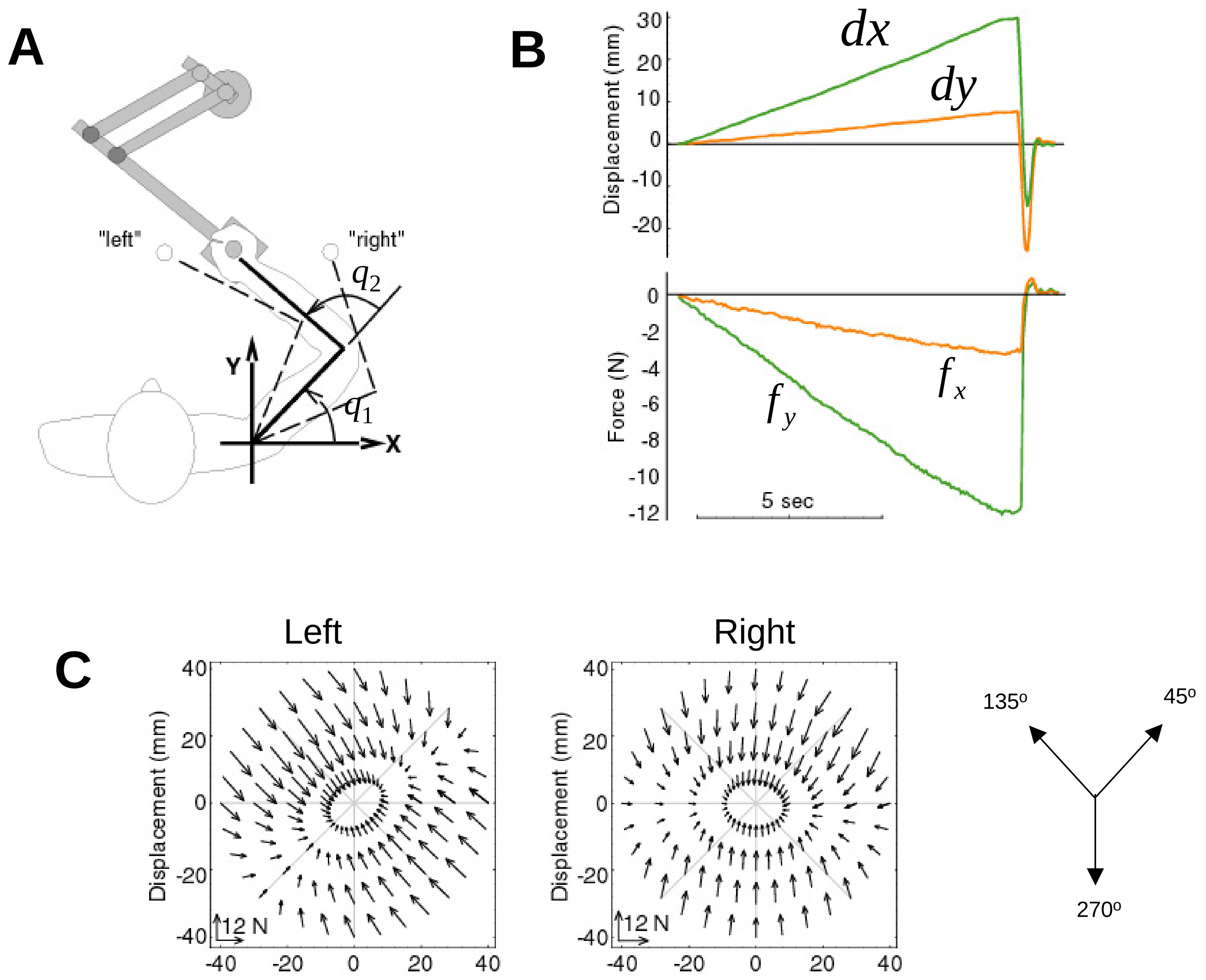
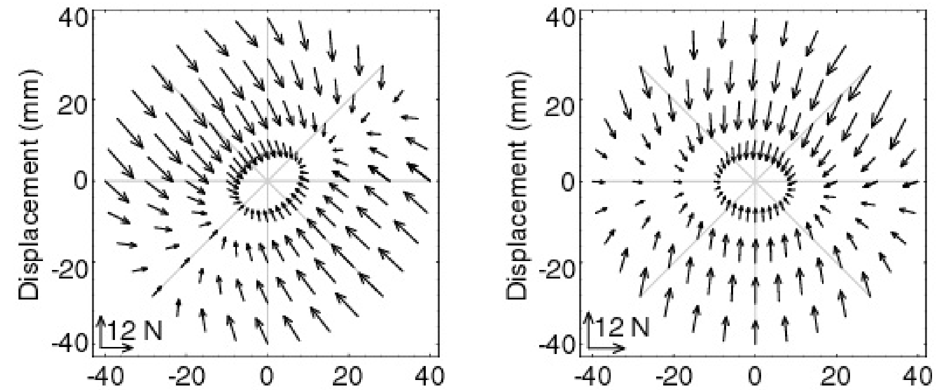


A
"left"
"right"
q_2
q_1
Y
X
B
Displacement (mm)
30
20
10
0
-10
-20
dx
dy
Force (N)
0
-2
-4
-6
-8
-10
-12
f_x
f_y
5 sec
C
Left
Right
Displacement (mm)
40
20
0
-20
-40
12 N
135°
45°
270°



$$\underline{df} \equiv \begin{bmatrix} df_x \\ df_y \end{bmatrix} \quad \underline{dx} \equiv \begin{bmatrix} dx_x \\ dx_y \end{bmatrix}$$

Data set : $\{\underline{dx}, \underline{df}\}_1, \{\underline{dx}, \underline{df}\}_2, \cdots \quad \{\underline{dx}, \underline{df}\}_n$

Objective : find the best fit to $K_x = \dfrac{\underline{df}}{\underline{dx}}$ where $K_x = \begin{bmatrix} K_{x11} & K_{x12} \\ K_{x21} & K_{x22} \end{bmatrix}$

$$\underline{df} = K_x \underline{dx}$$

error in fit for data set 1 : $\varepsilon \equiv \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \end{bmatrix} = \begin{bmatrix} df_x - K_{x11} dx_x - K_{x12} dx_y \\ df_x - K_{x21} dx_x - K_{x22} dx_y \end{bmatrix}$

cost function to minimize : $e \equiv \varepsilon^T \varepsilon = \left(df_x - K_{x11} dx_x - K_{x12} dx_y\right)^2 + \left(df_x - K_{x21} dx_x - K_{x22} dx_y\right)^2$

$$\frac{de}{dK_{x11}} = -2\left(df_x - K_{x11} dx_x - K_{x12} dx_y\right) dx_x = -2 \varepsilon_x dx_x$$

Gradient descent : $\left(K_{x11}\right)_{n+1} = \left(K_{x11}\right)_n - \eta \dfrac{de}{dK_{x11}} = \left(K_{x11}\right)_n + 2 \eta \varepsilon_x dx_x$

Arm's stiffness in joint coordinates

$$J(\underline{q}) = \frac{d\underline{x}}{d\underline{q}}$$

$$K_x = \frac{d\underline{f}}{d\underline{x}} \qquad K_j = \frac{d\underline{\tau}}{d\underline{q}}$$

$$\underline{\tau} = J(\underline{q})^T \underline{f}$$

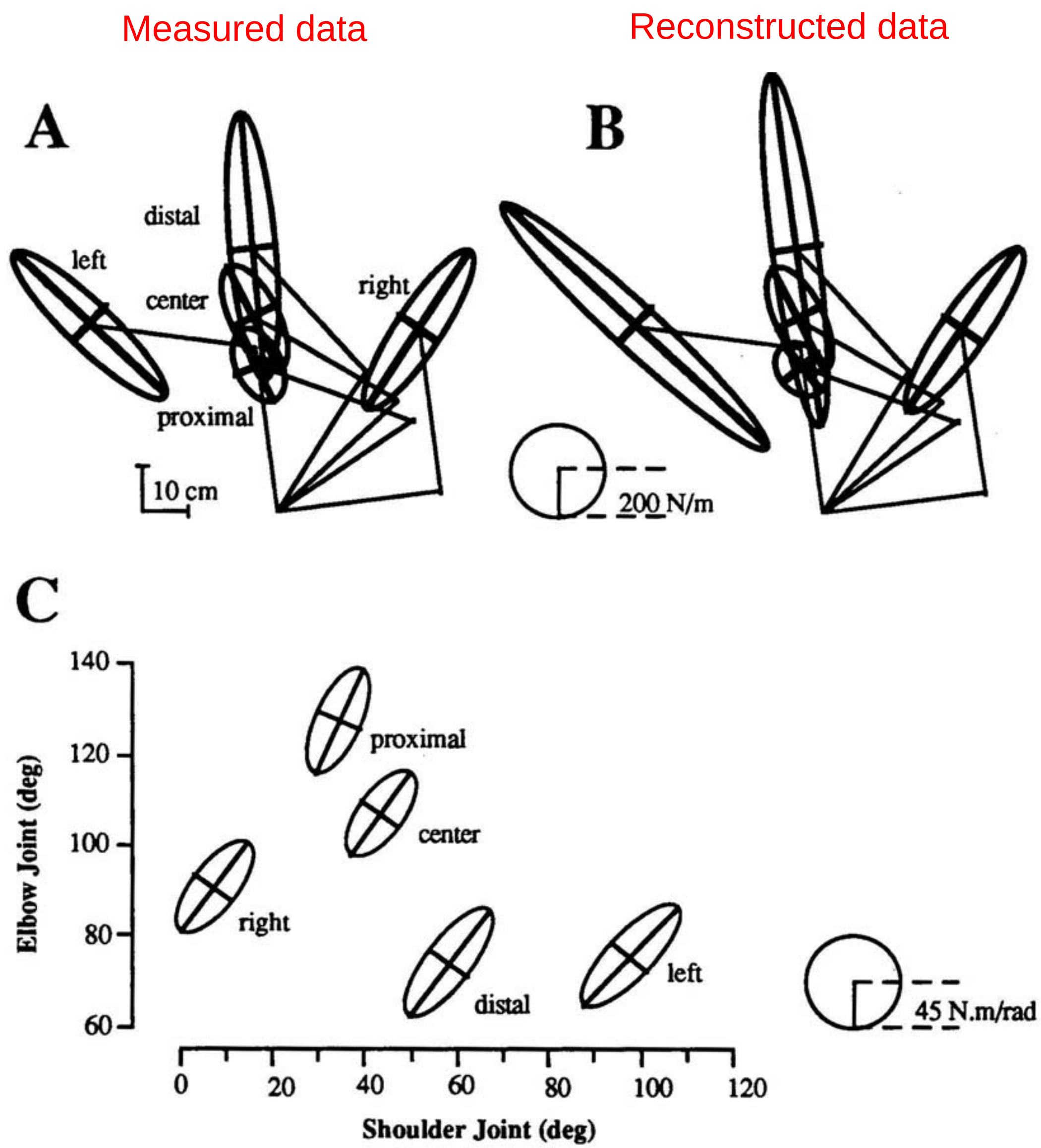
$$K_j = \frac{d\left(J(\underline{q})^T \underline{f}\right)}{d\underline{q}} = \frac{d\left(J(\underline{q})^T\right)}{d\underline{q}} \underline{f} + J(\underline{q})^T \frac{d\underline{f}}{d\underline{q}}$$

$$\text{for small displacements, assume } \frac{d\left(J(\underline{q})^T\right)}{d\underline{q}} \approx 0$$

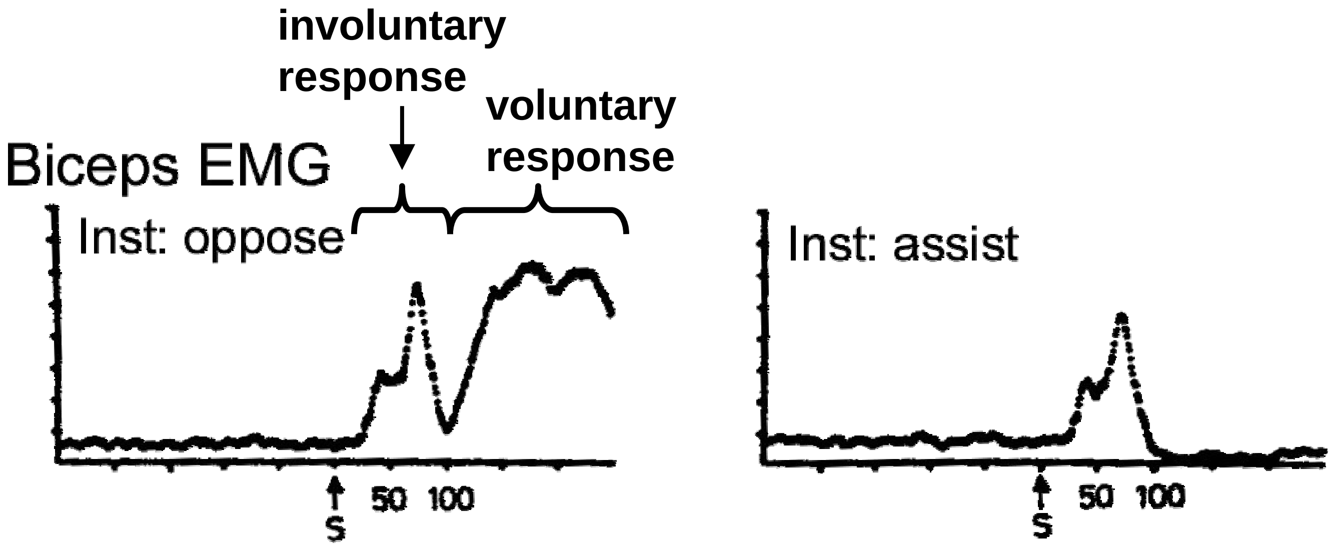
$$K_j = J(\underline{q})^T \frac{d\underline{f}}{d\underline{q}} = J(\underline{q})^T \frac{d\underline{f}}{d\underline{x}} J(\underline{q}) \qquad K_j = J(\underline{q})^T K_x J(\underline{q})$$

$$K_j = J(\underline{q})^T K_x \; J(\underline{q})$$

There is remarkable regularity in the stiffness of the arm when it is expressed in joint coordinates. K_j is essentially constant and does not vary as a function of arm position. The reconstructed data is from the K_j measured at the center position.

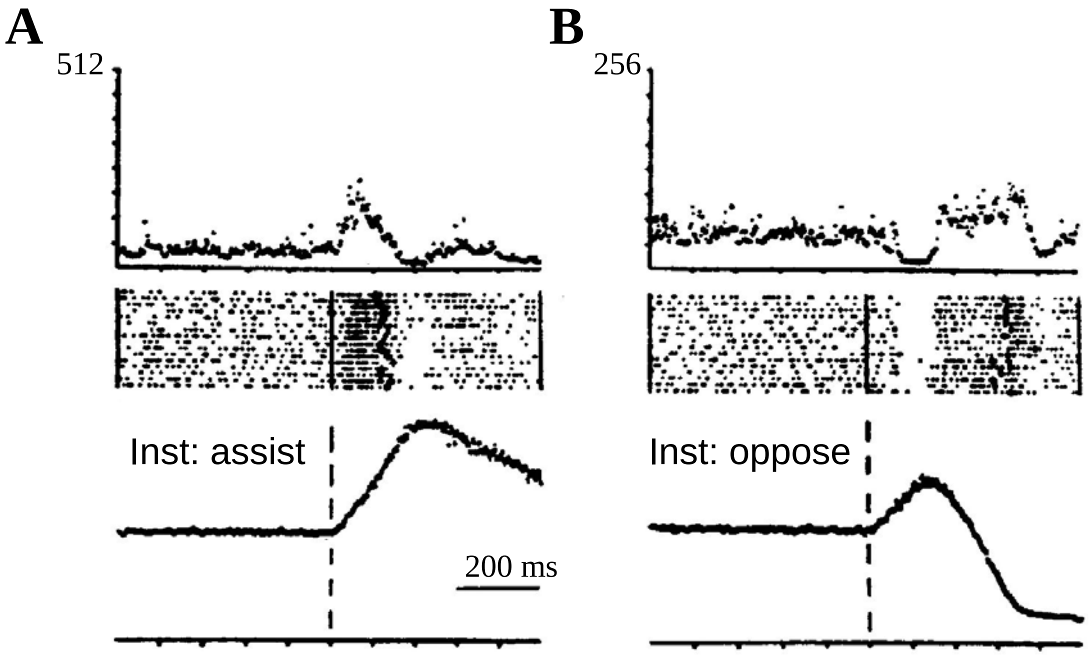


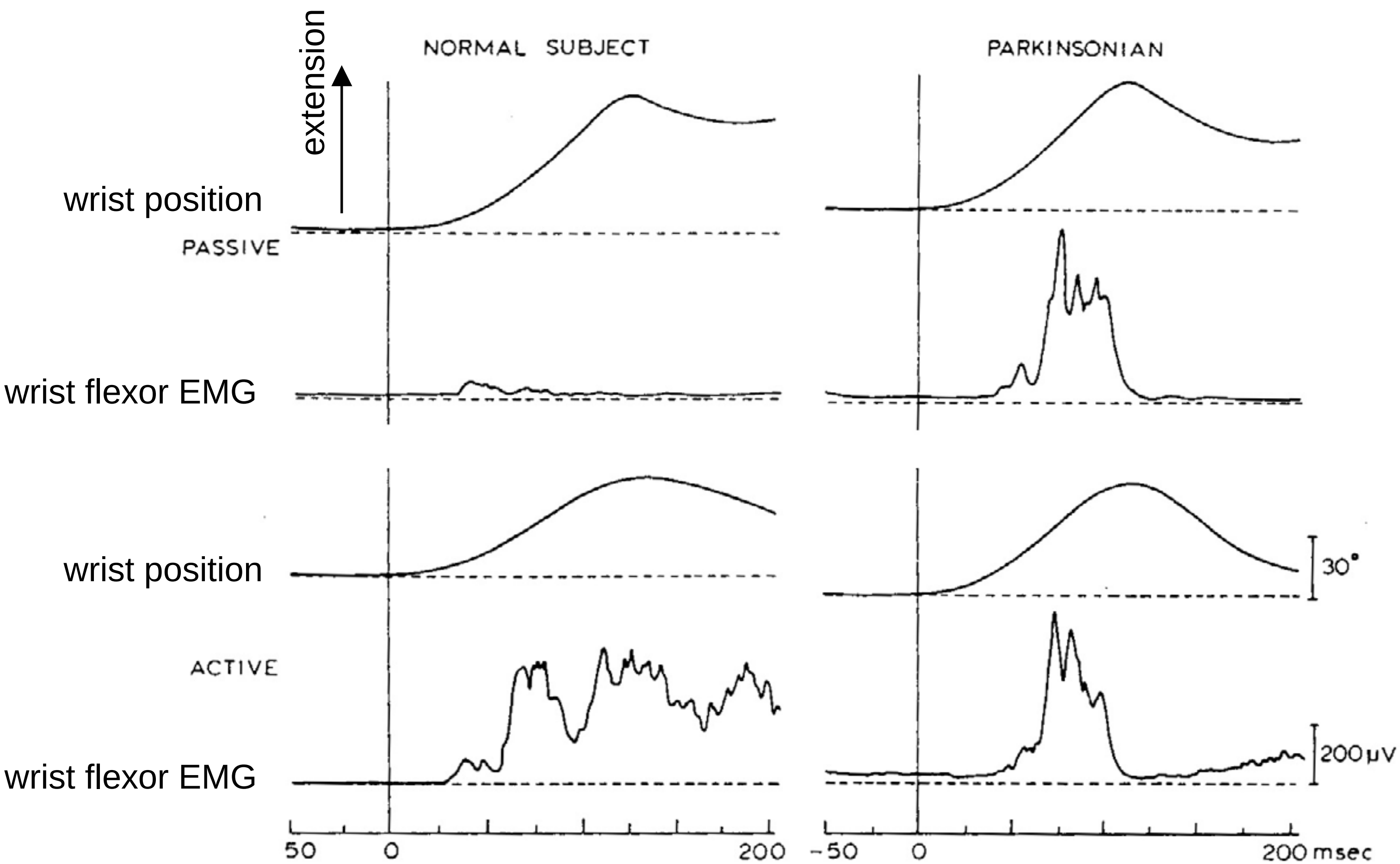
Time delays in the short- and long-loop reflexes



Torque perturbations were imposed on the elbow of a subject at random times (S indicates the time of perturbation). On each trial, an LED instructed the subject to either oppose the torque or assist the torque.

Instruction dependent activity in the cerebellar dentate nucleus in response to a perturbation




extension
NORMAL SUBJECT
PARKINSONIAN
wrist position
PASSIVE
wrist flexor EMG
wrist position
ACTIVE
wrist flexor EMG
30°
200 μV
50
0
200
-50
0
200 msec