Too many cooks in the kitchen: an experimental and mathematical approach to muscle redundancy

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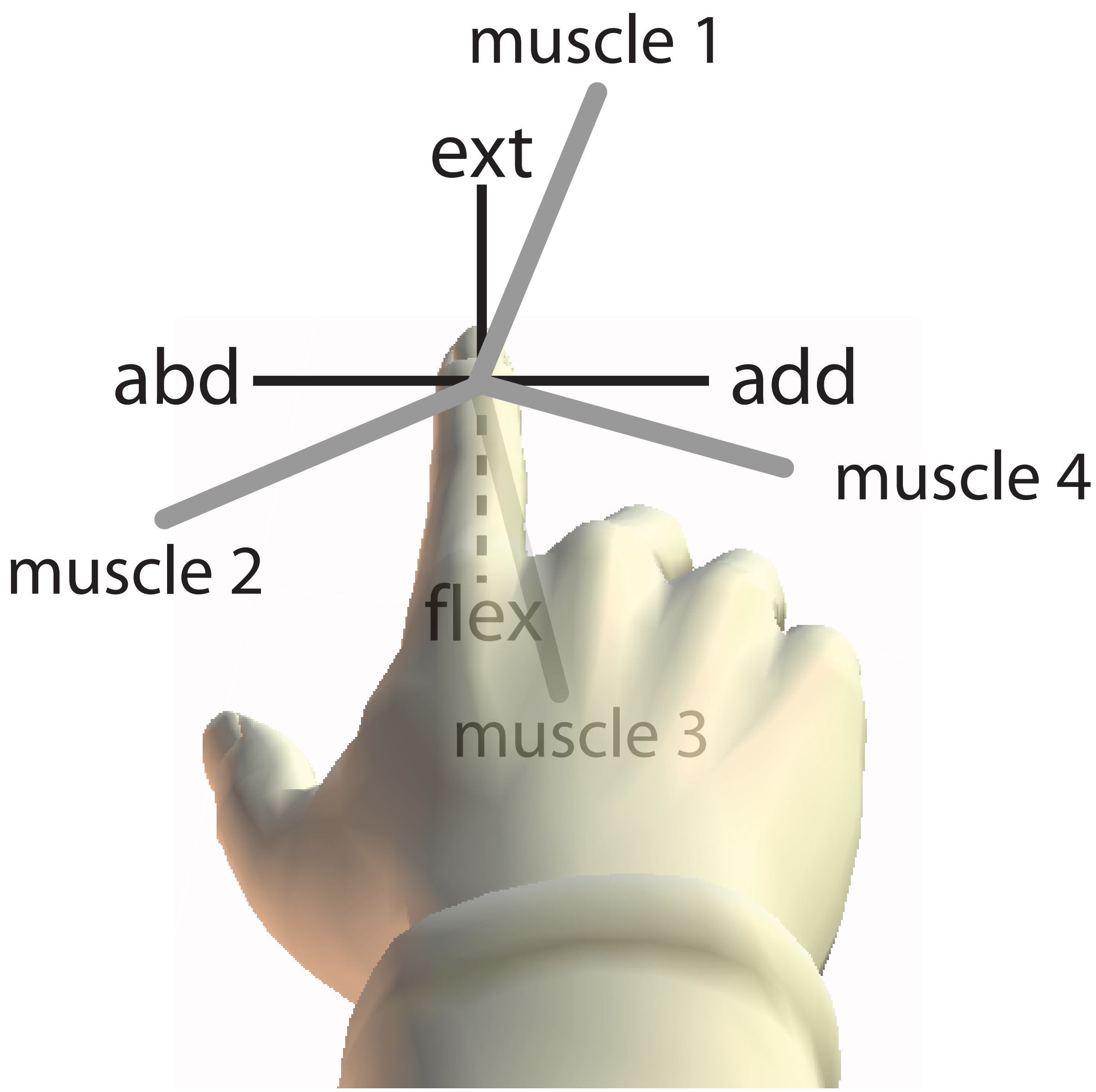
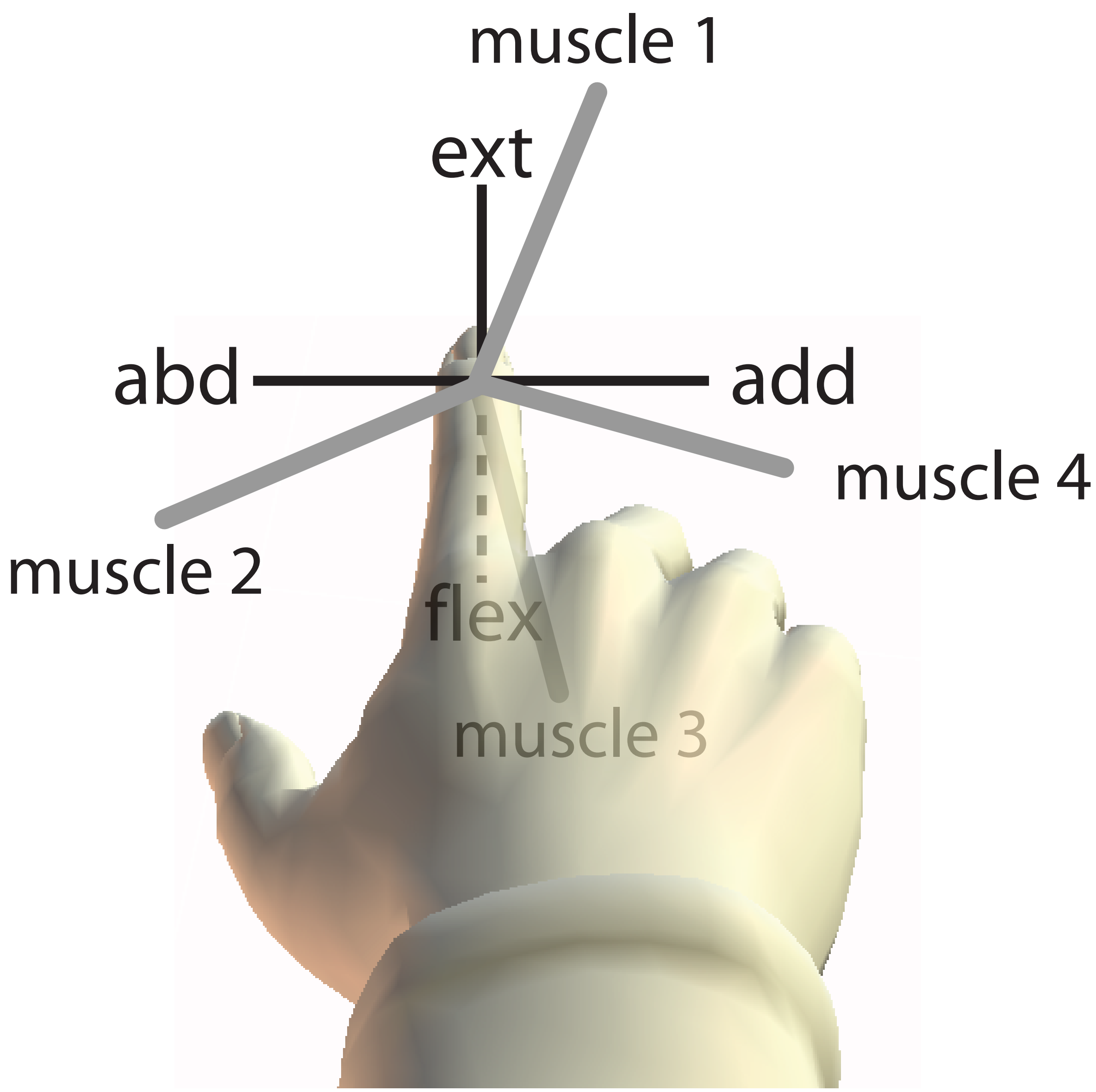
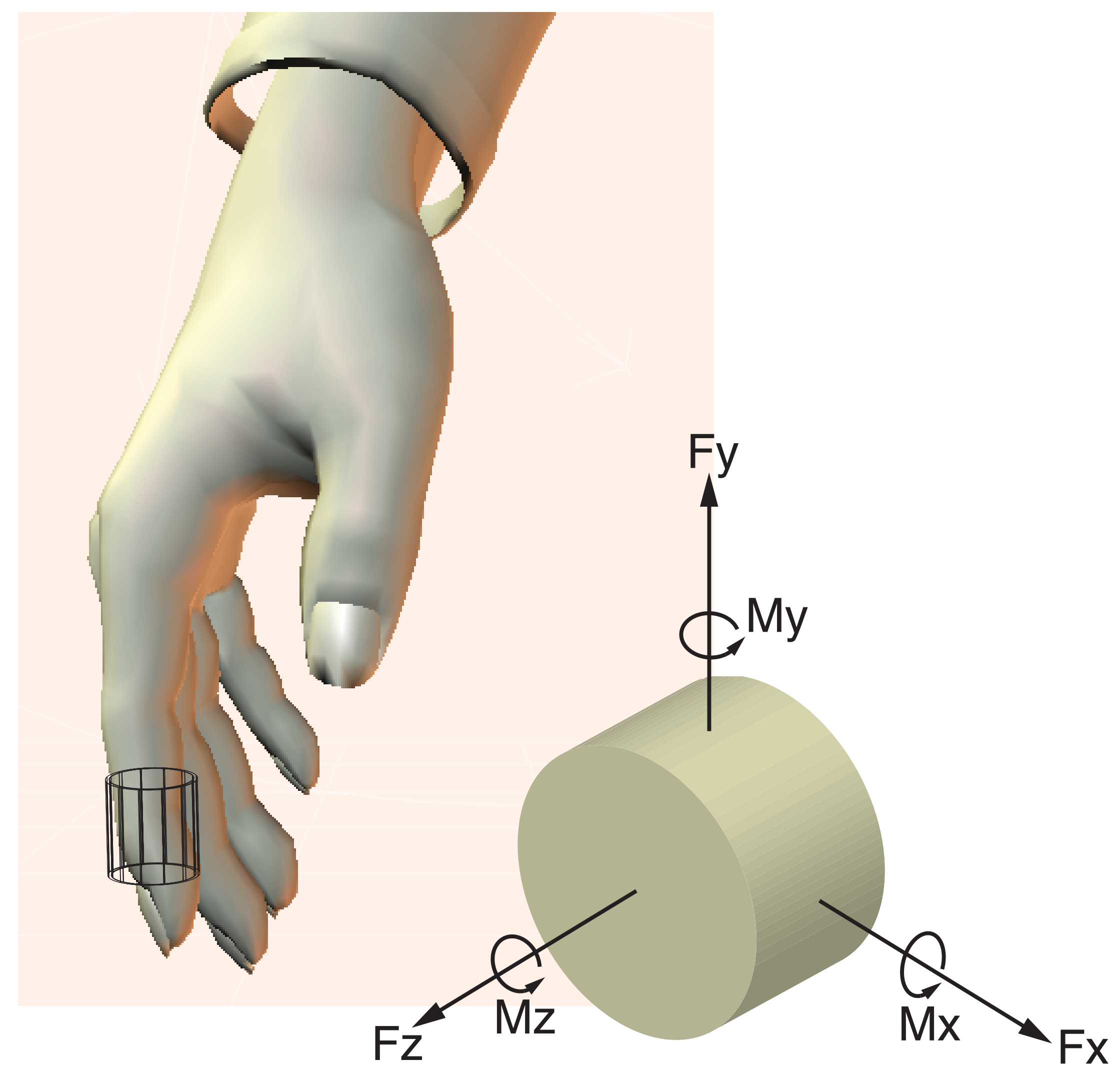
How might the brain think about muscles?



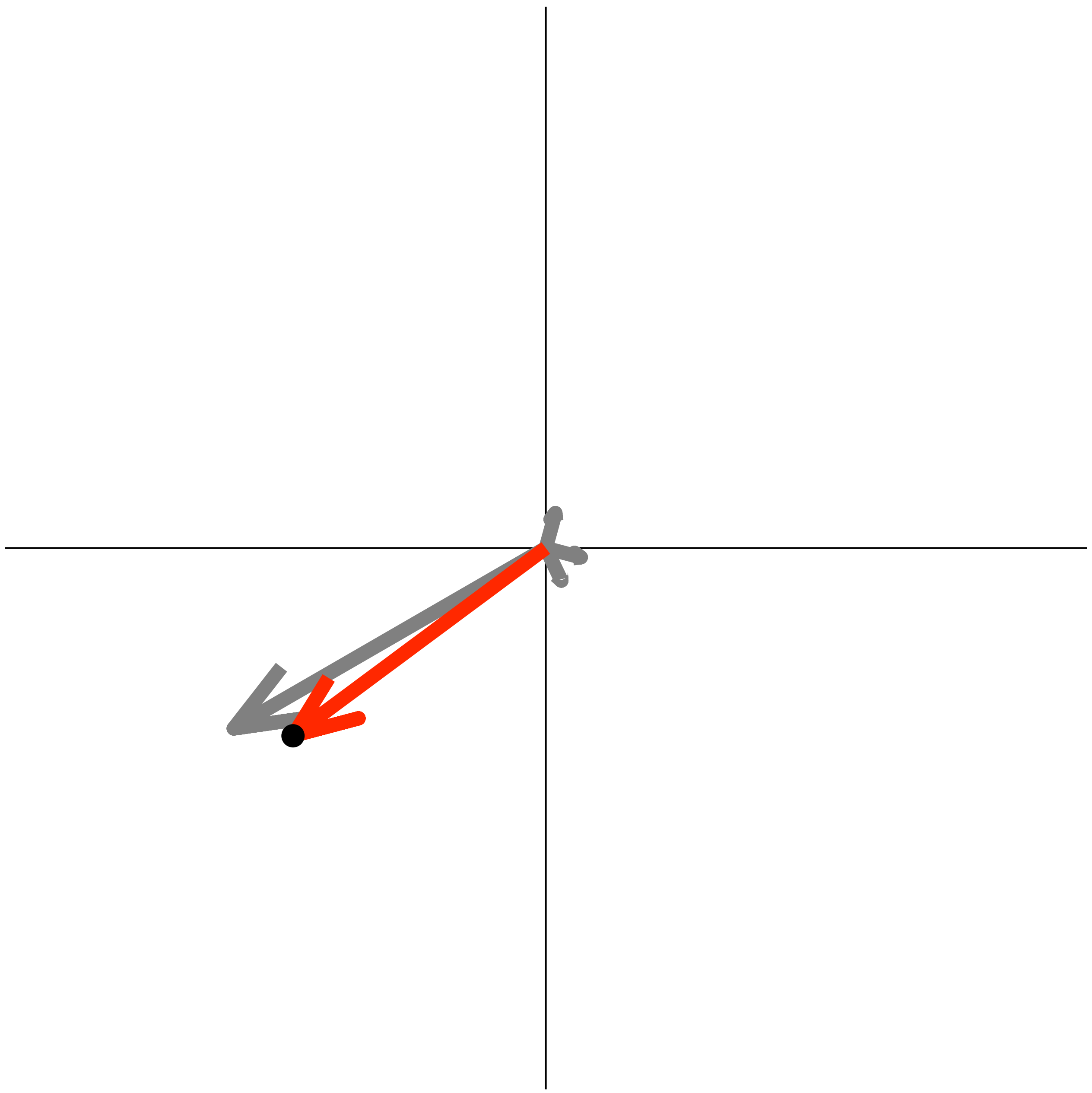
How might the brain think about muscles?



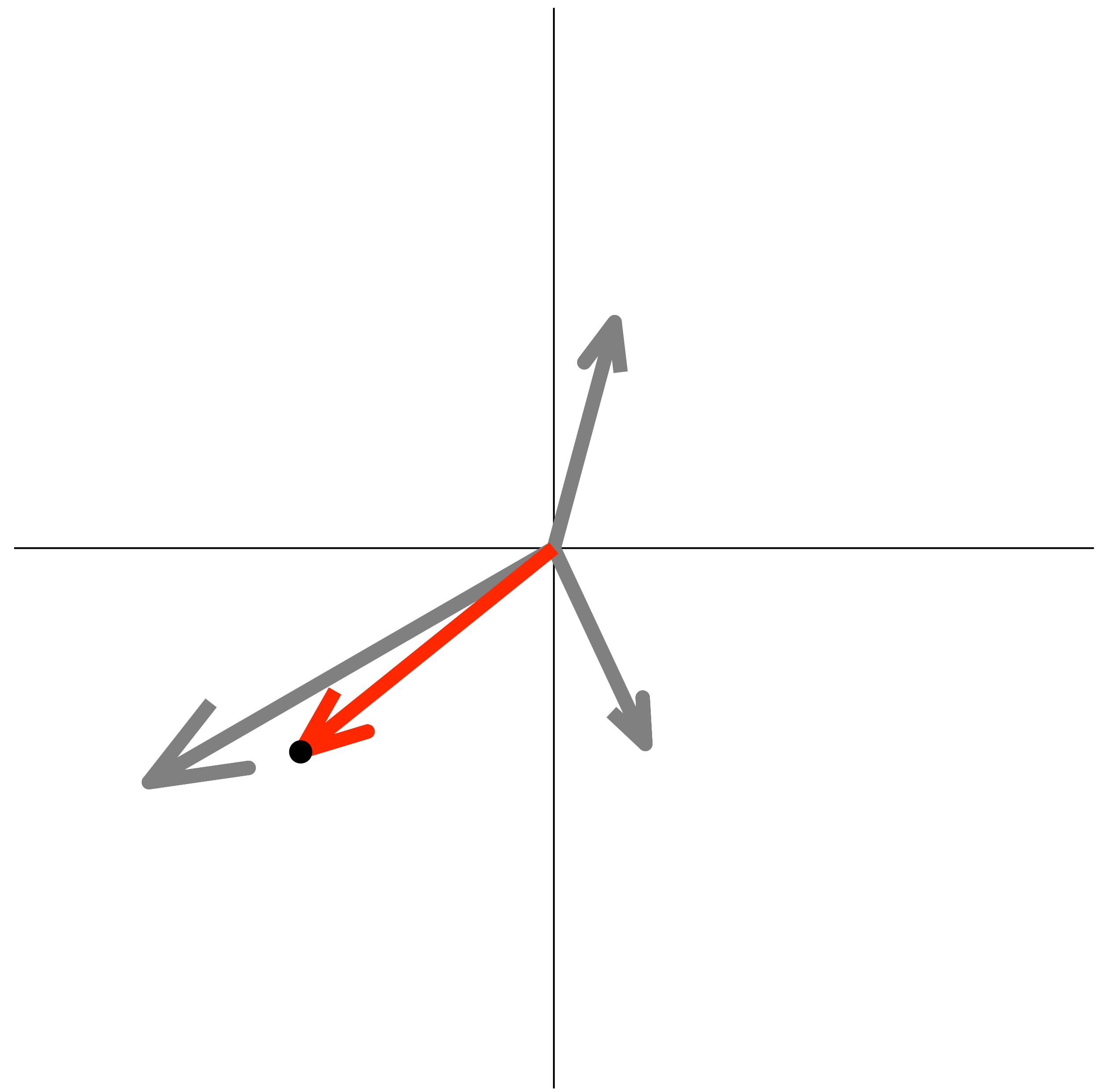


Muscle redundancy

“Prime mover”



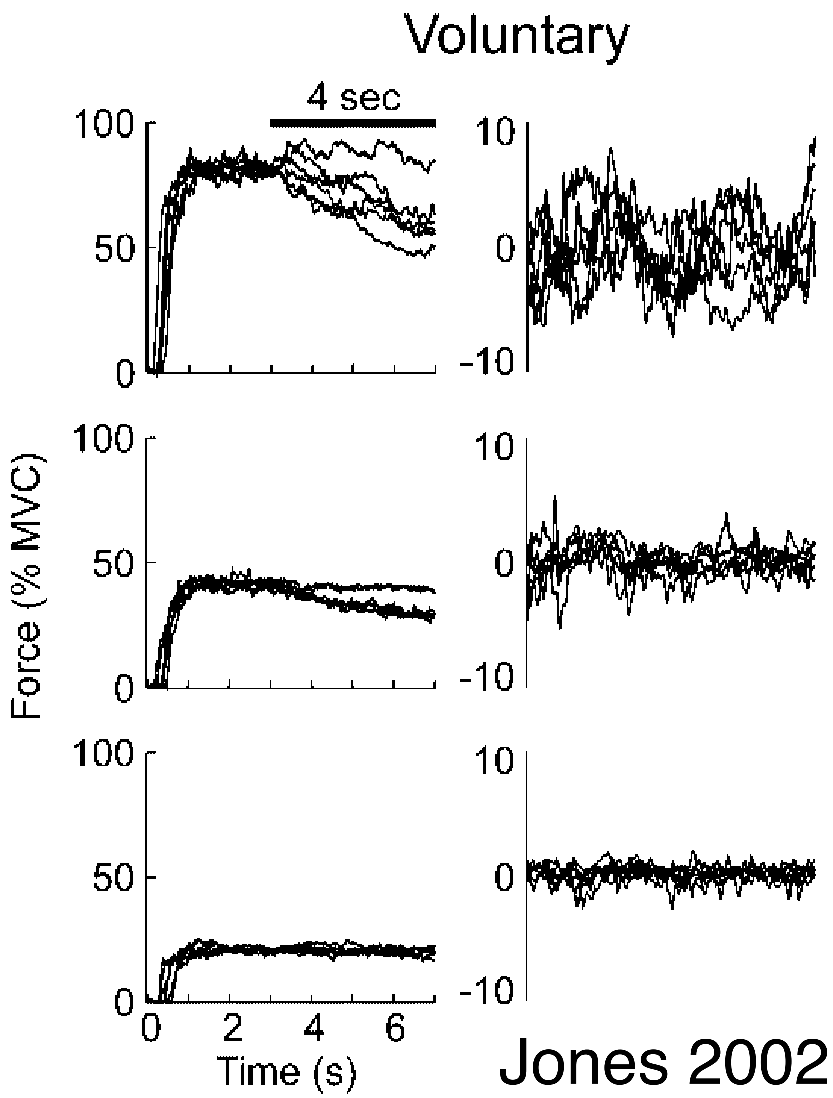
“Cooperation”



$$F(t) = F_1(t) + F_2(t) + F_3(t) + F_4(t)$$

Signal-dependent noise

$$\sigma_i \propto \mu_i$$

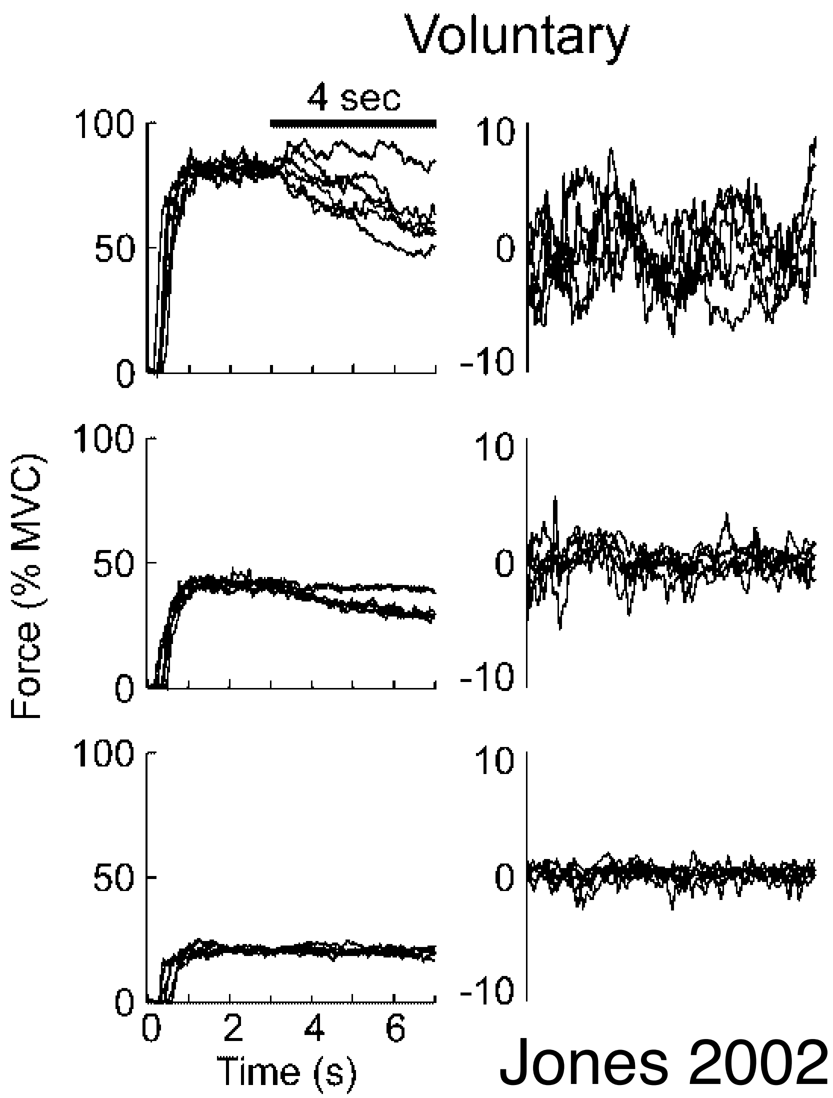


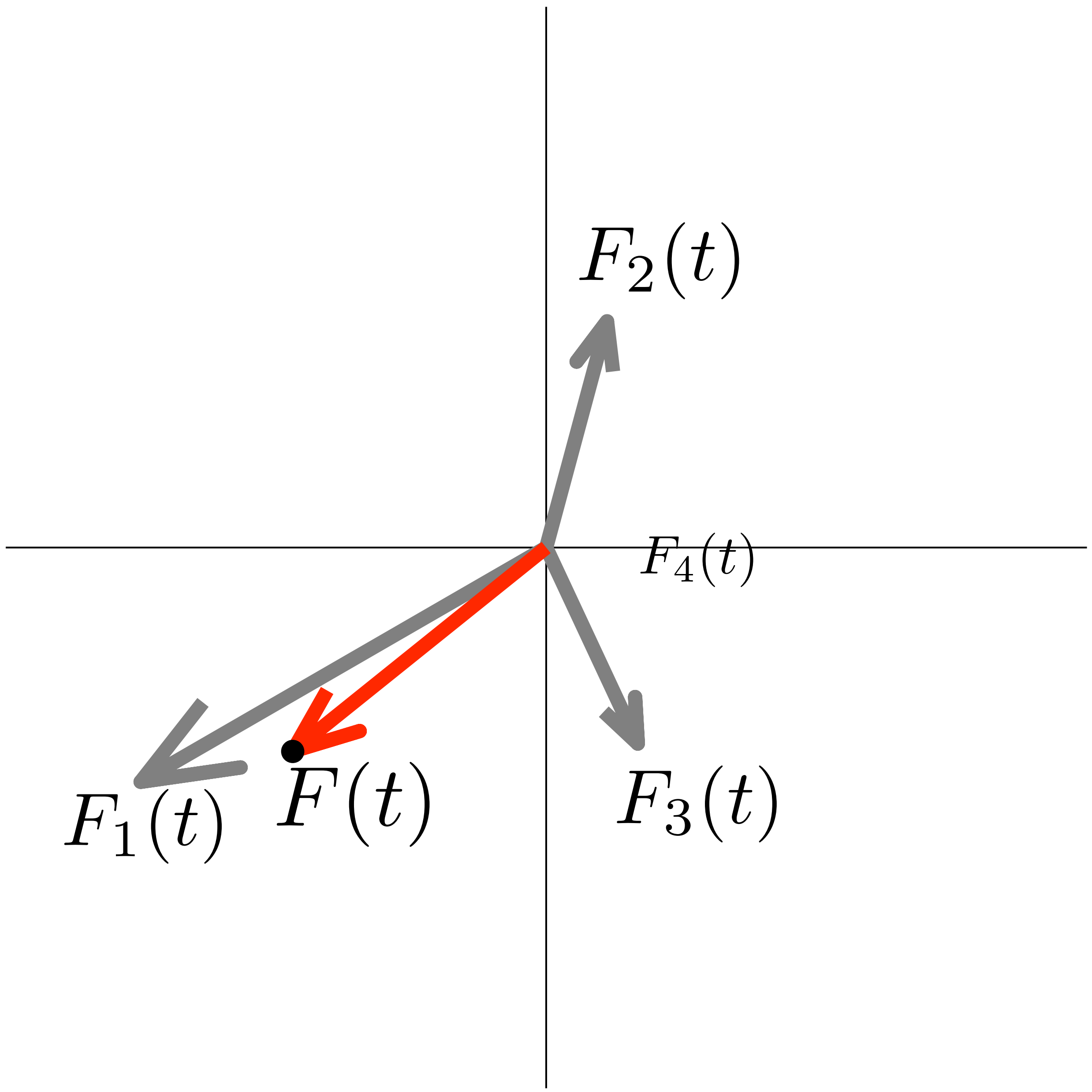
Jones 2002

Force variance carries information about mean force

Signal-dependent noise

$$\sigma_i \propto \mu_i$$

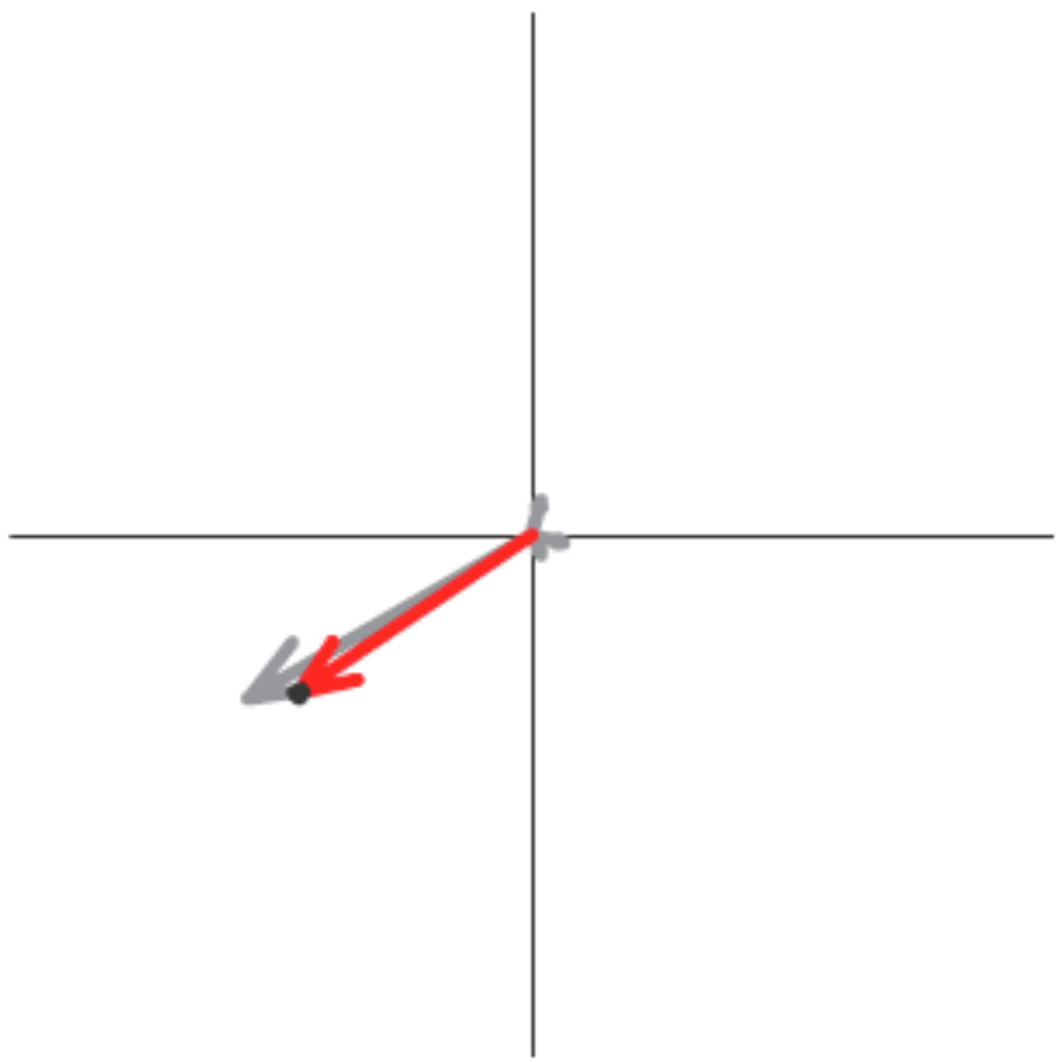




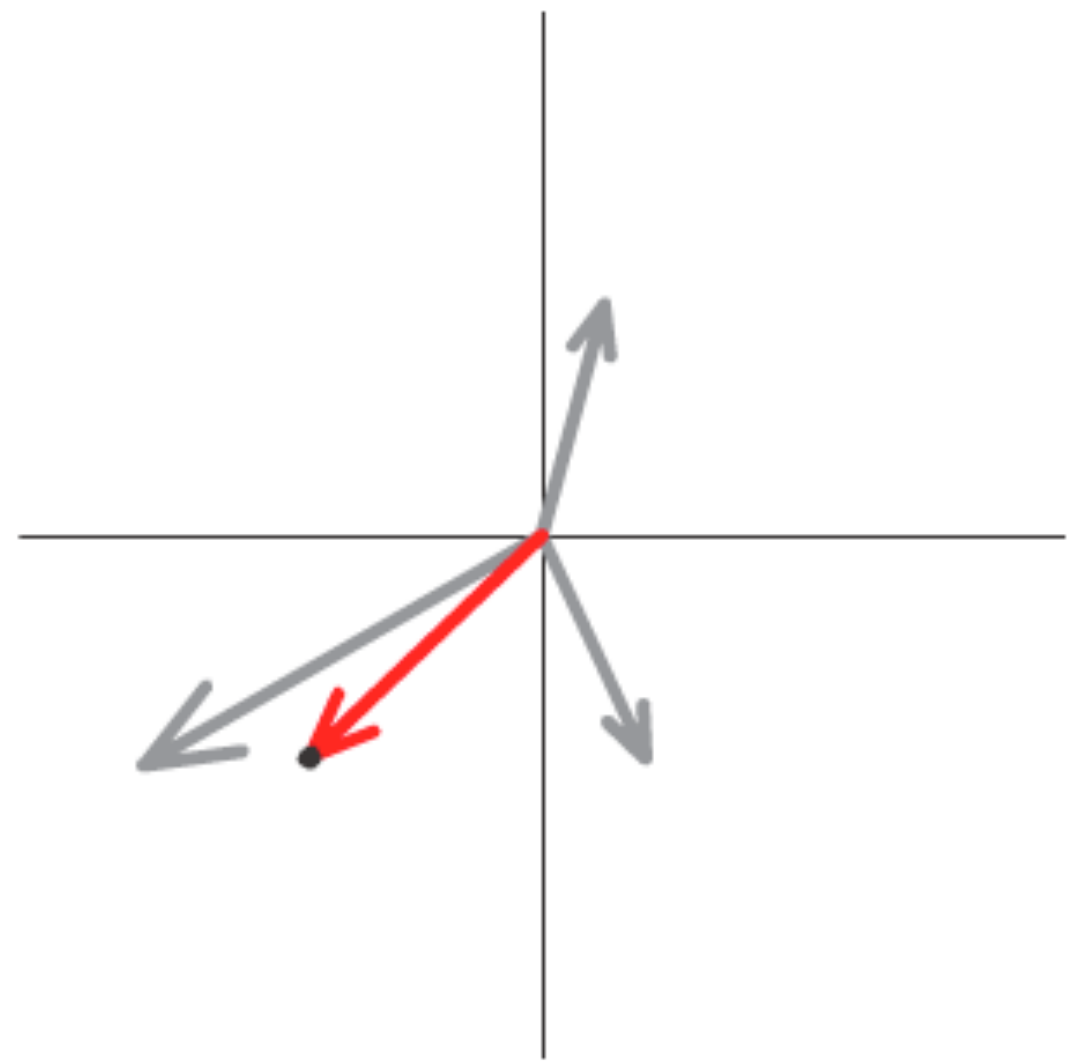
Force variance carries information about mean force

Force covariance ellipse

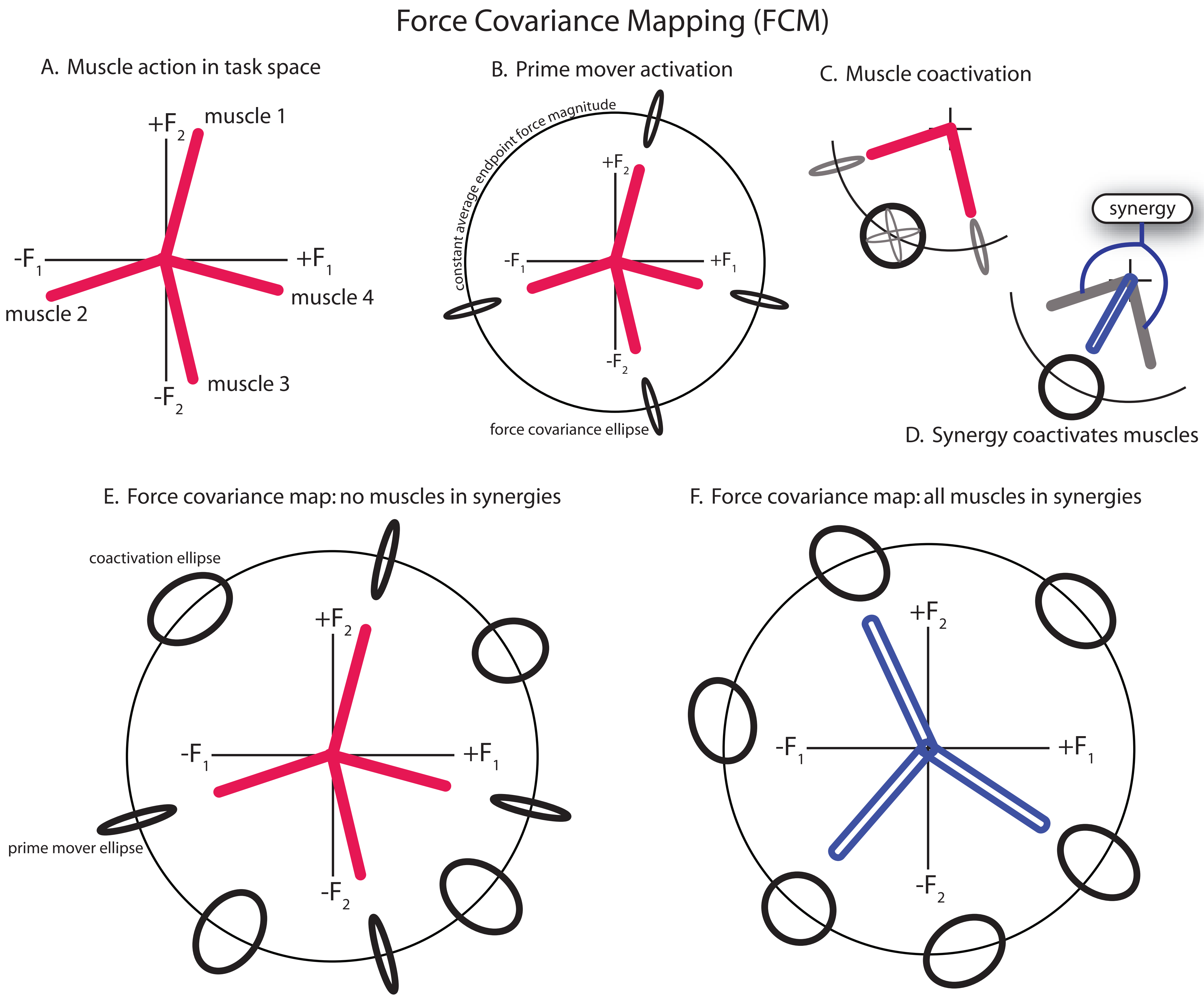
“Prime mover”



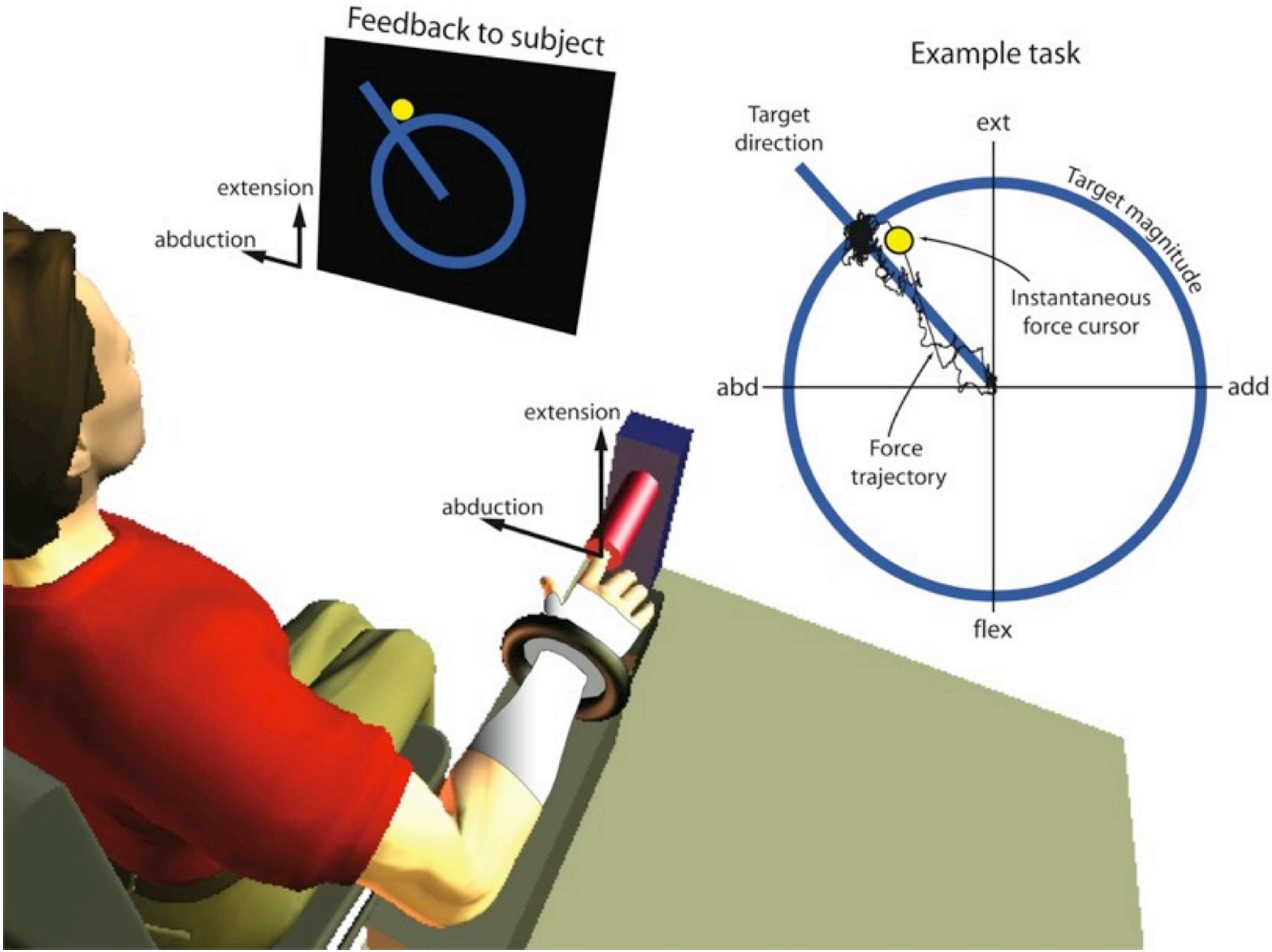
“Cooperation”



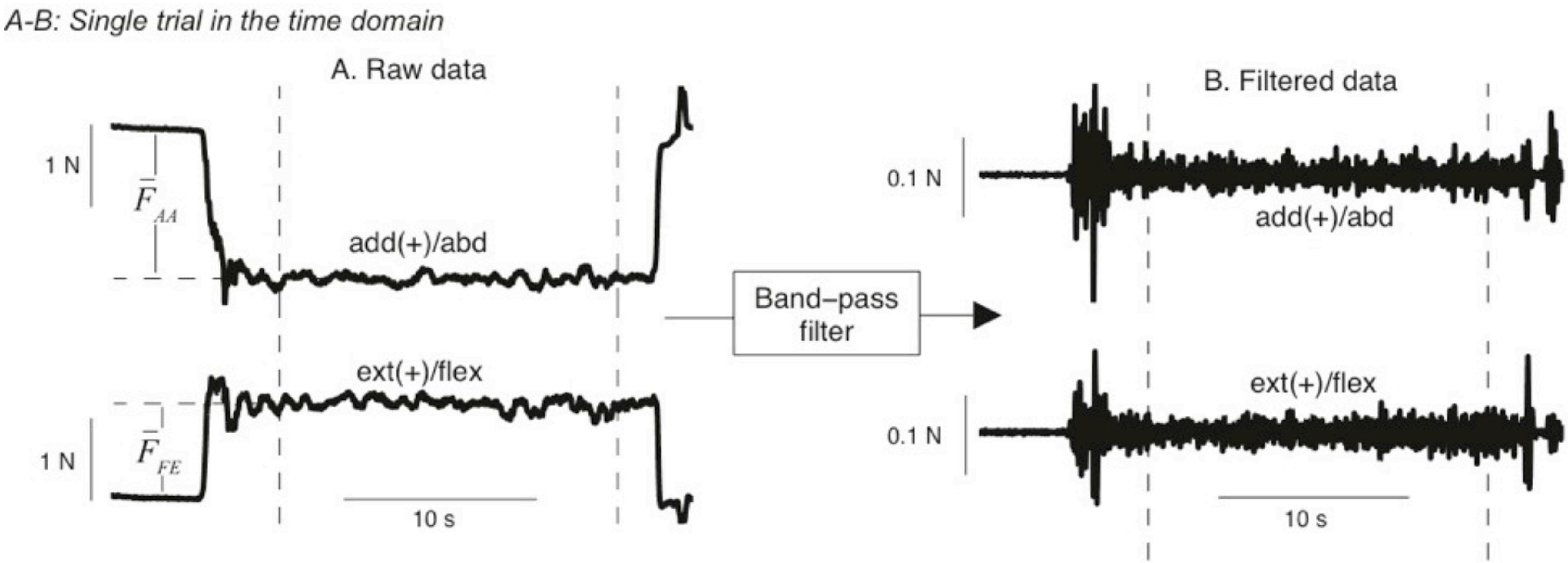
Force covariance mapping



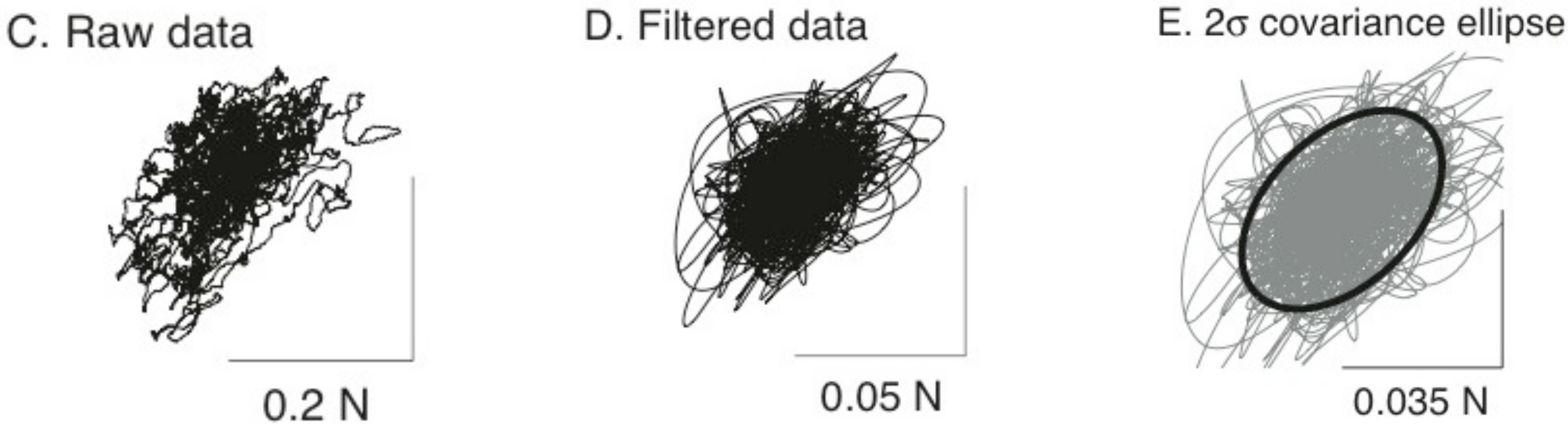
Experimental setup



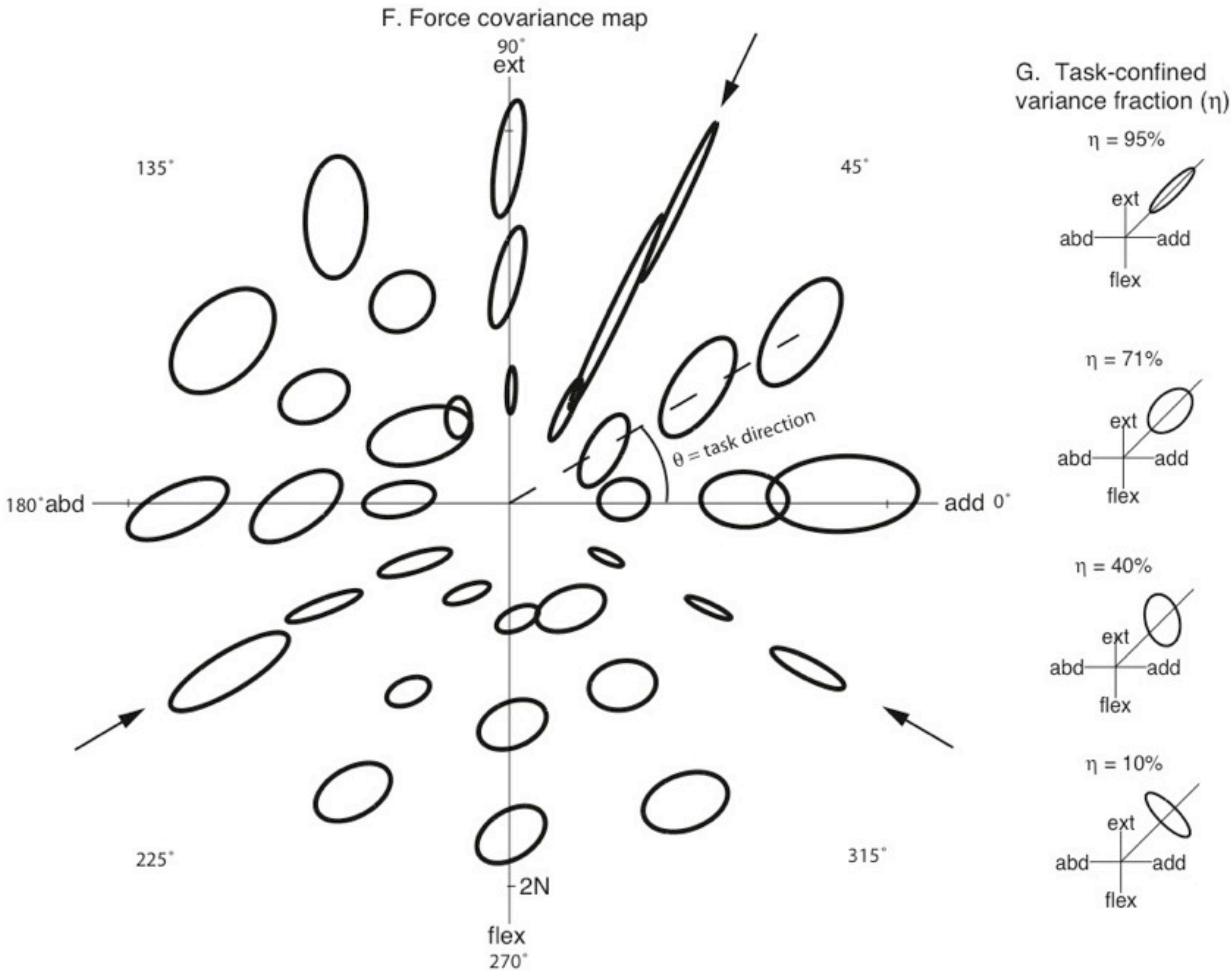
Data processing (time domain)



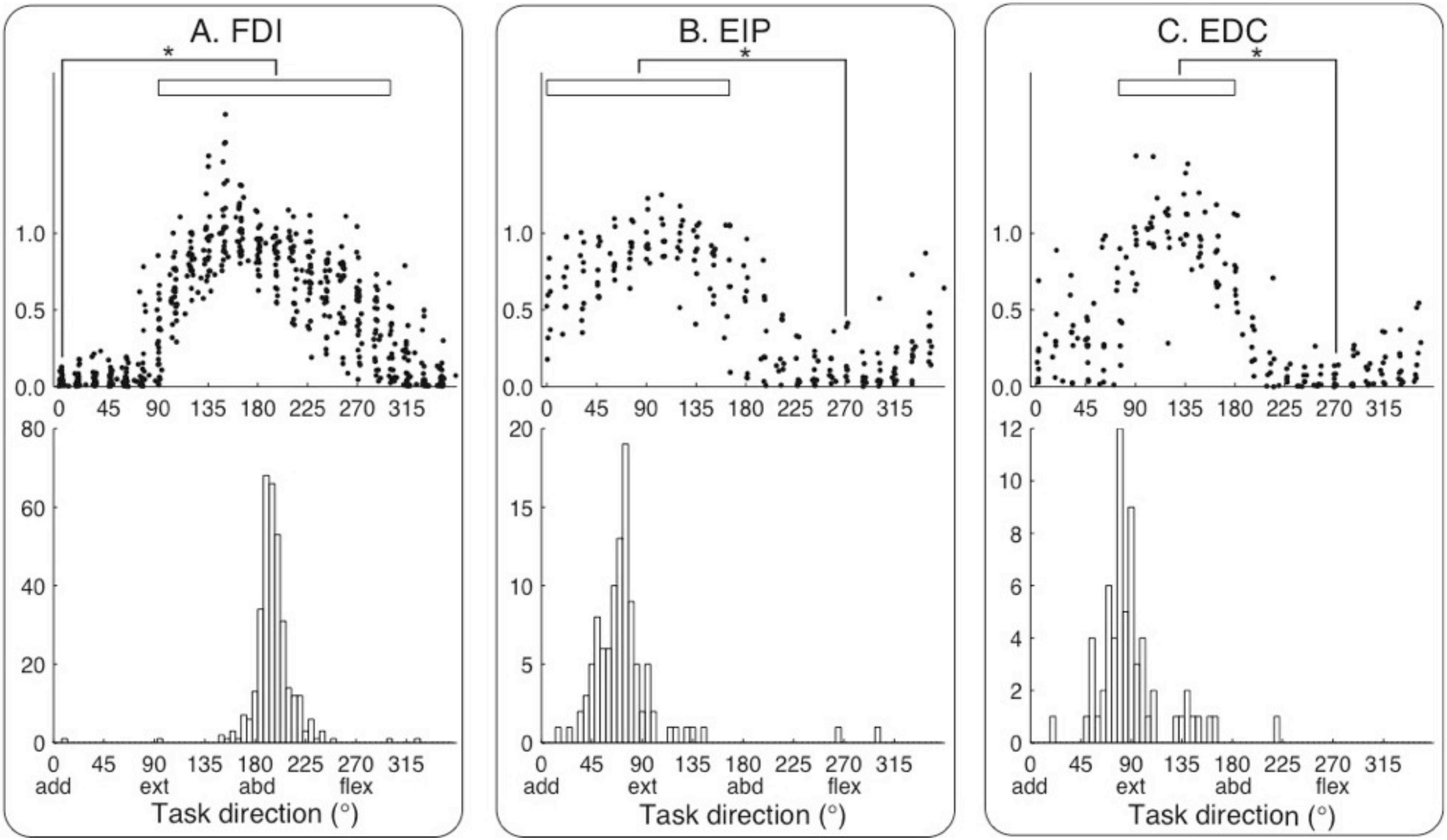
Data processing (task plane)



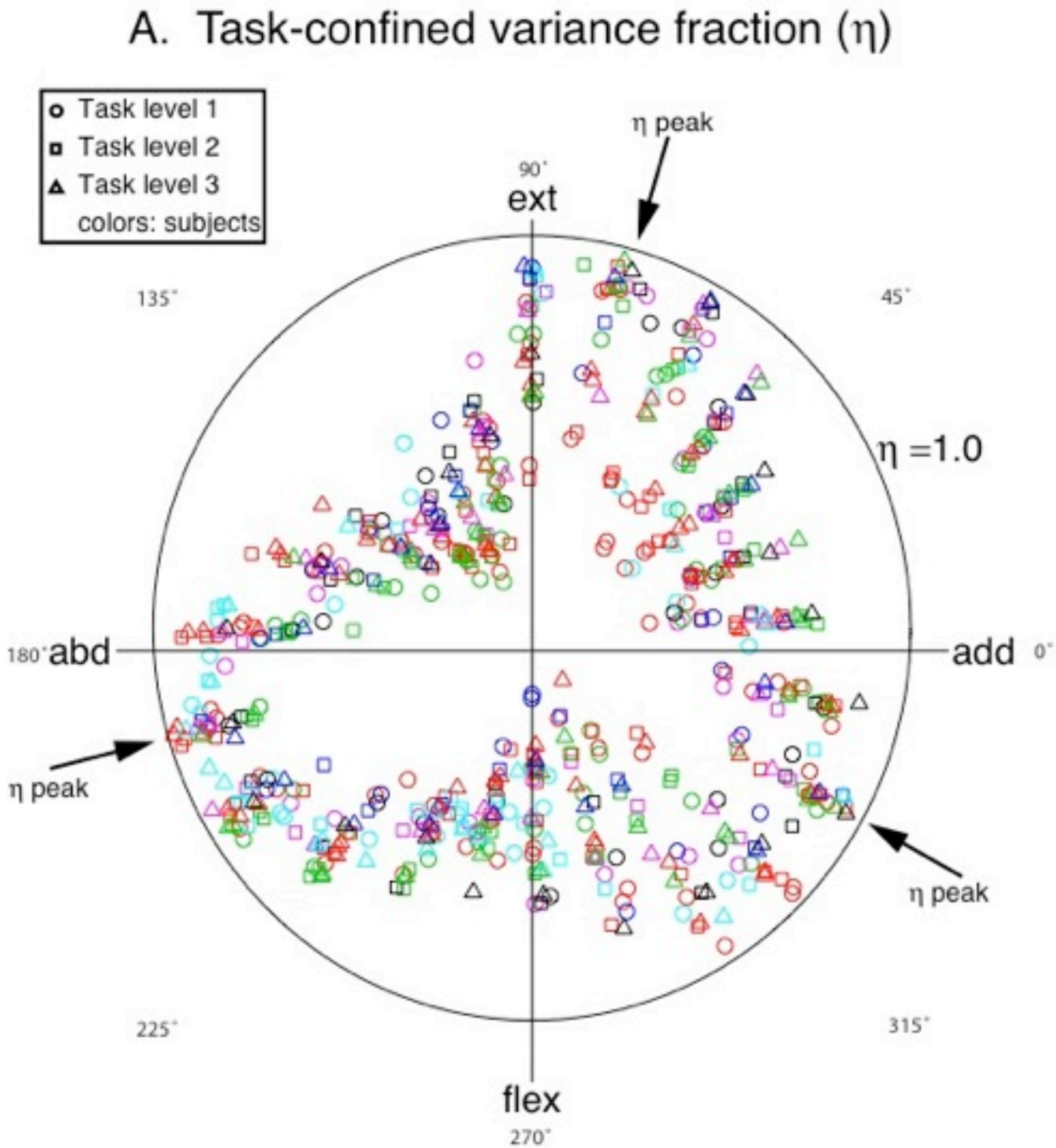
Representative data

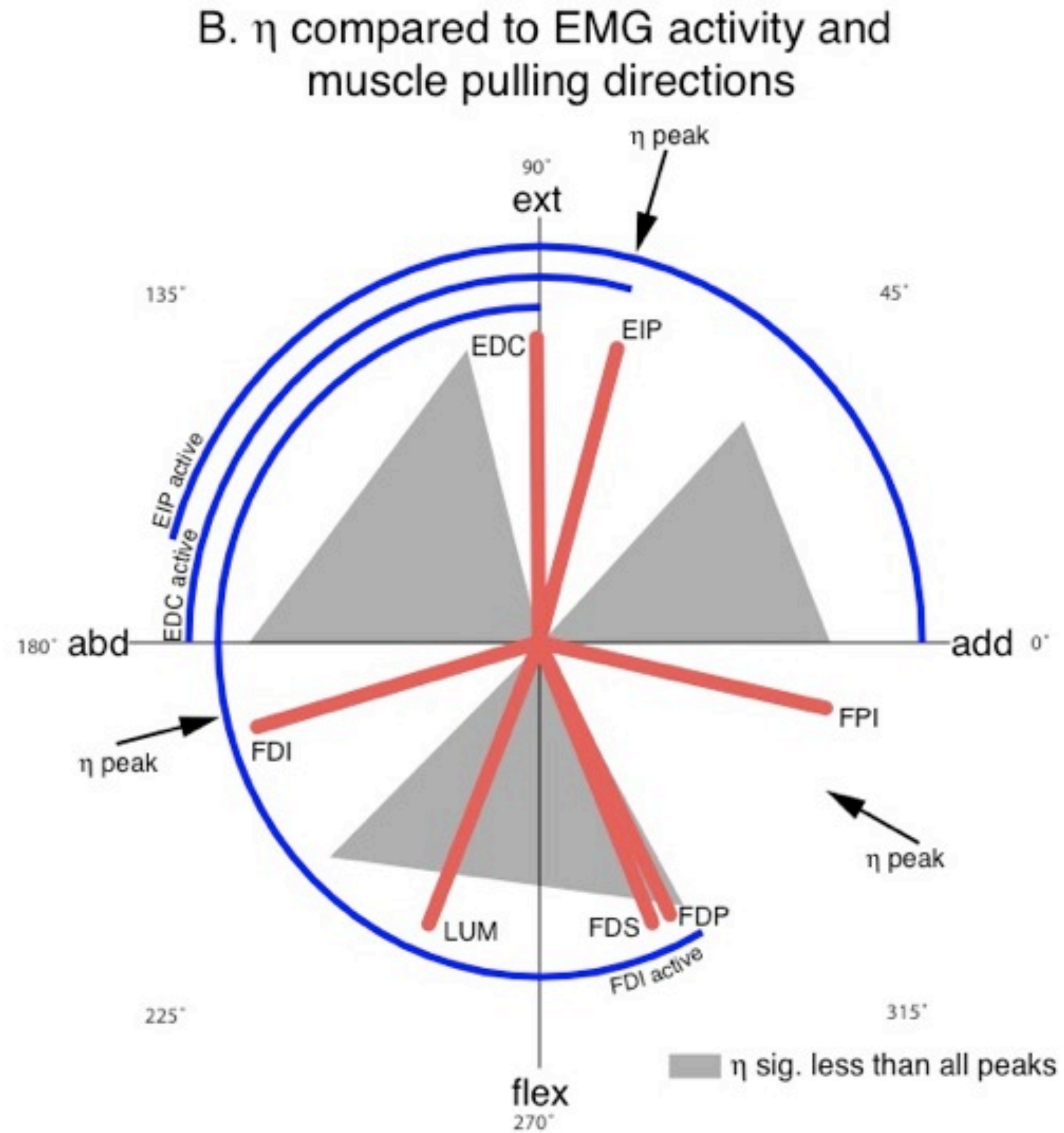


Muscle tuning

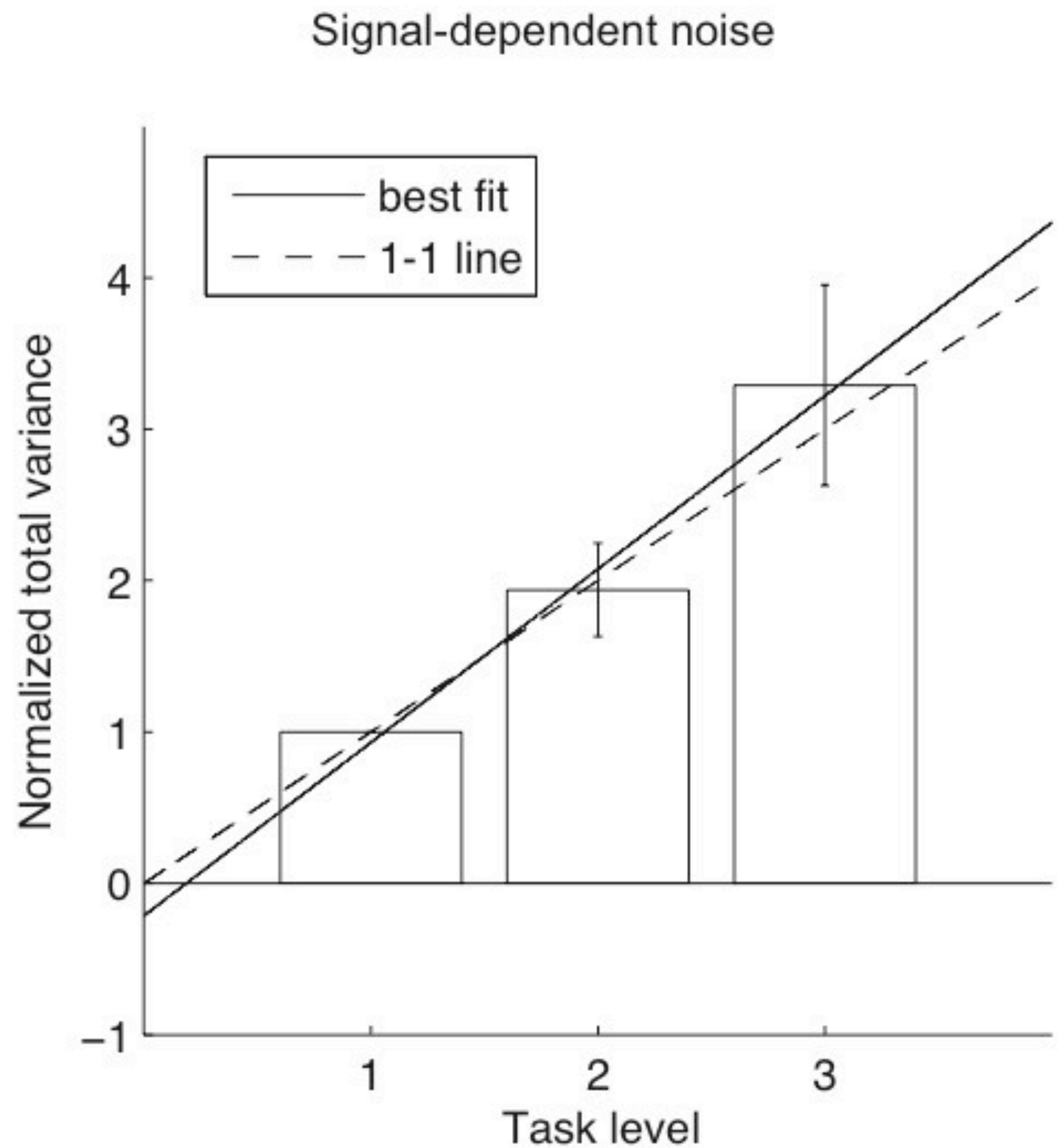


Results across subjects

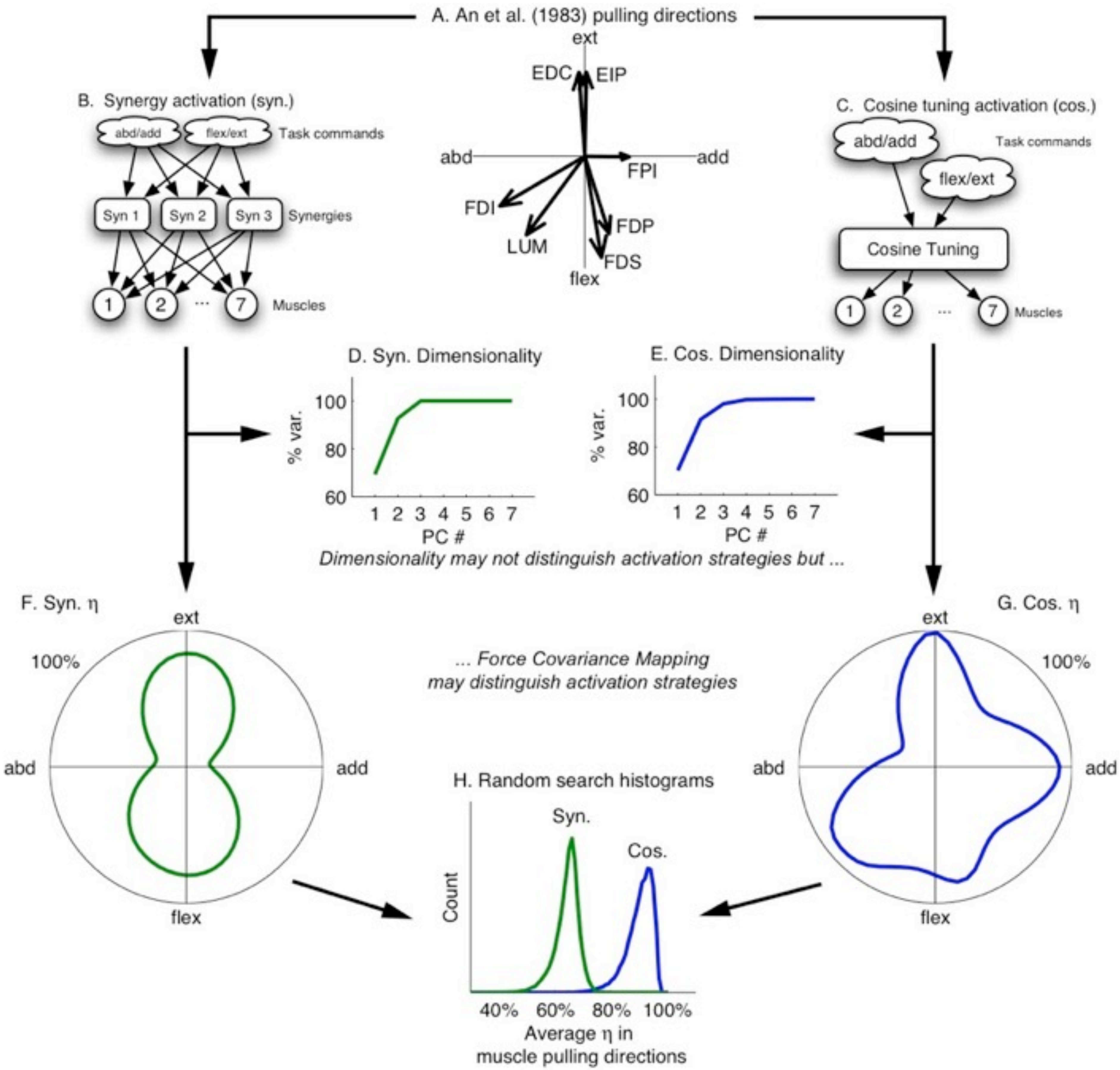




Observed signal-dependent noise



Model


A. An et al. (1983) pulling directions
ext
EDC
EIP
abd
add
FPI
FDI
LUM
FDP
FDS
flex
B. Synergy activation (syn.)
abd/add
flex/ext
Task commands
Syn 1
Syn 2
Syn 3
Synergies
1
2
...
7
Muscles
C. Cosine tuning activation (cos.)
abd/add
flex/ext
Task commands
Cosine Tuning
1
2
...
7
Muscles
D. Syn. Dimensionality
E. Cos. Dimensionality
% var.
100
80
60
1 2 3 4 5 6 7
PC #
Dimensionality may not distinguish activation strategies but ...
F. Syn. η
G. Cos. η
ext
100%
abd
add
flex
... Force Covariance Mapping
may distinguish activation strategies
H. Random search histograms
Syn.
Cos.
Count
40% 60% 80% 100%
Average η in
muscle pulling directions

Conclusions

1. Human movement unsteadiness contains a significant amount of information.

2. This information is likely related to how muscles are coordinated to achieve tasks.

3. Stuff that looks like noise is a good place to look for signal.

Equations: general

$$F(t) = \sum_{i=1}^{n} F_i(t)$$

$$\bar{F} = \sum_{i=1}^{n} \bar{F}_i$$

$$\mathrm{cov}[F] = \sum_{i=1}^{n} \mathrm{cov}[F_i]$$

Equations: scaling

$$\frac{1}{n}\,\mathrm{var}_T[F](\|\bar{F}\|) = \frac{1}{n}\sum_{i=1}^{n}\mathrm{var}_T[F_i](\|\bar{F}\|)$$

Equations: prime mover

$$\mathrm{cov}[F] = \mathrm{cov}(F_1) = E[F_1 F_1^T] - \bar{F_1}\bar{F_1}^T = \mathrm{var}[u_1] a_1 a_1^T$$

$$
\begin{aligned}
\mathrm{cov}[F] &= \mathrm{var}[u_1]\left(\left[\begin{array}{cc} 1 & 0 \\ 0 & 0 \end{array}\right] + \left[\begin{array}{cc} 0 & 0 \\ 0 & 1 \end{array}\right]\right) \\
&= \mathrm{var}[u_1] I_2
\end{aligned}
$$

Equations: synergy

$$\mathrm{cov}[F] = \|\bar{F}_1\|(\mathrm{cov}_1[F_1] + w\,\mathrm{cov}_1[F_2]) + \sum_{i=3}^{n} \mathrm{cov}[F_i]$$

$$\mathrm{cov}[S] = \|\bar{F}_1\| \begin{bmatrix} 1 & 0 \\ 0 & w \end{bmatrix}$$