MOTOR CONTROL IN THE UPPER EXTREMITY AND ITS IMPLICATIONS FOR NEUROREHABILITATION

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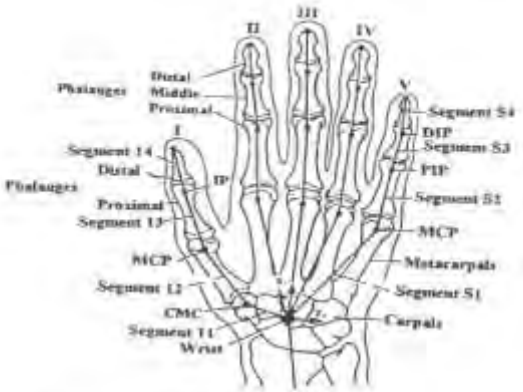
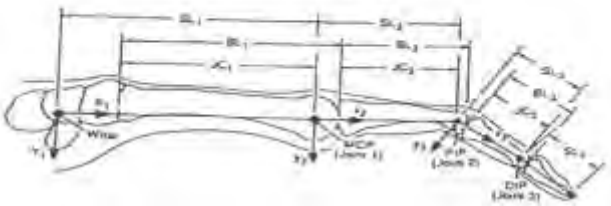
School of Applied Physiology
Center for Human Movement Studies
Georgia Tech

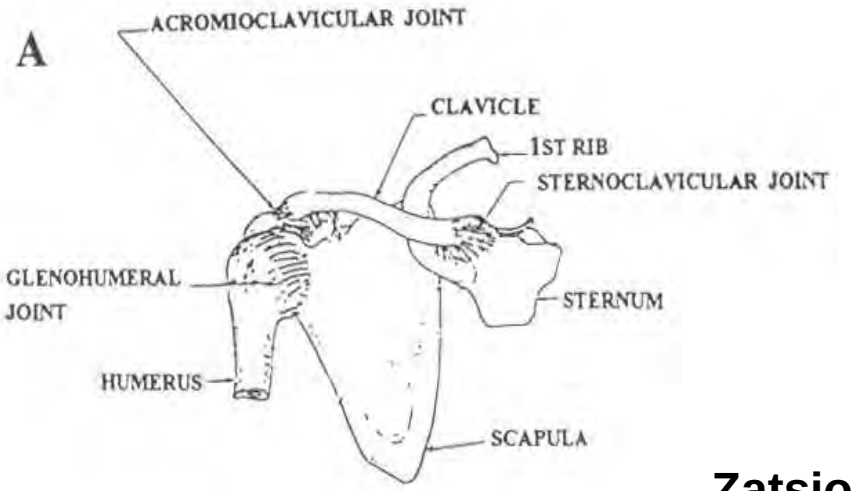
Talk Outline

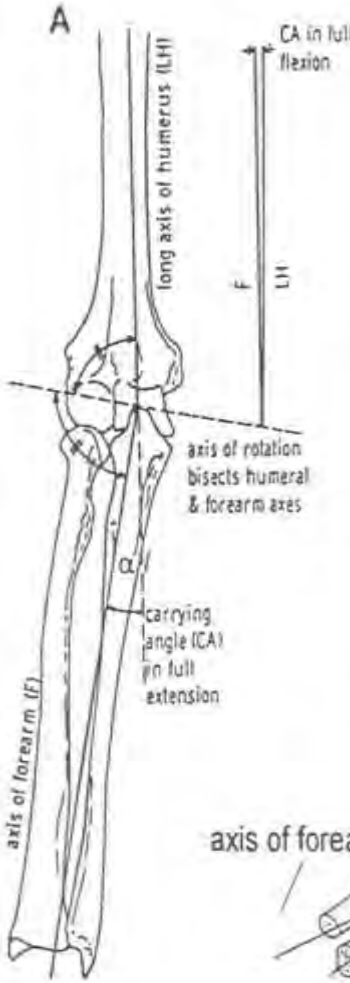
- Musculoskeletal redundancy
  - degrees-of-freedom problem
- Invariant characteristics of skilled arm movements
  - kinematics and kinetics
  - muscle activity
- Multi-joint control task in SCI individual
- Neuromechanical modeling
  - SIMM
  - AnyBody Technology
  - AnimatLab (GA State University)

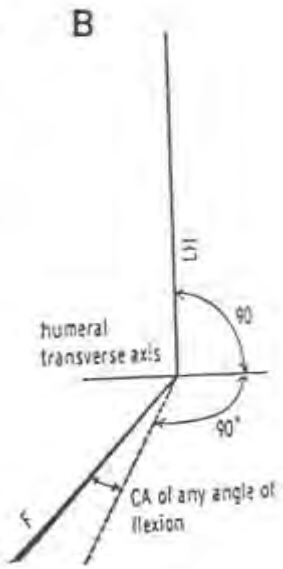
Kinematic redundancy

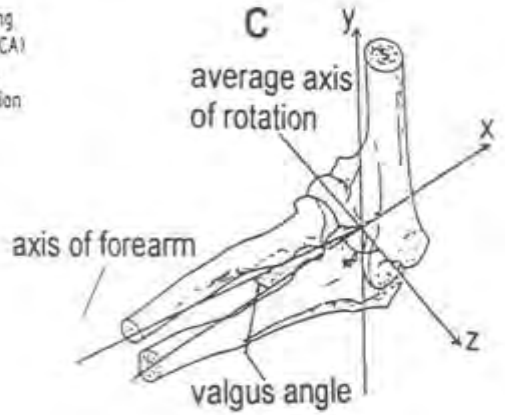






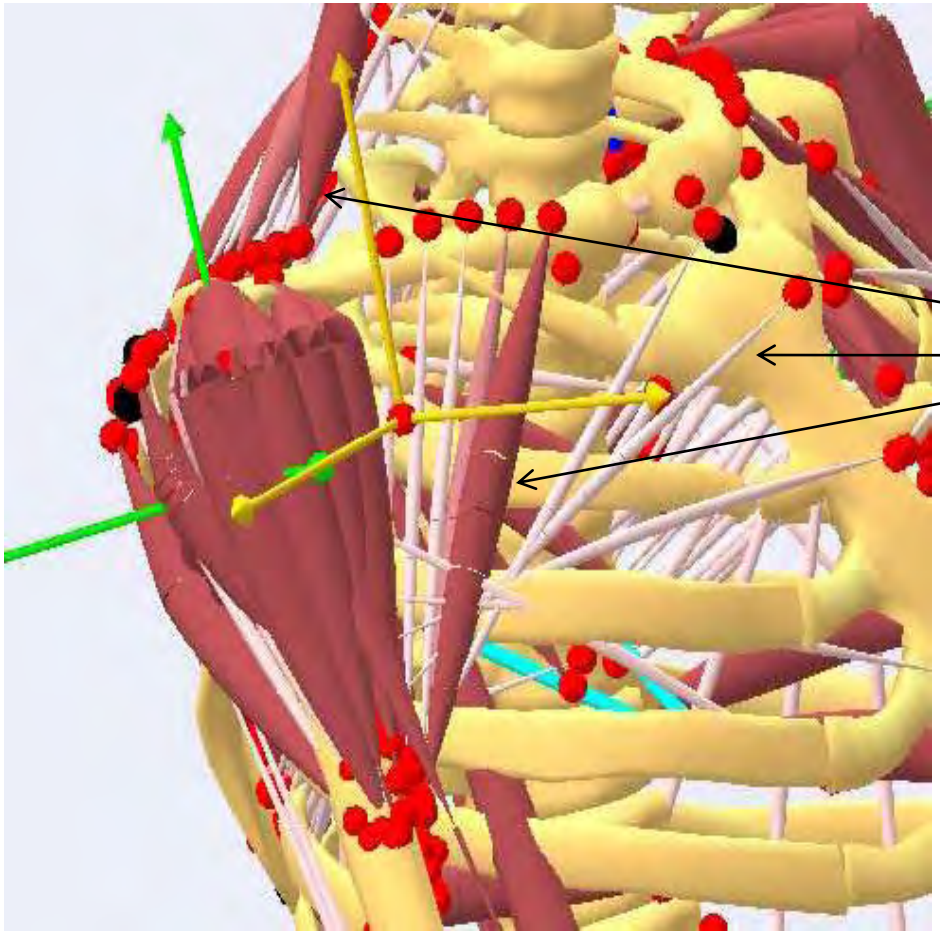






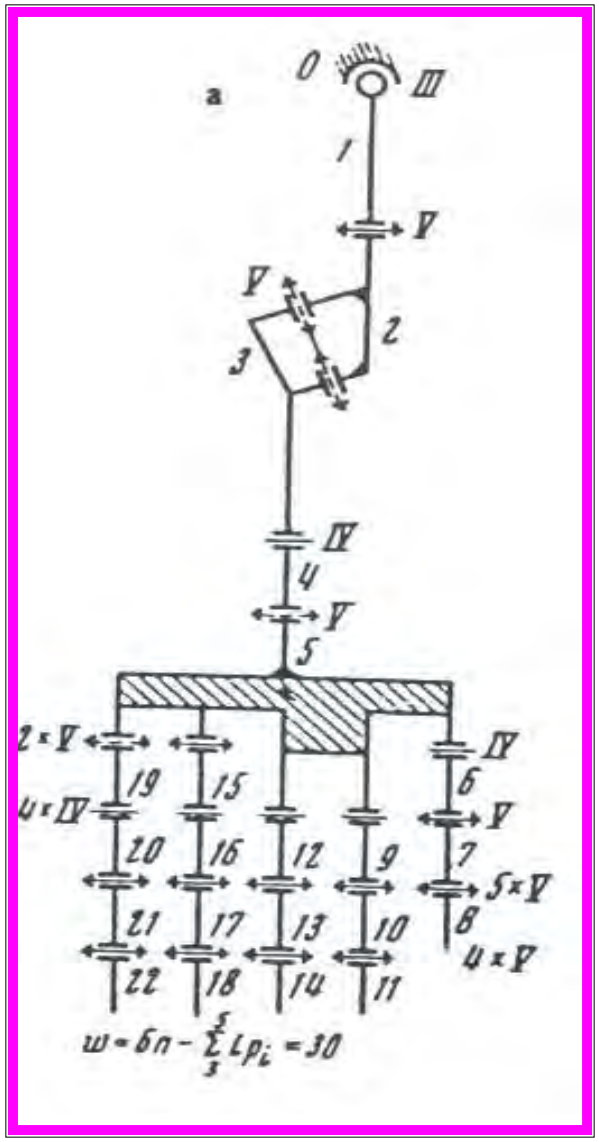
Zatsiorsky (1998) *Kinematics of Human Motion*

Muscle redundancy



Rusmussen, 2004

Kinematic redundancy



- Human arm is highly redundant
  - 22 joints
  - 30 DOF
  - 66 actons
  - 264 acton actions

  - 3 actons/joint
  - 2.2/DOF
  - 12 acton actions / joint

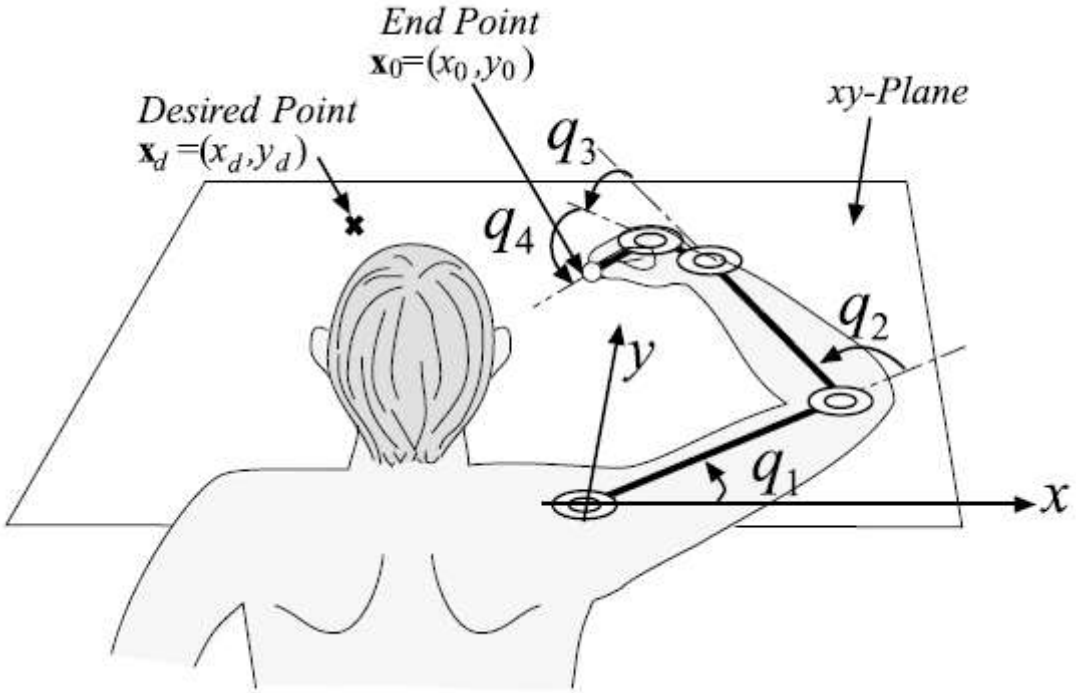
Morecki, Fidelus (1972). ***General Theory of Machines*****,**

Degrees-of-Freedom Problem

Nikolai A. Bernstein
(1896-1966)

- **The degrees-of-freedom problem**

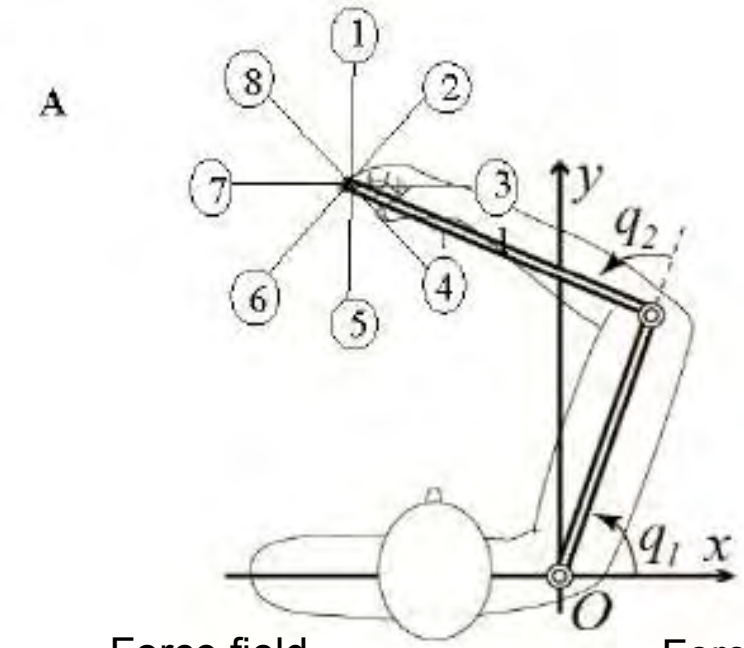
How does the nervous system specifies excessive degrees of freedom to execute movements ?



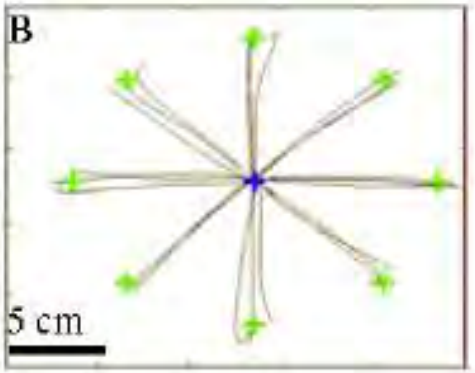
Arimoto, Sekimoto, Tahara (2010) ***Robotics***,

Invariant characteristics of human motion

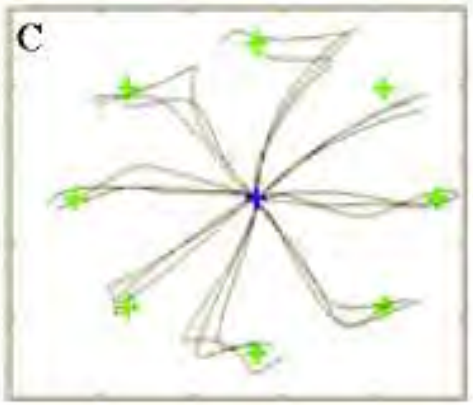
- Straight-line hand trajectory



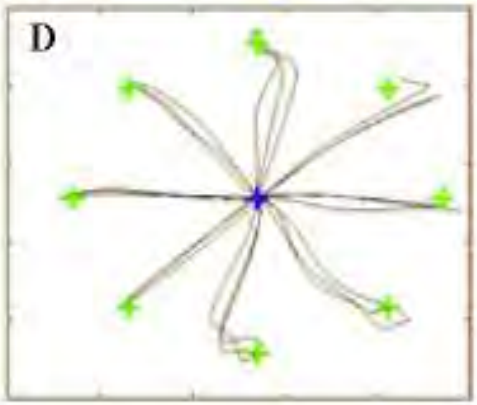
Null force field



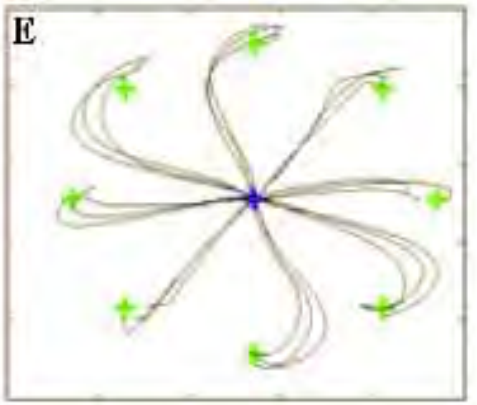
Force field



Force field

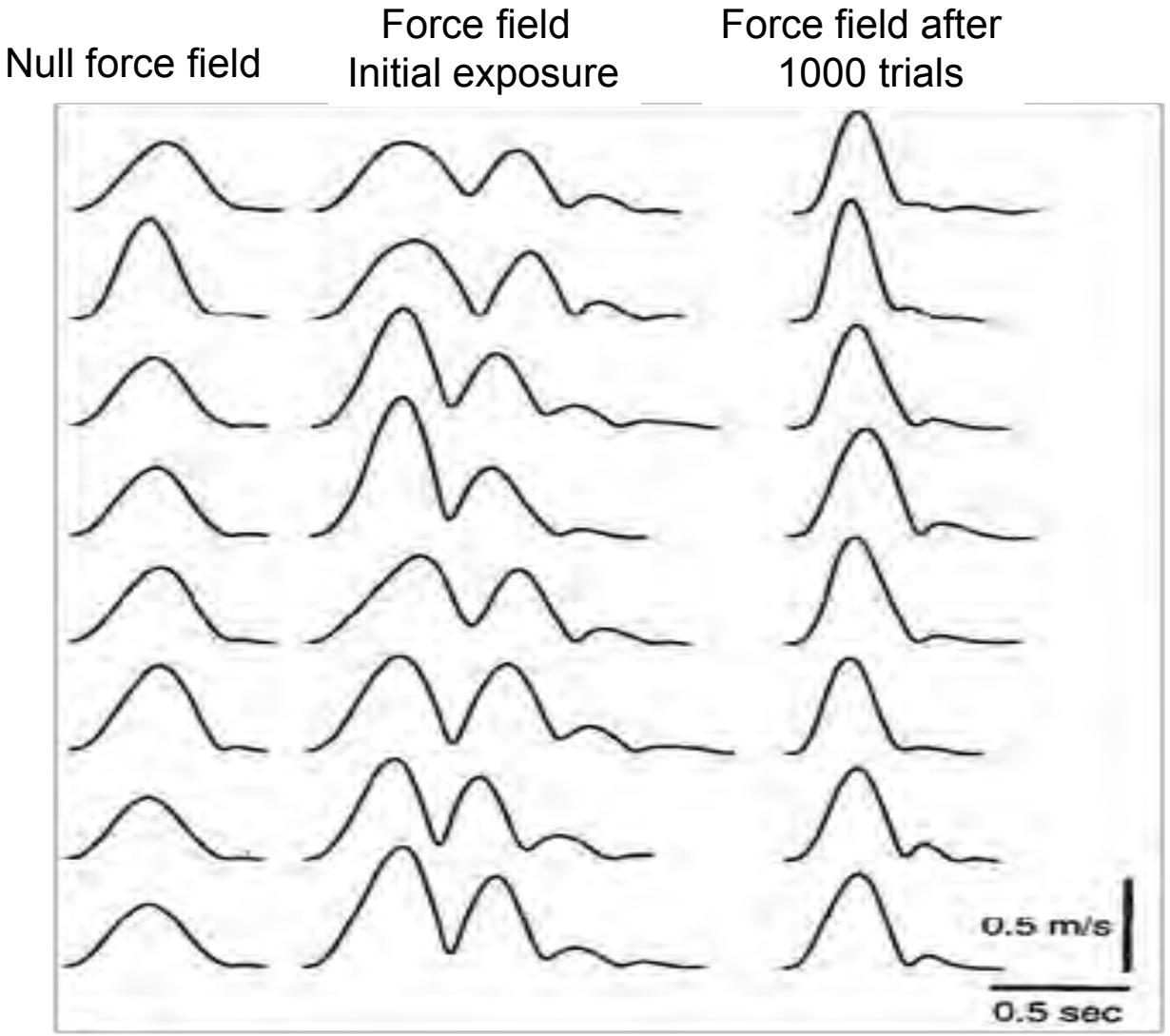


Catch trials



Invariant characteristics of human motion

- Bell-shape hand velocity profile

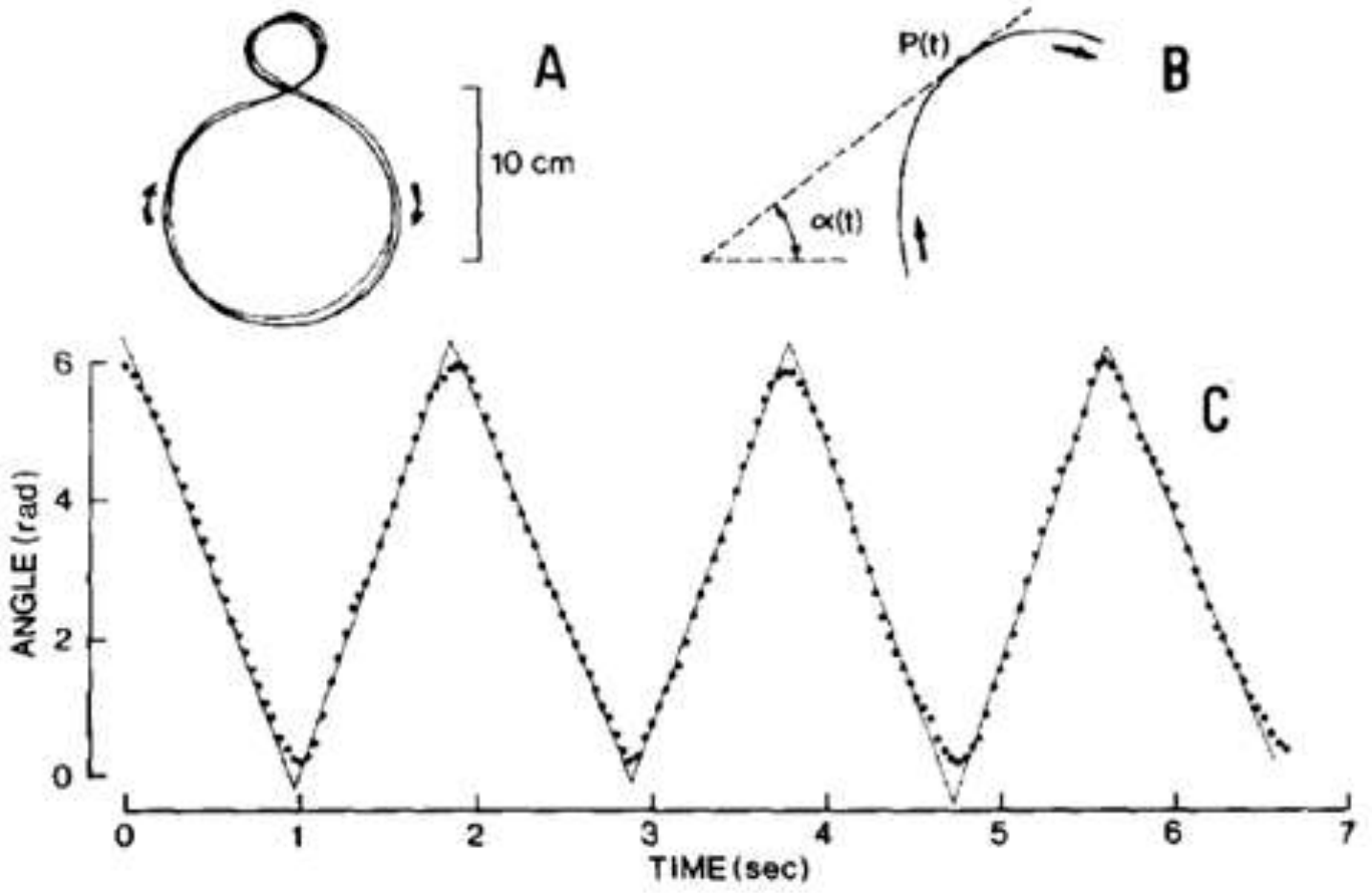


Shadmehr, Mussa-Ivaldi (1994) *J Neuroscience*

Invariant characteristics of human motion

- The two-thirds paw law

$$\dot{\alpha} = k \cdot C^{2/3}$$



Lacquaniti, Terzuolo, Viviani (1983) *Acta Psychologica*

Invariant characteristics of human motion

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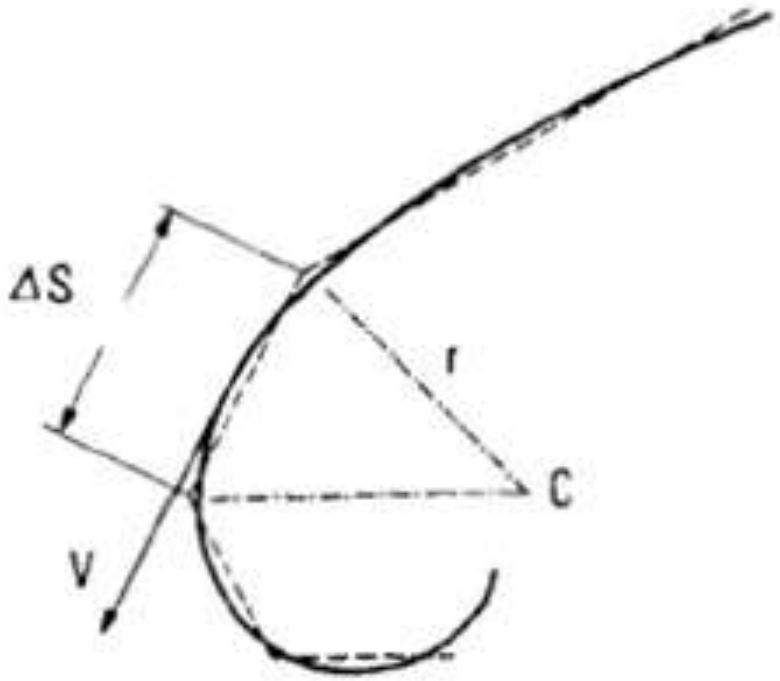


$$\frac{\Delta S}{r} \simeq \text{const} \quad \frac{V}{\Delta S} \simeq \text{const} \quad \Rightarrow \quad \frac{V}{r} \simeq \text{const}$$

Lacquaniti, Terzuolo, Viviani (1983) *Acta Psychologica*

Invariant characteristics of human motion

- Fitts's law: speed- accuracy trade-off

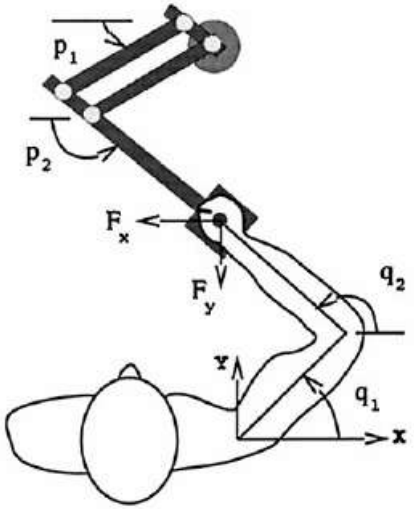
$$MT = a + b \cdot \log_2\left(\frac{2D}{W}\right),$$

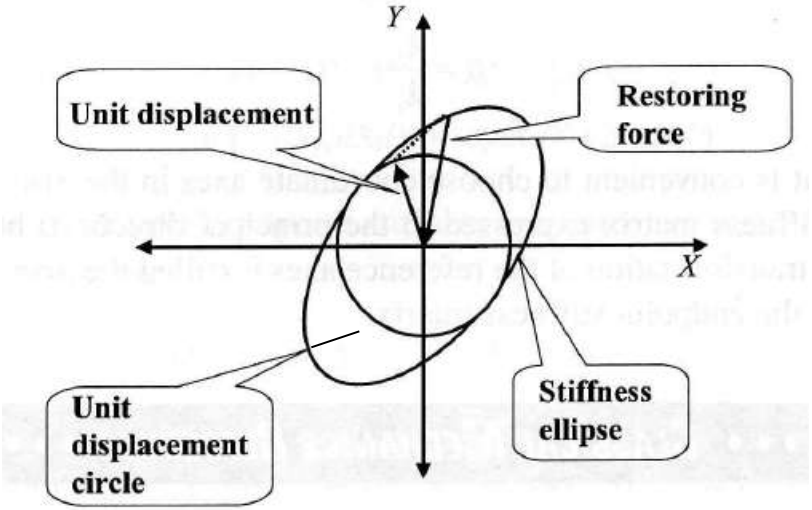
MT – movement time
D – movement distance
W – width of target
a, b – empirical constants

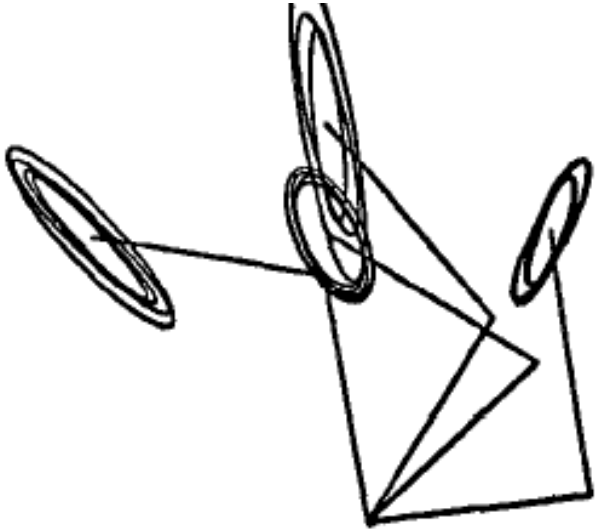
Fitts (1954) *J Exp Psychology*

Invariant characteristics of human motion

- Shape and orientation of arm stiffness ellipses

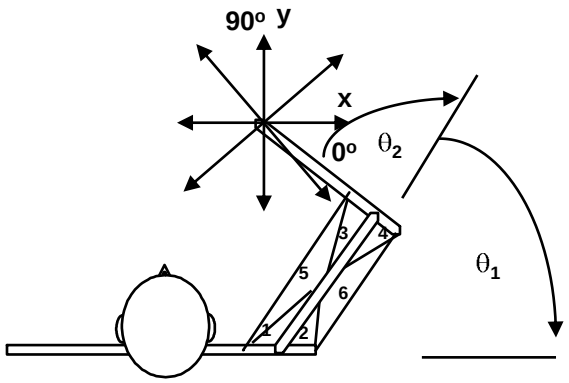




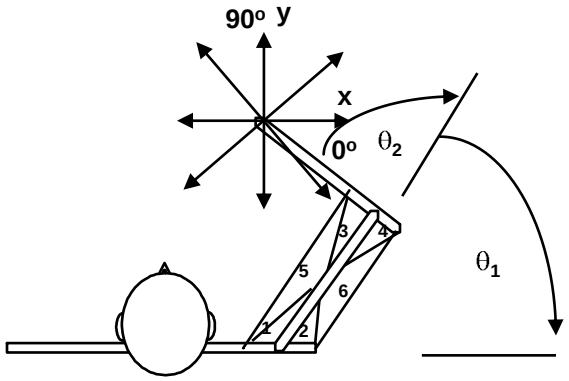


Mussa-Ivaldi, Hogan, Bizzi (1985) J Neuroscience

Invariant characteristics of human motion



Invariant characteristics of human motion



minimize objective function

$$\sum_{i=1}^{6} (F_i / PCSA_i)^3$$

subject to $d\mathbf{M} = \mathbf{D}\,d\mathbf{F}$,

$d\mathbf{F} \geq 0$,

where

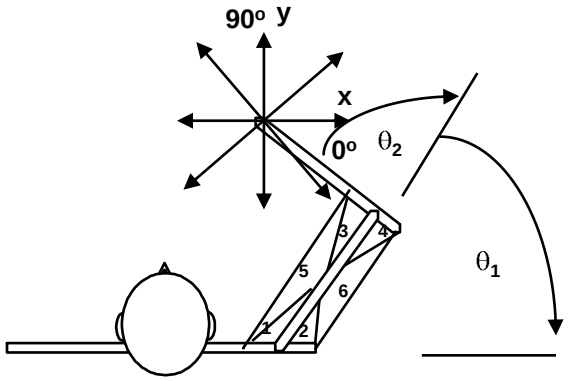
$d\mathbf{M}$, *joint moments*

$\mathbf{D}$, *muscle moment arms*

$d\mathbf{F}$, *muscle forces*

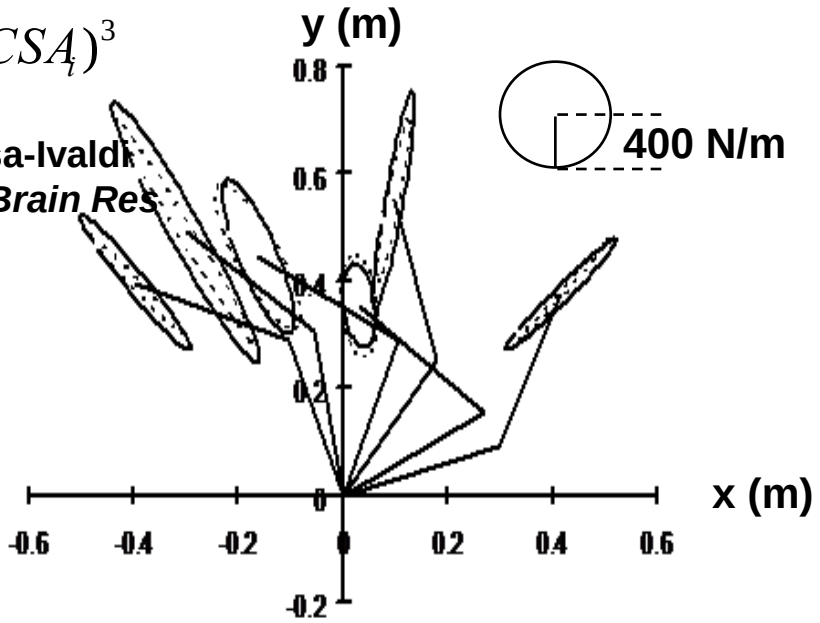
Prilutsky (2000) *Motor Control*

Invariant characteristics of human motion



$\sum_{i=1}^{6}(F_i / PCSA_i)^3$

Flash, Mussa-Ivaldi (1990) ***Exp Brain Res***



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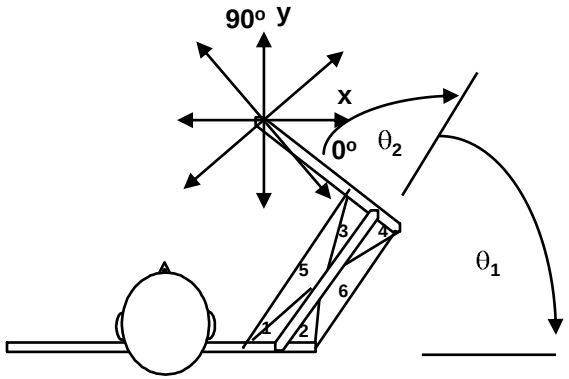

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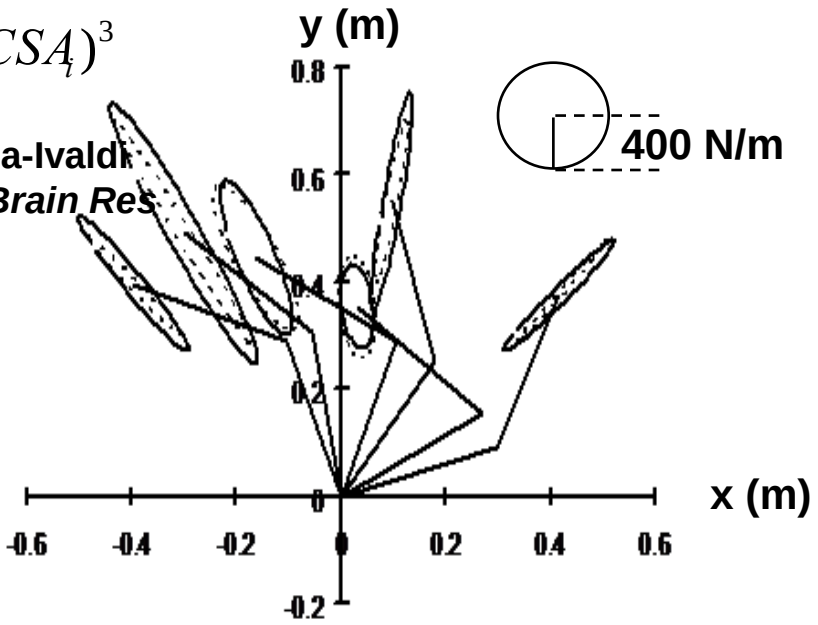

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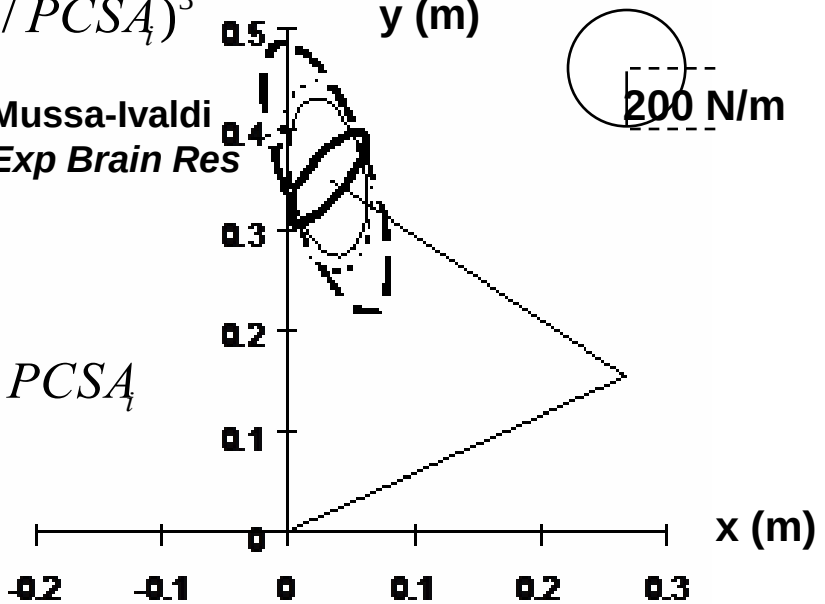
Flash, Mussa-Ivaldi (1990) *Exp Brain Res*

$\sum_{i=1}^{6} F_i^3$

$\sum_{i=1}^{6} F_i / PCSA_i$



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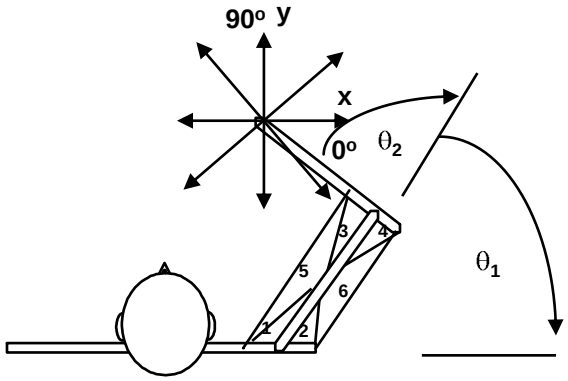
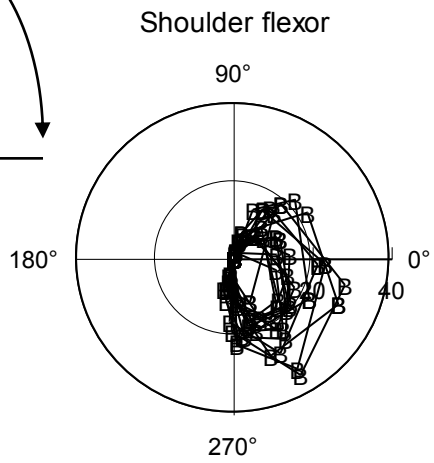
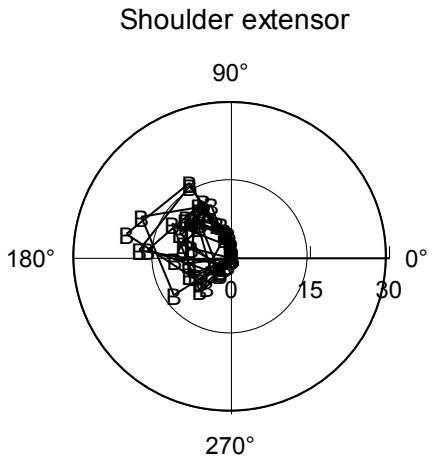
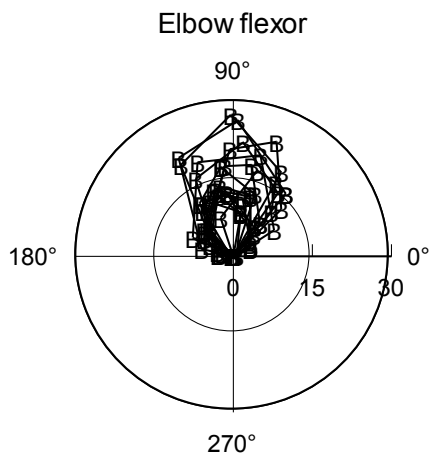
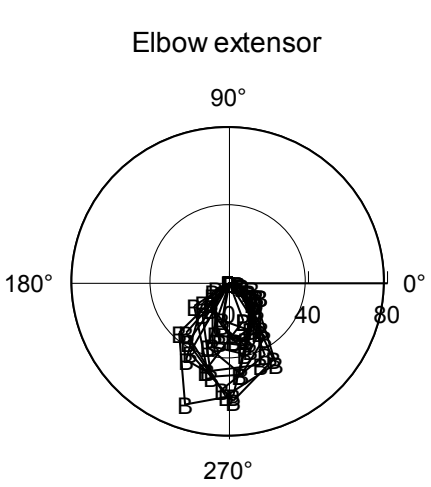


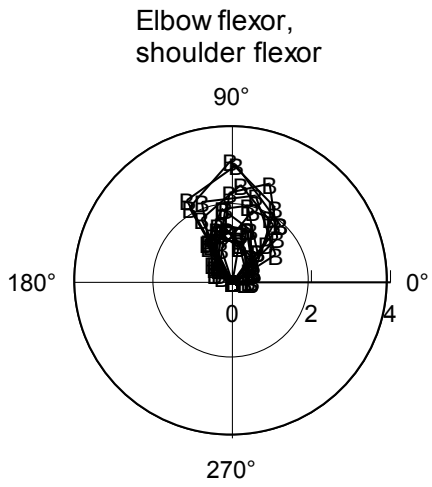
- Broad muscle tuning – synergistic action

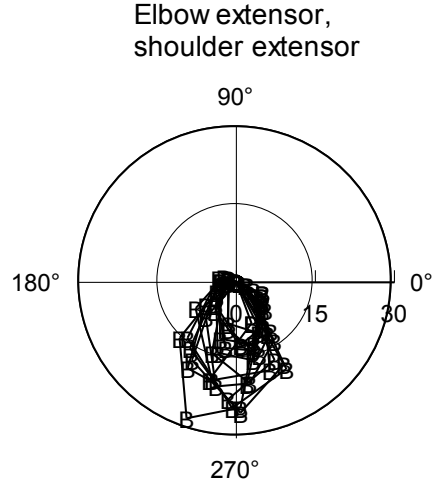








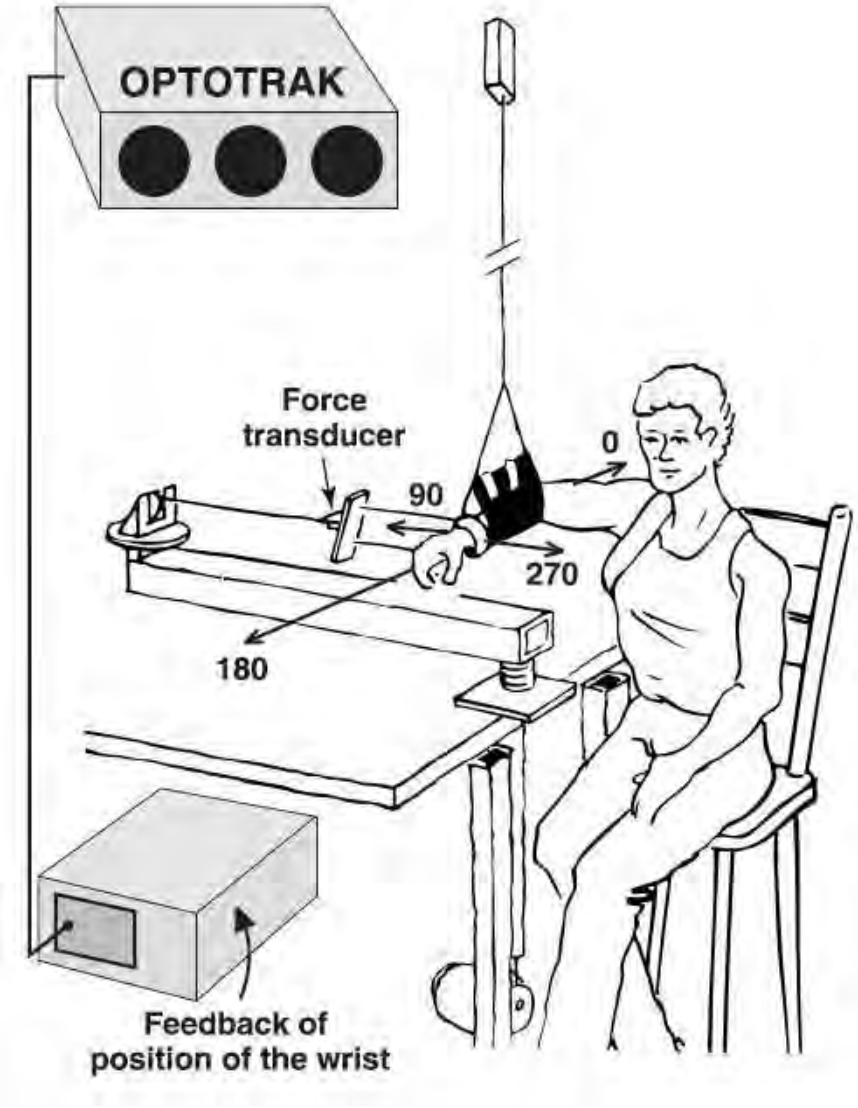




Prilutsky (2000) *Motor Control*

Invariant characteristics of human motion

- Broad muscle tuning – synergistic action



van Bolhuis, Gielen (1999) *Biological Cybernetics*

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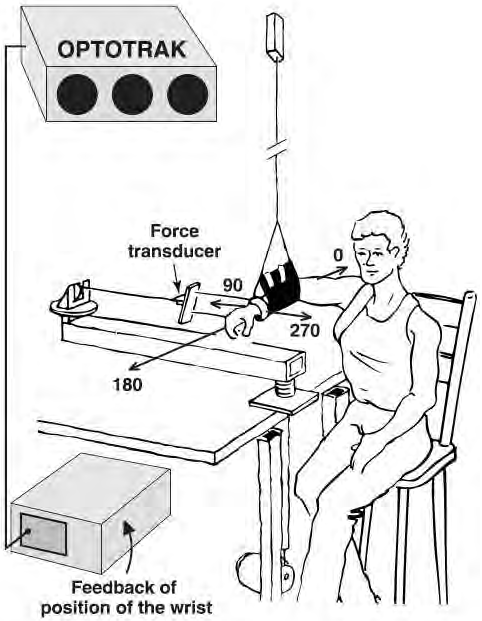
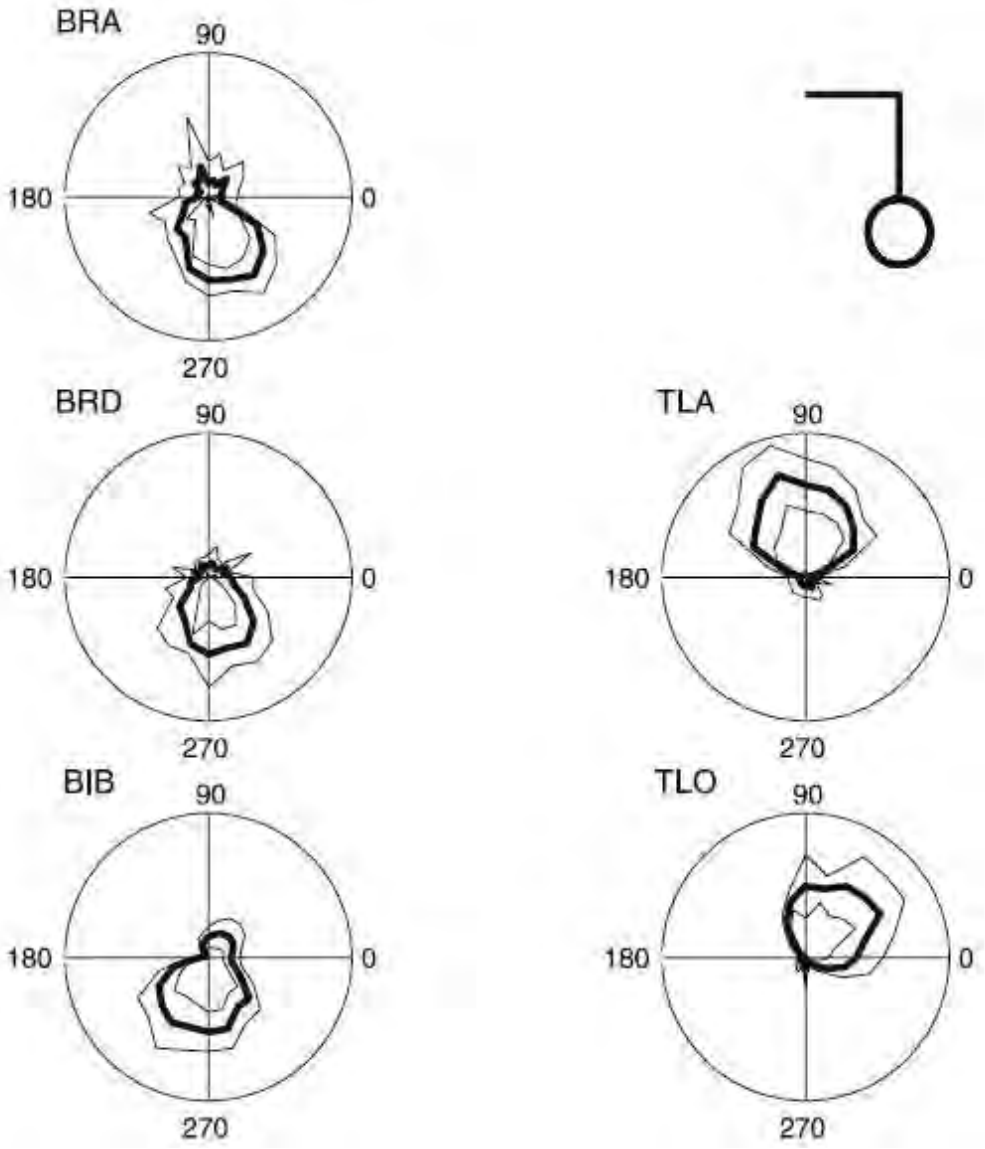




van Bolhuis, Gielen (1999) *Biological Cybernetics*

METHODS

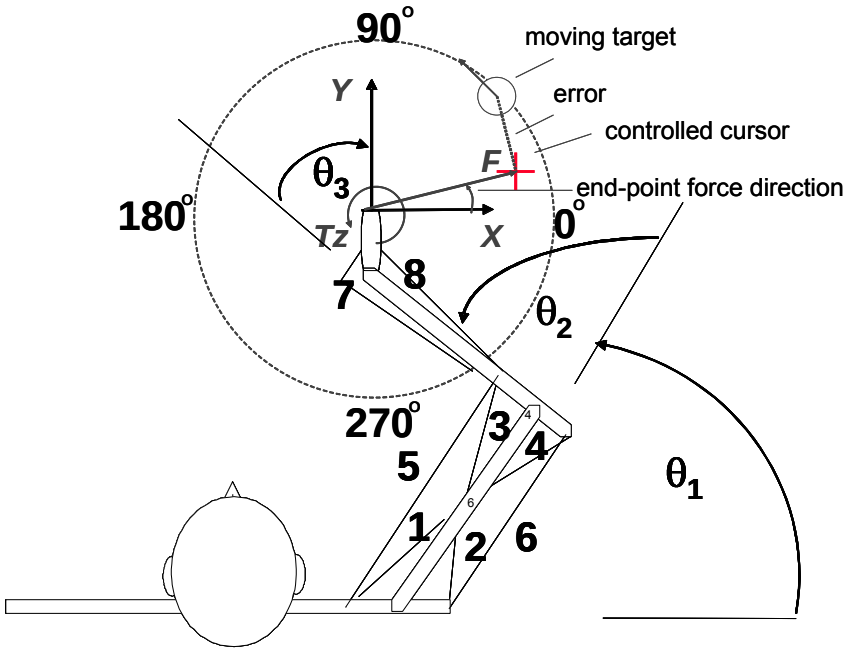
- Subjects

Group	Age (yr.)	Sex	Upper arm length (mm)	Fore arm length (mm)	Hand length (wrist to handle (mm)	Time since injury (mo)
C6-C7, N=6	30±6	M,F	266±26	257±23	60±28	18±17
Control N=6	27+9	M,F	279±23	258±20	89±10	-

METHODS

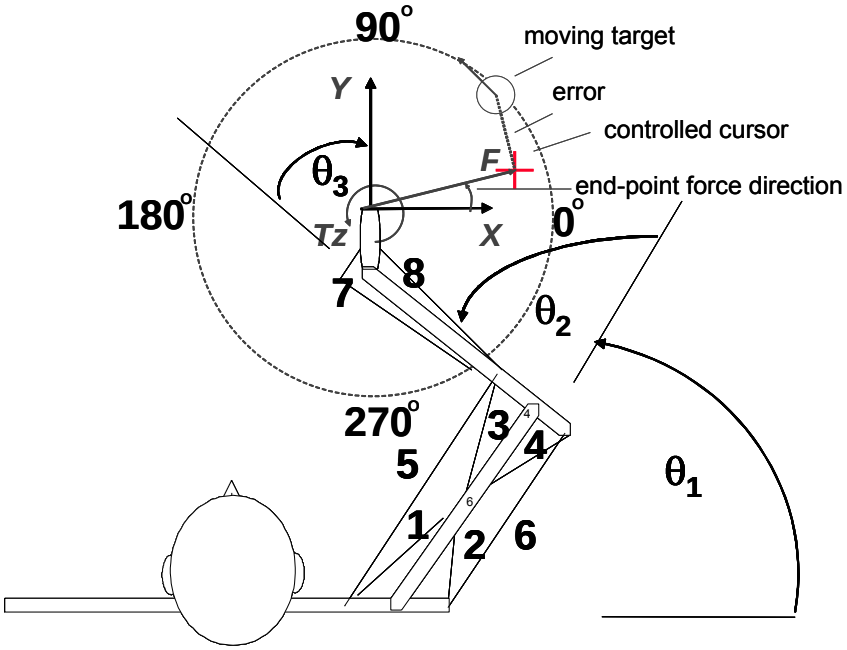
- Data collection

- handle forces and torque
- EMG of 8 muscles



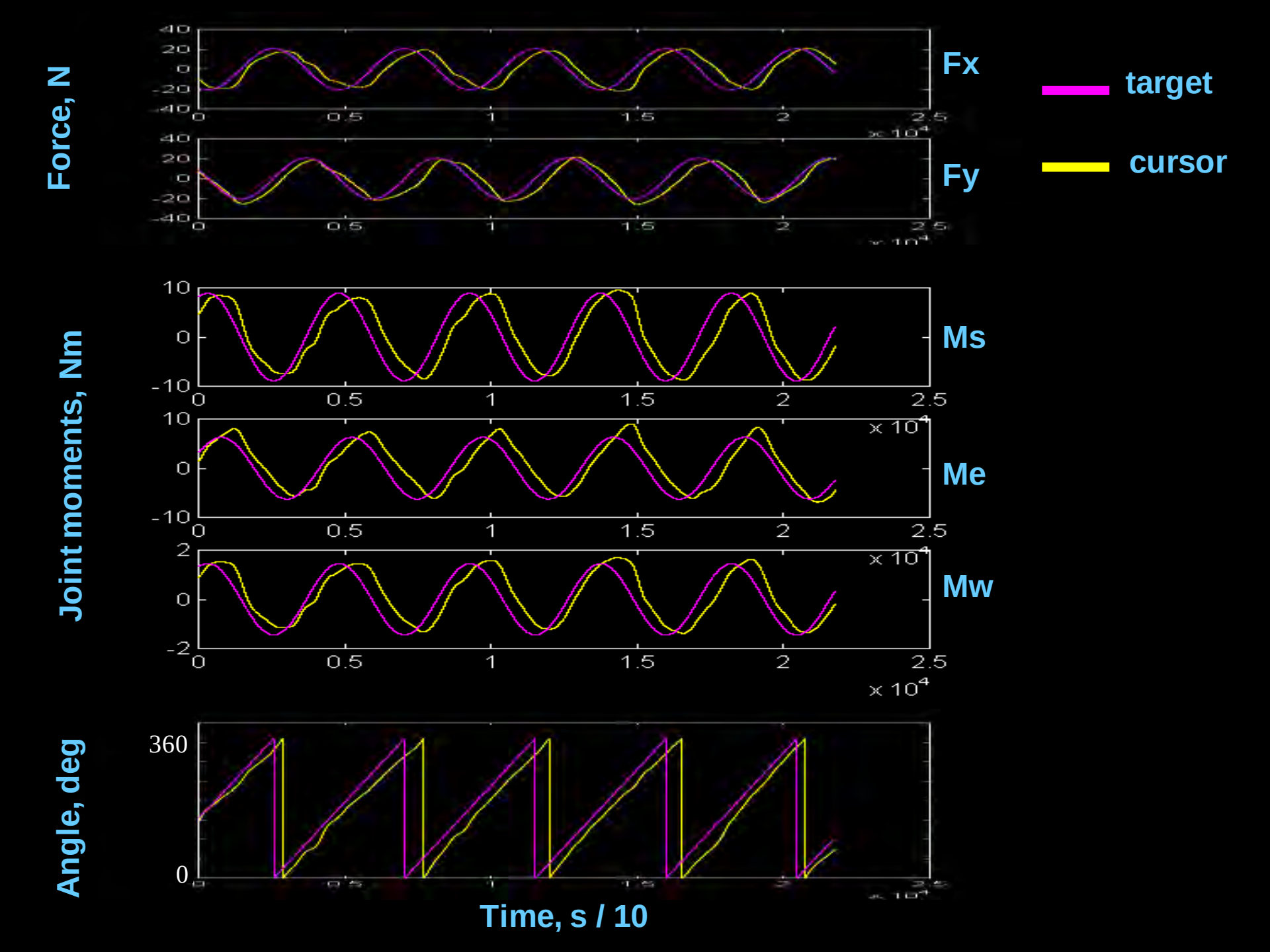
METHODS

- Joint moment calculations

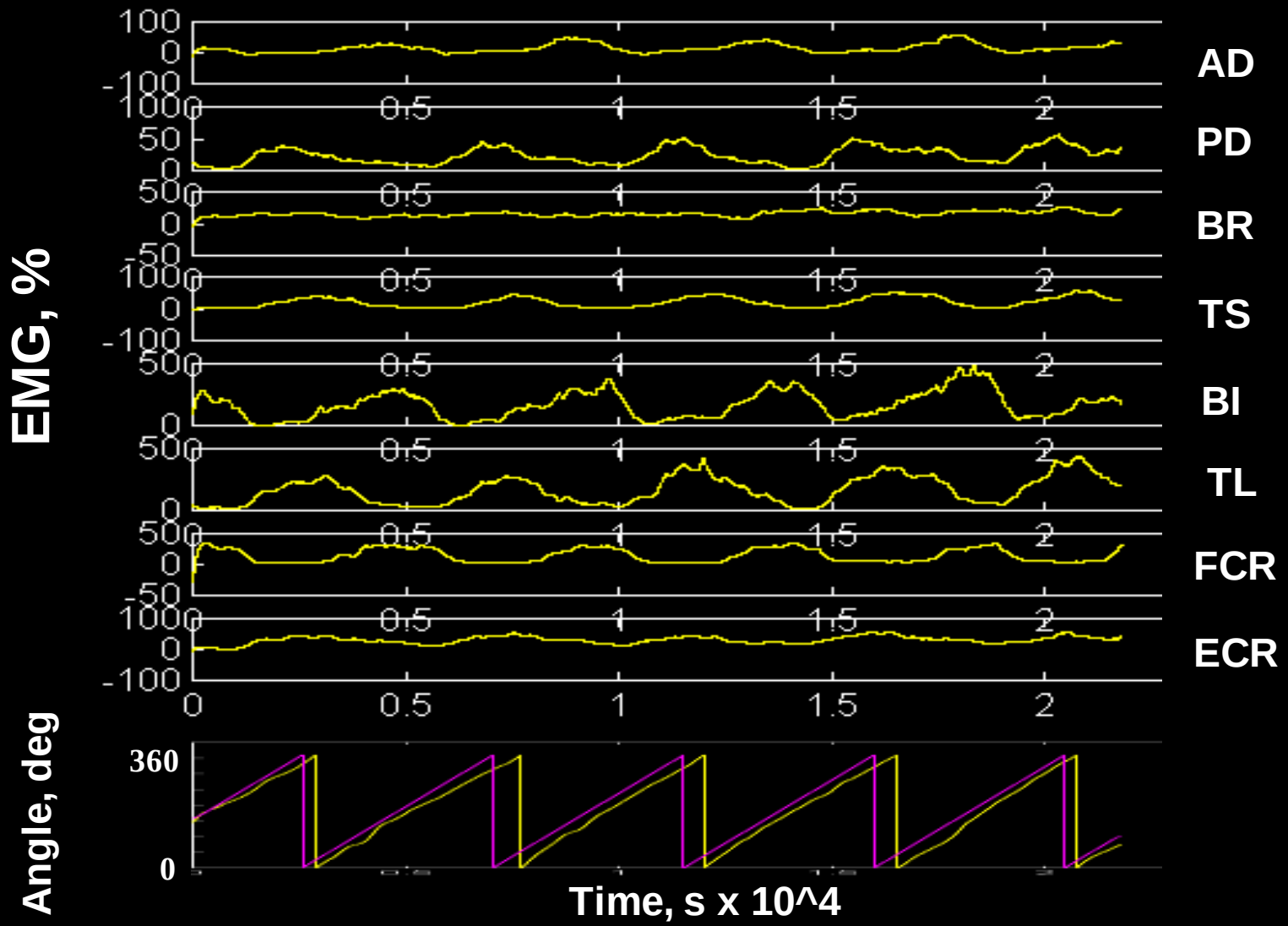


$$\begin{vmatrix} Ms \\ Me \\ Mw \end{vmatrix} = J^T \begin{vmatrix} F_x \\ F_y \\ T_z \end{vmatrix}$$

$$J^T = \begin{vmatrix} (l_1 \sin\alpha_1 + l_2 \sin\alpha_2 + l_3 \sin\alpha_3) & l_1 \cos\alpha_1 + l_2 \cos\alpha_2 + l_3 \cos\alpha_3 & 1 \\ (l_2 \sin\alpha_2 + l_3 \sin\alpha_3) & l_2 \cos\alpha_2 + l_3 \cos\alpha_3 & 1 \\ l_3 \sin\alpha_3 & l_3 \cos\alpha_3 & 1 \end{vmatrix}$$


Force, N
Fx
Fy
target
cursor
Joint moments, Nm
Ms
Me
Mw
Angle, deg
360
0
Time, s / 10

MUSCLE ACTIVATION



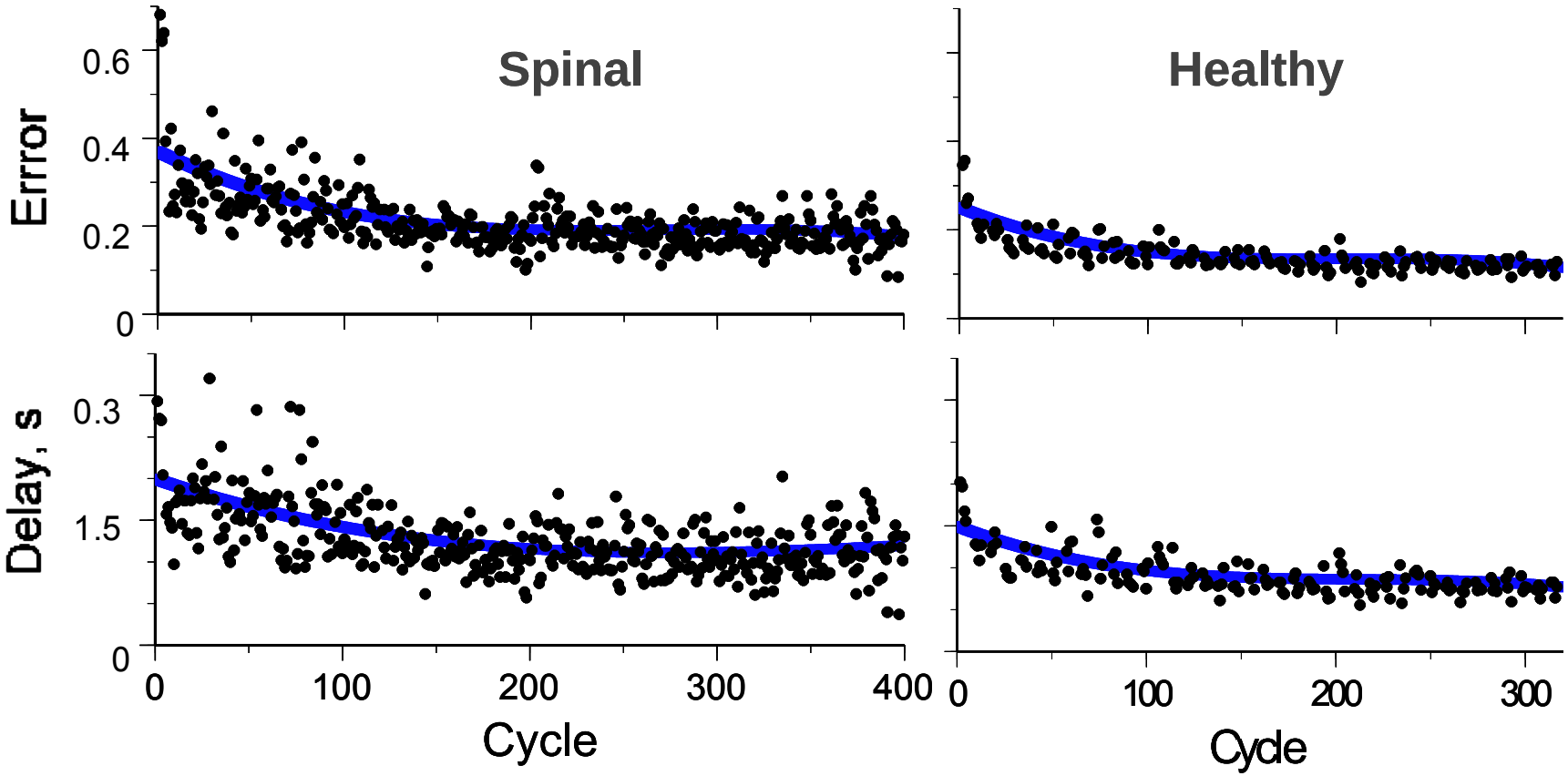
METHODS

- Data analysis

  - tracking error
  - time delay in tracking cycle
  - normalized EMG envelope peak
  - joint moment peak
  - EMG preferred direction for each muscle
  - moment preferred direction for each joint

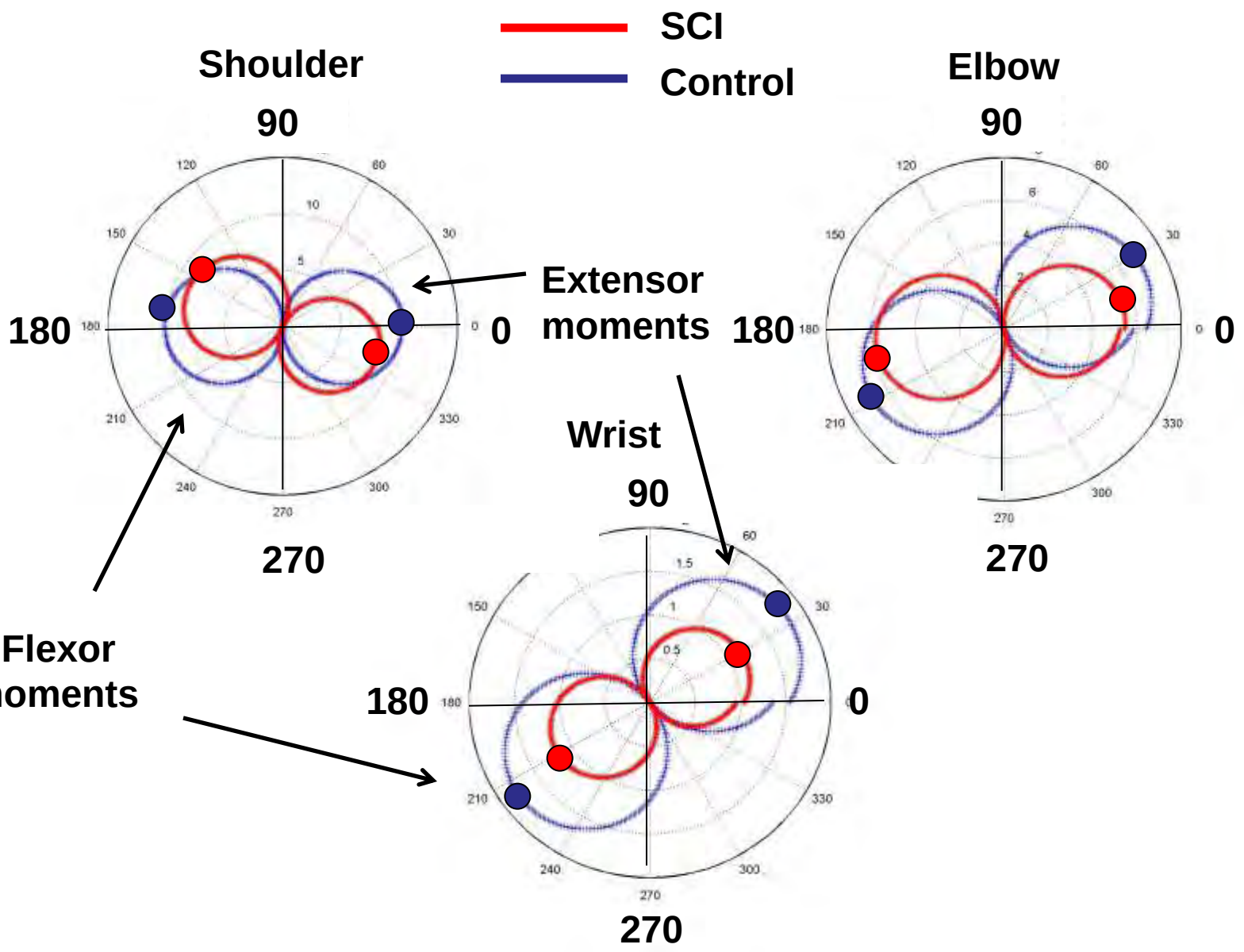
RESULTS

- Tracking error and delay



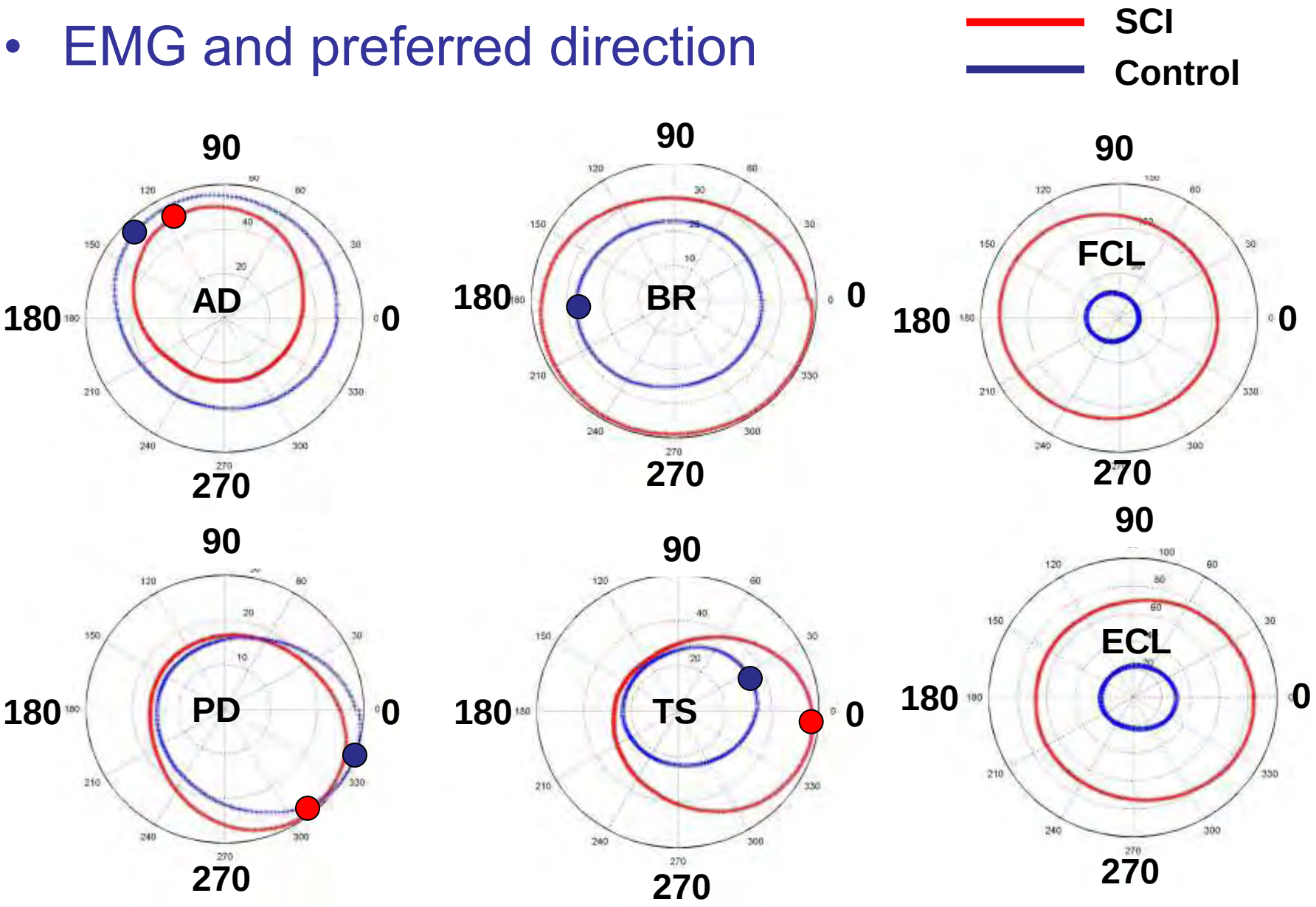
RESULTS

- Joint moments



RESULTS

- EMG and preferred direction



Summary

- Human arm is highly redundant
  - 22 joints, 30 DOF, 66 actons, 264 acton actions
  - 3 actons/joint, 2.2/DOF, 12 acton action / joint

- Movement control is simplified
  - kinematic invariants
  - muscle activity invariants

- Multi-joint control task in SCI individual
  - redundancy helps?

- Neuromechanical modeling – helps!
  - SIMM, USA
  - AnyBody Technology, Denmark
  - AnimatLab (GA State University)

Acknowledgments

Shepherd Center, Atlanta

Subjects
L. VanHiel
J. Tidwell
D. Backus

Center for Human Movement Studies
School of Applied Physiology, GA Tech

D. Ashley
L. Harley