Redundancy of the motor system

- **Biomechanical level**
  
  extra number of degrees of freedom ⇒ interjoint coordination

- **Muscular level**
  
  extra number of muscles ⇒ interjoint coordination

- **Neural level**
  
  extra number of motor units ⇒ 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

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

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

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.


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.


λ: soglia del riflesso di stiramento (variabile di controllo)
energia potenziale (non linear stiffness)


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

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 **use-dependent reorganization** of neural mechanisms made possible by **neural plasticity**.


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.

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).
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
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.


**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).

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

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 $\Leftrightarrow$ Energy function $\Leftrightarrow$ 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
Neuro Muscular System

Body

internal load

Explicit feedback

Force

Implicit feedback

Equilibrium point

Movement

12 N
Neuro Muscular System

Body Model

Action Representation

Task Representation

Environment

external load

internal load

Body

Neuro Muscular System
Neuro Muscular System

Body Model

Task Representation

Performance Evaluation

Environment
  external load

Action Representation

Task Representation

Performance Evaluation

Environment
  external load

Neuro Muscular System

Body
  internal load
Caratteristica comune: Robot Aptici & Intelligenti

Diagramma:
- **FORCEFIELD GENERATOR**
- **ADAPTIVE CONTROLLER**
- **PERFORMANCE EVALUATOR**
Haptics for Neural control of movement
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.

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

Internal model adaptation
- Cerebral cortex
- Prefrontal cortex
- Premotor cortex
- Motor cortex
- Parietal cortex

Context adaptation
- Basal ganglia

Cerebellum
- Lateral part
- Intermediate part & vermis

Impedance adaptation
- Environment
- Limb/Body
- Muscle viscoelasticity
- Spinal reflex system

Motor Controller

Limb/Body Muscle viscoelasticity

External dynamics

Courtesy of K. Ito
Basic neural mechanisms for motor control & motor adaptation

- Cerebral cortex
- Basal ganglia
- Thalamus
- Limbic system
- Brainstem
- Cerebellum
- Spinal cord

Parkinson disease

- Cerebellar ataxia

Narcolepsy

- Patterned movements
  - Saccade, Swallowing, Mastication
- Lateral system
  - Controlled movements of extremities
- Medial system
  - Postural reflex
  - Postural muscle tone
  - Locomotion

Courtesy of K. Ito
Stiffness and stiffness control
Muscle Co-contraction in Reaching Motion

Initial part: reciprocal activation
Final part: co-activation

Biceps
Triceps

0.5mV
0.1 sec

0.5mV

Agonist
Antagonist

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

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

- Destabilizing torque:
- Control torque:

\[-\tau_m + \tau_g = I\ddot{\vartheta}\]

\[\tau_g = mgh \vartheta\]

\[\tau_m = K_a \vartheta + \tau_{act}\]

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

Critical value of ankle stiffness

\[K_c = mgh\]

\[
\begin{align*}
K_a &> K_c \quad \Rightarrow \quad \text{The system is intrinsically asymptotically stable} \\
K_a &< K_c \quad \Rightarrow \quad \text{The system is unstable and must be stabilized by active control}
\end{align*}
\]
Analysis in the phase plane: the Phase portrait

Flowlines of the inverted pendulum
Direct estimate of ankle stiffness

Casadio, Morasso & Sanguineti, Gait and Posture, 2005
Direct measurement of ankle stiffness

\[ \tau_a = mg \cdot \Delta u(t) = I_a \ddot{\theta} + B_a \dot{\theta} + K_a \theta \]

\[ K_a \approx 65\% \; K_c \]
Inverse dynamics

Lagrangian formalism:

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

Dynamic motion equations:

\[ \tau = I(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) + J^T(q)F_{ext} \]
Inverse dynamics - interaction forces: self-generated disturbances

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

\[
-J^T(q)F_{virt} = I(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q)
\]
In spite of the strong anisotropy of biomechanics, normal reaching movements are remarkably isotropic & smooth.

\[
\begin{align*}
\mathbf{x}(t) &= \begin{bmatrix} x_o \\ y_o \end{bmatrix} + \begin{bmatrix} x_f - x_o \\ y_f - y_o \end{bmatrix} \left\{ 6 \left( \frac{t}{T} \right)^5 - 15 \left( \frac{t}{T} \right)^4 + 10 \left( \frac{t}{T} \right)^3 \right\}
\end{align*}
\]

Morasso, Exp Brain Res 1981
On the contrary, the reaching movements of cerebellar patients are anisotropic and the pattern of aiming errors is explained by the interaction forces. 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/comboination of haptic interaction schemes

\[ F = K(X - X_o) \]
\[ F = B \frac{dX}{dt} \]
\[ F = M \frac{d^2X}{dt^2} \]

Virtual elastic field \hspace{1cm} Virtual viscous field \hspace{1cm} Virtual inertial field

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

\[ T = J^T \cdot F \]

- Current drive to the motors

\[ I = K_T \cdot T \]

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

- Selection/combination of haptic interaction schemes

\[ F = K(X - X_o) \]
\[ F = B \frac{dX}{dt} \]
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Virtual elastic field \hspace{1cm} Virtual viscous field \hspace{1cm} Virtual inertial field

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

\[ T = J^T \cdot F \]

- Current drive to the motors

\[ I = K_T \cdot T \]

\[ J : \text{Jacobian matrix of the robot;} \]
\[ K : \text{torque constant of the motors} \]

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)

\[
\begin{bmatrix}
F_x \\
F_y
\end{bmatrix} = B \begin{bmatrix}
\dot{x} \\
\dot{y}
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
13 & -18 \\
18 & 13
\end{bmatrix} \begin{bmatrix}
\dot{x} \\
\dot{y}
\end{bmatrix}
\]
Velocity-dependent Force Field (VF)

\[
\begin{bmatrix}
F_x \\
F_y
\end{bmatrix} = B \begin{bmatrix}
x \\
y
\end{bmatrix} = \begin{bmatrix}
-10.1 & -18 \\
-11.2 & +11.1
\end{bmatrix} \begin{bmatrix}
x \\
y
\end{bmatrix}
\]
Internal Model Adaptation

Unperturbed reaching movements

Perturbed reaching movements

Compensated movements after learning

Compensation forces

After-effects

Shadmehr and Mussa Ivaldi
J. Neuroscience 1994
Impedance adaptation: Reaching Motion in Unstable Environments

Divergent force field

Initial position

Target

Free motion Null field

After learning

Before learning

After learning

After Effects

(E. Burdet et al, Nature, 2001)
Stiffness ellipses at middle trajectory during reaching

People can adjust the hand stiffness depending on the environment dynamics

NF: Free motion    DF: Unstable field

(Burdet et al, Science 2001)
Bimanual control of an unstable task: Stiffness vs. Intermittent Control Strategy

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

\[ M_{\text{load}} \left[ \ddot{x}_{\text{load}} \right] + B_{\text{load}} \left[ \dot{x}_{\text{load}} \right] + \begin{bmatrix} -K_{\text{load}} & 0 \\ 0 & K_{\text{load}} \end{bmatrix} \begin{bmatrix} x_{\text{load}} - x_0 \\ y_{\text{load}} - y_0 \end{bmatrix} = \vec{F}_l + \vec{F}_r \]
Stiffness Control Index: \( \frac{K_{\text{load}}}{K_{x_x}} \)

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

Symmetry Index: \( (\alpha_l + \alpha_r) \mod 2\pi \)
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<th>Height (m)</th>
<th>Weight (kg)</th>
<th>Max Grip Force (kg)</th>
<th>Strategy I:Intermittent</th>
<th>Strategy S:Stiffness</th>
<th>Hand Orientation H: Horizontal V: Vertical</th>
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