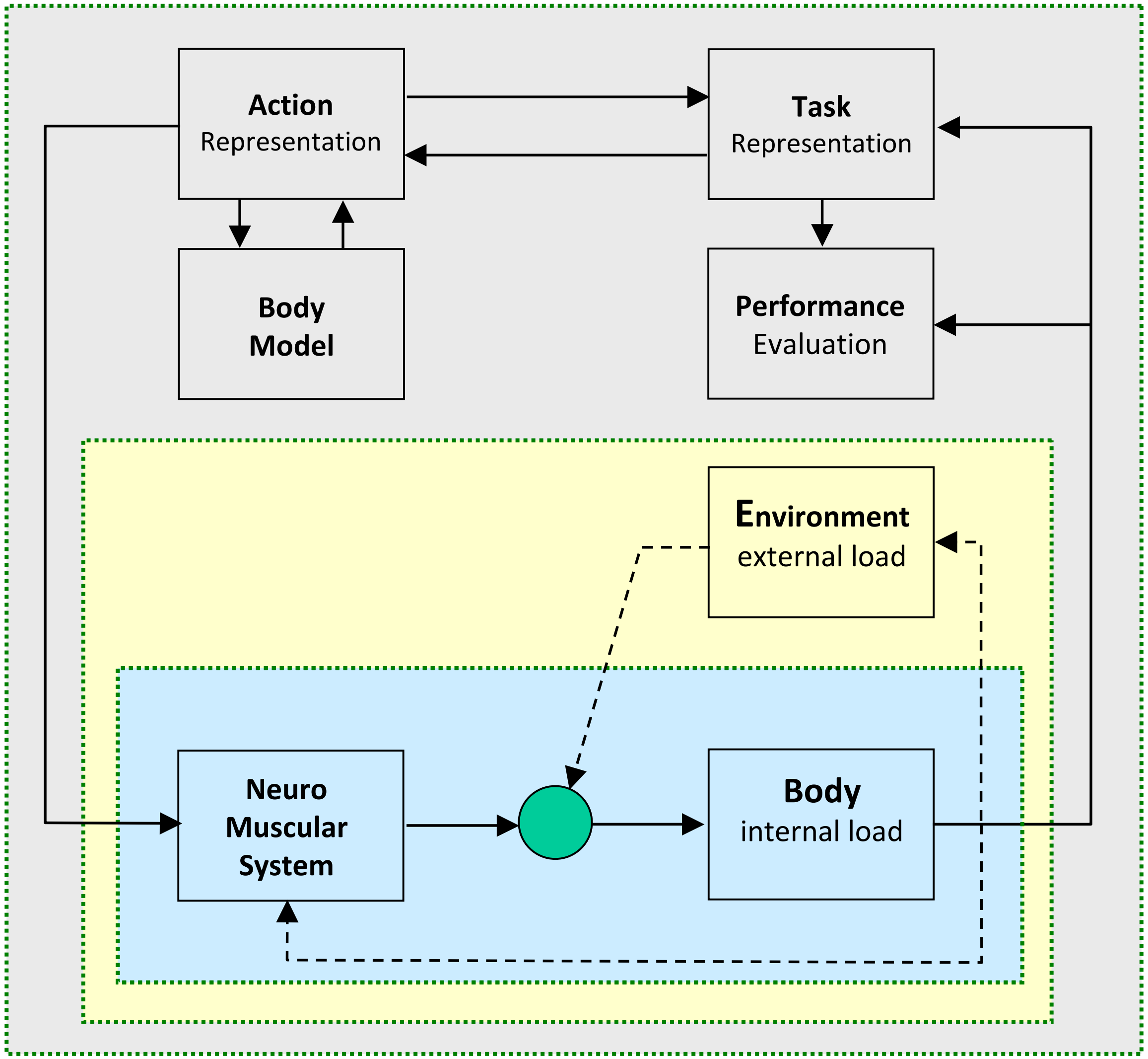

12 N


Equilibrium point
Neuro Muscular System
Force
Body internal load
Movement
Explicit feedback
Implicit feedback

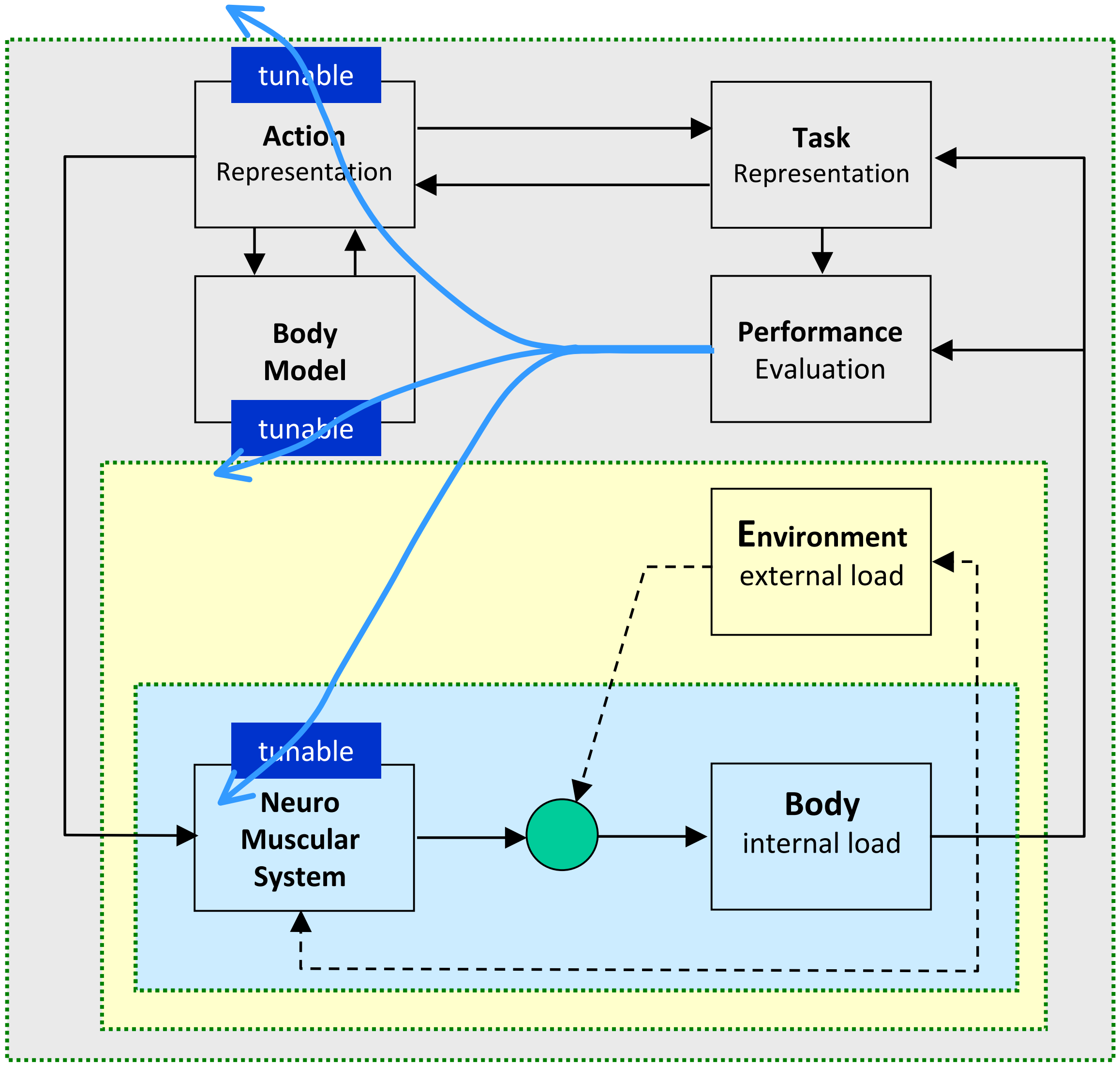


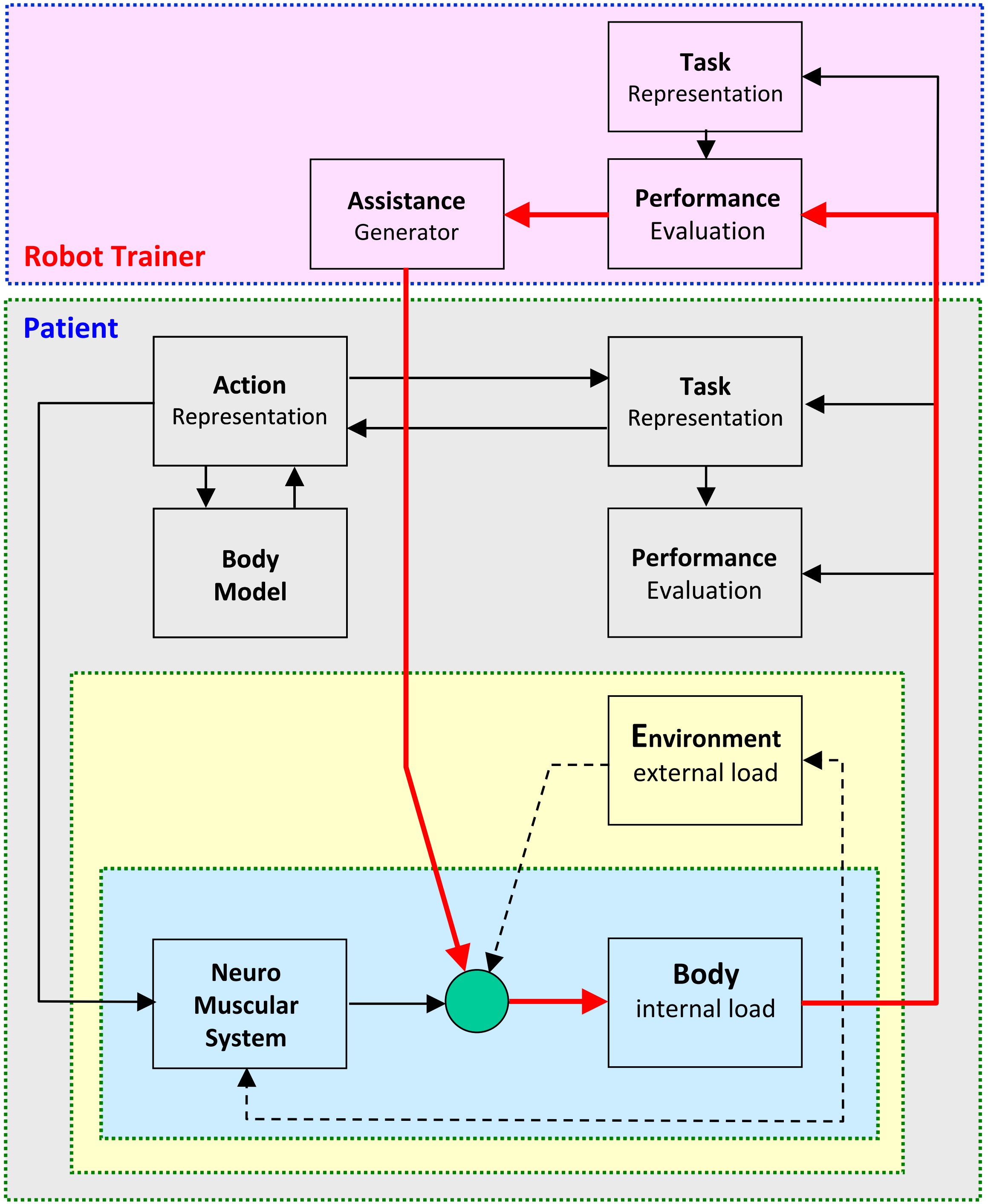
Environment
external load
Equilibrium
point
Neuro
Muscular
System
Body
internal load
Movement
Implicit feedback


Action
Representation
Task
Representation
Body
Model
Environment
external load
Neuro
Muscular
System
Body
internal load

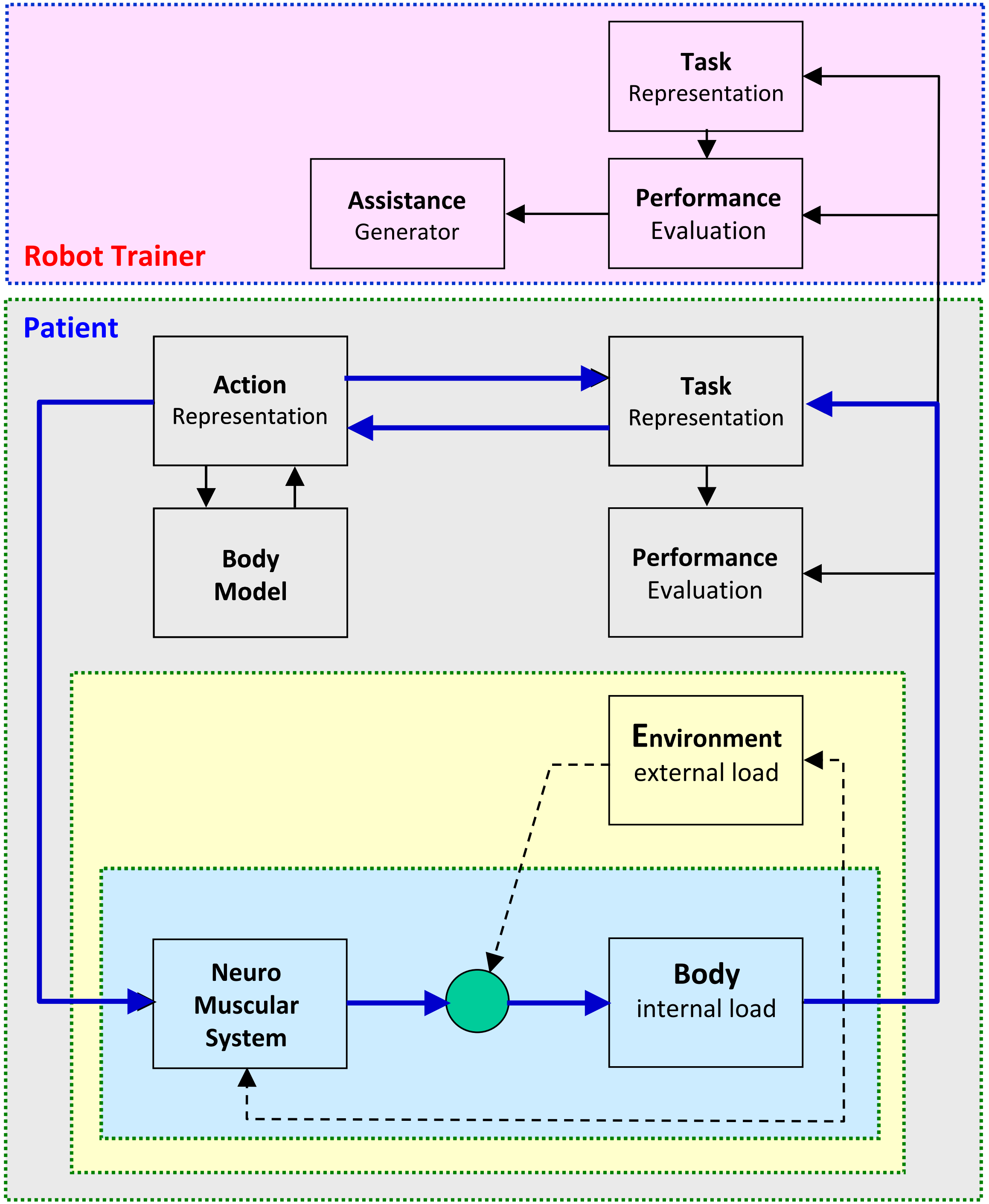


Action
Representation
Task
Representation
Body
Model
Performance
Evaluation
Environment
external load
Neuro
Muscular
System
Body
internal load

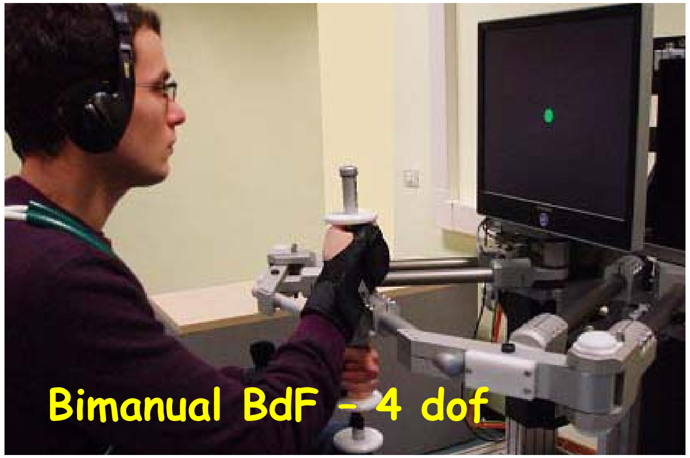

tunable
Action
Representation
Task
Representation
Body
Model
Performance
Evaluation
tunable
Environment
external load
tunable
Neuro
Muscular
System
Body
internal load



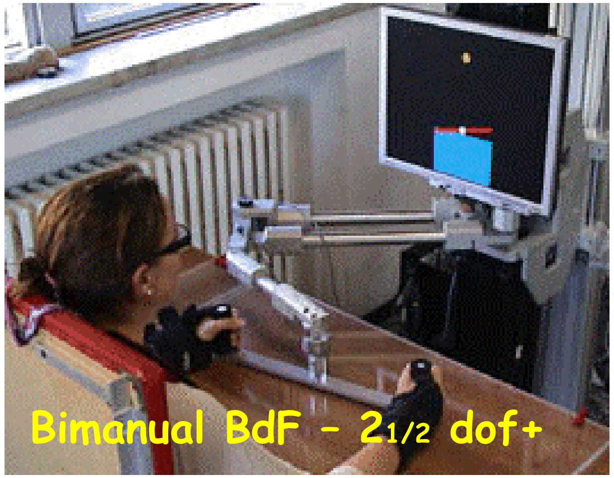
Robot Trainer
Task Representation
Assistance Generator
Performance Evaluation
Patient
Action Representation
Task Representation
Body Model
Performance Evaluation
Environment external load
Neuro Muscular System
Body internal load


Task
Representation
Assistance
Generator
Performance
Evaluation
Robot Trainer
Patient
Action
Representation
Task
Representation
Body
Model
Performance
Evaluation
Environment
external load
Neuro
Muscular
System
Body
internal load

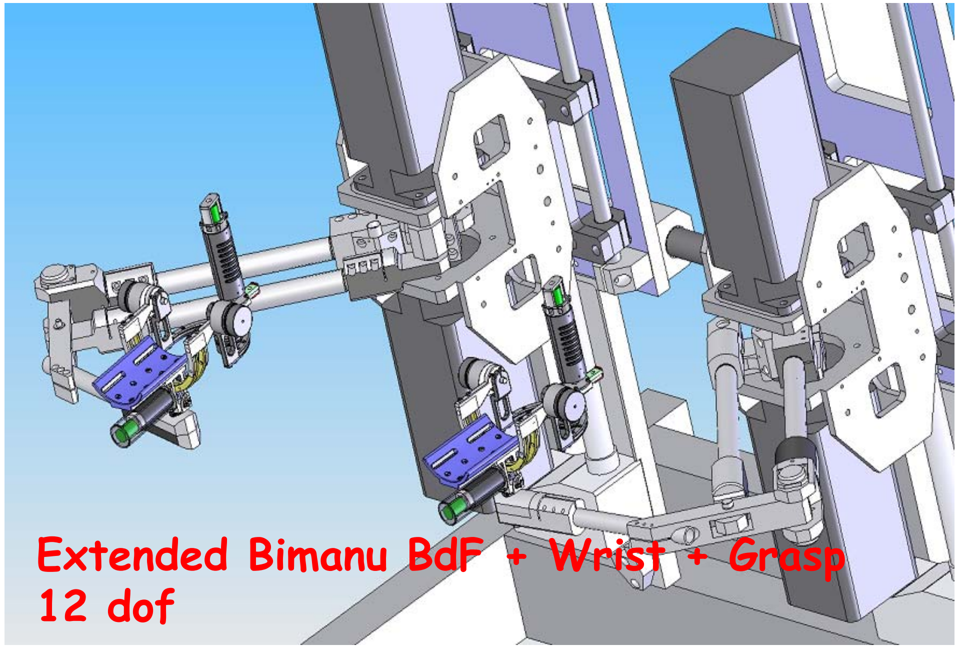
Braccio di Ferro 2dof (BdF)



Bimanual BdF - 4 dof

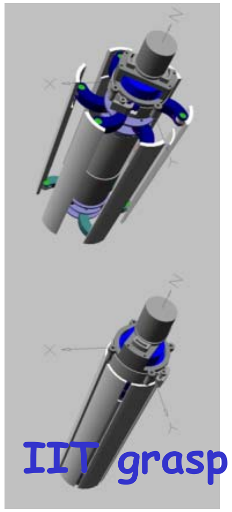


Bimanual BdF – $2_{1/2}$ dof+



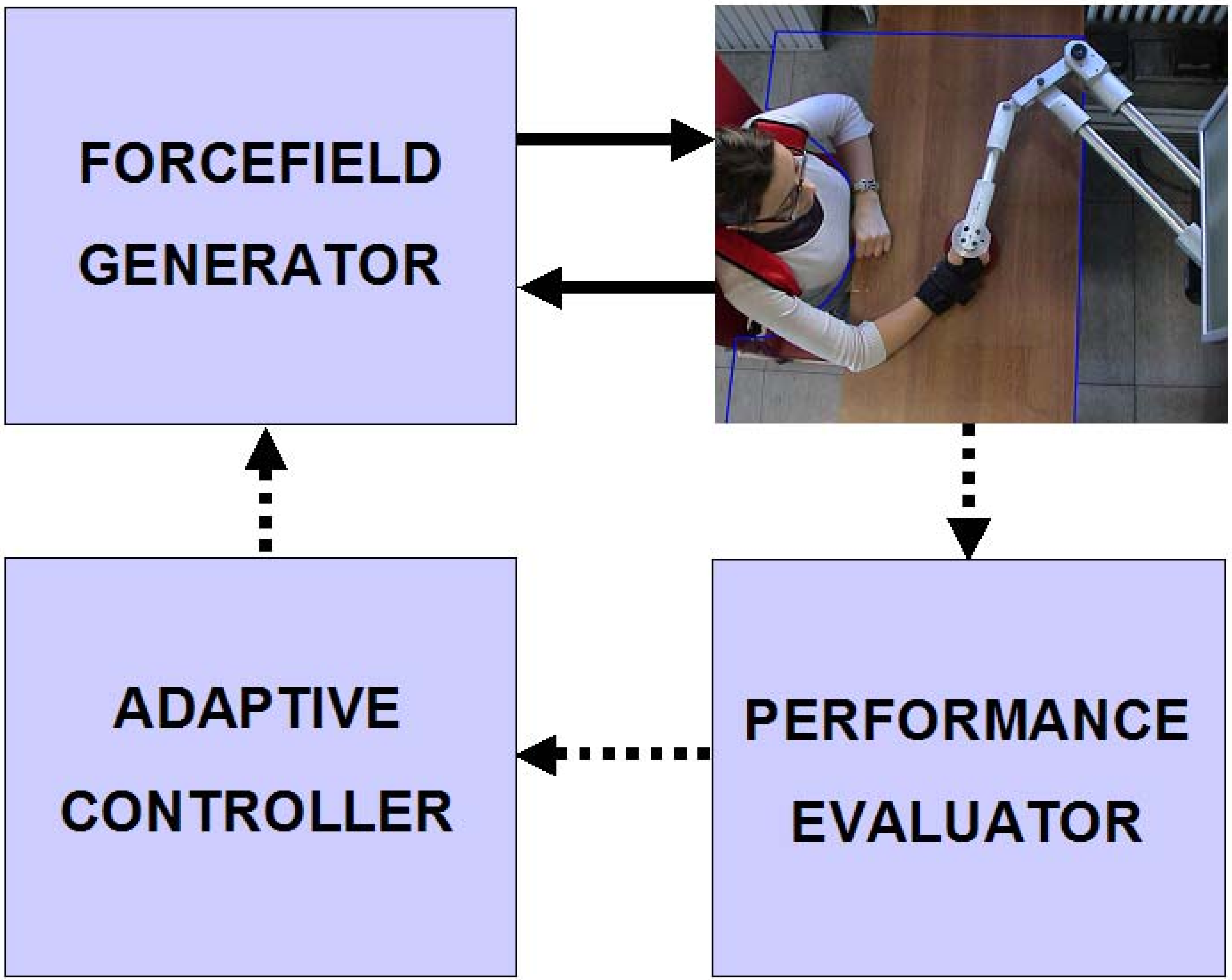
Extended Bimanu BdF + Wrist + Grasp
12 dof

IIT wrist robot: 3dof



IIT grasp robot

Caratteristica comune: Robot Aptici & Intelligenti



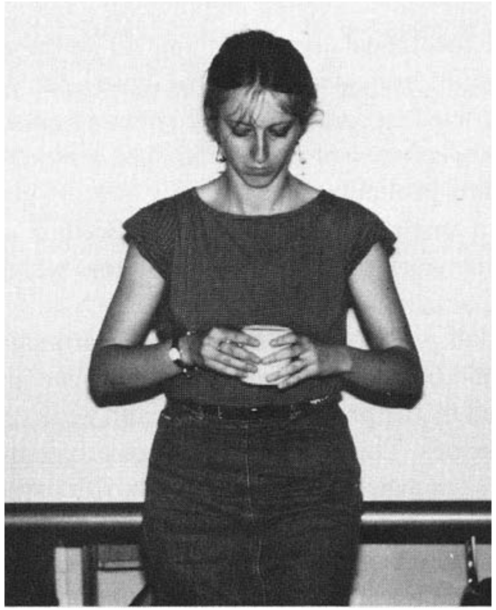
Haptics
for
Neural control of movment

Walking & Reading

In the reading situation, she is trying to link the arm to the trunk with large inertia , in order to reduce the number of degrees of freedom between trunk and hand.

The large inertia cuts off high frequency components and passes only low frequency components, which are compensated by the ocular pursuit system.

Walking & Carrying a full cup

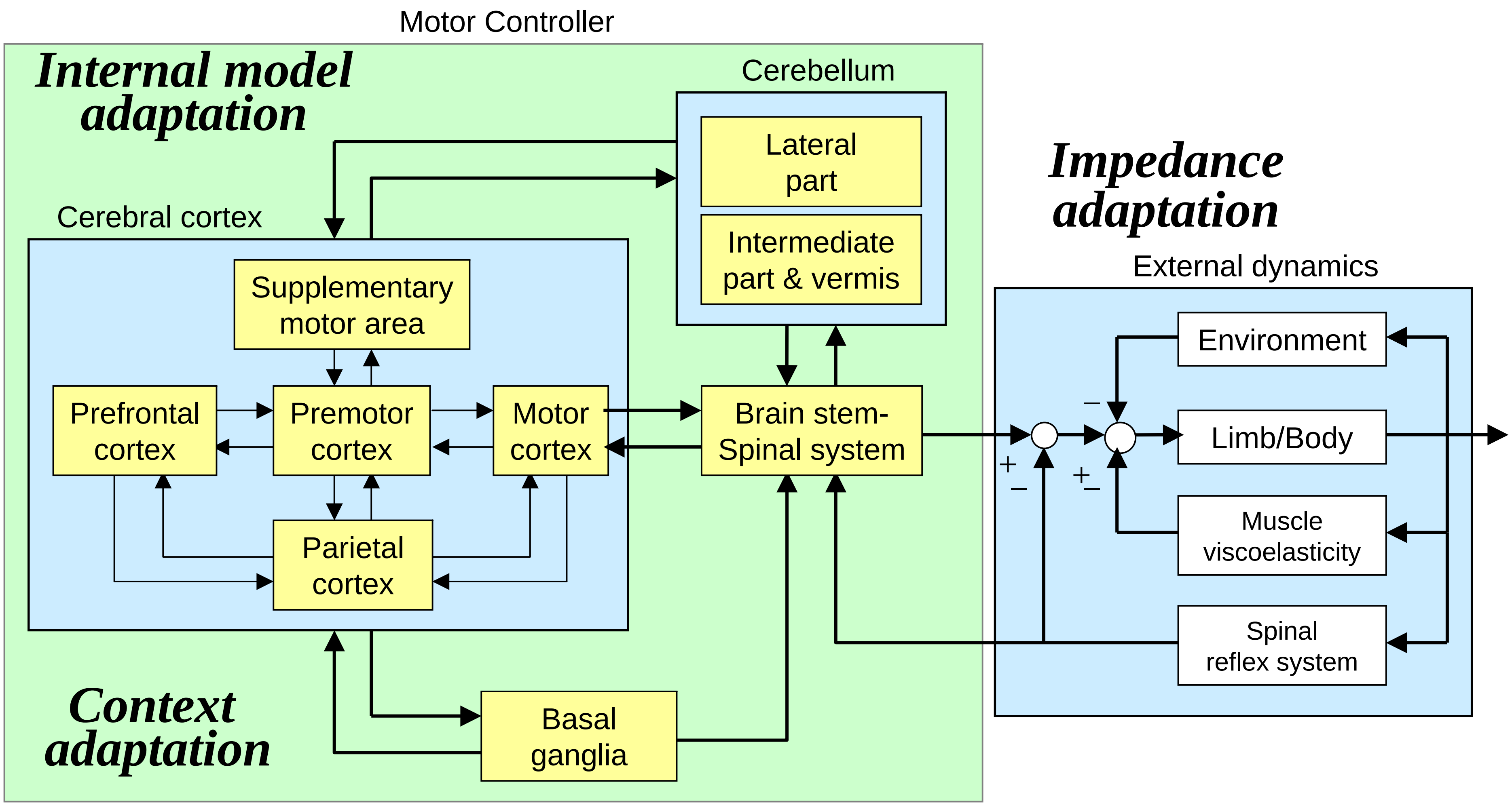


When carrying a full glass of water, she is trying to free the arm movement from the low frequency displacements of the trunk.

As a result, the movements of water in the glass are mainly dependent on the high frequency components of linear and rotational acceleration of the hand. The high frequency movements are compensated by the surface tension of the water

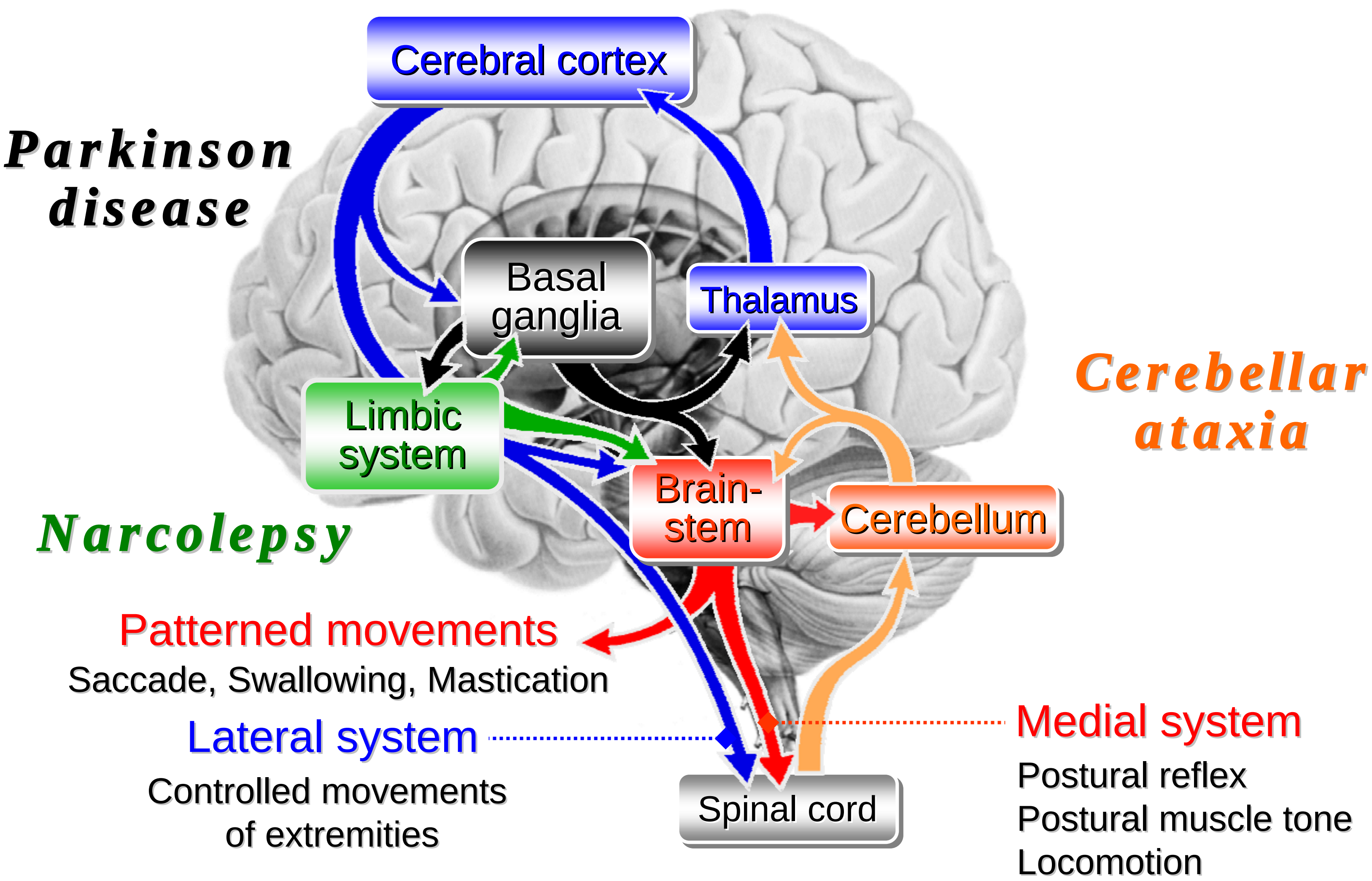
Courtesy of K. Ito

Basic neural mechanisms for motor control & motor adaptation



Courtesy of K. Ito

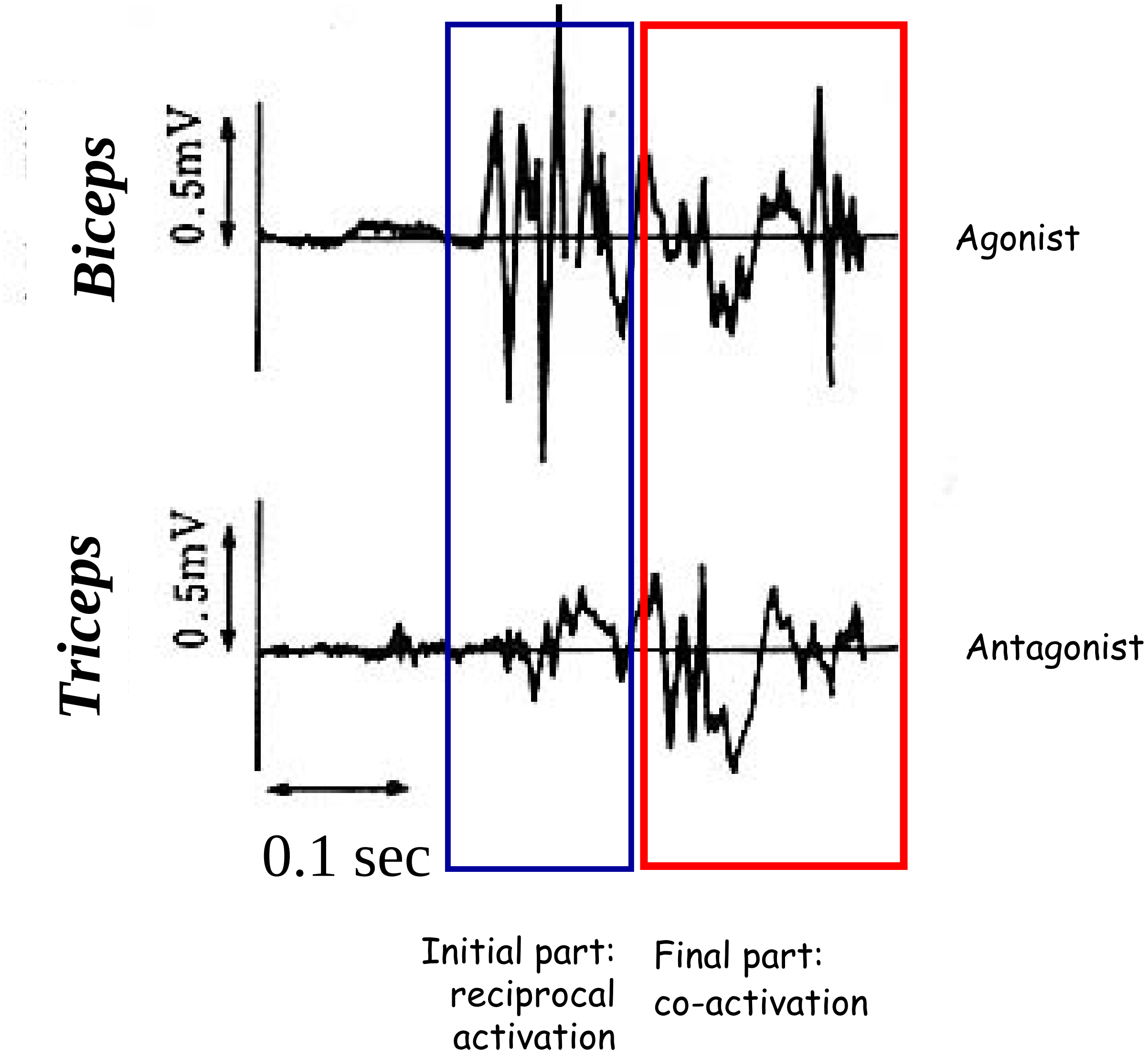
Basic neural mechanisms for motor control & motor adaptation

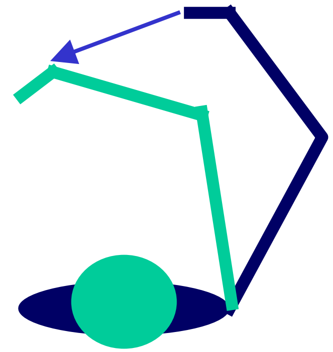


Courtesy of K. Ito

Stiffness and stiffness control

Muscle Co-contraction in Reaching Motion



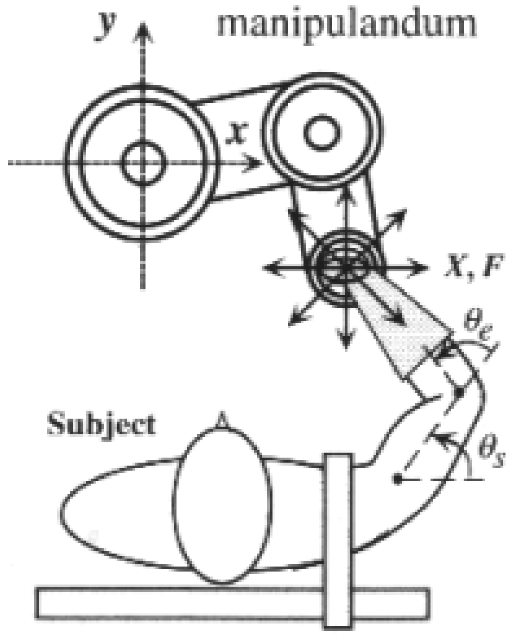


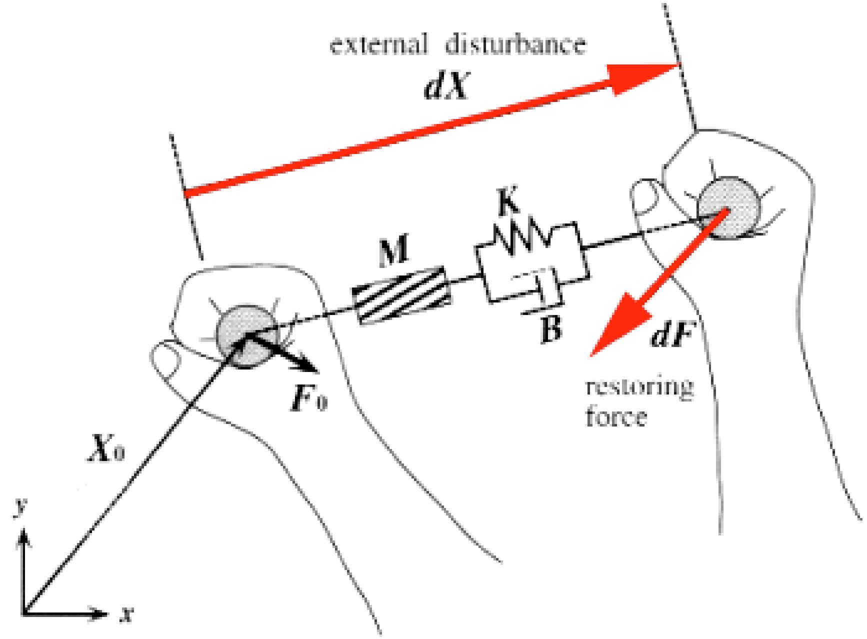
Fast movements:

Stiffness strategy in the terminal part of the movement (dissipation of kinetic energy)

Courtesy of K. Ito

Haptic robots: measuring the mechanical impedance of the human arm



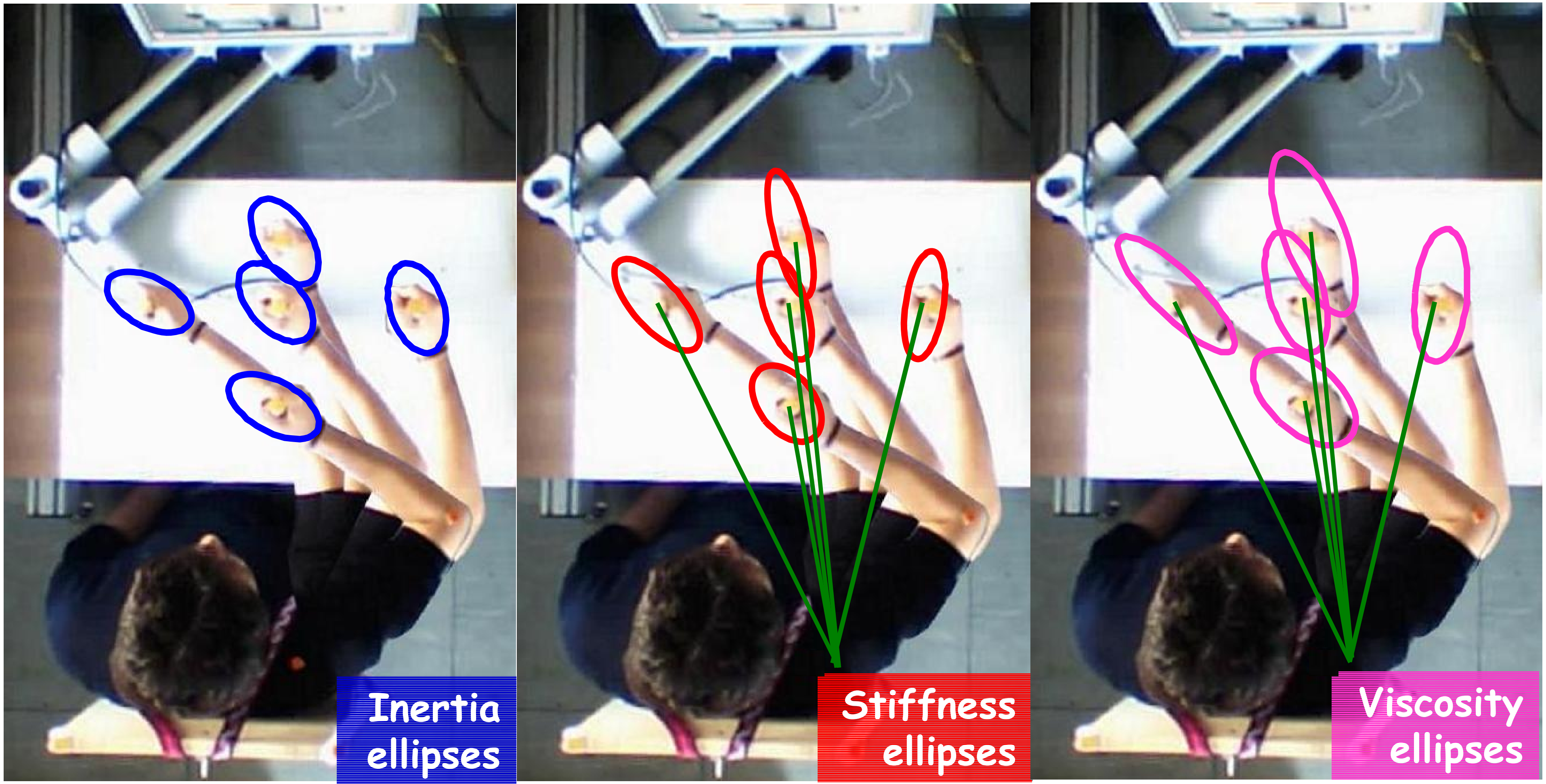


$$F = Kdx + B\dot{x} + M\ddot{x}$$

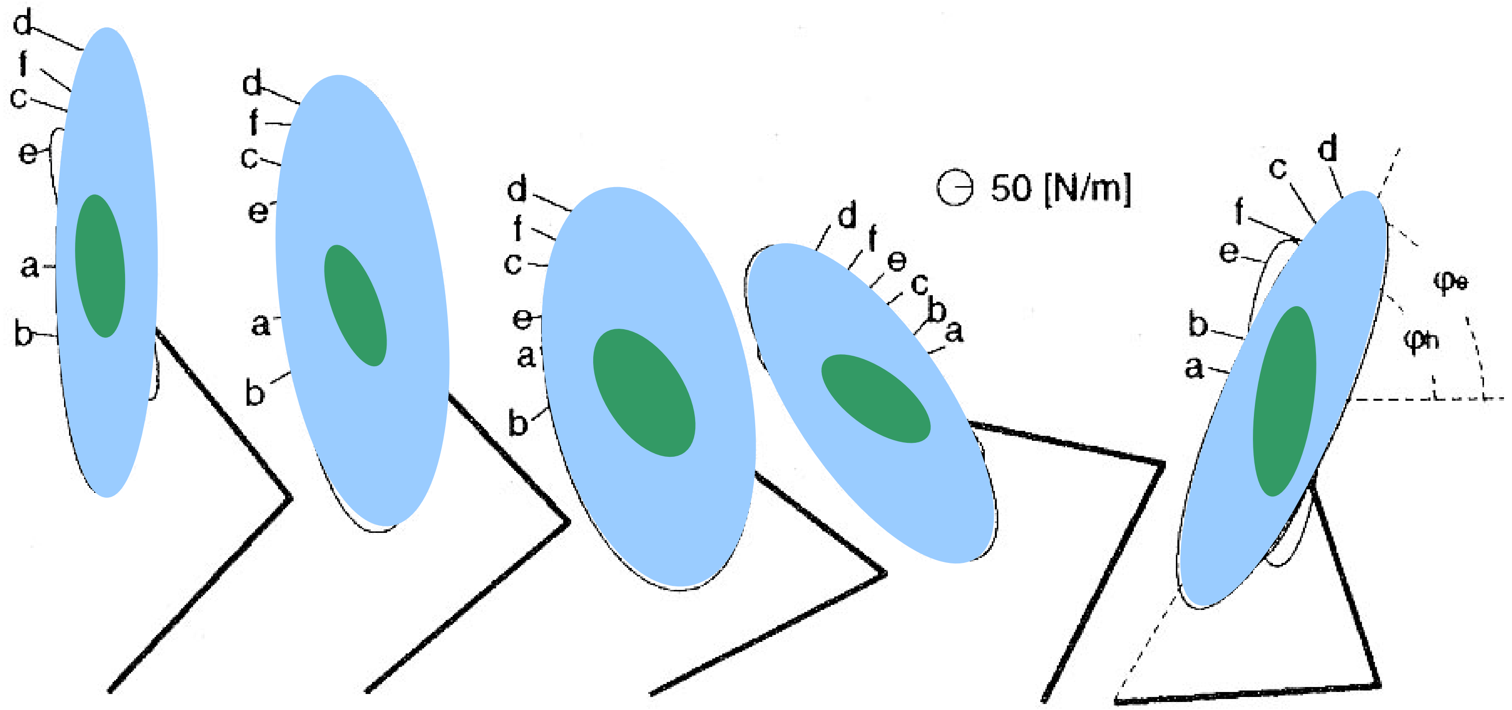
Mussa Ivaldi, Hogan, Bizzi; J Neurosci 1985

Tsuji, Morasso, Goto, Ito; Biol Cybern 1995

The mechanical impedance of the arm illustrates the anisotropy of arm dynamics



Stiffness Ellipses in Various Muscle Contractions & Arm Postures

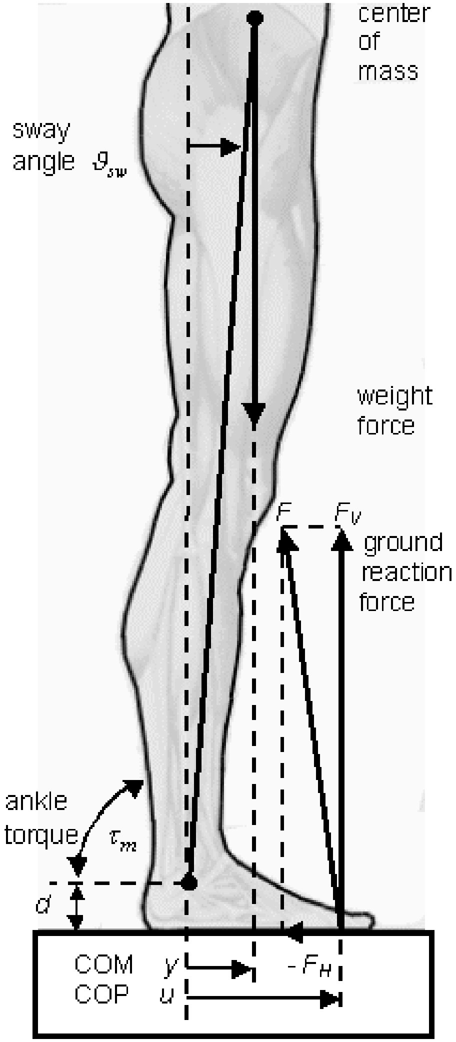


(1) Front far (2) Front middle (3) Front near (4) Left near (5) Right near

a: No contraction, b: 25% co-contraction, c: 50% co-contraction,
d: Max. co-contraction, e: Co-contraction by only shoulder joint,

(Gomi, J. Neuroscience, 1998）

The role of intrinsic ankle stiffness



$$-\tau_m + \tau_g = I\ddot{\vartheta}$$

- Destabilizing torque: $\tau_g = mgh\ \vartheta$
- Control torque: $\tau_m = K_a\vartheta + \tau_{act}$

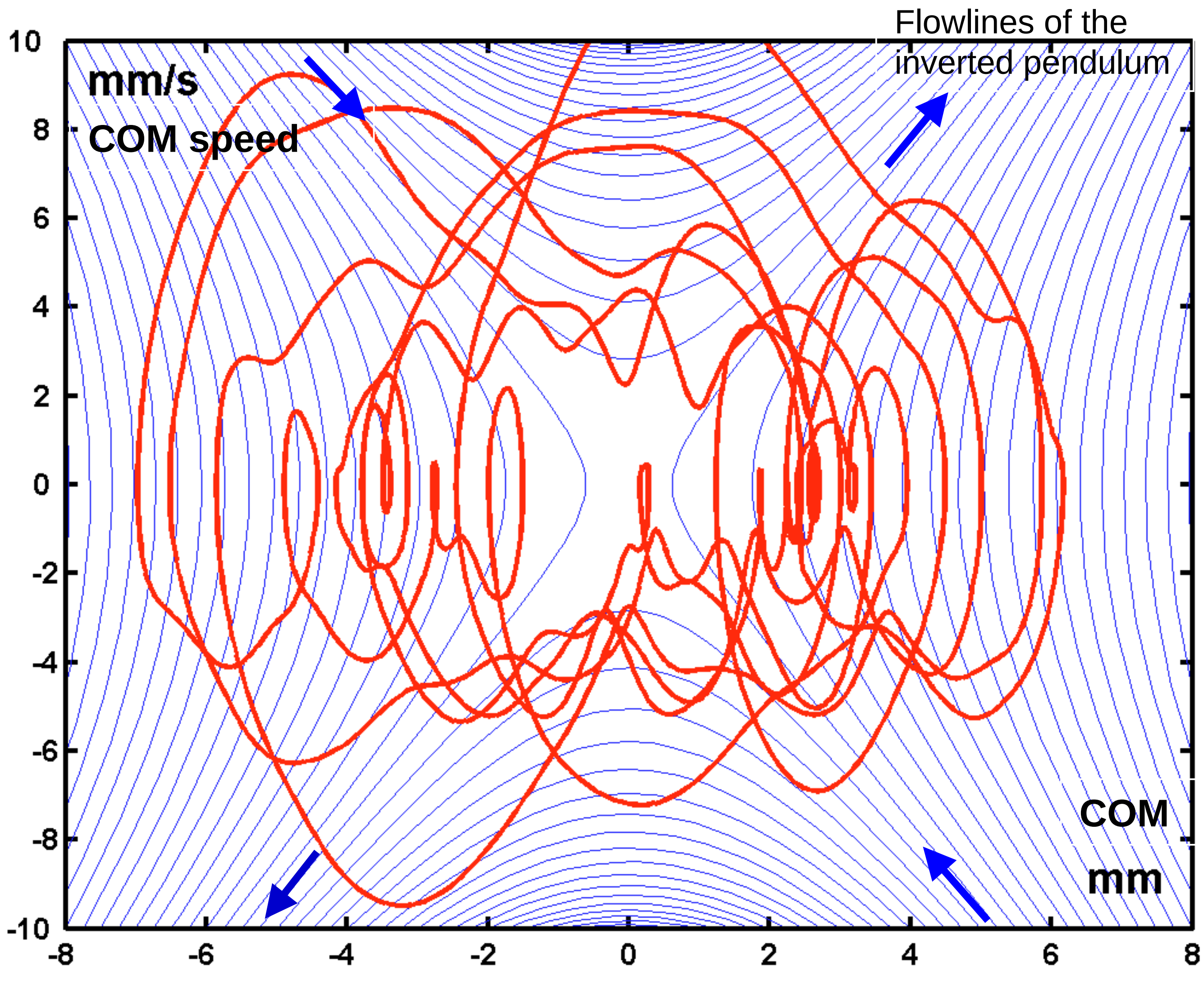
$$-\tau_{act} = I\ddot{\vartheta} - (mgh - K_a)\vartheta$$

Critical value of ankle stiffness $K_c = mgh$

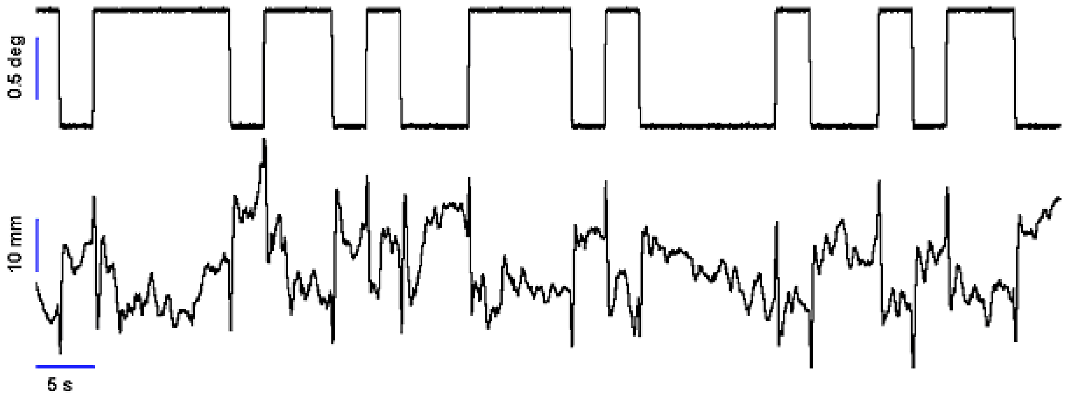
$$\begin{cases} K_a > K_c \Rightarrow \\ K_a < K_c \Rightarrow \end{cases}$$

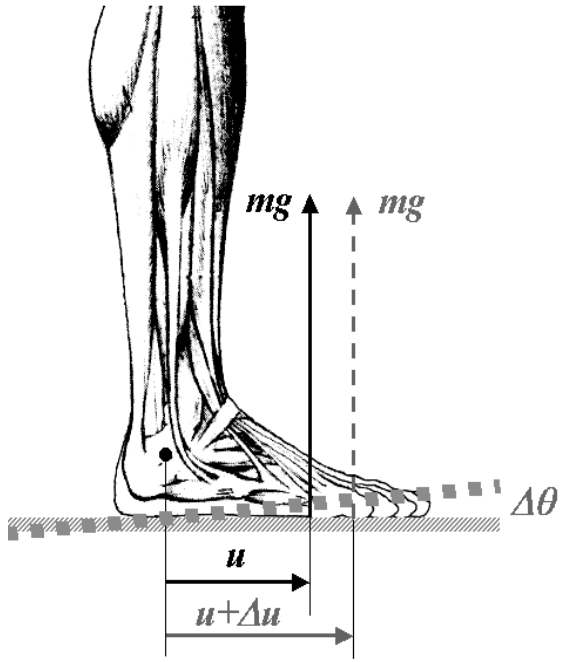
- $K_a > K_c \Rightarrow$ The system is intrinsically asymptotically stable
- $K_a < K_c \Rightarrow$ The system is unstable and must be stabilized by active control

Analysis in the phase plane: the Phase portrait



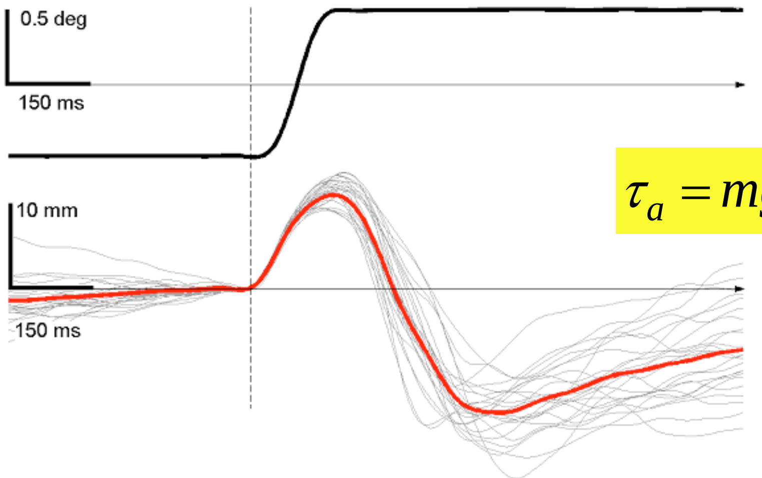
Direct estimate of ankle stiffness





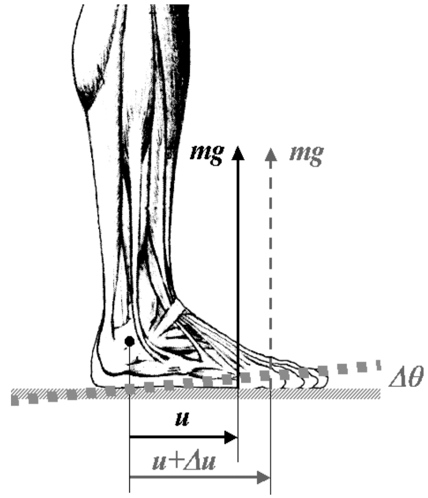
Casadio, Morasso & Sanguineti, Gait and Posture, 2005

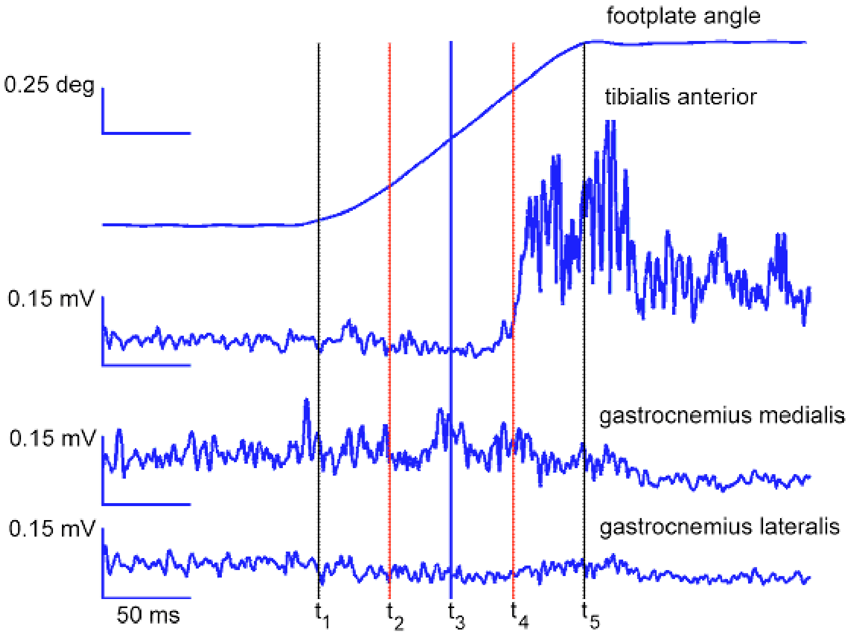
Direct measurement of ankle stiffness

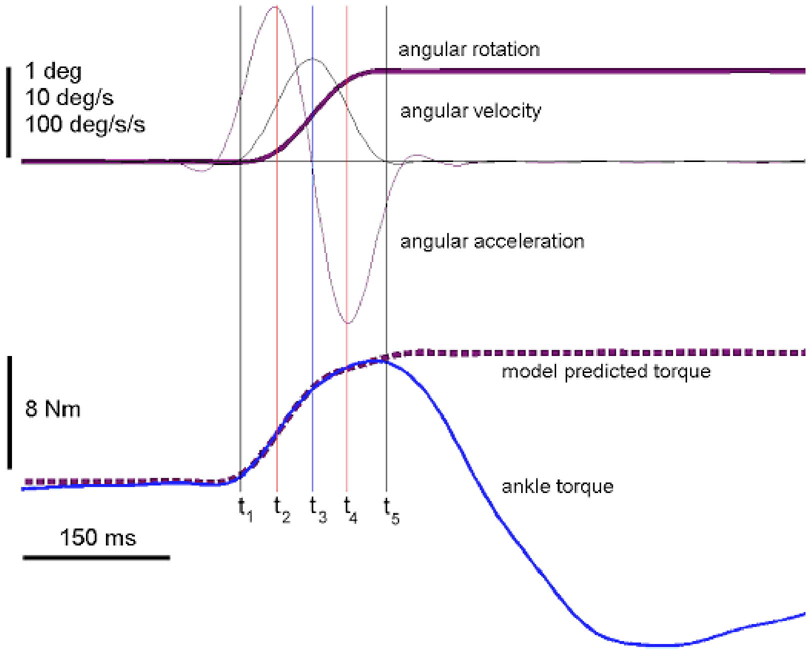


$$\tau_a = mg\cdot\Delta u(t) = I_a\ddot{\vartheta} + B_a\dot{\vartheta} + K_a\vartheta$$

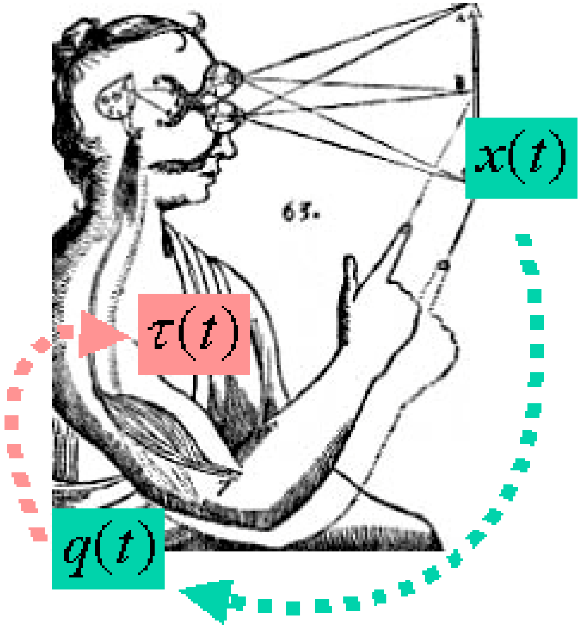
$$K_a \approx 65\%\ K_c$$







Inverse dynamics



Lagrangian formalism:

$$L(q,\dot{q}) = K(q,\dot{q}) - P(q)$$

Dynamic motion equations :

$$\tau = I(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + J^T(q)F_{ext}$$

Muscle torques

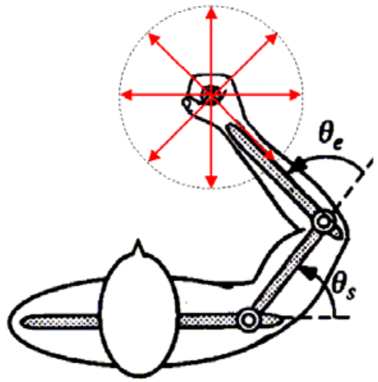
Inertial torques

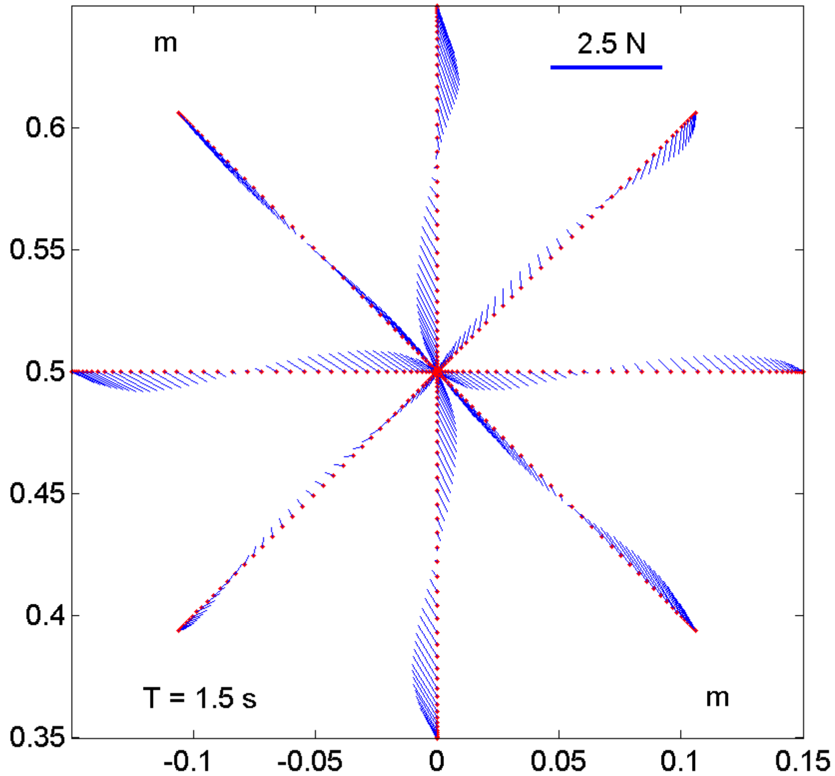
Coriolis torques

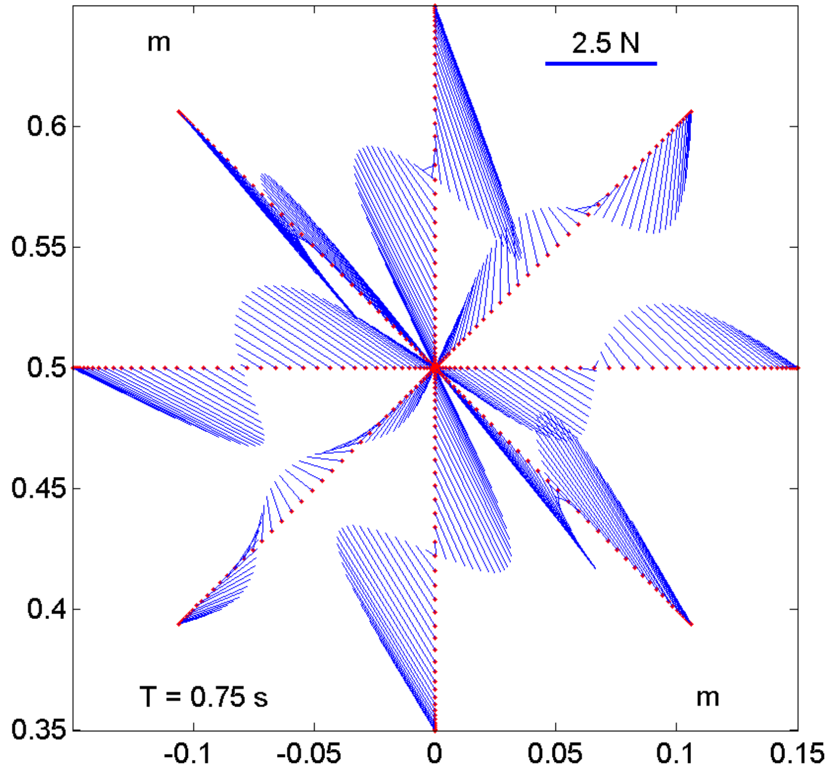
Gravitational torques

External torques

Inverse dynamics - interaction forces: self-generated disturbances







desired law of motion $q = q(t)$

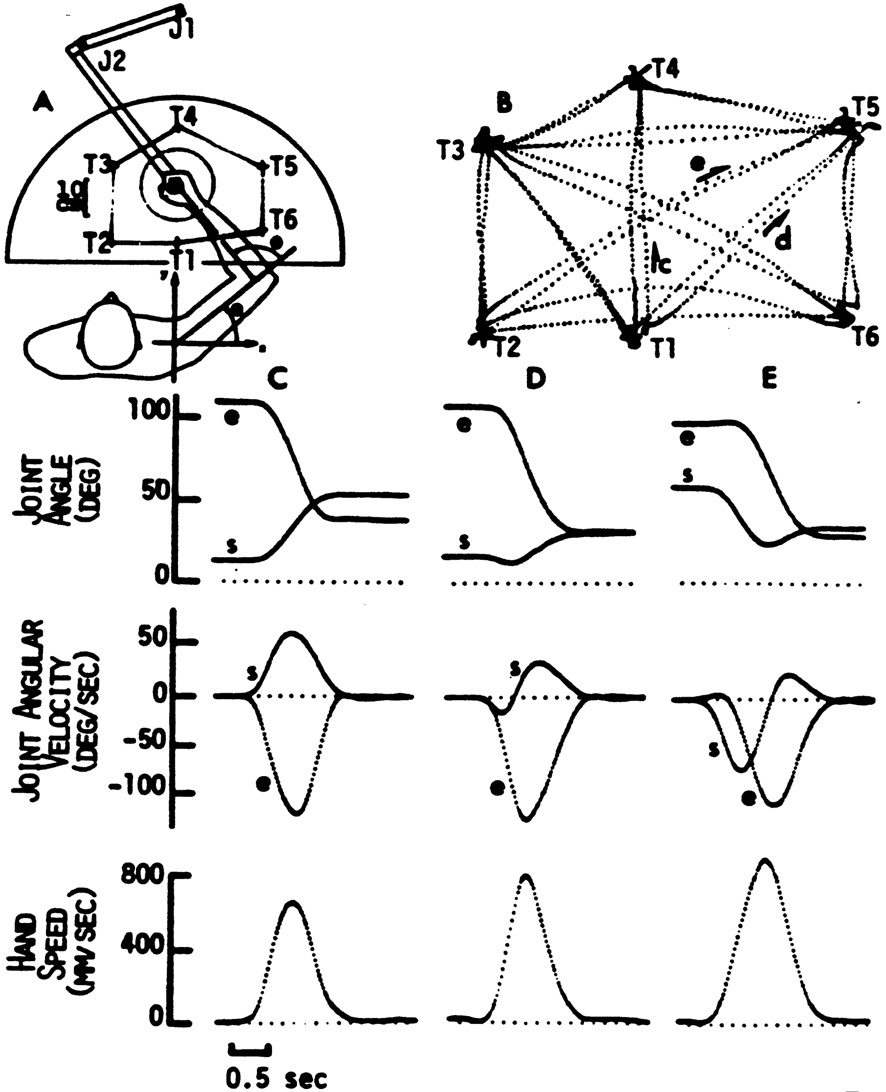
⇩

$$\tau = I(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q)$$

$$=$$

$$-J^T(q)F_{virt} = I(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q)$$

In spite of the strong anisotropy of biomechanics, normal reaching movements are remarkably isotropic & smooth

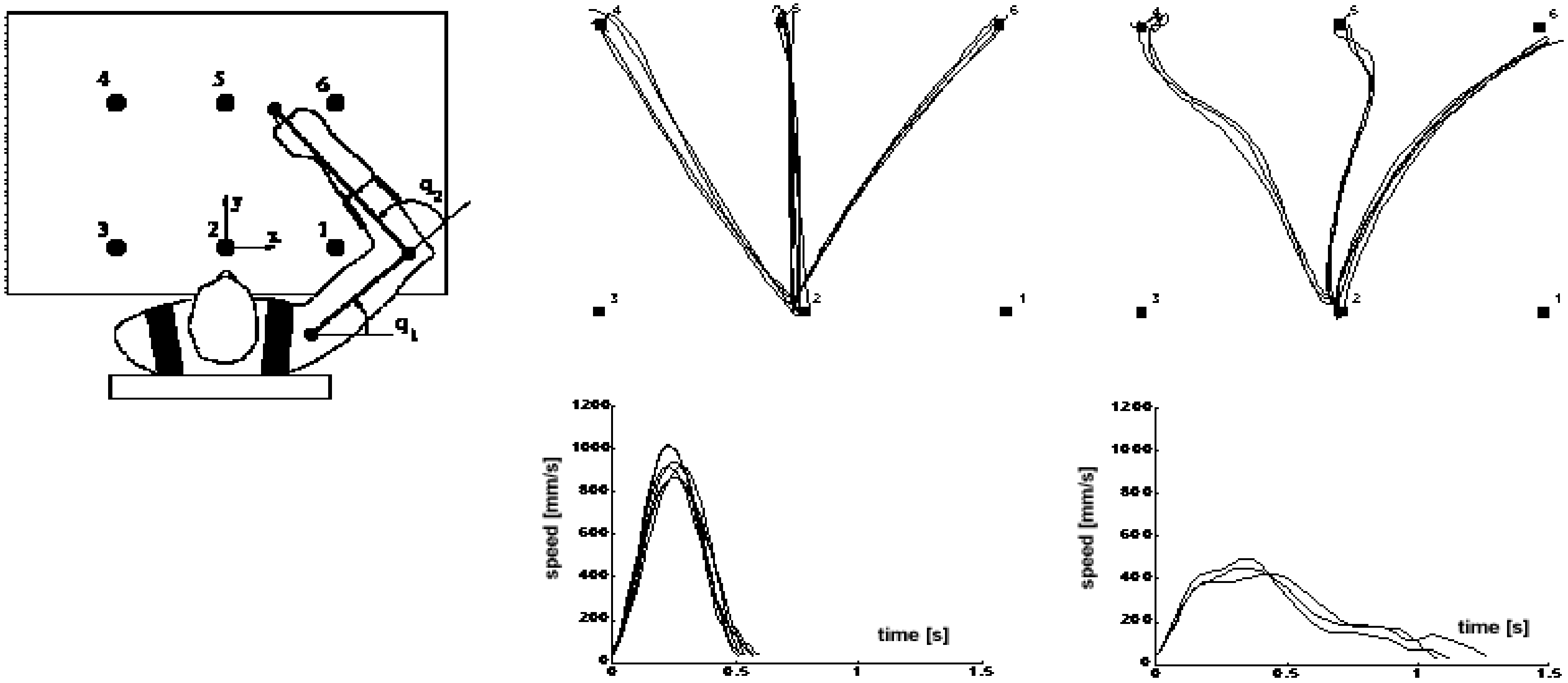


Morasso, Exp Brain Res 1981

MINIMUM JERK PROFILE

$$\begin{bmatrix} x(t) \\ y(t) \end{bmatrix} = \begin{bmatrix} x_o \\ y_o \end{bmatrix} + \begin{bmatrix} x_f - x_o \\ y_f - y_o \end{bmatrix} \left\{ 6\left(\frac{t}{T}\right)^5 - 15\left(\frac{t}{T}\right)^4 + 10\left(\frac{t}{T}\right)^3 \right\}$$

On the contrary, the reaching movements of cerebellar patients are anisotropic and the pattern of aiming errors is explained by the interaction forces



Sanguineti et al Hum Mov Sci 2003

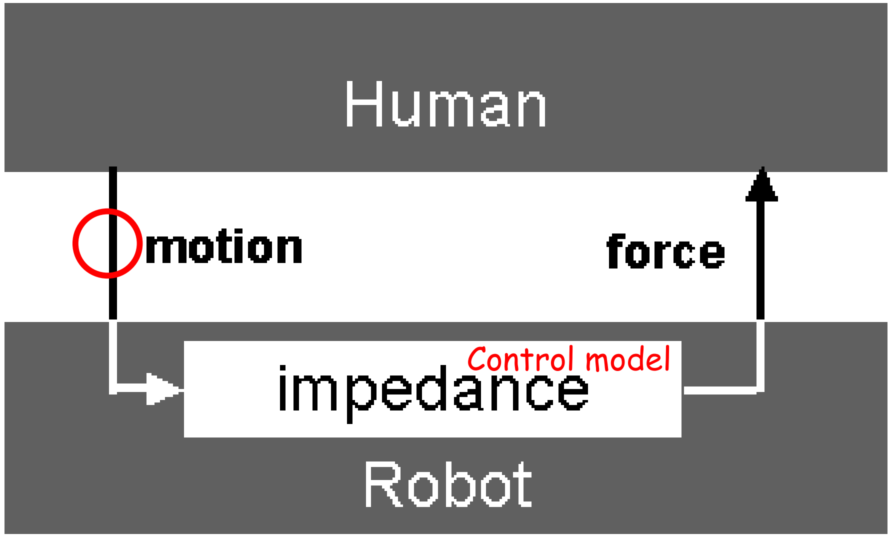
The compensation of aiming errors, in normal subjects, is achieved by an internal model of interaction disturbances.

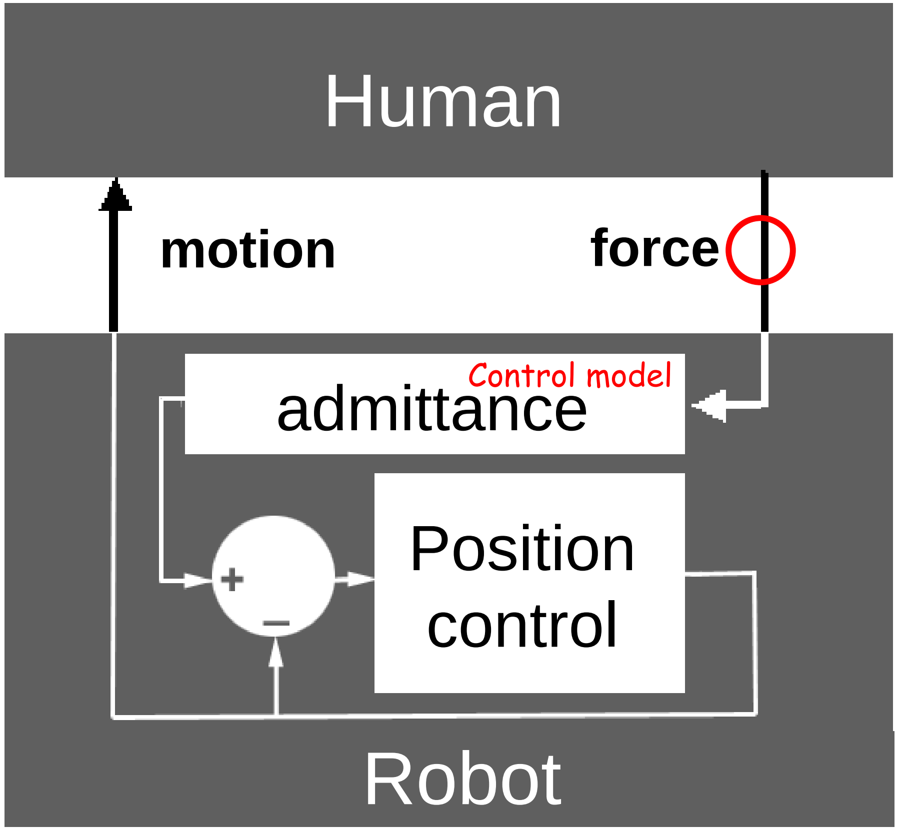
These experiments suggest that such internal model is at least partly stored in the cerebellum.

Haptic robots: generation of haptic virtual environments for the study of neuromotor control & motor learning

Controllo di Impedenza ⇔ Controllo di Ammettenza

(veramente aptico) (limitatamente aptico)





Reversibile, basso attrito e bassa inerzia

Un solo anello di controllo – La performance dipende da sensori di rotazione che sono robusti e molto precisi

Intrinsecamente stabile

Non reversibile

Due anelli di controllo – La performance dipende da un sensore di forza che è delicato e assai meno preciso

Potenzialmente instabile

Haptic rendering (impedance control scheme)

- **Measuring robot motion & mapping from the joint space to hand space**

- **Selection/combination of haptic interaction schemes**

$$F = K(X - X_o)$$

Virtual elastic field

$$F = B\frac{dX}{dt}$$

Virtual viscous field

$$F = M\frac{d^2X}{dt^2}$$

Virtual inertial field

......

- **Mapping from the hand space (force) to the joint space (torque)**

$$T = J^T \cdot F$$

- **Current drive to the motors**

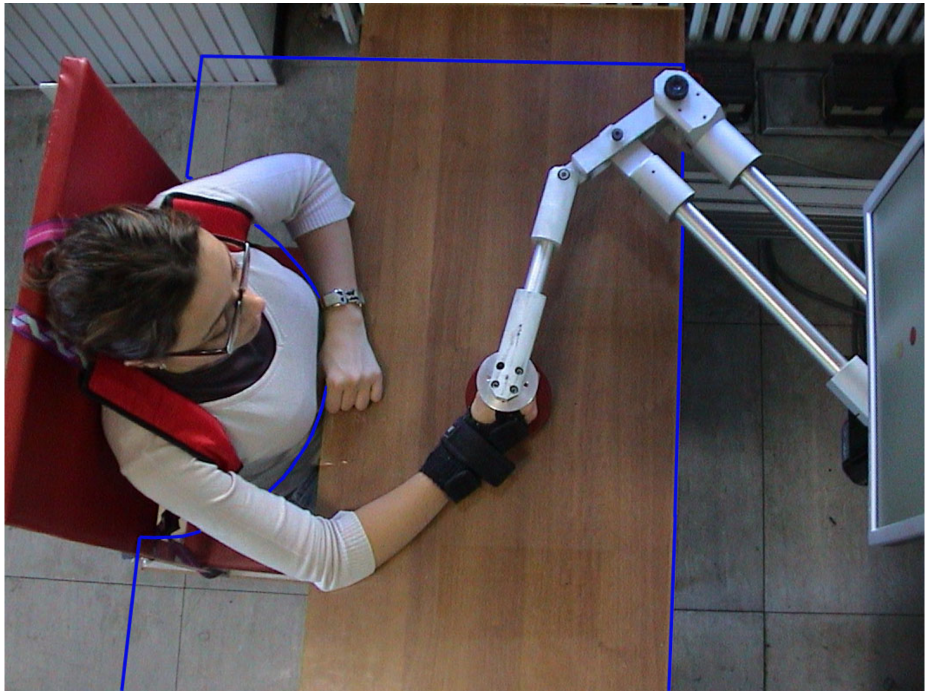
$$I = K_T \cdot T$$

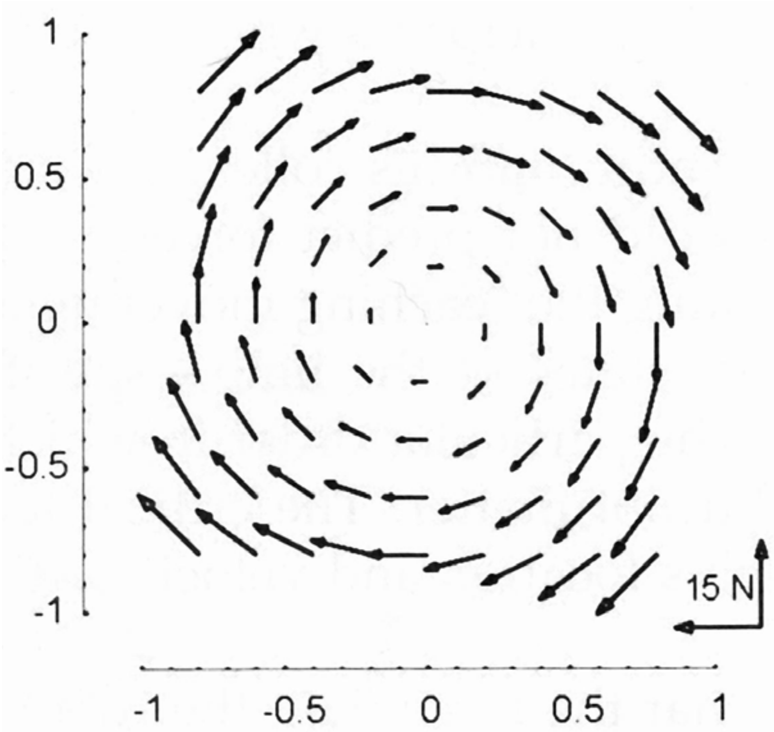
1 kHz

J :Jacobian matrix of the robot;
K : torque constant of the motors

Casadio M, Morasso P, Sanguineti V, Arrichiello V (2006) Braccio di Ferro: a new haptic workstation for neuromotor rehabilitation. Technol Health Care, 14, 123–142.

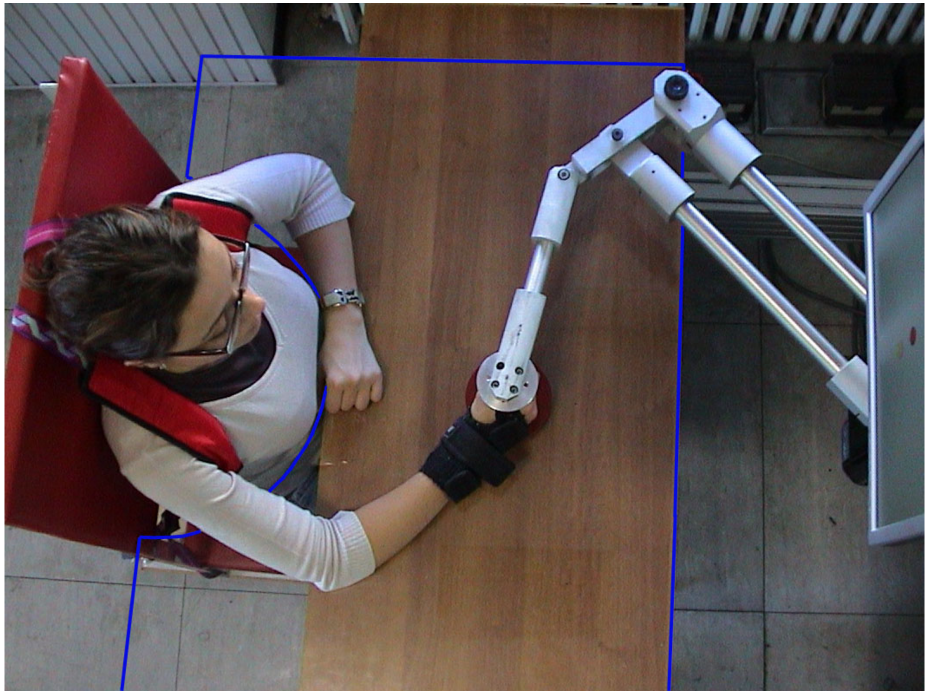
Velocity-dependent Force Field (VF)

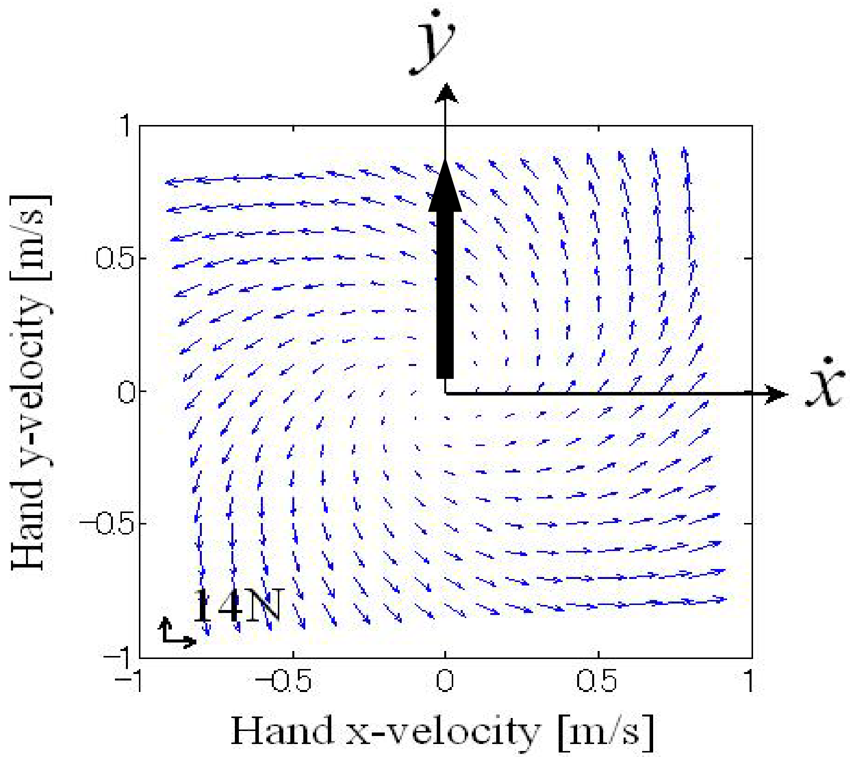




$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \mathbf{B}\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = \begin{bmatrix} 0 & -10 \\ 10 & 0 \end{bmatrix}\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix}$$

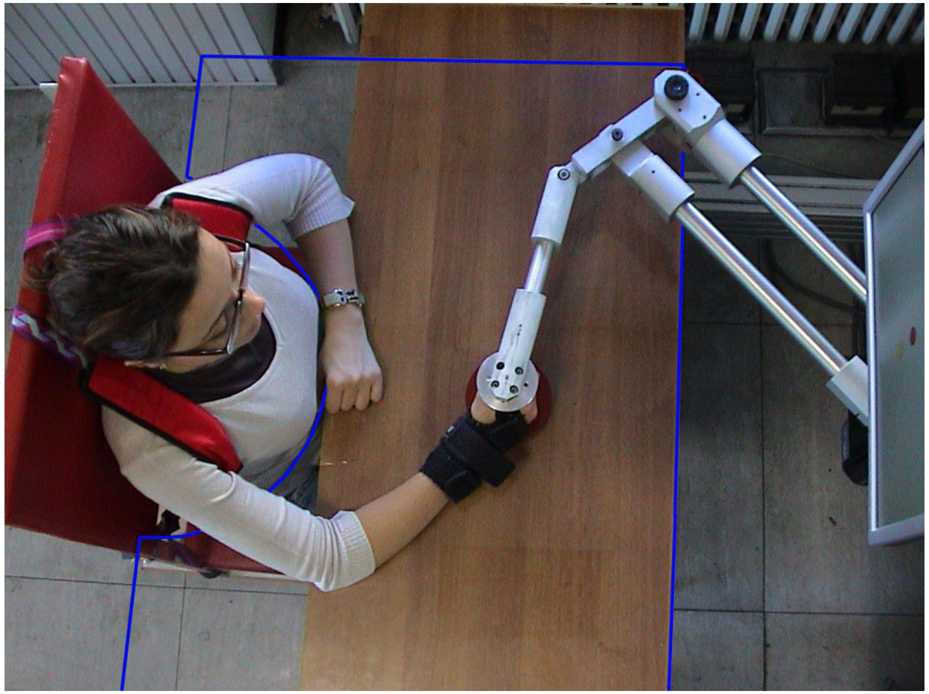
Velocity-dependent Force Field (VF)

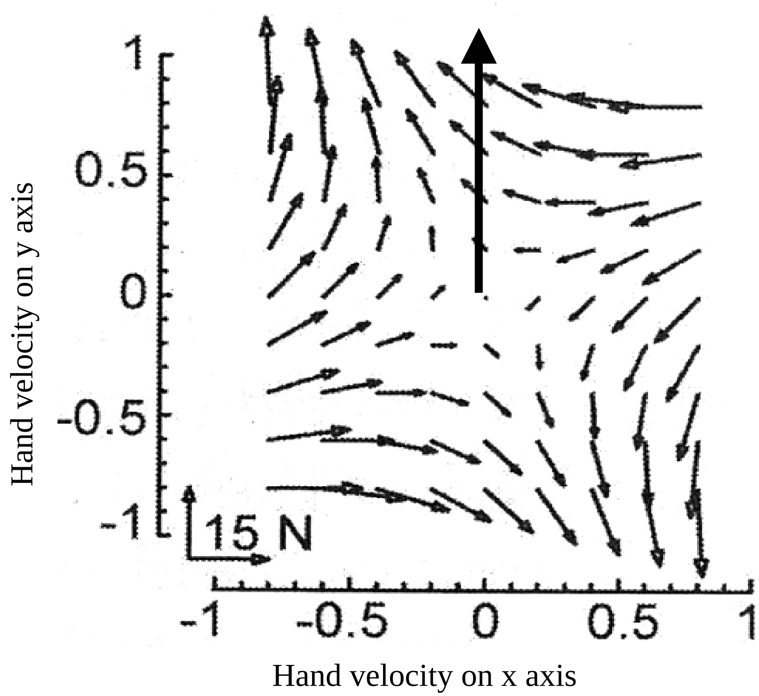




$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \boldsymbol{B} \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 13 & -18 \\ 18 & 13 \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix}$$

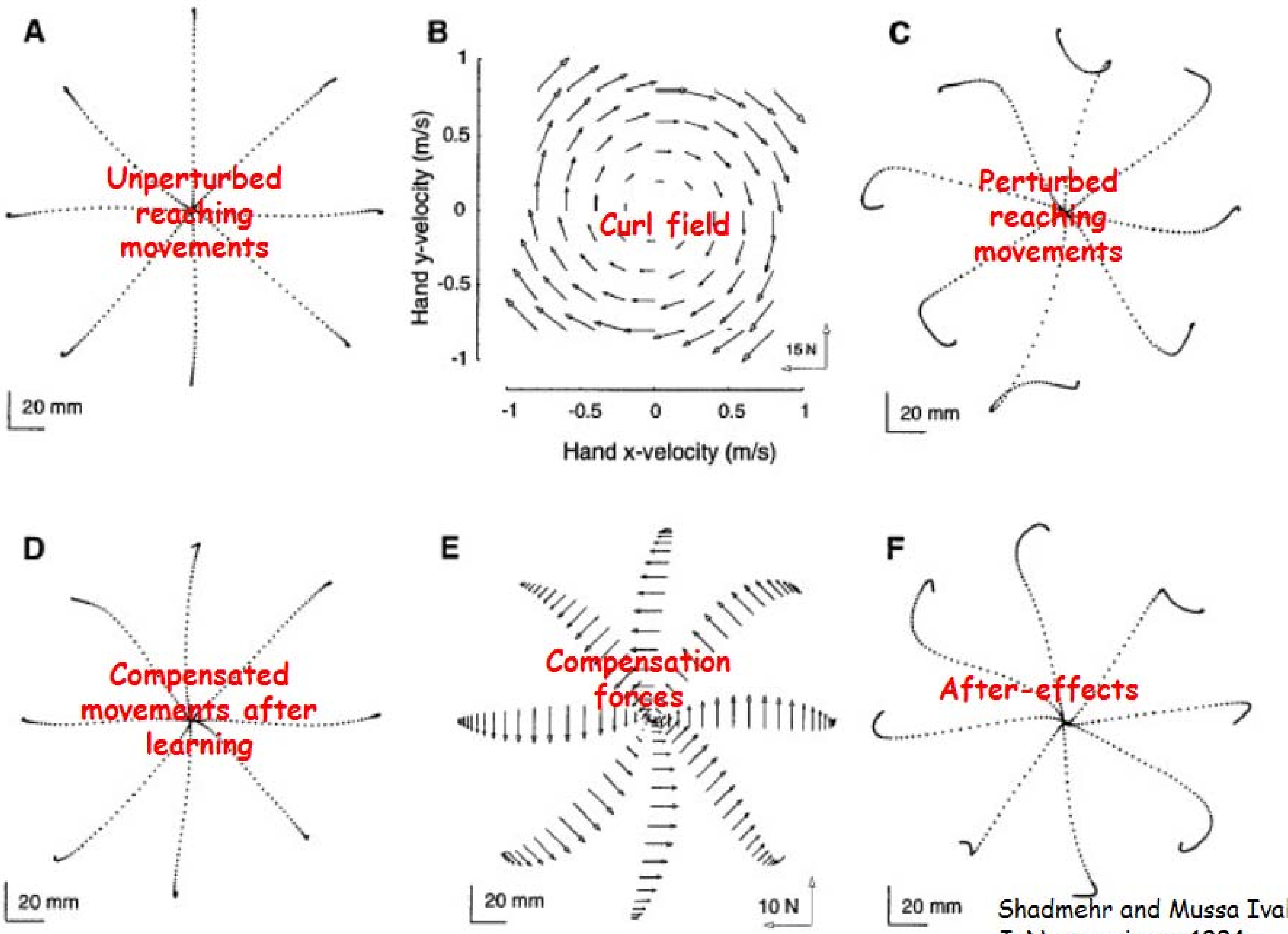
Velocity-dependent Force Field (VF)





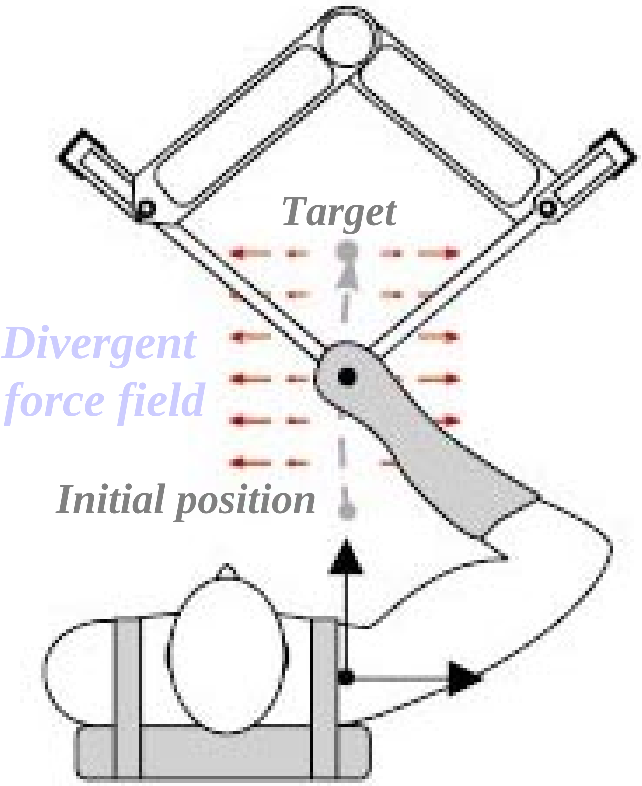
$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = B \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = \begin{bmatrix} -10.1 & -18 \\ -11.2 & +11.1 \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix}$$

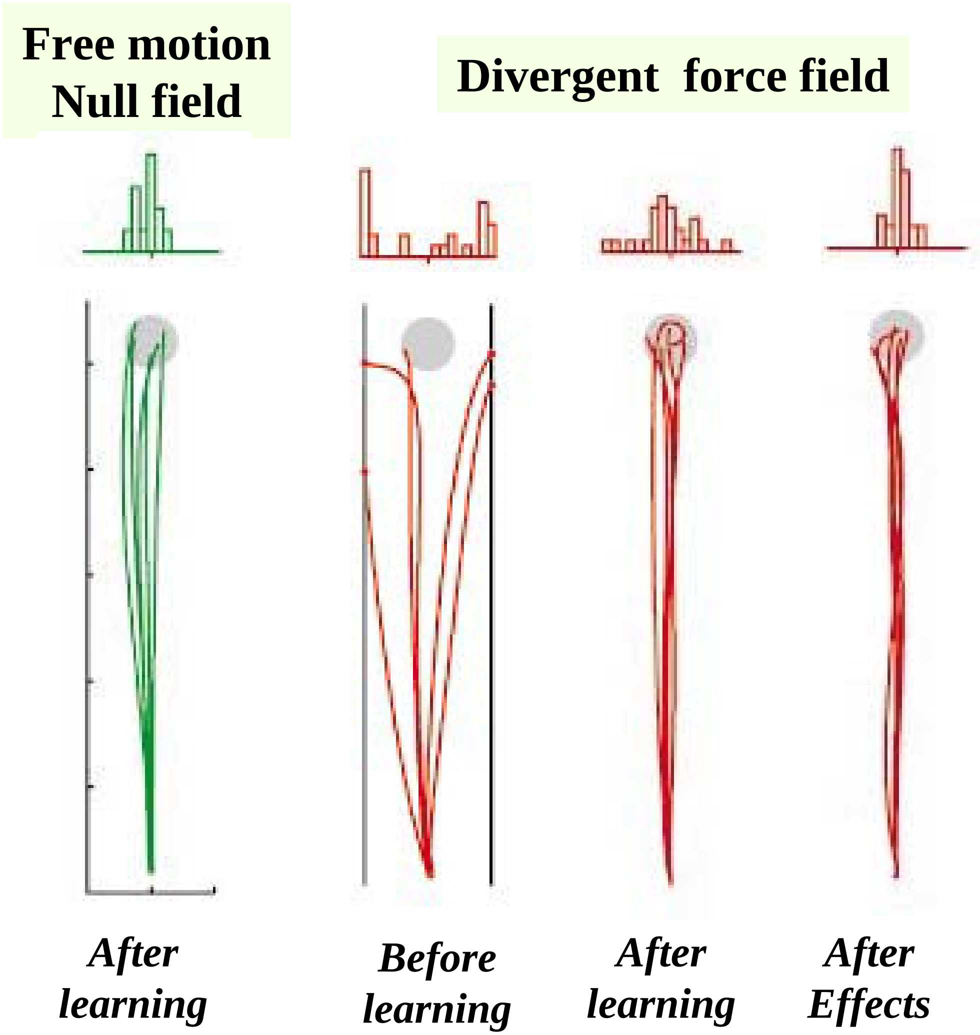
Internal Model Adaptation



Shadmehr and Mussa Ivaldi
J. Neuroscience 1994

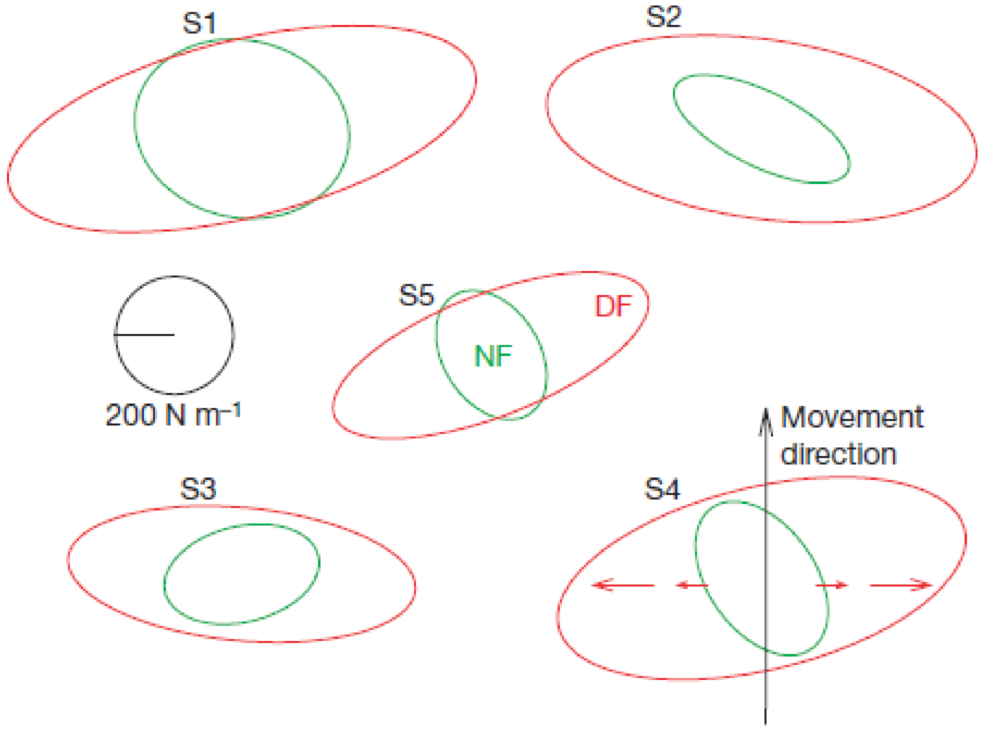
Impedance adaptation: Reaching Motion in Unstable Environments





(*E. Burdet et al, Nature, 2001*)

Stiffness ellipses at middle trajectory during reaching

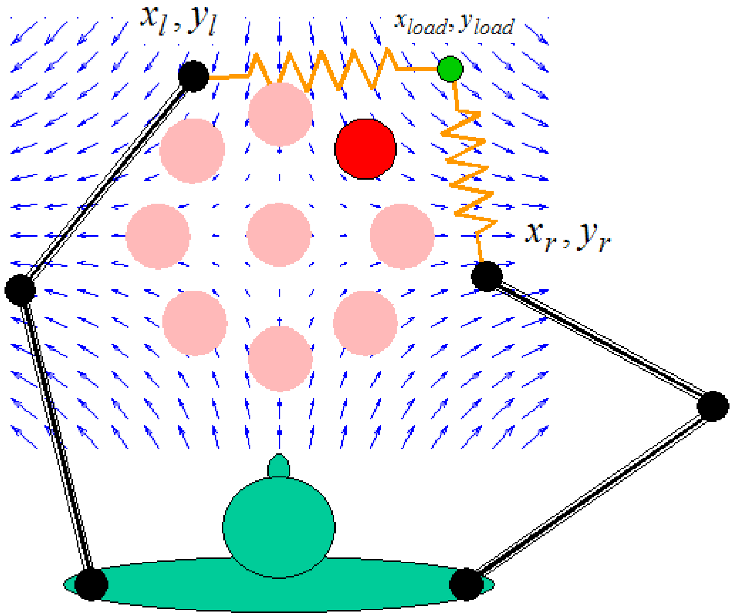


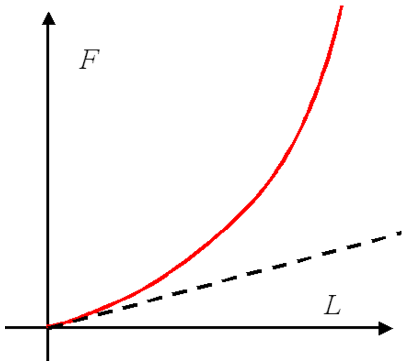
NF: Free motion DF: Unstable field

People can adjust the hand stiffness depending on the environment dynamics

(Burdet et al, Science 2001)

Bimanual control of an unstable task: Stiffness vs. Intermittent Control Strategy





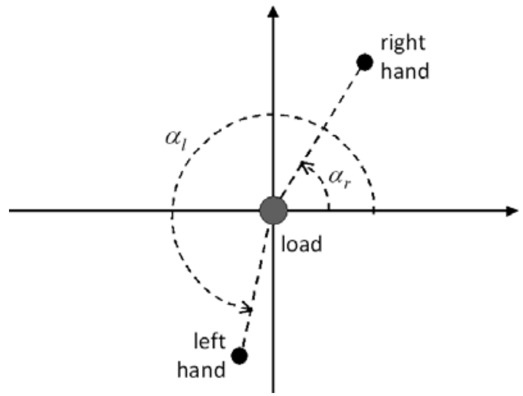
$$F = \frac{K}{4} L + \rho L^2$$

$$M_{load} \begin{bmatrix} \ddot{x}_{load} \\ \ddot{y}_{load} \end{bmatrix} + B_{load} \begin{bmatrix} \dot{x}_{load} \\ \dot{y}_{load} \end{bmatrix} + \begin{bmatrix} -K_{load} & 0 \\ 0 & +K_{load} \end{bmatrix} \begin{bmatrix} x_{load} - x_0 \\ y_{load} - y_0 \end{bmatrix} = \vec{F}_l + \vec{F}_r$$

Stiffness Control Index: $\dfrac{K_{load}}{K_{xx}}$

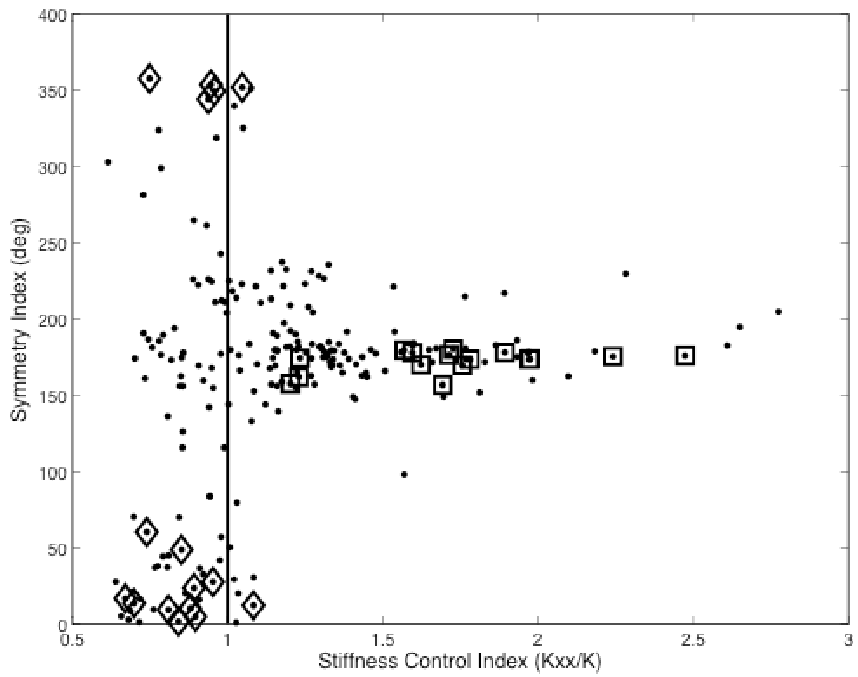
Symmetry Index: $(\alpha_r + \alpha_l) \bmod 2\pi$

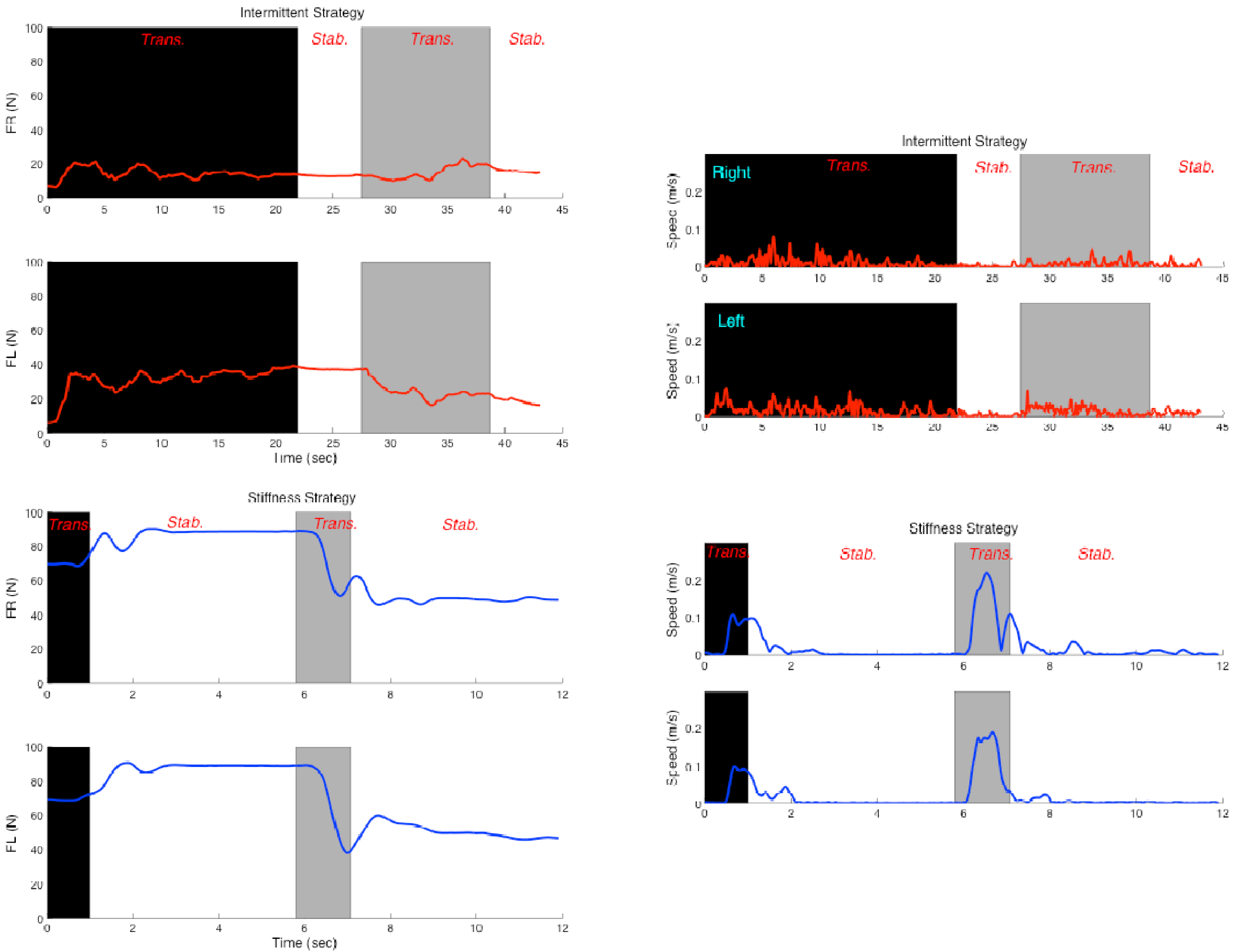
$$K_{xx} = \frac{K_{load}}{2} + \rho\left\{\delta_l\left[1+\left(\frac{x_{load}-x_l}{\delta_l}\right)^2\right] + \delta_r\left[1+\left(\frac{x_{load}-x_r}{\delta_r}\right)^2\right]\right\}$$



Intermittent control strategy

Stiffness control strategy




Intermittent Strategy
Trans.
Stab.
Trans.
Stab.
FR (N)
FL (N)
Time (sec)
Intermittent Strategy
Right
Left
Speed (m/s)
Stiffness Strategy
FR (N)
FL (N)
Time (sec)
Stiffness Strategy
Speed (m/s)

Subject	Gender	Height (m)	Weight (kg)	Max Grip Force (kg)	Strategy I:Intermittent S:Stiffness	Hand Orientation H: Horizontal V:Vertical
1	M	167	63	42	S	H
2	M	170	65	44	S	H
3	F	157	54	24	I	V&H
4	M	181	75	63	S	H
5	F	170	60	34	I	H
6	M	173	59	36	I	V&H
7	F	173	60	29	I	V&H
8	M	184	80	35	S	H
9	M	1.8	81	44	S	H
10	F	164	62	28	S	H&V
11	F	168	56	24	S&I	H&V
12	M	174	63	54	I	V
13	M	182	88	41	S	H
14	M	169	59	42	S	H