HUMAN ROBOTICS

- muscle mechanics and control
- single-joint neuromechanics
- multi-joint multi-muscle kinematics
- multi-joint dynamics and control
- motor learning and memory
- interaction control
- motion planning and online control
- integration and control of sensory feedback
- applications in neurorehabilitation and robotics

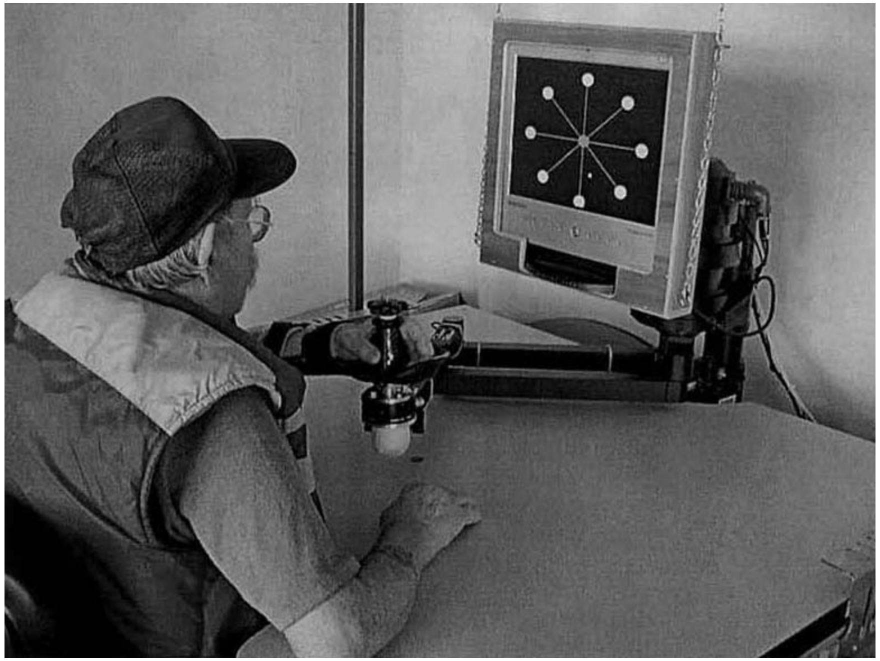
MOTOR LEARNING

- in humans, learning and adaptability is the rule
- learning new behaviours i.e. during infancy
- improve behaviours with practice
- we do not understand how humans/animals can learn complex behaviours
- similarities between rehabilitation and motor learning in healthy subjects as a tool to develop efficient rehabilitation strategies

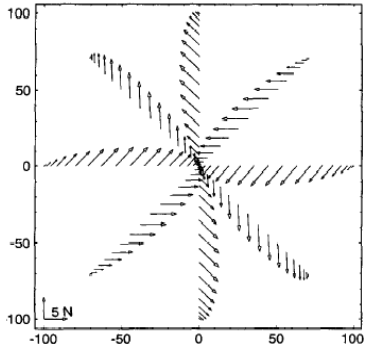
WHY DO HUMANS ADAPT MOTION?

- to manipulate objects we have to interact with the environment
- reaching, grasping: 150-600*ms*, delay of visual feedback: 100-250*ms*, stretch reflex delay > 30*ms*
- skilled actions require that humans learn to compensate for the environmental forces and instability in a feedforward way

EVIDENCE OF FEEDFORWARD



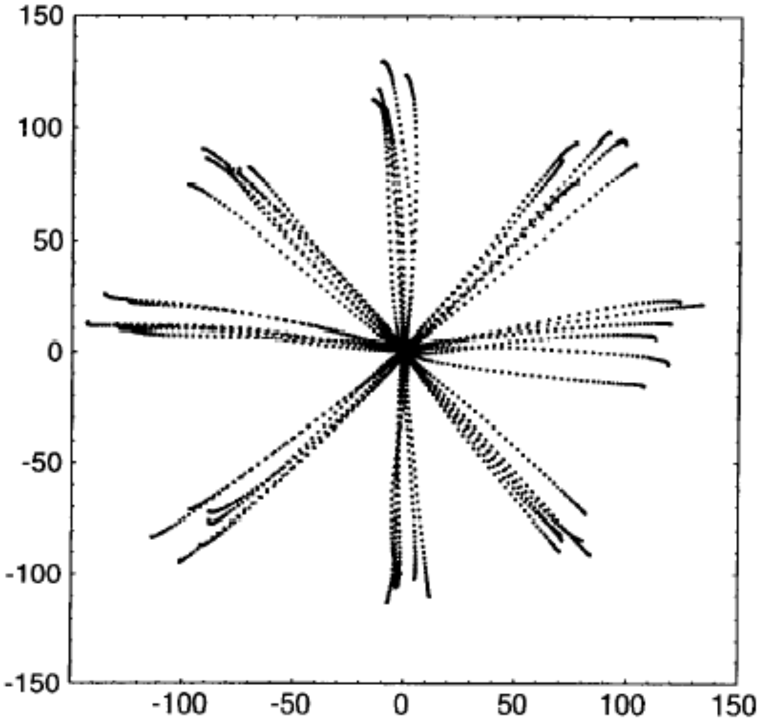
- 10*cm* horizontal reaching movements
- in any of 8 directions
- interacting with velocity dependent force field (VF) produced by a robotic manipulandum (force in *N*, velocity in *m/s*):



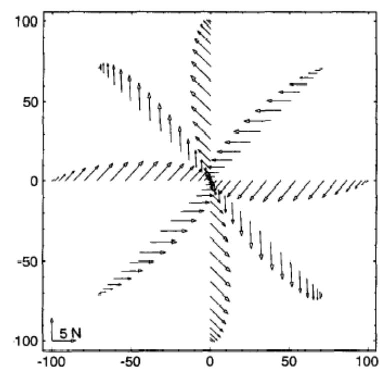
$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \begin{bmatrix} -10.1 & -11.2 \\ -11.2 & 11.1 \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix}$$

[Shadmehr&Mussa-Ivaldi, J Neuroscience 1994]

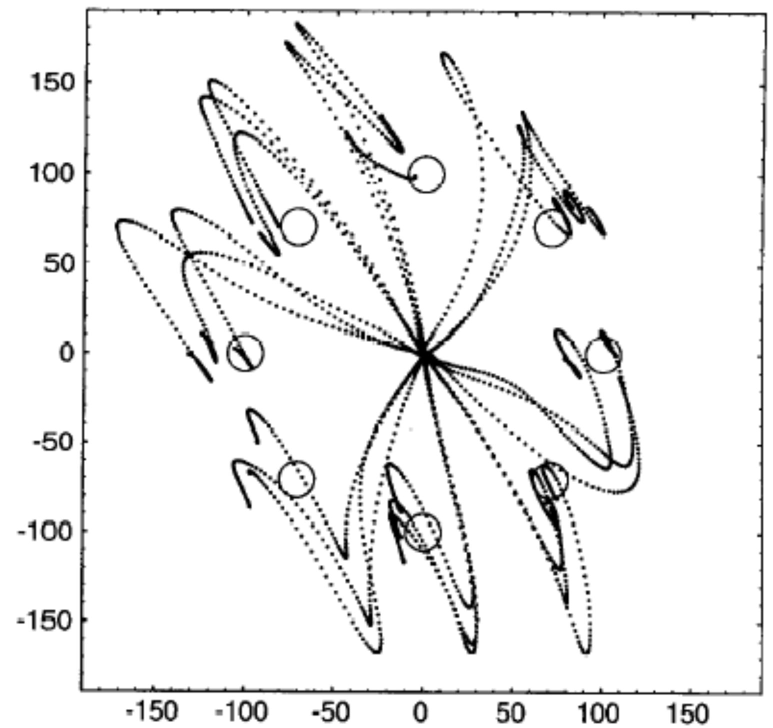
EVIDENCE OF FEEDFORWARD



free point-to-point movements in 8 directions



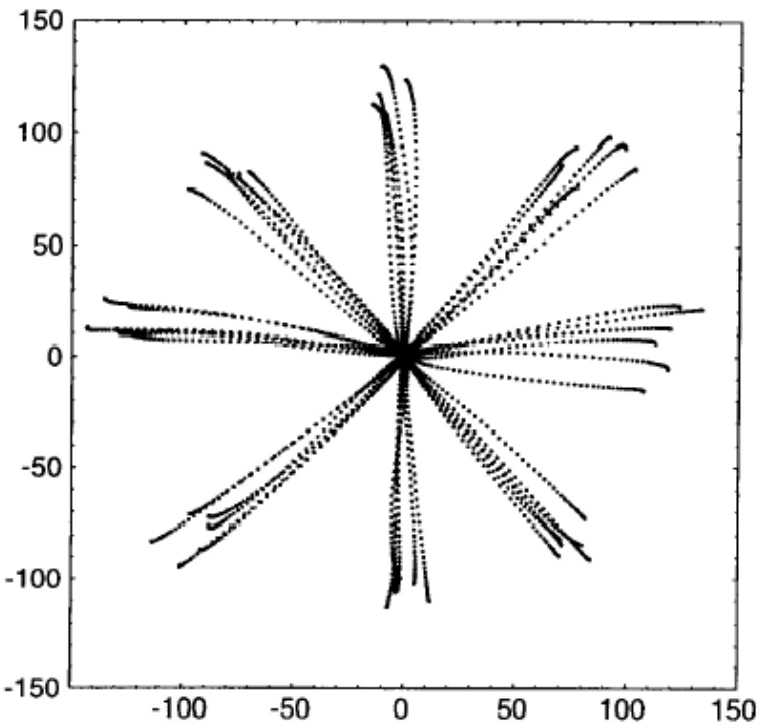
VF: velocity dependent force field



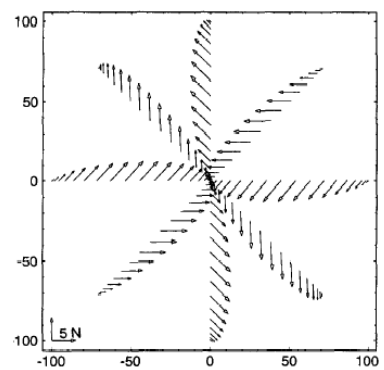
initial trials largely disturbed

[Shadmehr&Mussa-Ivaldi, J Neuroscience 1994]

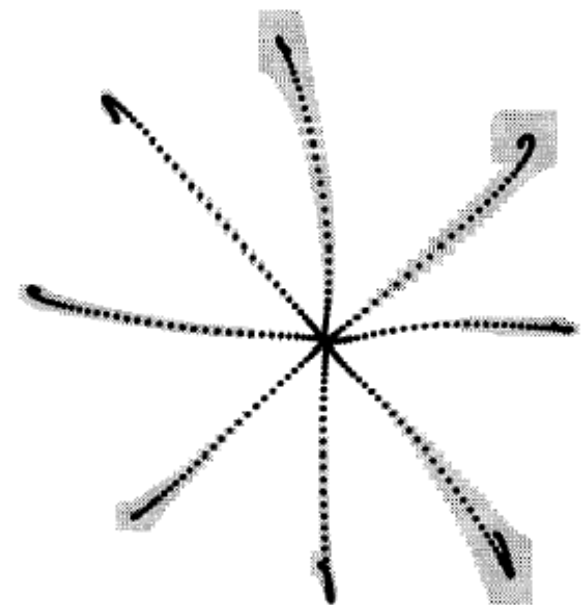
EVIDENCE OF FEEDFORWARD



free point-to-point movements in 8 directions



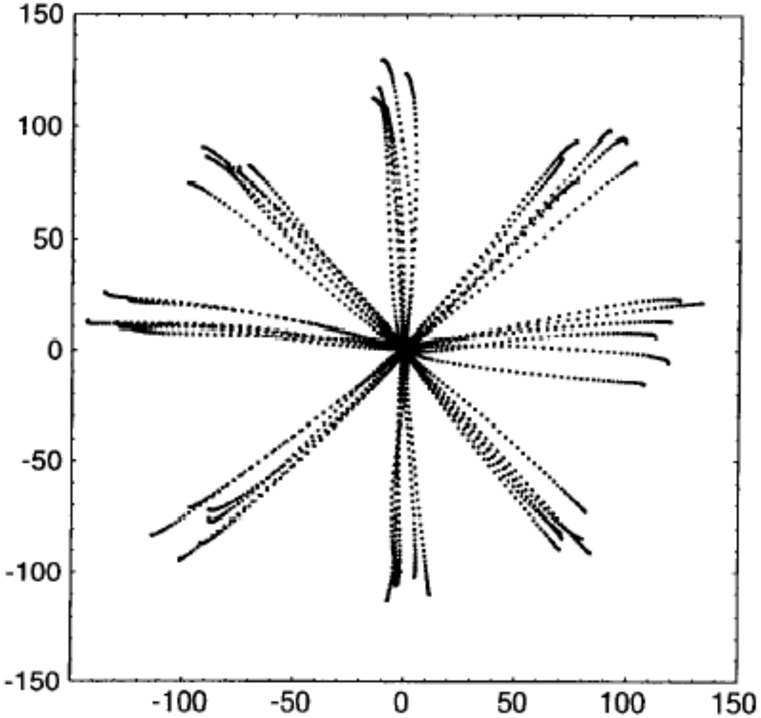
VF: velocity dependent force field



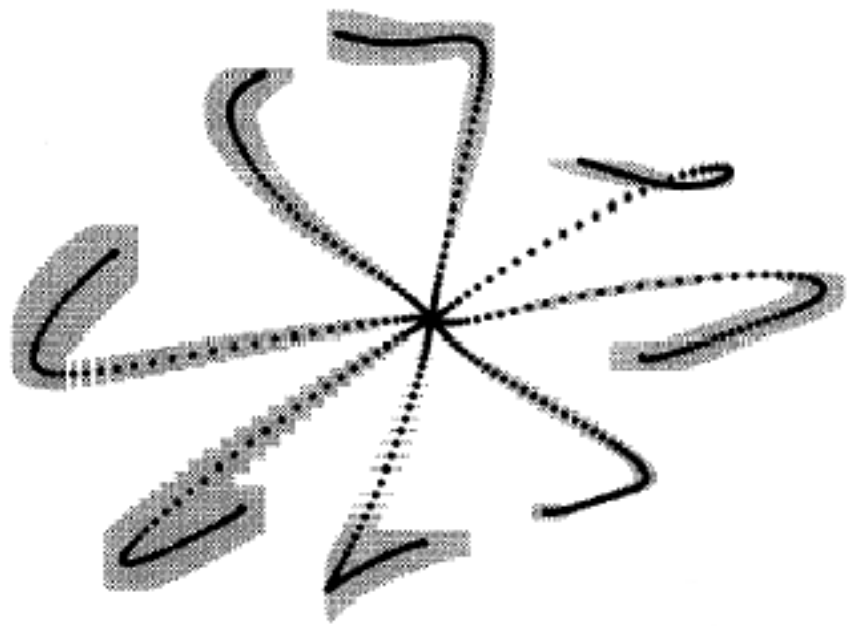
with learning the movements become similar to free movements

[Shadmehr&Mussa-Ivaldi, J Neuroscience 1994]

EVIDENCE OF FEEDFORWARD



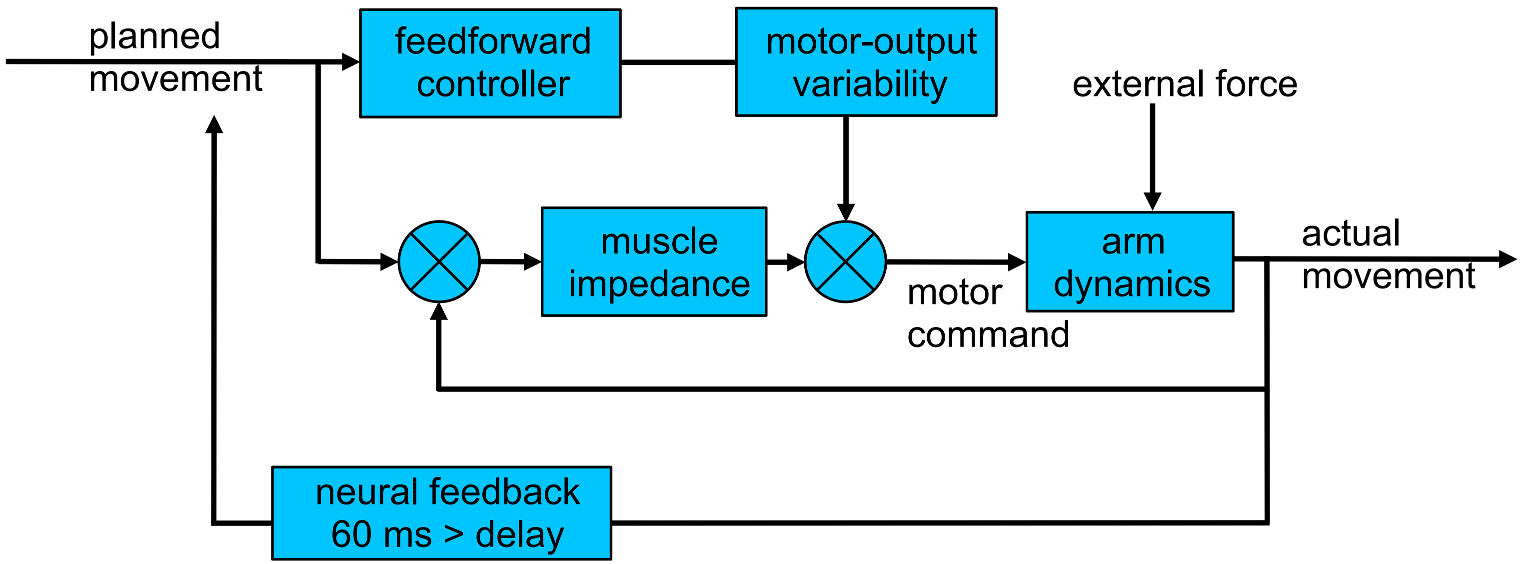
free point-to-point movements in 8 directions



after-effects of learning: when the force field disappears the trajectories are deformed by the memory of the learned dynamics

[Shadmehr&Mussa-Ivaldi, J Neuroscience 1994]

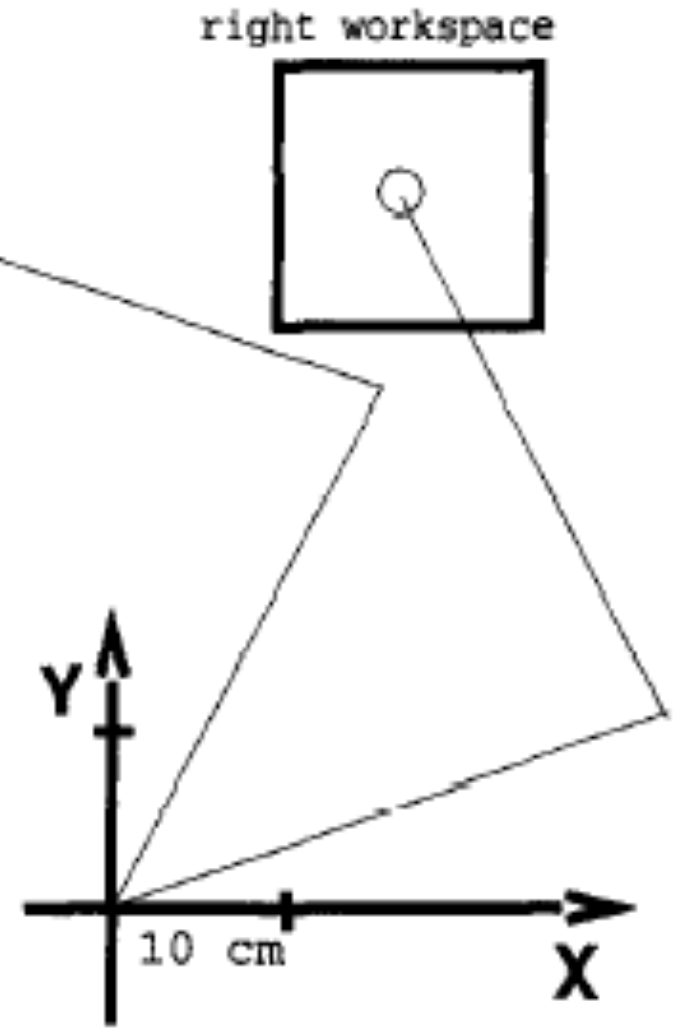
CONTROL OF HUMAN ARM



- muscle impedance provides stability
- reflexes generally also contributes to stability
- neural feedback is too slow and weak to explain fast motion

-> feedforward controller using an inverse model, which allows suitable commands to be executed

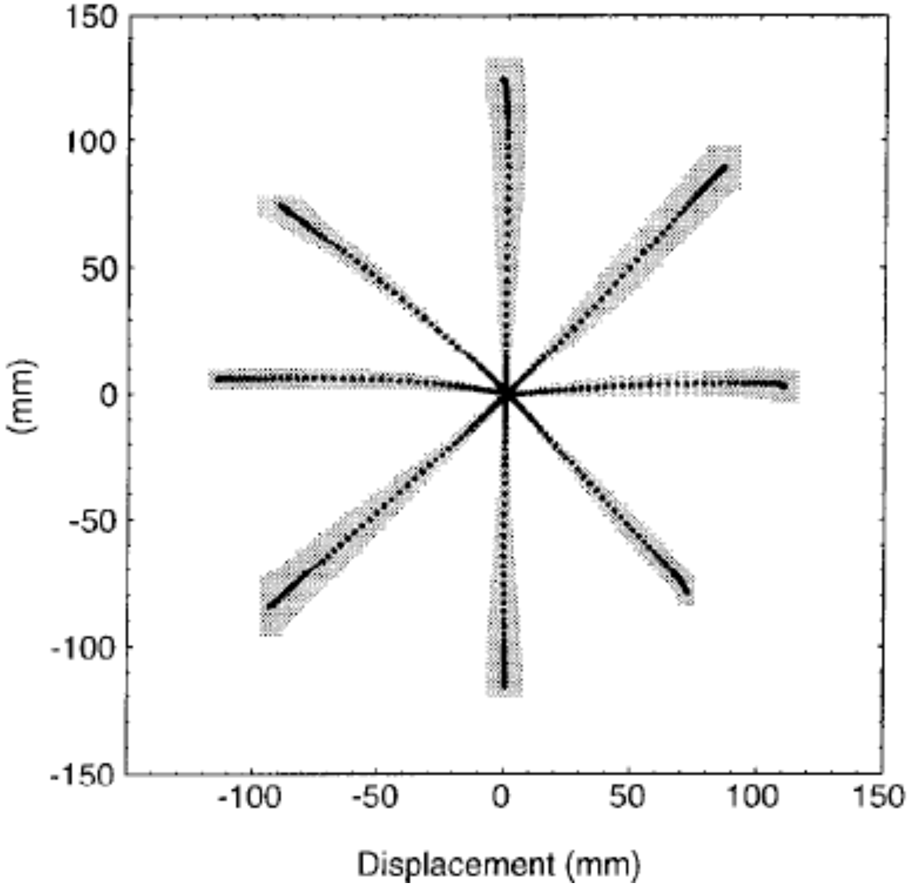
GENERALIZATION ?



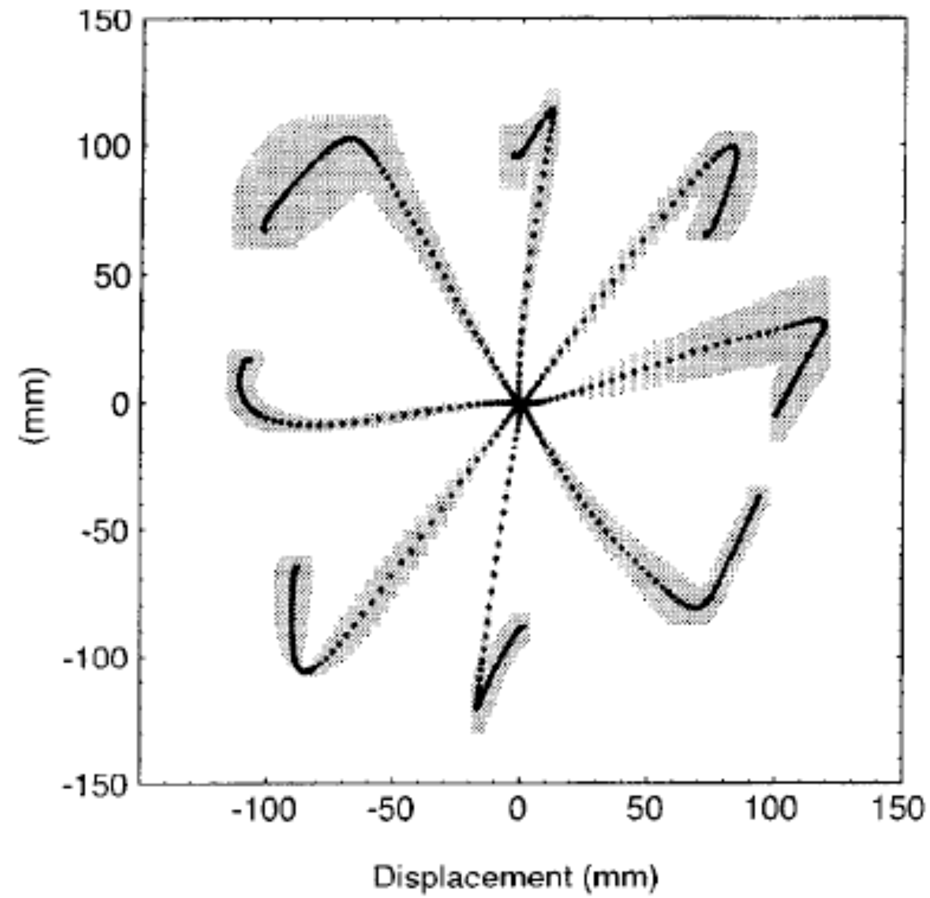
movements are trained in the right workspace and tested in the left workspace

test in the left workspace whether the CNS has generalised, and if yes in which coordinates

EVIDENCE OF GENERALIZATION



NF trials in left workspace



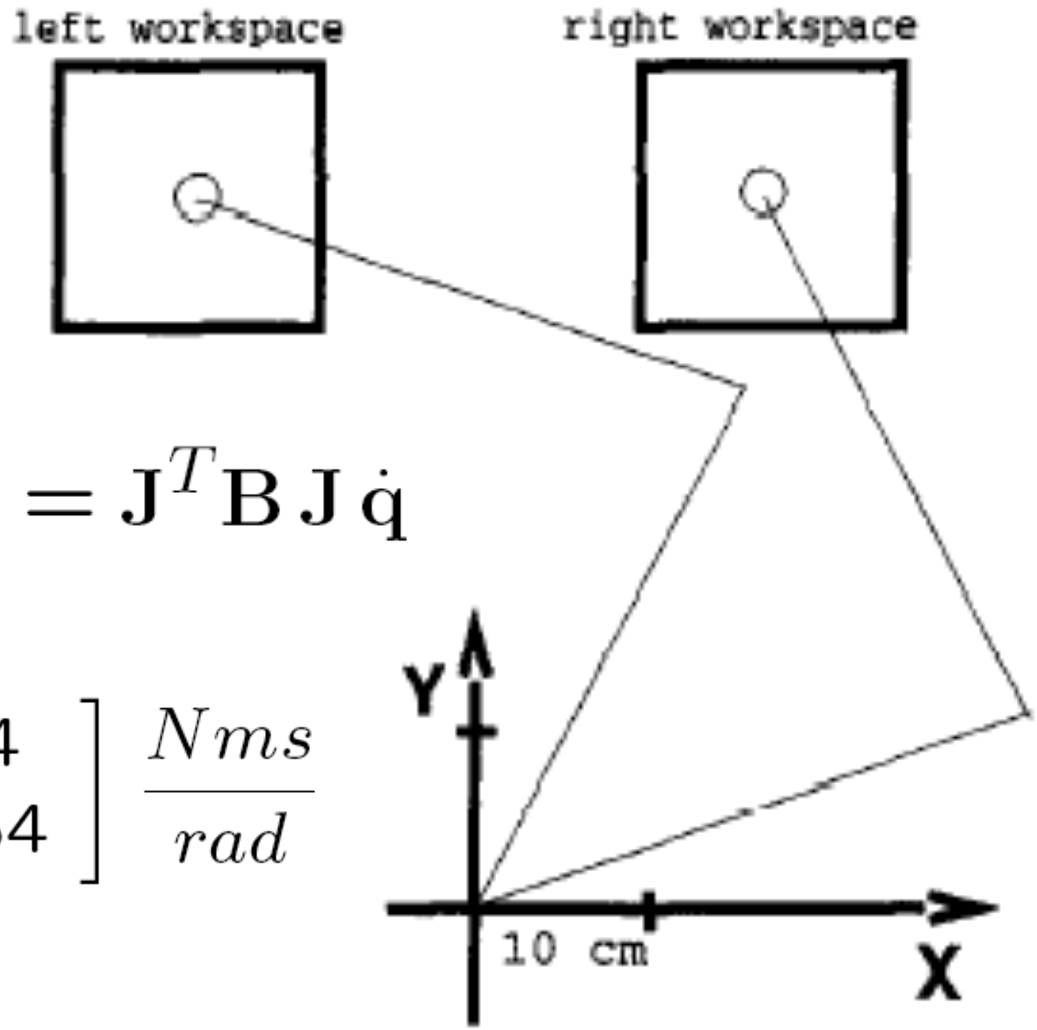
... after training VF in right workspace

GENERALIZATION ?

$$\mathbf{B} = \begin{bmatrix} -10.1 & -11.2 \\ -11.2 & 11.1 \end{bmatrix} \frac{Ns}{m}$$

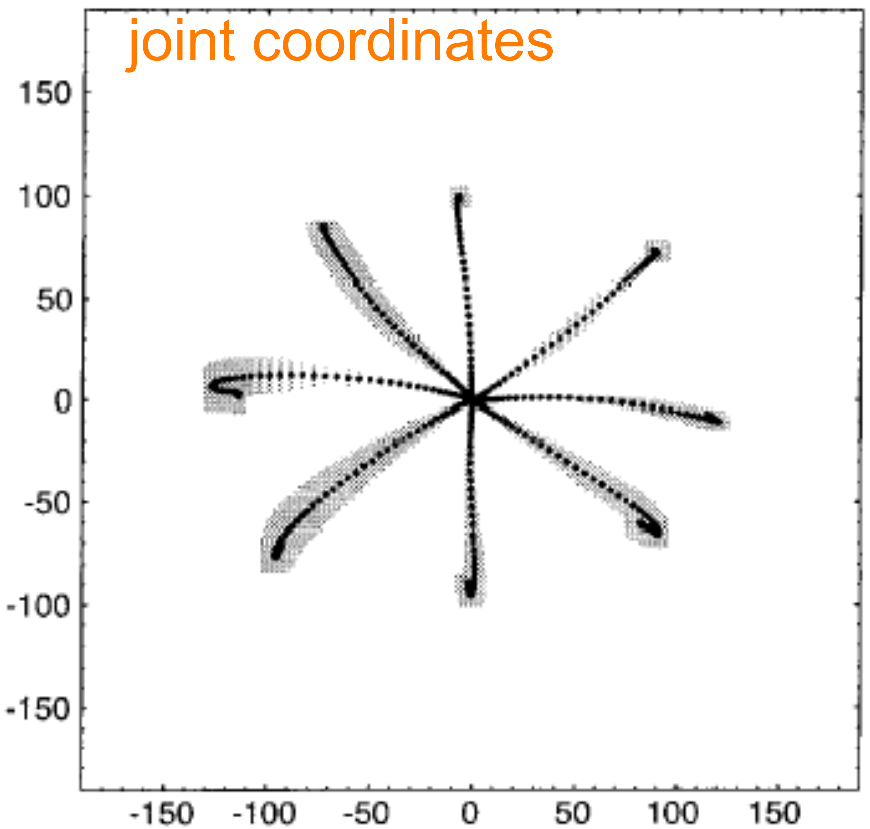
$$\mathbf{W}\dot{\mathbf{q}} = \boldsymbol{\tau} = \mathbf{J}^T\mathbf{F} = \mathbf{J}^T\mathbf{B}\,\dot{\mathbf{x}} = \mathbf{J}^T\mathbf{B}\,\mathbf{J}\,\dot{\mathbf{q}}$$

$$\mathbf{W} = \mathbf{J}^T\mathbf{B}\mathbf{J} = \begin{bmatrix} 1.66 & 0.64 \\ 0.64 & -1.54 \end{bmatrix} \frac{Nms}{rad}$$



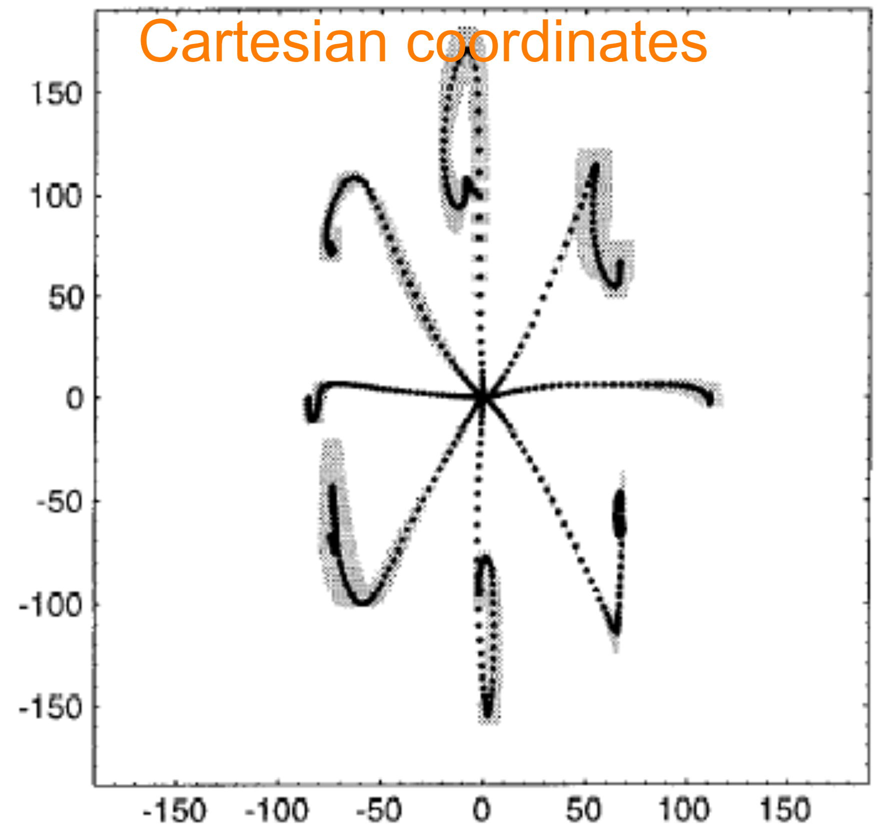
CODING IN JOINT RATHER THAN IN TASK SPACE

force field transformed in joint coordinates



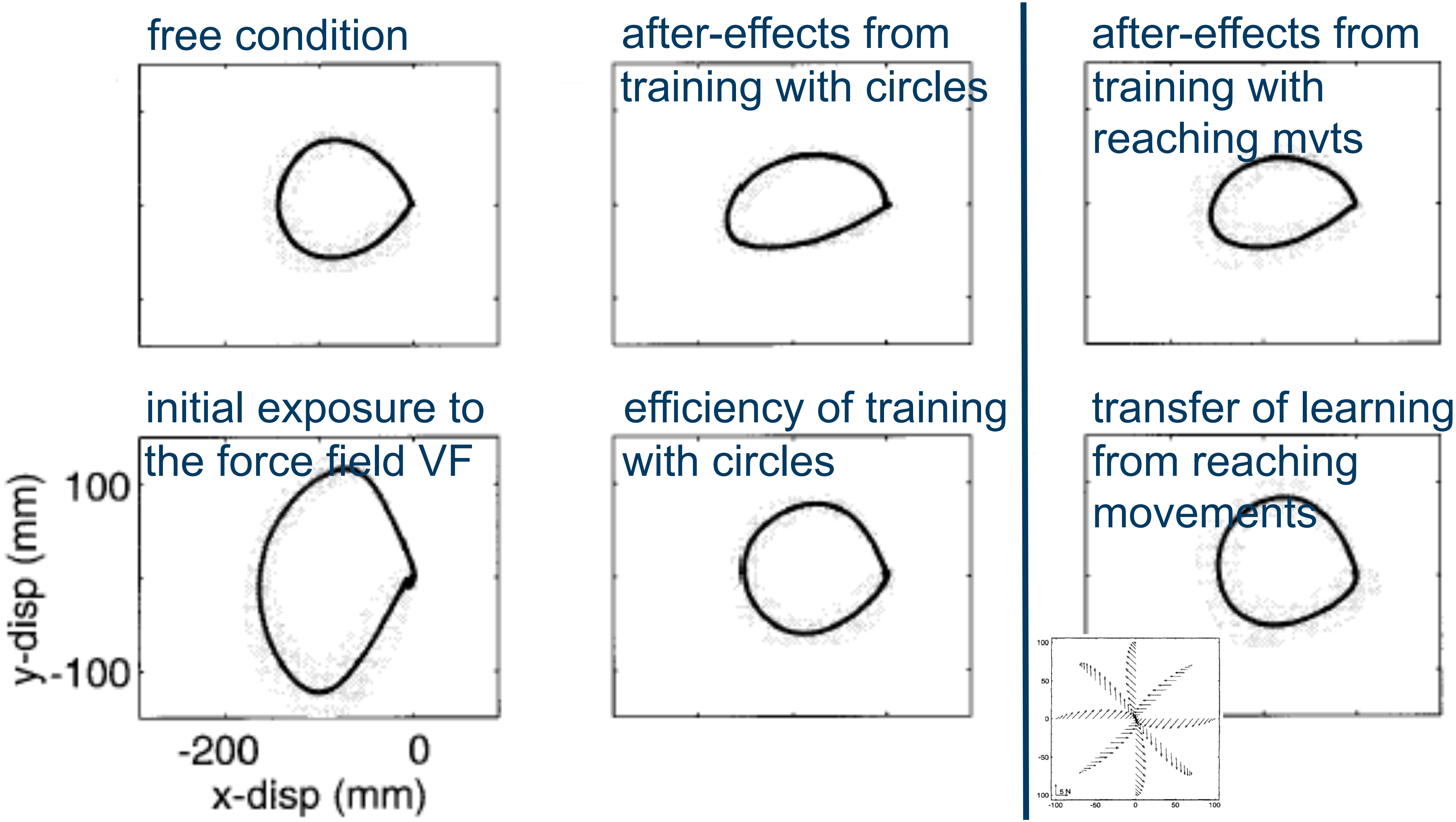
1. evidence for generalisation

force field transformed in Cartesian coordinates



2. in joint rather than in Cartesian coordinates

INVERSE MODEL IS STATE DEPENDENT



the CNS does not learn by rote memorisation, but forms a state dependent internal model

[Conditt et al., J Neurophysiology 1997]

IMPORTANCE OF KINEMATIC ERROR FOR MOTOR LEARNING (1)

- 20*cm* long reaching movement in forward direction

- learning a lateral force:

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \begin{bmatrix} -15\,\dot{y} \\ 0 \end{bmatrix}$$

- after learning trajectory constrained to a channel:

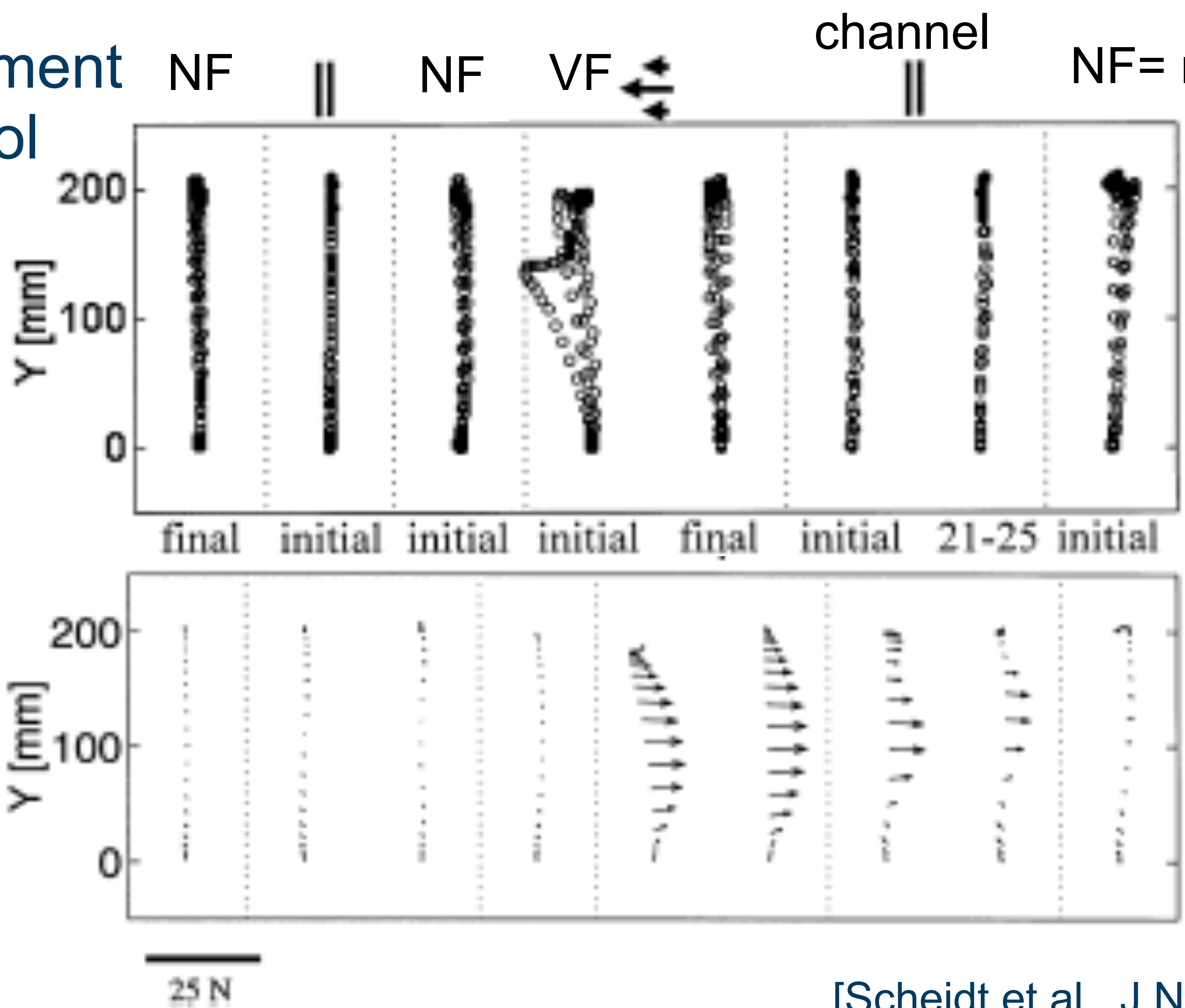
$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \begin{bmatrix} -6000\,x - 60\,\dot{x} \\ 0 \end{bmatrix}$$

[Scheidt et al., J Neurophysiology 2000]

IMPORTANCE OF KINEMATIC ERROR FOR MOTOR LEARNING (2)

experiment protocol

NF= null field

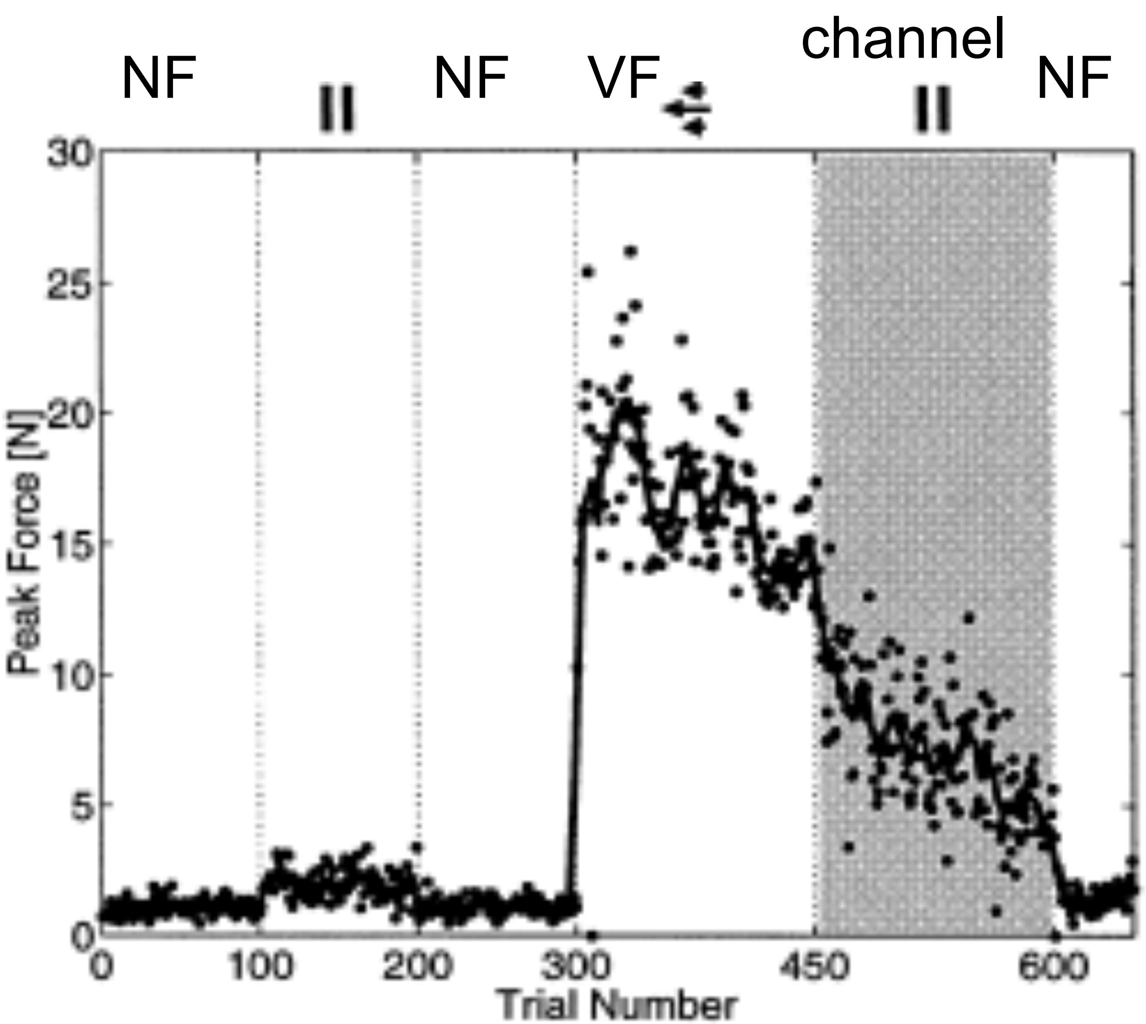


trajectories

force

[Scheidt et al., J Neurophysiology 2000]

IMPORTANCE OF KINEMATIC ERROR FOR MOTOR LEARNING (3)



- the force learned to compensate for the VF decreases much slower with than without channel
- this indicates that force cannot guide learning, but kinematic error

[Scheidt et al., J Neurophysiology 2000]

LEARNING STABLE TASKS

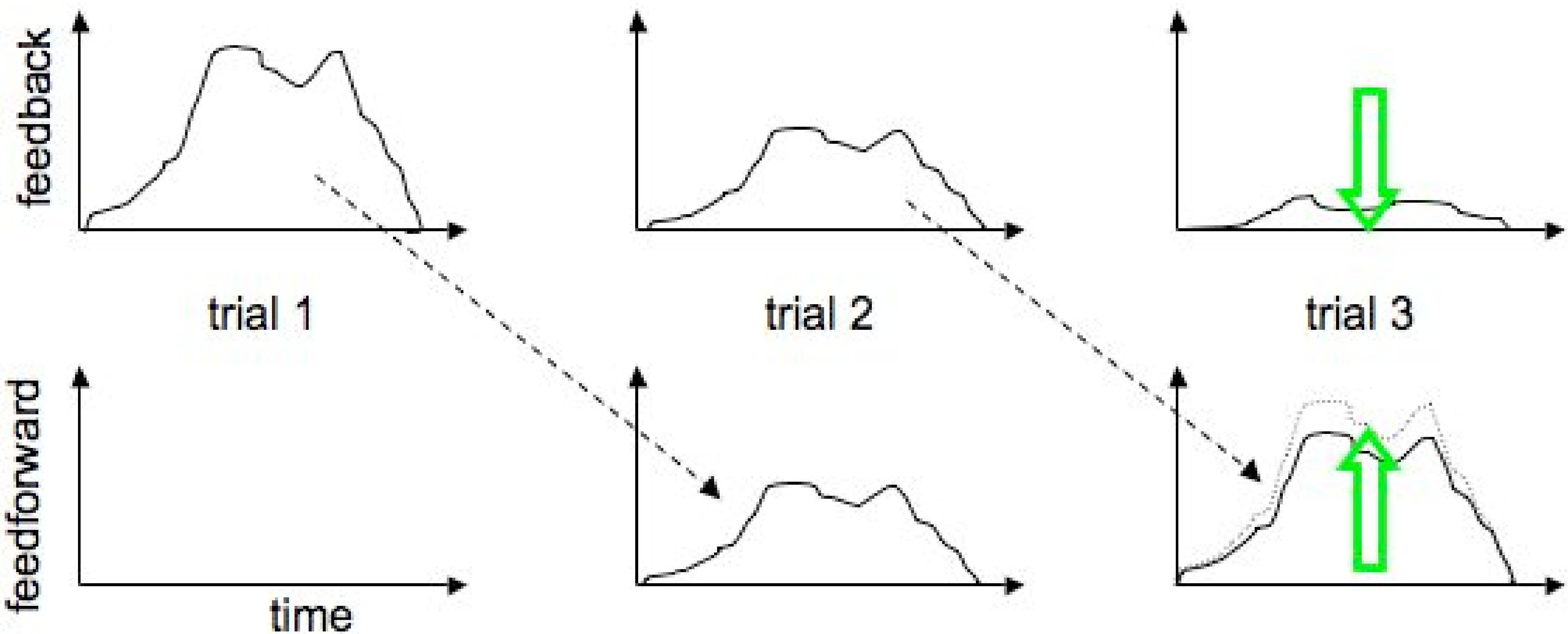
The experimental results suggest that:

- an feedforward model is formed during learning
- this model is coded in joint coordinates **q** rather than in Cartesian coordinates
- it is a function of the state: $\tau_{FF} = \mathbf{f}(\dot{\mathbf{q}}, \ddot{\mathbf{q}}, \mathbf{q})$
- the kinematic error is used to adapt this internal model to changing conditions

ITERATIVE CONTROL IN ROBOTS (1)

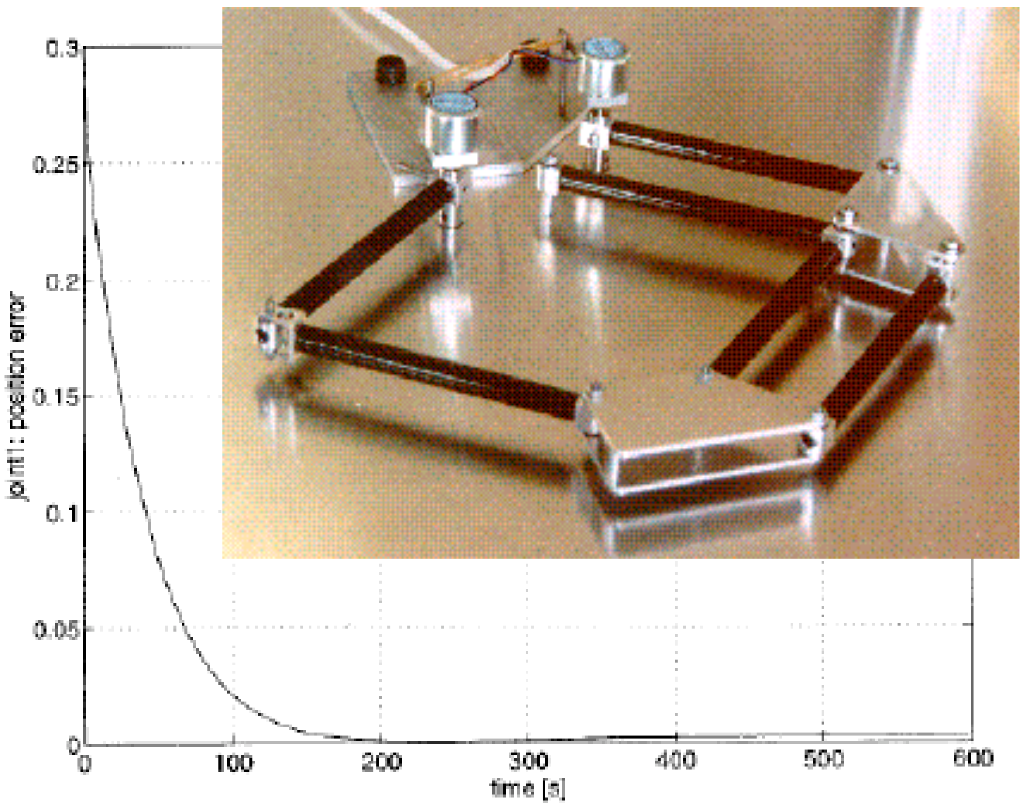
- for tasks such as welding or milling, robots have to follow a trajectory
- nonlinear control to perform good trajectory tracking
- compensating for the task dynamics by using a feedforward term: $\tau = \tau_{FF} + \tau_{FB}$
- start with $\tau_{FF}(t) = 0$
- robot already follows the trajectory, thus the feedback is indicative of the task dynamics
- $\tau_{FF}^{k+1}(t) = \tau_{FF}^{k}(t) + \alpha\,\tau_{FB}^{k}(t)$, $0<\alpha<1$

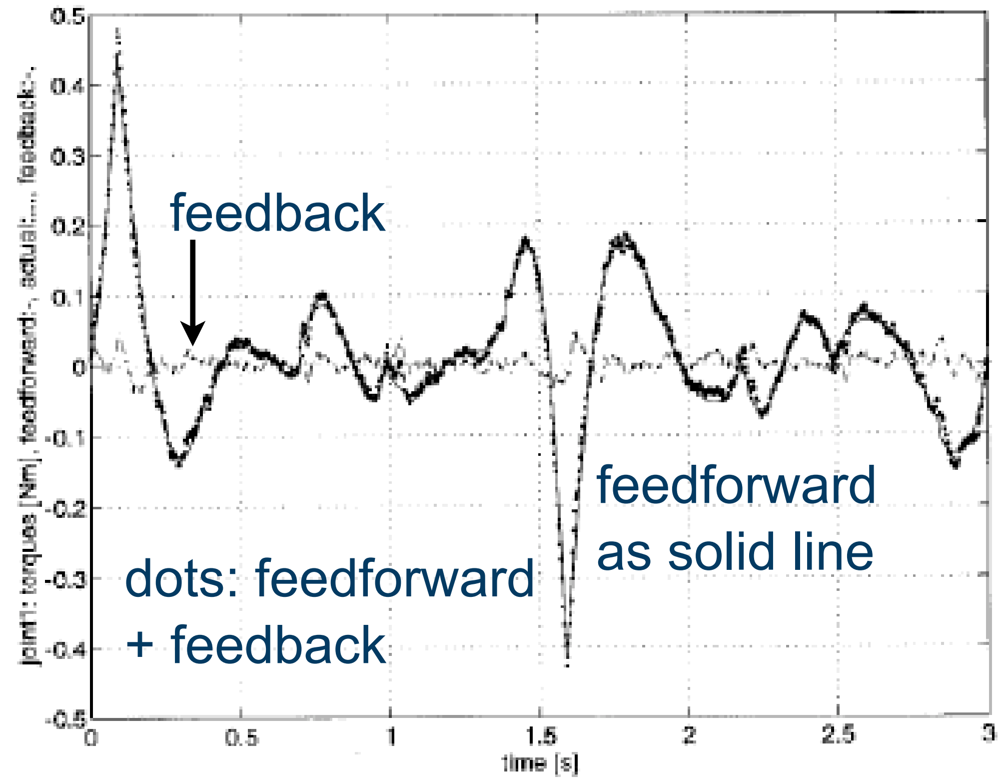
ITERATIVE CONTROL IN ROBOTS (2)



- robot already follows the trajectory, thus the feedback is indicative of the task dynamics
- $\tau_{FF}^{k+1}(t) = \tau_{FF}^{k}(t) + \alpha\,\tau_{FB}^{k}(t)\ ,\ \ 0<\alpha<1$

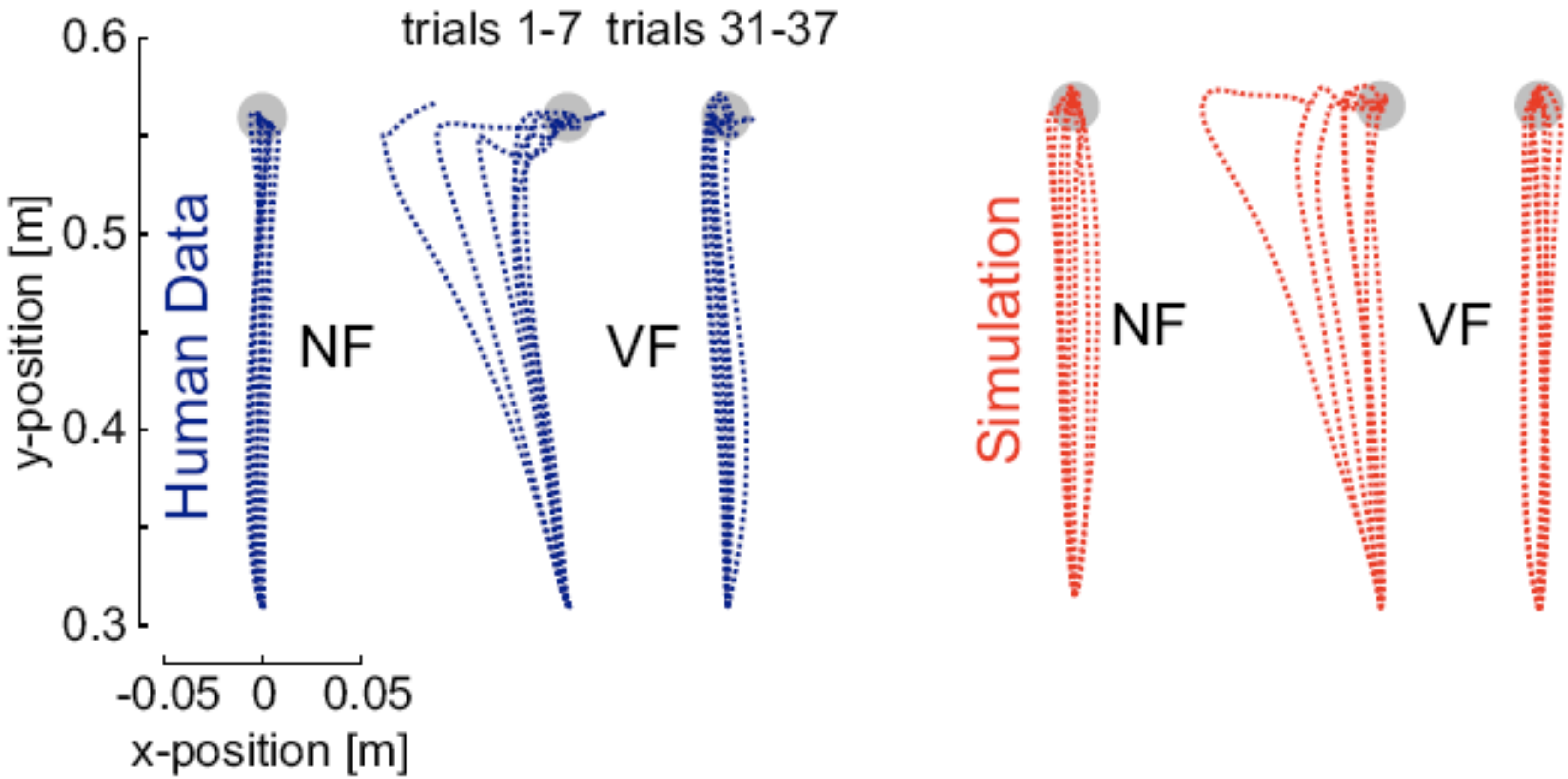
ITERATIVE CONTROL IN ROBOTS (3)





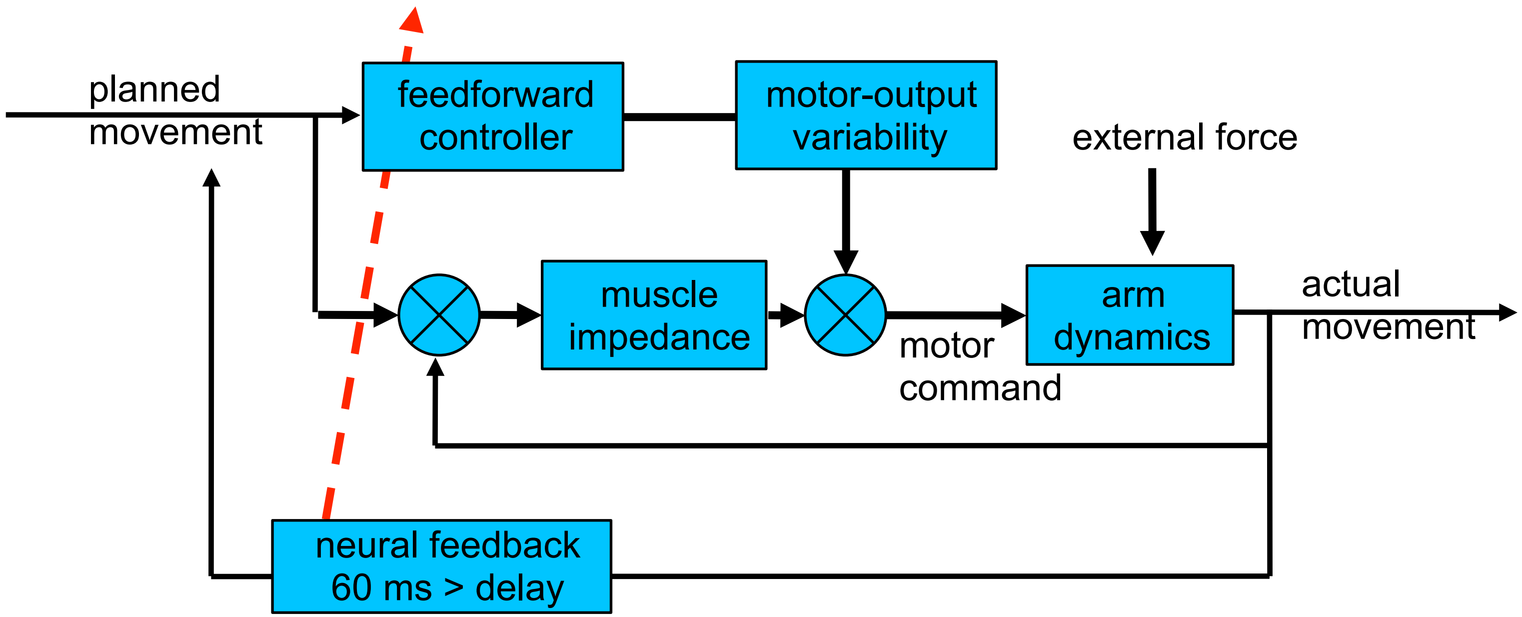
- (integrated) tracking error decreases
- feedback is reduced to almost 0

ITERATIVE CONTROL IN HUMANS



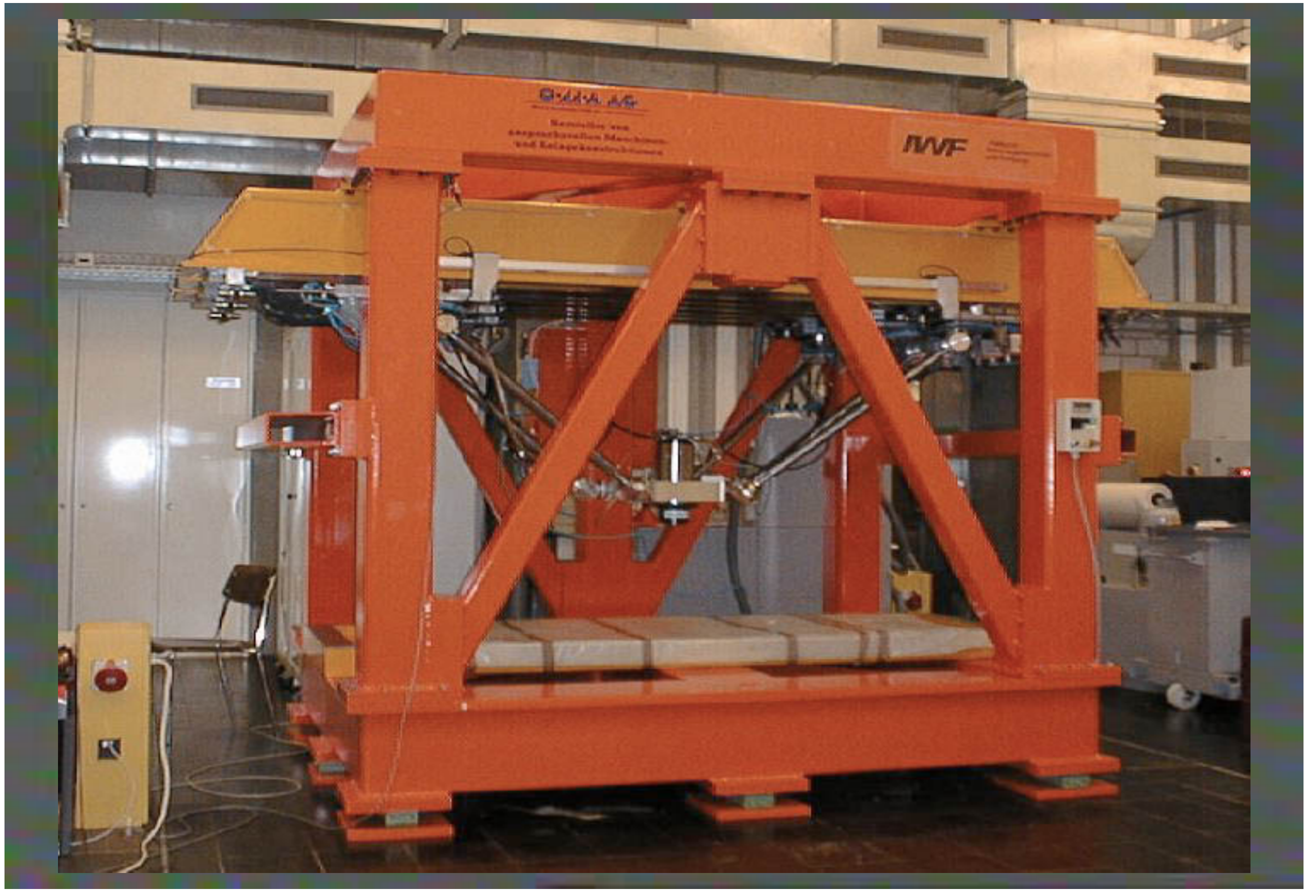
- an efficient computational model of motor learning with good predictions
- valid for a single repeated movement

NONLINEAR ADAPTIVE CONTROL



- an efficient computational model of motor learning

ADAPTIVE CONTROL IN ROBOTS



- robots can learn their dynamics in a similar way: (adaptive control: Craig, Slotine, Wen, Horowitz, etc)

SUMMARY (1)

- to investigate human motor control, one can study the adaptation of movements to novel dynamics produced by a haptic interface

- the experimental results suggest that a feedforward model of the task is formed during learning using mainly the kinematic error

- this model is coded in intrinsic coordinates of the joint or muscles, and is a function of a state space rather than the result of rote memorization

SUMMARY (2)

- iterative learning algorithms incorporating feedback into the feedforward trial after trial reproduces well the experimental results, suggesting that this is a plausible model of motor adaptation

- this is also an efficient algorithm to learn compensating for nonlinear robot dynamics in trajectory tracking tasks