HUMAN MOTOR CONTROL

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introduction

WHAT IS (HUMAN) MOTOR CONTROL?

Action (force, displacement)

Body: bones, muscles, tendons, skin
Nervous system (sensory, motor, ...)

How the nervous system is organized so that the many individual muscles and joints become coordinated to produce an action?

Decision, planning, anticipation, preparation

All what occur before an action
Not in the scope

WHY STUDY MOTOR CONTROL?

- **Build tools to investigate or treat diseases affecting the sensorimotor system**

- **Develop computer algorithms and hardware that can be incorporated in products designed to assist in the tasks of daily living**

— Burdet et al., 2013, *Human Robotics,* MIT Press

HOW TO STUDY MOTOR CONTROL?

- **Experimental**

- observe, measure, quantify
- search for «regular» patterns

psychophysics, *neurophysiology*, *brain imaging*, *neuropsychology*

- **Computational**

- what is the problem to be solved?
- reveals the nature of constraints that the physical world puts on the solution of the problem

CLASSIFICATION OF ACTION

- **Genetically defined / Learned (skills)**

e.g. reflex vs industrial, artistic and athletic skills

- **Reflex / Voluntary**
- **Discrete / Continuous (rhythmic)**
- **Posture / force / displacement**
- **Repertoire**

e.g. walking, running, flying, reaching, grasping, speaking, singing, writing, drawing, looking, smiling, swimming, standing, ...

! It is unclear whether a single set of principles can account of all classes of actions

ACTION AND THE ENVIRONMENT

- An action occurs in a environment

- The action cannot be isolated from its environment

- The environment provides goals, instructions, cues, interactions, …

- The action modifies the environment

ACTION AND THE BODY

- **The body grows during development, changes with training and aging, and is modified by injuries and diseases**

short-term (fatigue)
mid-term (muscle tear)
long-term (amputation)

motor development
motor learning

- **Prothestics**

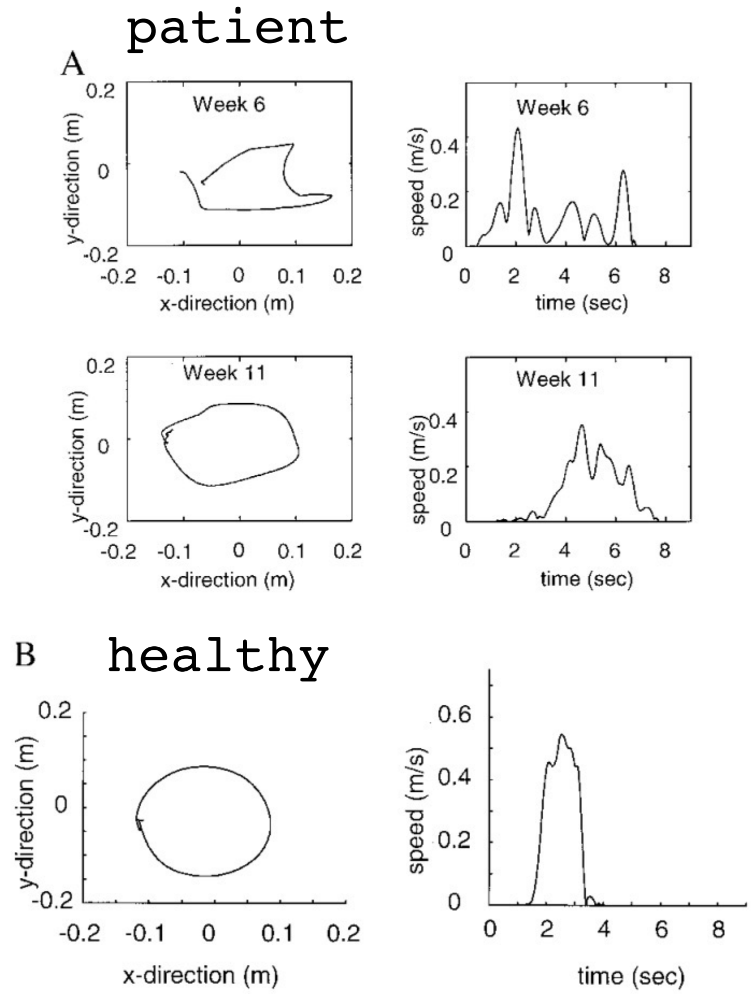
augmentation

U.S. Bionic Knee and Ankle Prosthesis Pioneer **Hugh Herr** Named European Inventor Award 2016 Finalist

ACTION AND THE NERVOUS SYSTEM

Acute and chronic changes in neural organization lead to motor disorders

e.g. stroke, Parkinson disease, ...



— Krebs et al., 1999, *Proc Natl Acad Sci USA* 96:4645

rehabilitation

MIT-Manus

ACTION AND THE NERVOUS SYSTEM

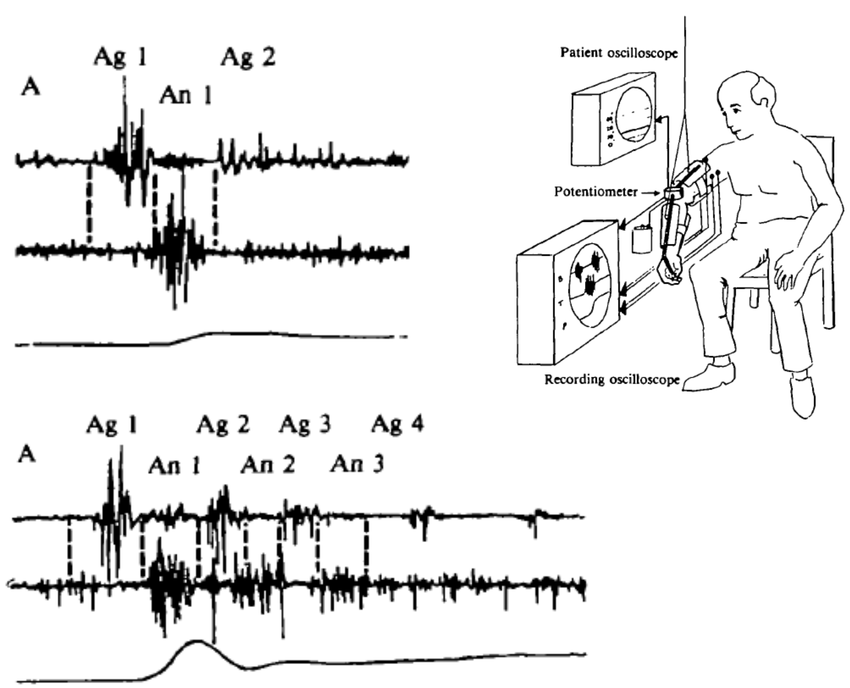
Acute and chronic changes in neural organization lead to motor disorders

e.g. stroke, Parkinson disease, ...

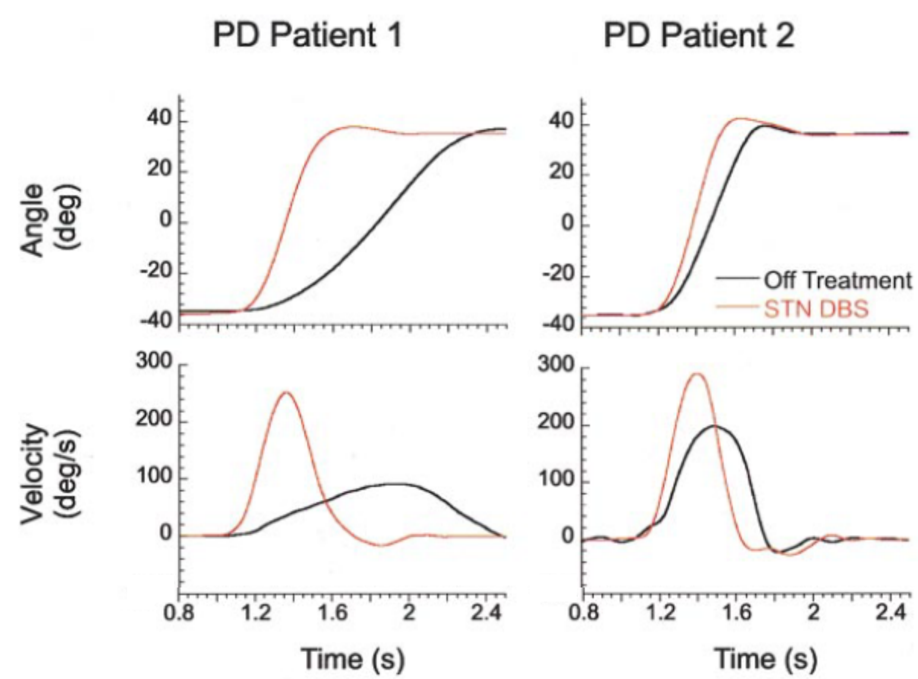
treatment

healthy

patient



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

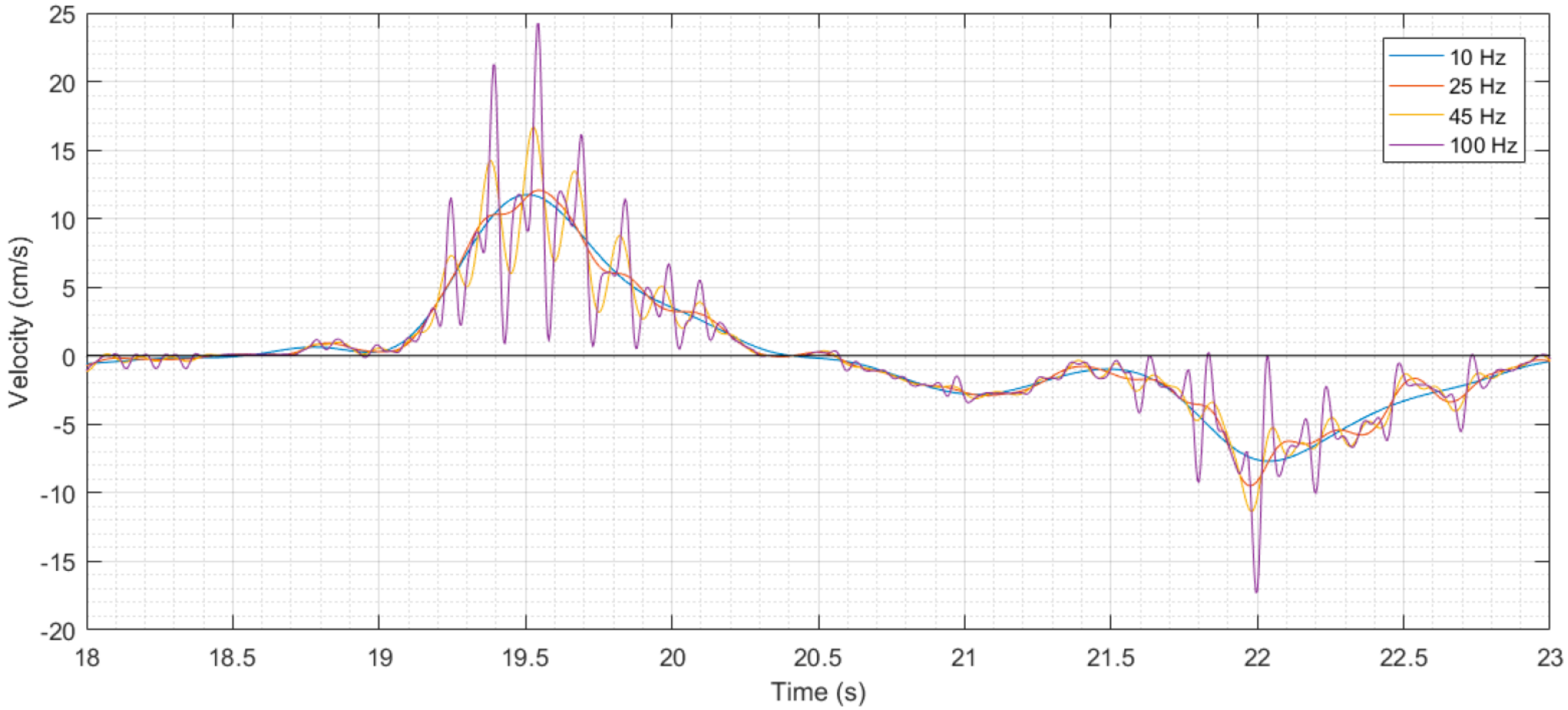


DBS = deep brain stimulation

—Vaillancourt et al., 2004, *Brain* 127:491

DISCLAIMER

Do not believe what you see
quite any property in motor control depends on data processing (filtering)



NOT IN THE SCOPE

- **Motor development/training/ adaptation/learning**

- **Motor repertoire**

posture, walking, running, jumping, flying, swimming, throwing, kicking, drawing, writing, keyboarding, speaking, singing, smiling, ...

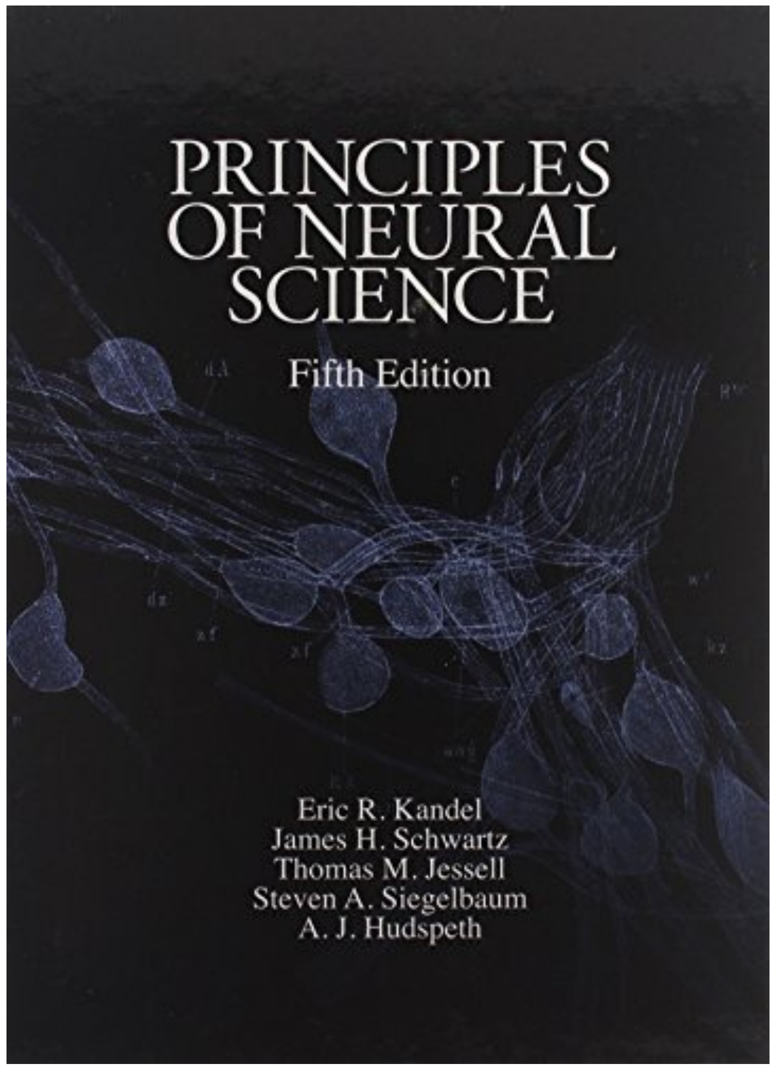
- **Psychology of movement**

movement preparation, reaction time, errors, ...

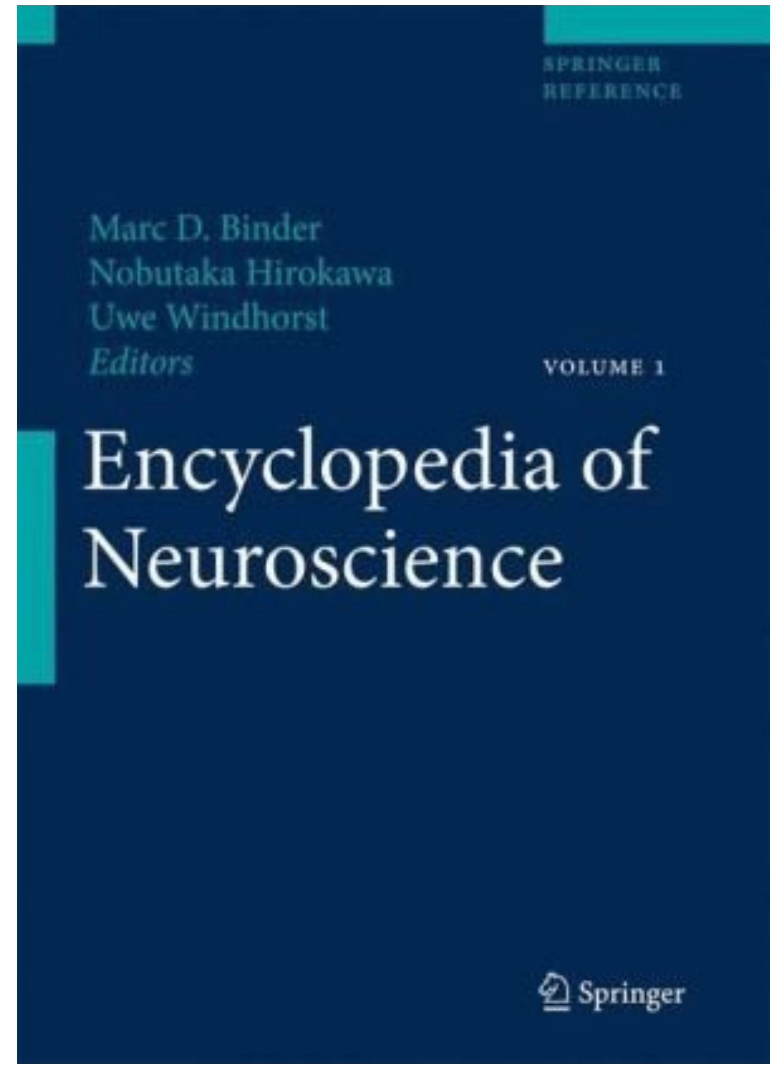
- **Methods for the study of movements**

- **History of motor control**

CREDITS



Kandel ER, Schwartz JH, Jessell TM, Siegelbaum SA, Hudspeth AJ, eds (2013) Principles of Neural Science, 5th ed. New York, NY: McGraw-Hill Professional.



Binder MD, Hirokawa N, Windhorst U, eds (2008) Encyclopedia of Neuroscience. Berlin: Springer.

OUTLINE

1. The organization of action
Main vocabulary

2. Computational motor control
Main concepts

3. Biological motor control
Basic introduction

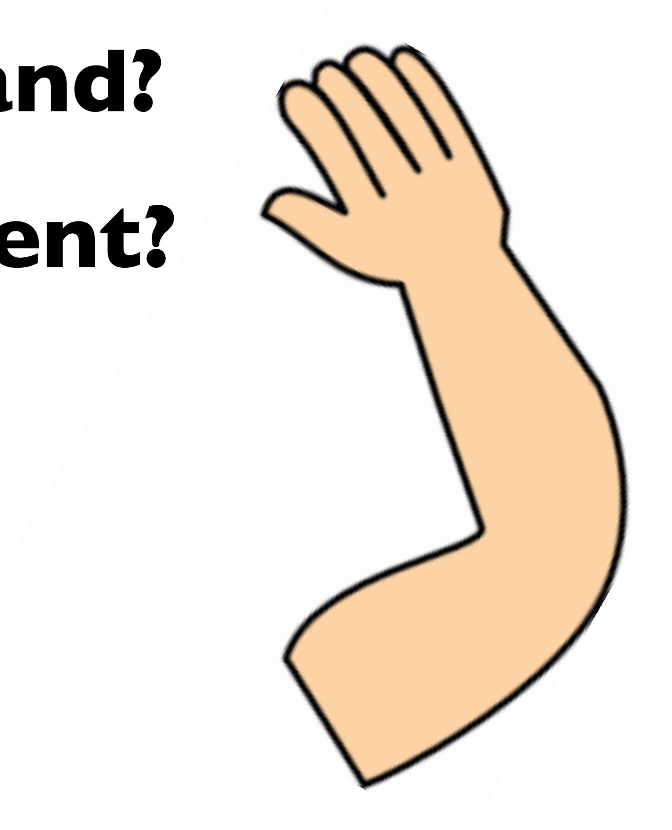
4. Models and theories
Main ideas and debates

I

1. The organization of action

EXAMPLE - TAKE OF COFFEE

- Where is my body? Where is the bar?
- How to reach the bar?
- Where is the cup? Where is my arm?
- How to reach the cup?
- How to calculate the motor command?
- How to interact with the environment?
- Is the command correct?
- How to do better at the next trial?



WHERE IS THE CUP? WHERE IS MY ARM?

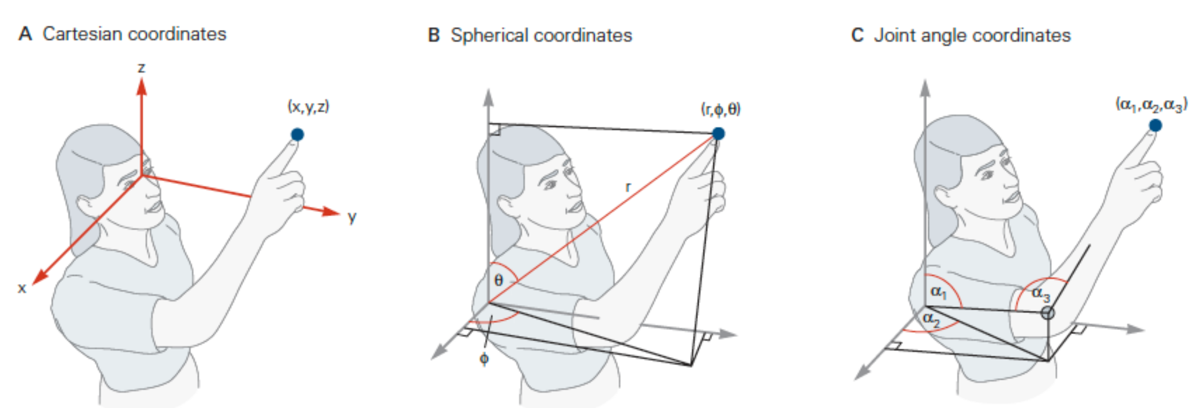
- **Modalities**

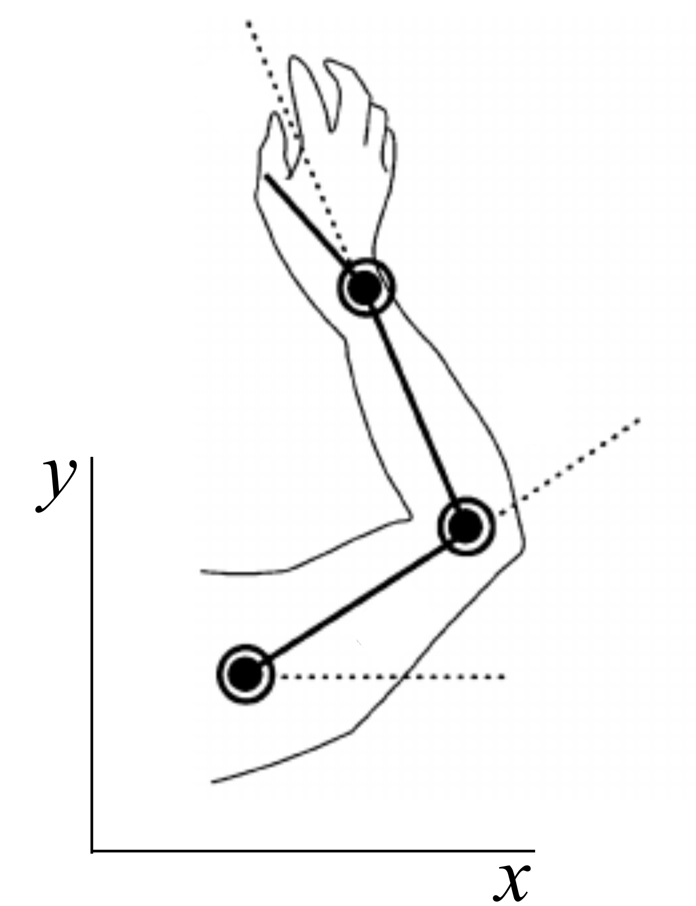
vision, proprioception, … / multimodal integration

- **Reference frames**

— target position: in a fixed frame (earth), but perceived in a moving frame (body)
— arm position: in body-related frame

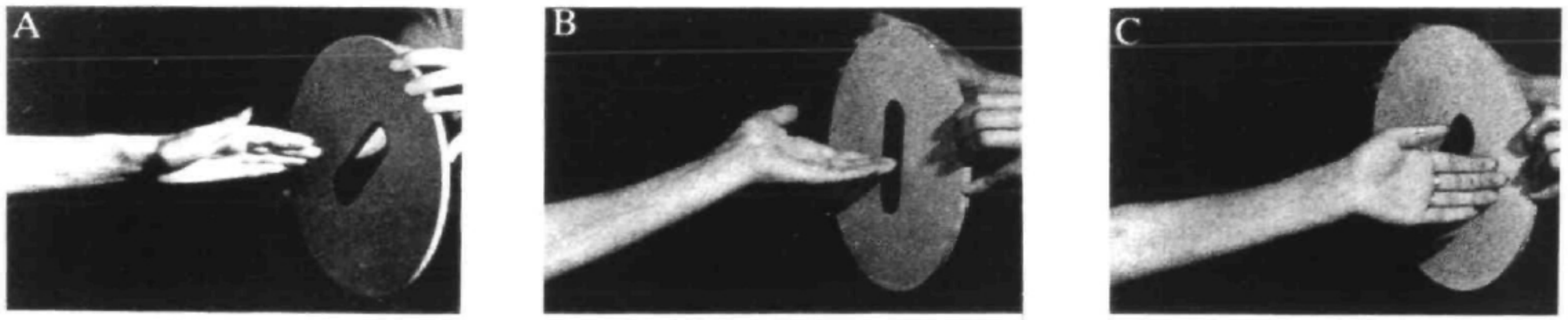
In which frame is the movement represented?
What kind of coordinate systems are used?





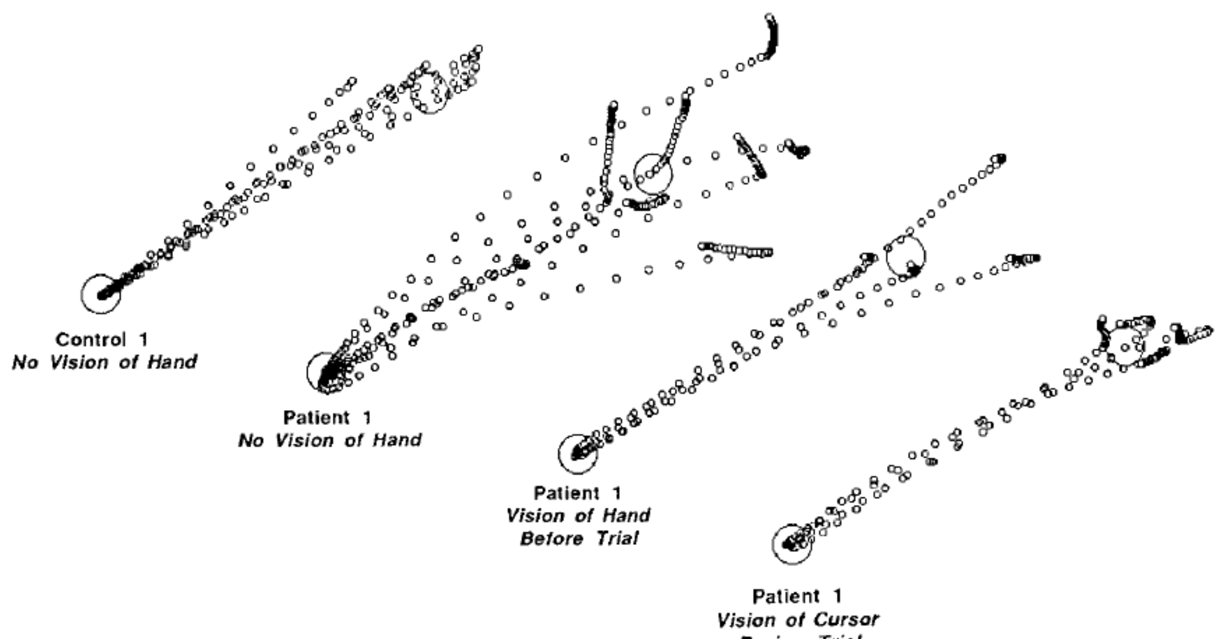
WHERE IS THE CUP? WHERE IS MY ARM?

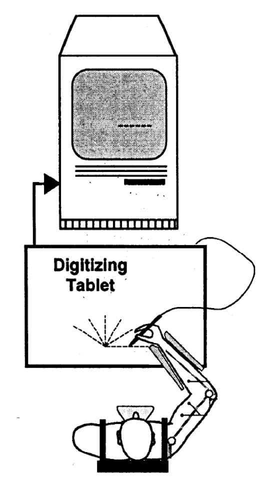
optic ataxia (visuomotor coordination)

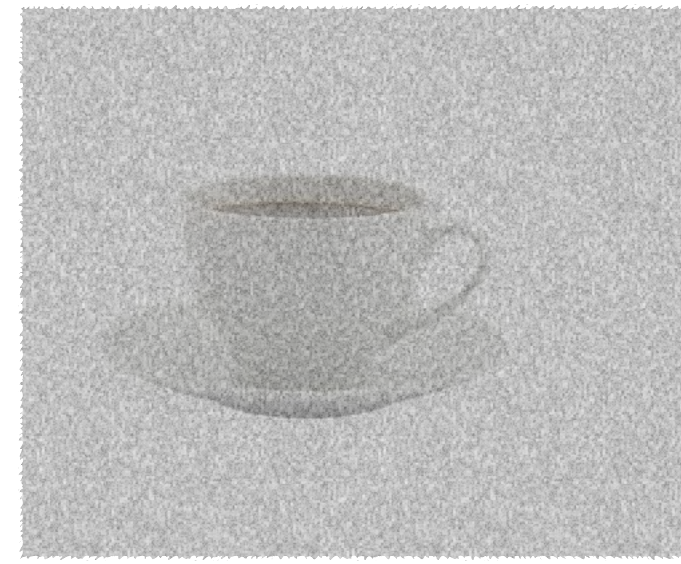


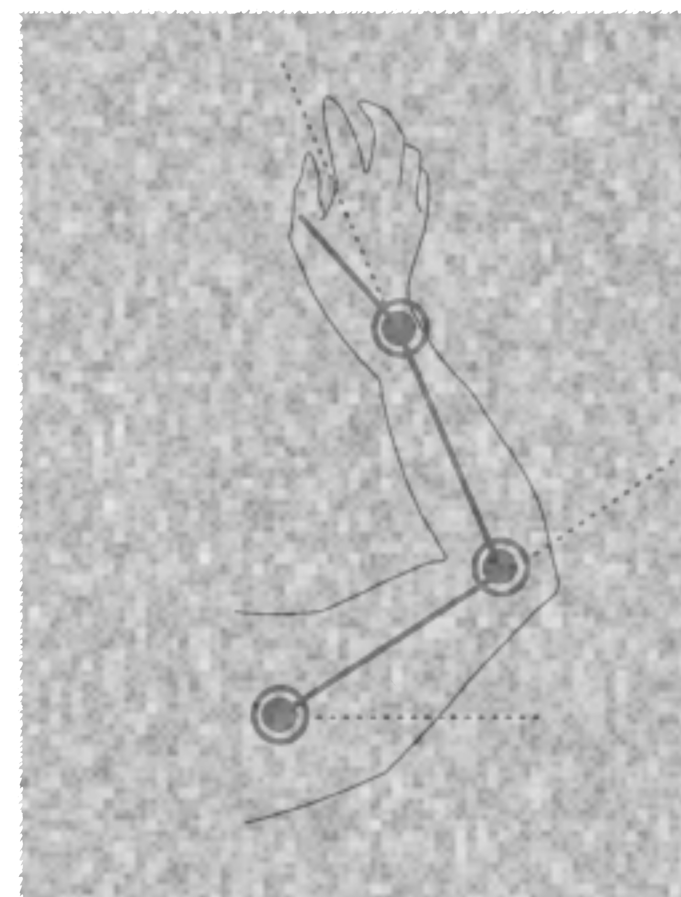
`normal` `orientation error` `spatial error`

deafferentation (loss of proprioception)









uncertainty
noise

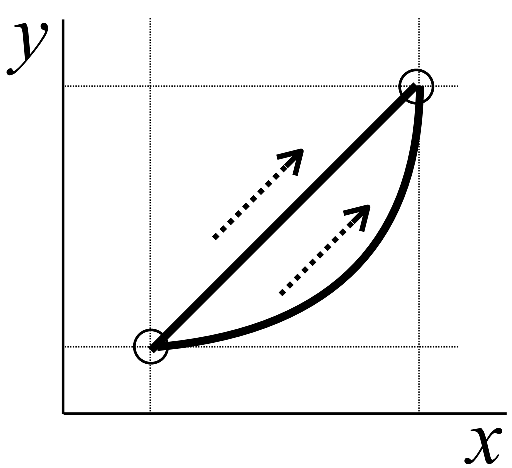
— Perenin & Vighetto, 1988, *Brain* 111:643
— Ghez et al., 1990, *CSHSQB* 55:837

HOW TO REACH THE CUP?

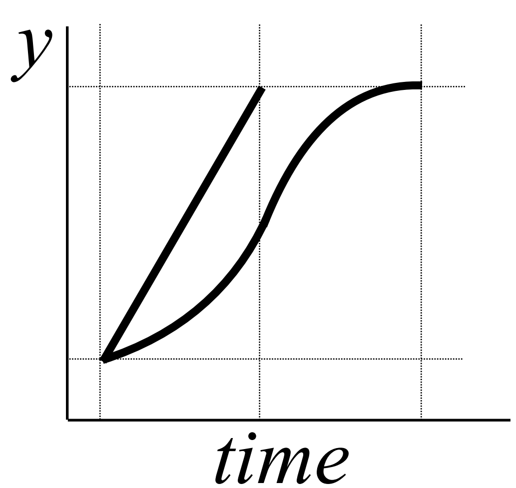
- **Choice of a *task-space* trajectory**

path, time course along the path

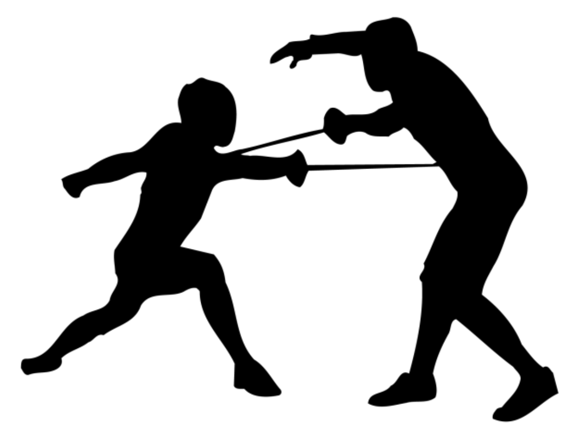
[hand, end-point, end-effector trajectory]

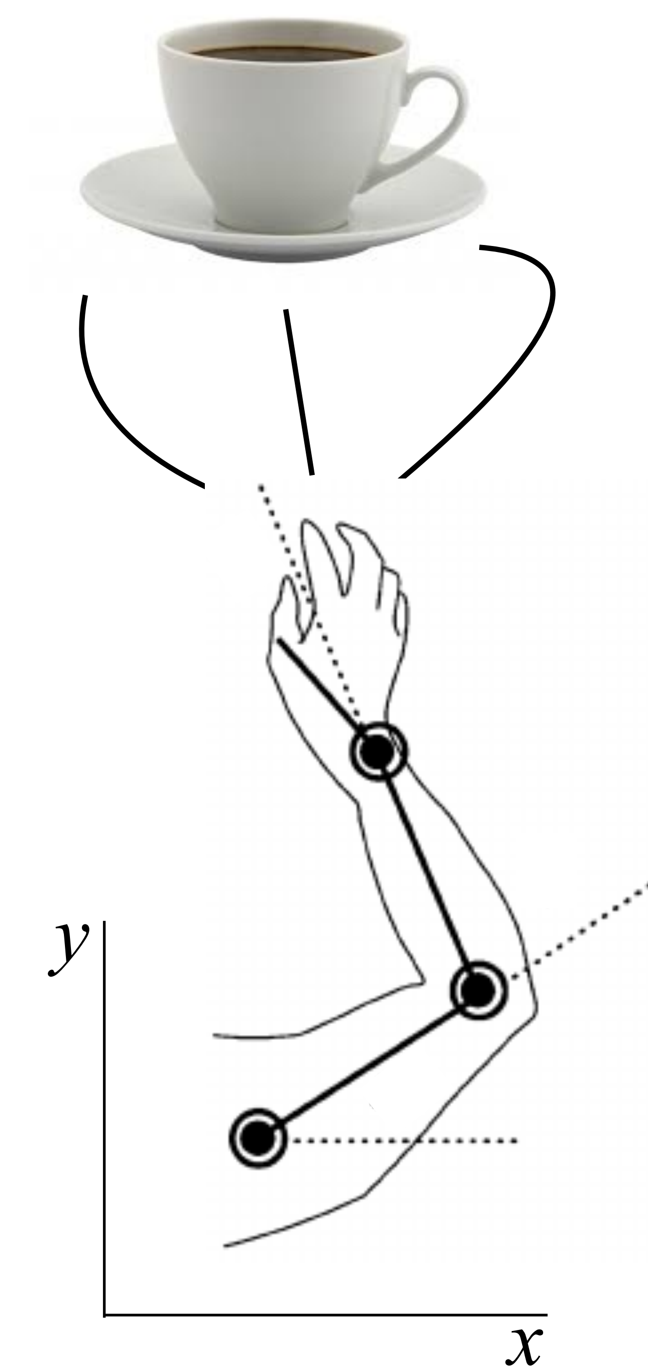


$$f(x, y) = 0$$



$$x = x(t)$$
$$y = y(t)$$





HOW TO REACH THE CUP?

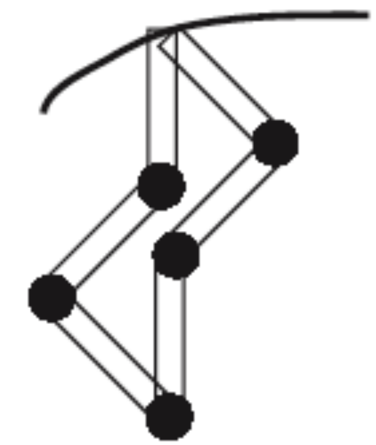
- **Choice of a *body-space* trajectory**

- DOF = degrees of freedom

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

- kinematic redundancy

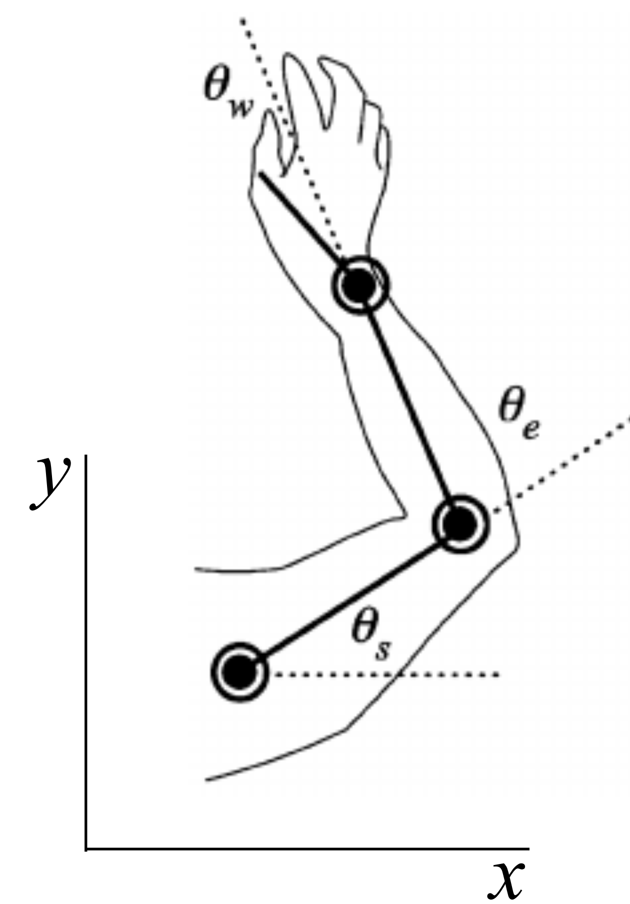
  number of DOF > *task-space* dimension



- **Kinematics**

- coordinate transformation
- inverse kinematics is an ill-posed problem

$$\begin{cases} x = L_s \cos\theta_s + L_e \cos(\theta_s + \theta_e) + L_w \cos(\theta_s + \theta_e + \theta_w) \\ y = L_s \sin\theta_s + L_e \sin(\theta_s + \theta_e) + L_w \sin(\theta_s + \theta_e + \theta_w) \end{cases}$$



degrees-of-freedom problem
redundancy
nonlinearity

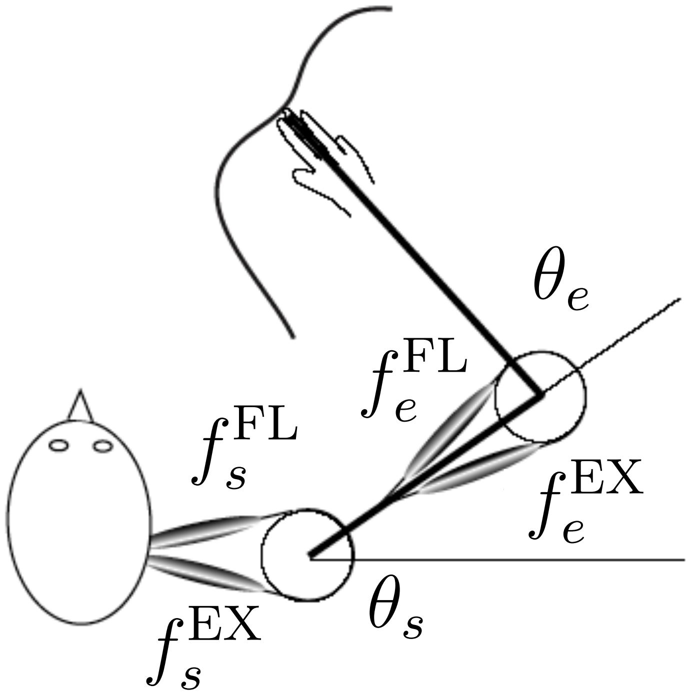
— Saltzman, 1979, *J Math Psychol* 20:91

HOW TO CALCULATE THE COMMAND?

- **Joint torques**
to produce a desired *body-space* trajectory

- **Dynamics**
direct/inverse transformation (Newton's law)

$$\begin{aligned}\tau_s =&(I_s + I_e + m_e l_s l_e \cos\theta_e + \frac{m_s l_s^2 + m_e l_e^2}{4} + m_e l_s^2)\ddot{\theta}_s + \\ &(I_e + \frac{m_e l_e^2}{4} + \frac{m_e l_s l_e}{2}\cos\theta_e)\ddot{\theta}_e - \\ &\frac{m_e l_s l_e}{2}\dot{\theta}_e^2 \sin\theta_e - m_e l_s l_e \dot{\theta}_s \dot{\theta}_e \sin\theta_e \\ \tau_e =&(I_e + \frac{m_e l_s l_e}{2}\cos\theta_e + \frac{m_e l_e^2}{4})\ddot{\theta}_s + \\ &(I_e + \frac{m_e l_e^2}{4})\ddot{\theta}_e + \frac{m_e l_s l_e}{2}\dot{\theta}_s^2 \sin\theta_e\end{aligned}$$



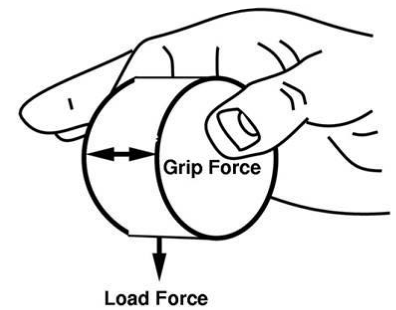
- **Force distribution**
dynamic redundancy

$$\begin{cases} \tau_s = \mu_s^{\mathrm{FL}} f_s^{\mathrm{FL}} - \mu_s^{\mathrm{EX}} f_s^{\mathrm{EX}} \\ \tau_e = \mu_e^{\mathrm{FL}} f_e^{\mathrm{FL}} - \mu_e^{\mathrm{EX}} f_e^{\mathrm{EX}} \end{cases}$$

HOW TO INTERACT?

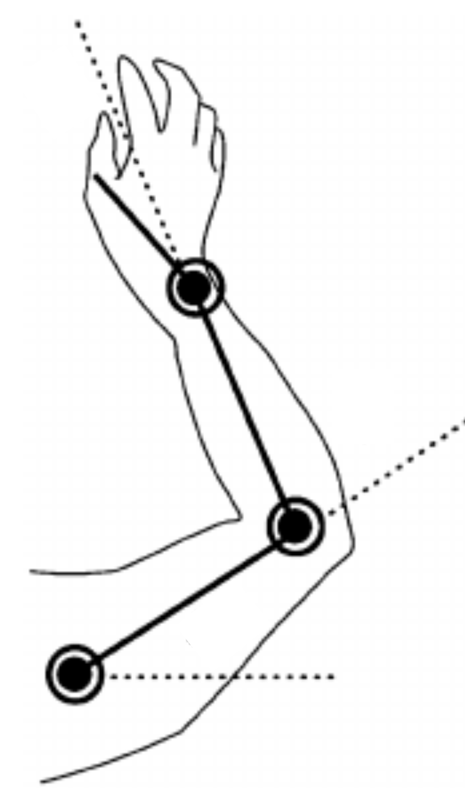
- **Stable**

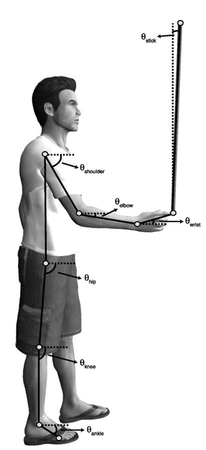
e.g. firmly grasped, rigid objects

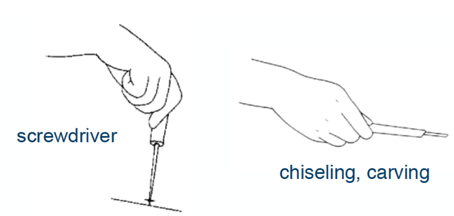


- **Unstable: tool manipulation, posture and gait control**

e.g. using a drill, stick balancing, balancing a tray, riding a bicycle







interaction
stable / unstable

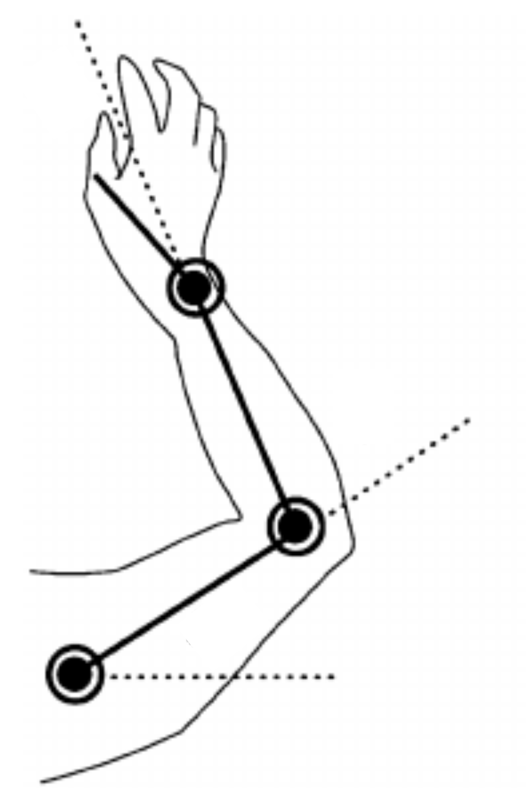
IS THE COMMAND CORRECT?

- **Origin of errors**

localization of the target (target/eye, eye/head, ...)
localization of hand and arm (vision or not)
estimation of physical characteristics
fatigue, injury (muscle tear)
perturbations (e.g. the target has been displaced)
obstacles

- **Solution: feedback**

sensory information, online movement correction
need for flexbility — but: slowness, **time delays**



sensory information
nonstationarity
perturbation/correction
slowness/time delays

HOW TO DO BETTER AT THE NEXT TRIAL?

- **Adaptation, motor learning**

biomechanical interface: tool, telemanipulation
visuomotor transformation (gains, rotations, ...)
dynamic transformation (inertia, viscosity, stiffness)

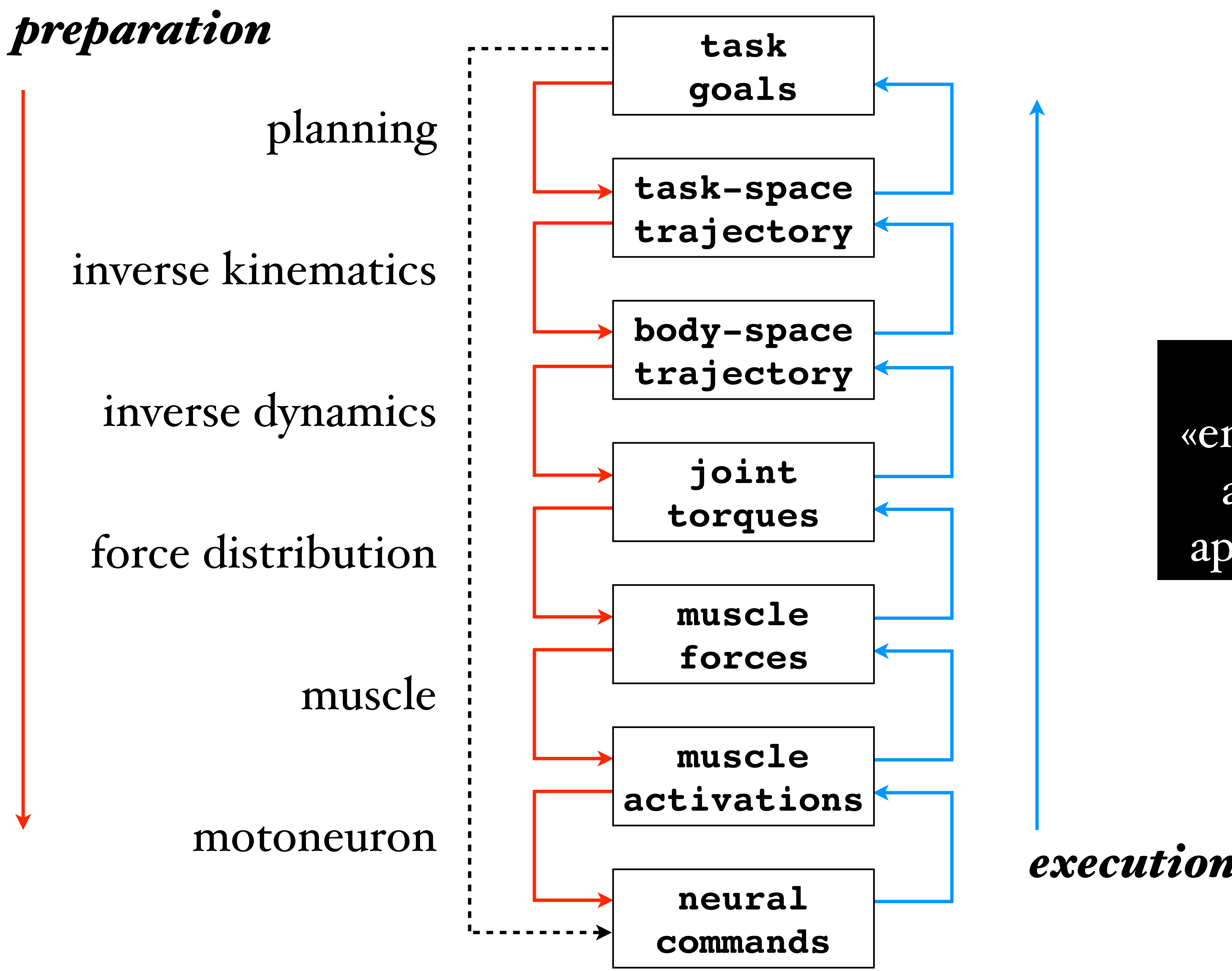
- **Nature of adaptation and learning**

temporary vs permanent
interferences
learning vs development

- **Error signals**

all or none (success / failure) — quantitative

SUMMARY



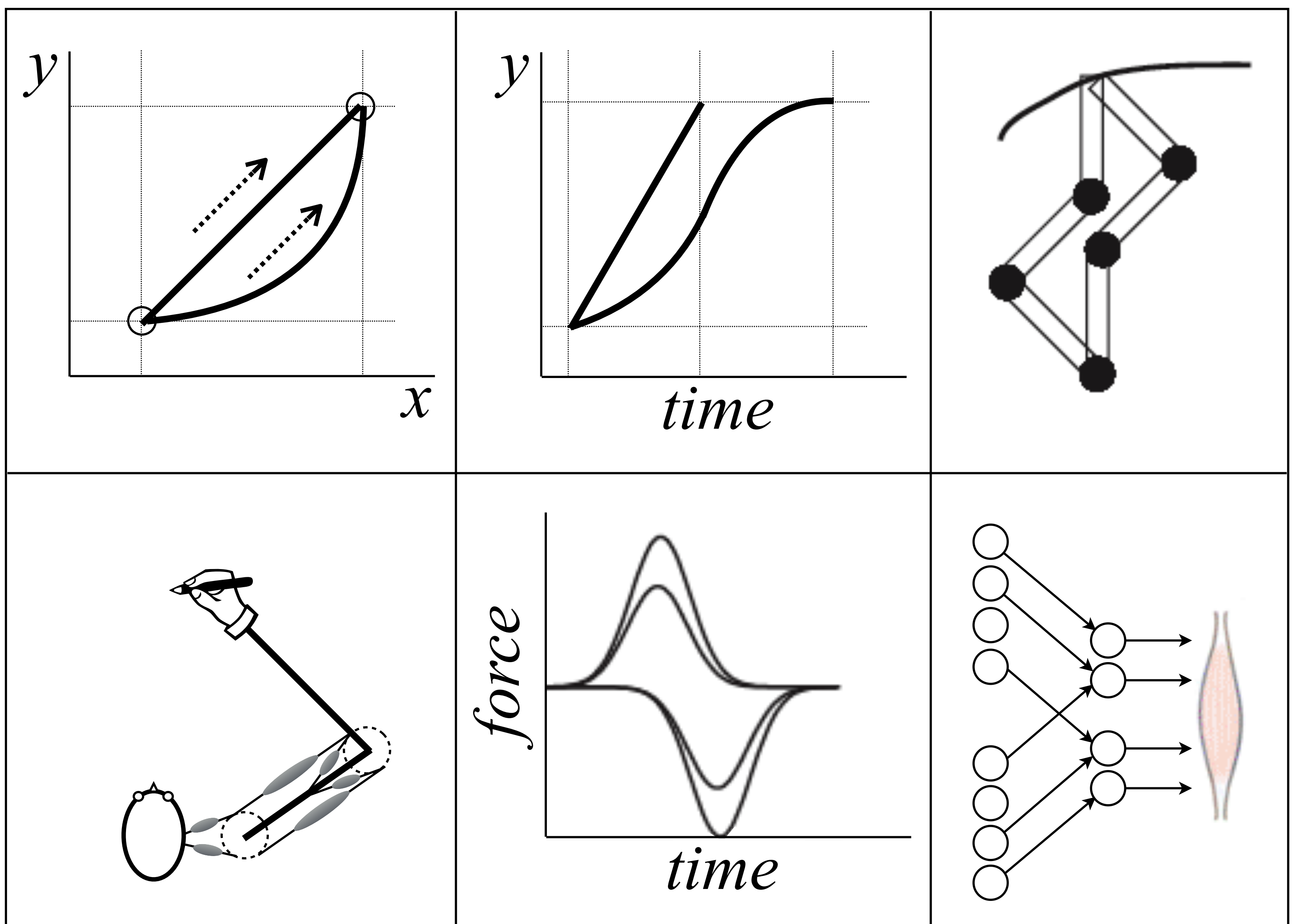
Is this «engineering» approach appropriate?

THE DEGREES OF FREEDOM PROBLEM

Redundancy, nonlinearity

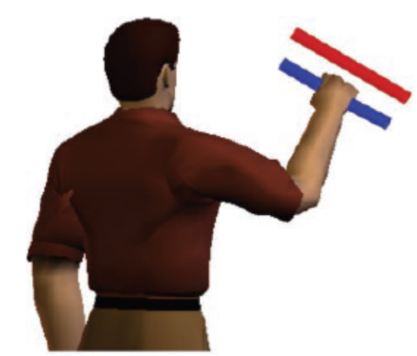
In task space, body space, muscle space, neural space

Problem of **degrees of freedom** (Bernstein's problem)



→ *Coordination*

```
example
upper arm
7 dof
26 muscles
100 MUs
10?? neurons
```

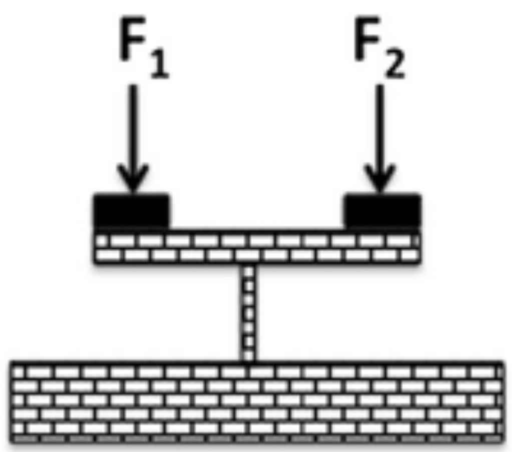


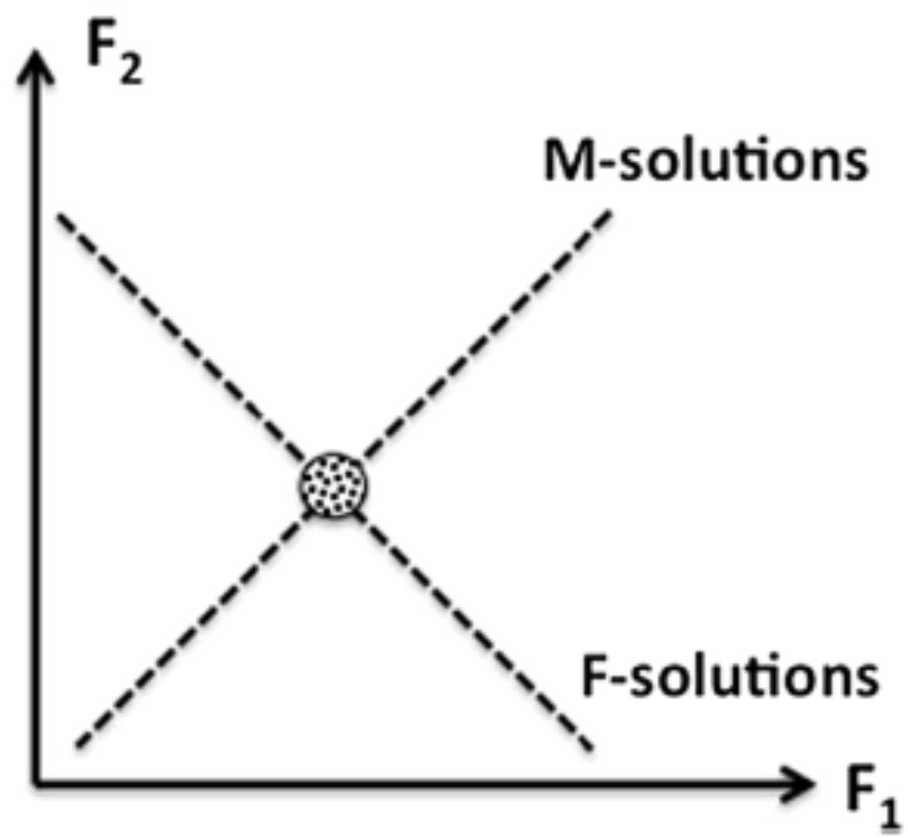
— Bernstein, 1967, *The Co-ordination and Regulation of Movement*, Pergamon

Redundant problems

$$F_{TOT} = F_1 + F_2$$

$$M_{TOT} = F_1 d_1 + F_2 d_2 = 0$$





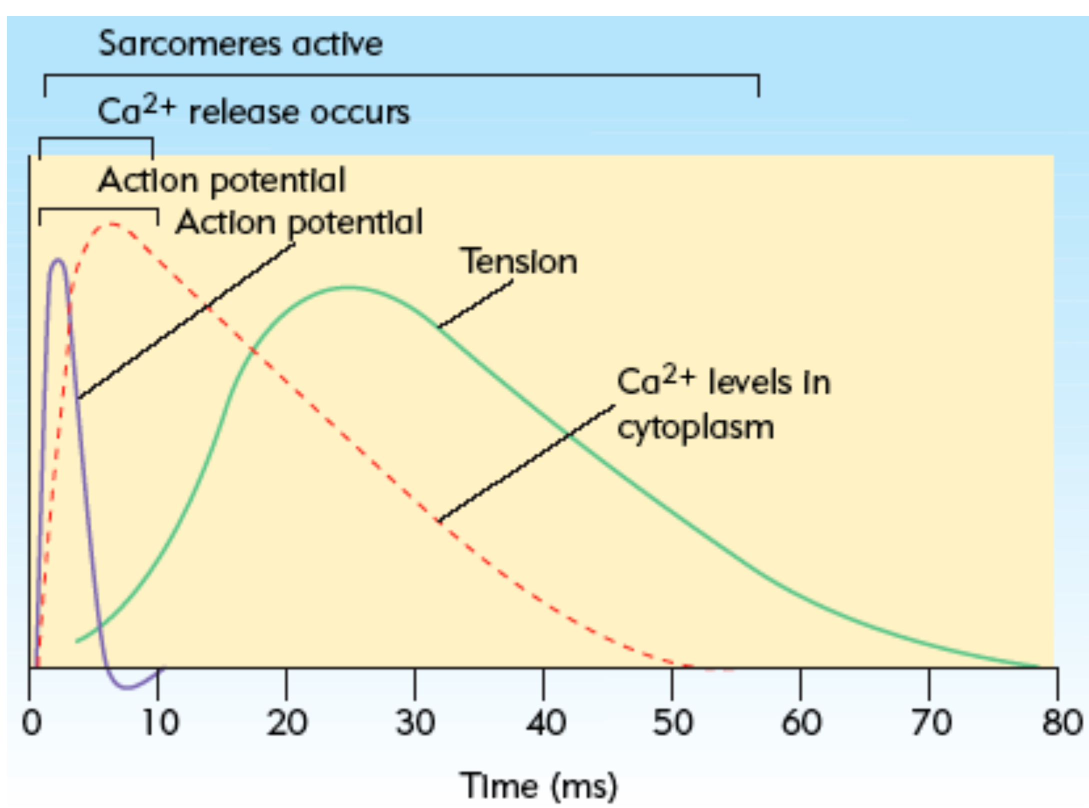
accurate total force production: F-solutions
zero total moment of force: M-solutions

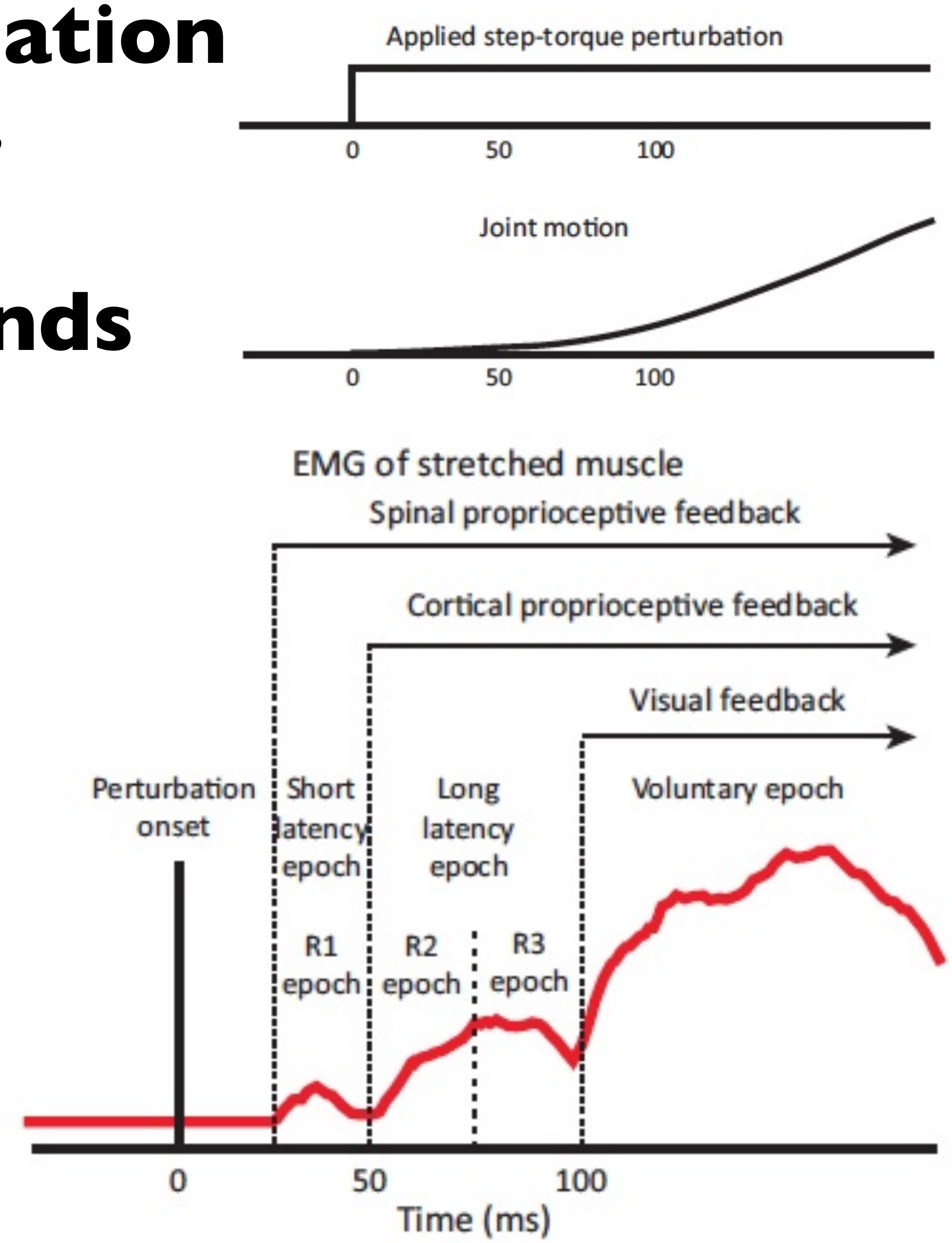
SLOWNESS / TIME DELAYS

- **In afferent sensory information**
  receptor dynamics, conduction delays

- **In efferent motor commands**

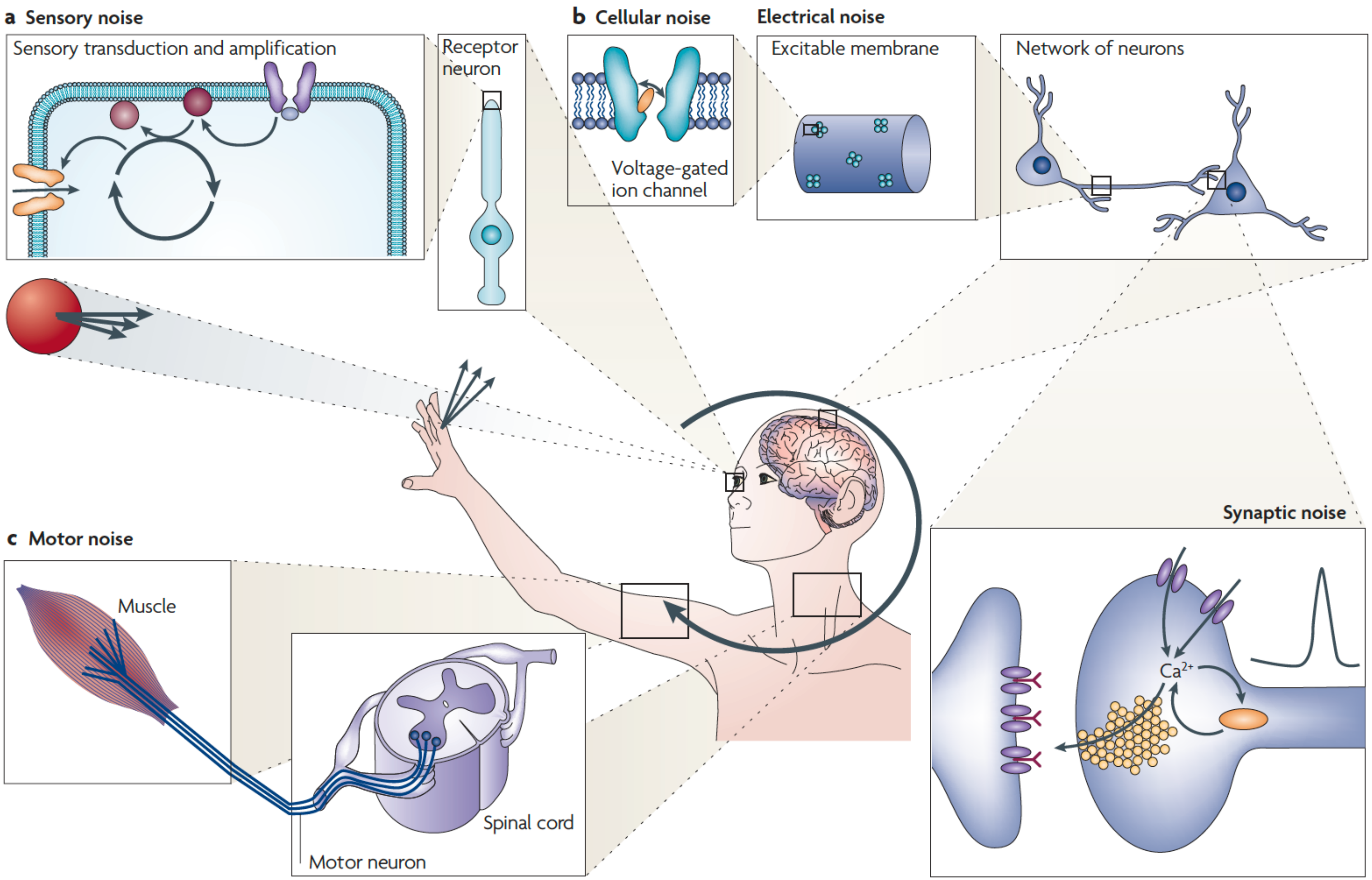
«We live in the past»





— Scott, 2012, *Trends Cogn Sci* 16:541

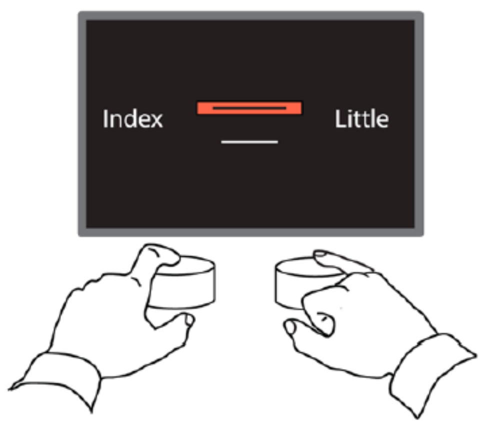
NOISE

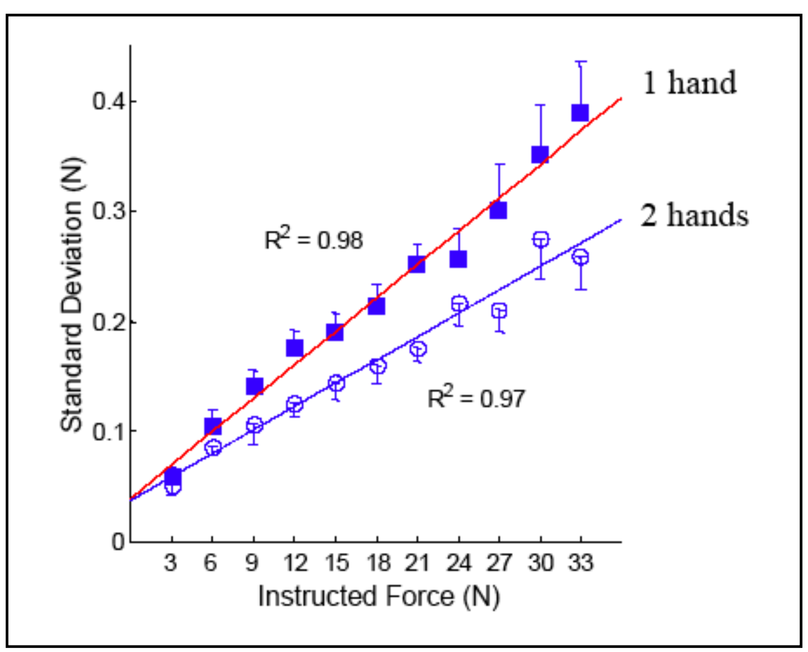


— Faisal et al., 2008, *Nat Rev Neurosci* 9:292

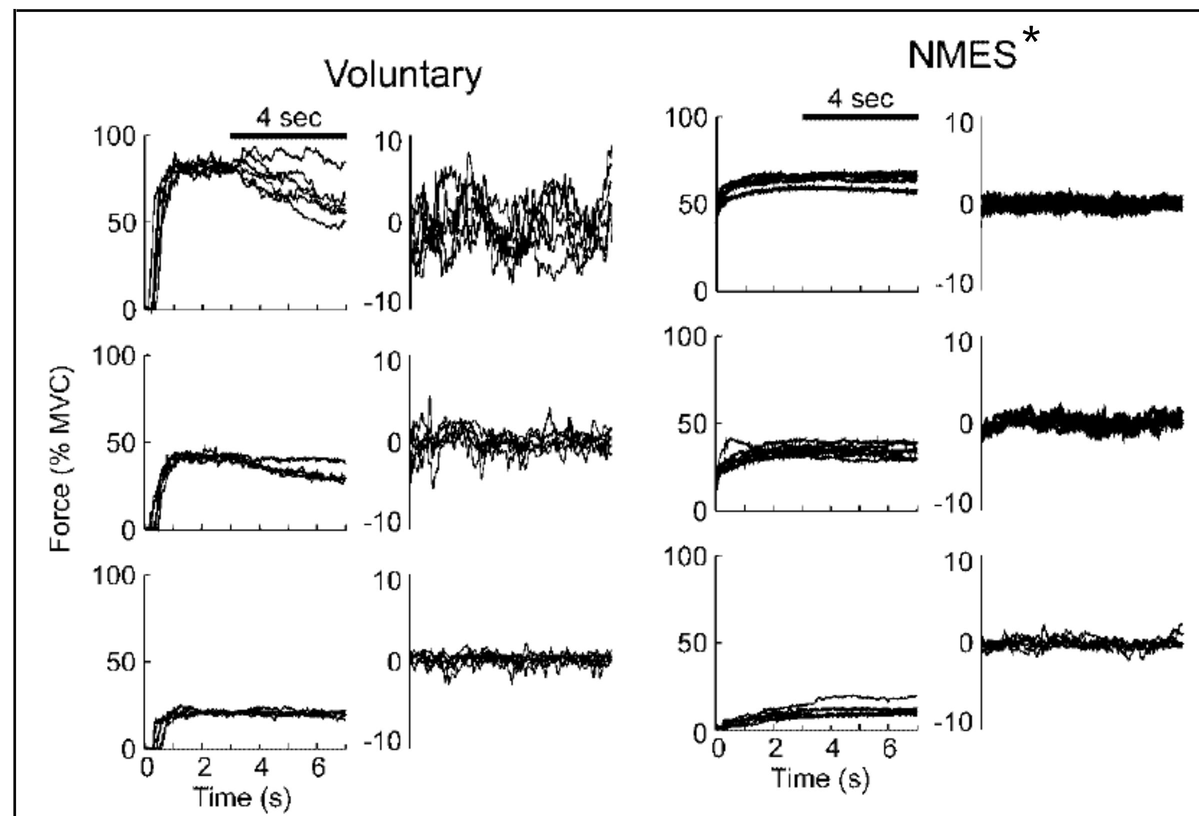
NOISE

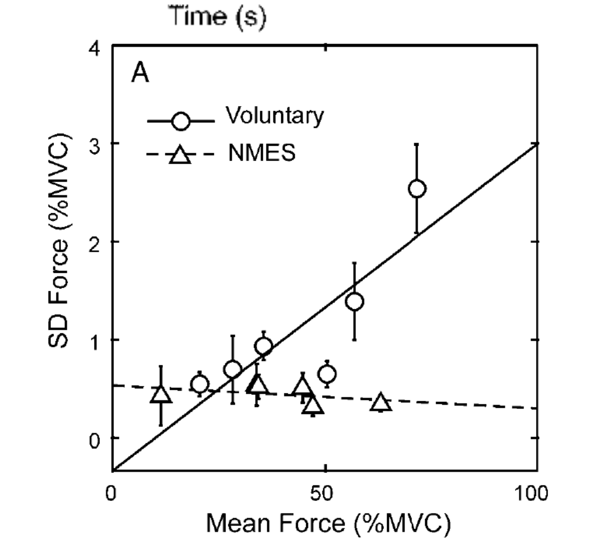
Signal-dependent motor noise





— Todorov, 2002, *Neural Comput* 14:1233





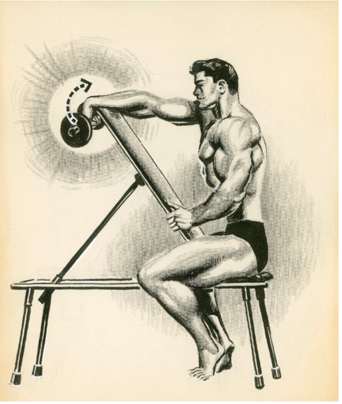
(*) electrical stimulation

— Jones et al., 2002, *J Neurophysiol* 88:1533

NONSTATIONARITY

- **Growth**

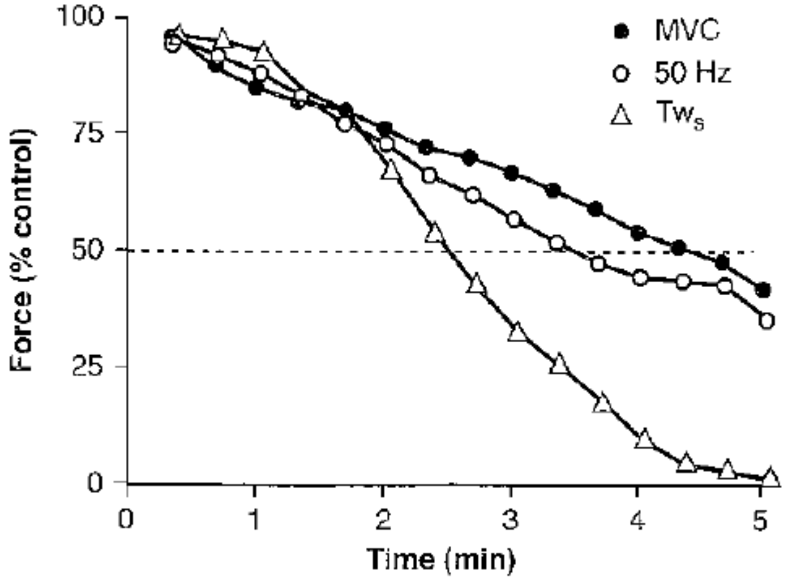
development, ageing, training



- **Fatigue**

muscle fatigue

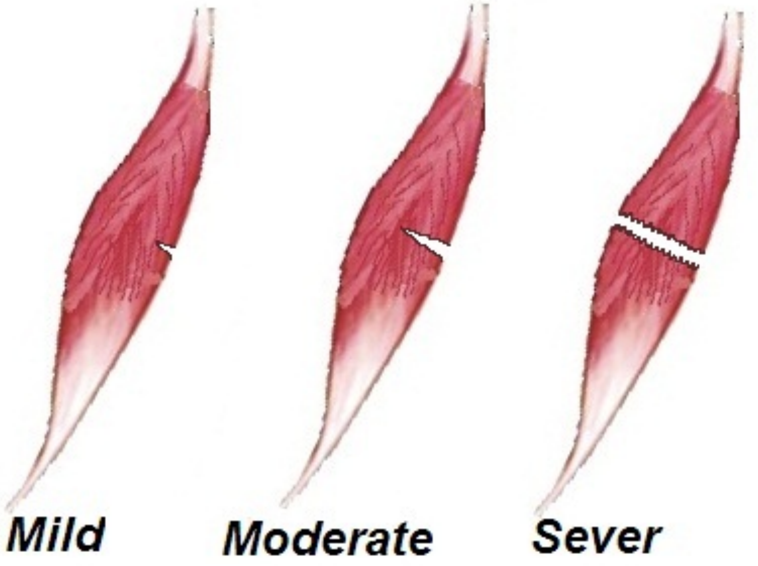
changes in force during a fatiguing contraction that involved intermittent contractions



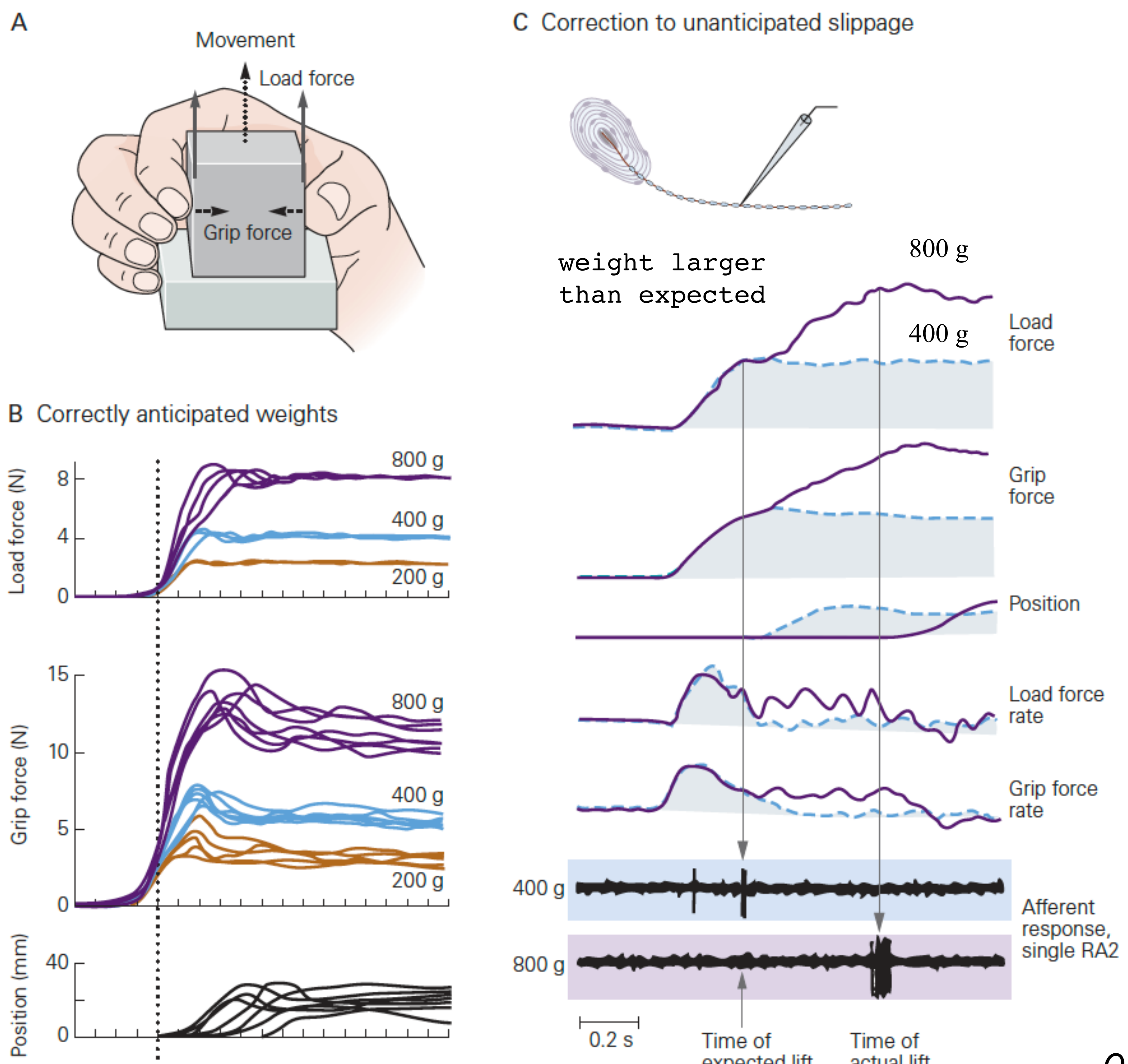
— Bigland-Ritchie et al., 1986, *J Appl Physiol* 61:421

- **Injury**

muscle tears



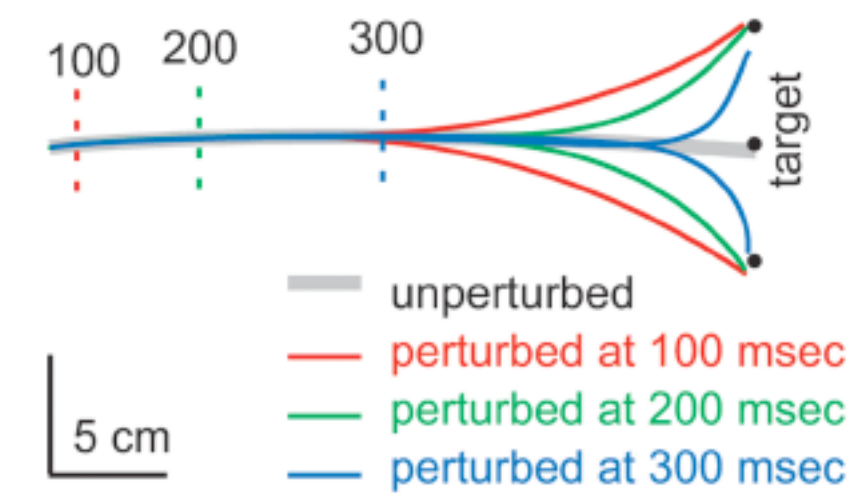
INTERACTION (RIGID OBJECTS)

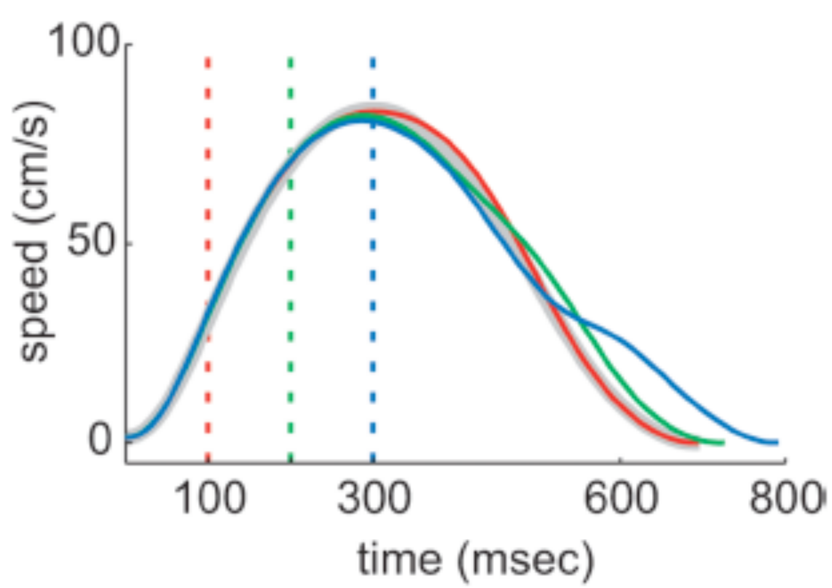


— Johansson & Cole, 1992, *Curr Opin Neurobiol* 2:815

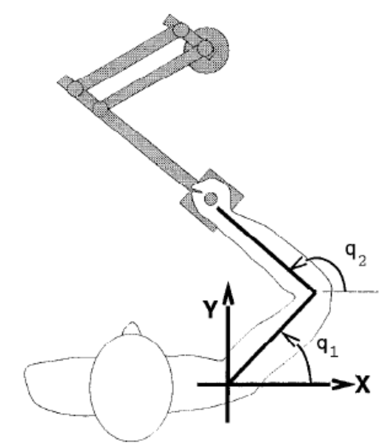
PERTURBATION — CORRECTION

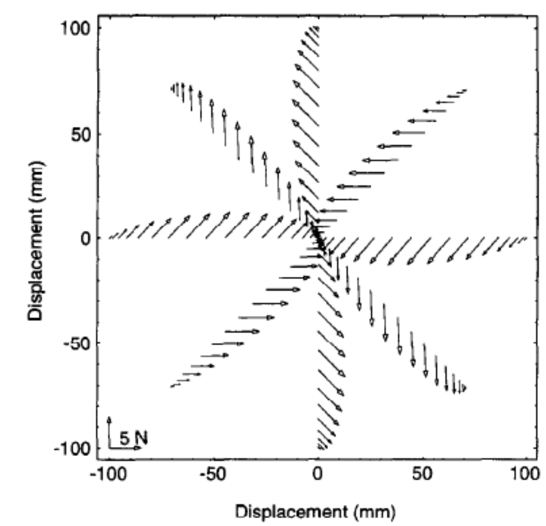
Motor control is highly flexible in space and time

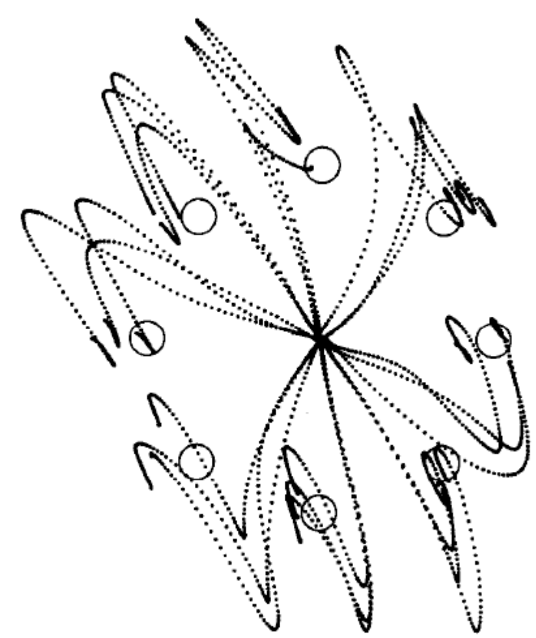


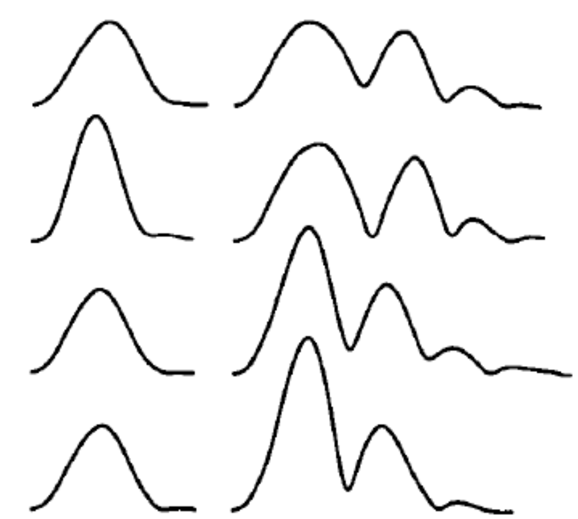


— Liu & Todorov, 2007, *J Neurosci* 27:9354







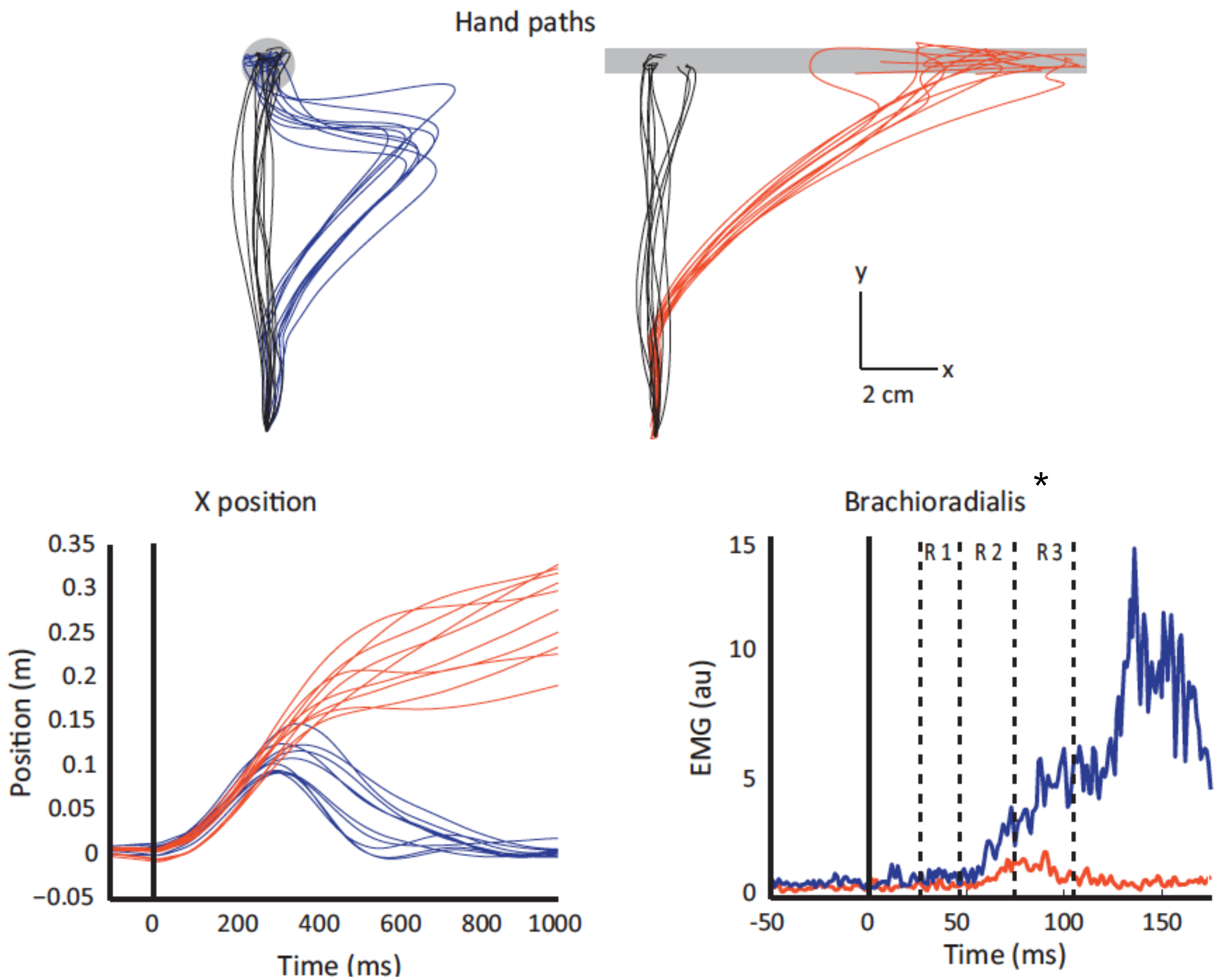


— Shadmehr & Mussa-Ivaldi, 1994, *J Neurosci* 14:3208

PERTURBATION — CORRECTION

Error corrections

only if perturbations affect the behavioral goal / ignored if they do not



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

(*) elbow flexor

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

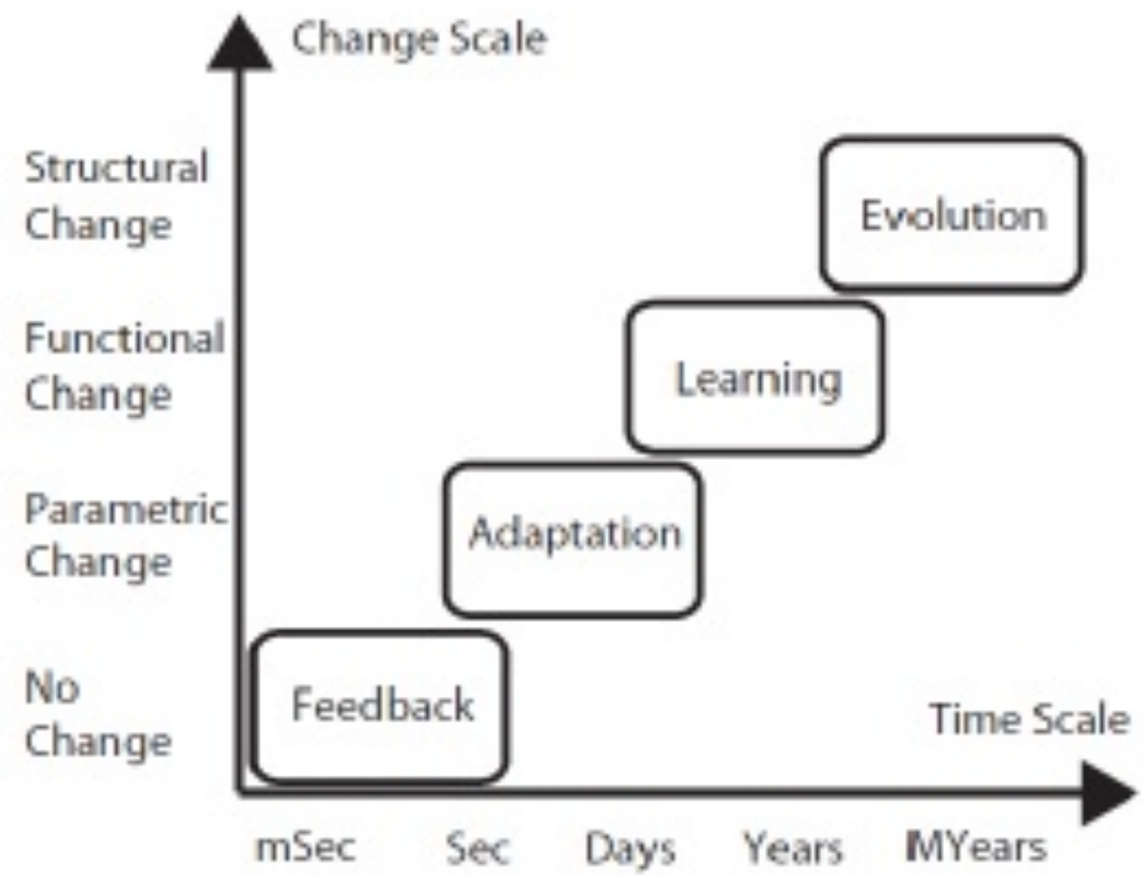
→ **Corrective responses do not return to a desired trajectory**

ADAPTATION — LEARNING

- **Adaptation**
regain former capabilities in altered circumstances e.g. *prism*, *force fields*, ...

- **Learning**
change, resulting from practice or a novel experience, in the capability for responding e.g. *piano*, *golf*

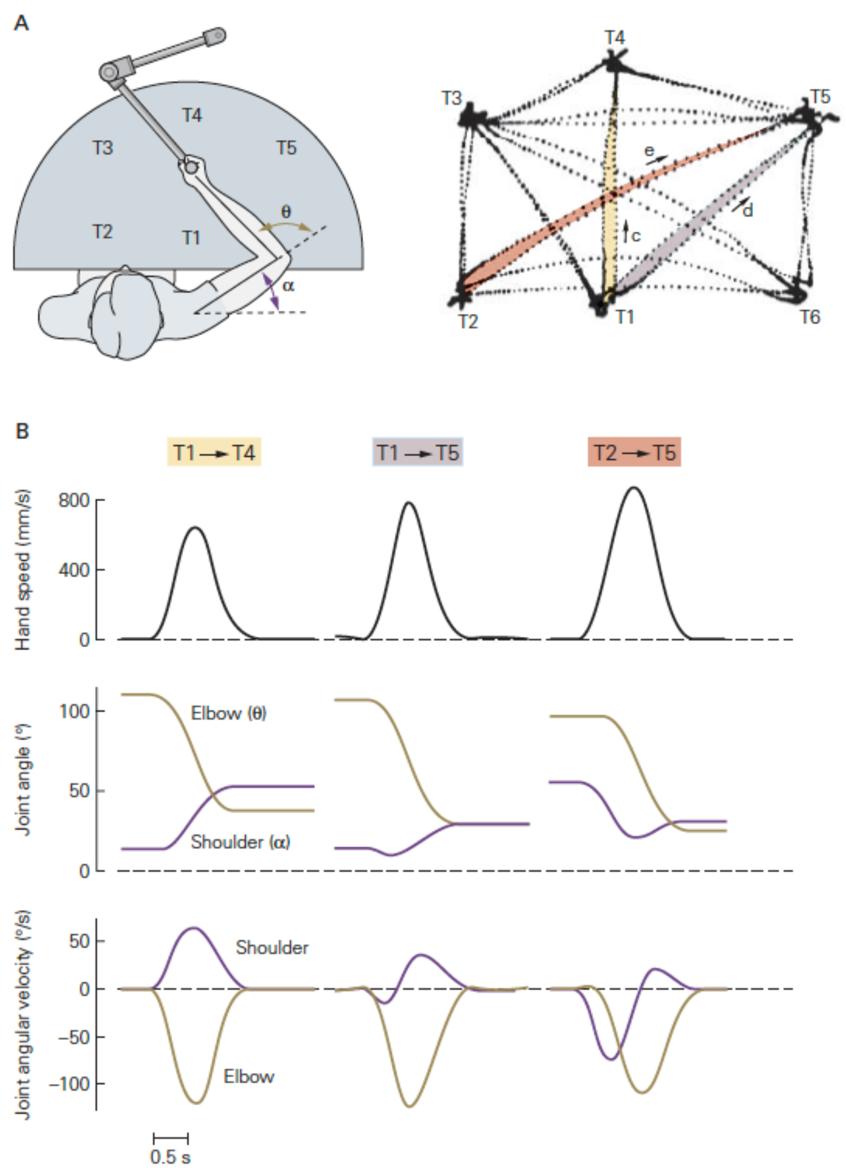
➜ motor skills

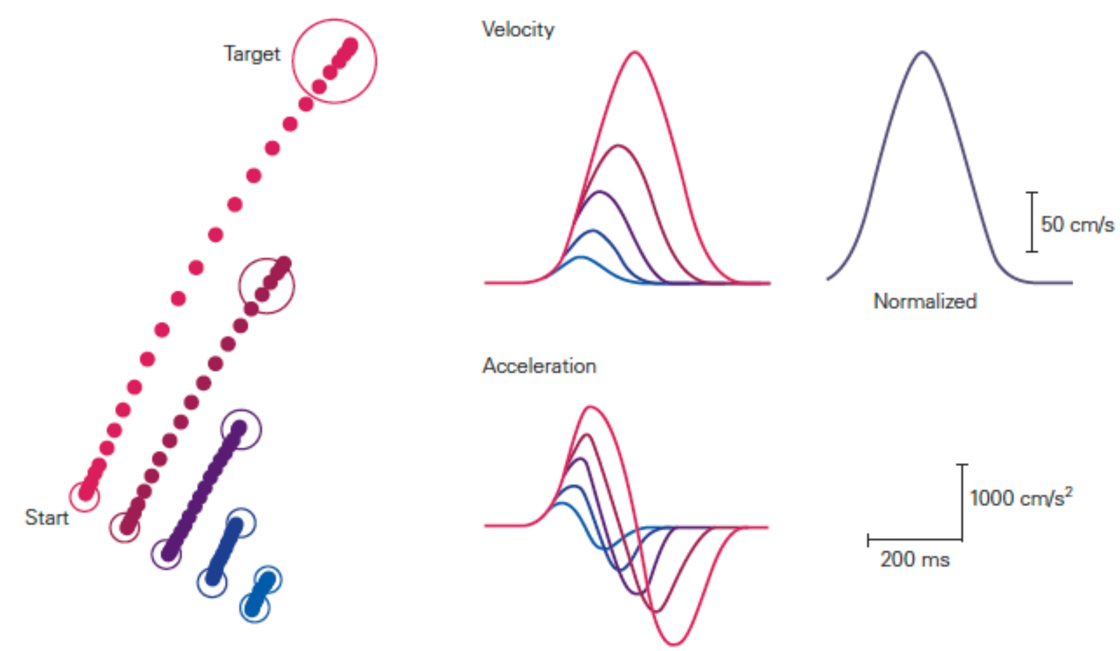


MOTOR INVARIANTS

Trajectories

point-to-point movements: straight, bell-shaped velocity profiles

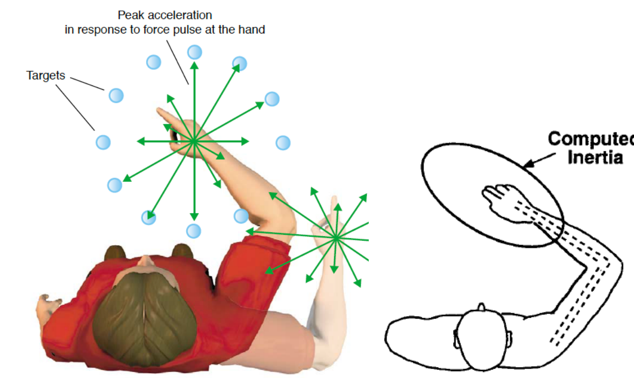




— Morasso, 1981, *Exp Brain Res* 42:223

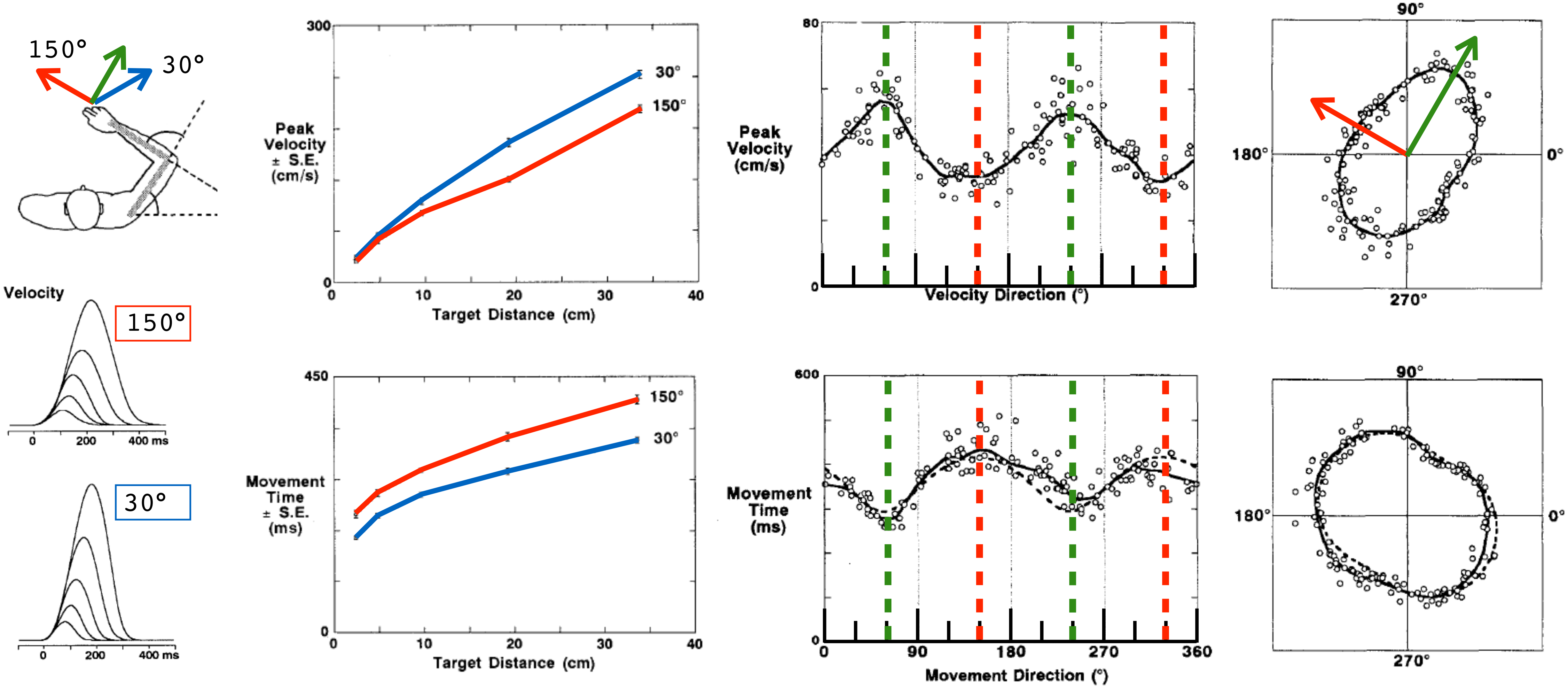
— Gordon et al., 1994, *Exp Brain Res* 99:112

MOTOR INVARIANTS



Scaling laws

duration and velocity scale with amplitude and load



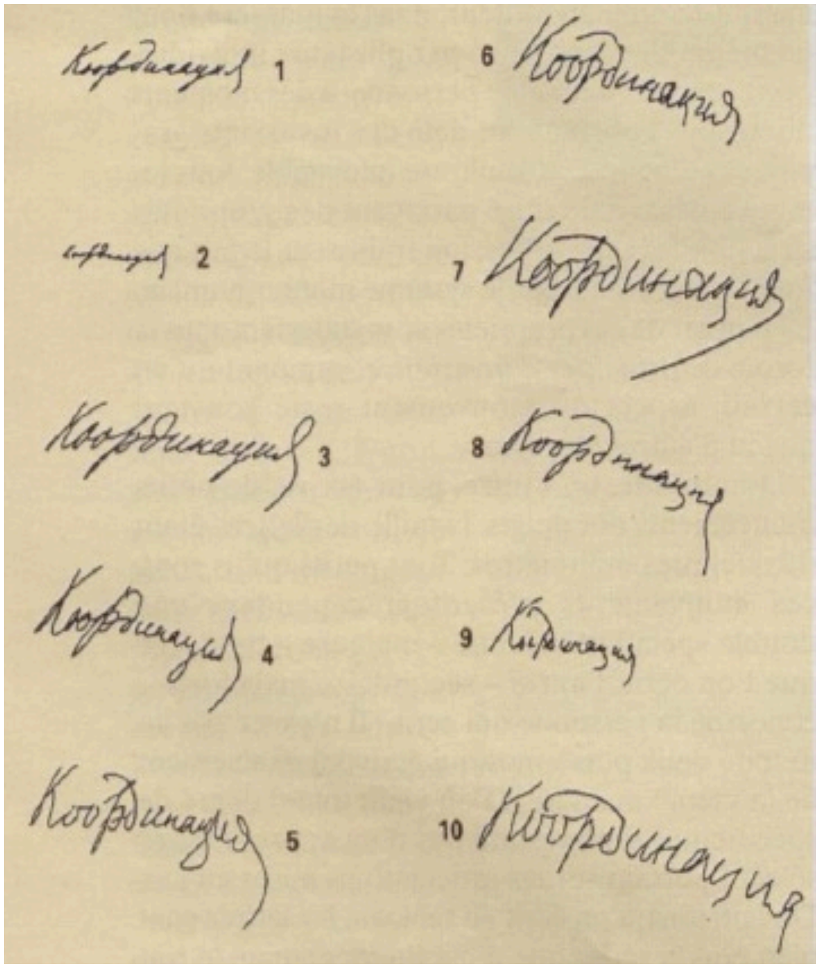
— Gordon et al., 1994, *Exp Brain Res* 99:112

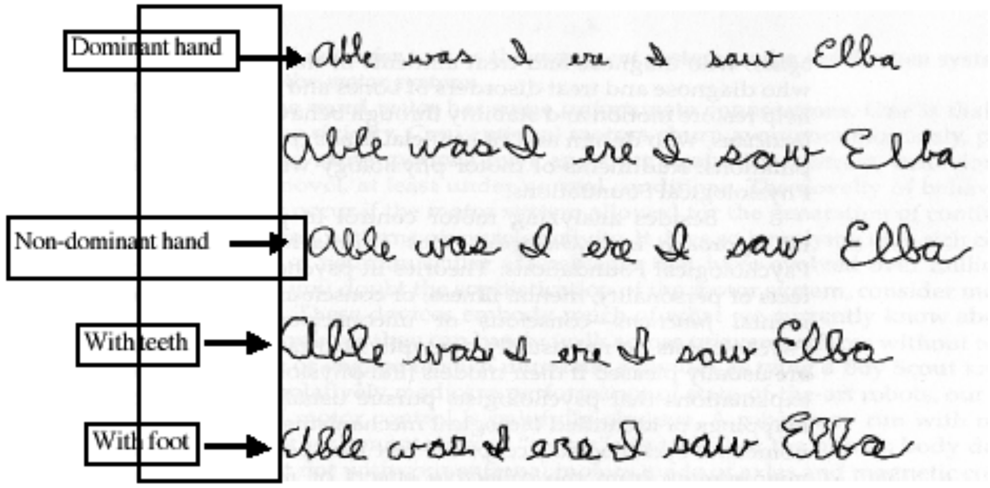
MOTOR INVARIANTS

Motor equivalence

Actions are encoded in the central nervous system in terms that are more abstract than commands to specific muscles

Bernstein writes the word «Coordination» in russian



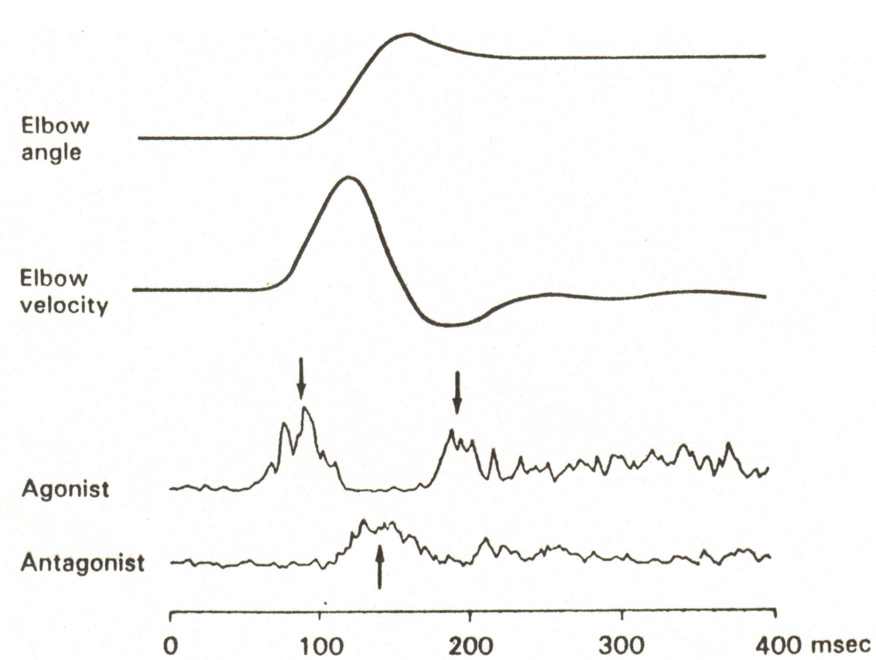


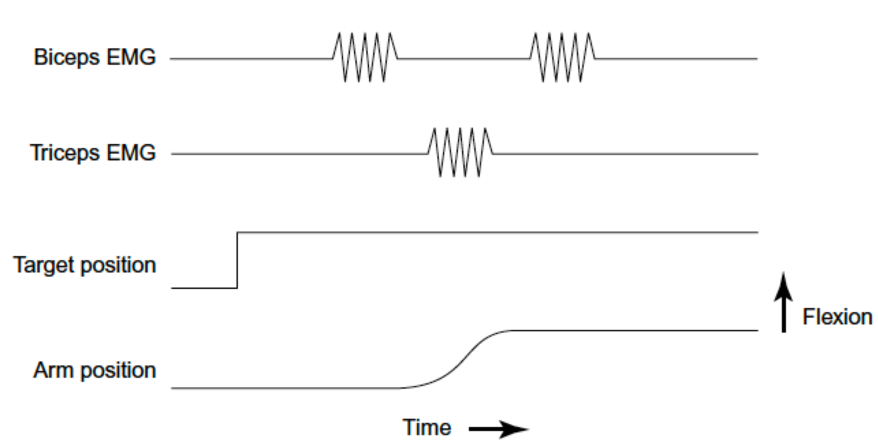
(1) right hand, normal size
(2) right hand, small size
(3) pen attached above the wrist
(4) pen attached to the elbow
(5) pen attached to the elbow
(6) pen attached to the shoulder
(7) pen attached to right foot’s big toe
(8) pen between the teeth
(9) left hand
(10) pen attached to left foot’s big toe

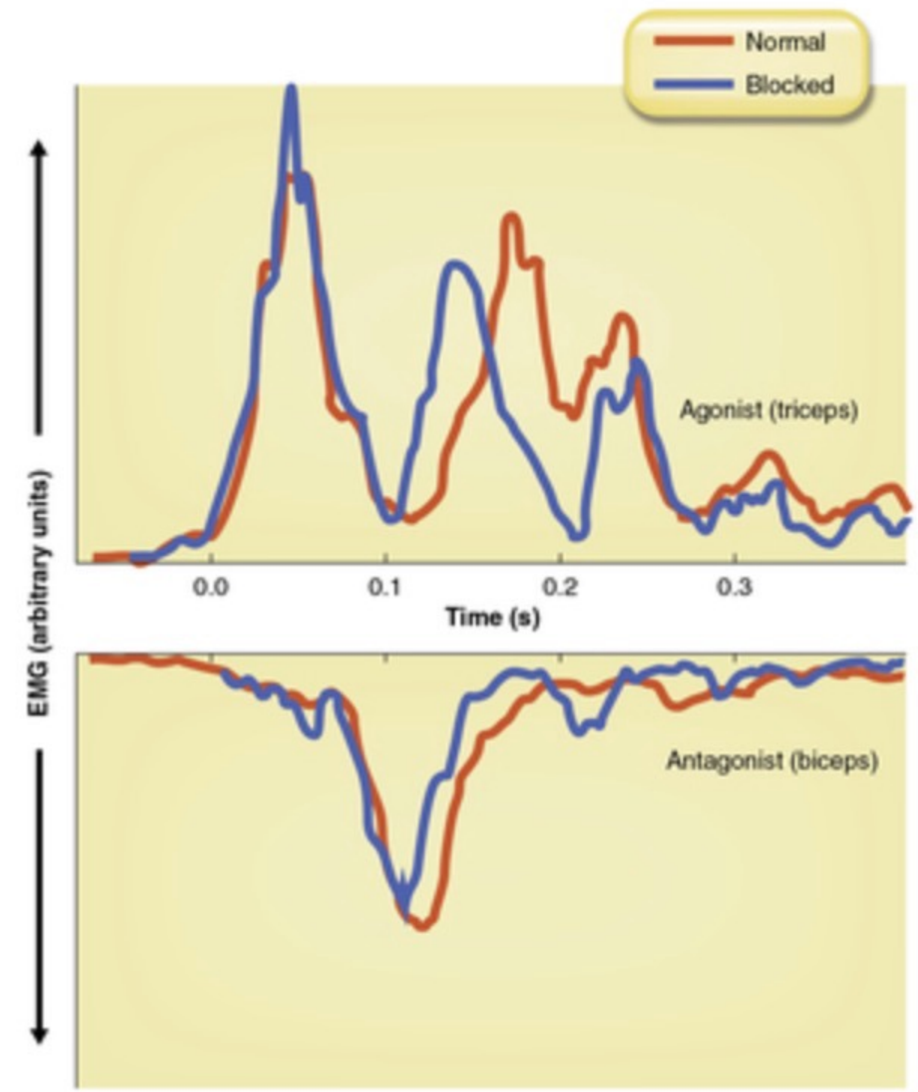
MOTOR INVARIANTS

EMG

triphasic pattern during fast movements



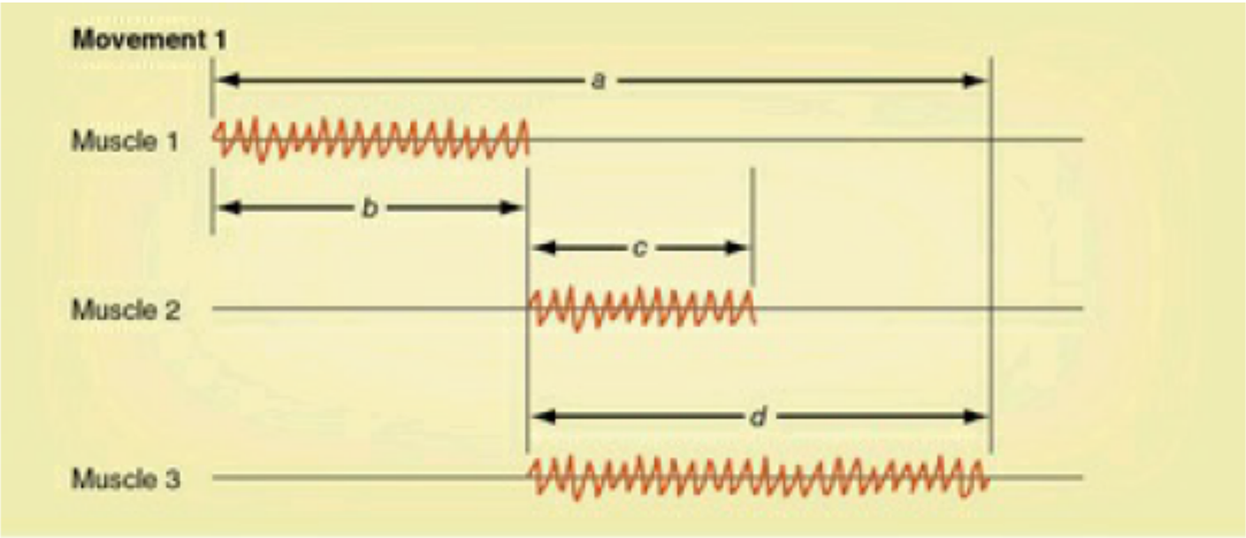


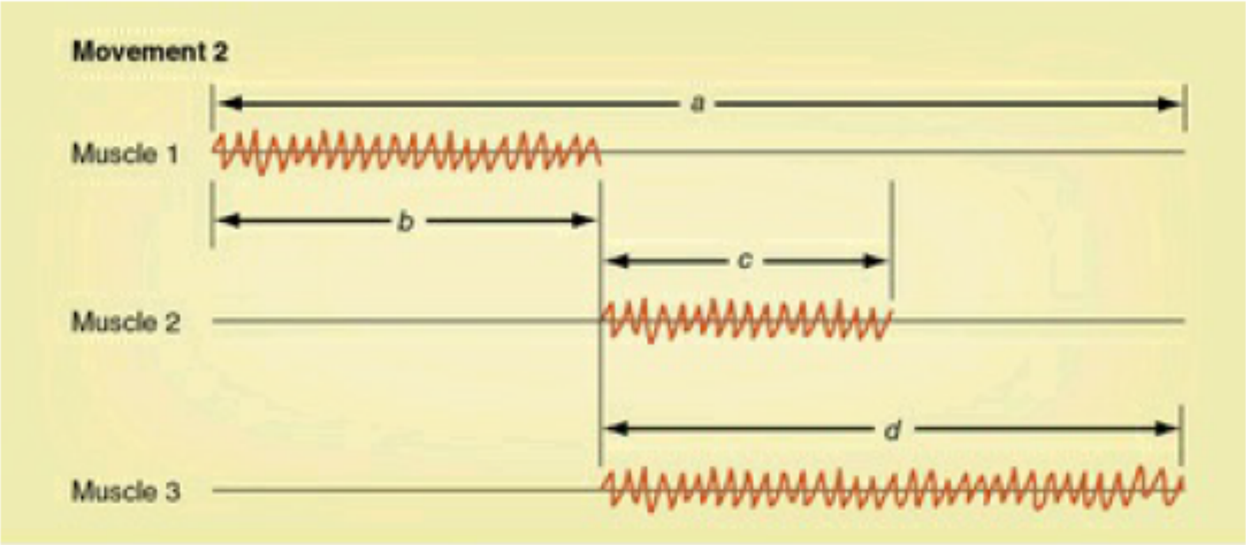


—Wadman et al., 1979, *J Hum Mov Stud* 5:3

RELATIVE TIMING

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





hypothetical relative timing of EMG traces

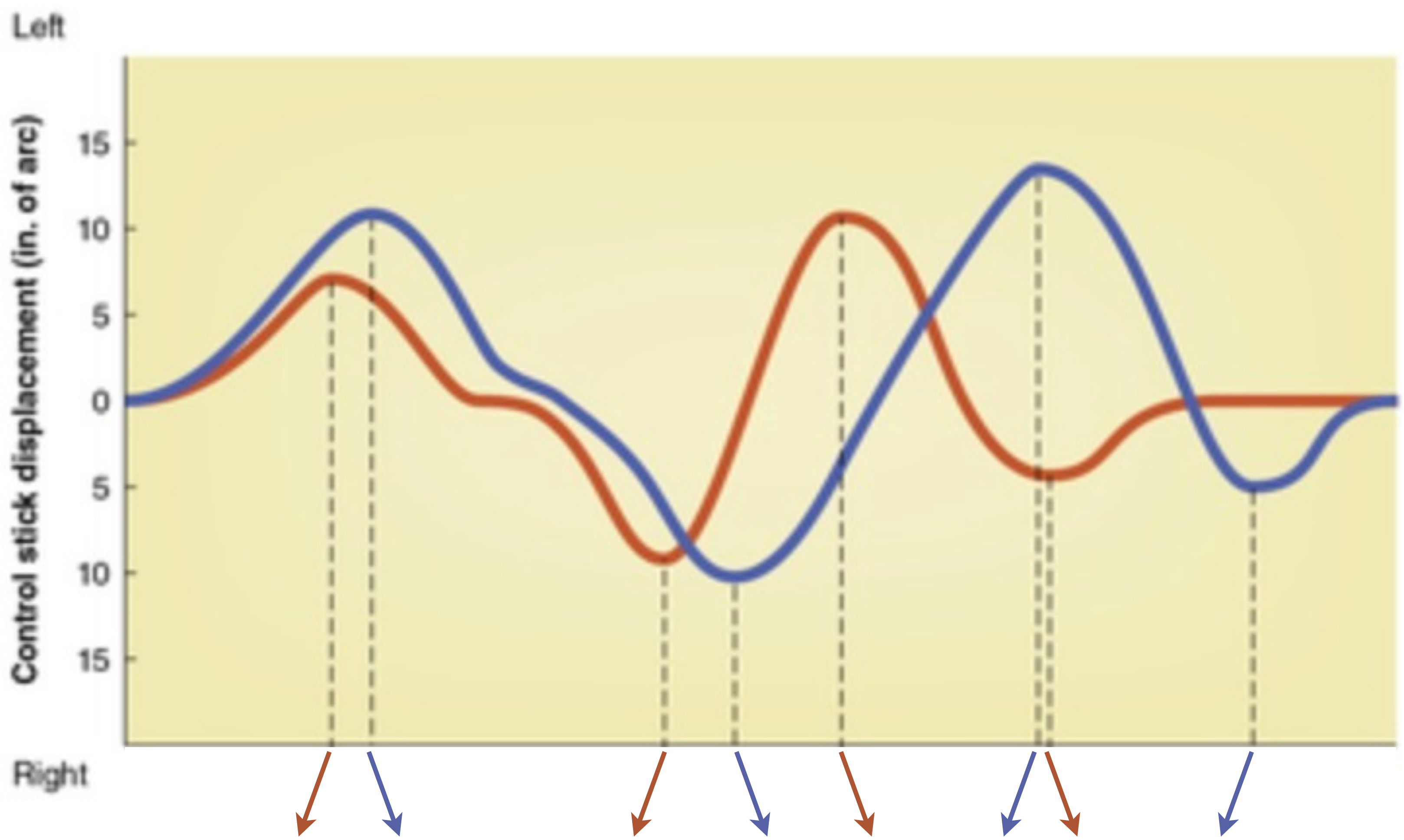
b/a = 0.4
c/a = 0.3
d/a = 0.6

— Schmidt & Lee, 2014, *Motor Learning and Performance*, Human Kinetics

RELATIVE TIMING

Reproduction of a pattern of movement

movements are sped up or slowed proportionally



pattern to reproduce

too fast reproduction

$\times \frac{3.59}{2.94}$

0.66 **0.75** 1.72 **1.95** 2.28 **2.90** 2.94 3.59

0.81 **2.10** **2.78**

— Schmidt & Lee, 2014, *Motor Learning and Performance,* Human Kinetics

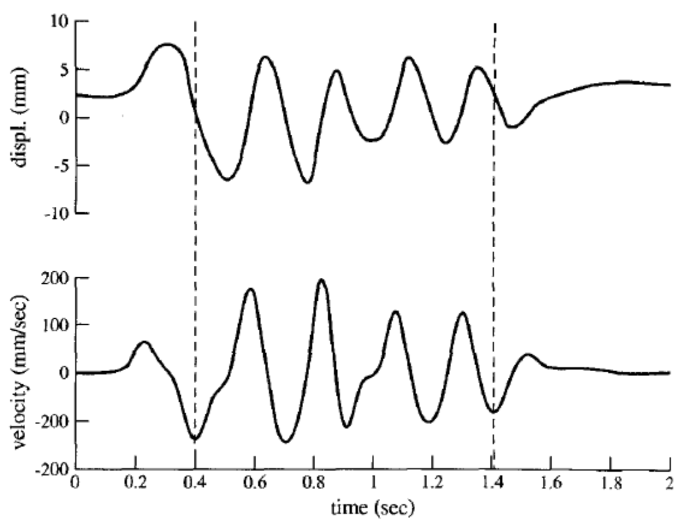
RELATIVE TIMING IN SPEECH

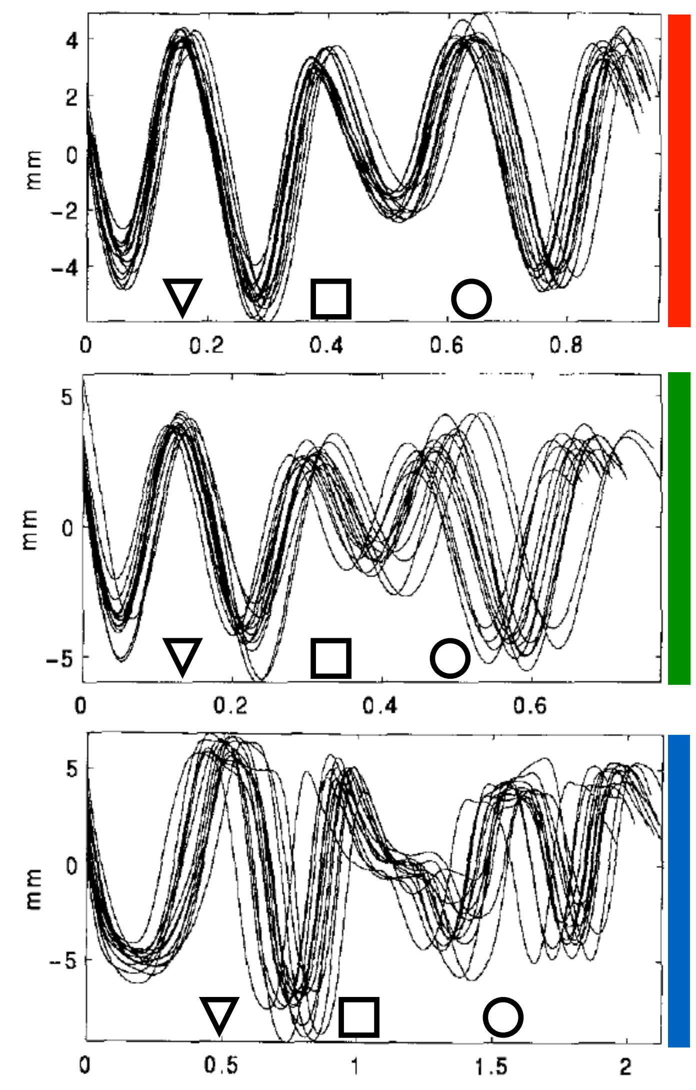
Speech

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

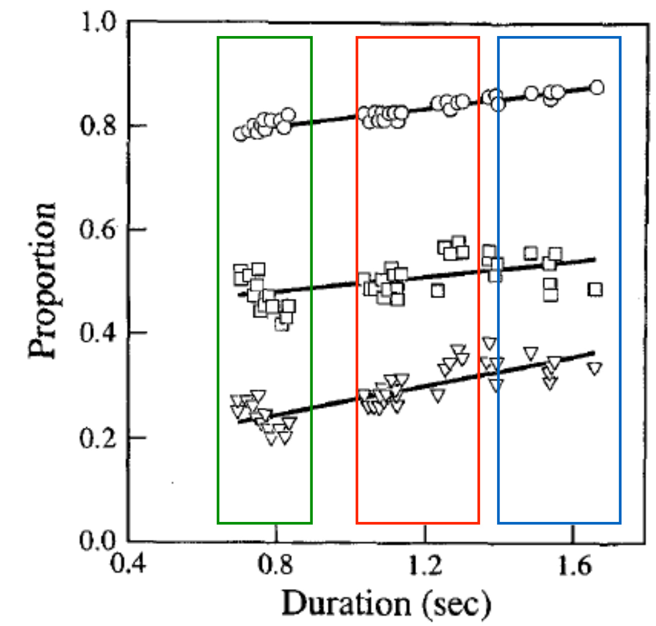
test of the *proportional duration* model

normal
fast
slow

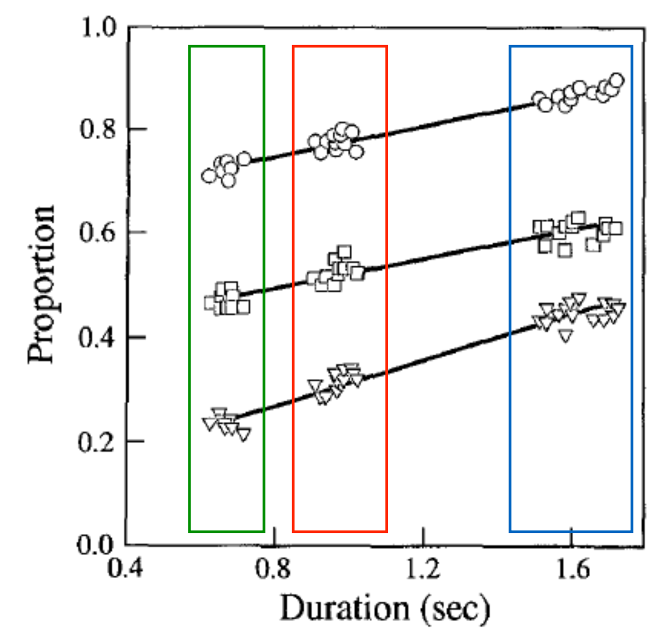




Subject 5



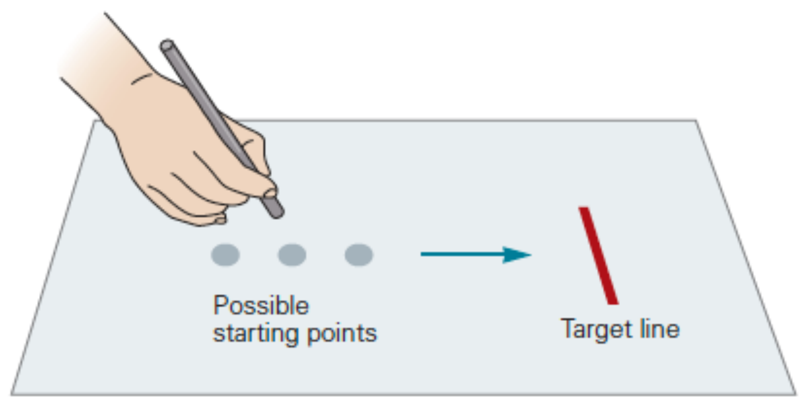
Subject 7

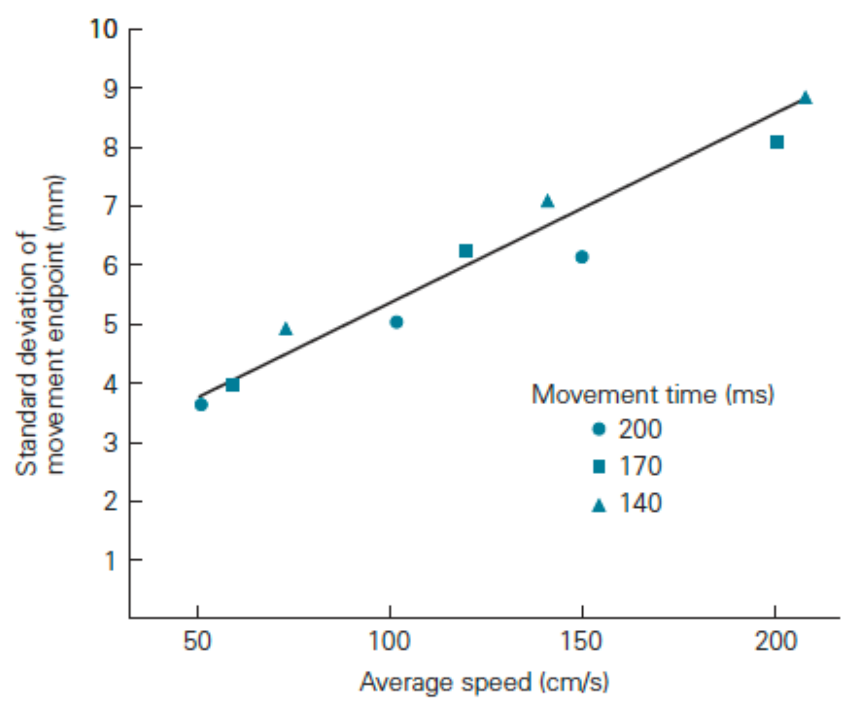


— Smith et al., 1995, *Exp Brain Res* 104:493

MOTOR VARIABILITY

Spatial accuracy varies with speed





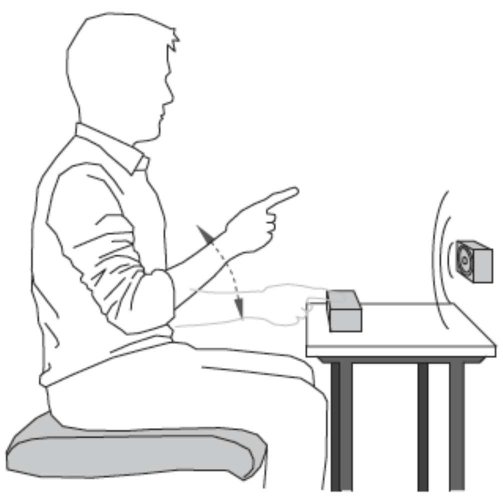
— Kandel et al., 2013,
Principles of Neural Science,
McGraw-Hill

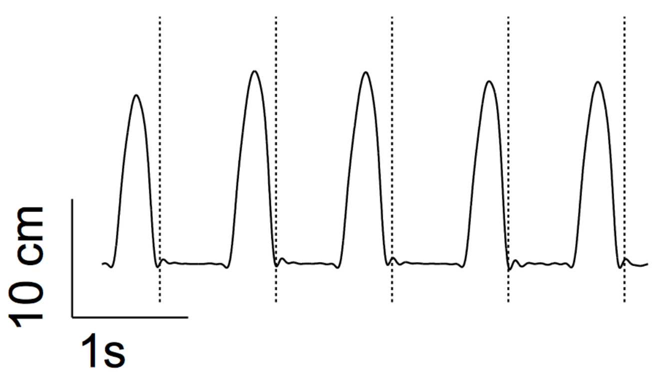
— Schmidt et al., 1979,
Psychol Rev 86:415

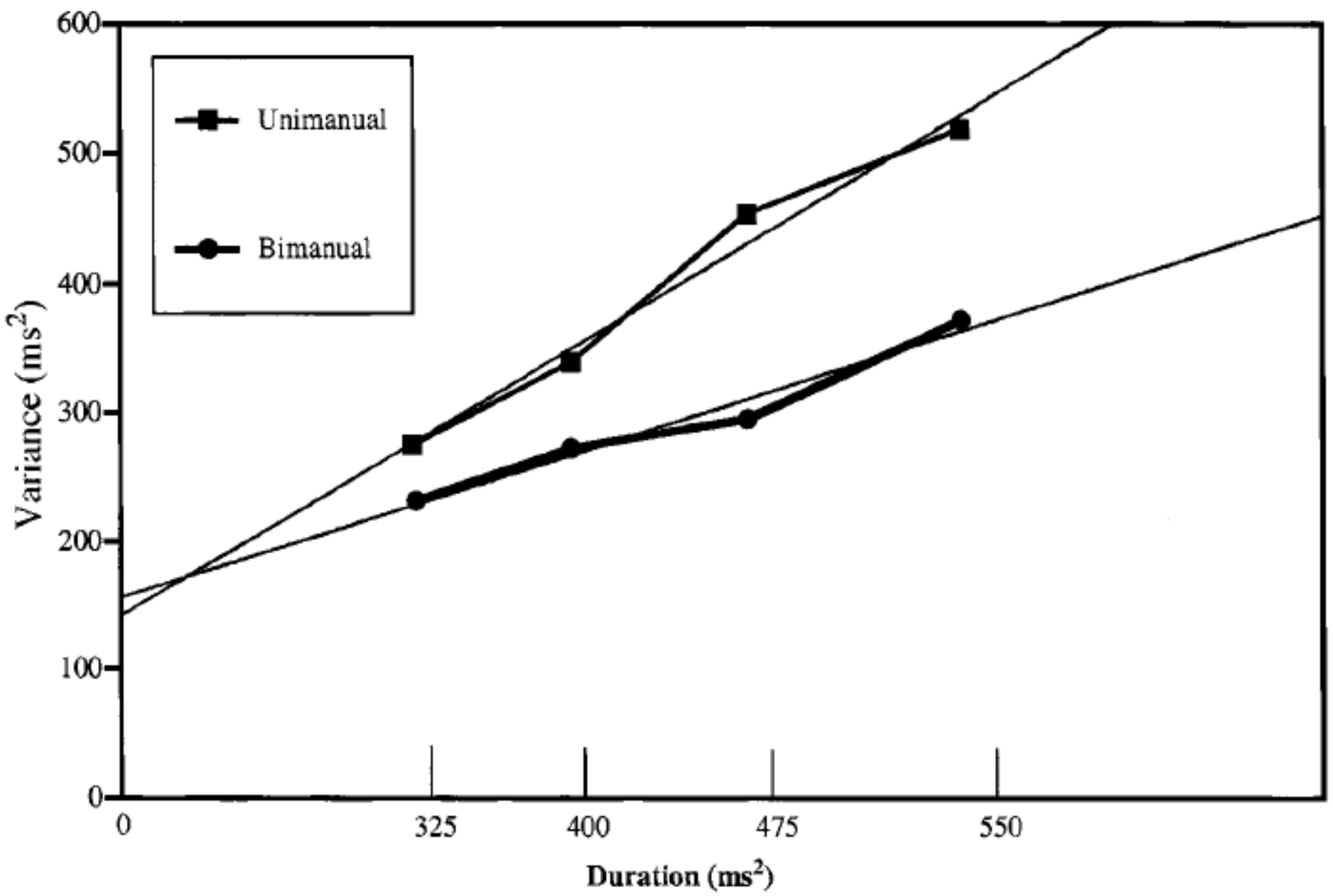
MOTOR VARIABILITY

Temporal accuracy varies with duration

tapping task

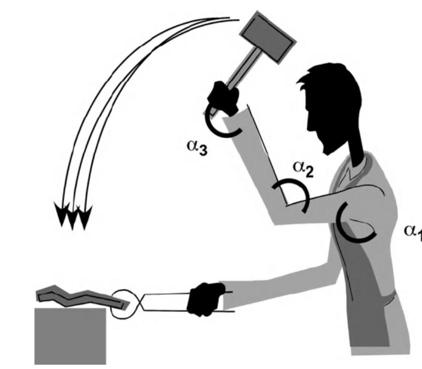






— Ivry & Richardson, 2002, *Brain Cogn* 48:117

MOTOR VARIABILITY



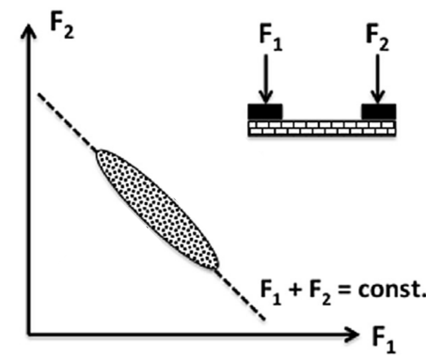
Structured variability

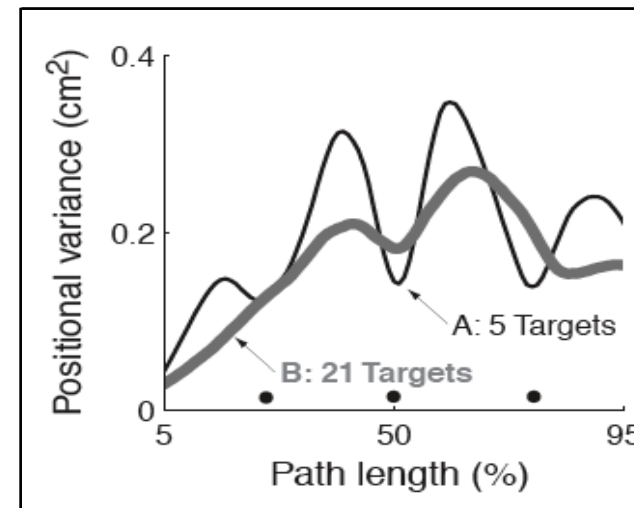
«Repetition without repetition» (Bernstein)

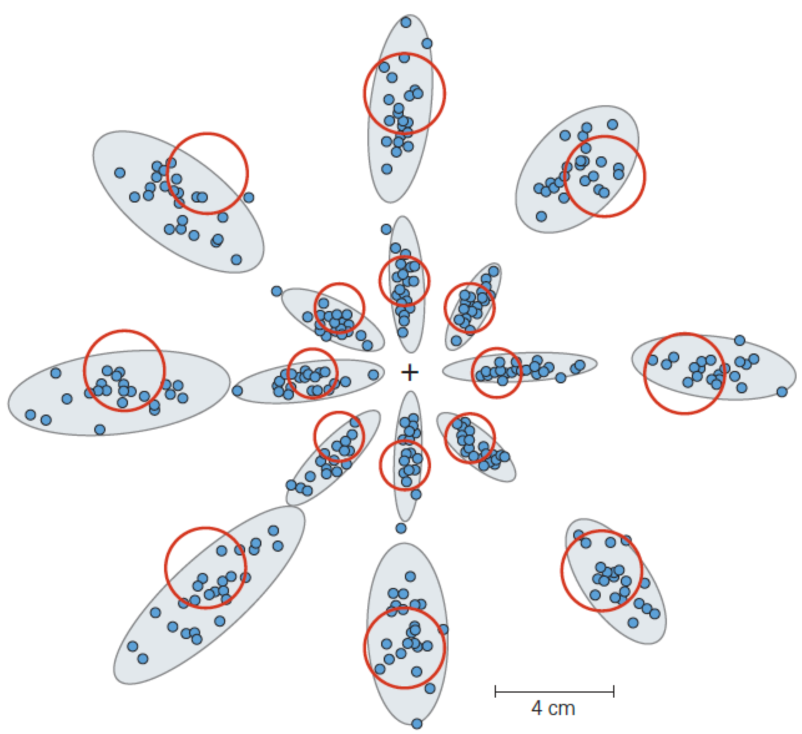
«Uniqueness and stability/consistency» (Glencross)

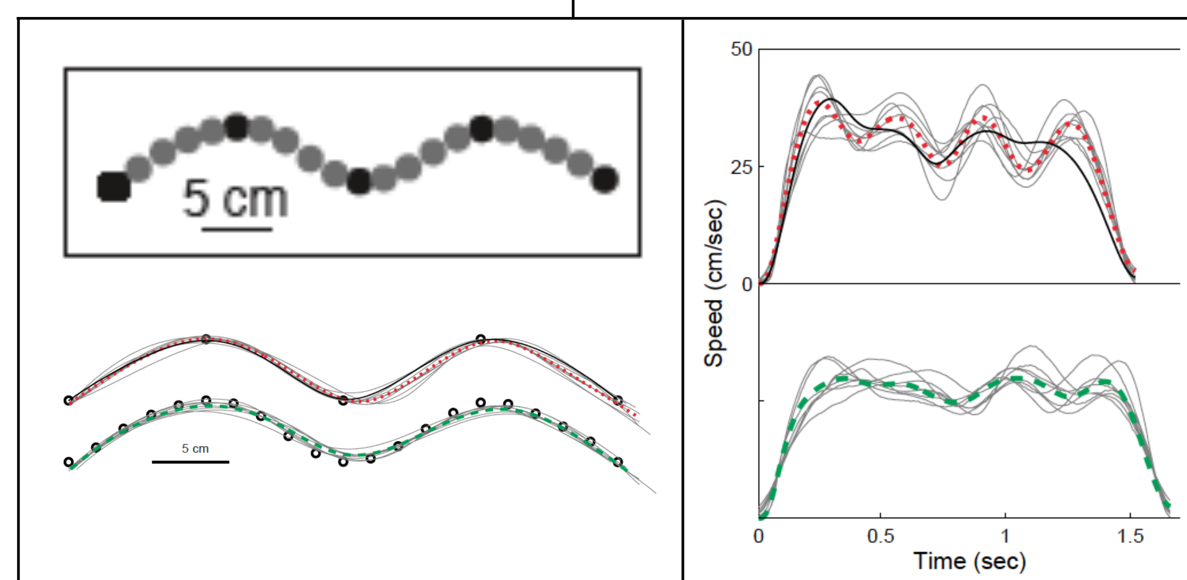
uncontrolled manifold

minimum intervention principle









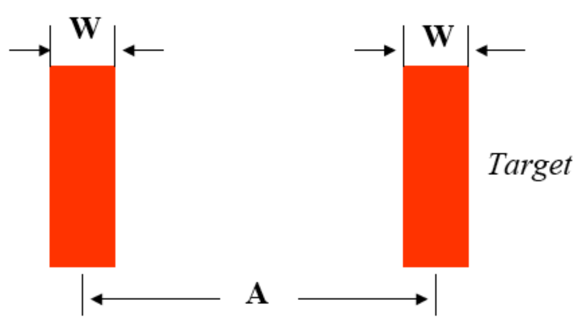
— Gordon et al., 1994, *Exp Brain Res* 99:97

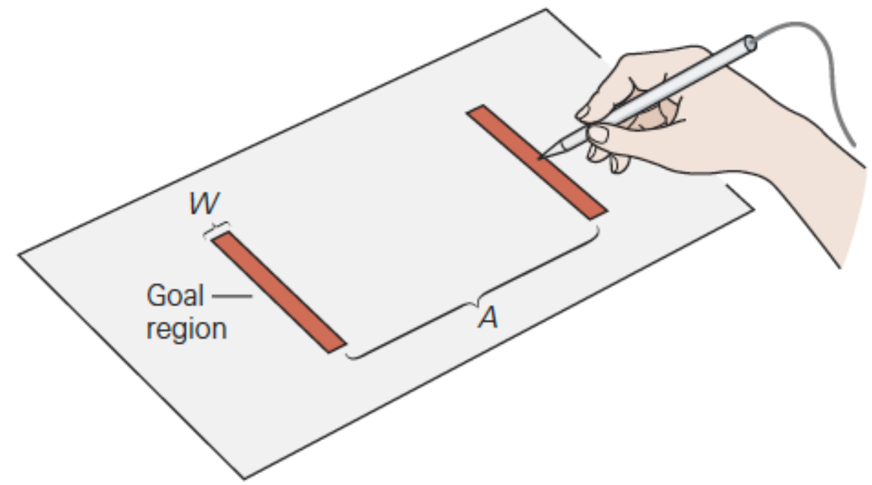
— Todorov & Jordan, 2002, *Nat Neurosci* 5:1226

LAWS OF MOVEMENT

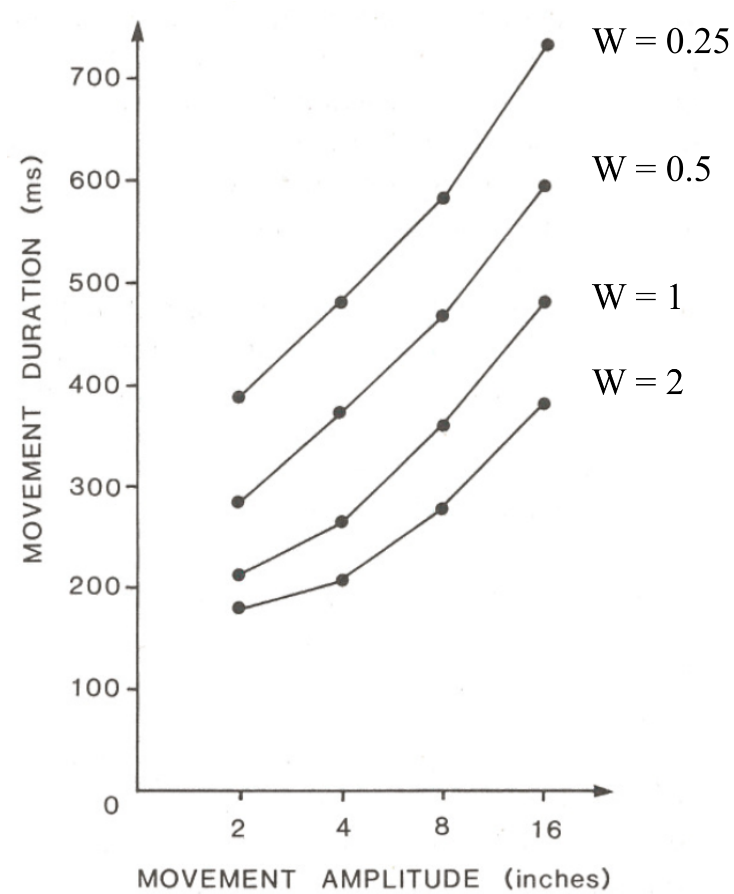
Fitts' law

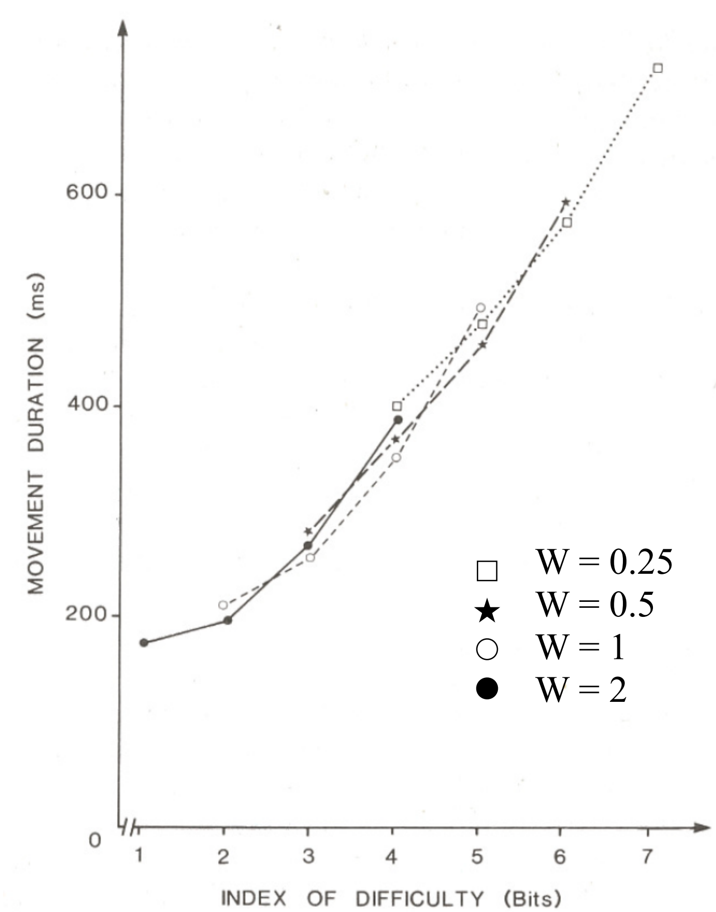
speed/accuracy trade-off





$$\text{MT} = \text{a} + \text{b}\ \underbrace{[\text{Log}_2\ (2\text{A}/\text{W})]}_{\text{ID (index of Difficulty)}}$$





— Fitts, 1954, *J Exp Psychol* 47:381

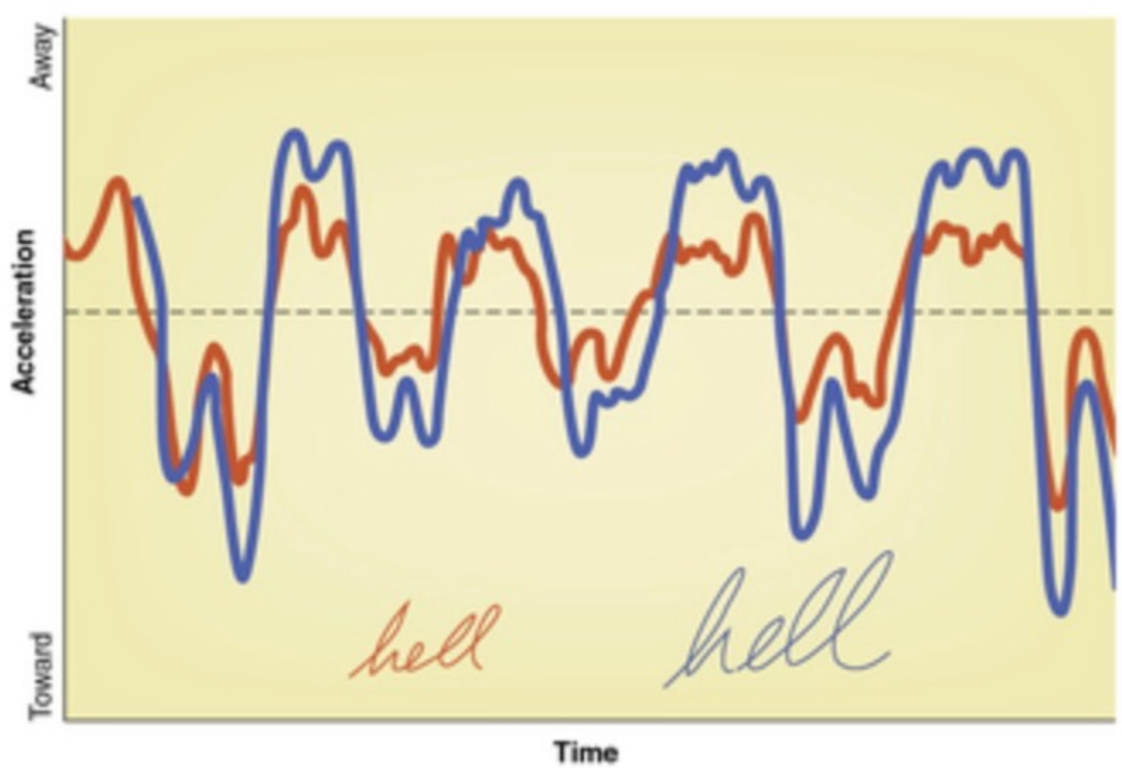
— Jeannerod, 1988, *The Neural and Behavioural Organization of Goal-Directed Movements*, Clarendon Press

ISOCHRONY PRINCIPLE

Maintain constant duration

compensatory increase of speed with increasing amplitude

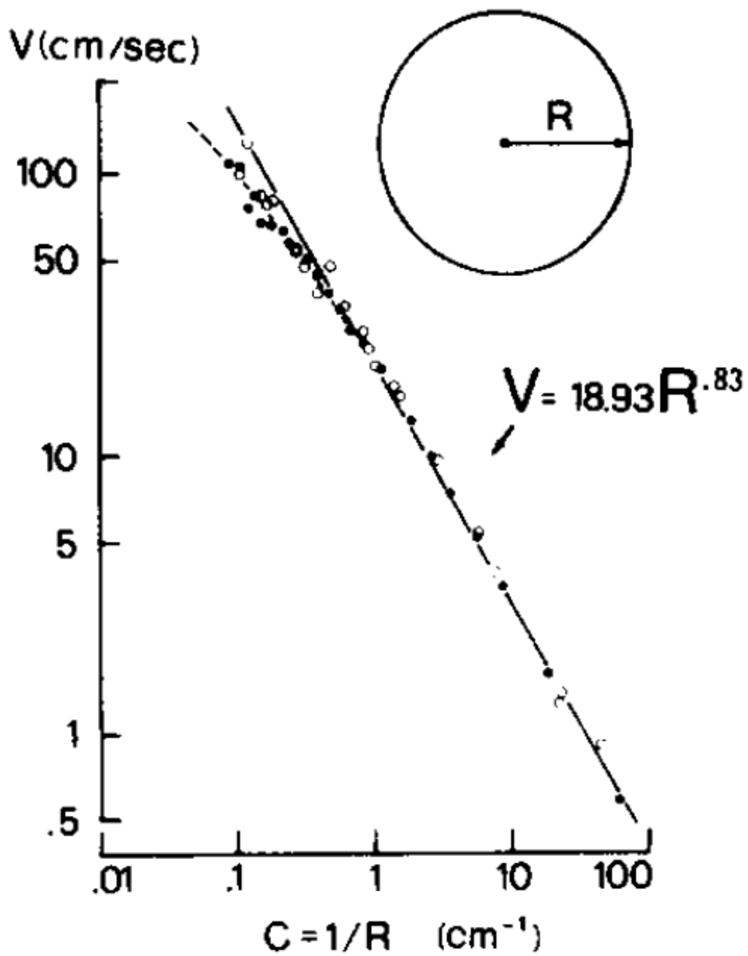
handwriting



— Hollerbach, 1978, *Doctoral Dissertation*, MIT

—Viviani & McCollum, 1983, *Neuroscience* 10:211

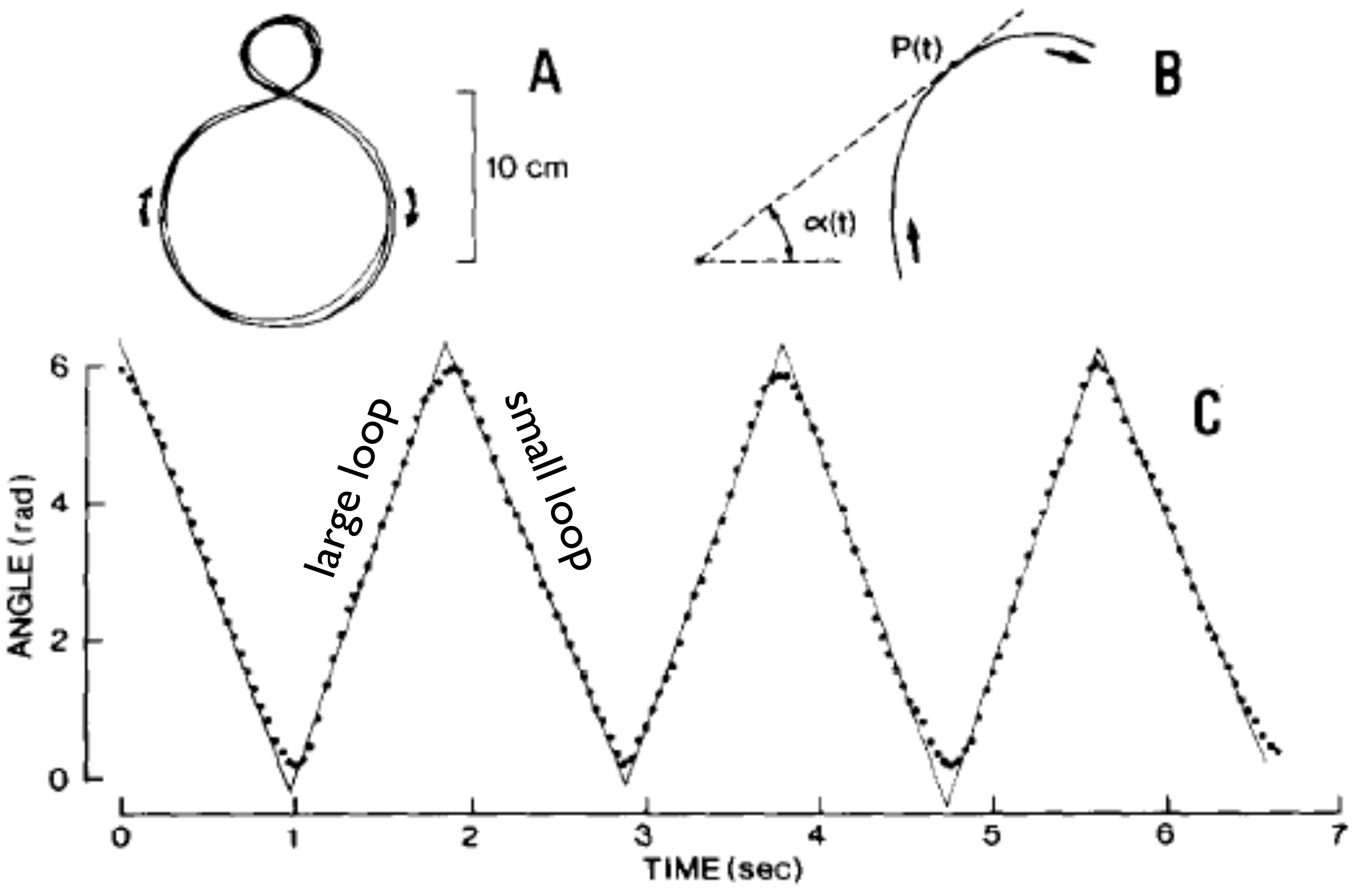
circle drawing



ISOGONY PRINCIPLE

Equal angles are described in equal time

in a drawing task



— Lacquaniti et al., 1983, *Acta Psychol* 54:115

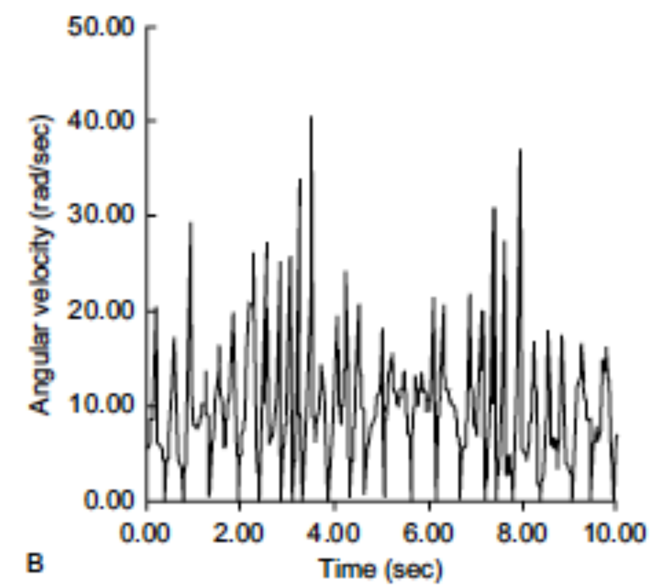
TWO-THIRD POWER LAW

Relationship between angular velocity and curvature

in a scribbling task

$$v(t) = kr(t)^{1/3}$$

$$a(t) = kc(t)^{2/3}$$



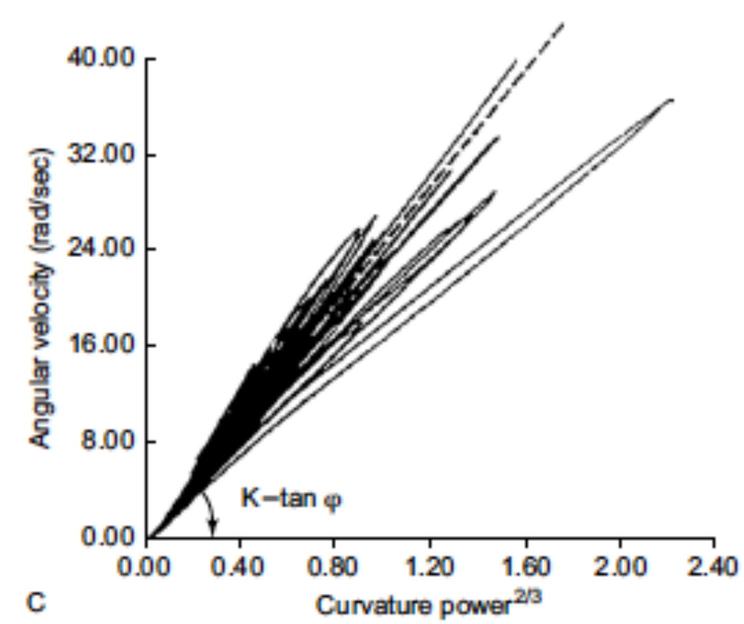
$\mathbf{x}(t) = [x(t), y(t)]^T$ trajectory

$a(t)$ angular velocity

$v(t) = ||\dot{\mathbf{x}}(t)||$ tangential velocity

$c(t)$ curvature

$r(t) = 1/c(t)$ radius of curvature



— Lacquaniti et al., 1983, *Acta Psychol* 54:115

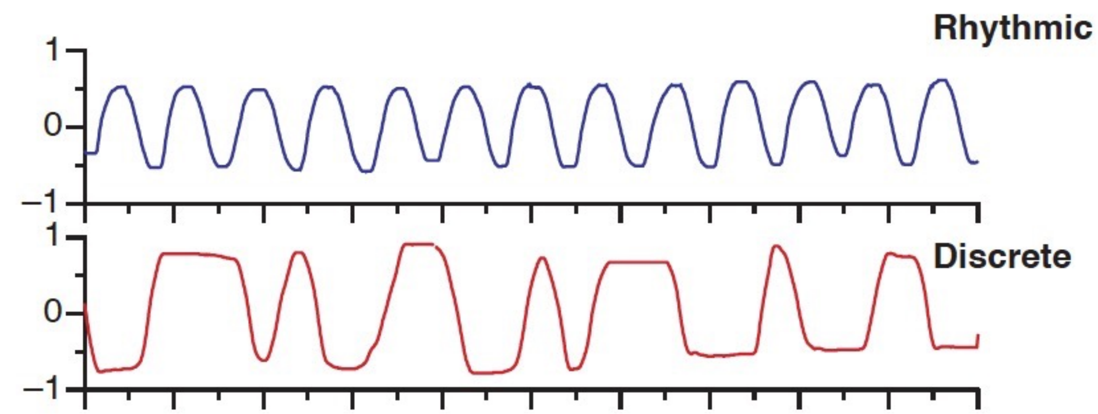
RHYTHMIC AND DISCRETE ACTIONS

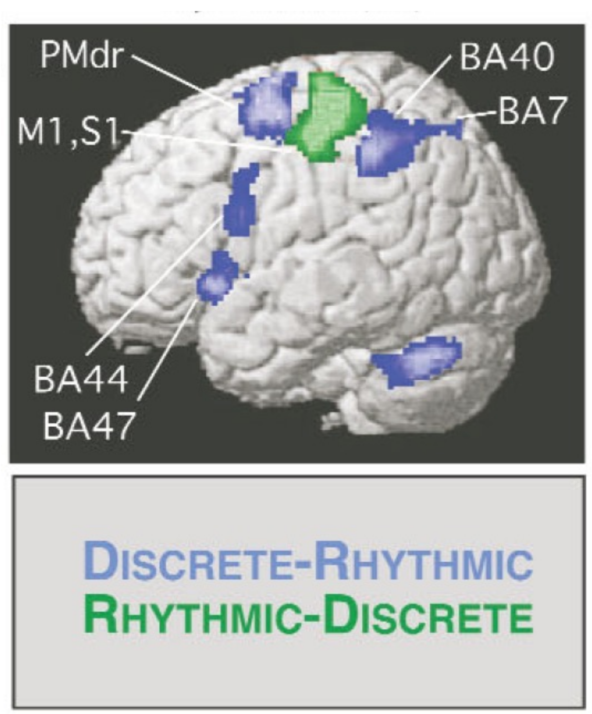
- **Rhythmic**

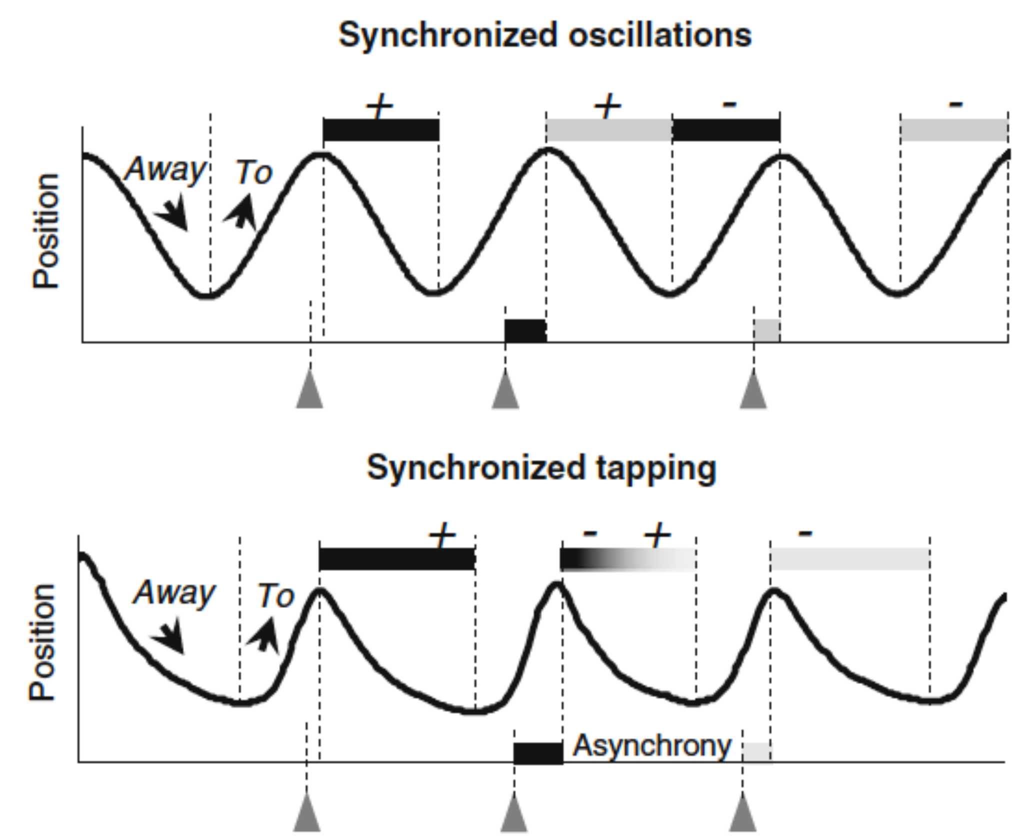
e.g. walking, chewing, scratching

- **Discrete**

e.g. reaching, grasping, kicking



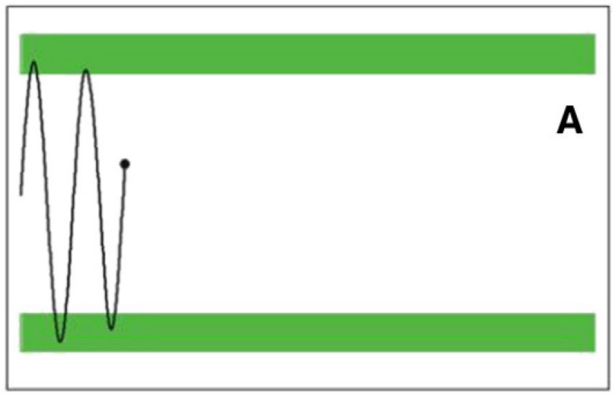




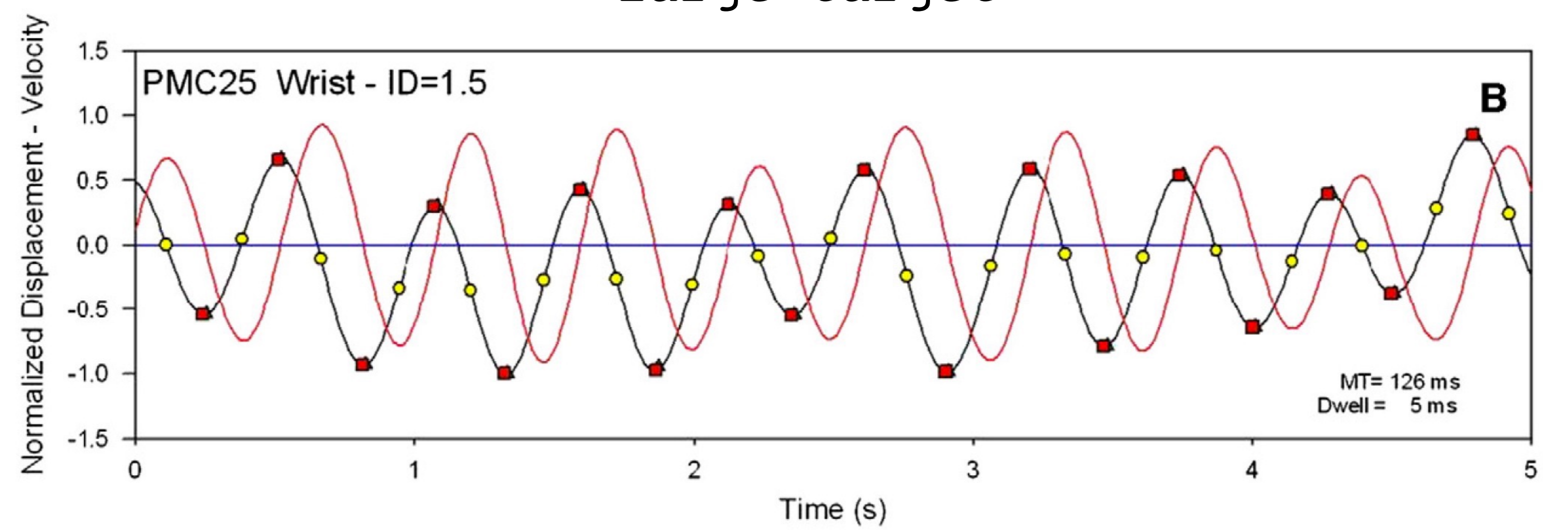
— Schaal et al., 2004, *Nat Neurosci* 7:1136

— Torre & Balasubramaniam, 2009, *Exp Brain Res* 199:157

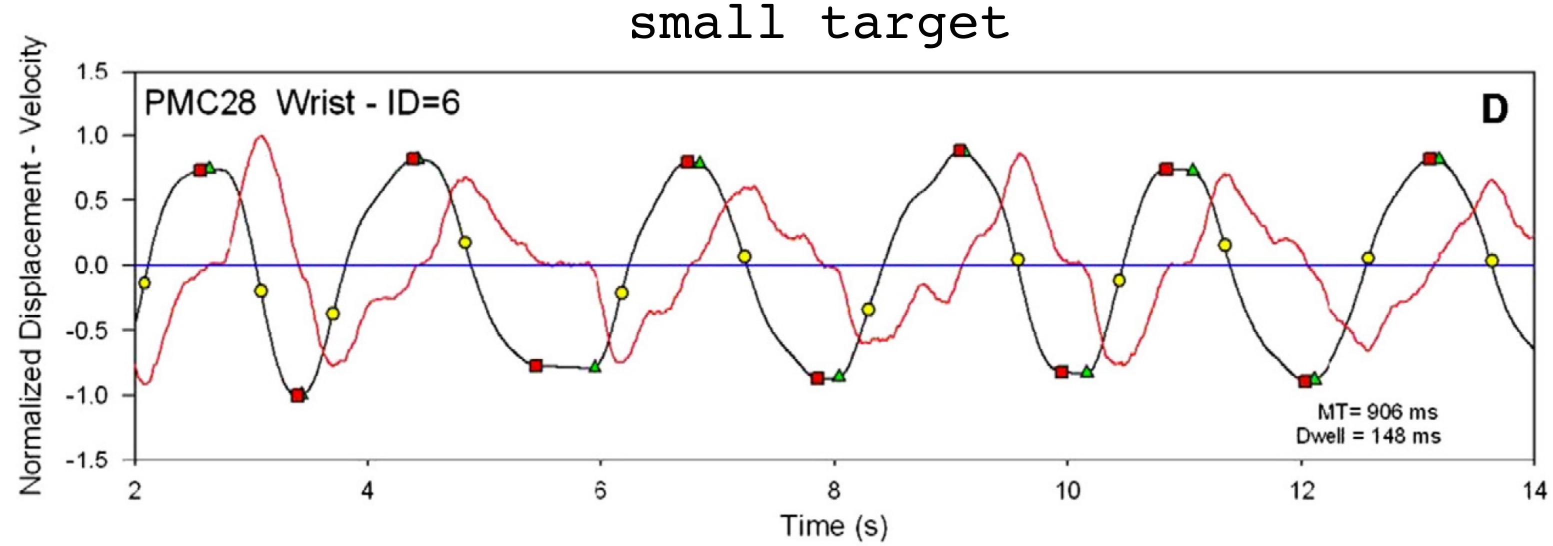
SLOW MOVEMENTS



large target



small target



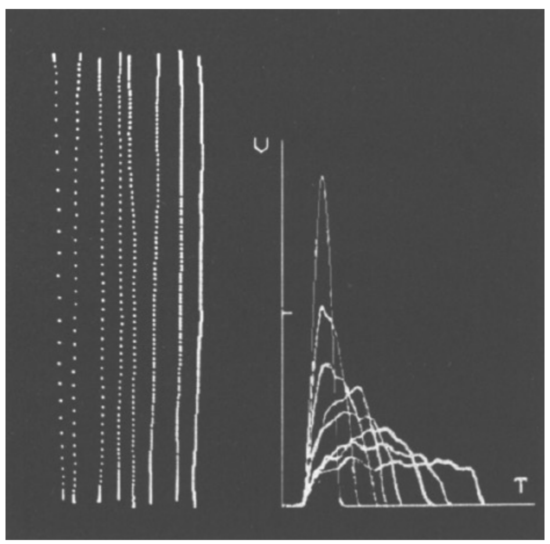
position
velocity

— Boyle & Shea, 2011, *Acta Psychol* 137:382

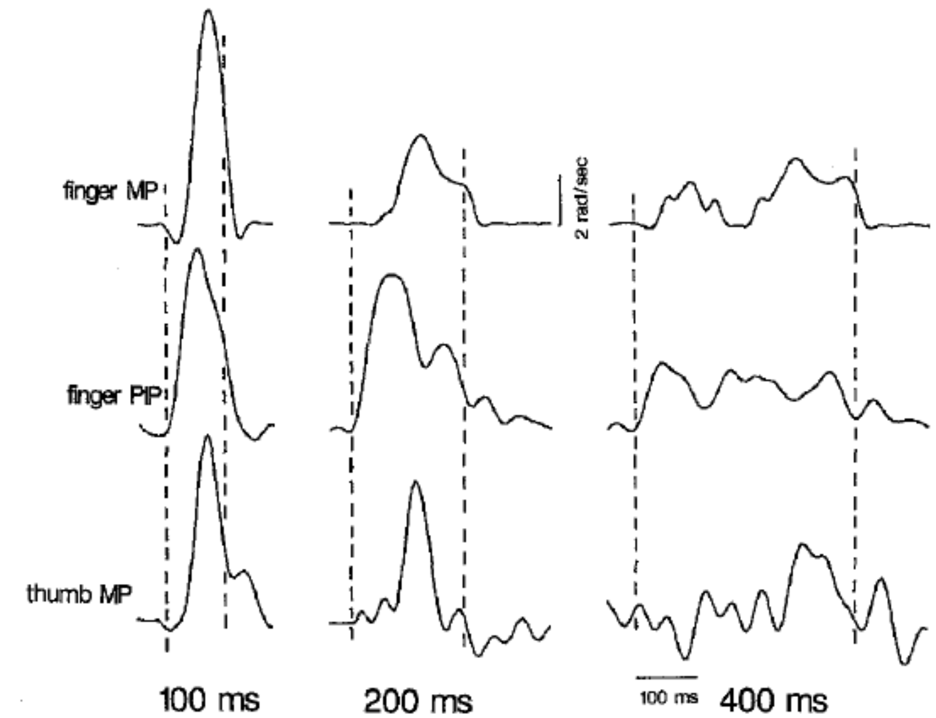
SLOW MOVEMENTS

Are not smooth

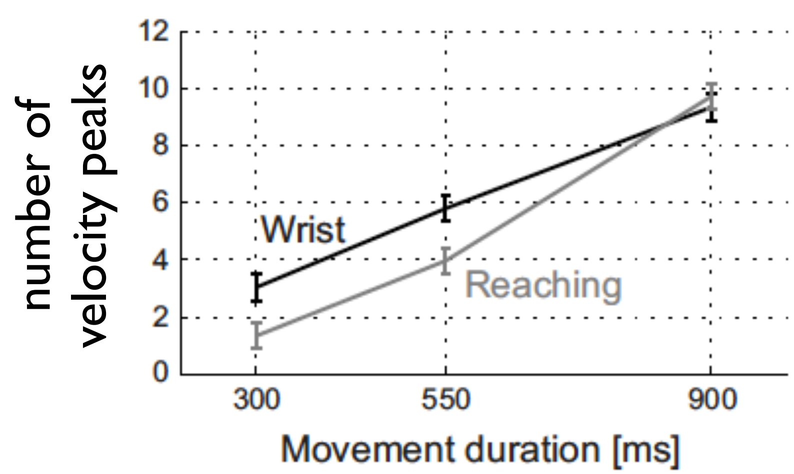
segmentation



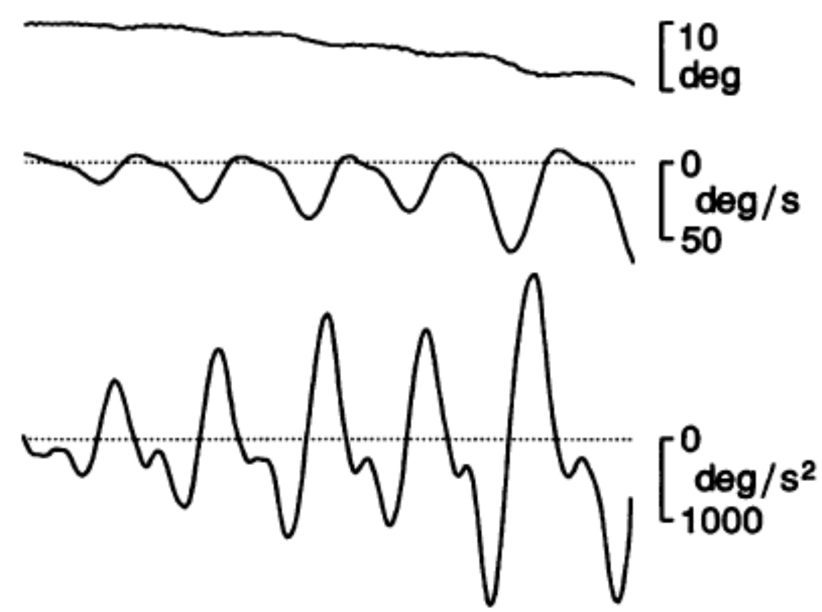
— Morasso et al., 1983, *Acta Psychol* 54:83



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



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



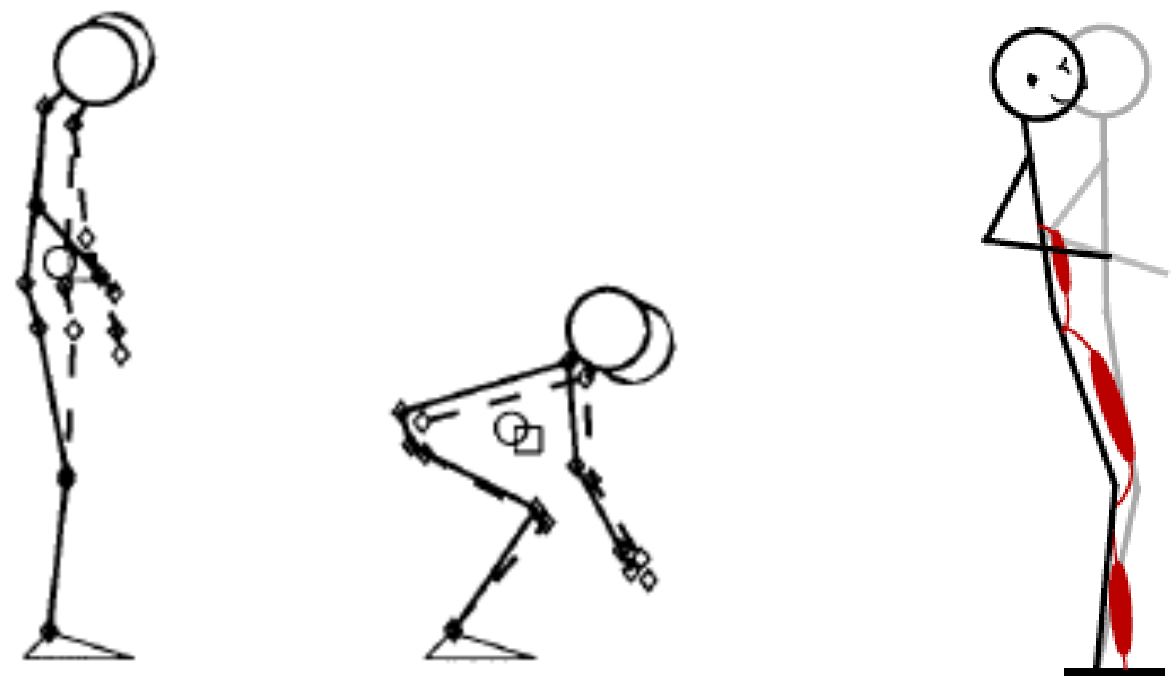
—Vallbo & Wessberg, 1993, *J Physiol (Lond)* 469:673

POSTURE AND MOVEMENT

Definition

movement — large and rapid displacement of focal body segments to subserve a goal-directed action

posture — small and slow displacements of the whole body to achieve postural orientation and equilibrium maintenance

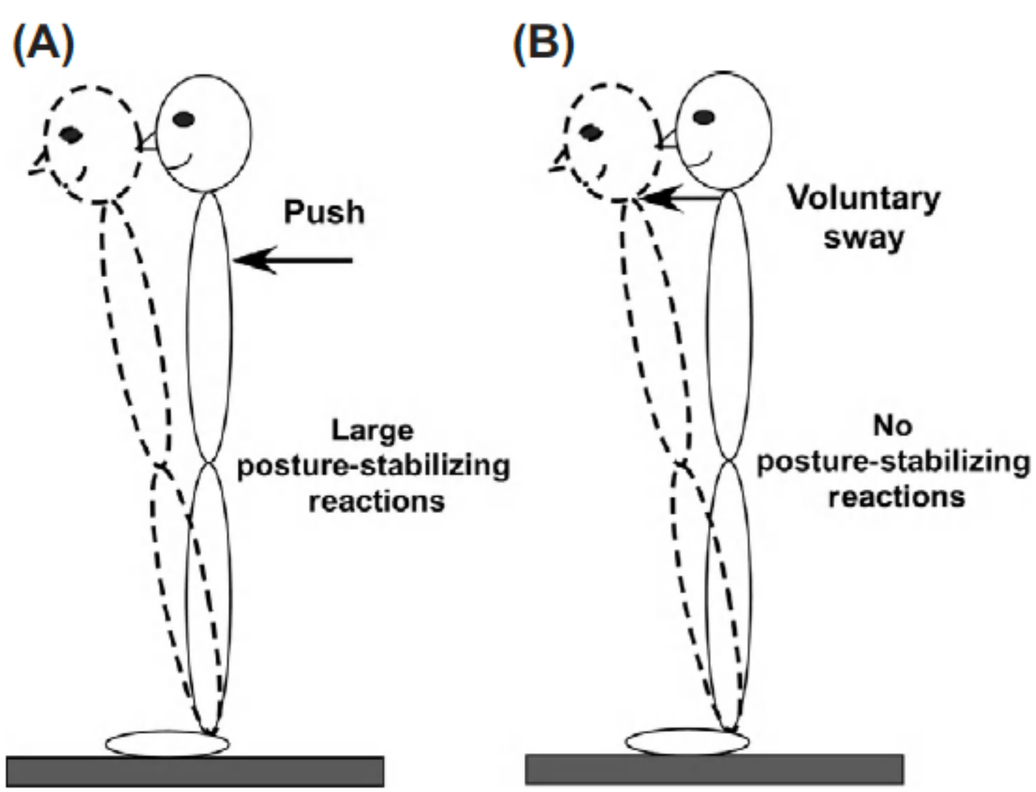


motor behavior is a continuous superimposition of movement and posture periods

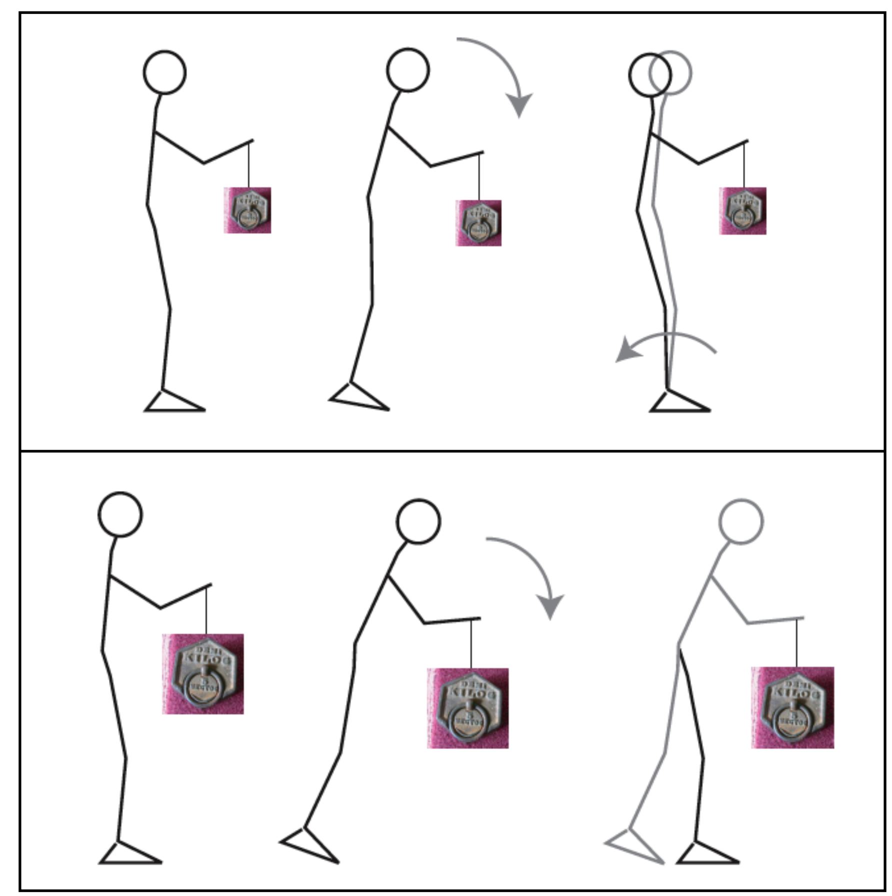
POSTURE AND MOVEMENT

Paradox

how is it that we can move from one posture to another without triggering resistance from all these posture-stabilizing mechanisms? (von Holst)



— Latash, 2012, *Fundamentals of Motor Control,* Academic Press



```
single kinematic chain
single motor program?
```

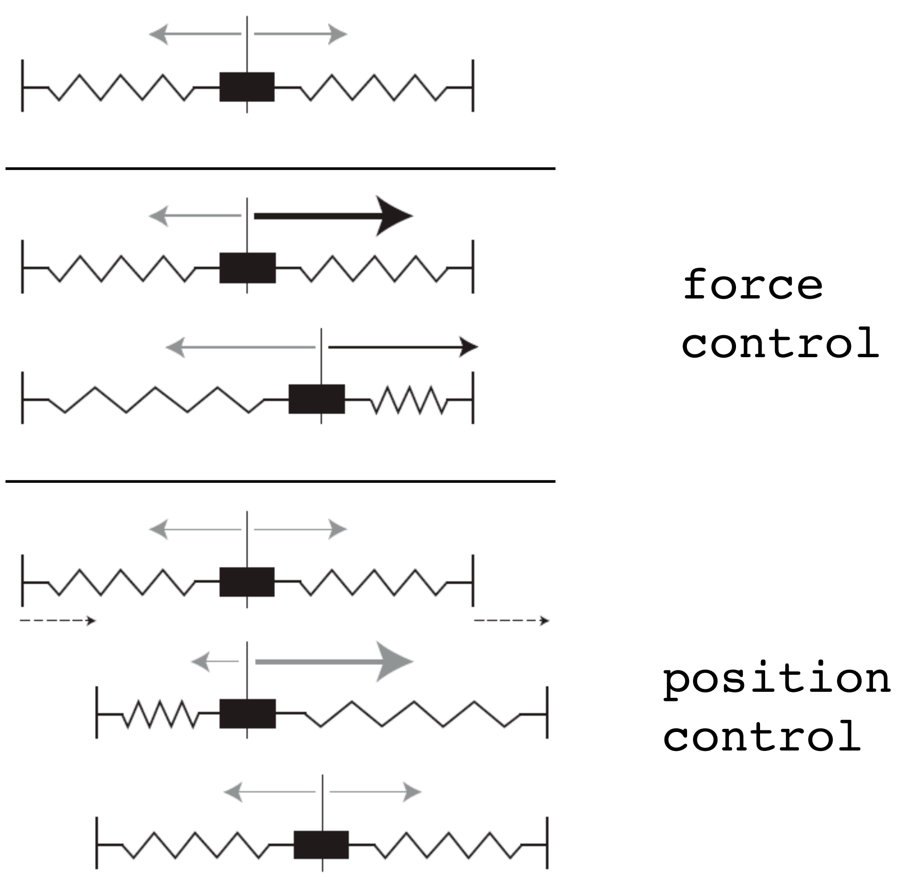
POSTURE AND MOVEMENT

Shared or separated processes?

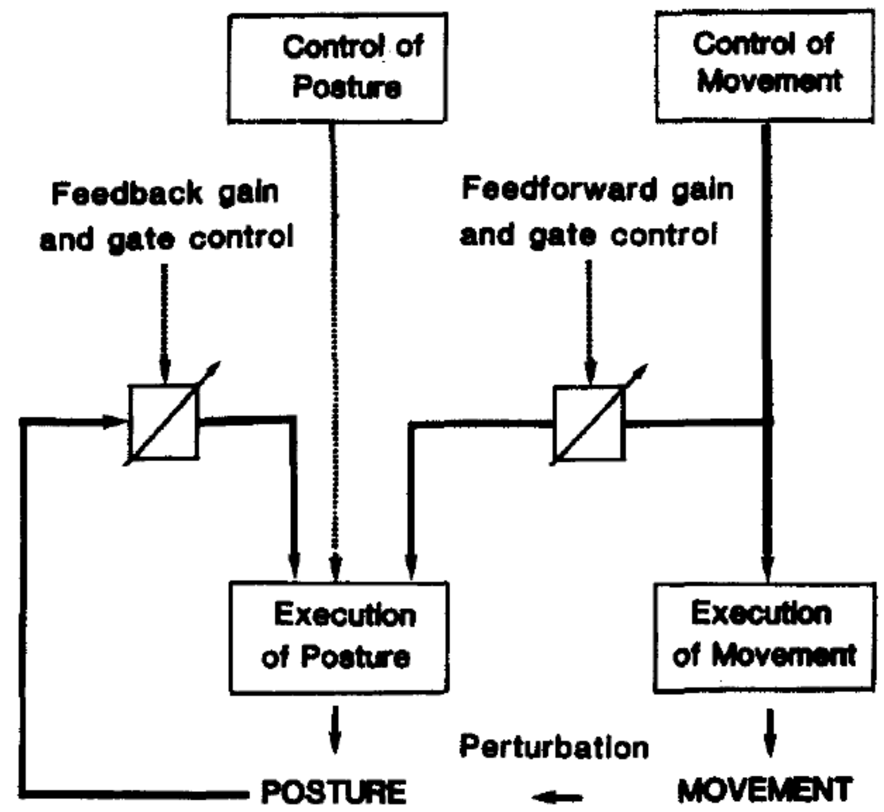
— movement derives from posture

— movement and posture are subserved by different processes

— *posture derives from movement?*



— Ostry & Feldman, 2003, *Exp Brain Res* 153:275



— Massion, 1992, *Prog Neurobiol* 38:35

WHAT IS MOTOR CONTROL?

- **Complex problem with multiple levels of redundancy (task-space, body-space, muscle-space, neural-space), nonlinearities, uncertainty, noise and time delays**

- **Flexible in time and space**

- **Apparent ease in the control of action**

- **Stereotyped behaviors, structured variability**

motor constancy, uniqueness of action, stability and consistency of action, modifiability of action

— Bernstein, 1967, *The Co-ordination and Regulation of Movements*, Pergamon

— Glencross, 1980, in *Tutorials in Motor Behavior*, North-Holland

WHAT IS «NOT» MOTOR CONTROL?

- **Multijoint movements are not scaled-up versions of single-joint movements. Multijoint movements are influenced by intersegmental dynamics**

- **No « elementary » movements which would be equivalent to elementary sensory stimuli (complex problems to solve even for the simplest motor acts)**

- **Not a chain of reflexes. Not a rigid « trajectory-following » system**