MOTOR CONTROL

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DISCLAIMER

Nothing about

- Biomechanics
- Muscles
- Sensory receptors
- Motoneurons
- Reflexes
- Spinal cord
- Ascending/descending tracts
- Motor cortex

- Neurophysiology
- Neuropsychology
- Brain imaging

- Motor learning/skills
- Attention

- Posture, walking, writing, speaking
QUESTIONS

1. Why is ACTION an interesting object in the field of Cognitive Sciences?

2. Why robotic artifacts can be useful in the field of Cognitive Science?
ACTIONS

• Are driven by goals and they can reach these goals or fail to do so;

• Often involve some degree of volitional control;

• Require planning and decisions among alternatives;

• Involve prediction or anticipation of an intended outcome;

• Are often, albeit not always, associated with a sense of agency, that is, the agent’s conscious awareness of carrying out the particular action and of its goals.

— Engel et al., 2013, Trends Cogn Sci 17:202
“To move things is all that Mankind can do … For such the sole executant is muscle, whether in whispering a syllable or in felling a forest.”
— Charles Sherrington, 1924, The Linacre Lecture

“The infinite diversity of external manifestation of cerebral activity can be reduced ultimately to a single phenomenon - muscular movement. Whether it's the child laughing at the sight of a toy, or Garibaldi smiling when persecuted for excessive love for his native country, or a girl trembling at the first thought of love, or Newton creating universal laws and inscribing them on paper - the ultimate fact in all cases is muscular movement.”
“Absolutely all the properties of external manifestations of brain activity described as animation, passion, mockery, sorrow, joy, etc., are merely results of a greater or lesser contraction of definite groups of muscles, which, as everyone knows, is a purely mechanical act.”
— Ivan Sechenov, 1863, in Reflexes of the Brain
GOOD REASONS

“For cognitions to be communicated, they must be physically enacted. It follows from this observation that a complete account of the cognitive system must explain how it transmits information to the environment as well as how it takes information in and retains and elaborates it.”

“The basic idea is that cognition should not be understood as a capacity for deriving world-models, which might then provide a database for thinking, planning, and problem-solving. Rather, it is emphasized that cognitive processes are so closely intertwined with action that cognition would best be understood as 'enactive', as the exercise of skillful know-how in situated and embodied action.”

“Cognition is not detached contemplation of the world, but a set of processes that determine possible actions. According to their view, the criterion for success of cognitive operations is not to recover pre-existing features or to construct a veridical representation of the environment. Instead, cognitive processes construct the world by bringing forth action-relevant structures in the environmental niche. In a nutshell, cognition should be understood as the capacity of generating structure by action, that is, of 'enacting' a world.”
— Engel et al., 2013, Trends Cogn Sci 17:202
Cognition and Action

What to move where

Cognitive science

Moving

Motor control

« In cognitive science, we are currently witnessing a ‘pragmatic turn’, away from the traditional representation-centered framework towards a paradigm that focuses on understanding cognition as ‘enactive’, as skillful activity that involves ongoing interaction with the external world. The key premise of this view is that cognition should not be understood as providing models of the world, but as subserving action and being grounded in sensorimotor coupling. Accordingly, cognitive processes and their underlying neural activity patterns should be studied primarily with respect to their role in action generation. »

— Engel et al., 2013, *Trends Cogn Sci* 17:202
TYPES OF ACTION

Walking, running, reaching, grasping, speaking, singing, writing, drawing, looking, smiling, keyboarding, …
Every action has a specific direction (left/right, toward/away, ...), and intensity (velocity, force, ...)

- Anticipatory electrical activities (EEG, EMG)
- Invariant profiles
- Scaling with task conditions

— Gordon et al., 1994, Exp Brain Res 99:112
Lexical decision task
Judge the lexical status (word/nonword) of a letter string, and indicate the decision by moving a handle in one direction (word) or in the other direction (nonword).

Faster movements for words vs nonwords


ACTION REFLECTS MOTIVATION

— Aarts et al., 2008, Science 319:1639
— Takikawa et al., 2002, Exp Brain Res 142:284
ACTION IS DECISION MAKING

— Stevens et al., 2005,
*Curr Biol* 15:1865
THE ORGANIZATION OF ACTION
THE ORGANIZATION OF ACTION

Idea, symbol, object

Space/time displacement/force in task space

Trajectory formation in body space

Joint/muscle force, activations

Neural commands

Neural Commands → Muscle Activations → Joint motions → Hand Trajectories → Task Goals
**Kinematics**

position, velocity, acceleration in task/body space

\[
\begin{align*}
    x &= L_1 \cos(\theta_1) + L_2 \cos(\theta_1 + \theta_2) \\
    y &= L_1 \sin(\theta_1) + L_2 \sin(\theta_1 + \theta_2)
\end{align*}
\]

**Dynamics**

force/torque (Newton’s law)

\[
\begin{align*}
    \tau_1 &= (I_1 + I_2 + m_2 l_1 l_2 \cos \theta_2 + \frac{m_1 l_1^2}{4} + \frac{m_2 l_2^2}{4}) \ddot{\theta}_1 + \\
          &\quad \left( I_2 + \frac{m_2 l_2^2}{4} + \frac{m_2 l_1 l_2}{2} \cos \theta_2 \right) \ddot{\theta}_2 - \\
          &\quad \frac{m_2 l_1 l_2}{2} \dot{\theta}_2^2 \sin \theta_2 - m_2 l_1 \dot{\theta}_1 \dot{\theta}_2 \sin \theta_2 \\
    \tau_2 &= (I_2 + \frac{m_2 l_1 l_2}{2} \cos \theta_2 + \frac{m_2 l_2^2}{4}) \ddot{\theta}_1 + \\
          &\quad \left( I_2 + \frac{m_2 l_2^2}{4} \right) \ddot{\theta}_2 + \frac{m_2 l_1 l_2}{2} \dot{\theta}_1^2 \sin \theta_2
\end{align*}
\]

**Degrees of freedom**

« the least number of independent coordinates required to specify the position of the system elements without violating any geometrical constraints »

**PROBLEMS**

**Redundancy**
In task space, body space, muscle space, neural space
Problem of degrees of freedom (Bernstein’s problem)
600 muscles, 200 joints

PROBLEMS

Noise
At all stages of sensorimotor processing (sensory, cellular, synaptic, motor)

— Faisal et al., 2008, Nat Rev Neurosci 9:292
— Todorov, 2002, Neural Comput 14:1233
PROBLEMS

Delays
In afferent sensory information and efferent motor commands

“We live in the past” — Scott, 2012, Trends Cogn Sci 16:541
**MOTOR INVARIANTS**

**Trajectories**
Point-to-point movements are straight with bell-shaped velocity profiles.
Motor equivalence
Actions are encoded in the central nervous system in terms that are more abstract than commands to specific muscles.
MOTOR INVARIANTS

Scaling laws
Duration and velocity scale with amplitude and load

— Gordon et al., 1994, Exp Brain Res 99:112
EMG
Triphasic pattern during fast movements

— Wadman et al., 1979, J Hum Mov Stud 5:3
MOTOR VARIABILITY

Uncontrolled manifold, structured variability
« Repetition without repetition » (Bernstein)

— Gordon et al., 1994, Exp Brain Res 99:97

Are motor invariants really invariants or simply by-products of control?

Motor variability is as important as motor invariants (structure of variability)
FLEXIBILITY

Motor control is highly flexible in space and time


Corrective responses are directed back to the circular target, whereas responses for the rectangular bar are redirected to a new location along the bar.

Corrective responses do not return to a desired trajectory

— Nashed et al., 2012, J Neurophysiol 109:999

(* ) elbow flexor
Fitts’ law
Speed/accuracy trade-off

\[ MT = a + b \left\{ \log_2 \left( \frac{2A}{W} \right) \right\} \]

ID (index of Difficulty)

RELATIVE TIMING

Set of ratios of the durations of intervals within a motor act

hypothetical relative timing of EMG traces

\[
\begin{align*}
\frac{b}{a} & = 0.4 \\
\frac{c}{a} & = 0.3 \\
\frac{d}{a} & = 0.6
\end{align*}
\]

RELATIVE TIMING

Speech
lower lip displacement during production of «buy
Bobby a puppy» at different rates

normal
case
slow
—— Smith et al., 1995,
Exp Brain Res 104:493
ISOCHRONY PRINCIPLE

Maintain constant duration
compensatory increase of speed with increasing amplitude


ISOGONY PRINCIPLE

Equal angles are described in equal time in a drawing task

RHYTHMIC AND DISCRETE ACTIONS

• **Rhythmic**
  e.g. walking, chewing, scratching

• **Discrete**
  e.g. reaching, grasping, kicking

— Schaal et al., 2004, *Nat Neurosci* 7:1136
SLOW MOVEMENTS

Are not smooth segmentation


— Darling et al., 1988, Exp Brain Res 73:225

— Salmond et al., 2017, J Neurophysiol 117:1239

— Vallbo & Wessberg, 1993, J Physiol (Lond) 469:673
SKILLED/UNSKILLED ACTIONS

Training can decrease error/variability, increase success/speed/accuracy, e.g. playing billiards (human), e.g. lever pull (mouse)

— Serradj et al., 2021, bioRxiv 436415

— Haar et al., 2020, Sci Rep 10:20046
COMPUTATIONAL MOTOR CONTROL

Descriptive (mechanistic) vs normative models

- Descriptive statements present an account of how the world is
- Normative statements present an evaluative account, or an account of how the world should be

Action characteristics result from properties of synapses, neurons, neural networks, muscles, …

Action characteristics result from principles, overarching goals, …

Problems: planning, control, estimation, learning
THEORETICAL BASES

**Dynamical systems theory**
Describes the behavior in space and time of complex, coupled systems.

\[
\begin{align*}
x[n] & \quad \text{state} \quad y[n] \quad \text{output (observation)} \\
u[n] & \quad \text{input (control)}
\end{align*}
\]

\[
\begin{align*}
x[n + 1] &= f(x[n], u[n]) & \text{state equation} \\
y[n] &= g(x[n]) & \text{output equation} \\
y[n + 1] &= h(x[n], u[n])
\end{align*}
\]

**state**: "the smallest possible subset of system variables that can represent the entire state of the system at any given time".

**Control theory**
Deals with the behavior of dynamical systems with inputs, and how their behavior is modified by feedback.

**reference**
- desired trajectory
- fixed point
**TWO CONTROL PRINCIPLES**

**Open-loop (feedforward)**
The controller is an *inverse* model of the system.

- Predictive control
- Model-based
- Sensitive to modeling uncertainty
- Sensitive to unexpected, unmodeled perturbations

**Closed-loop (feedback)**
The controller is a function of an error signal.

- Error correction
- No model
- Not sensitive to modeling uncertainty
- Robust to perturbations
INTERNAL MODELS

Direct (forward) model
Model of the causal relationship between inputs and their consequences (states, outputs).

Inverse model
Model of the relationship between desired consequences and corresponding inputs.

Ill-defined model

— Wolpert & Ghahramani, 2000, Nat Neurosci 3:1212
ROLE OF FORWARD MODELS

A system can use a direct model rather than an external feedback to evaluate the effect of command and its associated error. Avoid the instability due to delays in feedback loops.
THE KALMAN FILTER

Combines a forward model and a state observation to obtain the best state prediction in the presence of delays and noise

— Wolpert & Ghahramani, 2000, Nat Neurosci 3:1212
TWO MAIN THEORIES

**Task-dynamics approach**
Generalized closed-loop systems. Movements result from convergence to attractors of a dynamical system.

$\ddot{x} + b\dot{x} + k(x - x_f) = 0$

$x = x(t, m, b, k)$


**Internal model approach**
Builds an inverse model of the system to follow a prescribed trajectory or match some constraints (e.g. optimization).

$\ddot{x} + b\dot{x} + k(x - x_f) = u$

$u = u(t, m, b, k)$

$x = x(t, u)$

**Action systems approach**
*Dynamical systems*
*Ecological psychology*

**Information processing approach**
*Cognitive approach*
*MOTOR programs*
**Bimanual coordination**

— start in opposition phase
— increasing frequency (1-5 Hz)

\[ \dot{\phi} = -\frac{dV}{dt} \]

\[ V = -a \cos \phi - b \cos 2\phi \]

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**phenomenological model**

— Haken et al., 1985, *Biol Cybern* 51:347
The interaction between the behavior and the environment leads a better adaptation of the former to the latter. The tendency could lead to an optimal behavior, i.e. the best behavior corresponding to a goal, according to a given criterion.

The idea is to describe a movement not in terms of its characteristics (kinematics, dynamics), but in an abstract way, using a global value to be maximized or minimized.

E.g. smoothness, energy, variability, …

*Debated issue (e.g. — Schoemarker, 1991, Behav Brain Sci 14:205)
Extension of the internal model approach

Define an « objective function »:
minimization/maximization of task and action
related quantities (cost, utility)

Find the smallest \( u(t) \) (t in \([t_o; t_f]\)) such that
\[ x(t_o) = x_o, \ x(t_f) = x_f \]
and
\[ m\ddot{x} + b\dot{x} + k(x - x_f) = u \]

— Todorov, 2004, Nat Neurosci 7:907
FROM MOVEMENT TO ACTION

Movement

\[ \dot{x} = f(x, u) \]

\[ J^* = \min_u \int_{t_0}^{t_f} \|u(t)\|^2 \, dt \]

Minimizing costs, fixed time
FROM MOVEMENT TO ACTION

Action

\[ \dot{x} = f(x, u) \]
FROM MOVEMENT TO ACTION

Reinforcement learning

\[ V(x_t) = E[r_t + \gamma r_{t+1} + \gamma^2 r_{t+2} + ... | x_t] \]

Maximizing benefits, open time

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**FROM MOVEMENT TO ACTION**

**Reward/effort trade-off**

\[
J^* = \max_u \int_0^\infty e^{-t/\gamma} \left[ \rho r \delta(||\mathbf{x}^* - \mathbf{x}(t)||) - \varepsilon ||\mathbf{u}(t)||^2 \right] dt
\]

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FROM MOVEMENT TO ACTION

Reward/effort trade-off

- Graph showing utility vs. distance (cm)
- Scatter plots for duration vs. distance (cm)
- Cartesian coordinates for x (cm) and y (cm)
FROM MOVEMENT TO ACTION

Reward/effort trade-off

— Shadmehr & Mussa-Ivaldi, 1994, J Neurosci 14:3208
EXTENSION

Bayesian inference
ANATOMICAL ARCHITECTURE

— Scott, 2004, Nat Rev Neurosci 5:534
COMPUTATIONAL NEUROANATOMY

— Scott, 2004, Nat Rev Neurosci 5:534
— Guigon et al., 2007, Eur J Neurosci 26:250
CEREBELLAR DEFICITS

Ataxia

dysmetria

dysdiadochokinesia
CEREBELLAR DEFICIT

Deficit in predictive grip force control

— Nowak et al., 2007, Neuropsychologia 45:696
The cerebellum is involved in predicting the sensory consequences of action

Activity in the right lateral cerebellar cortex shows a positive correlation with delay.

The cerebellum is involved in signalling the sensory discrepancy between the predicted and actual sensory consequences of movements.

BASAL GANGLIA DEFICITS

Movements and EMG are segmented

— Hallett & Khoshbin, 1980, *Brain* 103:301

— Berardelli et al., 1984, *Neurosci Lett* 47:47
BASAL GANGLIA DEFICITS

— Georgiou et al., 1993, *Brain* 116:1575
BASAL GANGLIA DEFICITS

Reaching to moving targets

Paradoxical kinesia in PwPD

— Schenk et al., 2003, Neuropsychologia 41:783
PARKINSON’S DISEASE AND MOTIVATION

— Schmidt et al., 2008, *Brain* 131:1303
The computational model is « wrong »
does not explain: discrete/rhythmic actions, skilled/unskilled actions, isochrony, slow movements, …

— Guigon, 2021, Psychol Rev in press

The computational neuroanatomy is « wrong »
does not explain: the role of the motor cortex, the contribution of the basal ganglia to motor control, how the cerebellum can implement a state estimator, where motor memories are stored, …

— Serradj et al., 2021, bioRxiv 436415
— Dhawale et al., 2021, Nat Neurosci 24:1256
lamprey-like swimming robot to explore the mechanisms of visually-guided swimming in the lamprey

salamander robot driven by a spinal cord model replicates the typical swimming and walking gaits of the salamander

The field of robotics is heavily inspired by biology; a clearer understanding of how nature accomplishes efficient and precise motor control is critical to the development of advanced robotic systems.

As human interaction with technology continues to expand, ergonomic design and intuitive control based on the principles of human movement and motor control will also become increasingly important.