

# Muscle synergies without a brain or spinal cord

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Postdoctoral Research Associate  
Biomedical Engineering  
University of Southern California



University of Michigan  
in collaboration with  
The Rehabilitation Institute of Chicago

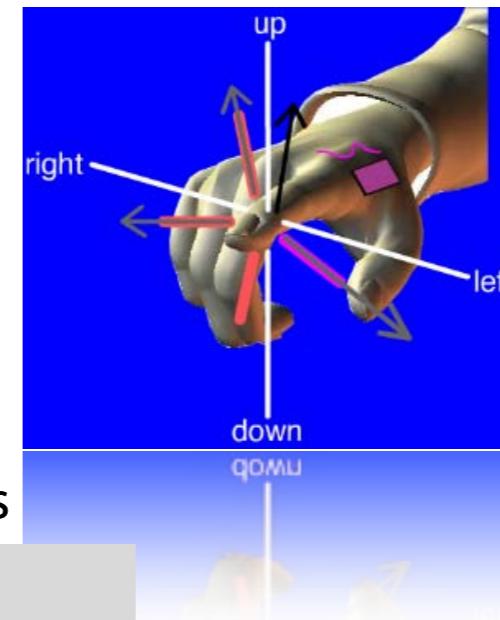


# Multi-muscle mechanics and neural coordination

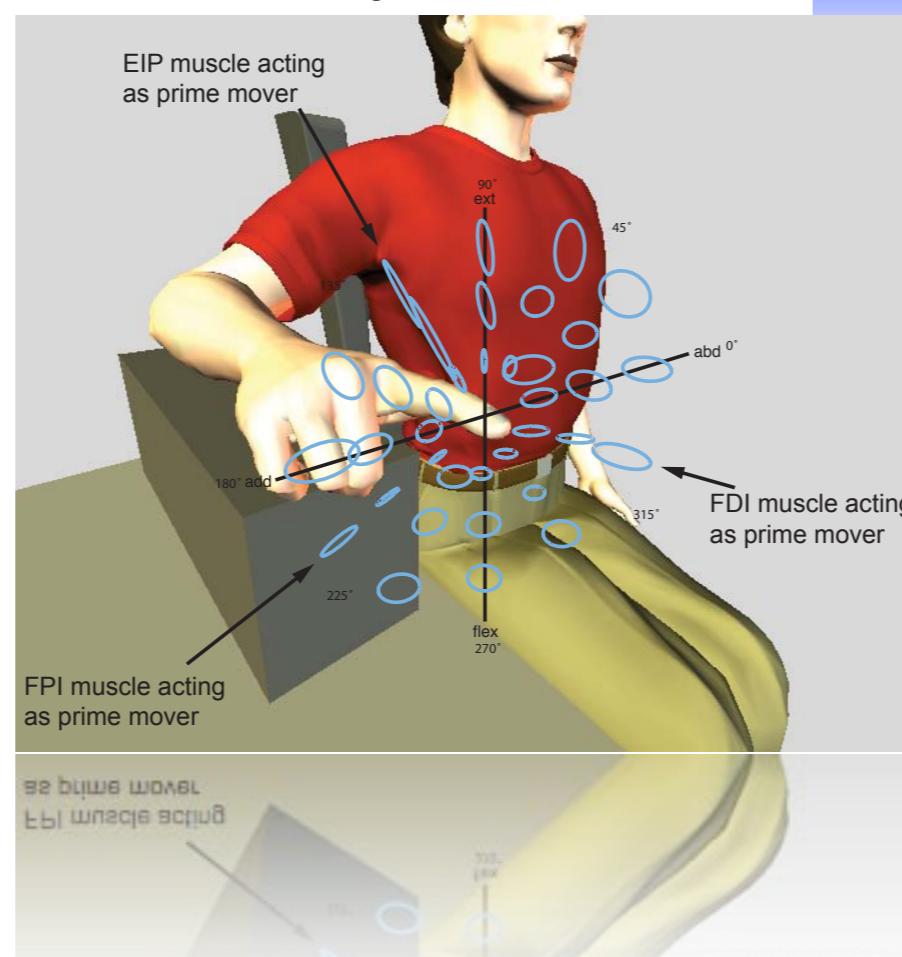
Muscle activation for movement



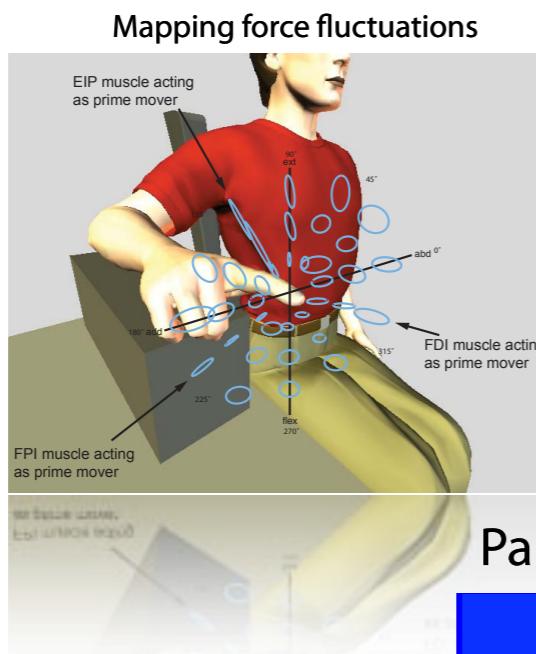
Pairing EMG and force fluctuations



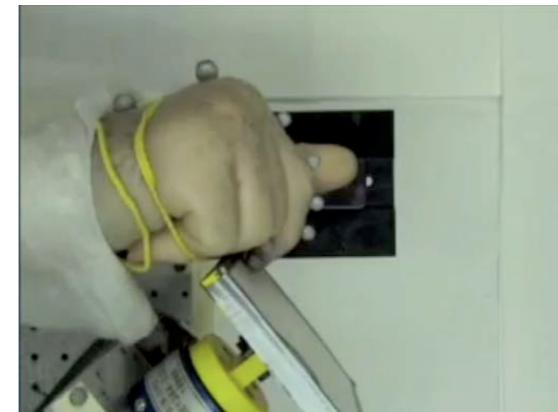
Mapping force fluctuations



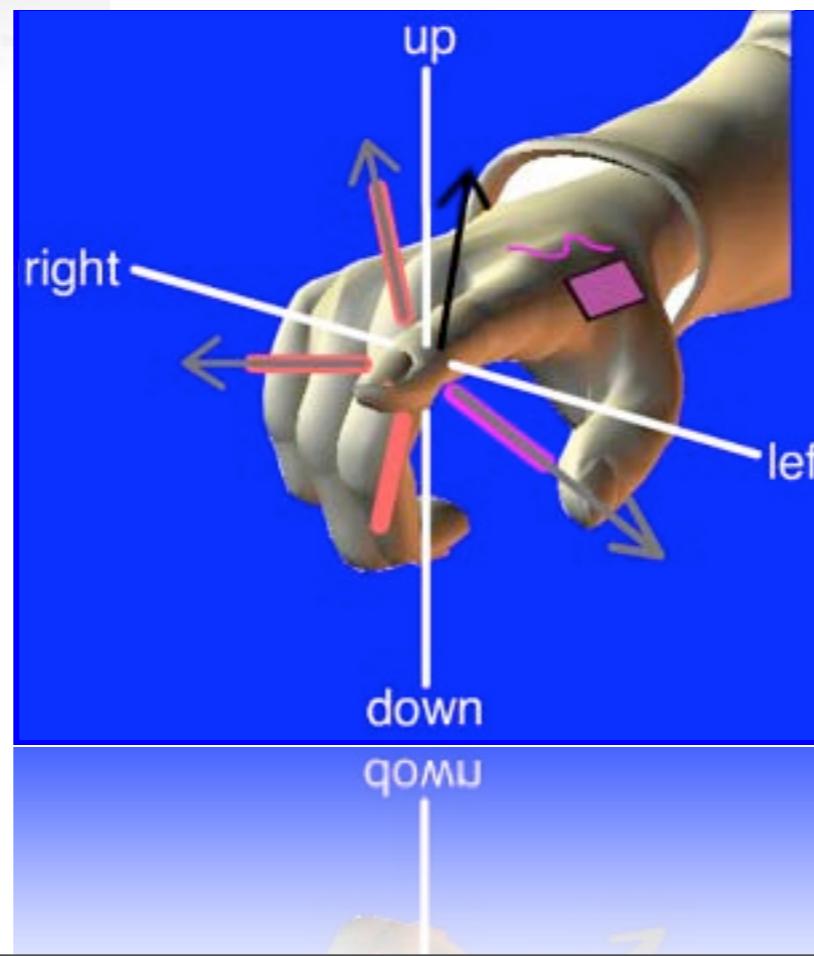
# Multi-muscle mechanics and neural coordination



**Muscle activation for movement**

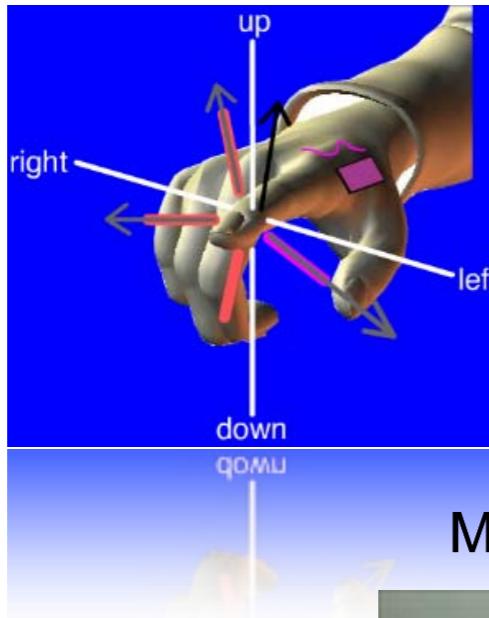


**Pairing EMG and force fluctuations**

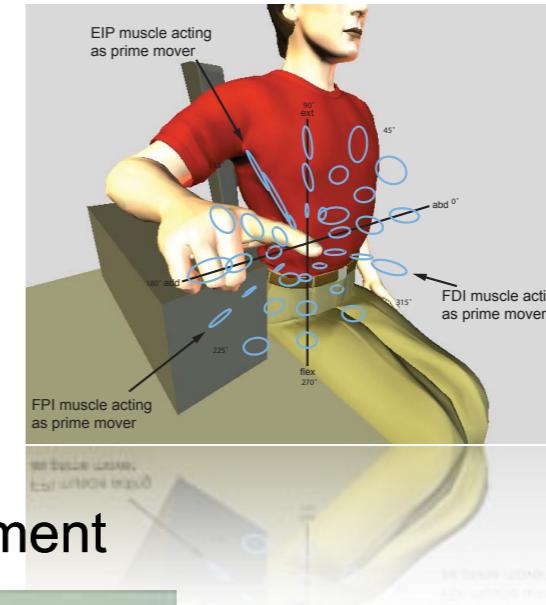


# Multi-muscle mechanics and neural coordination

Pairing EMG and force fluctuations



Mapping force fluctuations

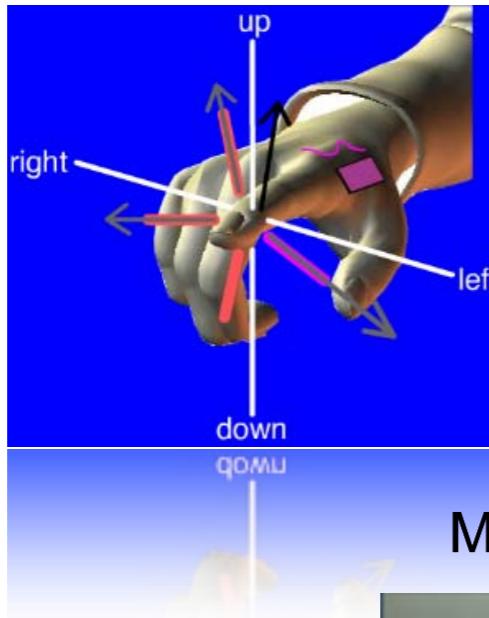


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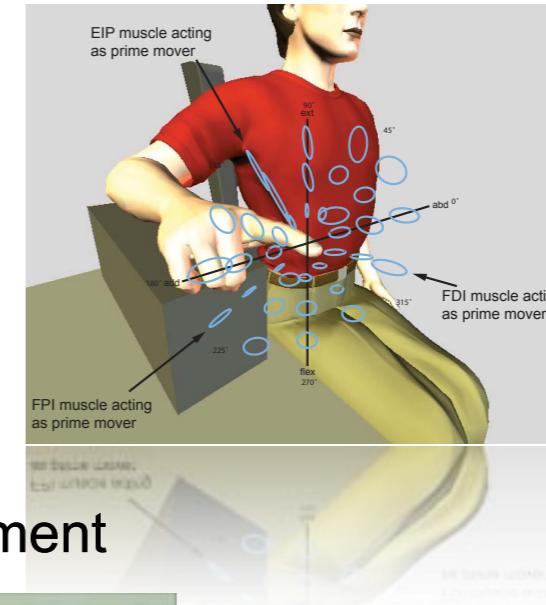


# Multi-muscle mechanics and neural coordination

Pairing EMG and force fluctuations



Mapping force fluctuations



Muscle activation for movement



**The problem with synergies**

**No synergies for finger muscles**

**Where do muscle synergies come from?**

**Muscle synergies may not be necessary**

**Towards clinical application**

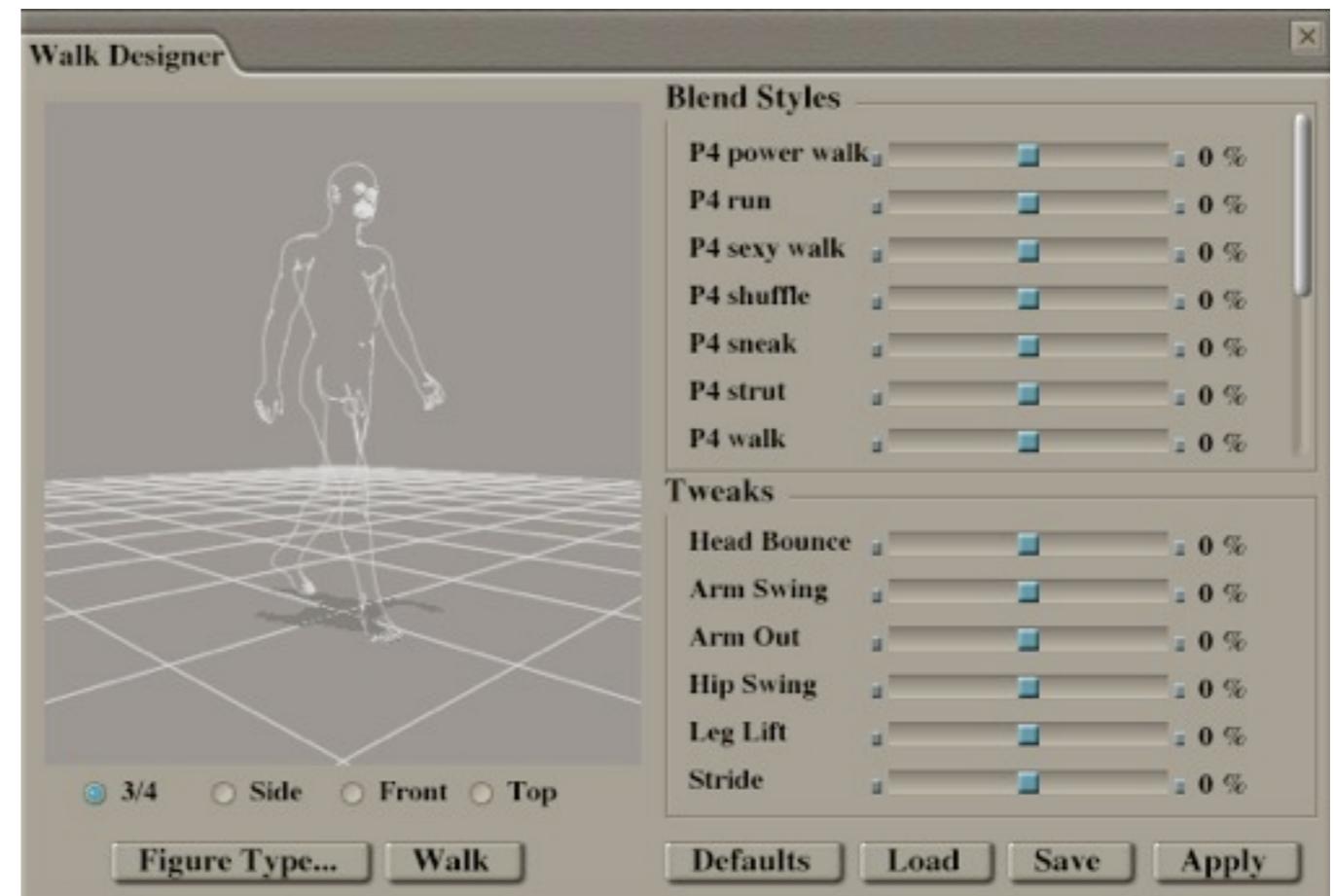
# The problem with synergies

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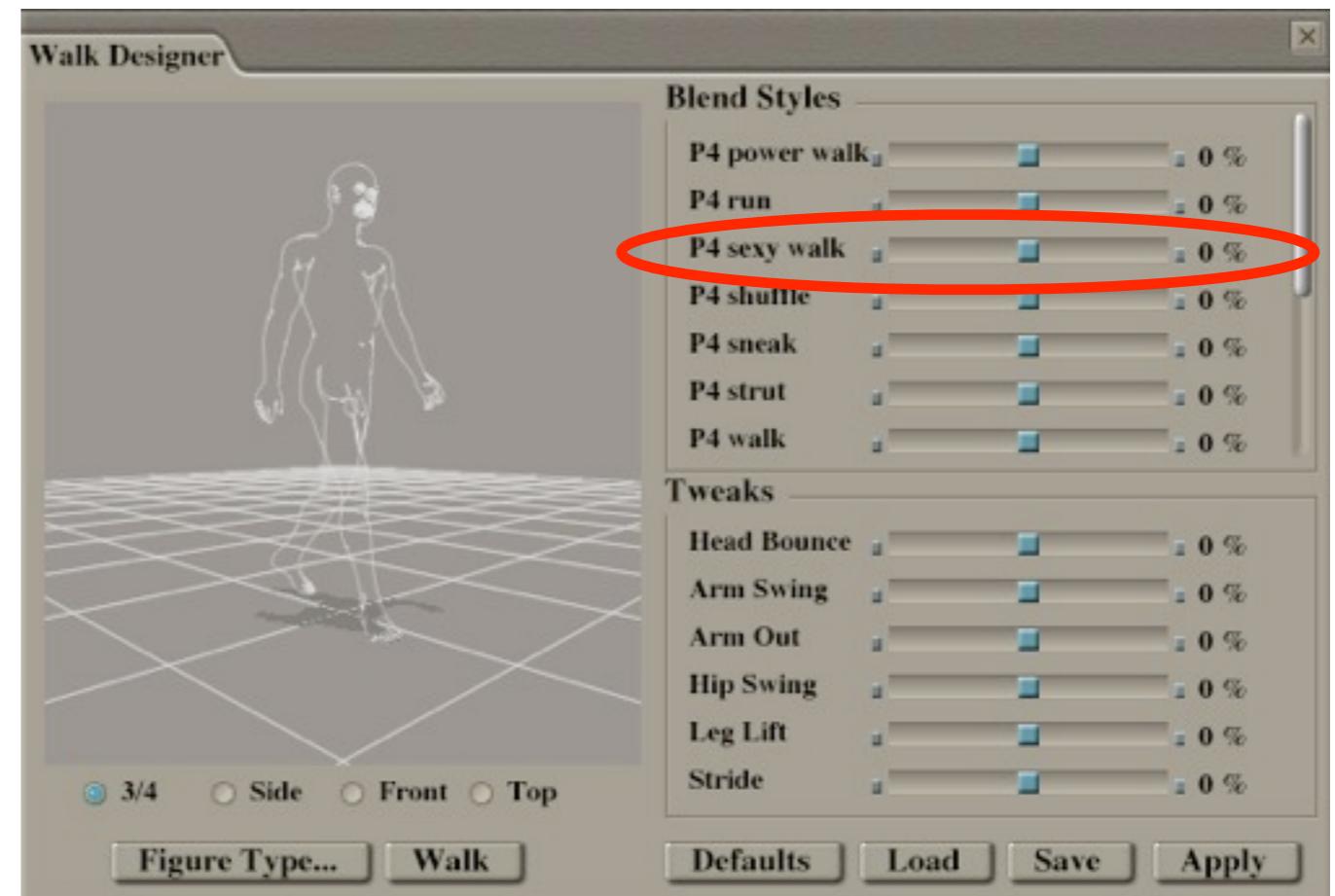
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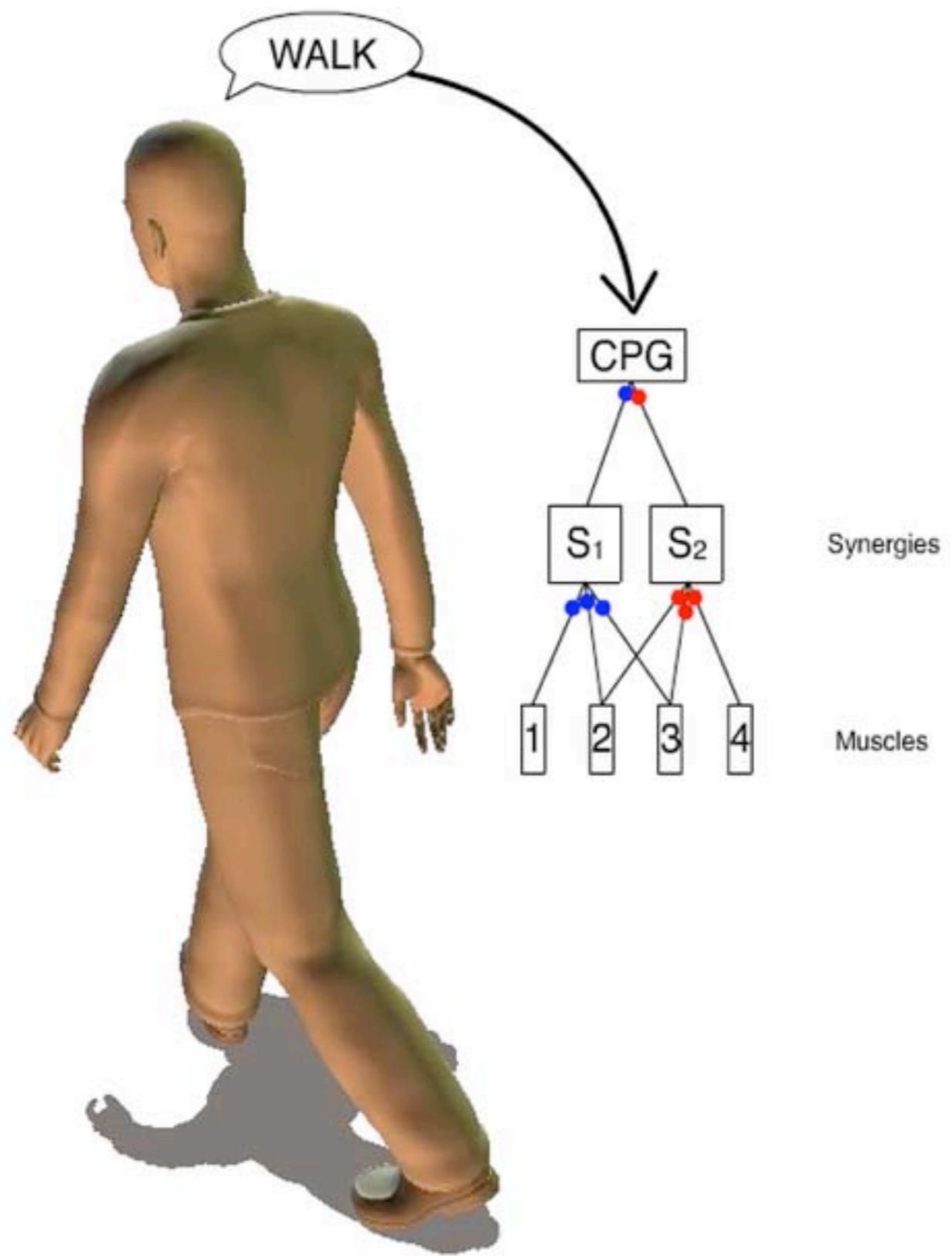
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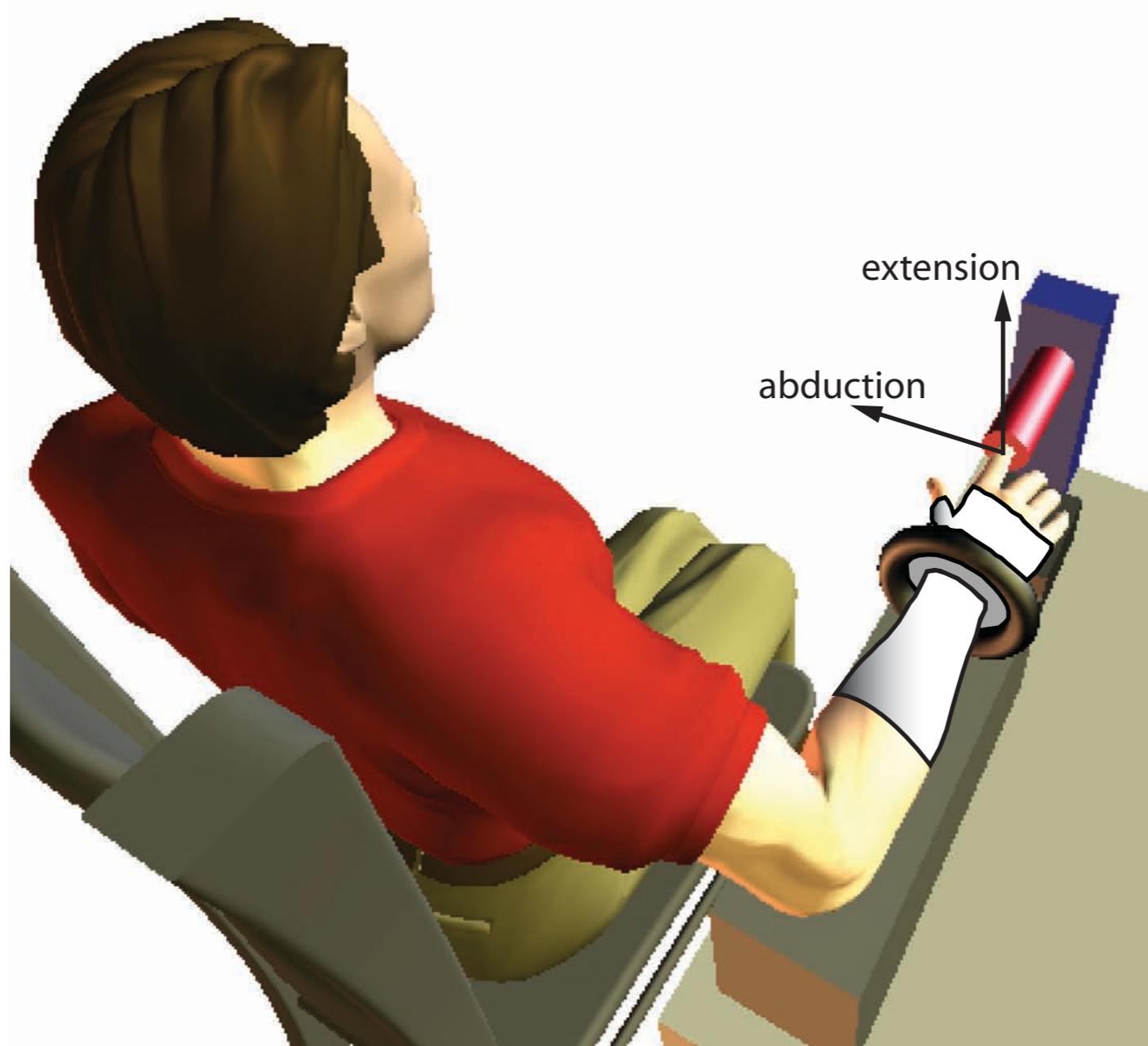
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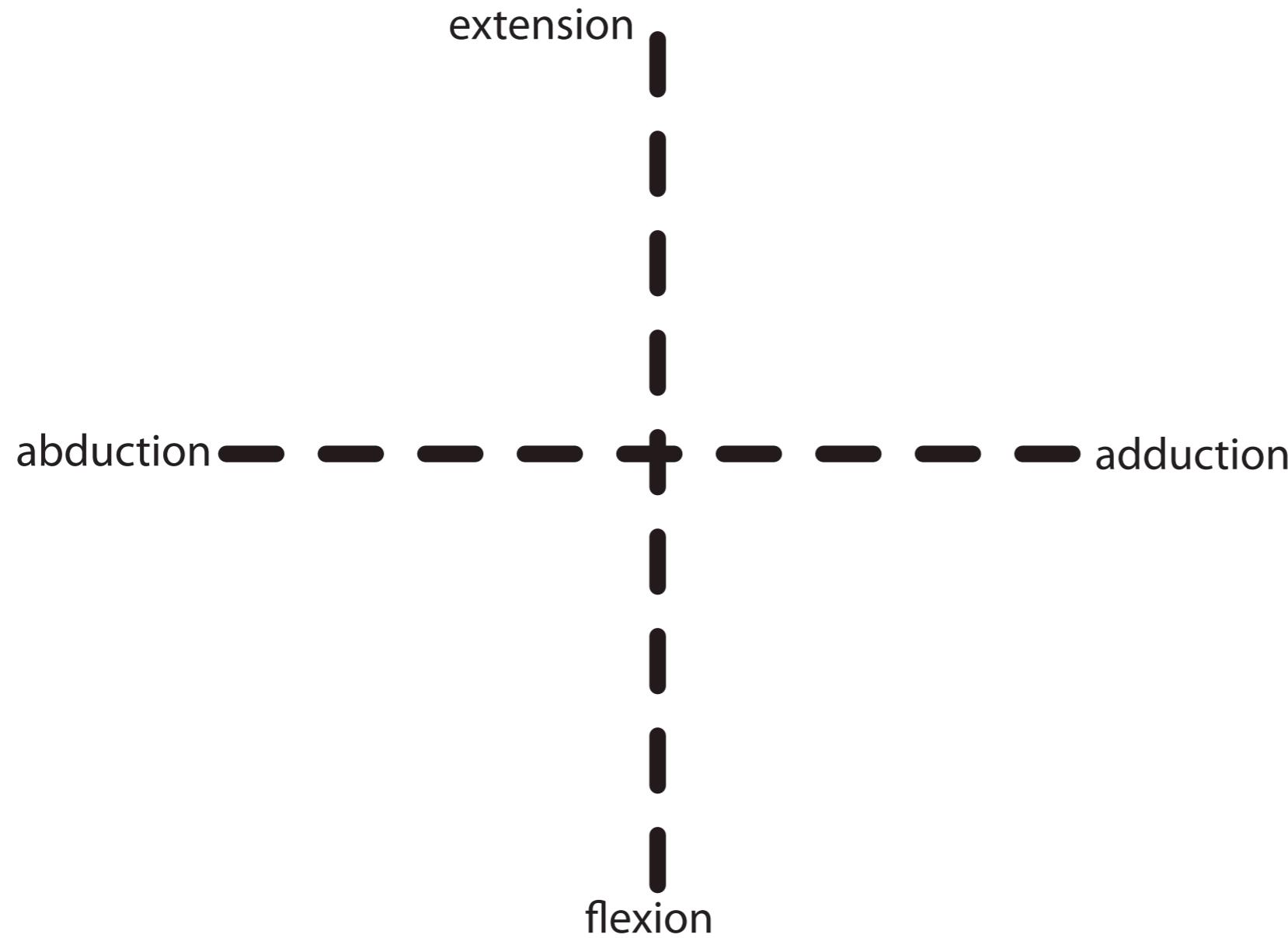
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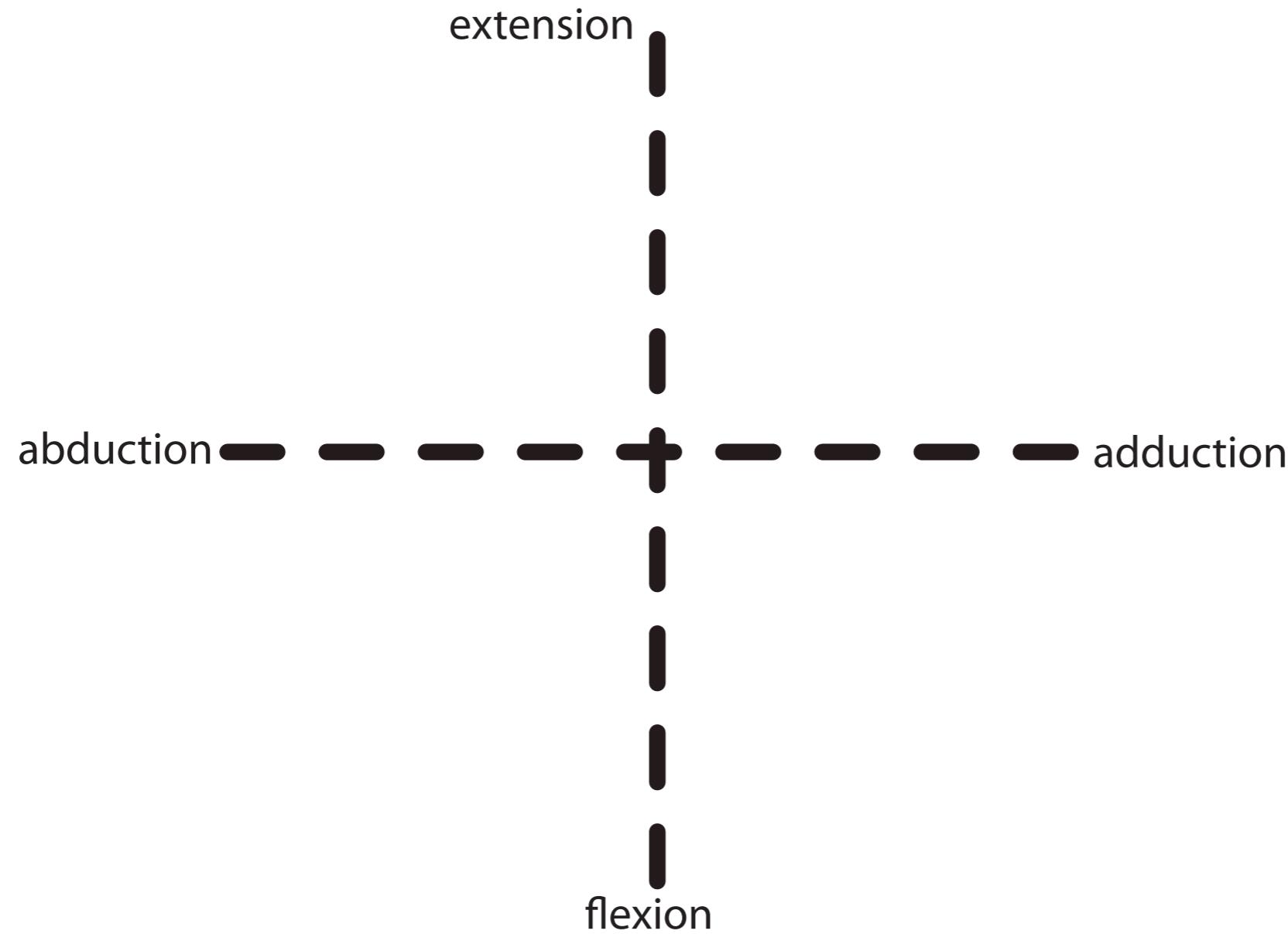
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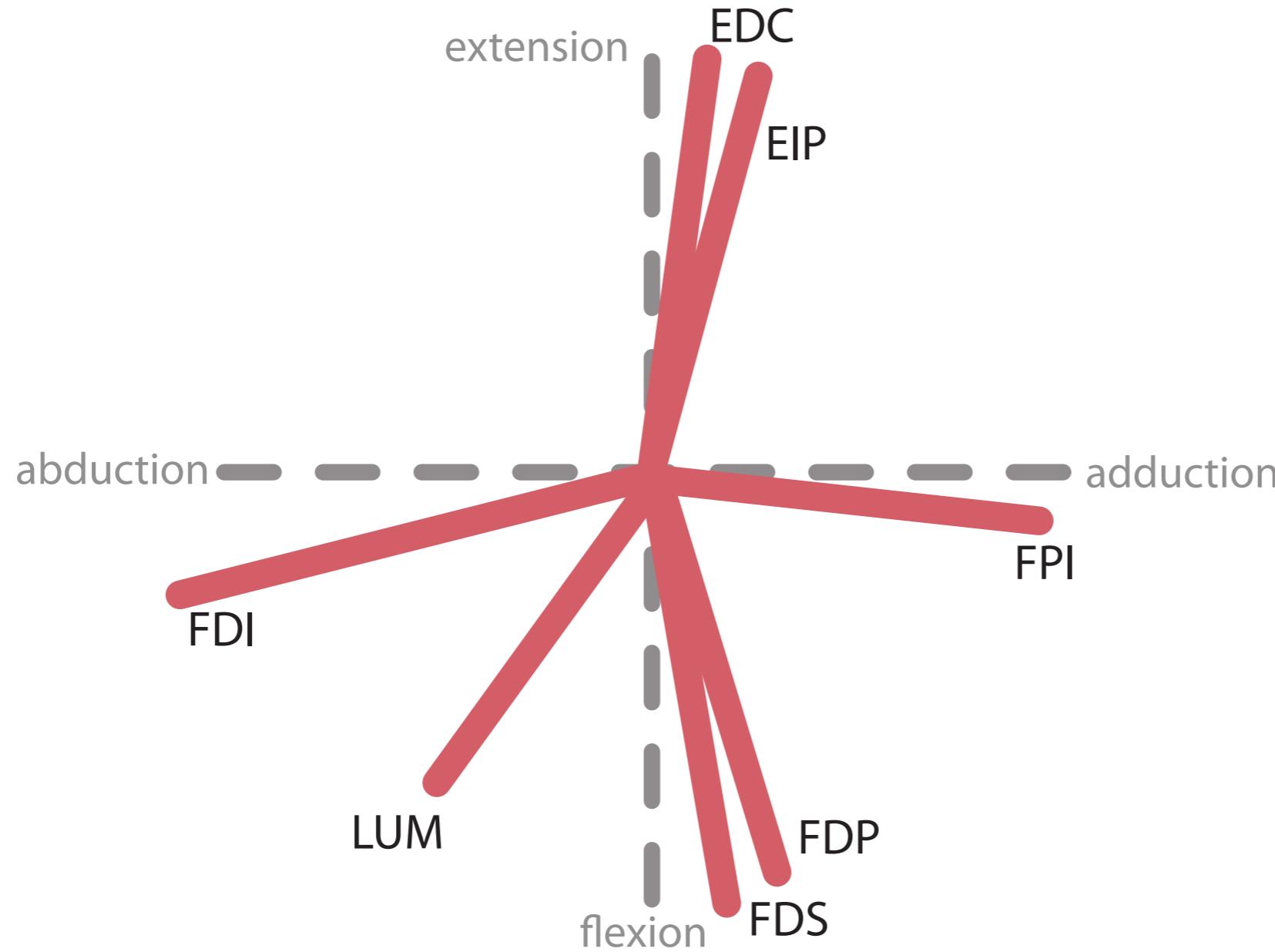
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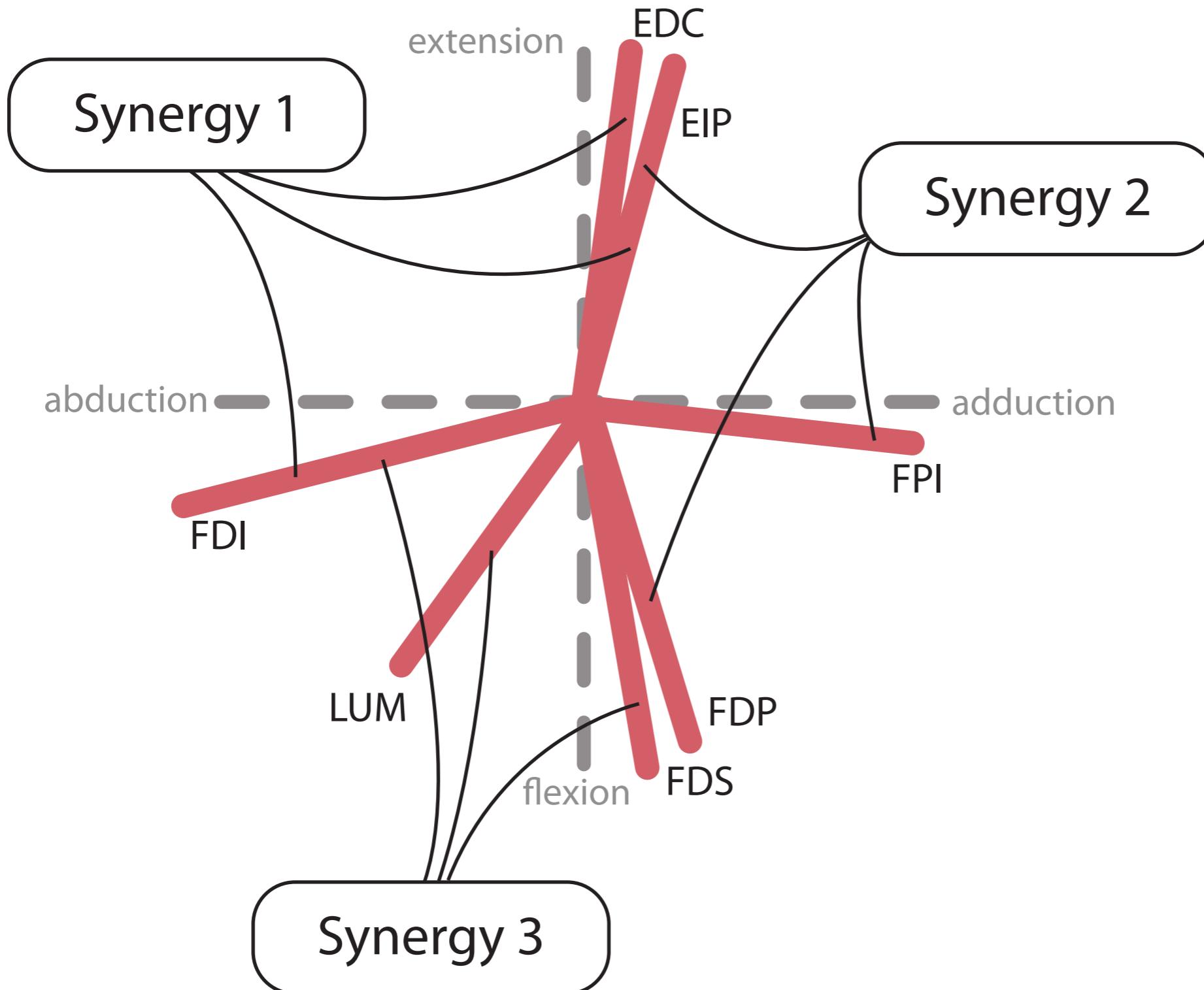
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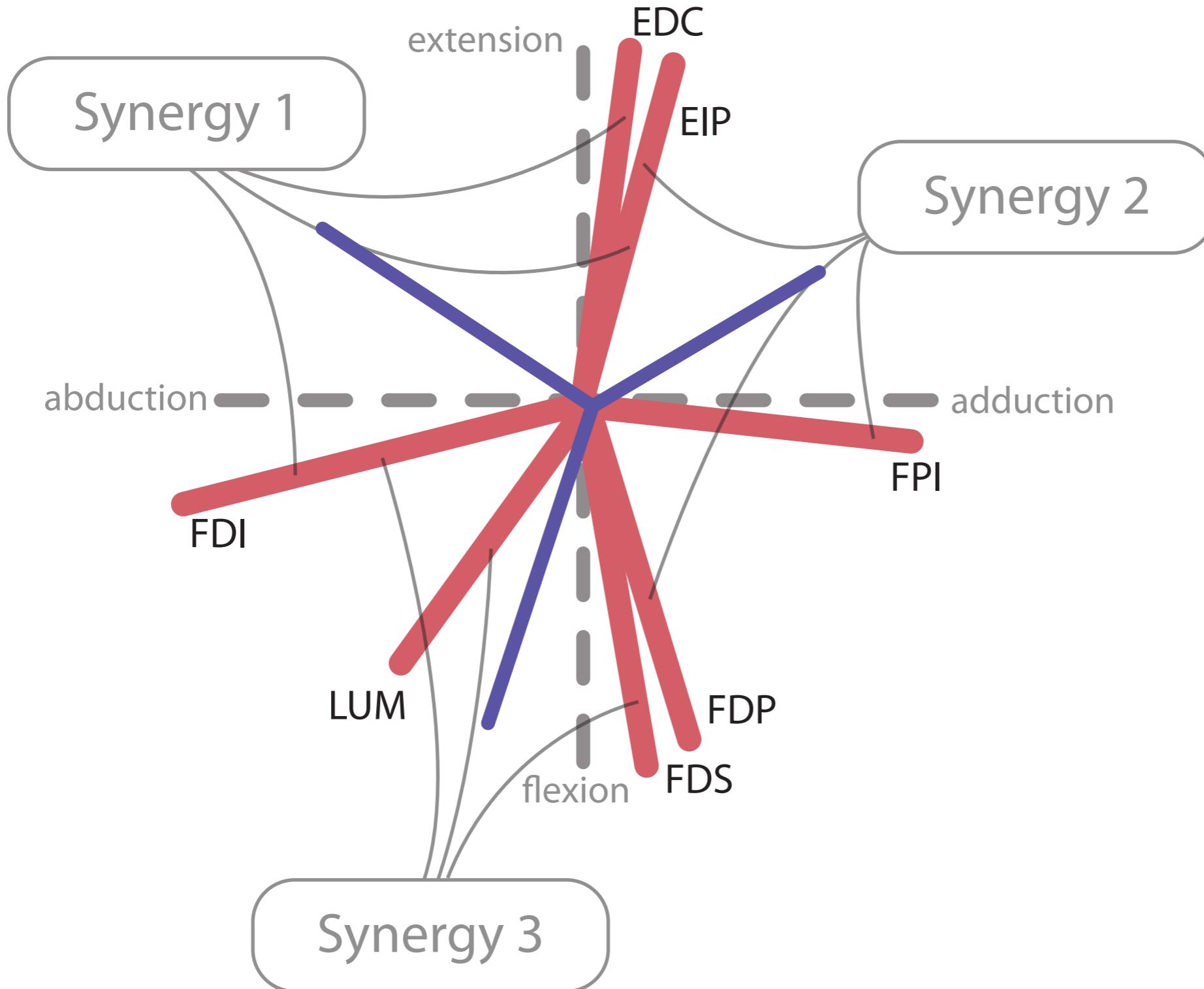
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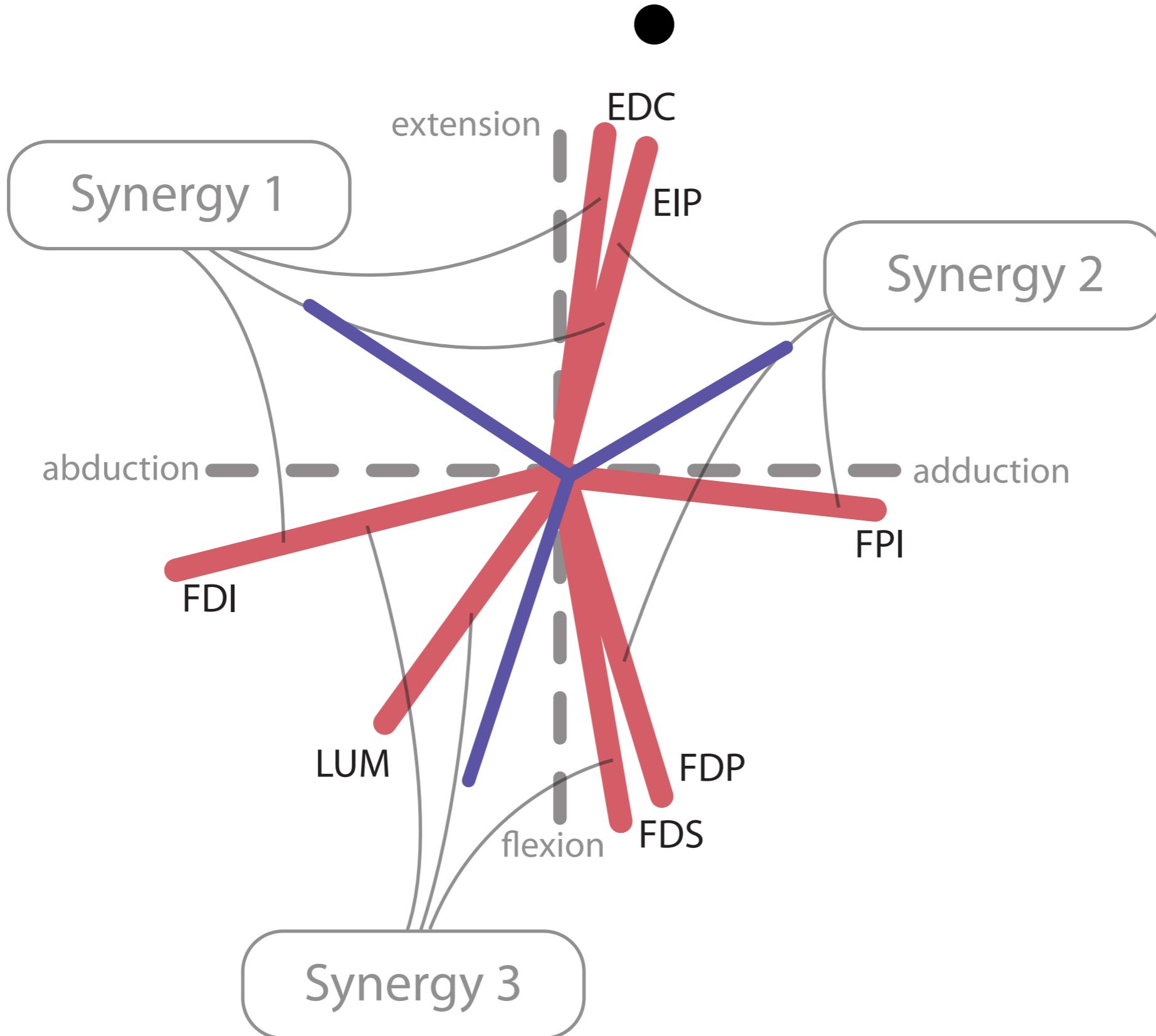
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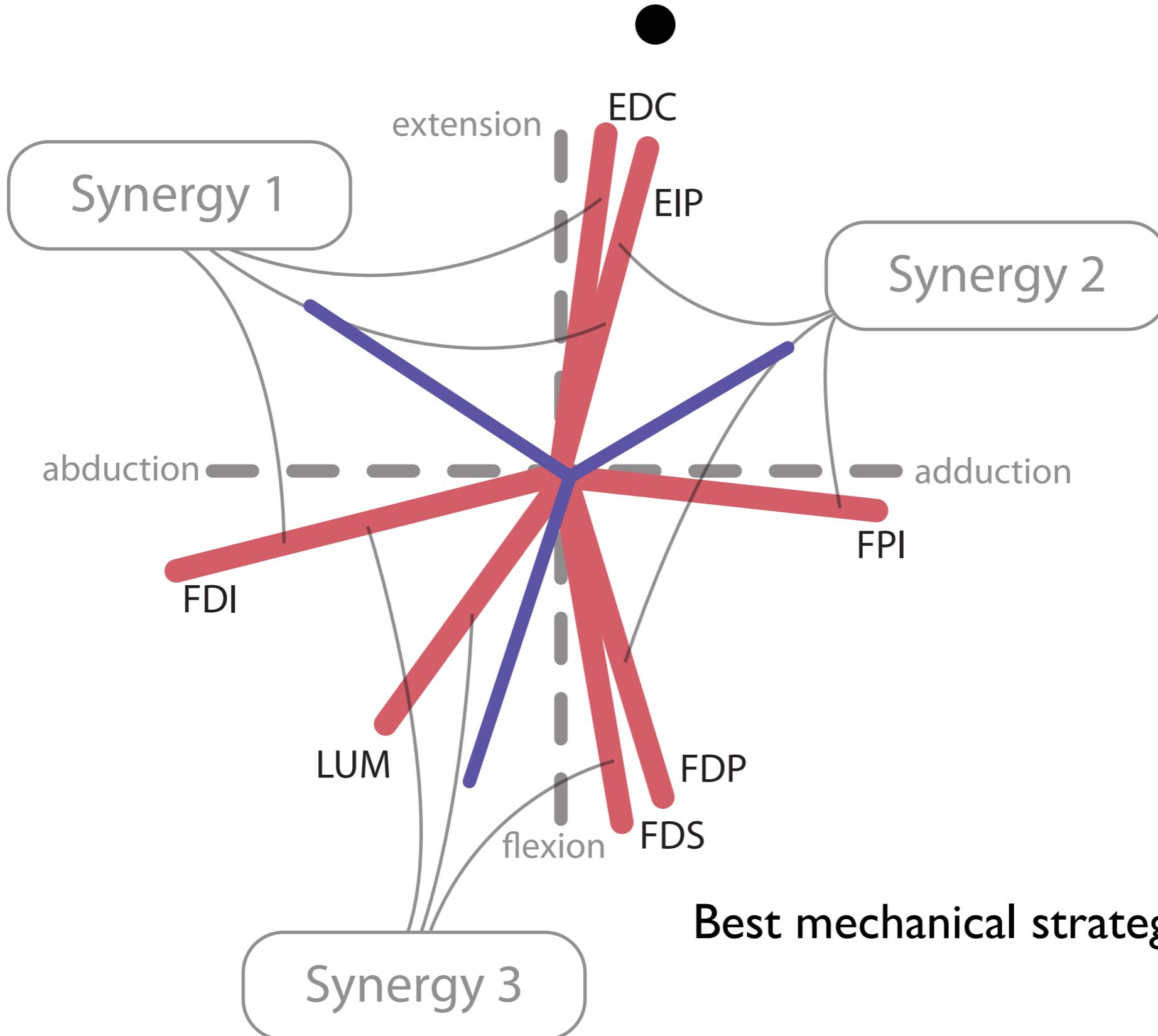
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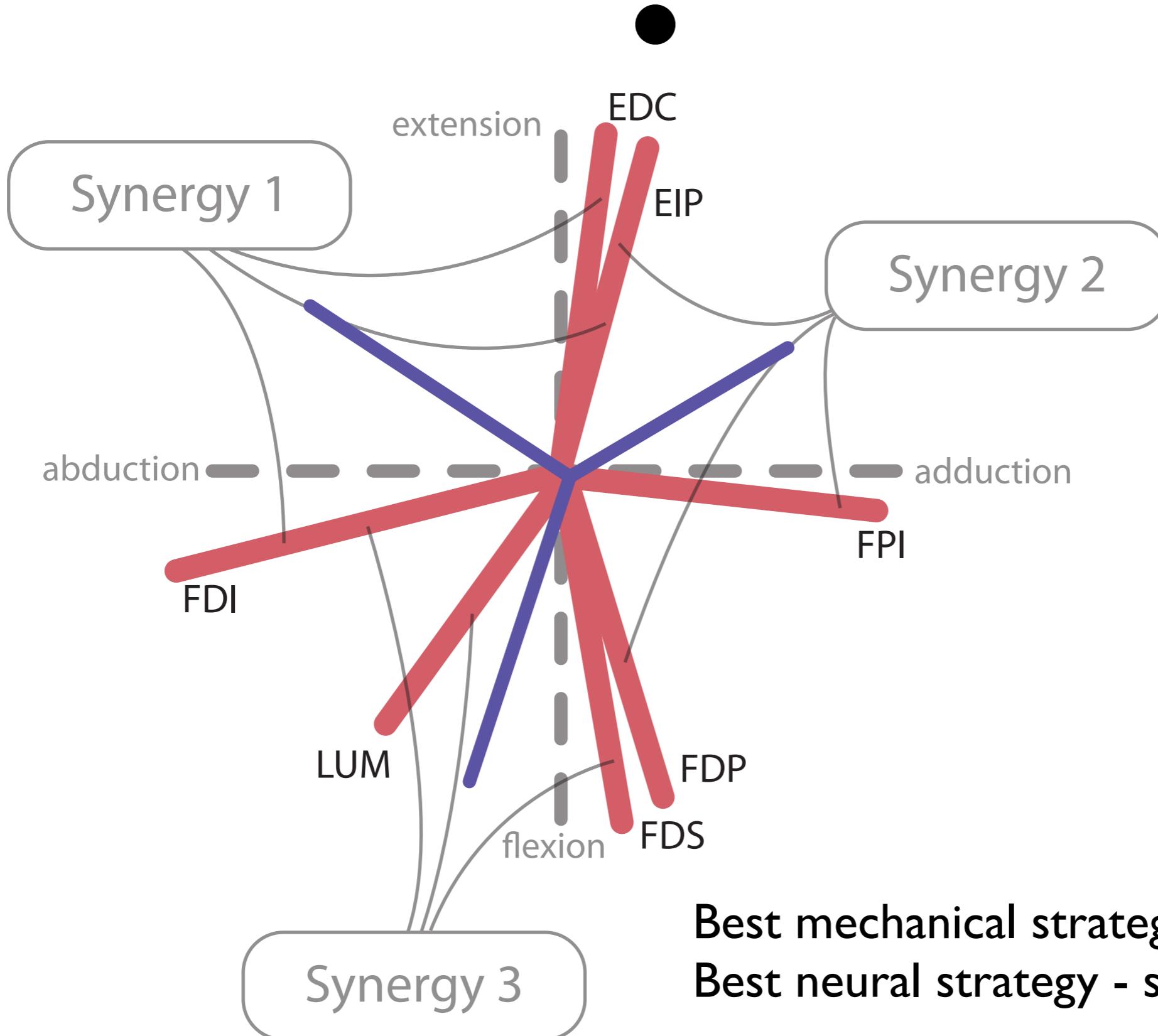


# The problem with synergies



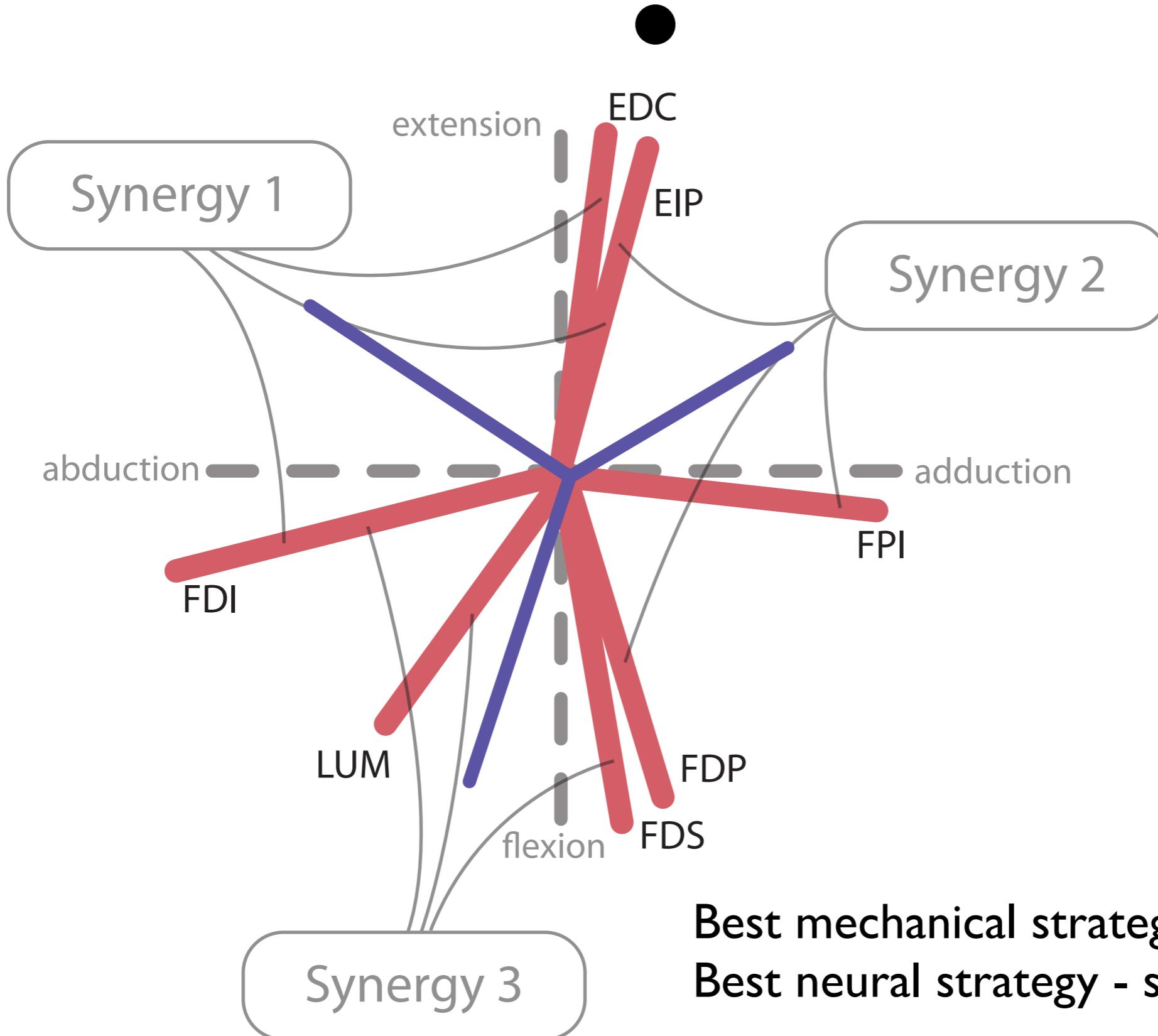
Best mechanical strategy - extensors only

# The problem with synergies



Best mechanical strategy - extensors only  
Best neural strategy - synergy 1 and 2

# The problem with synergies



Best mechanical strategy - extensors only  
Best neural strategy - synergy 1 and 2

**Neuro-mechanical conflict!**

**The problem with synergies**

**No synergies for finger muscles**

**Where do muscle synergies come from?**

**Muscle synergies may not be necessary**

**Towards clinical application**

The problem with synergies

No synergies for finger muscles

Where do muscle synergies come from?

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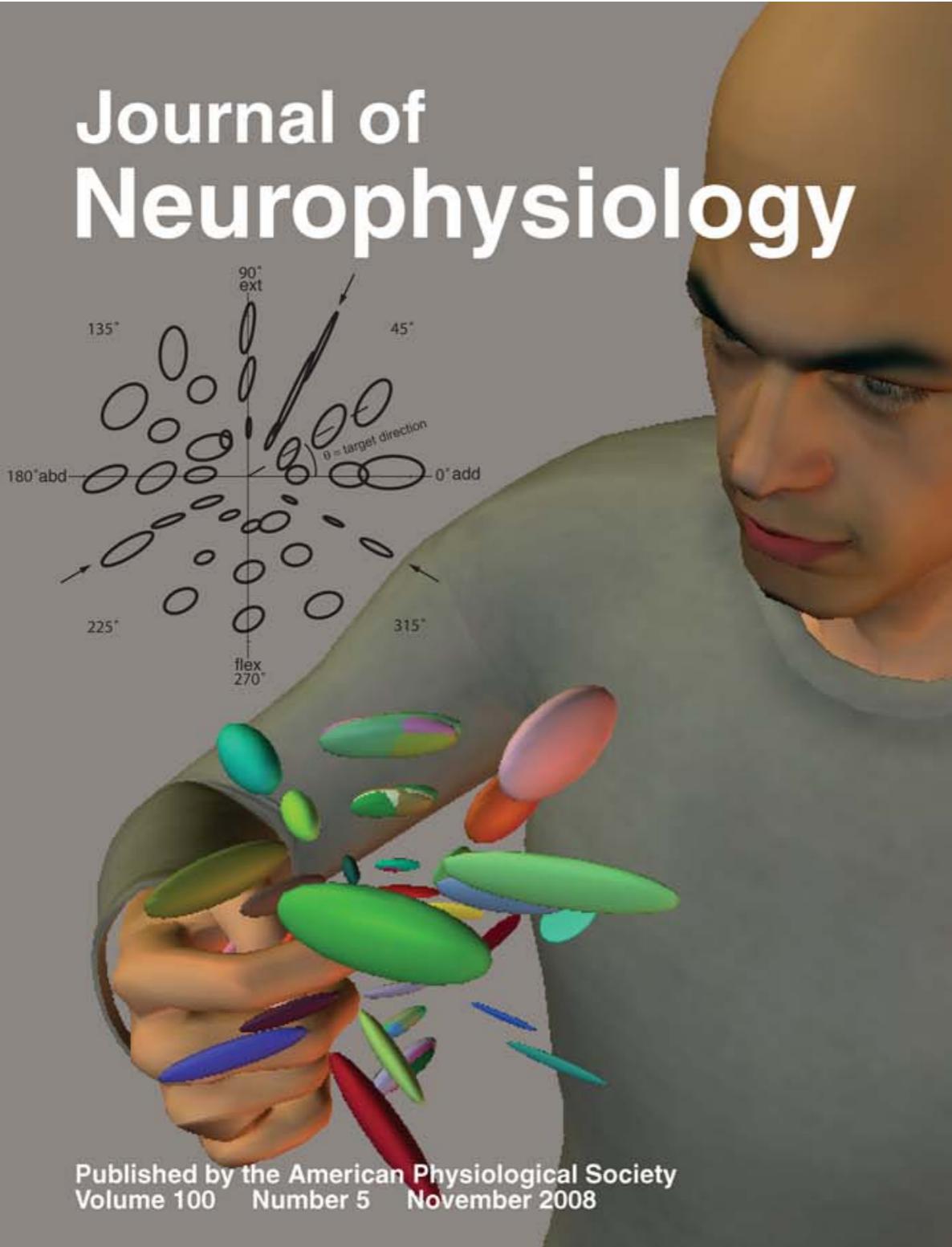
# No synergies for finger muscles

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*J Neurophysiol* 100: 000–000, 2008.  
First published MONTH; doi:10.1152/jn.90274.2008.

## Endpoint Force Fluctuations Reveal Flexible Rather Than Synergistic Patterns of Muscle Cooperation

Jason J. Kutch,<sup>1,3</sup> Arthur D. Kuo,<sup>2</sup> Anthony M. Bloch,<sup>1</sup> and William Z. Rymer<sup>3</sup>

<sup>1</sup>Applied and Interdisciplinary Mathematics and <sup>2</sup>Mechanical Engineering and Biomedical Engineering, University of Michigan, Ann Arbor, Michigan; and <sup>3</sup>Sensory Motor Performance Program, Rehabilitation Institute of Chicago, Chicago, Illinois

Submitted 15 February 2008; accepted in final form 10 September 2008

**Kutch JJ, Kuo AD, Bloch AM, Rymer WZ.** Endpoint force fluctuations reveal flexible rather than synergistic patterns of muscle cooperation. *J Neurophysiol* 100: 000–000, 2008. First published MONTH; doi:10.1152/jn.90274.2008. We developed a new approach to investigate how the nervous system activates multiple redundant muscles by studying the endpoint force fluctuations during isometric force generation at a multi-degree-of-freedom joint. We hypothesized that, due to signal-dependent muscle force noise, endpoint force fluctuations would depend on the target direction of index finger force and that this dependence could be used to distinguish flexible from synergistic activation of the musculature. We made high-gain measurements of isometric forces generated to different target magnitudes and directions, in the plane of index finger metacarpalphalangeal joint abduction-adduction/flexion-extension. Force fluctuations from each target were used to calculate a covariance ellipse, the shape of which varied as a function of target direction. Directions with narrow ellipses were approximately aligned with the estimated mechanical actions of key muscles. For example, targets directed along the mechanical action of the first dorsal interosseous (FDI) yielded narrow ellipses, with 88% of the variance directed along those target directions. It follows the FDI is likely a prime mover in this target direction and that, at most, 12% of the force variance could be explained by synergistic coupling with other muscles. In contrast, other target directions exhibited broader covariance ellipses with as little as 30% of force variance directed along those target directions. This is the result of cooperation among multiple muscles, based on independent electromyographic recordings. However, the pattern of cooperation across target directions indicates that muscles are recruited flexibly in accordance with their mechanical action, rather than in fixed groupings.

### INTRODUCTION

The CNS can typically utilize many different muscle combinations when controlling multiple degrees of freedom (DOF) of the body. To simplify task control (Bernstein 1967), it has been proposed that the CNS enforces muscle synergies: fixed patterns of activation among multiple muscles acting about the relevant DOF (d'Avella et al. 2003; Drew et al. 2008; Giszter et al. 2007; Ivanenko et al. 2006; Overduin et al. 2008; Saltiel et al. 2001; Ting and Macpherson 2005; Tresch et al. 2006). Alternatively, the CNS could use a task-specific muscle coordination pattern without requiring fixed patterns, perhaps reflecting the optimization of movement according to some suitable performance criteria (Buchanan and Shreeve 1996; Harris and Wolpert 1998; Kuo 1994; Todorov and Jordan 2002; Valero-Cuevas 2000; Valero-Cuevas et al. 1998). It is

also unclear whether some force in some directions is generated by a “prime mover” muscle (Thomas et al. 1986) or whether all force generation involves the cooperation of multiple muscles (Buchanan et al. 1986; Keenan et al. 2006). These questions remain unresolved, in spite of multiple attempts to characterize muscle activation patterns across multiple DOFs.

The synergistic activation hypotheses and the task-specific flexible activation hypotheses are not incompatible; strategies could apply to voluntary skilled tasks different from those applying to stereotypical reflexive tasks. To separate these hypotheses in voluntary tasks, we introduce a new method for assessing muscle force contributions to net force generation at a multiple DOF joint: the metacarpalphalangeal (MCP) joint of the index finger. This method uses high-gain force measurements recorded at the finger tip to estimate the various muscle contributions to net joint force. In contrast, most prior studies investigating muscle coordination across multiple DOFs have focused on the use of electromyographic (EMG) recordings. Although such EMG recordings provide valuable information about muscle activity, they offer significant disadvantages for studying muscle coordination in multiple muscle systems. For example, it is not always possible to record EMGs from all muscles that may contribute to a task. Also, the identification of muscle-level synergies from EMGs in natural behaviors may also be complicated by the existence of biomechanical or task-planning constraints unrelated to muscle synergies. If the CNS chooses to generate force in stereotypical ways, it may cause muscle activation patterns to appear to obey simplifying activation constraints, even if other activation patterns are possible.

An alternative approach to studying muscle coordination involves mapping isometric endpoint force variability for an array of targets distributed uniformly across the endpoint force space. Stochastic effects may enter such tasks in several ways, but one of the most significant is *signal-dependent noise* (SDN) (Enoka et al. 1999; Galganski et al. 1993; Laidlaw et al. 2000; Schmidt et al. 1979; Slifkin and Newell 1999), where isometric force variability increases with average isometric force. Such SDN may arise from the sequential recruitment of motor units with larger twitch forces as the muscle force requirement increases (Jones et al. 2002). If muscle force variability increases with average muscle force, then differing neuromotor control strategies can generate different patterns of endpoint force variability. For example, one muscle acting alone will

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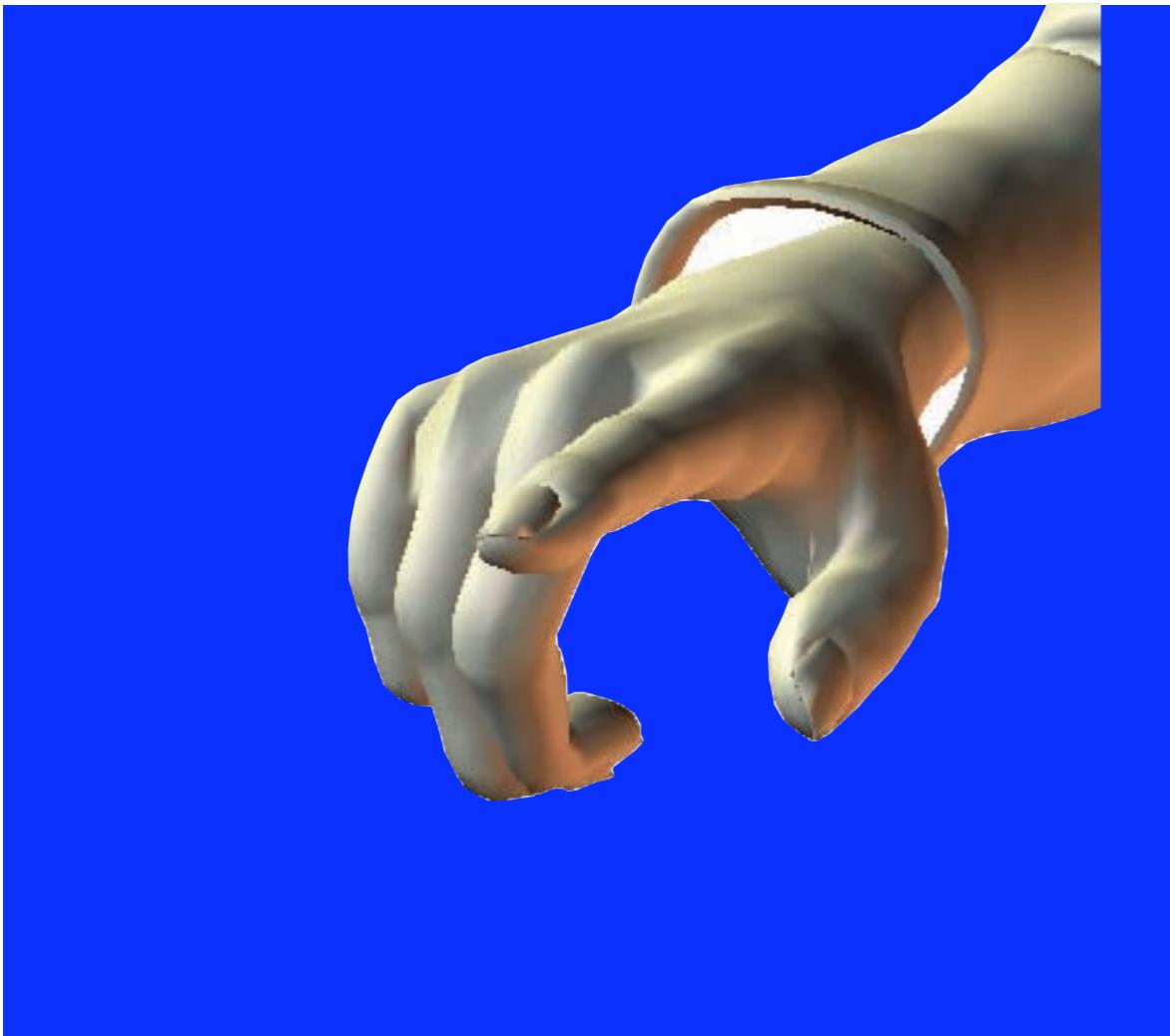
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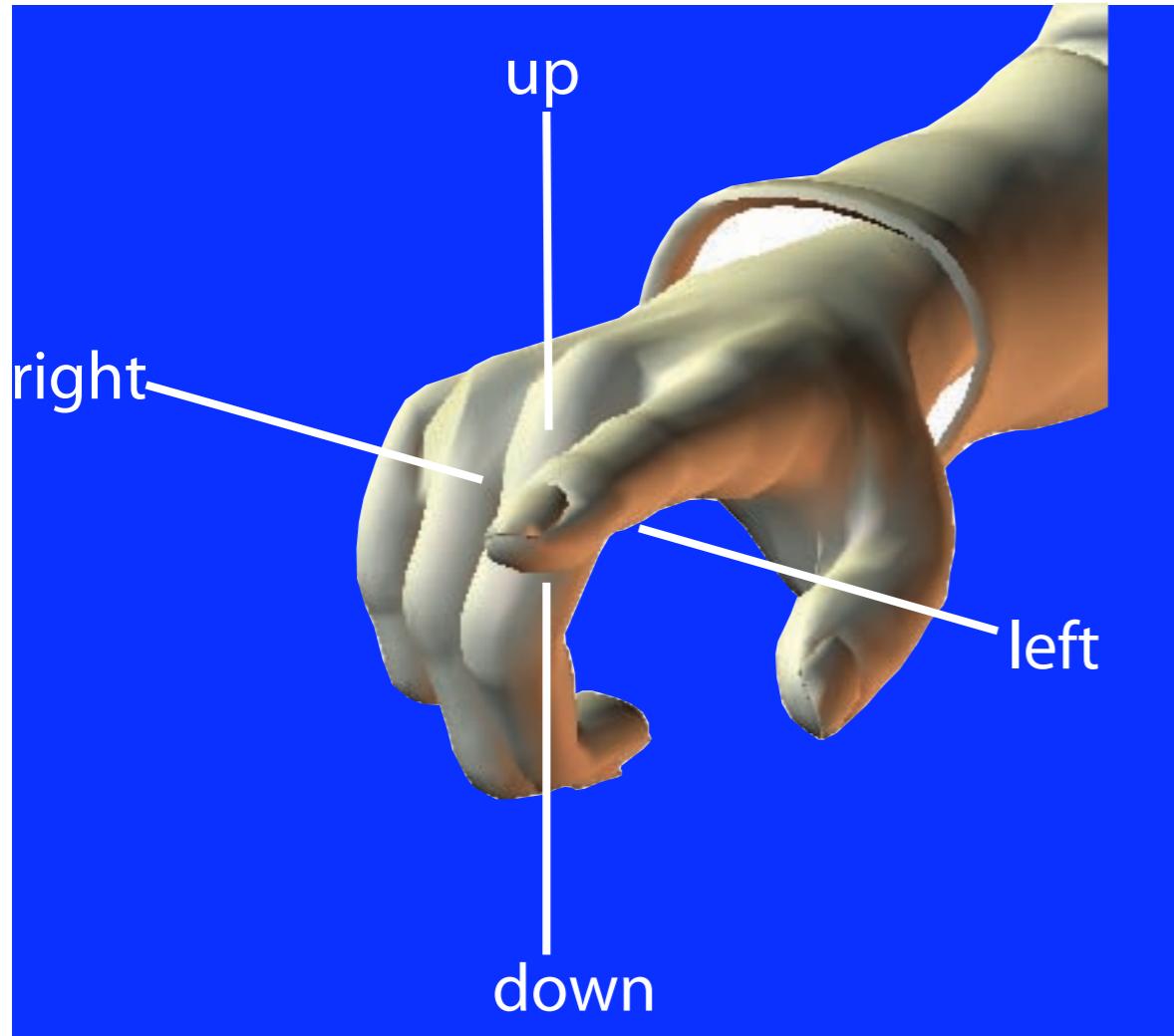
# No synergies for finger muscles

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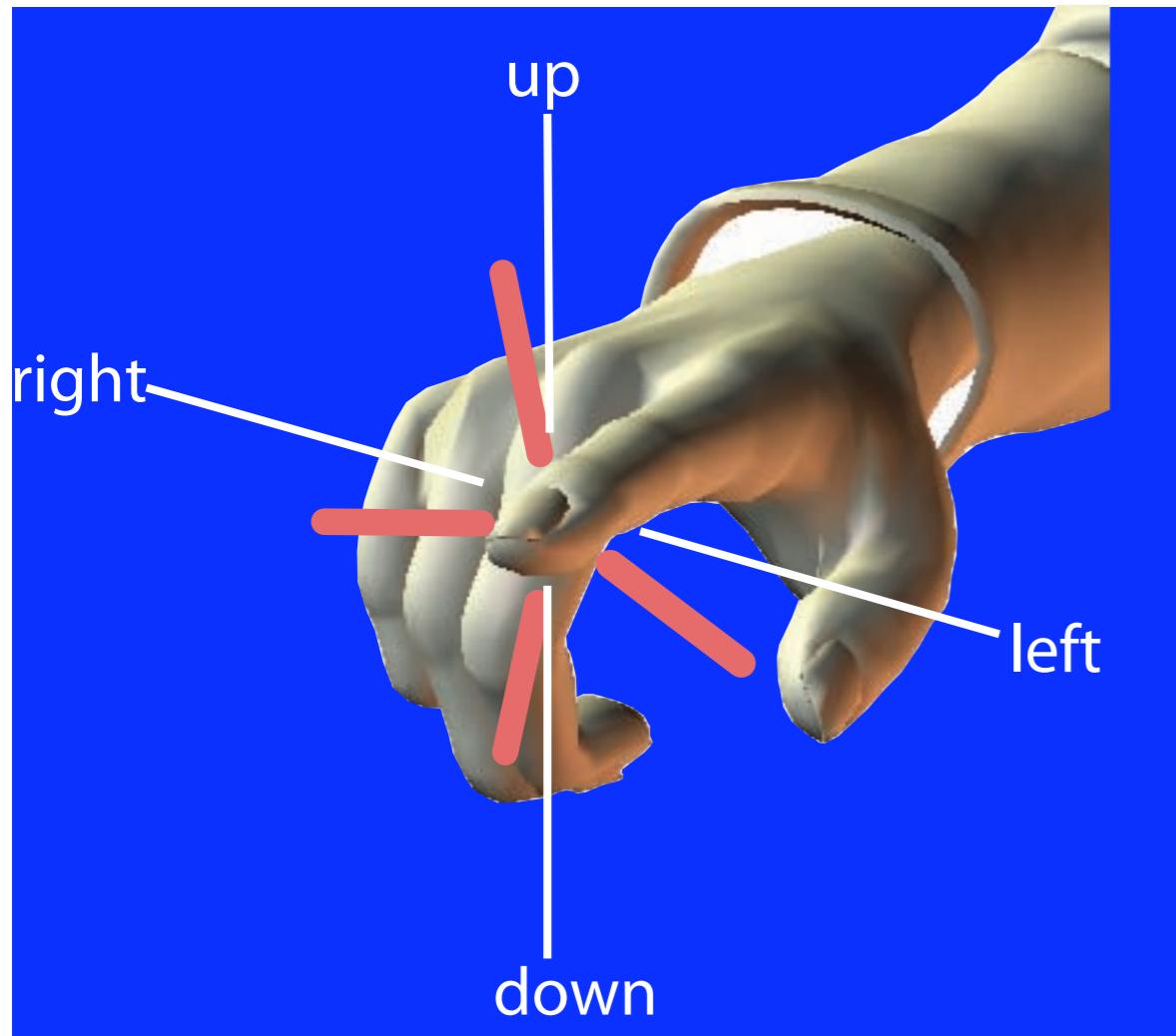
- Endpoint

# No synergies for finger muscles



- Endpoint
- Task space (what the endpoint can do)

# No synergies for finger muscles

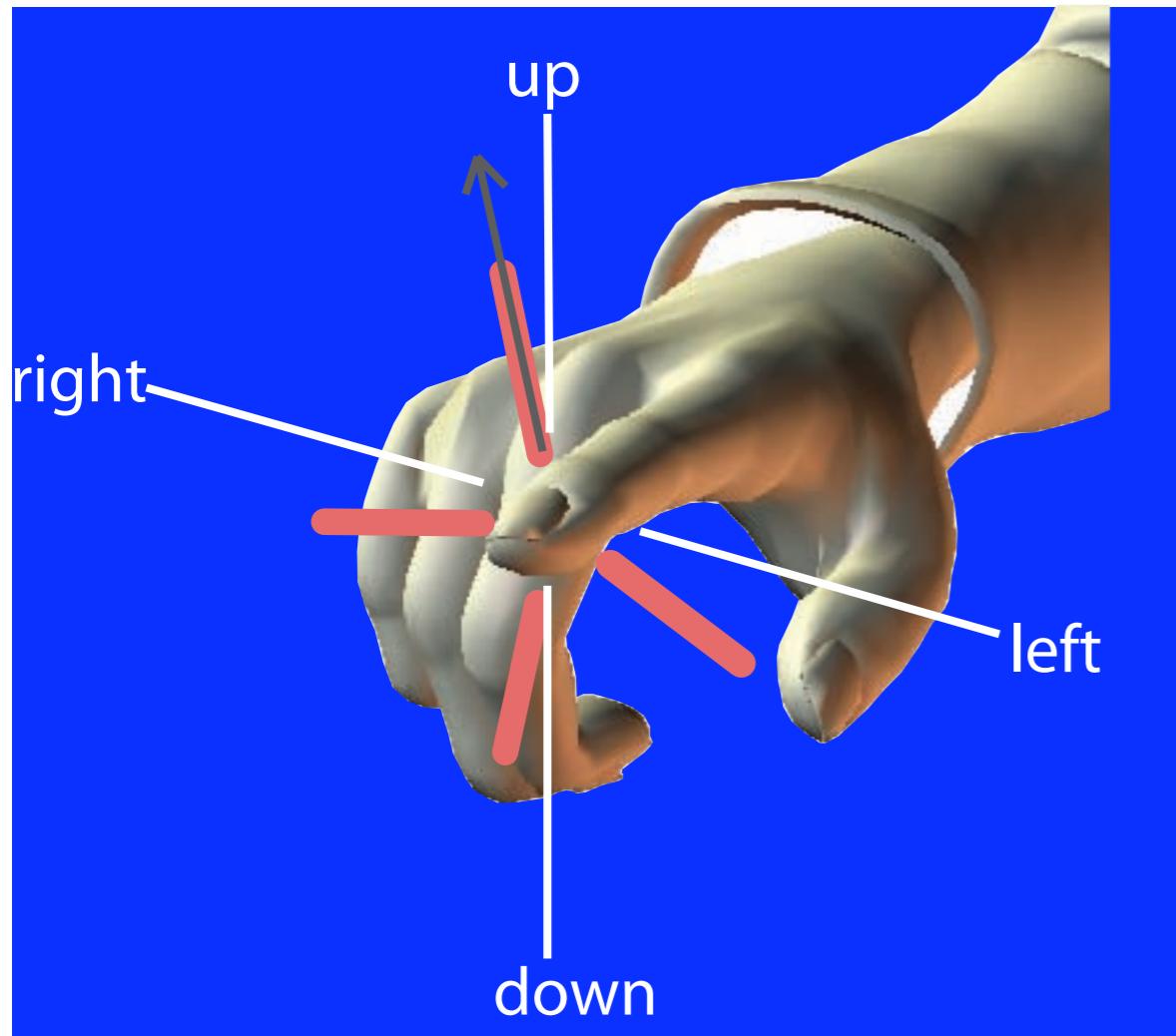


- Endpoint
- Task space (what the endpoint can do)
- Muscle action (direction of capability)

Westling et al. 1990

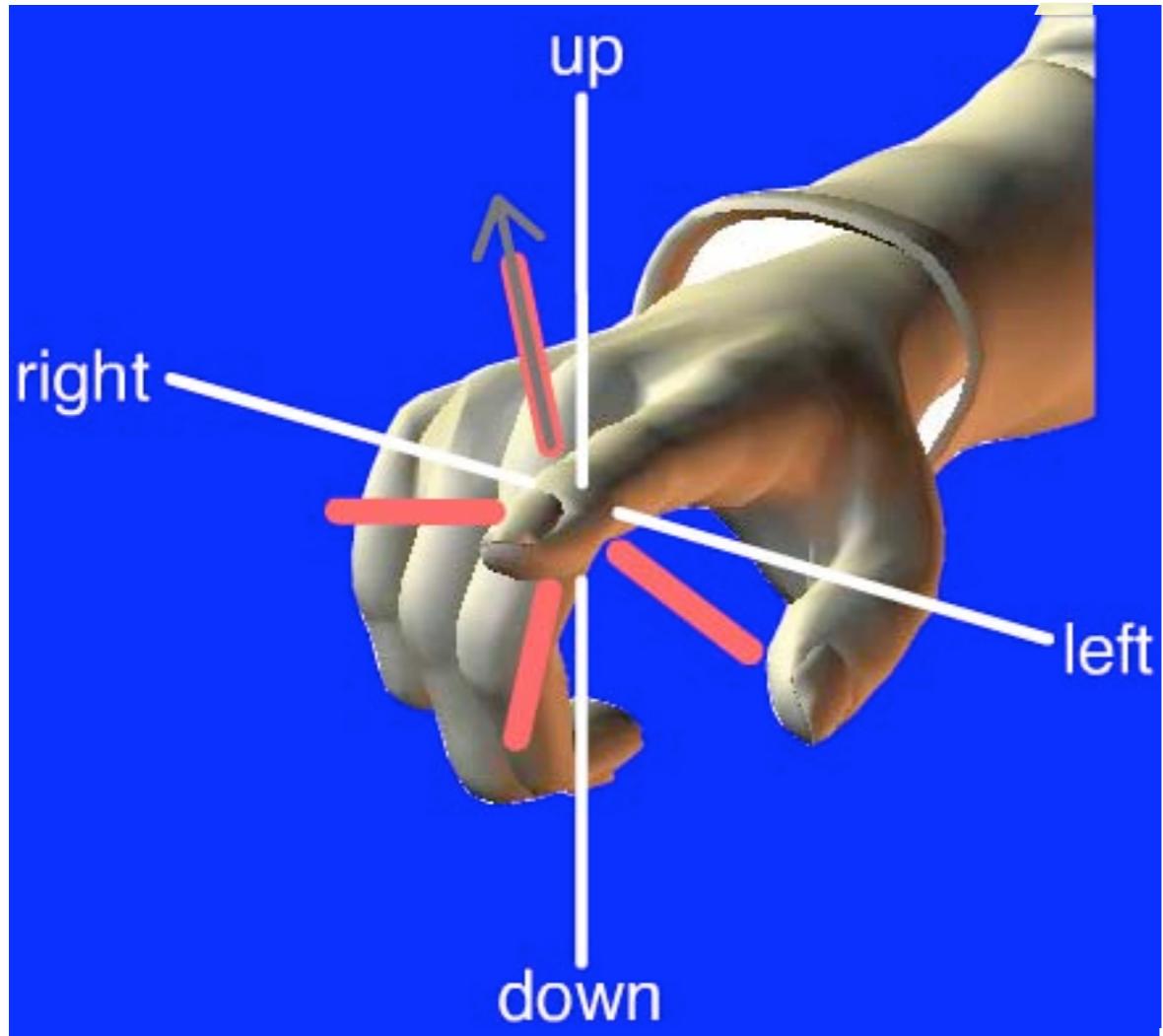


# No synergies for finger muscles



- Endpoint
- Task space (what the endpoint can do)
- Muscle action (direction of capability)
- Muscle endpoint vector (force applied)

# No synergies for finger muscles

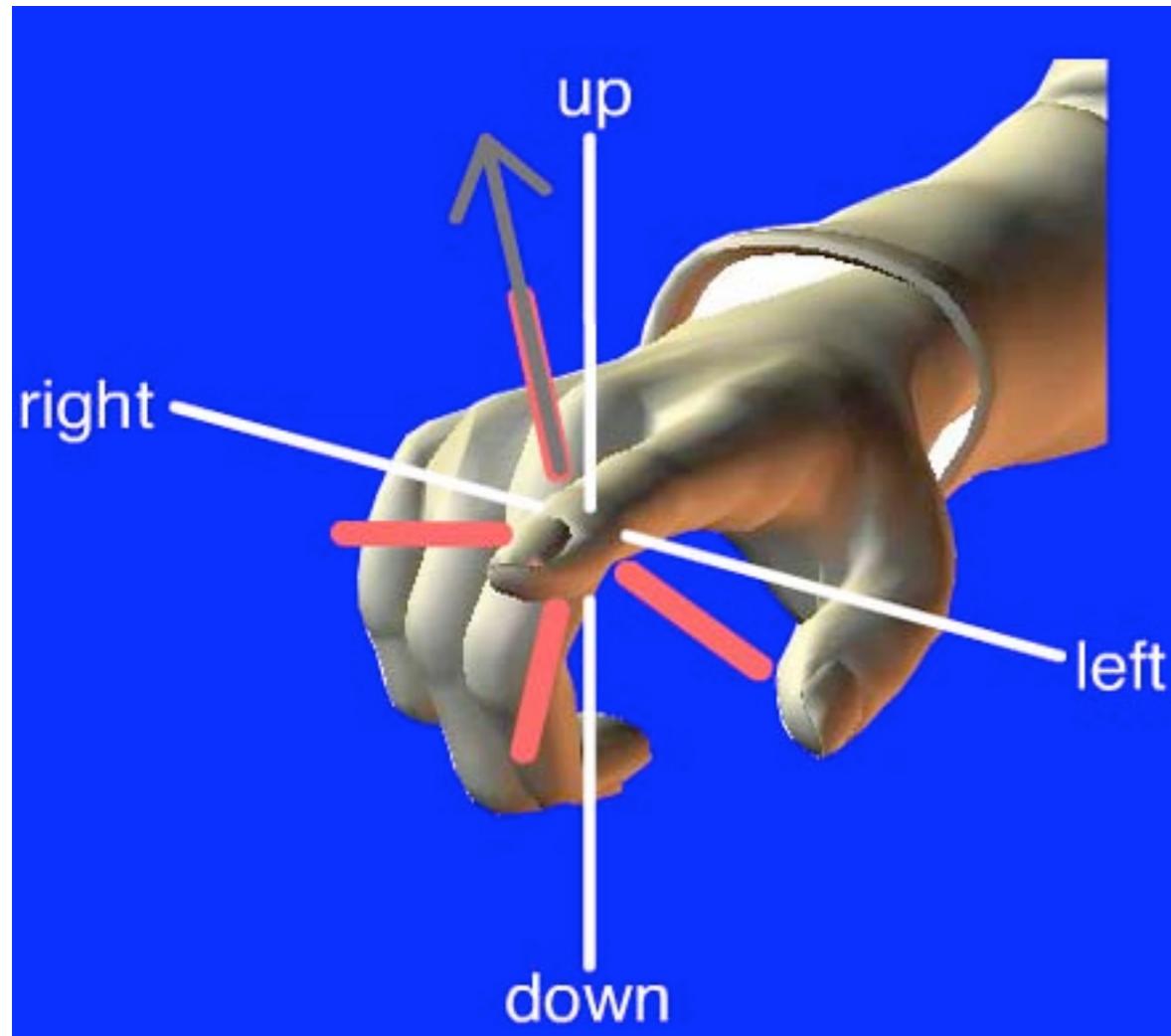


- Endpoint
- Task space (what the endpoint can do)
- Muscle action (direction of capability)
- Muscle endpoint vector (force applied)
- Signal-dependent noise  
(more fluctuation for more force)

Thomas et al. 1991

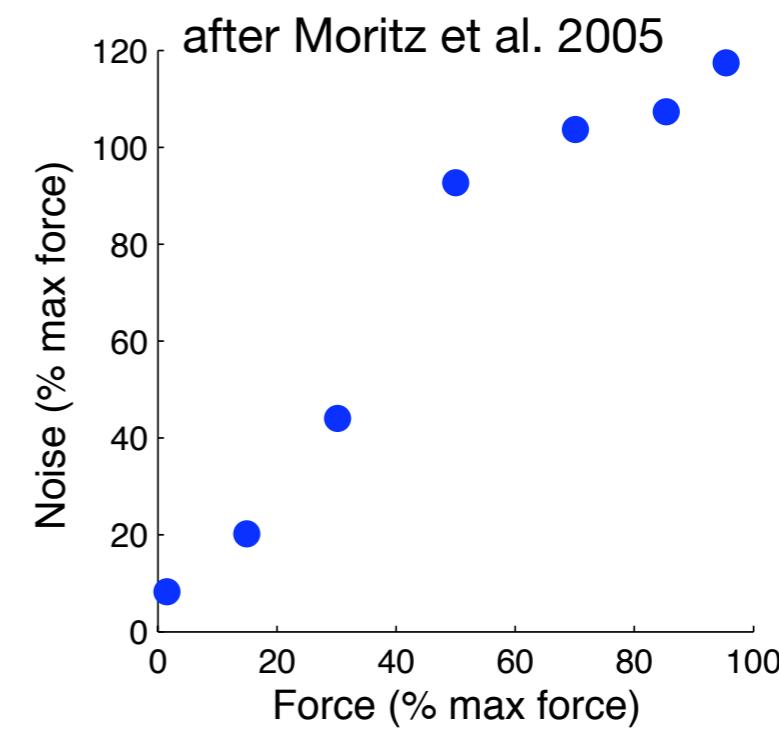


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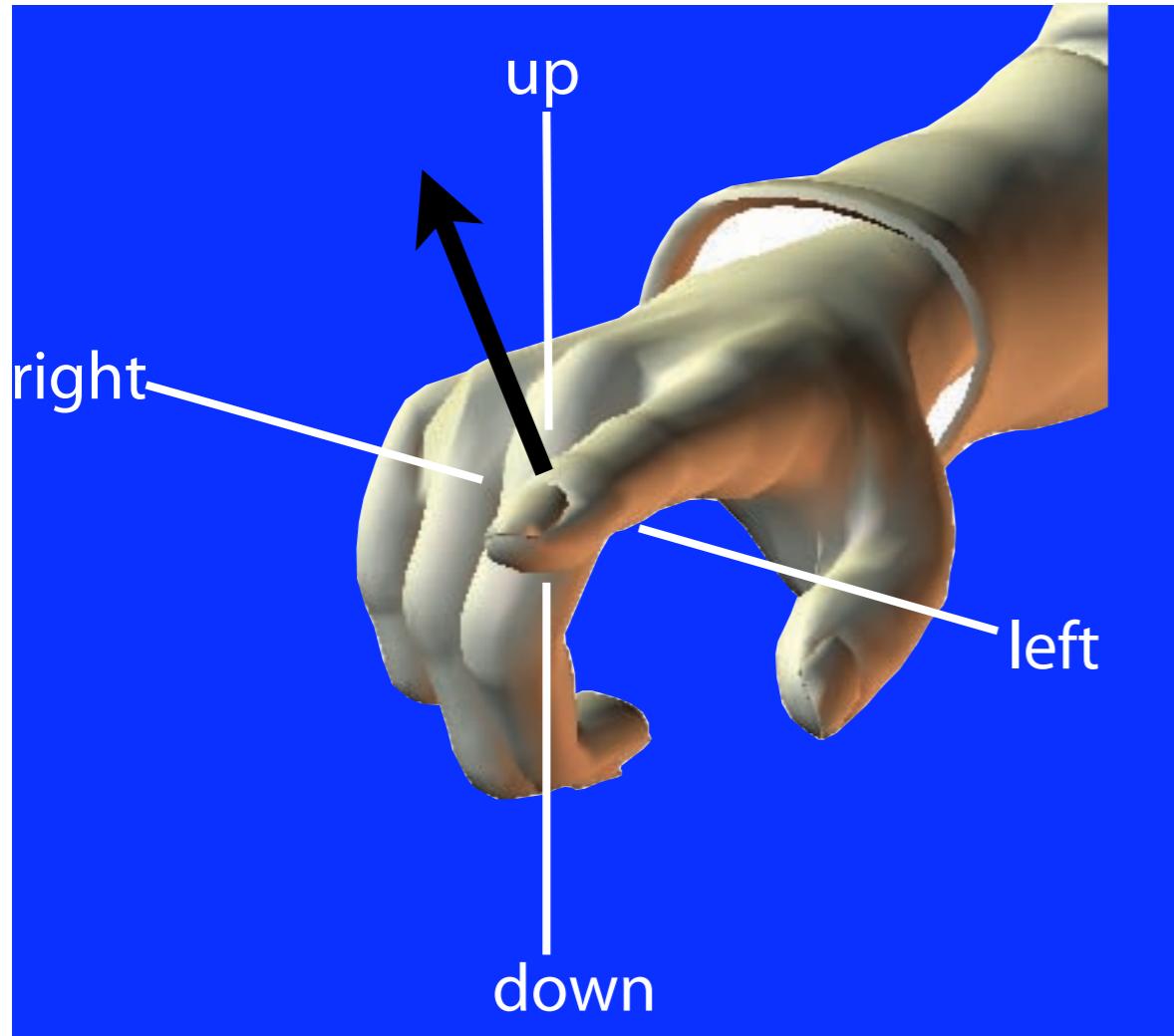


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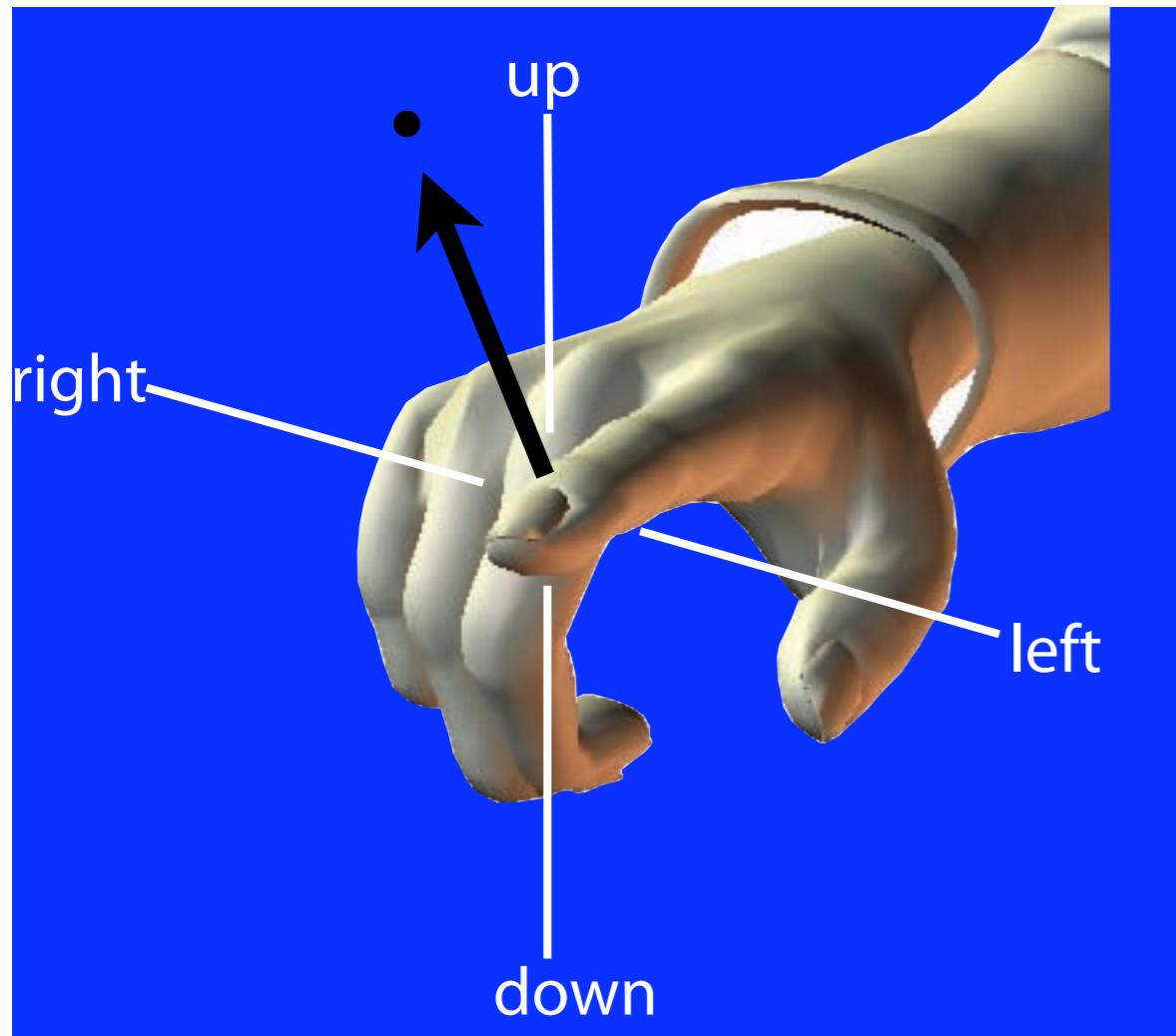


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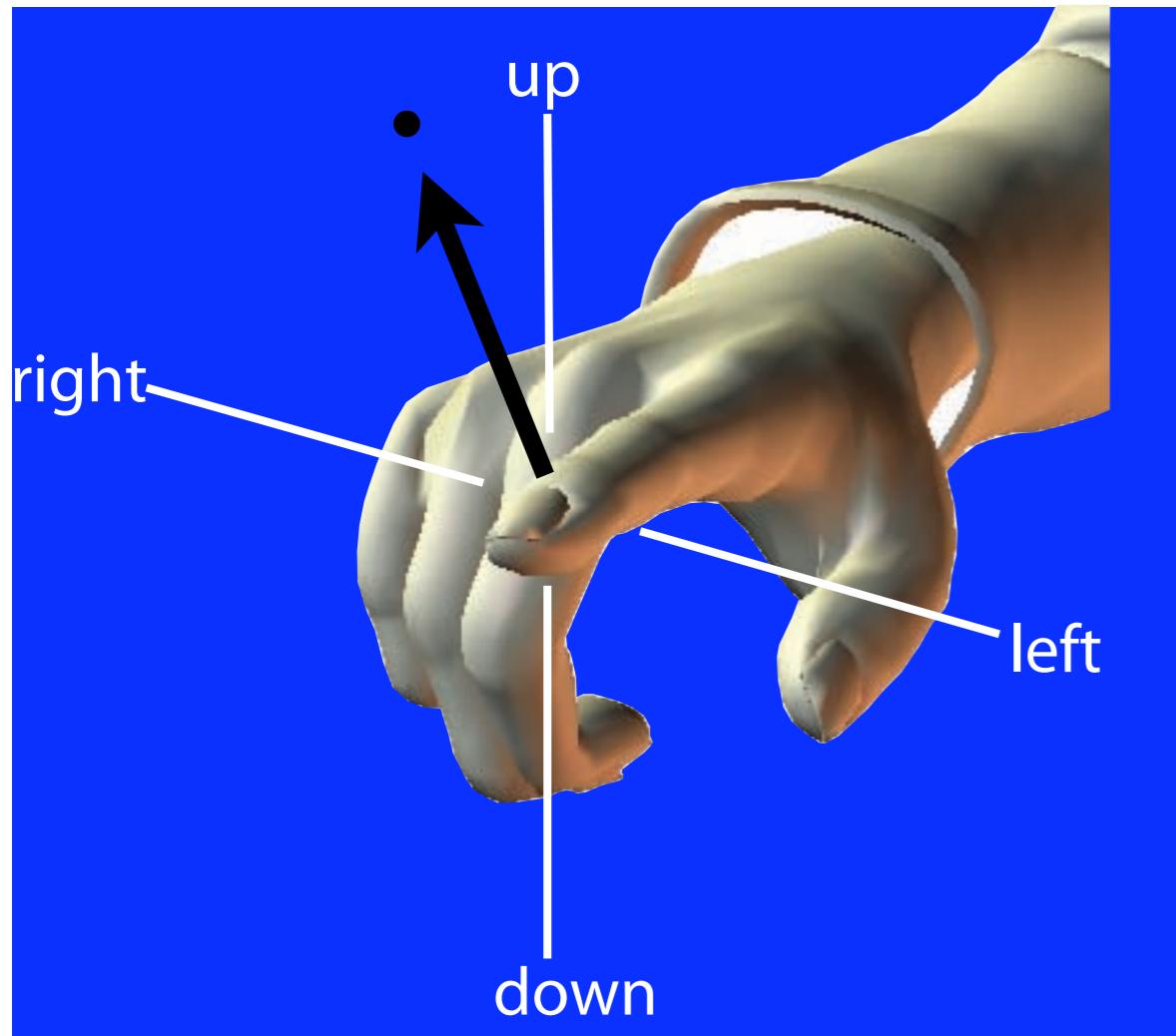
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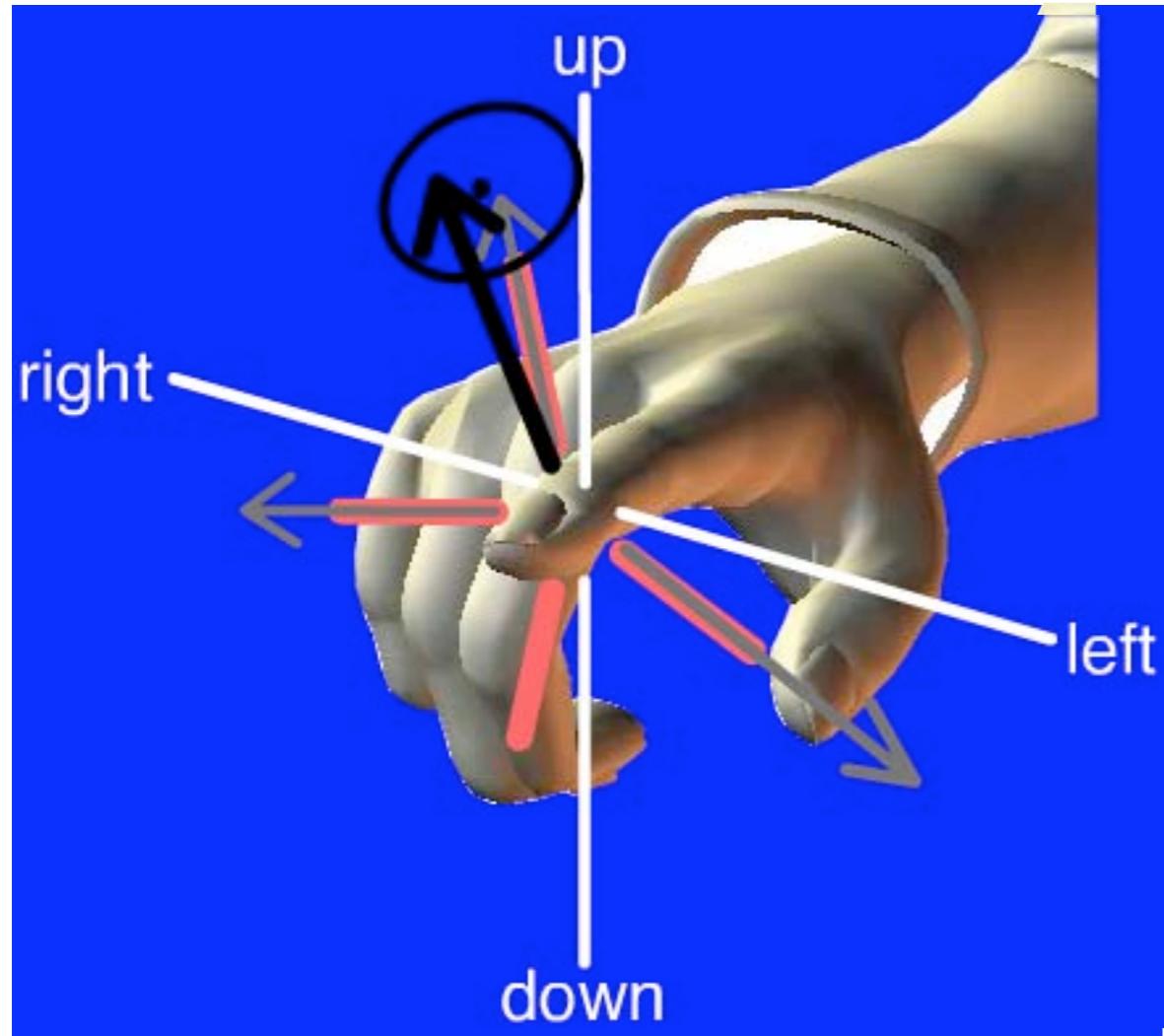
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New Concepts

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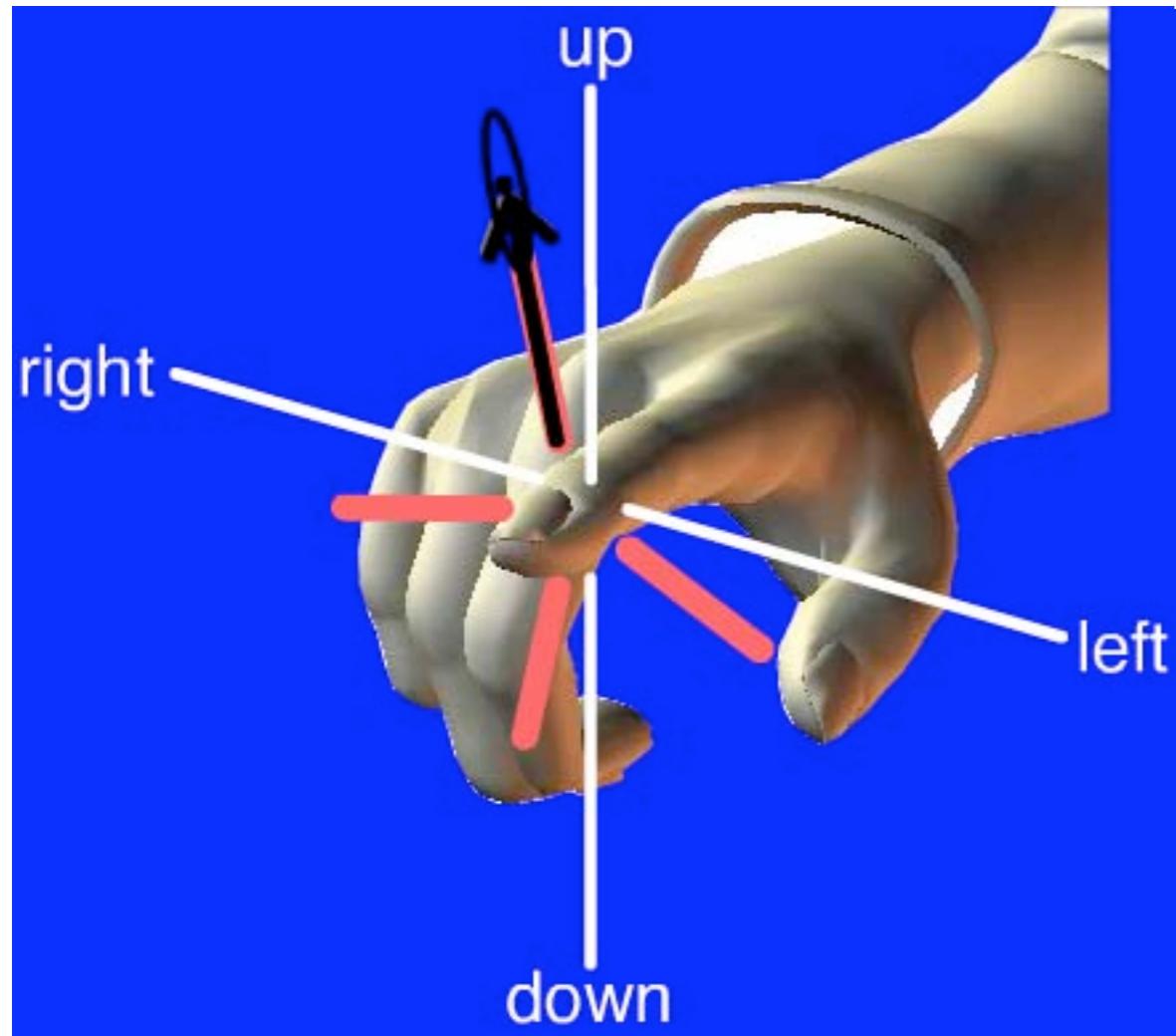
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## New Concepts

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- Non-directed ellipse (multiple muscle)

# No synergies for finger muscles



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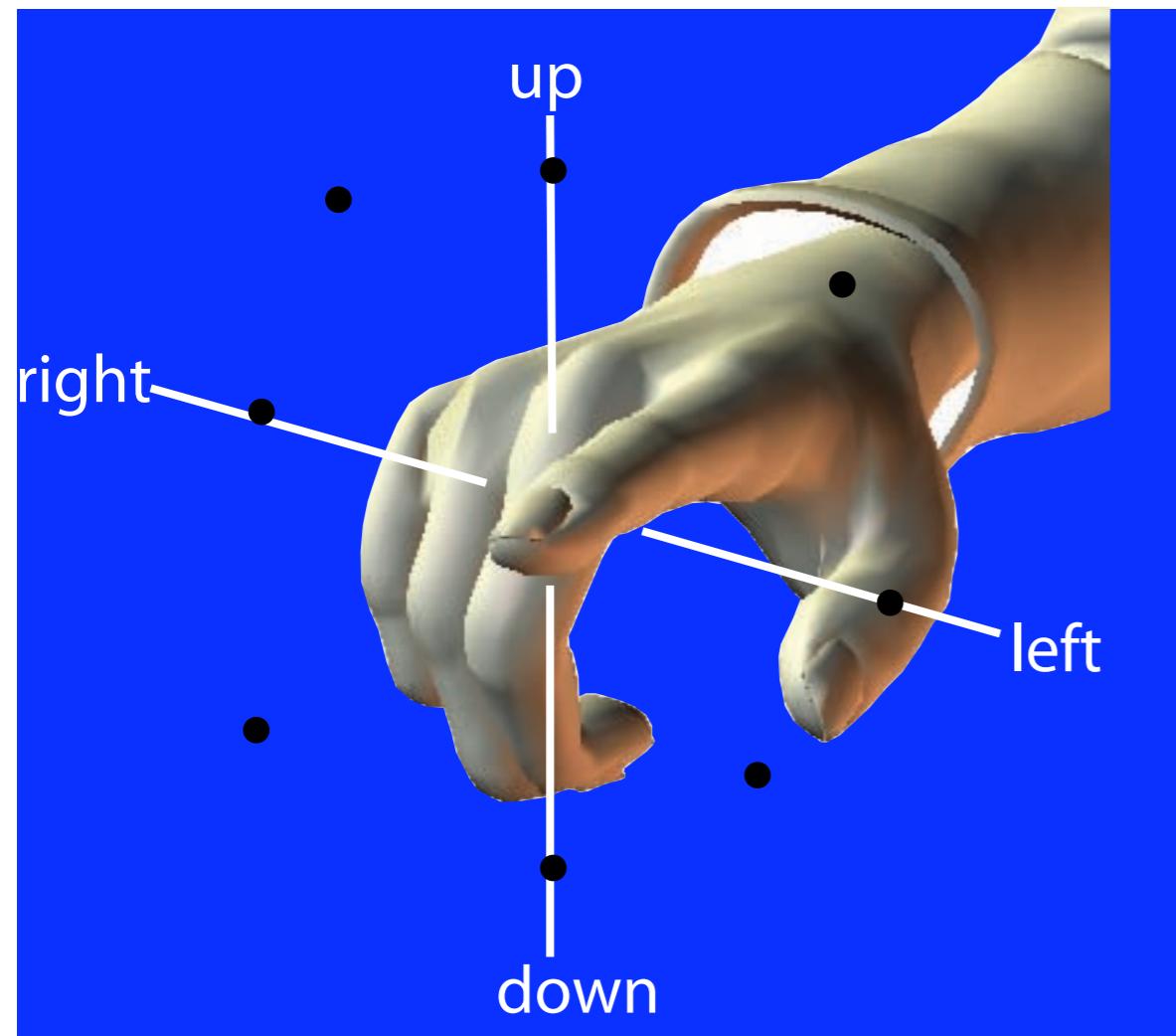
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## New Concepts

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- Non-directed ellipse (multiple muscle)
- Directed ellipse (primary muscle)

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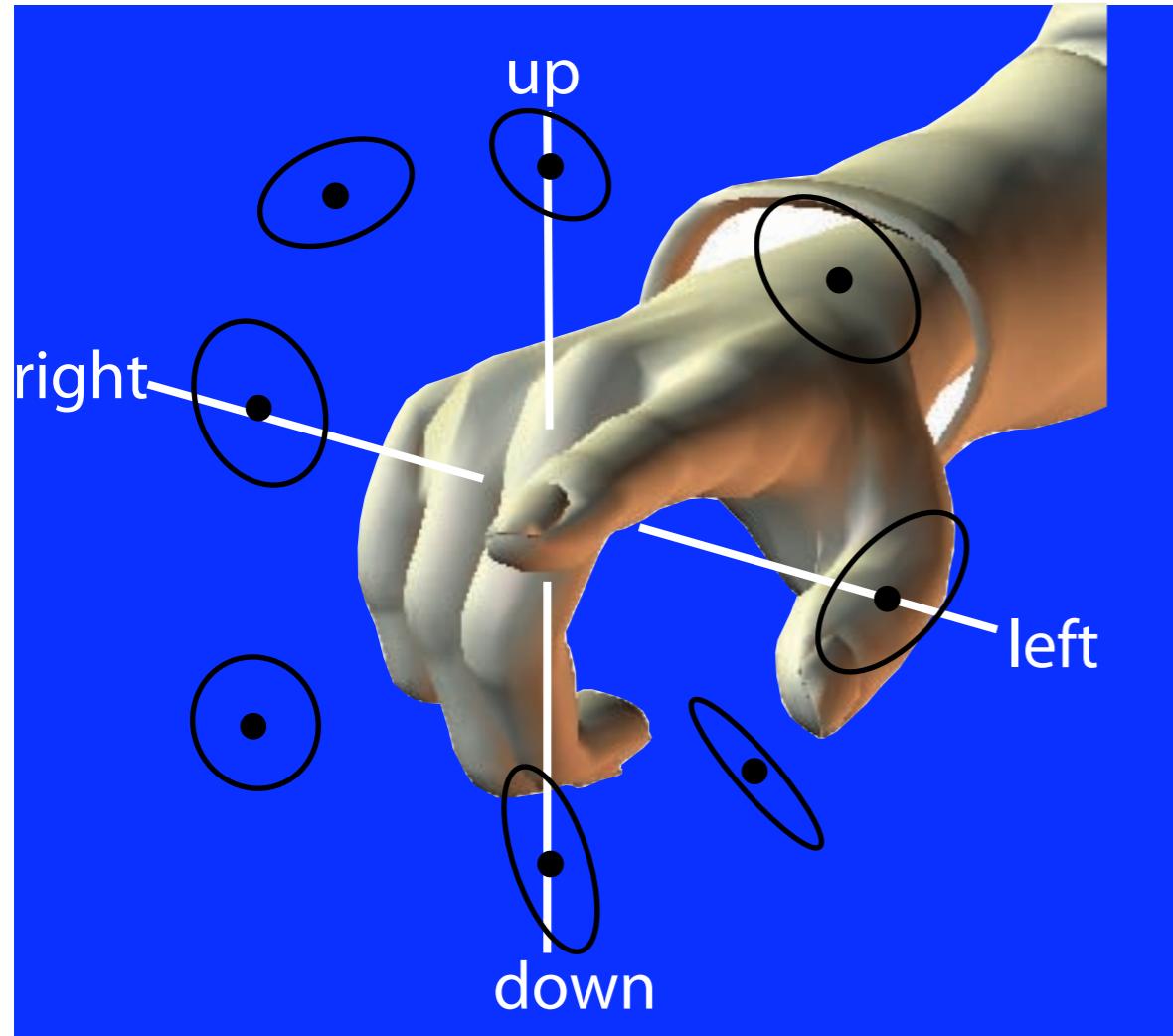
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## New Concepts

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- Non-directed ellipse (multiple muscle)
- Directed ellipse (primary muscle)
- Grid of force tasks

# No synergies for finger muscles



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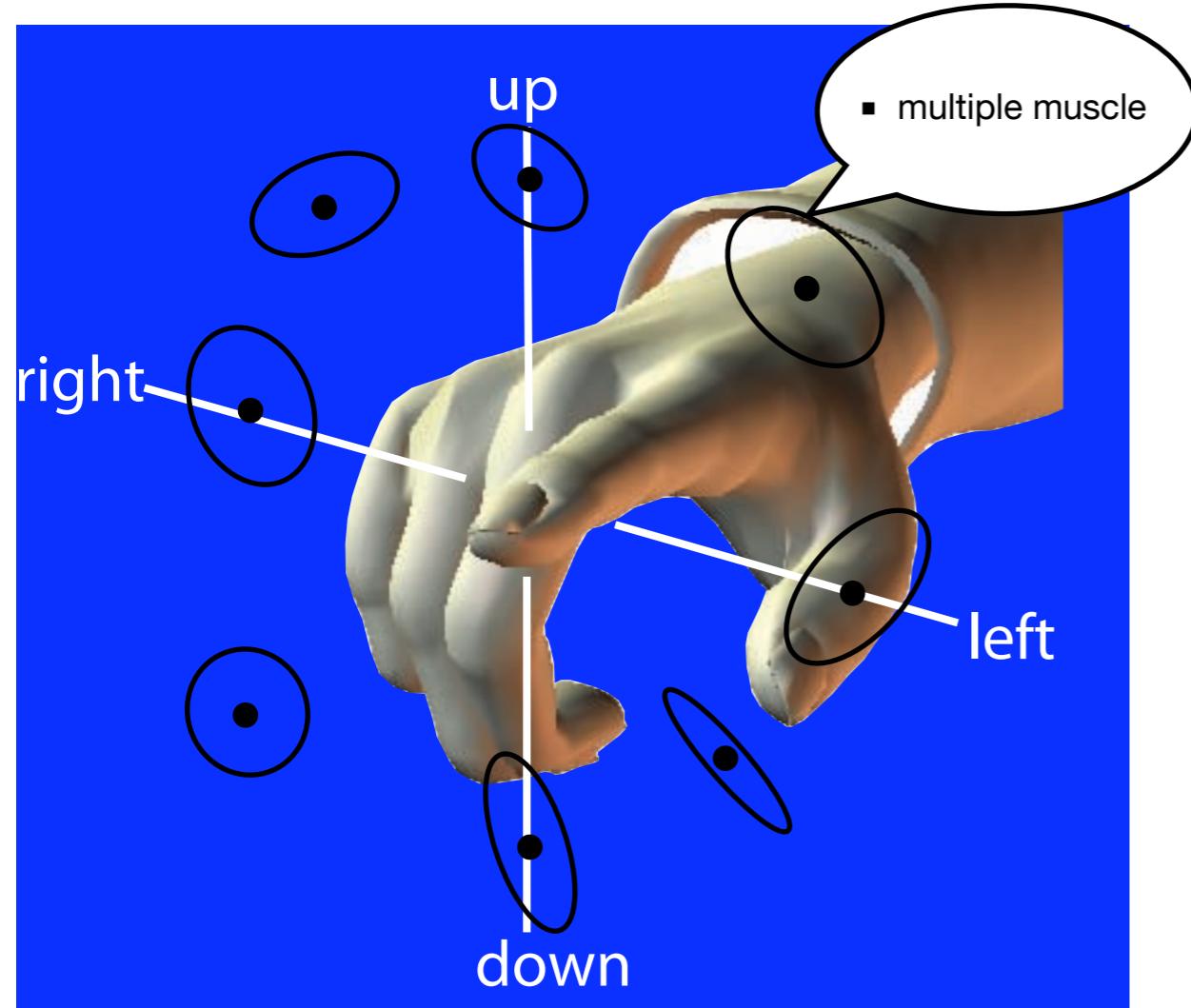
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- *Force Covariance Map (FCM)*

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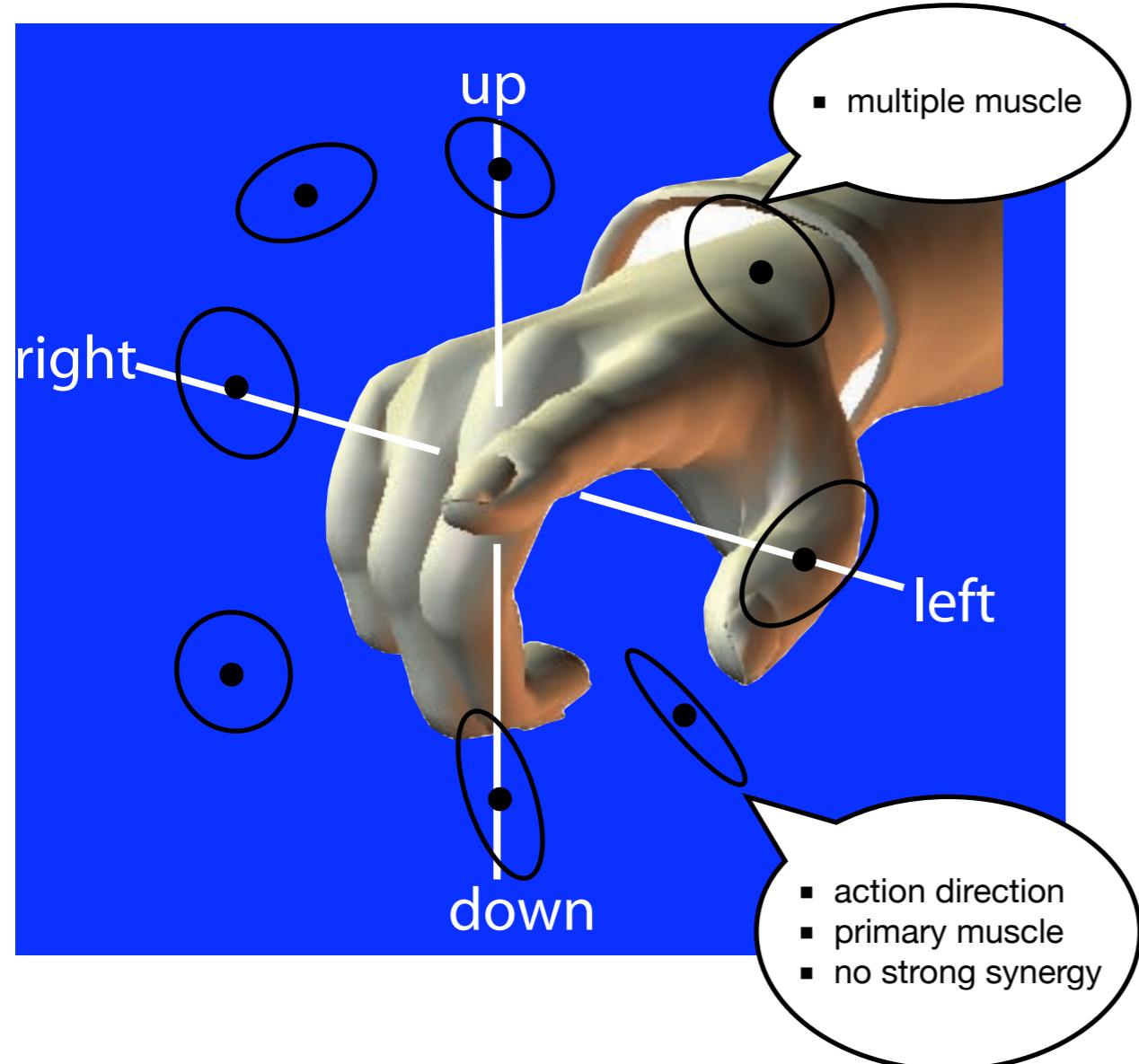
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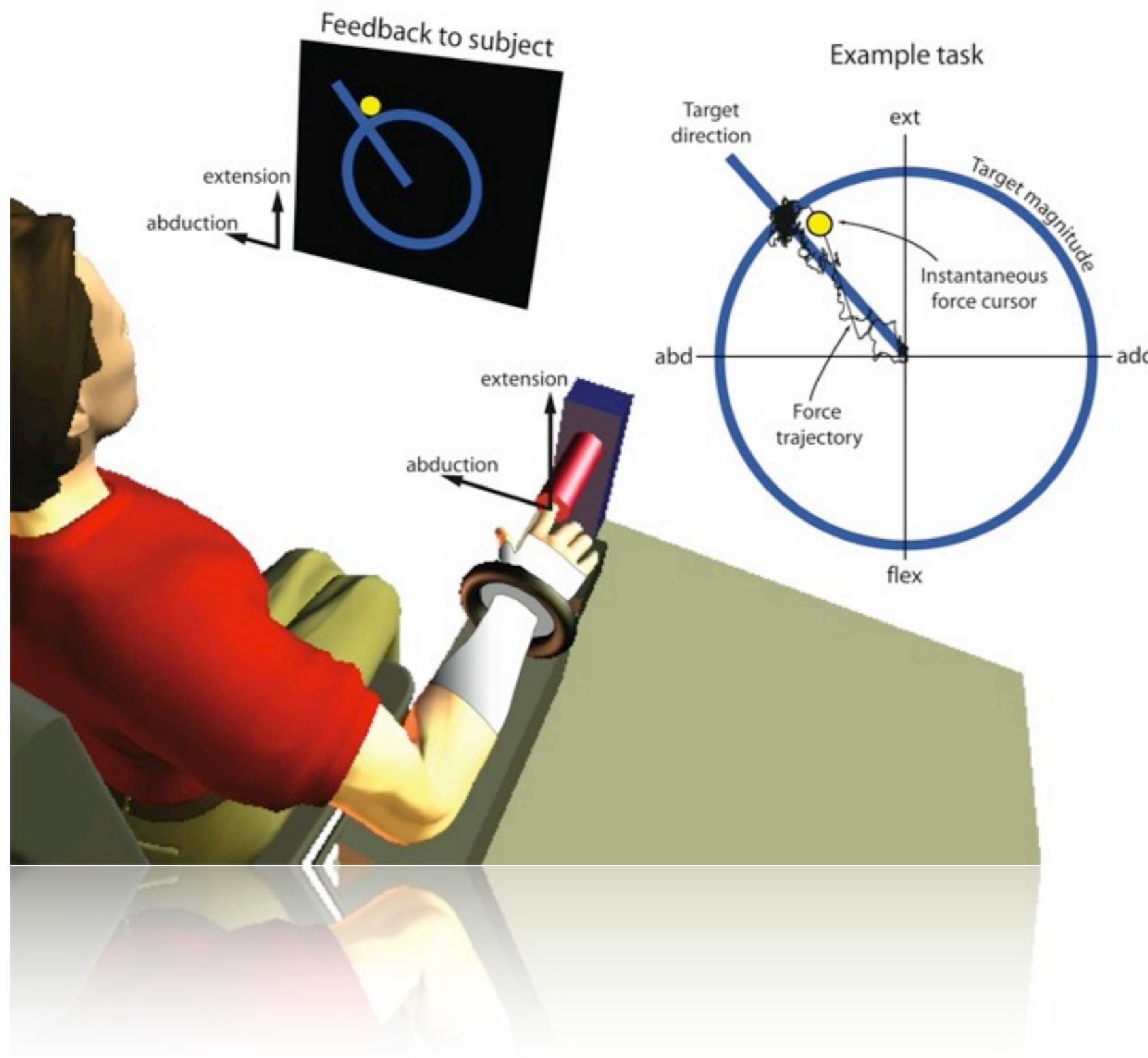
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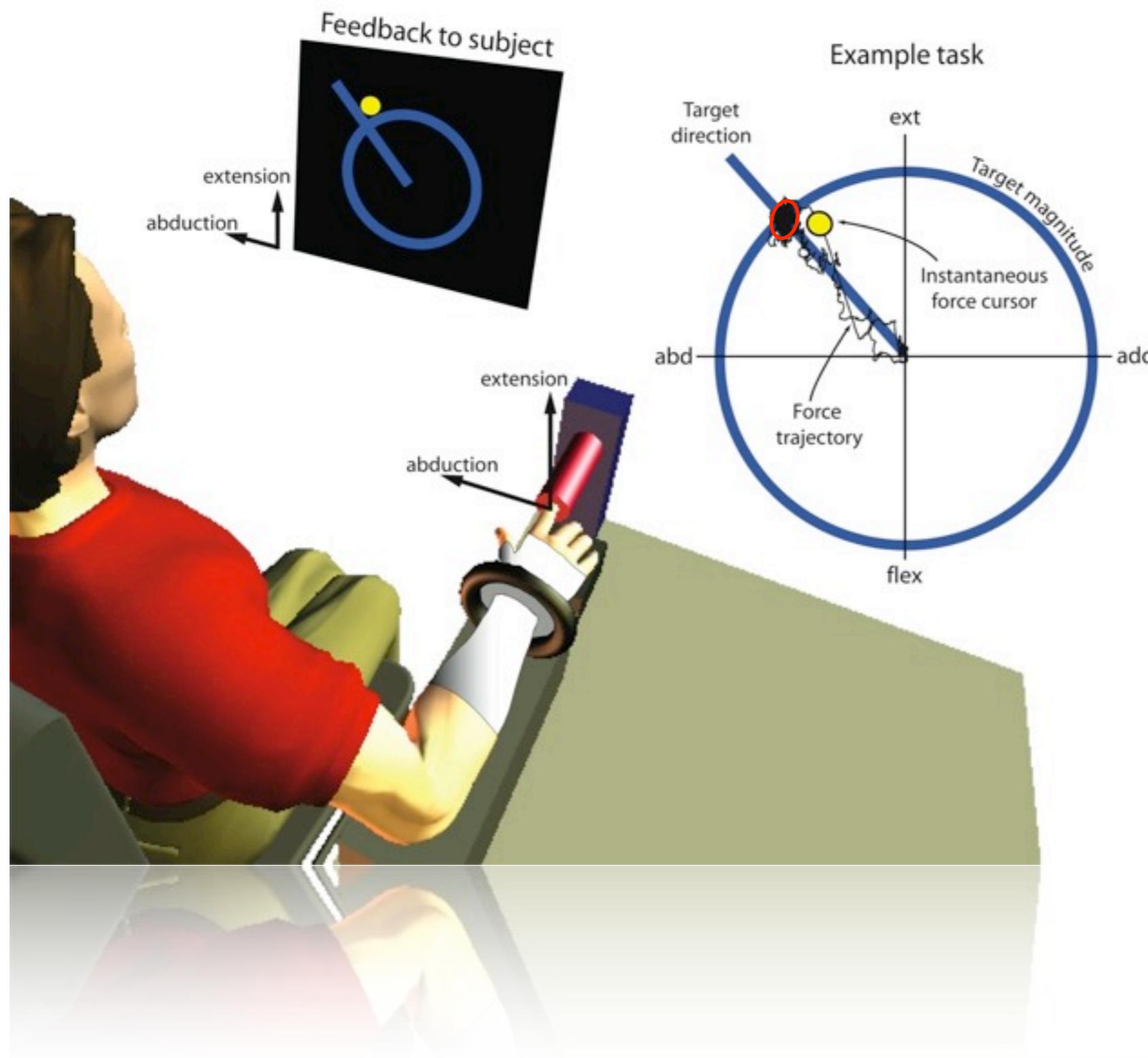
# No synergies for finger muscles



## Details:

1. Load cell (JR3, Woodland, CA) has 1 mN smallest measurable load
2. Load amplified using lightweight aluminum tube
3. Low electrical noise environment
4. Table vibration minimized
5. Surface EMG measured using silver electrodes with self-contained preamplifiers (Delsys, Boston, MA)
6. Subject's given a target and a force cursor
7. Targets span plane with radial grid

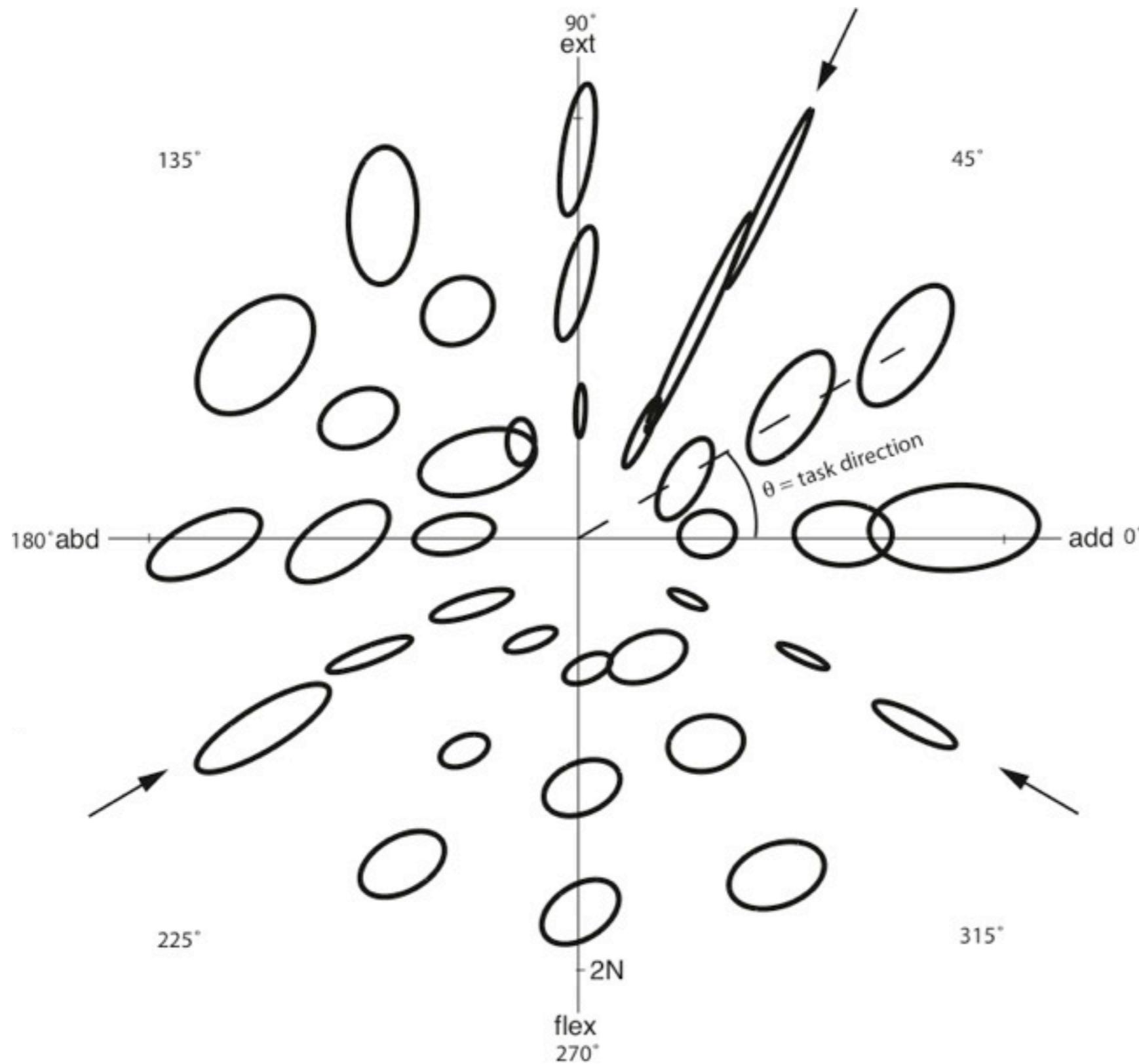
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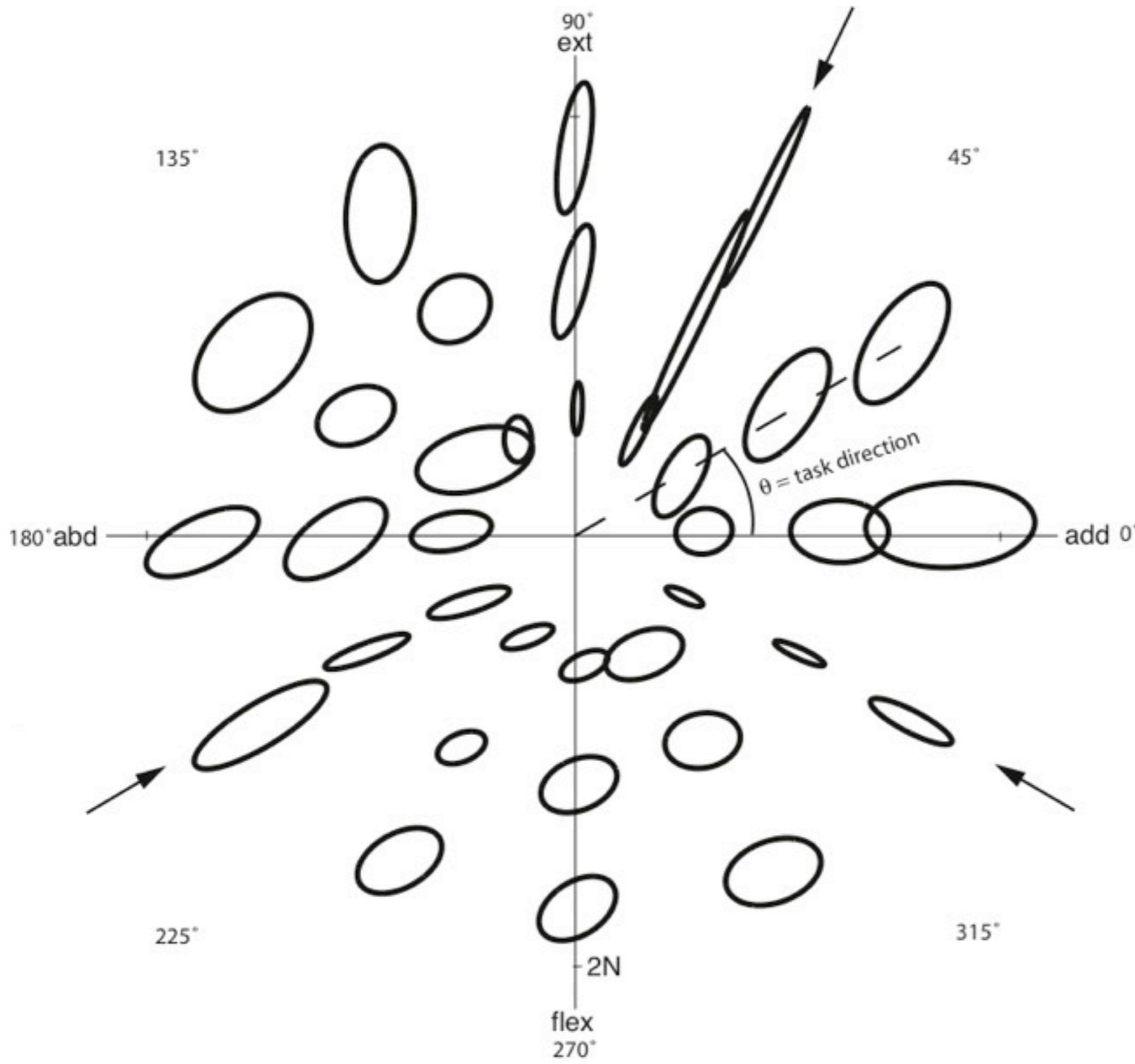
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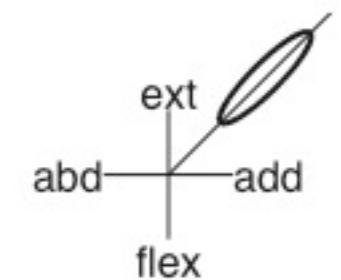


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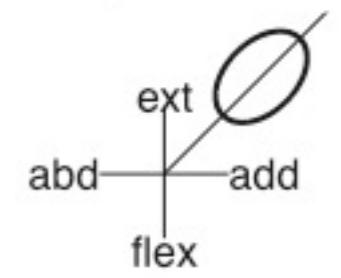


Task-directed variance fraction

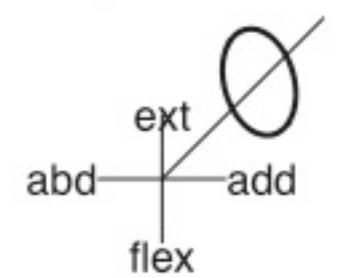
$$\eta = 95\%$$



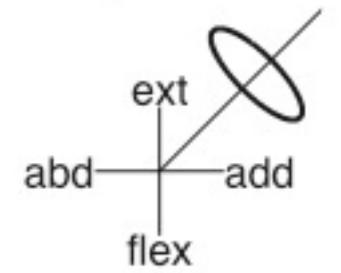
$$\eta = 71\%$$



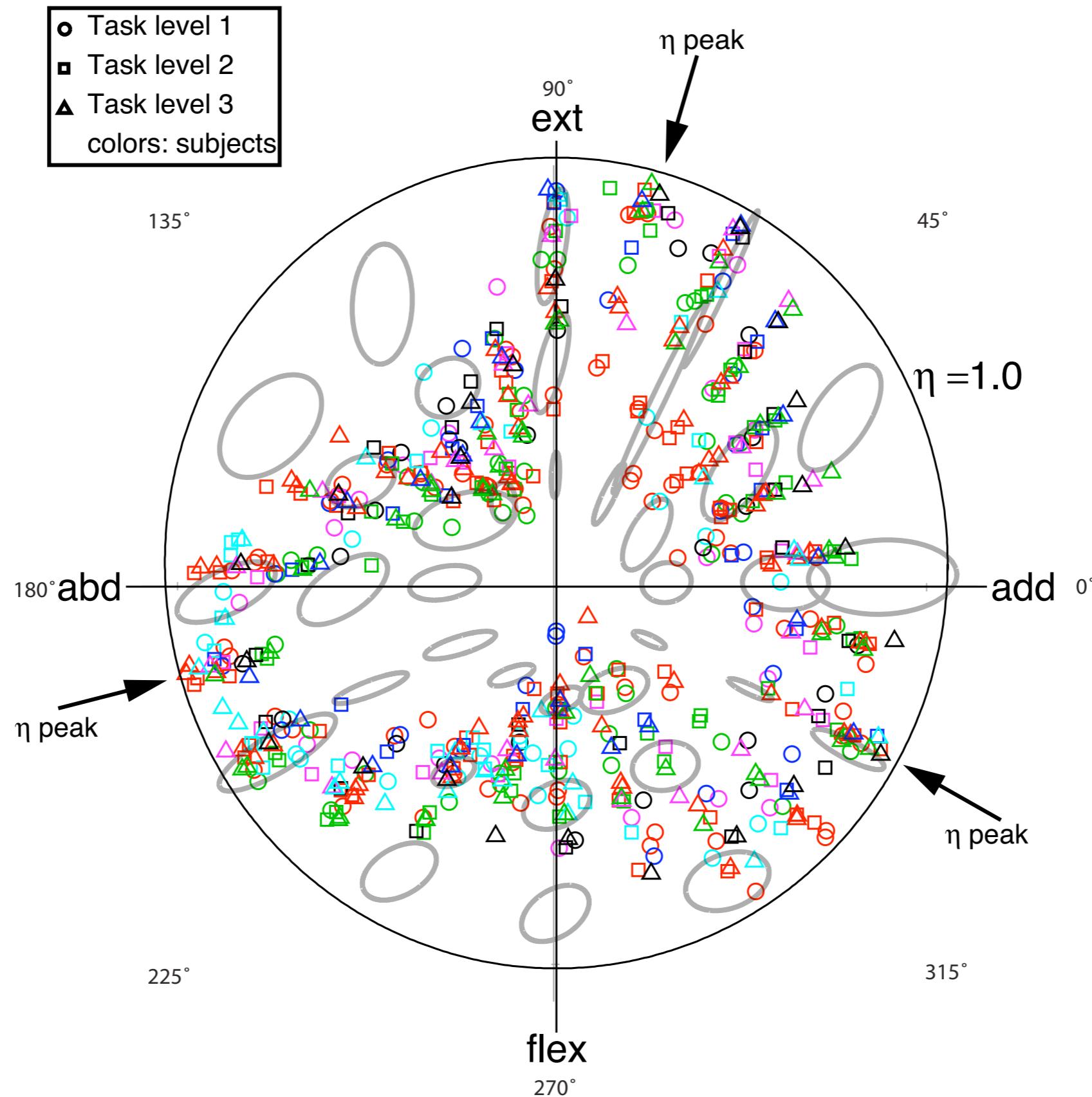
$$\eta = 40\%$$



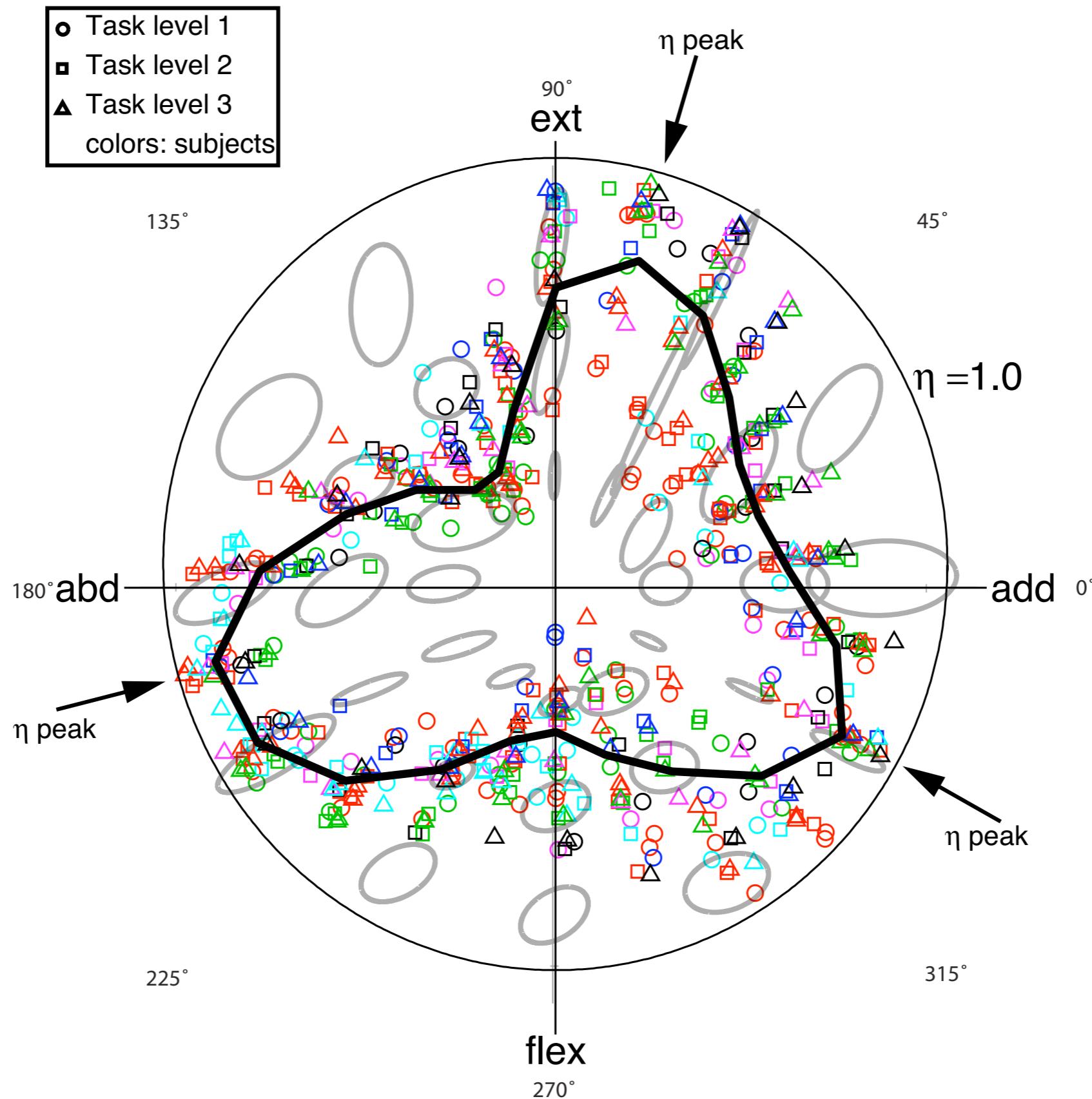
$$\eta = 10\%$$



# No synergies for finger muscles



# No synergies for finger muscles



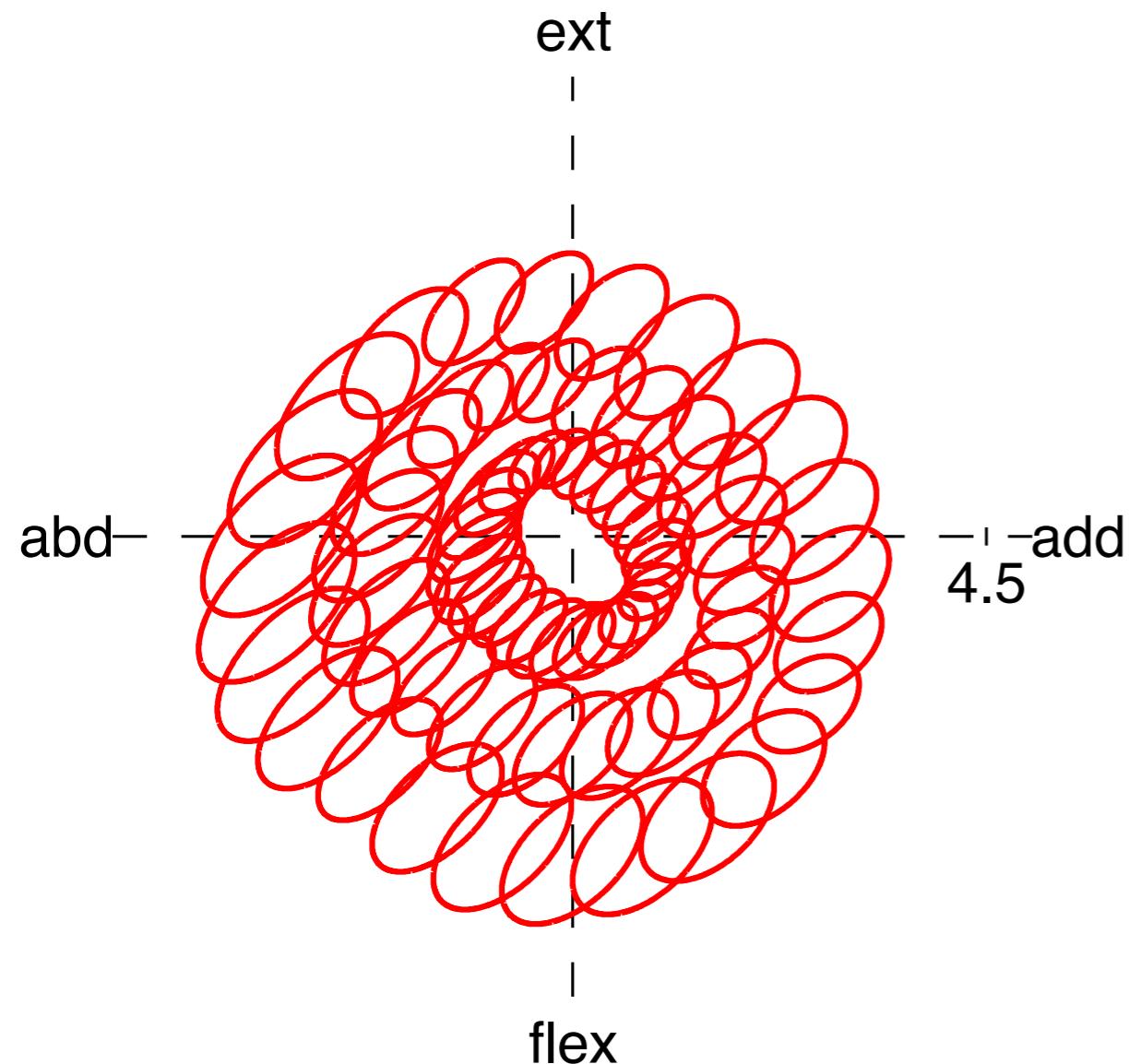
# No synergies for finger muscles

Synergy

Minimum effort

# No synergies for finger muscles

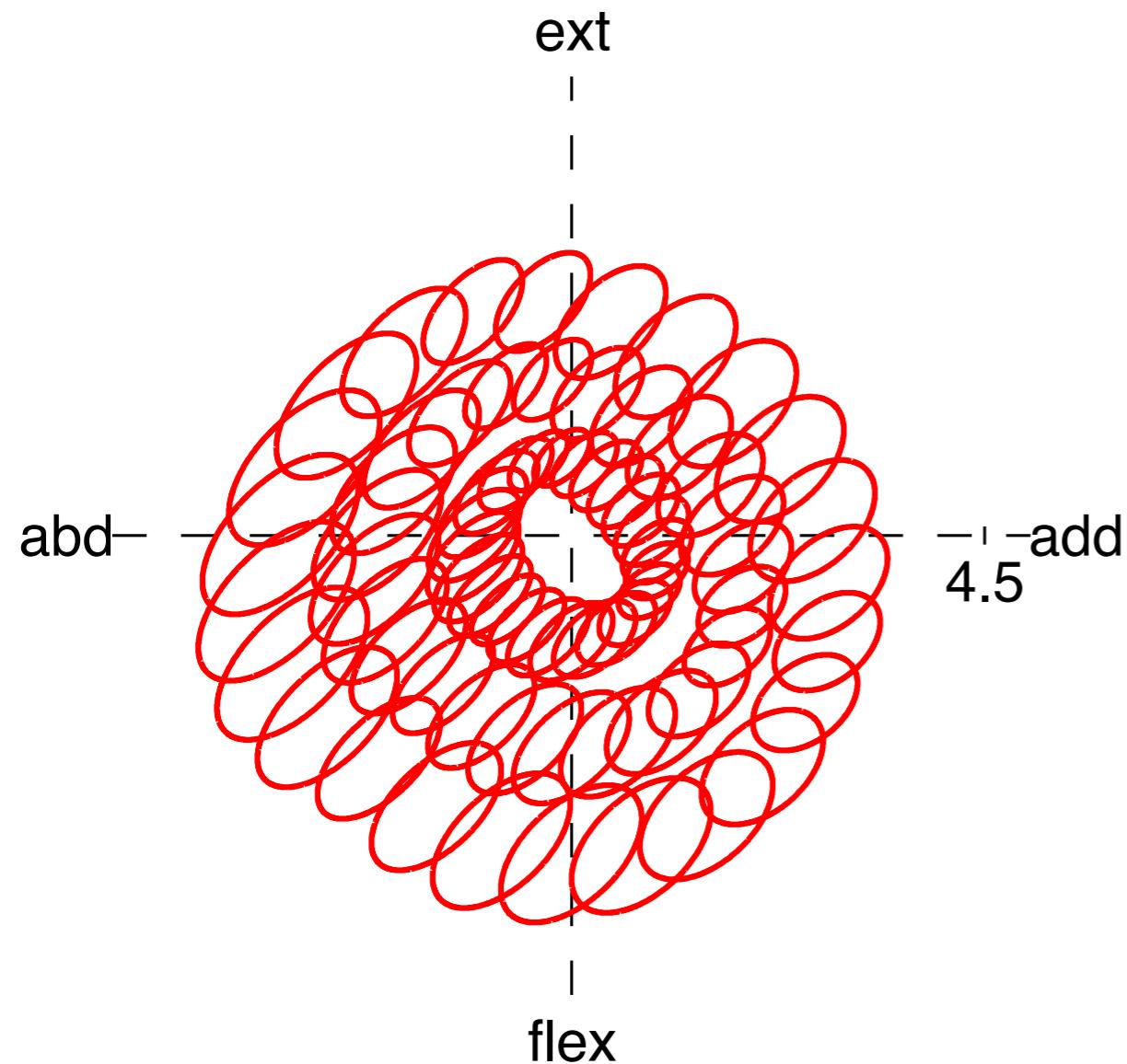
Synergy



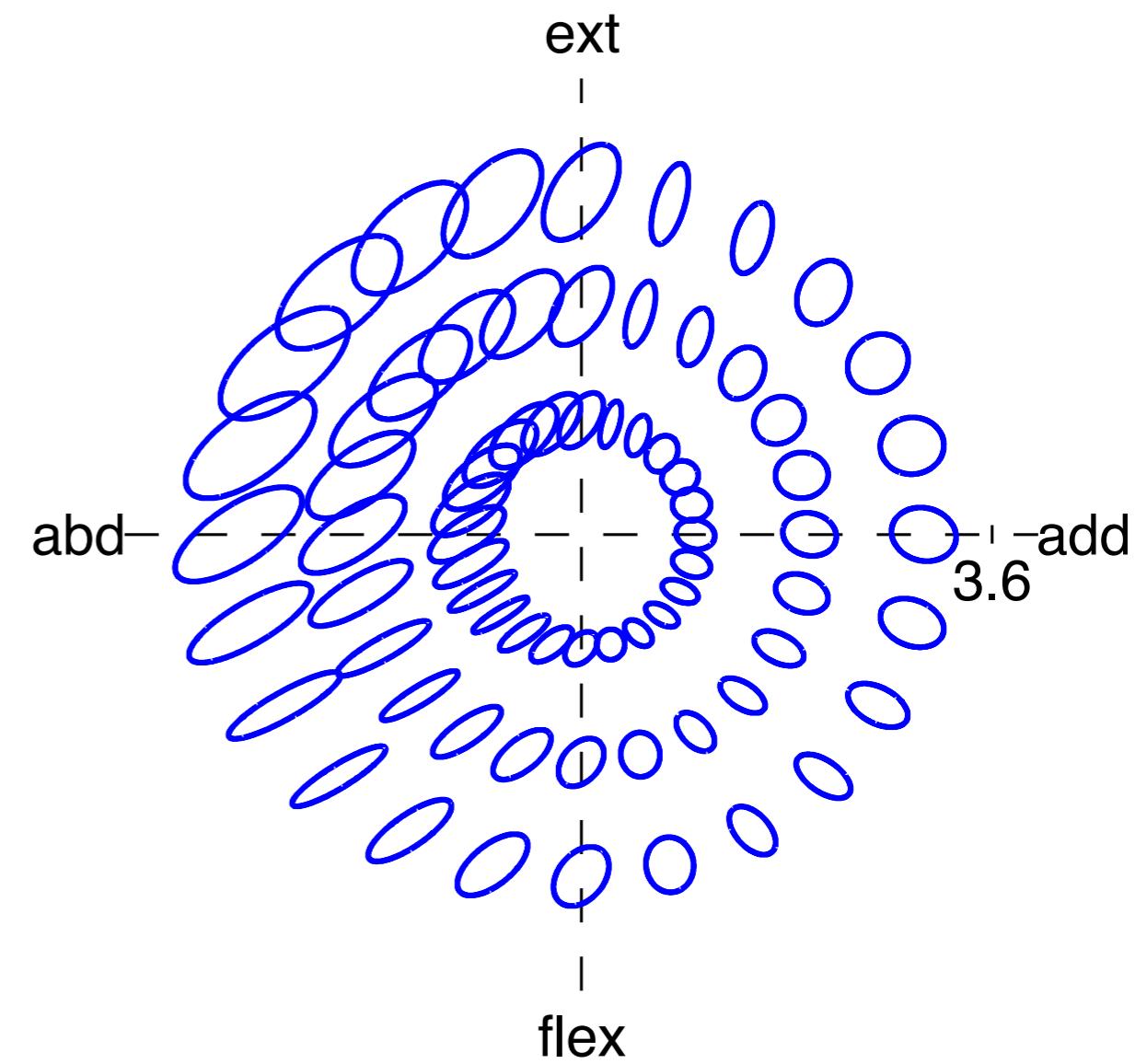
Minimum effort

# No synergies for finger muscles

Synergy



Minimum effort



The problem with synergies

No synergies for finger muscles

Where do muscle synergies come from?

Muscle synergies may not be necessary

Towards clinical application

The problem with synergies

No synergies for finger muscles

Where do muscle synergies come from?

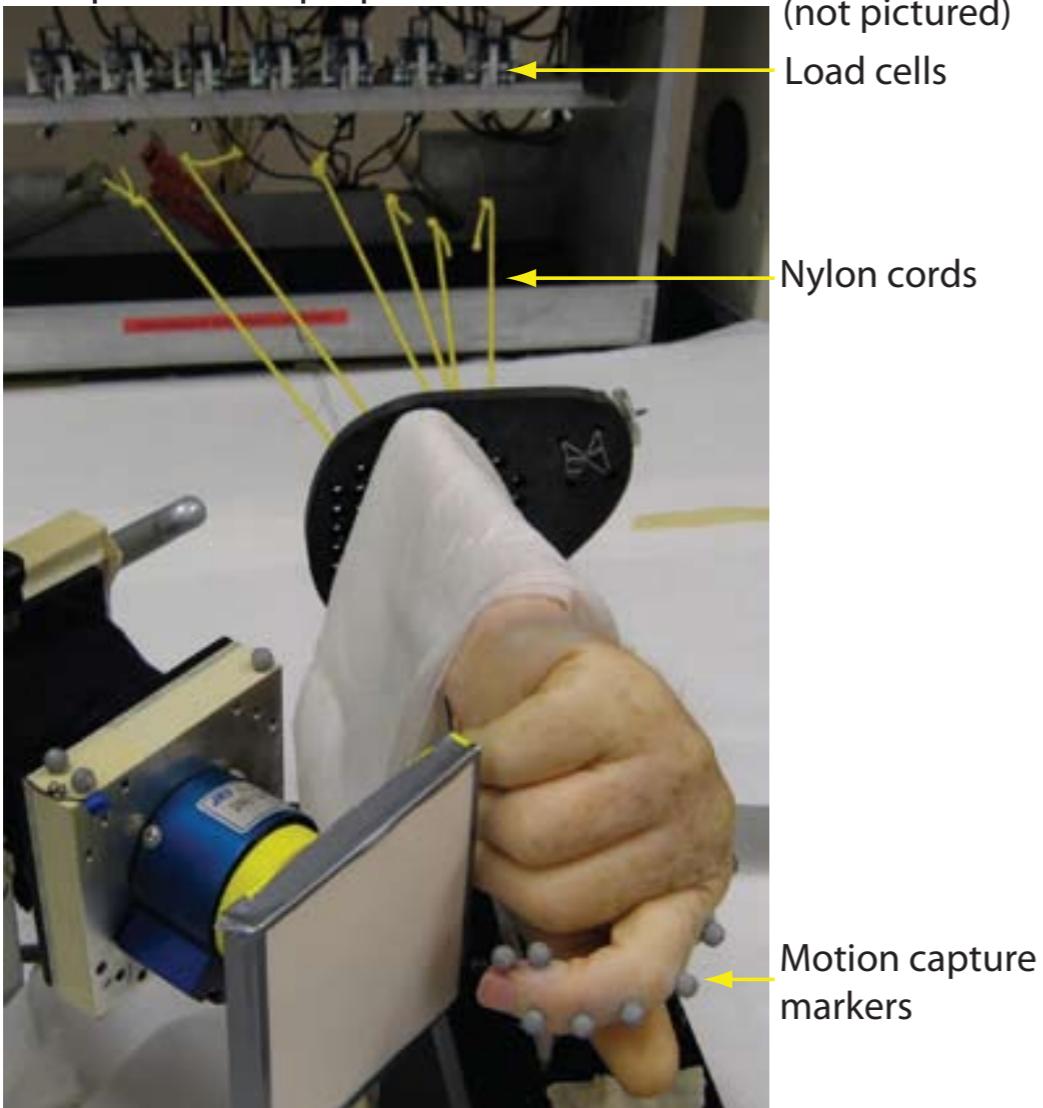
Muscle synergies may not be necessary

Towards clinical application

# Where do muscle synergies come from?

# Computer-controlled cadaver hand

A. Experimental preparation

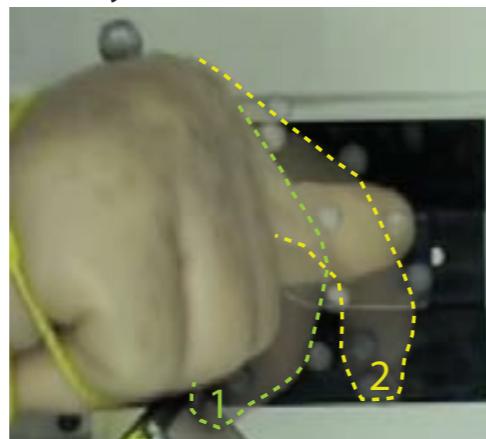


Tapping

B. Recording mode



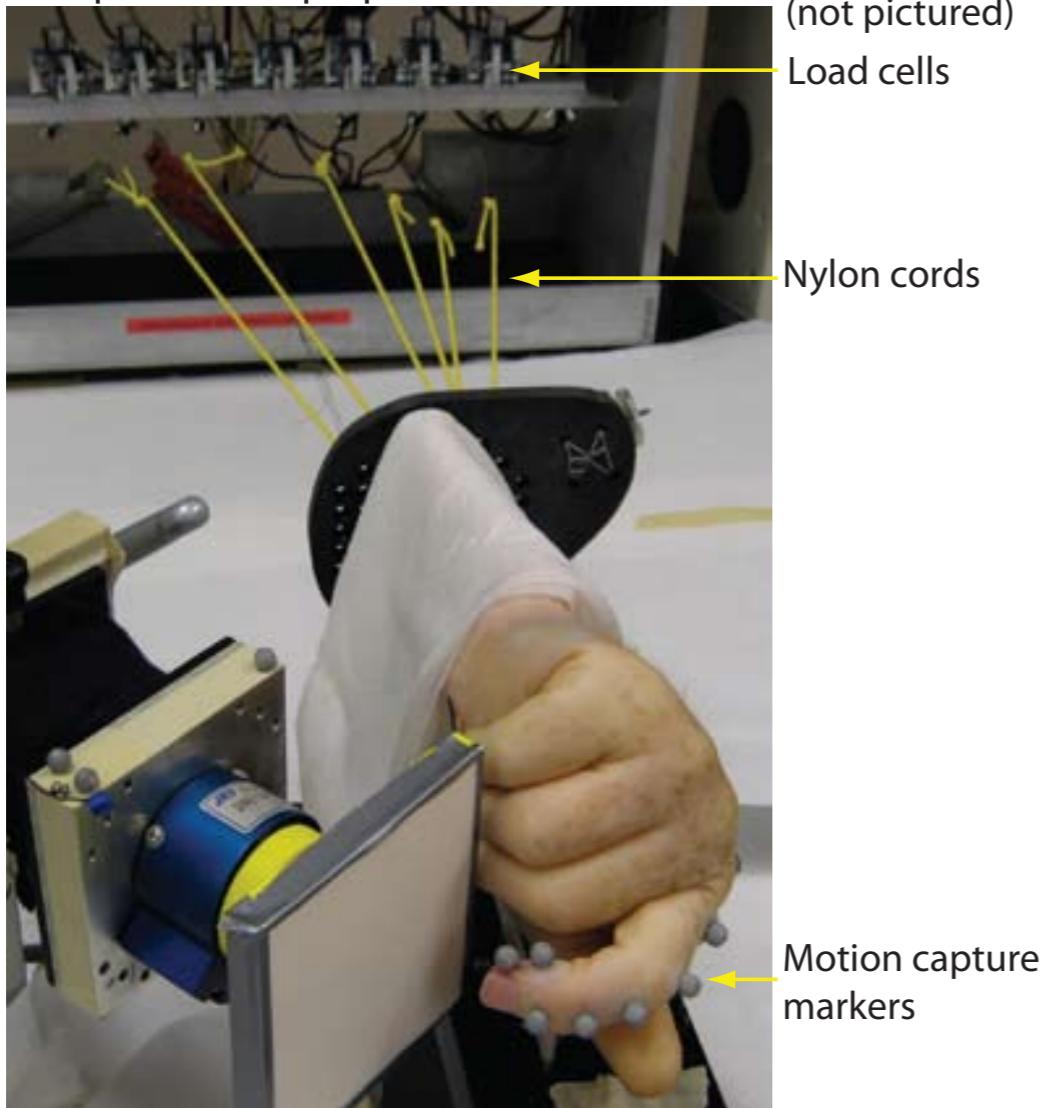
C. Playback mode



Scratching

# Computer-controlled cadaver hand

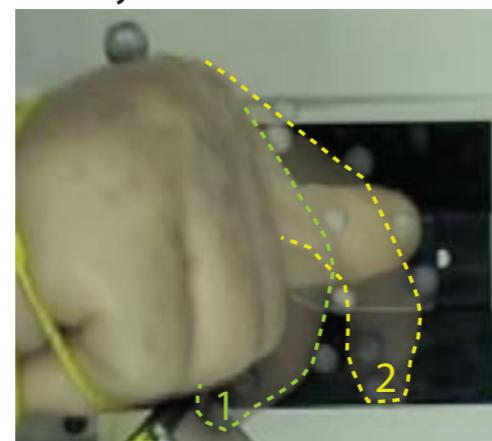
A. Experimental preparation



B. Recording mode



C. Playback mode



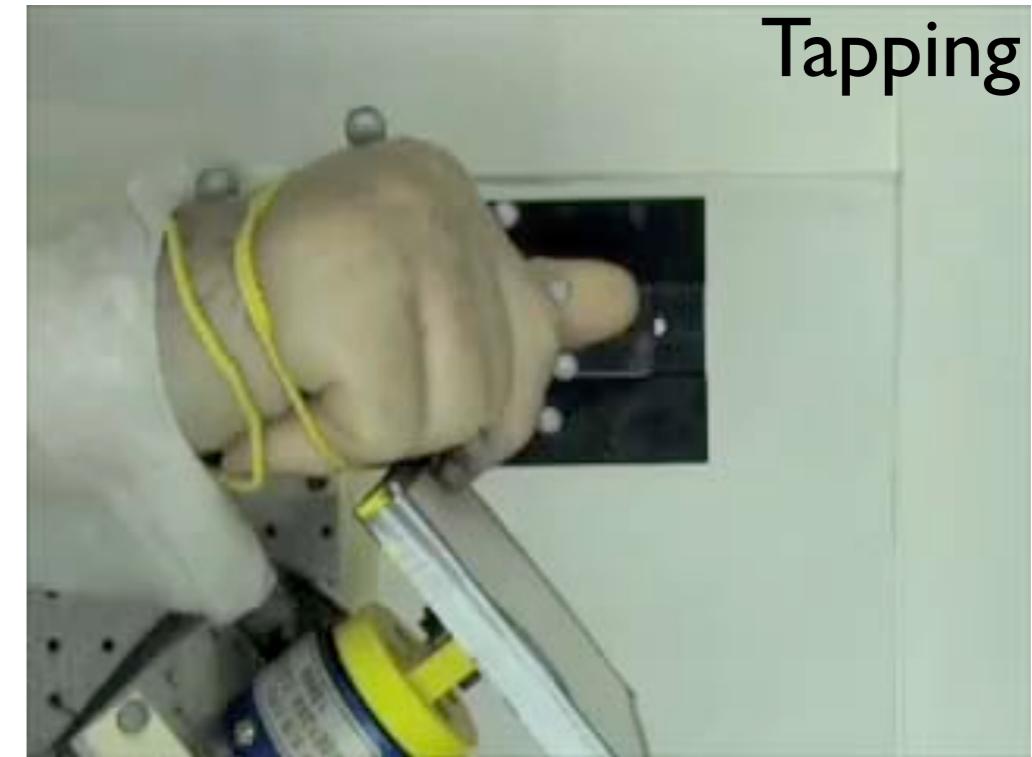
Motors and encoders  
(not pictured)

Load cells

Nylon cords

Motion capture  
markers

Tapping

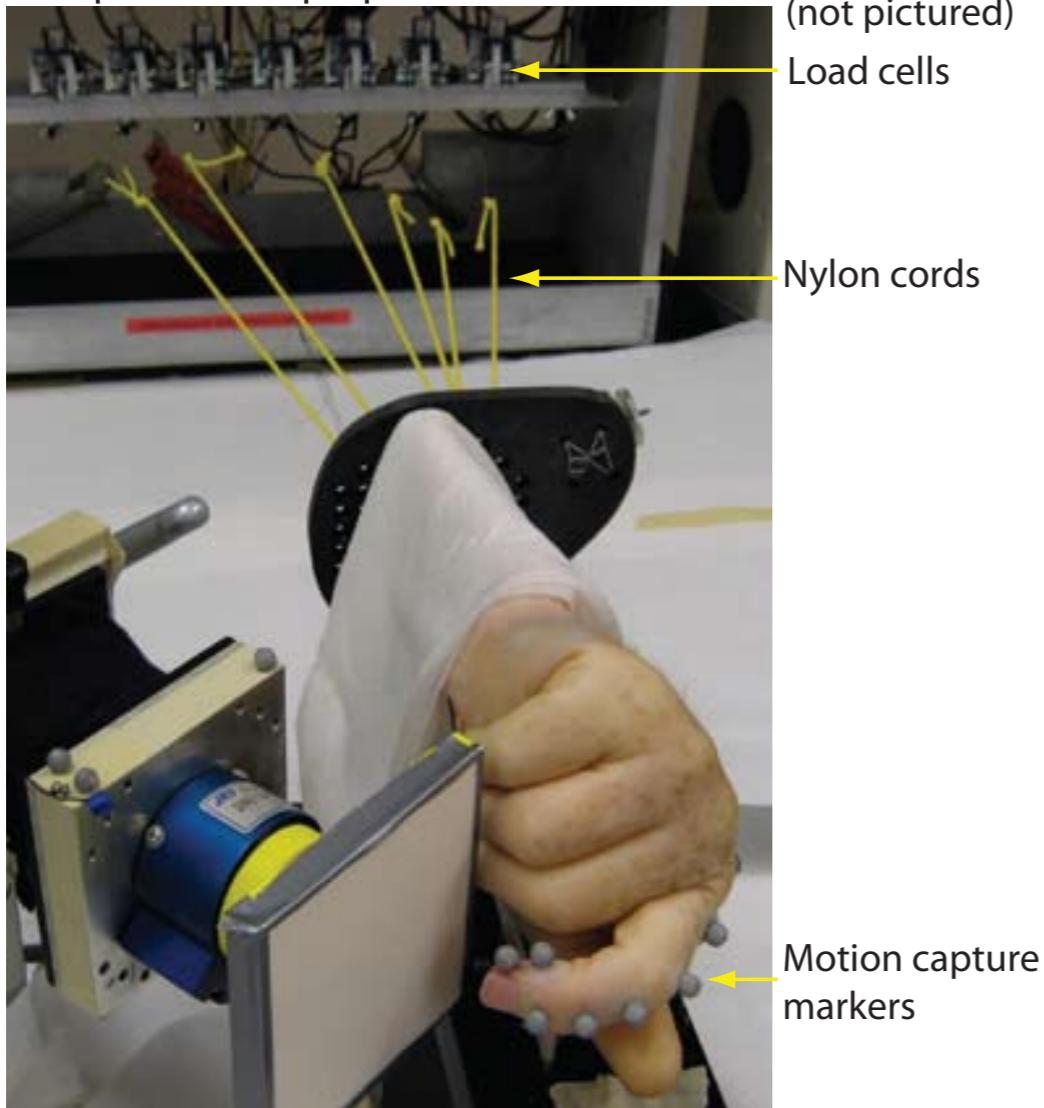


Scratching



# Computer-controlled cadaver hand

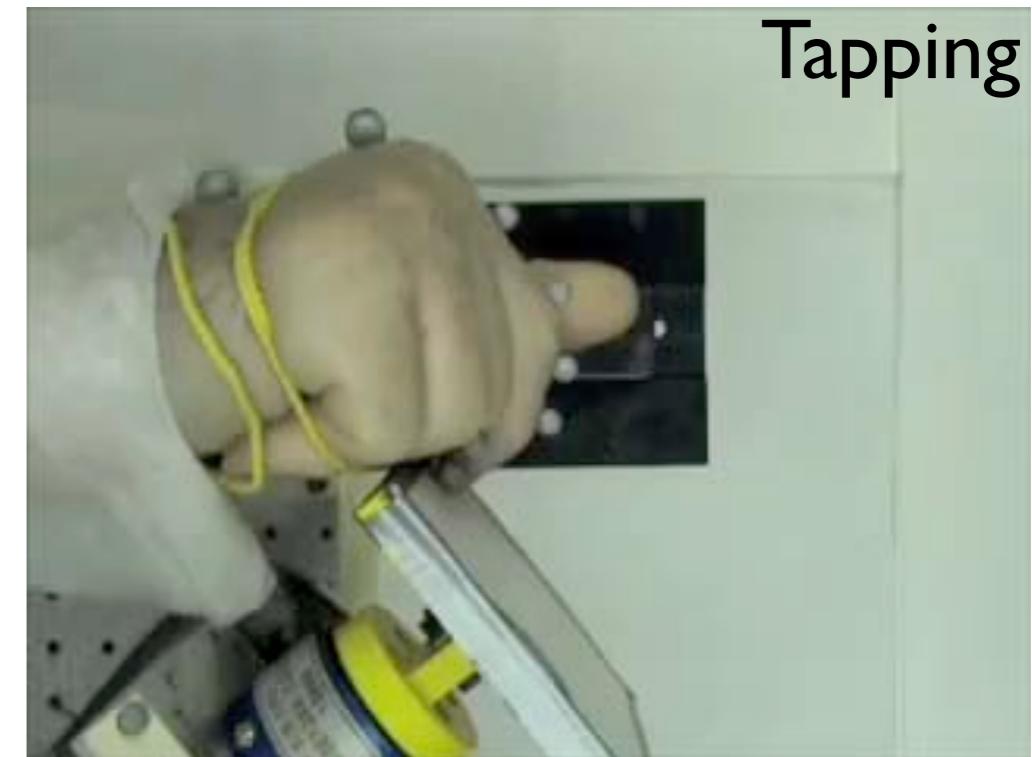
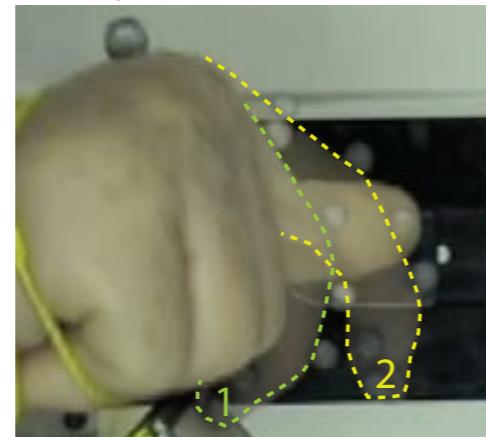
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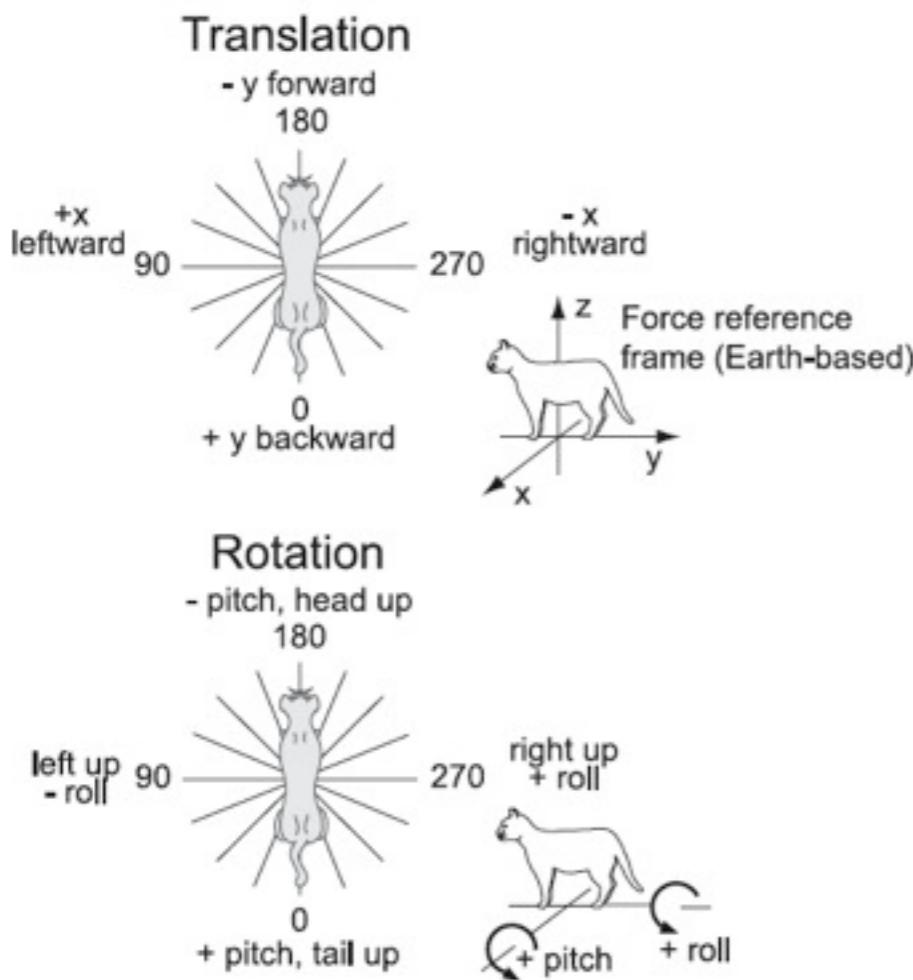
B. Recording mode



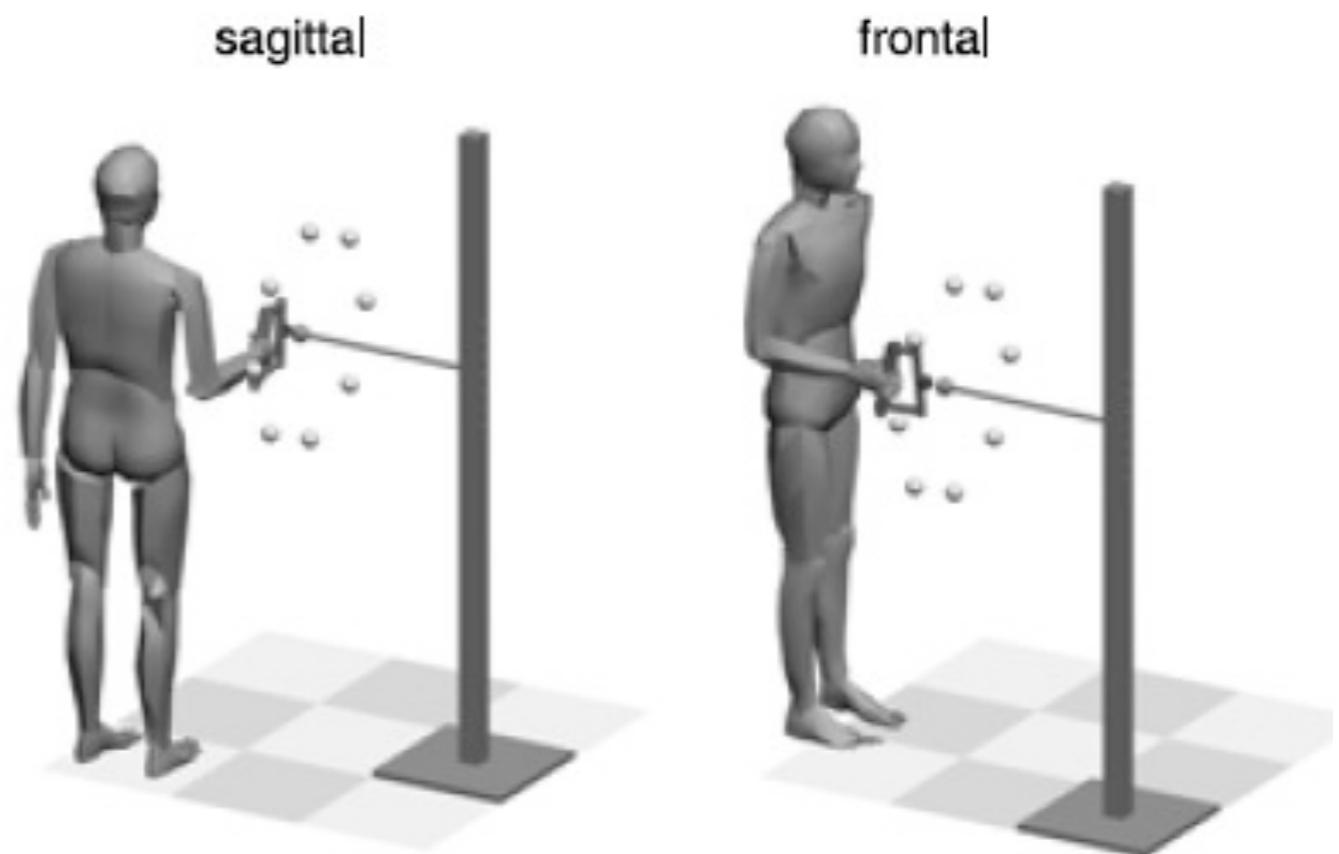
C. Playback mode



# Where do muscle synergies come from?

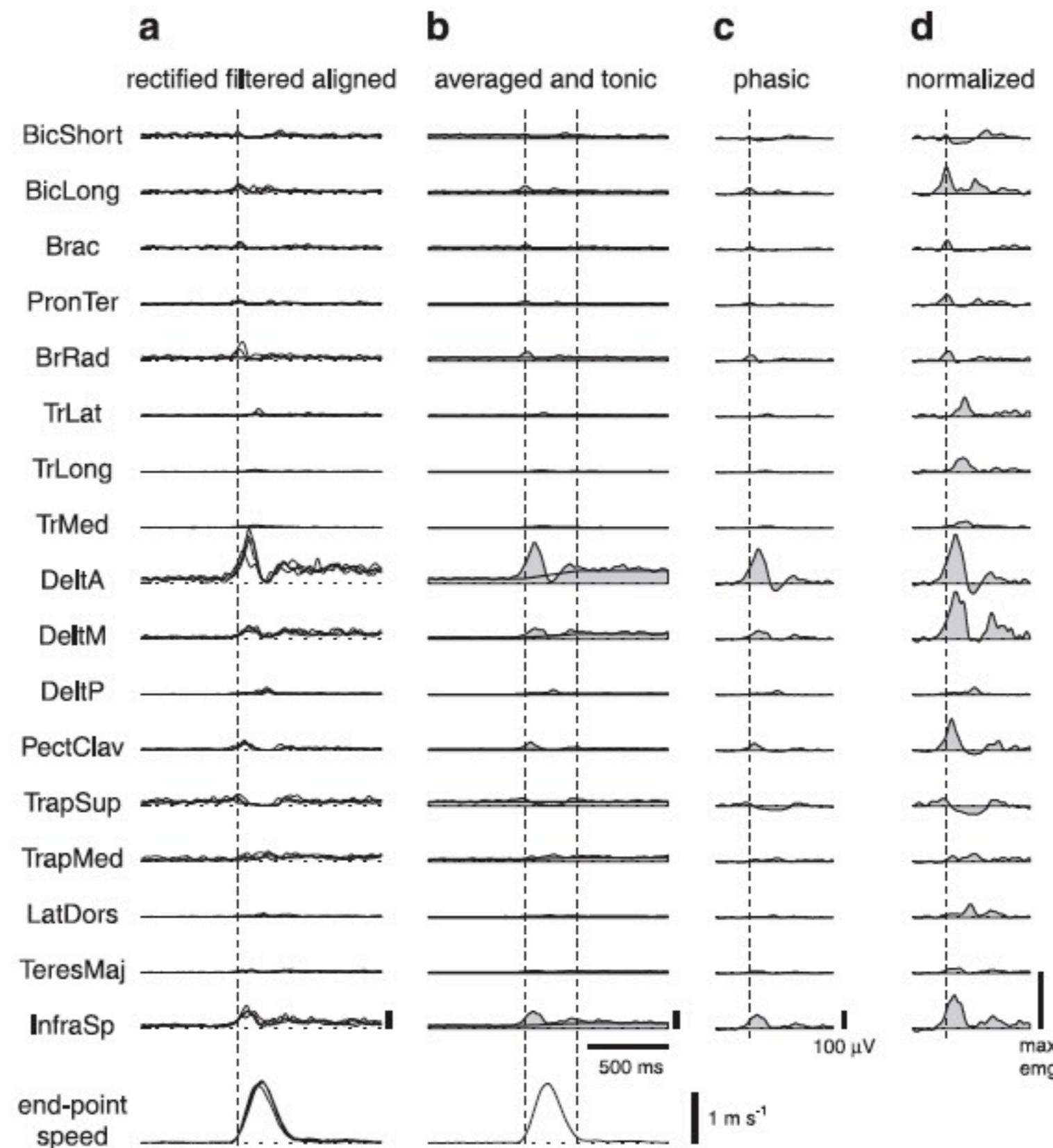


Torres-Oviedo et al. 2006



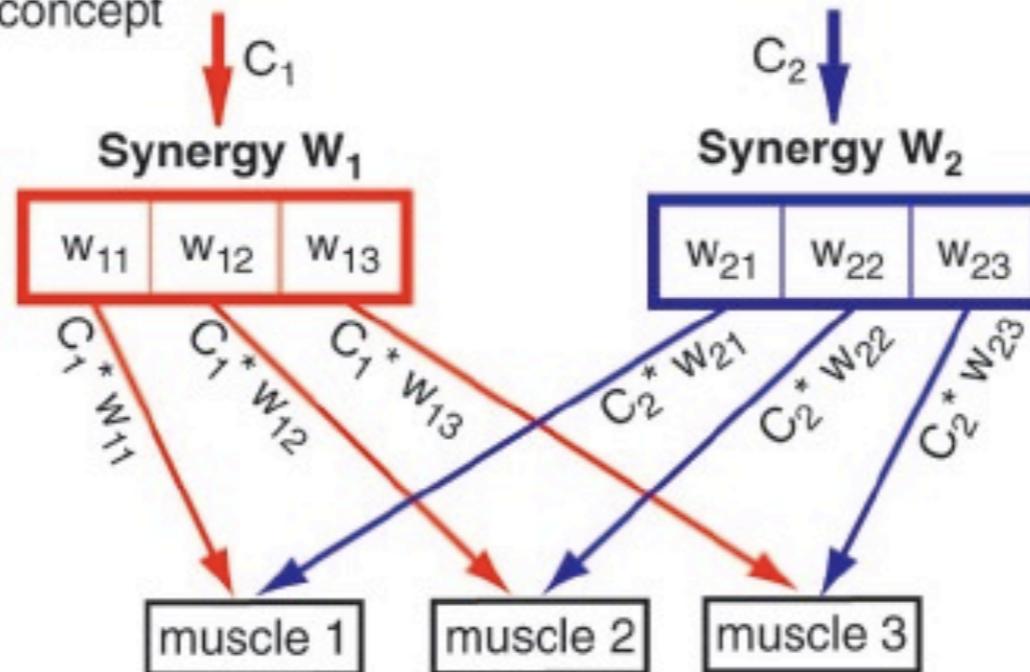
d'Avella et al. 2006

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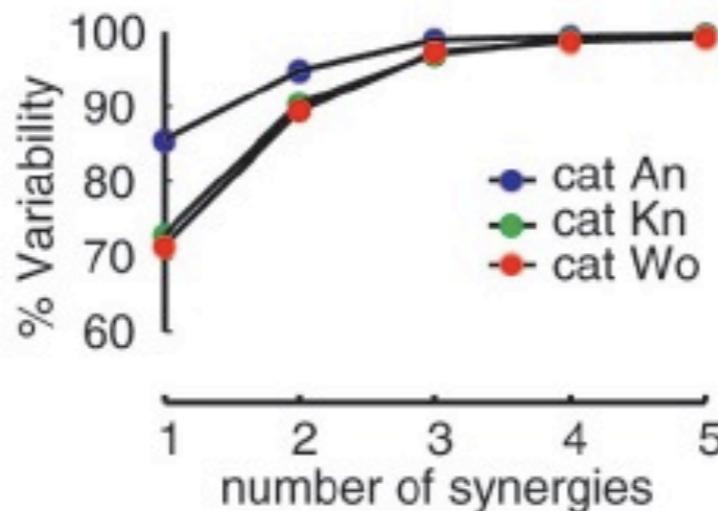


# Where do muscle synergies come from?

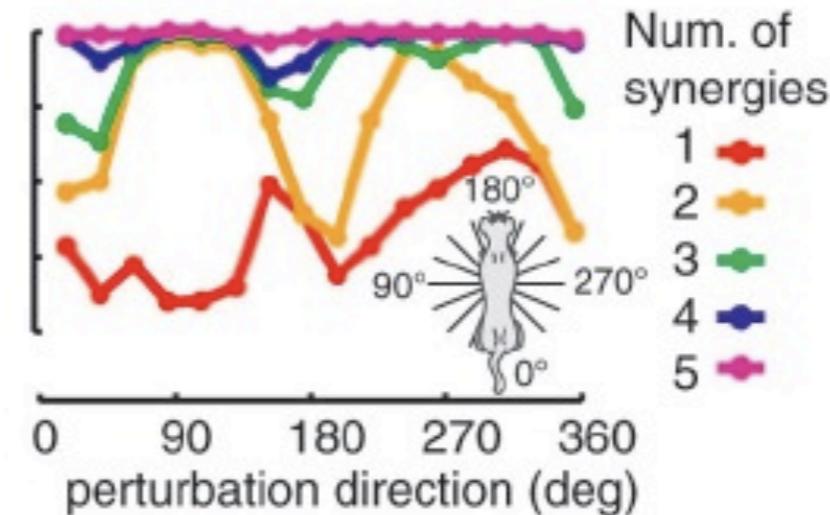
**A** Synergy concept



**B** Overall variability accounted for



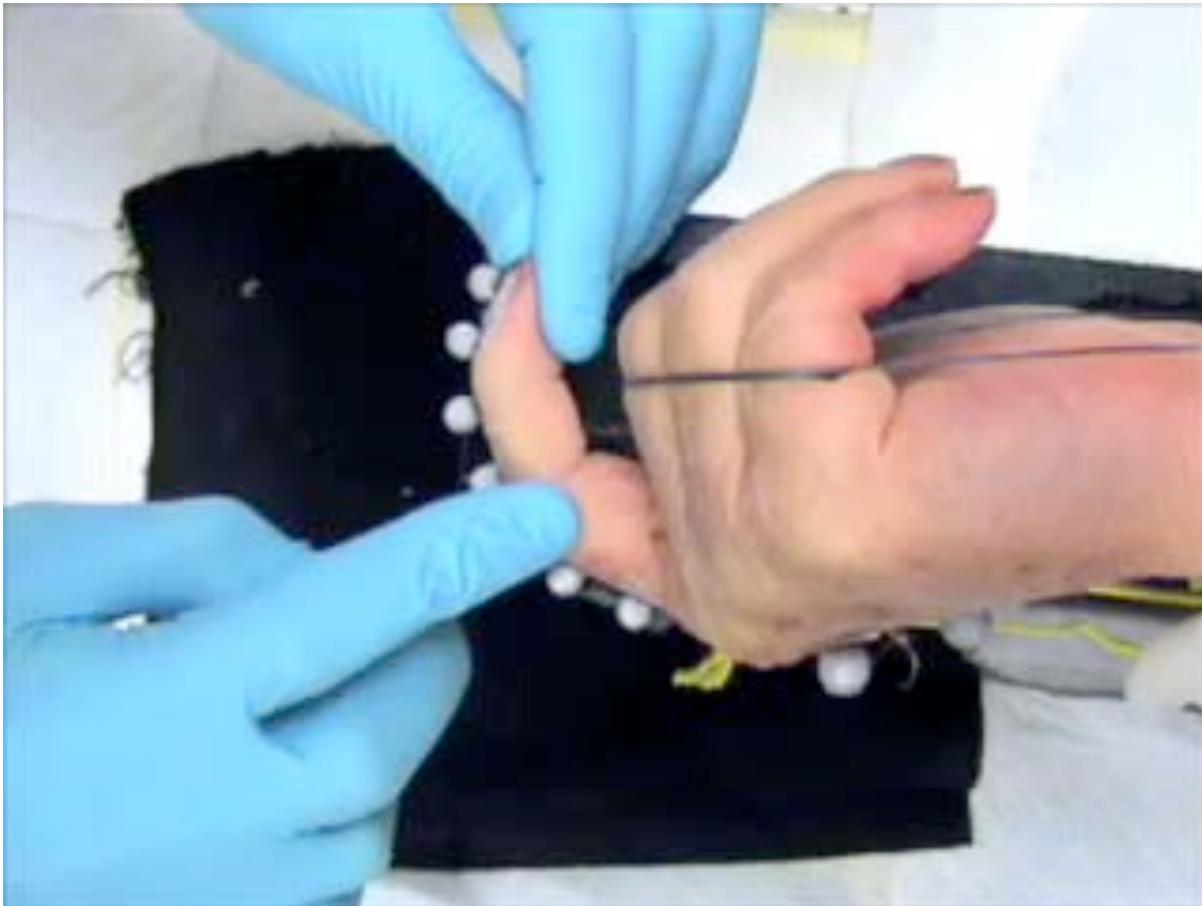
**C** VAF by perturbation direction



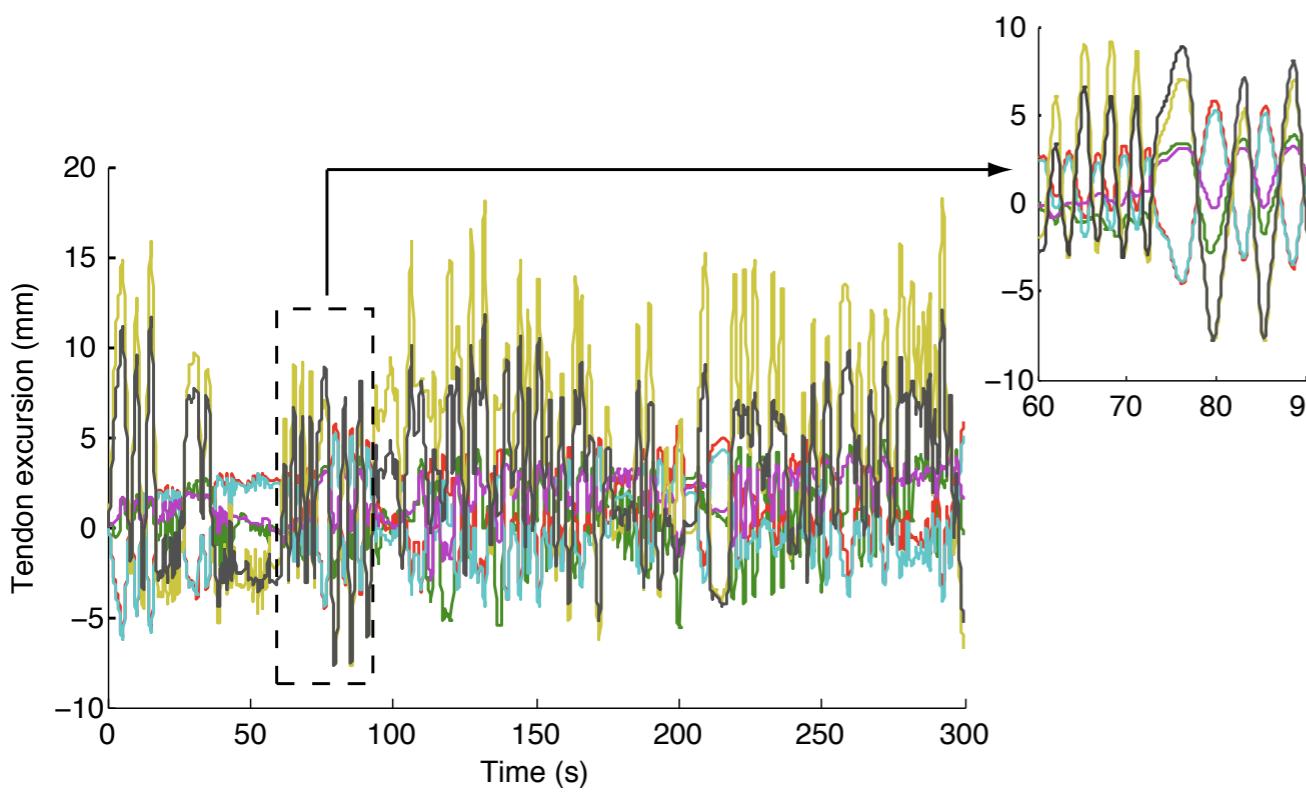
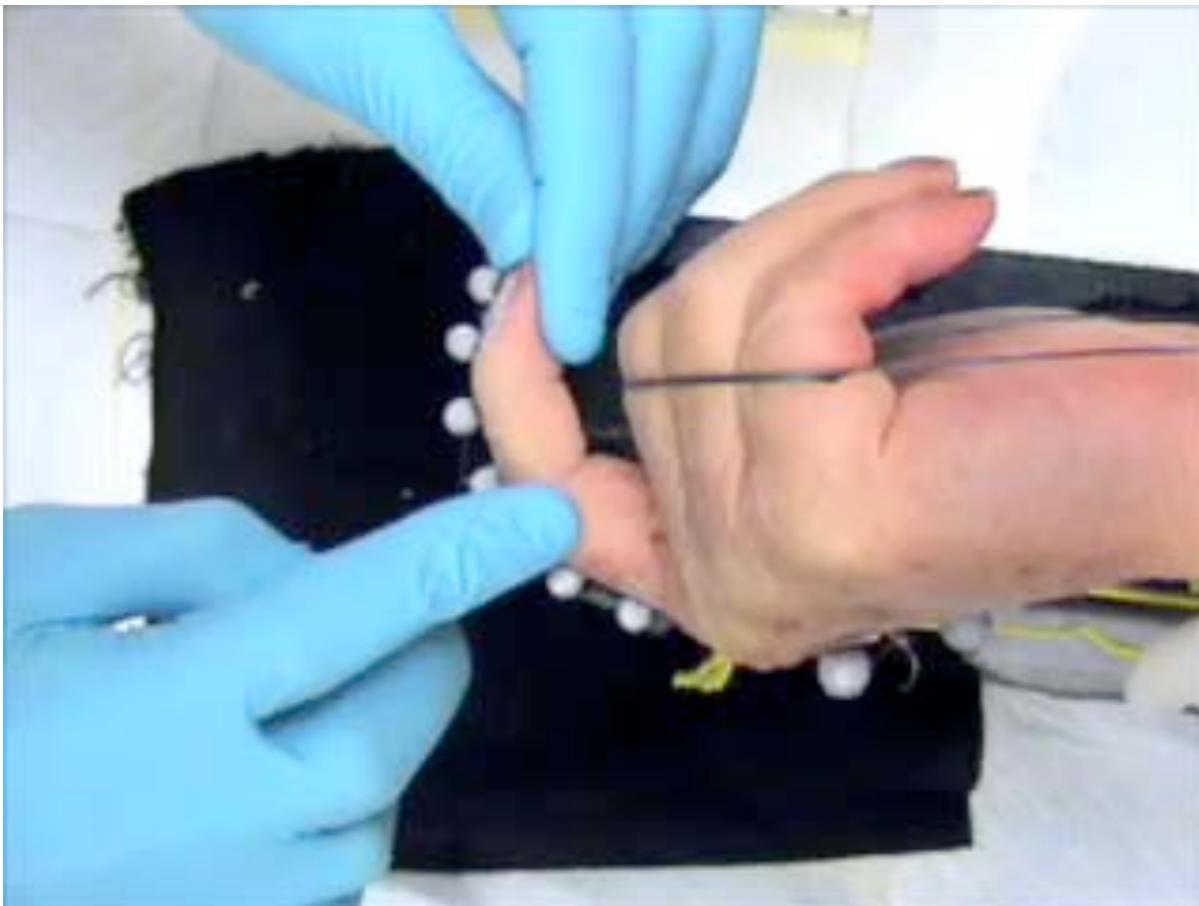
Ting and Macpherson, 2005

# Where do muscle synergies come from?

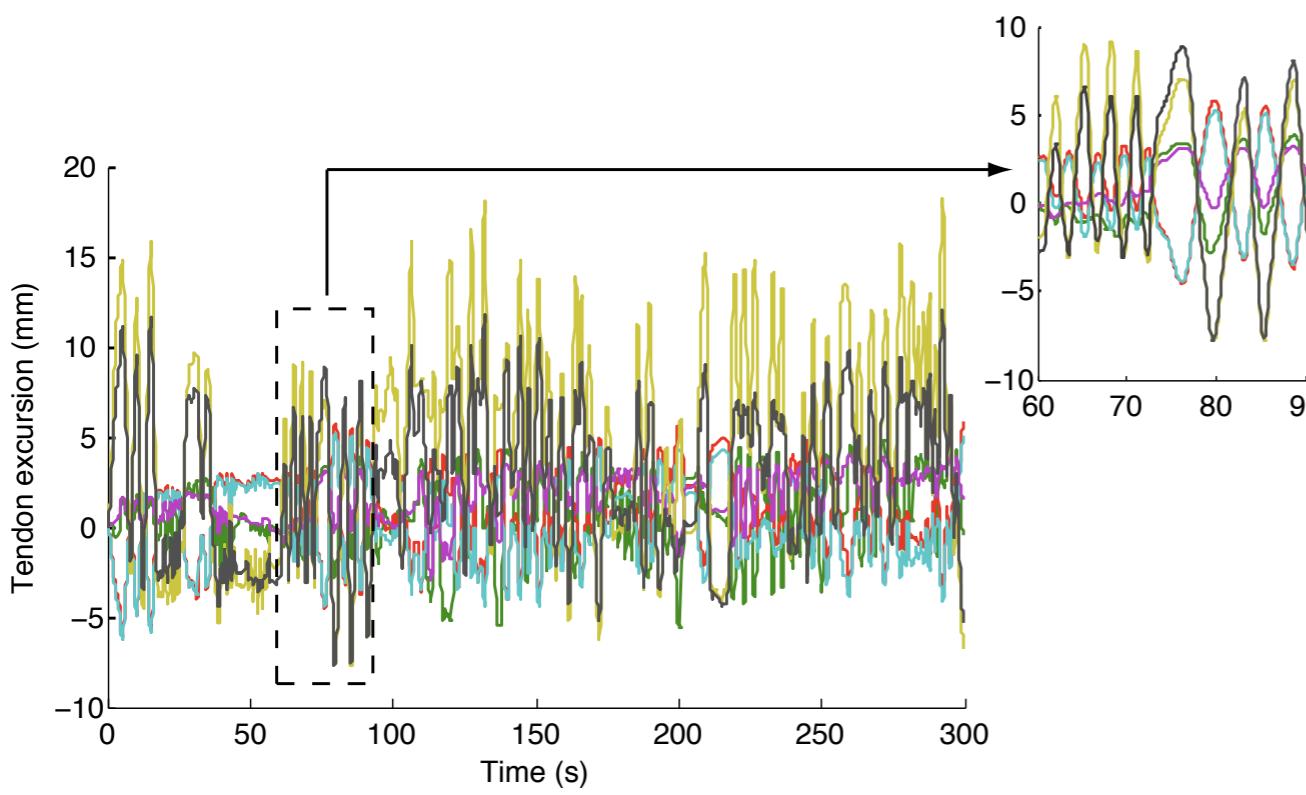
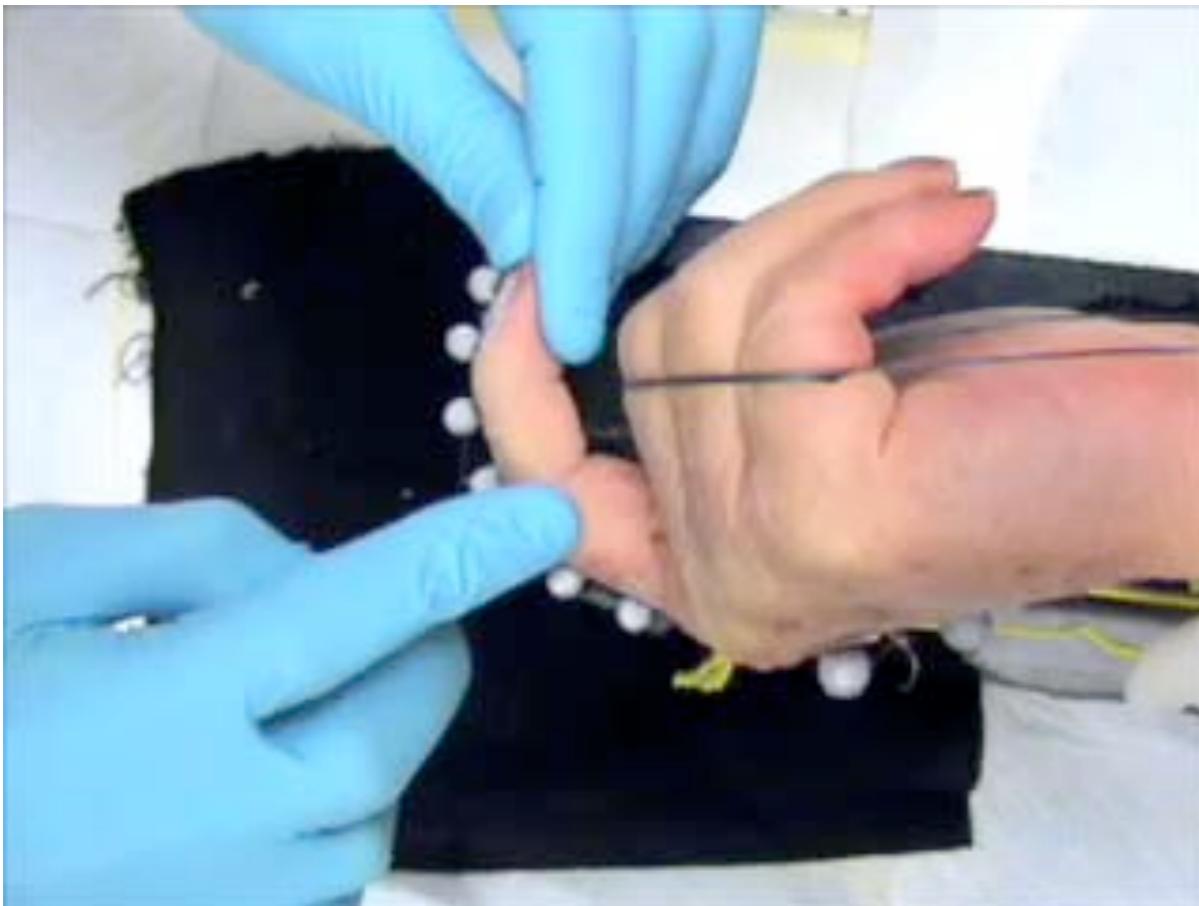
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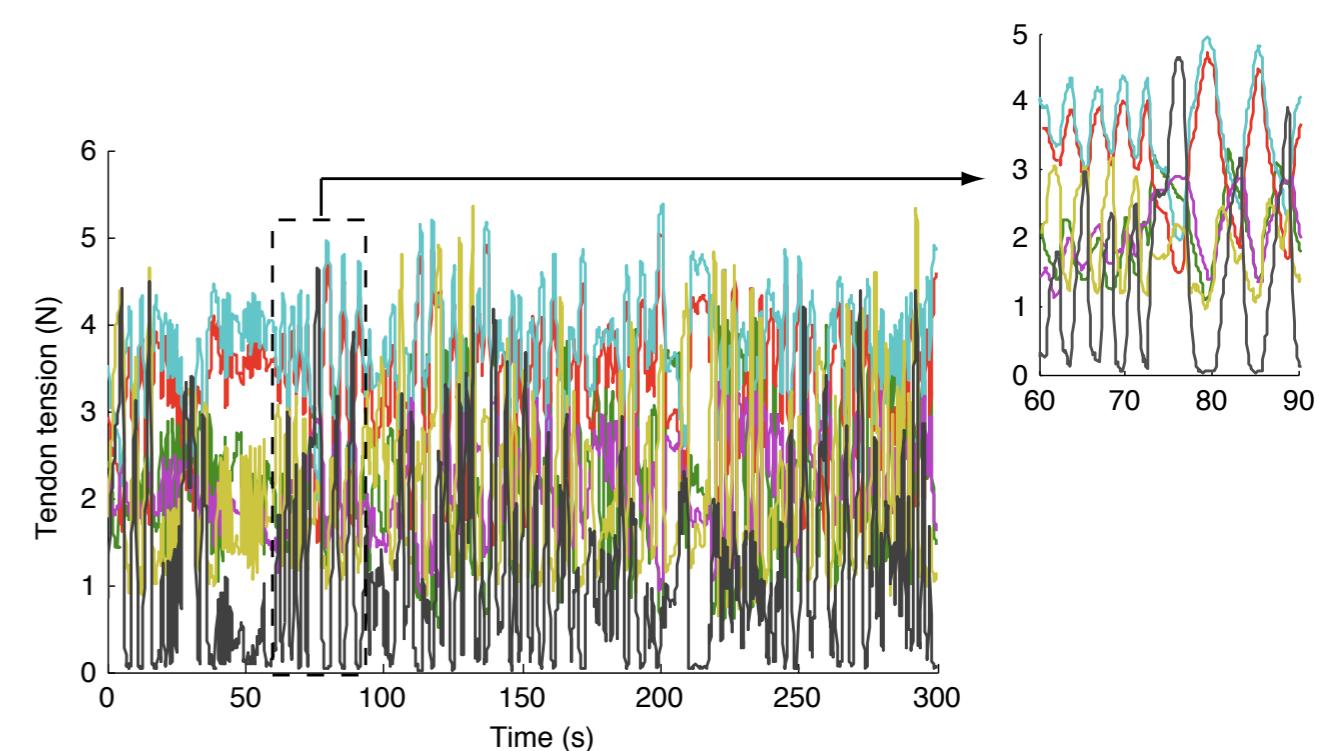
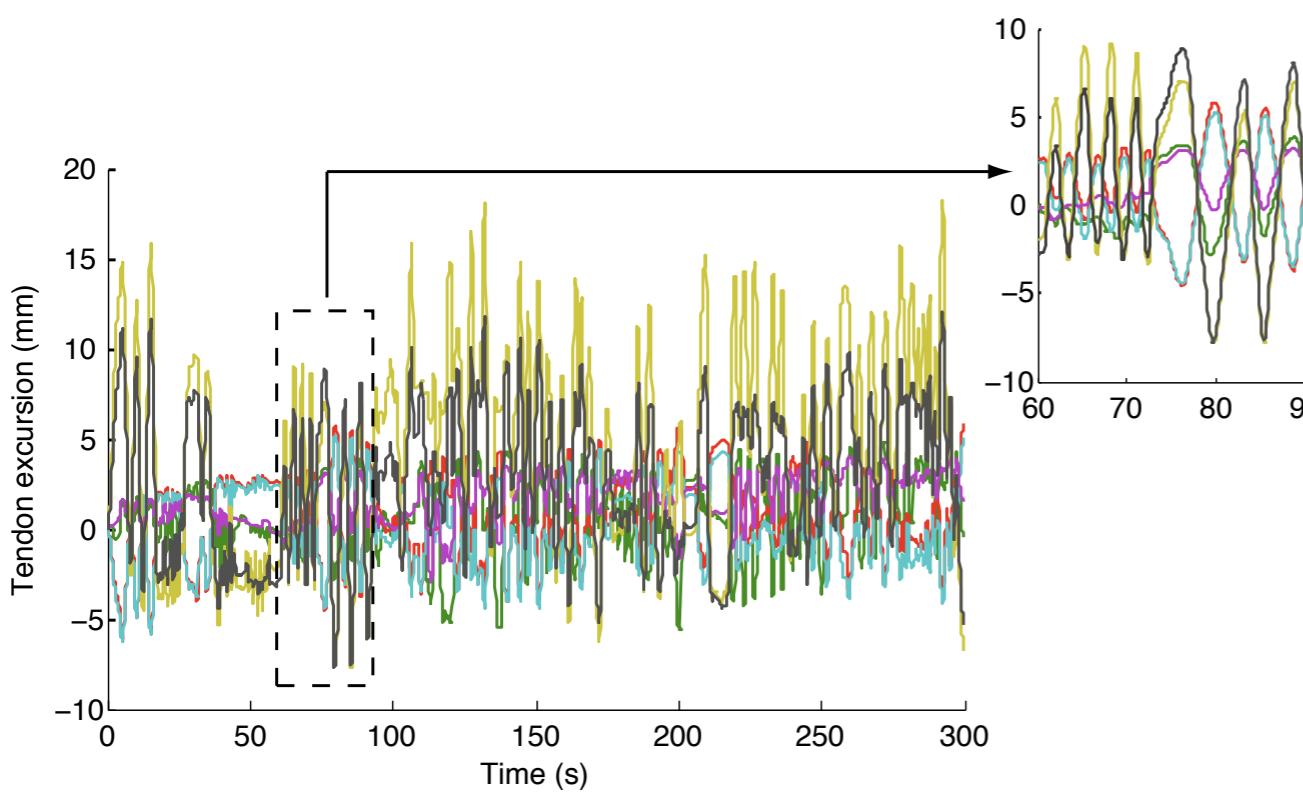
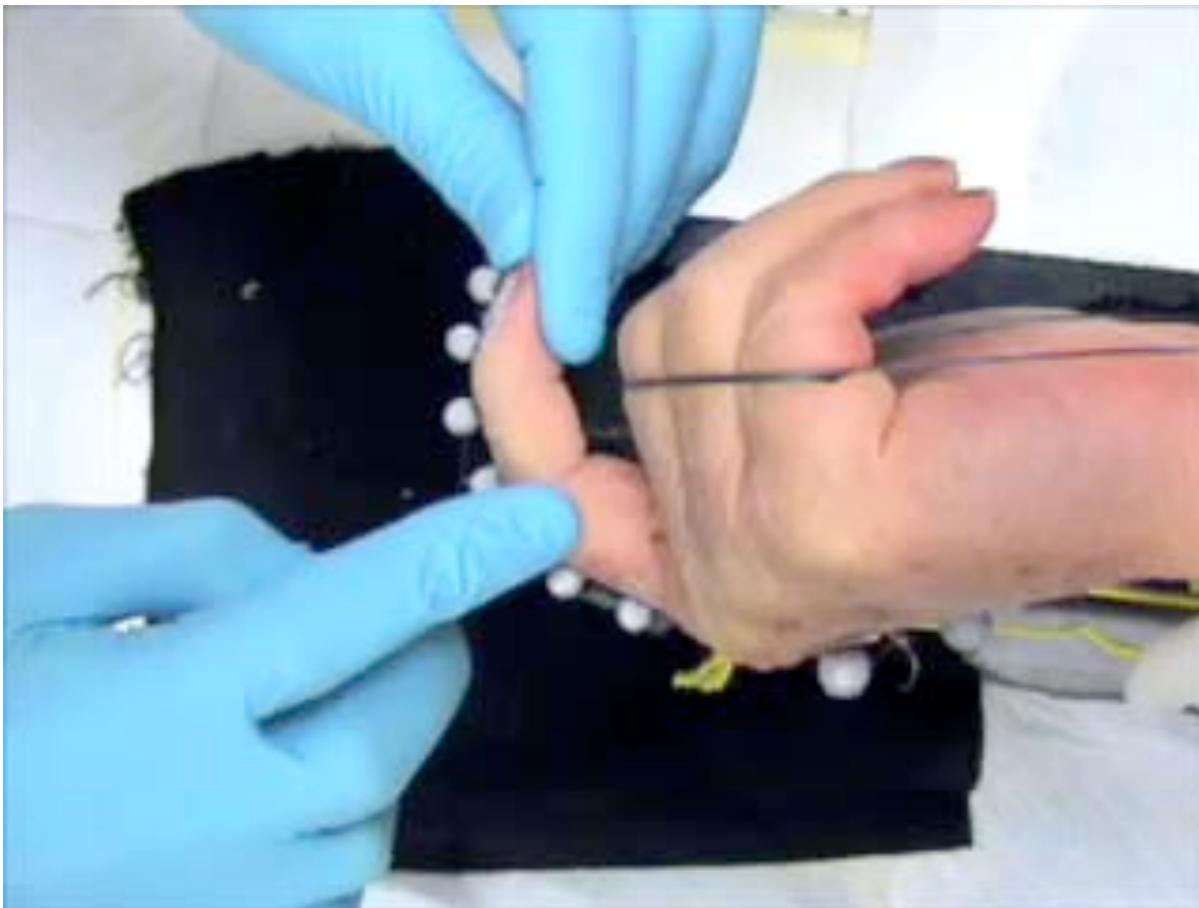
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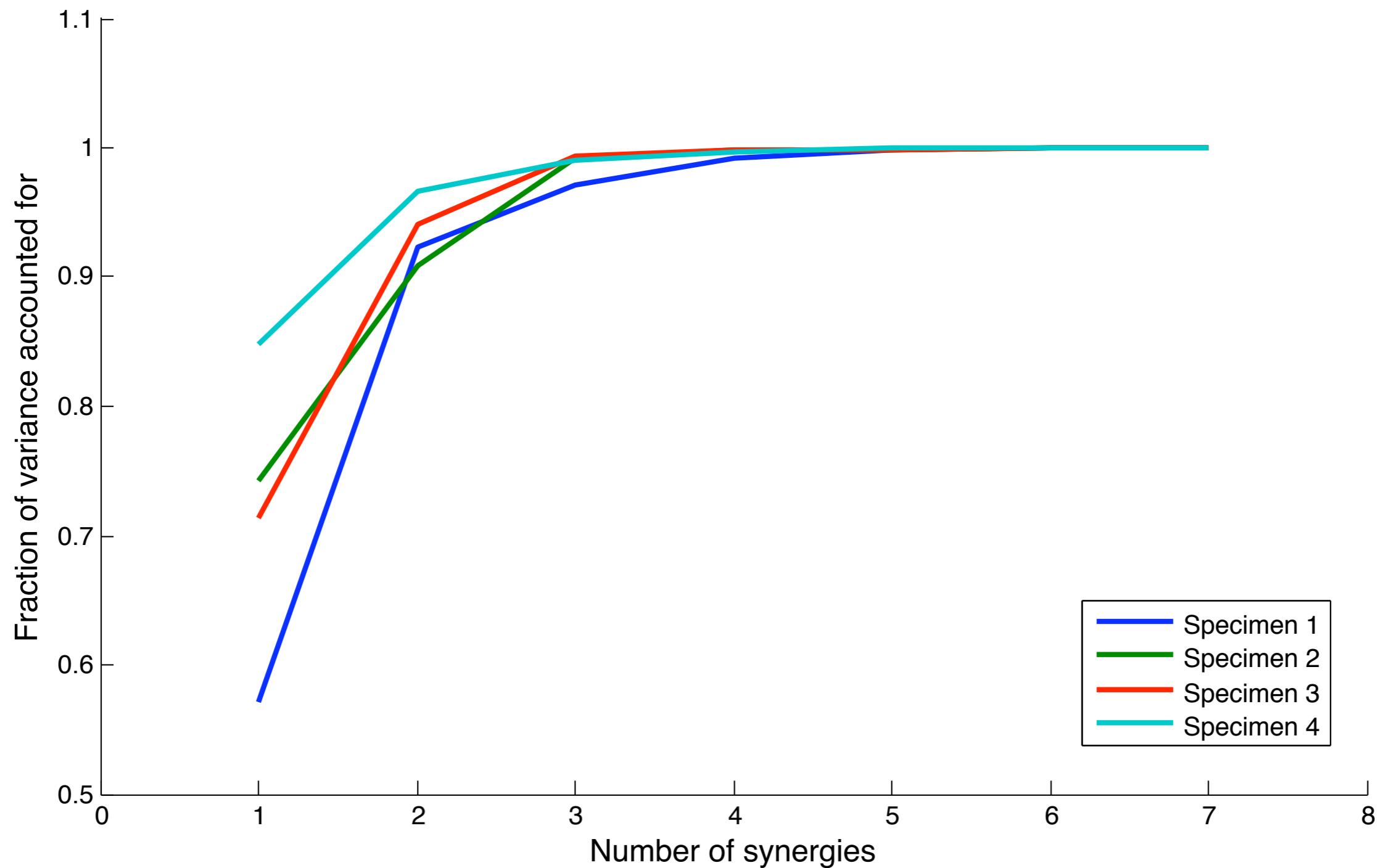
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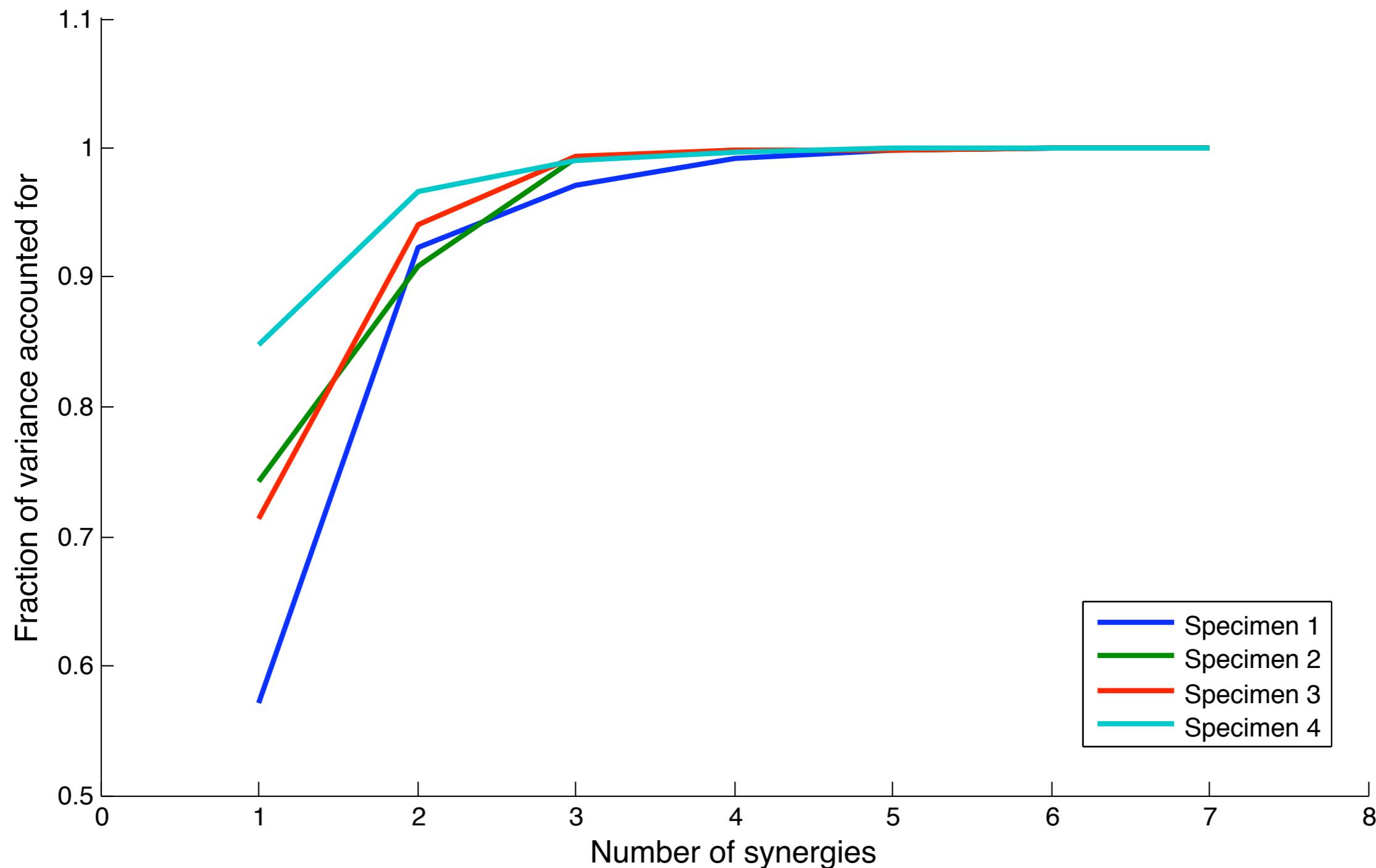
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Biomechanical constraints play under-appreciated role in observing muscle synergies

The problem with synergies

No synergies for finger muscles

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Towards clinical application

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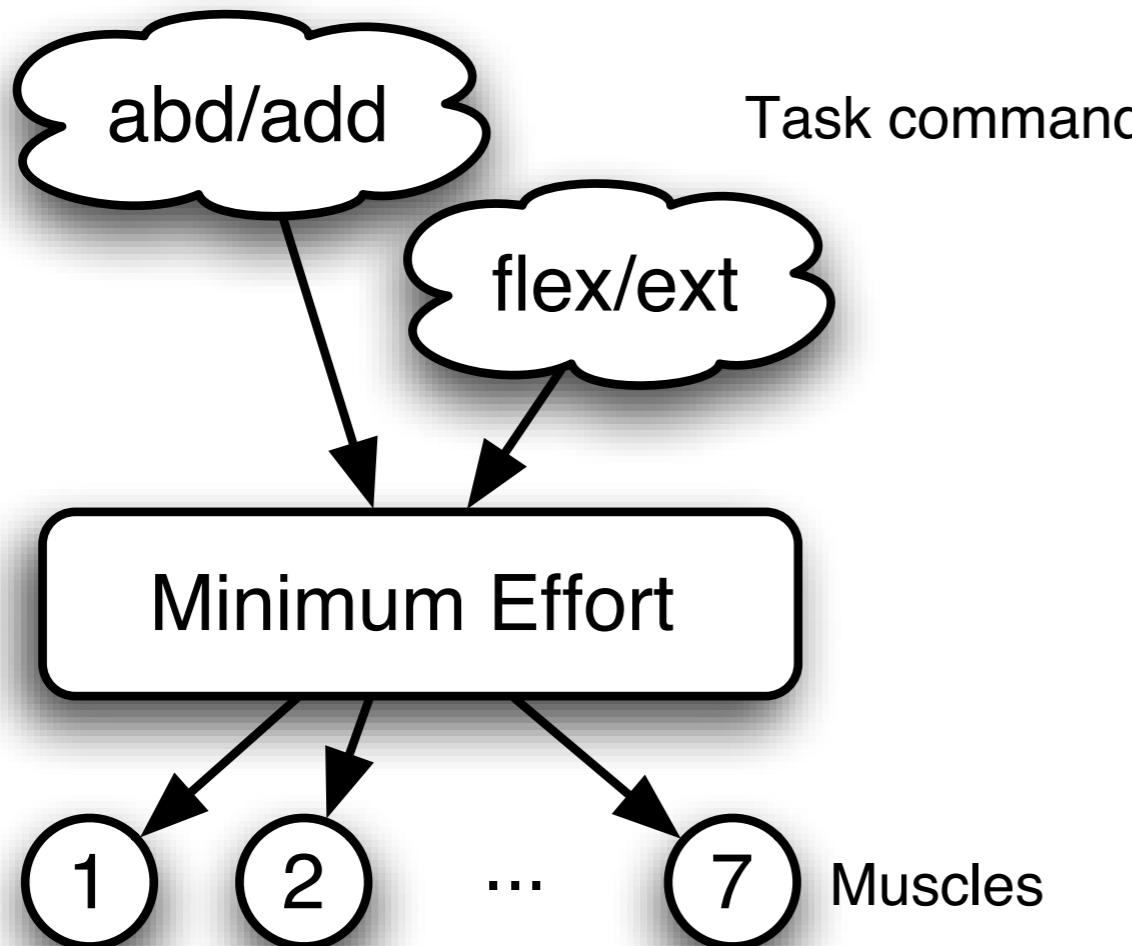
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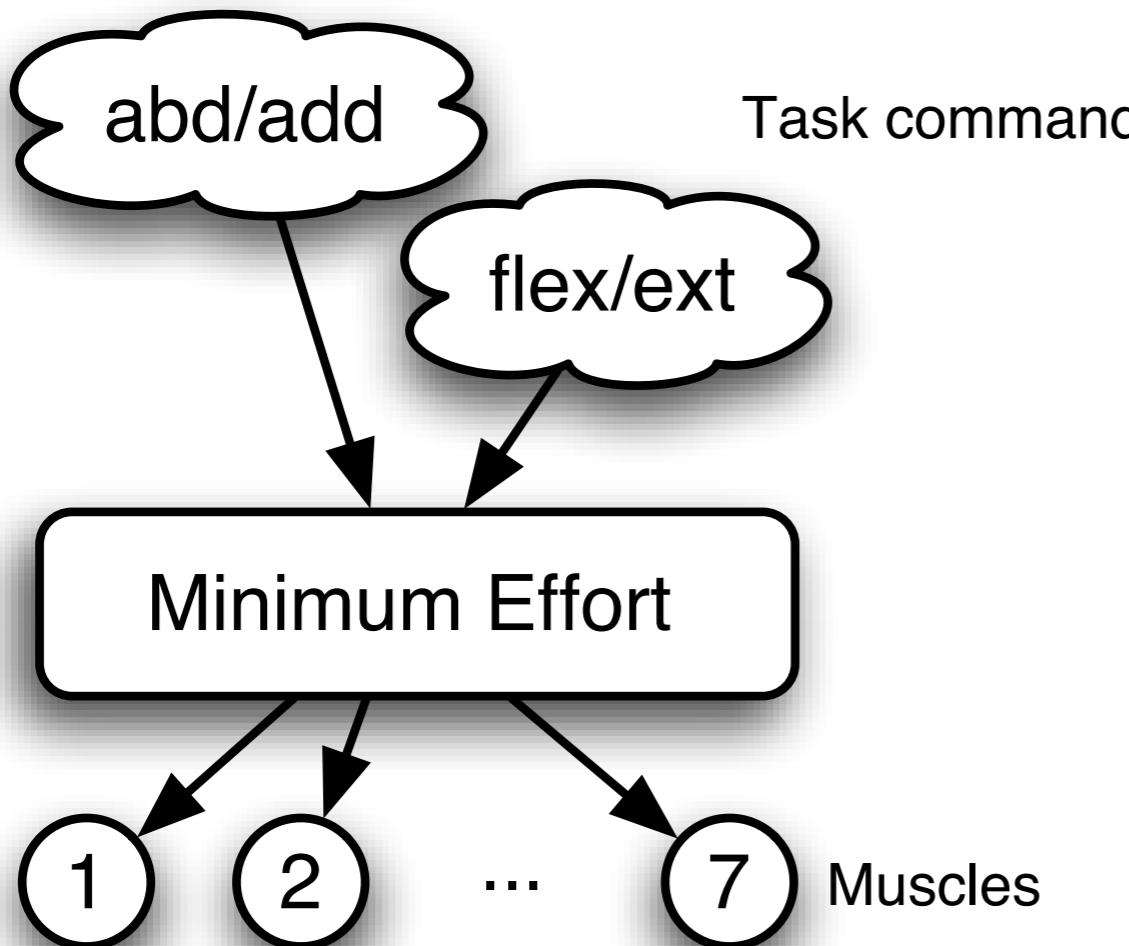
Towards clinical application

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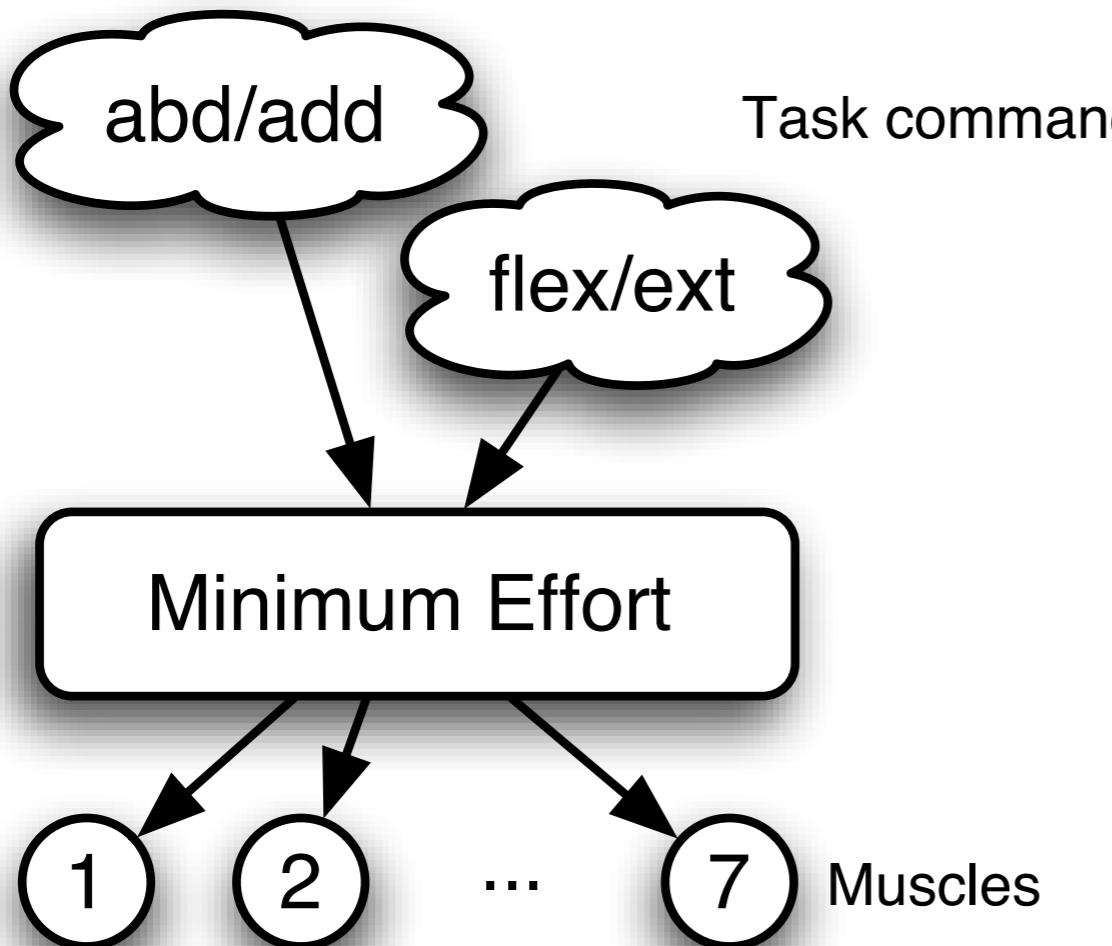


# Muscle synergies may not be necessary



Reasoning:

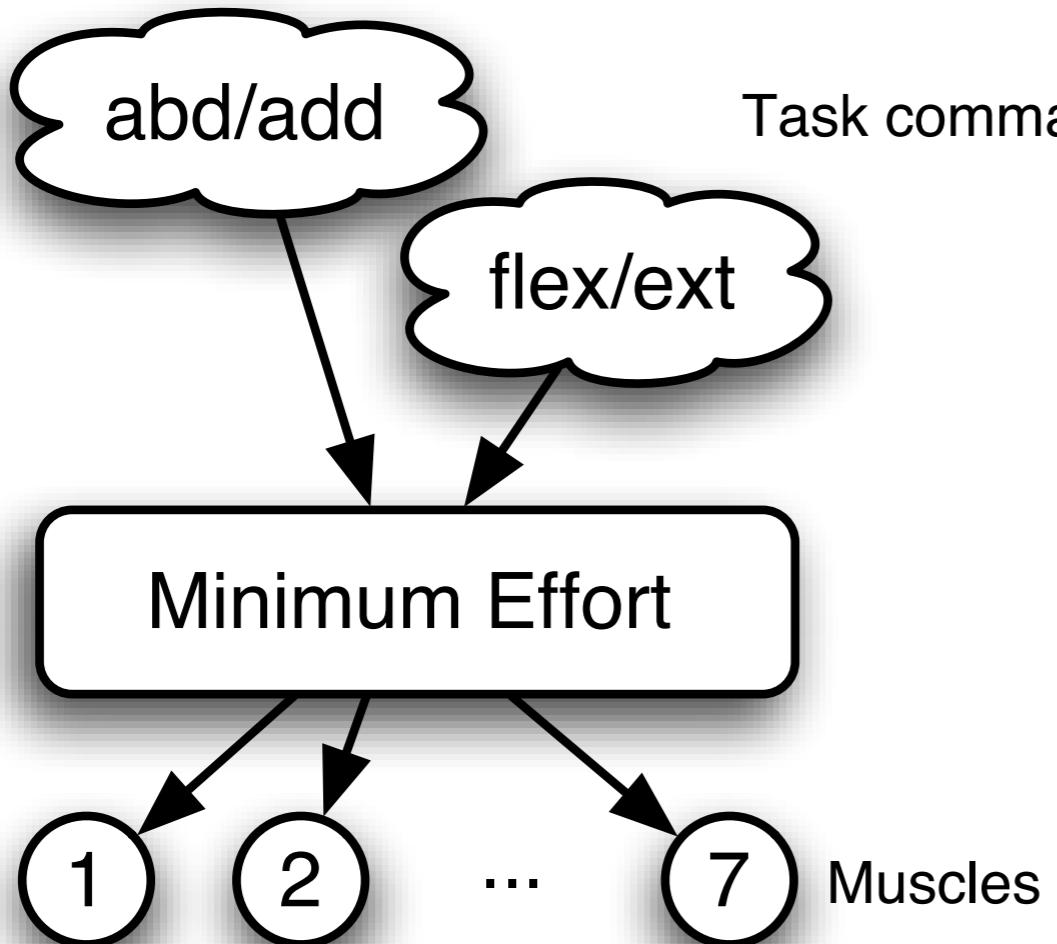
# Muscle synergies may not be necessary



Reasoning:

I. Todorov (2002): minimize squared muscle inputs gives rise to cosine tuning

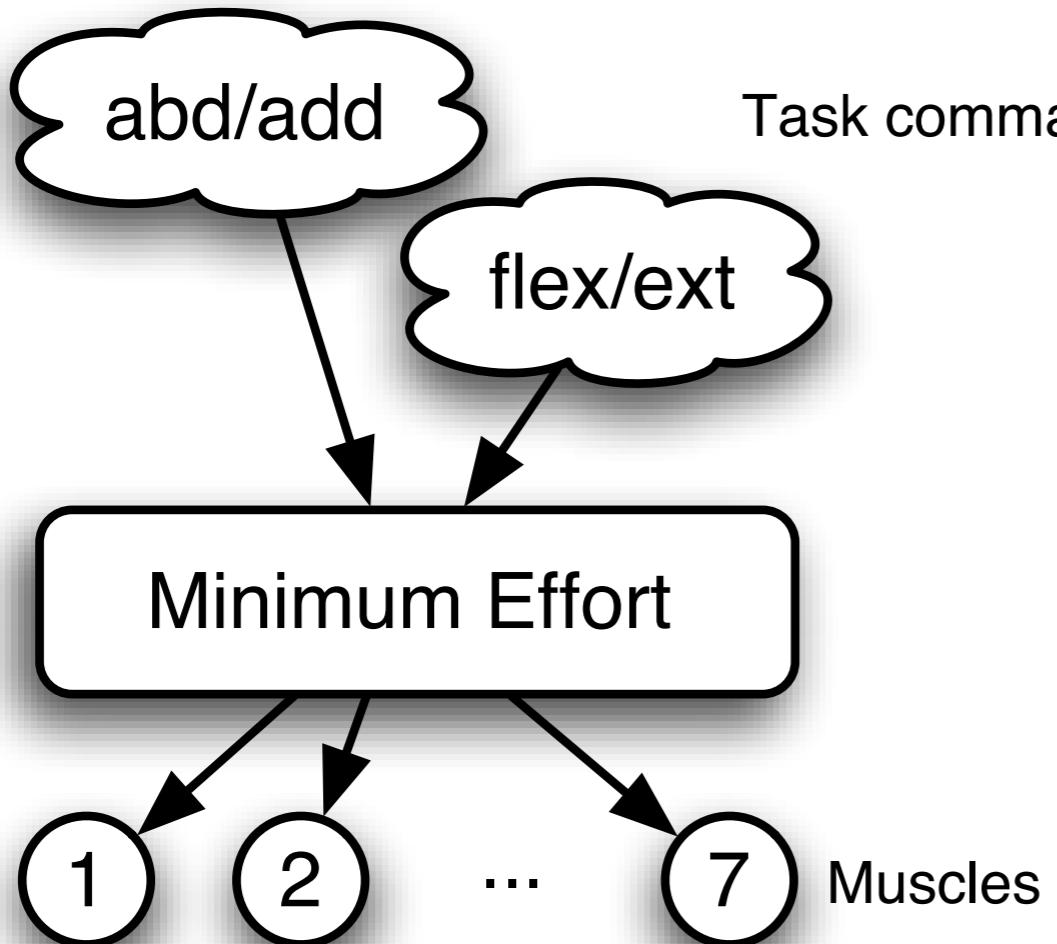
# Muscle synergies may not be necessary



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1. Todorov (2002): minimize squared muscle inputs gives rise to cosine tuning
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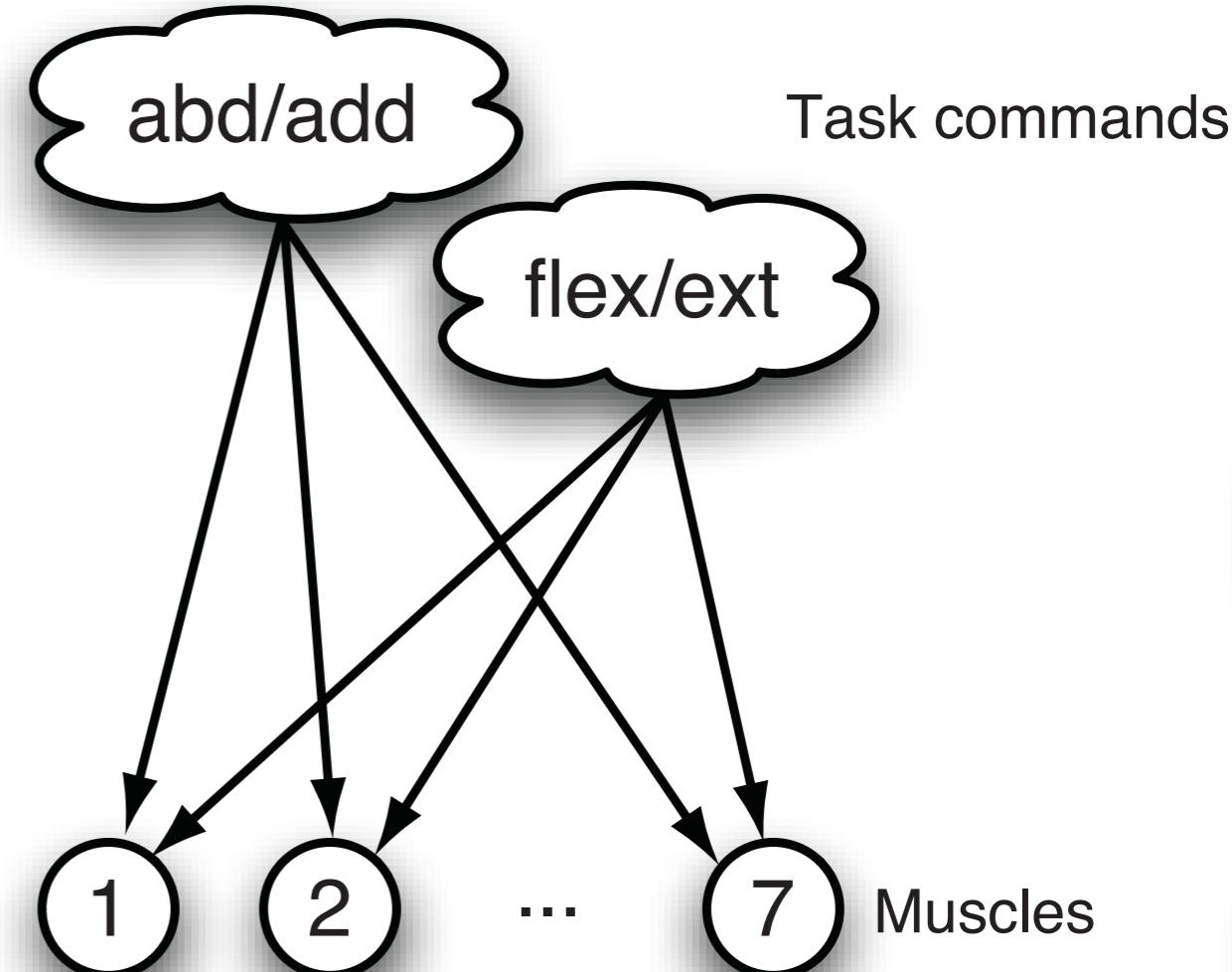
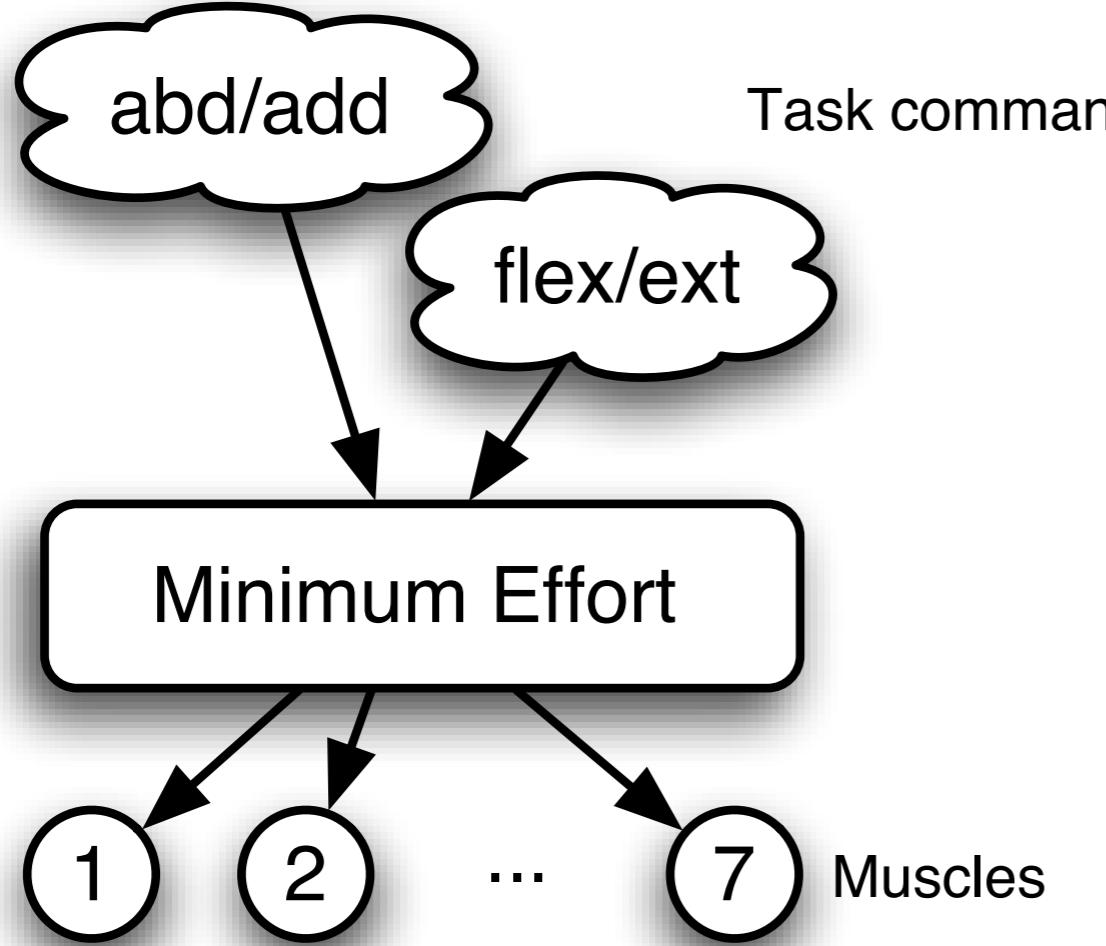
# Muscle synergies may not be necessary



Reasoning:

1. Todorov (2002): minimize squared muscle inputs gives rise to cosine tuning
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3. Put 2 & 2 together: tuned motoneurons could minimize effort.

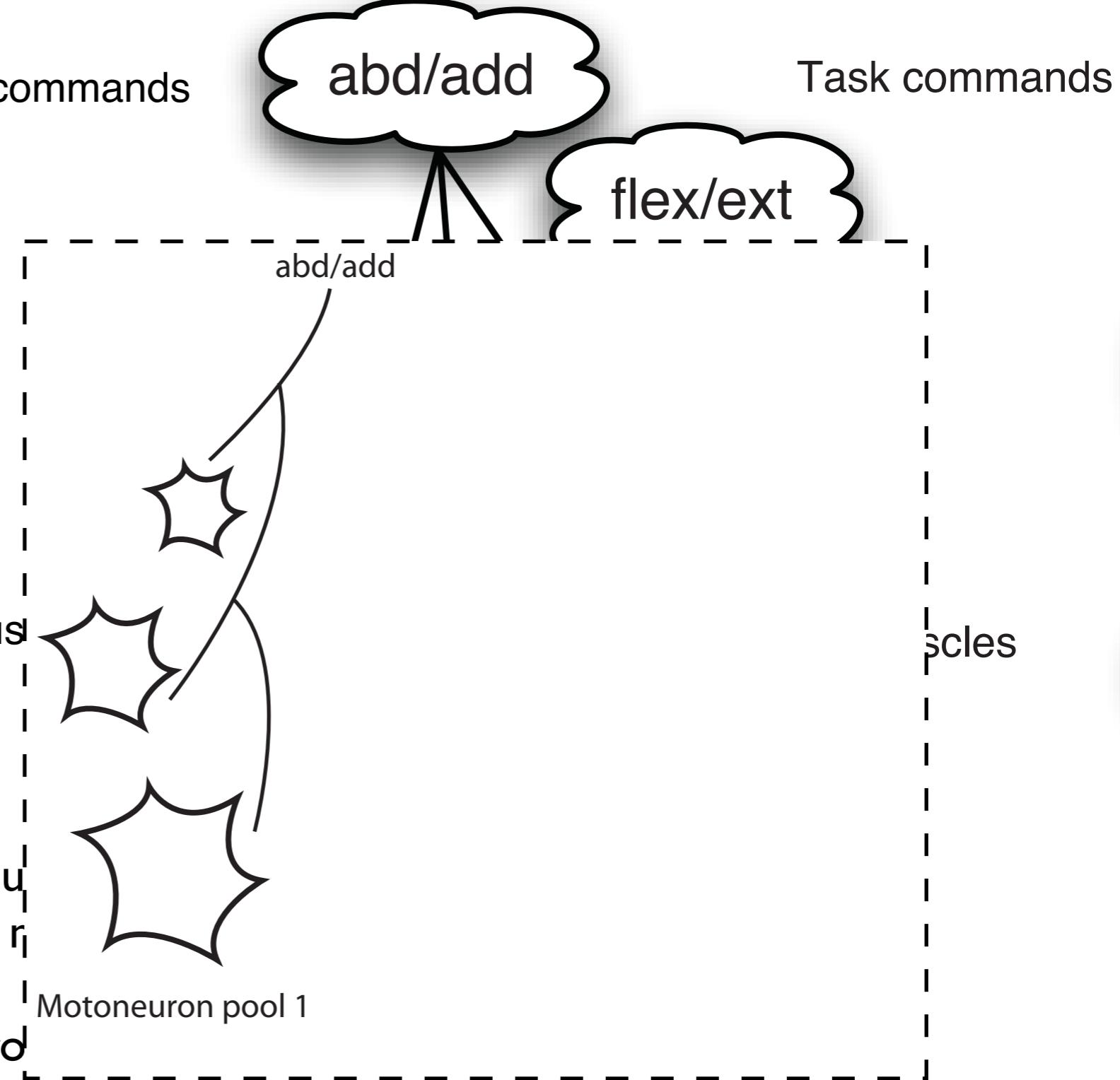
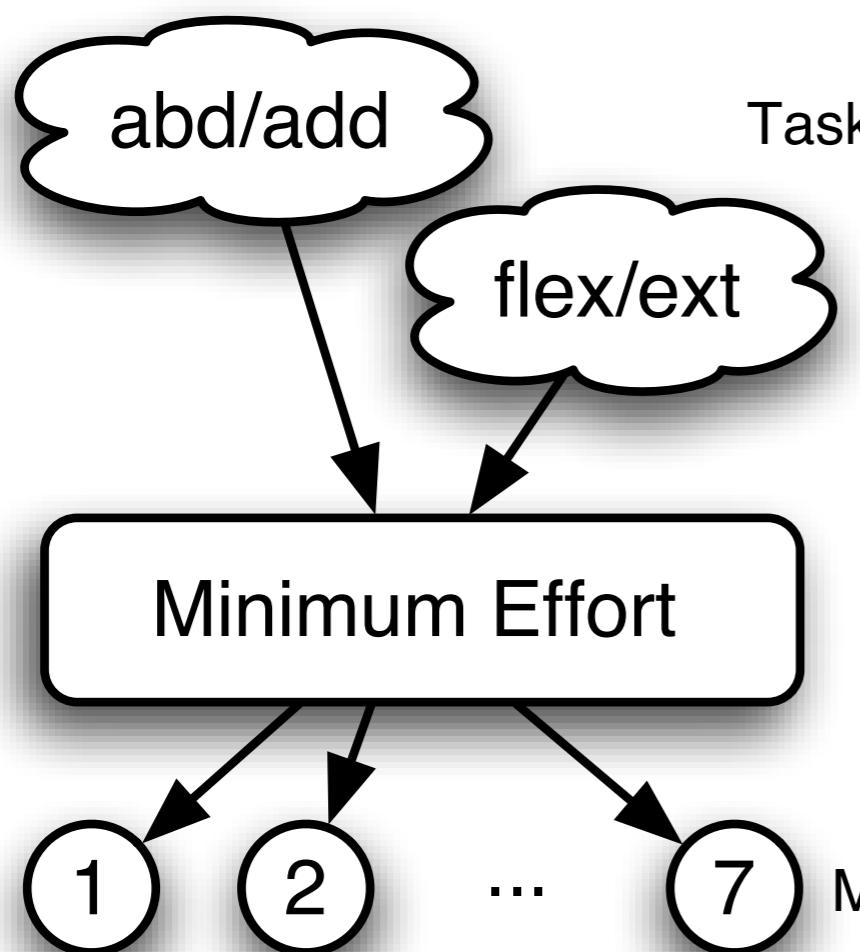
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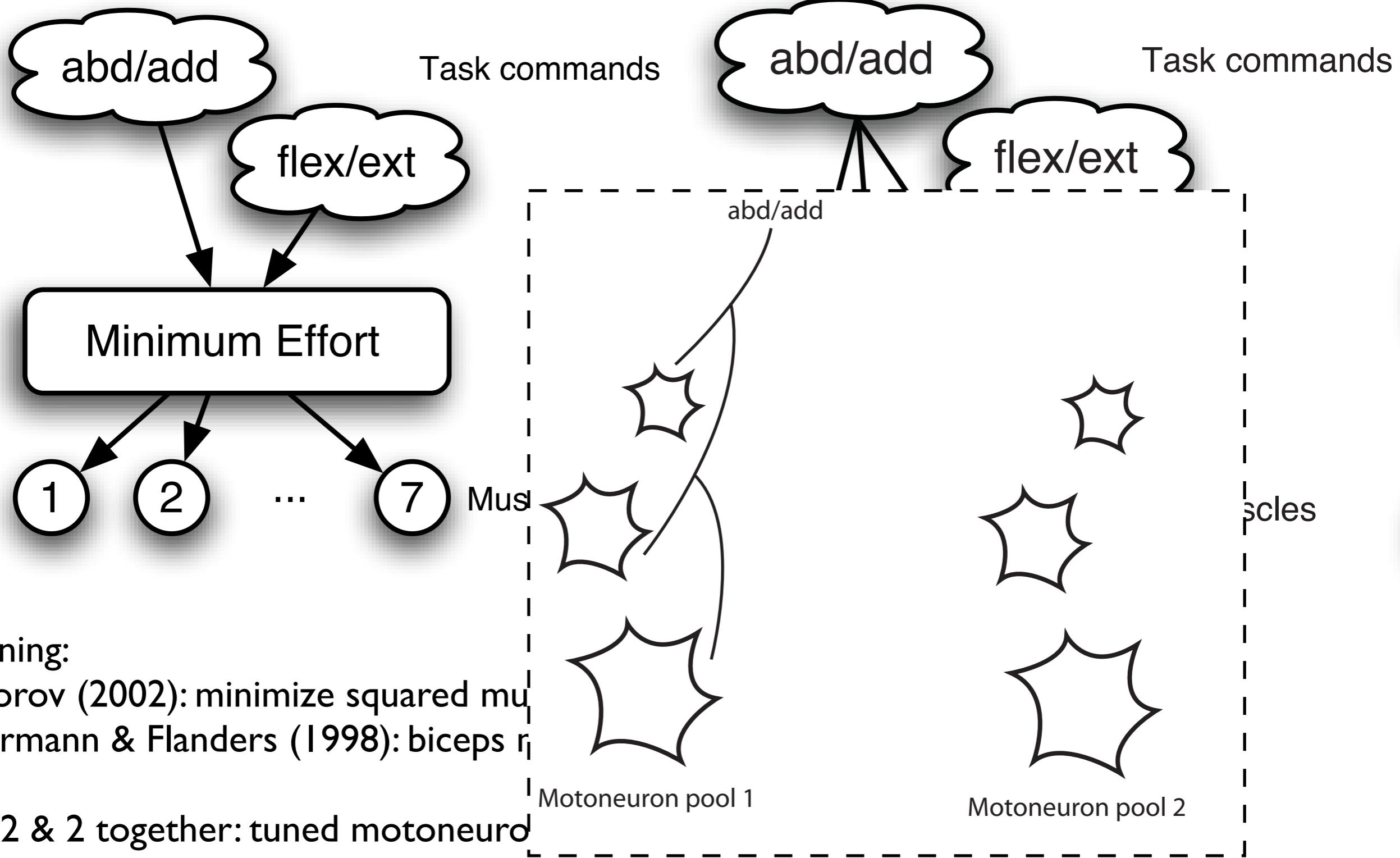
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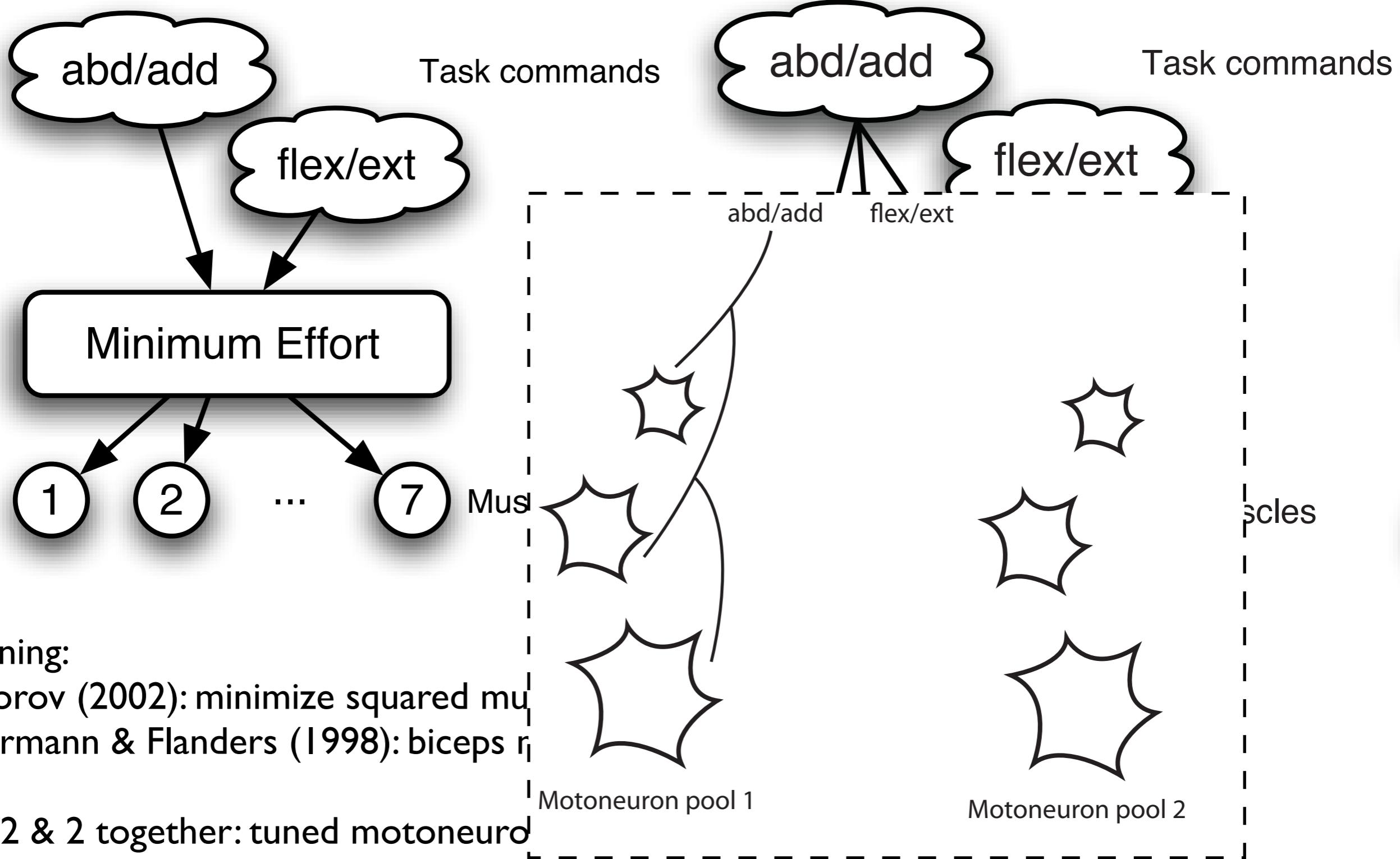
Reasoning:

1. Todorov (2002): minimize squared mu
2. Herrmann & Flanders (1998): biceps r
- ...
3. Put 2 & 2 together: tuned motoneuro

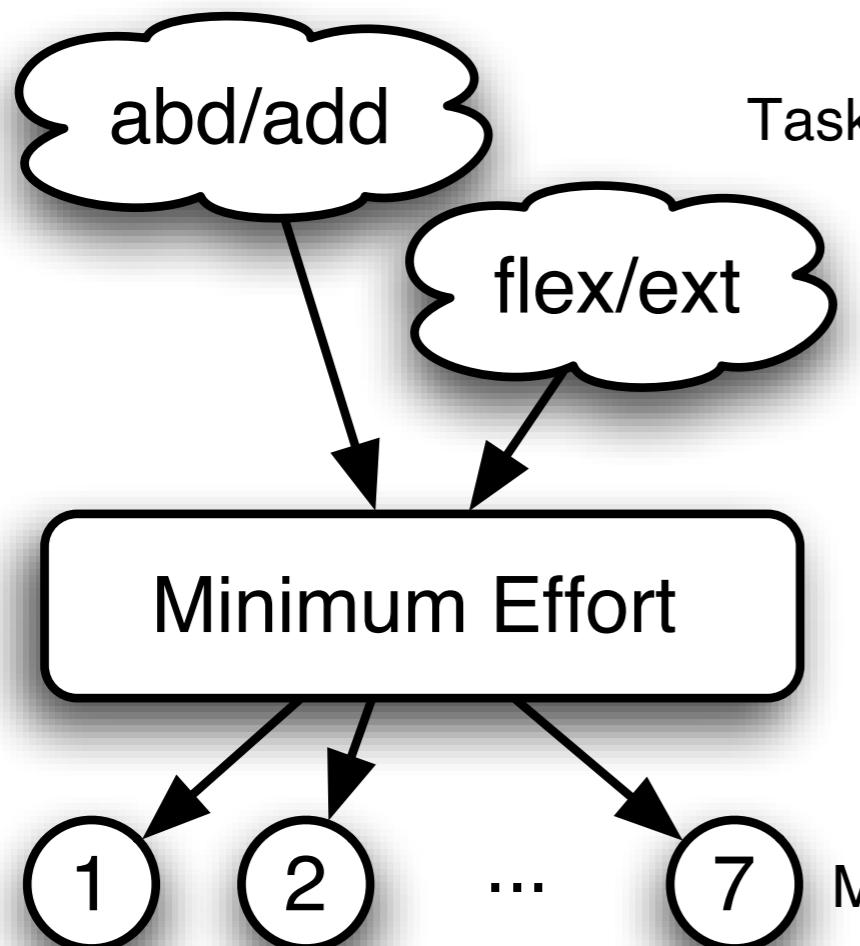
# Muscle synergies may not be necessary



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# Muscle synergies may not be necessary



Task commands

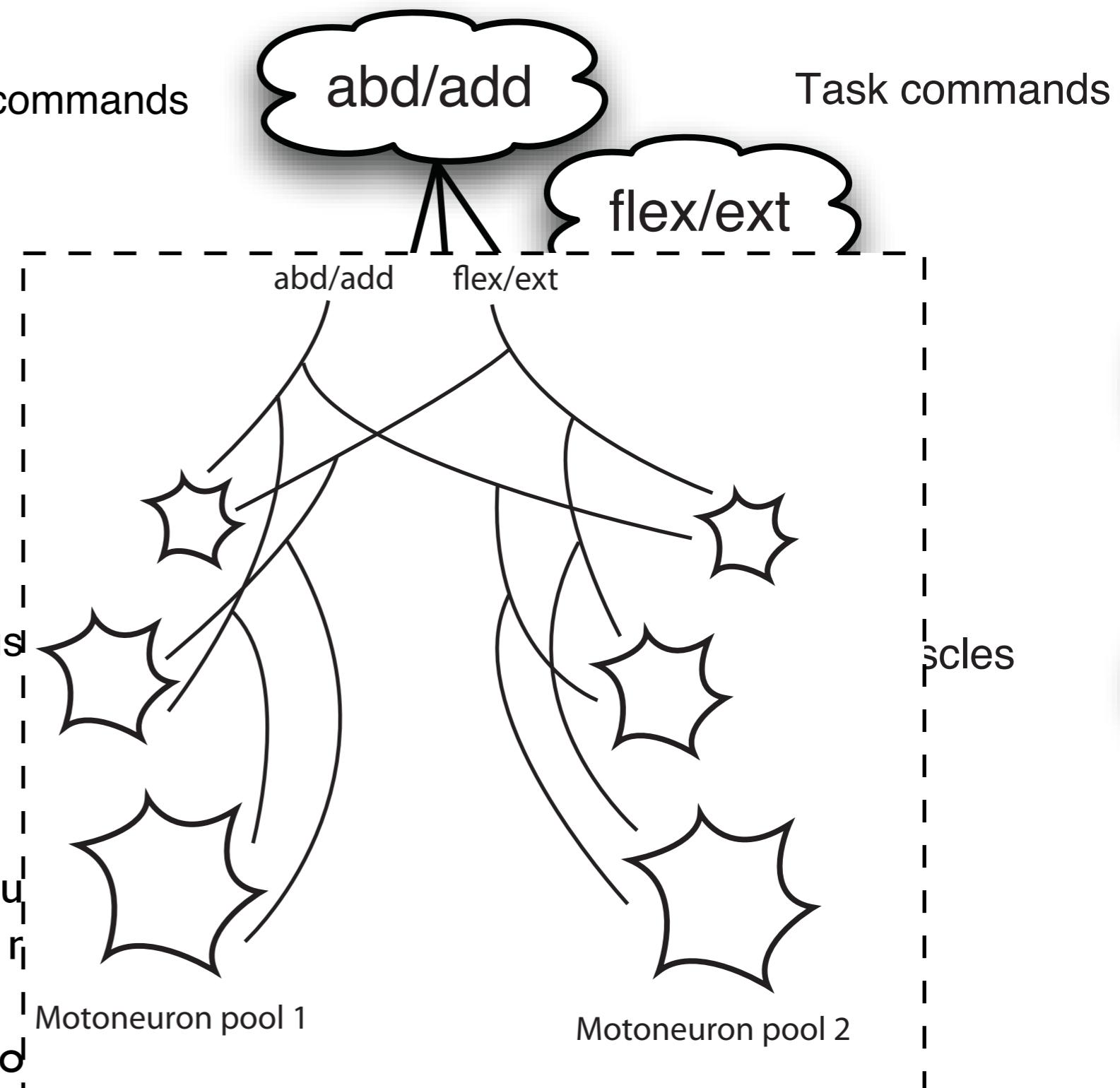
7

...  
1  
2

Minimum Effort

Reasoning:

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- ...  
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Task commands

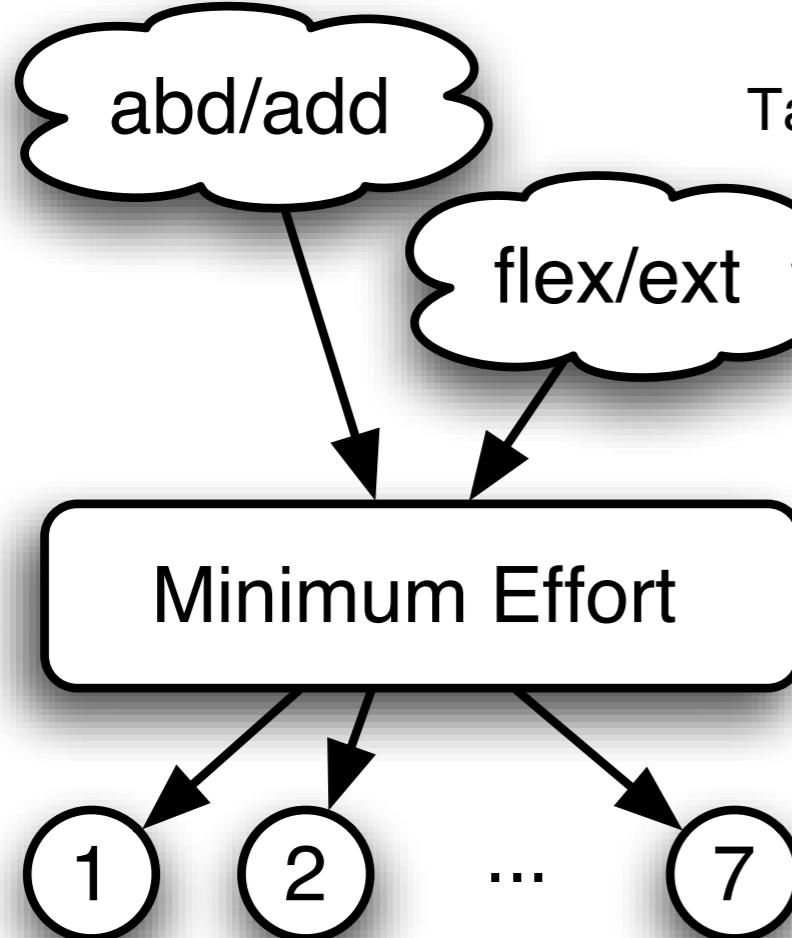
Mus...

Motoneuron pool 1

Motoneuron pool 2

scles

# Muscle synergies may not be necessary

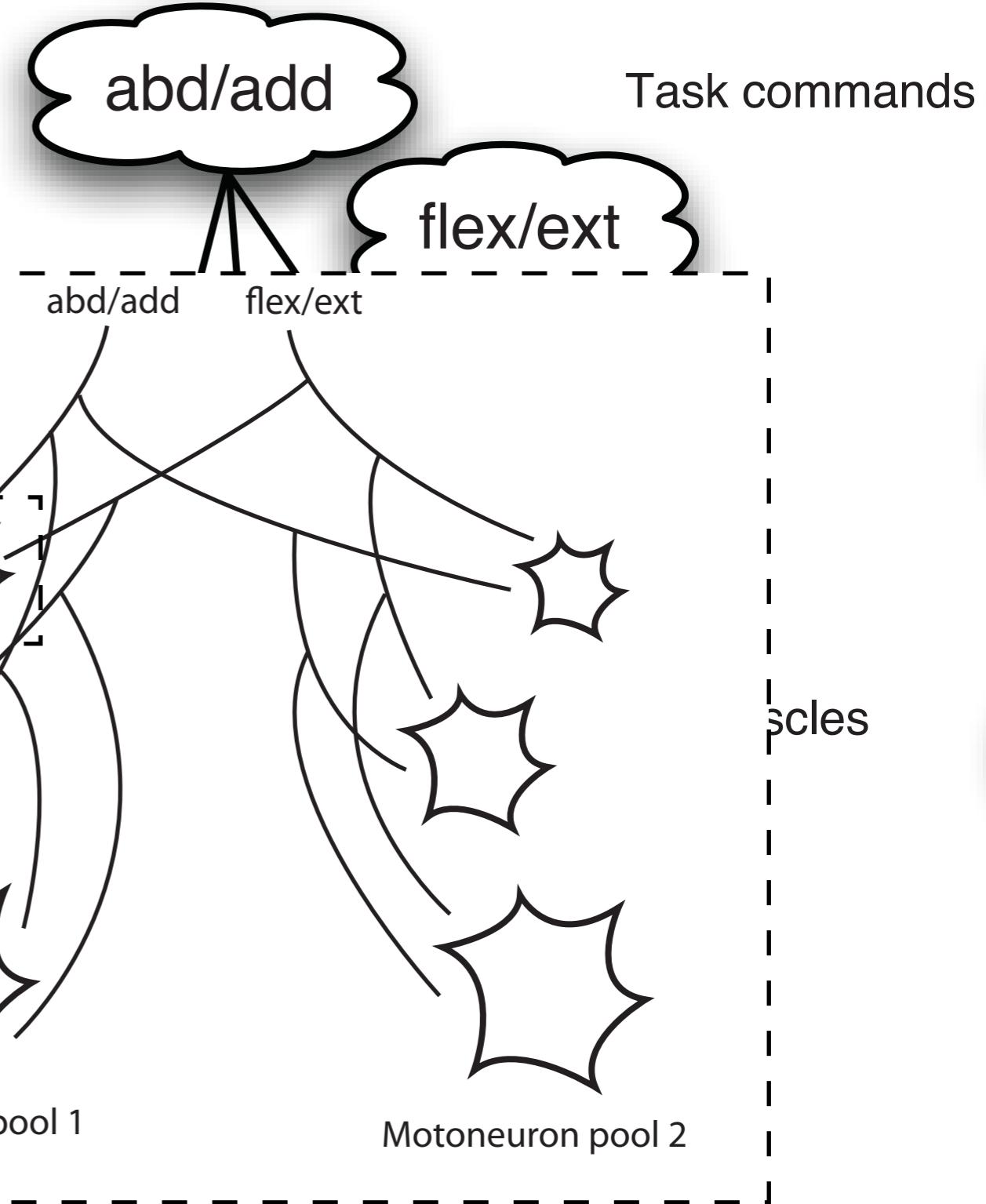


Task commands

...  
Mus...

1  
2  
7

Minimum Effort



Task commands

scles...

abd/add

flex/ext

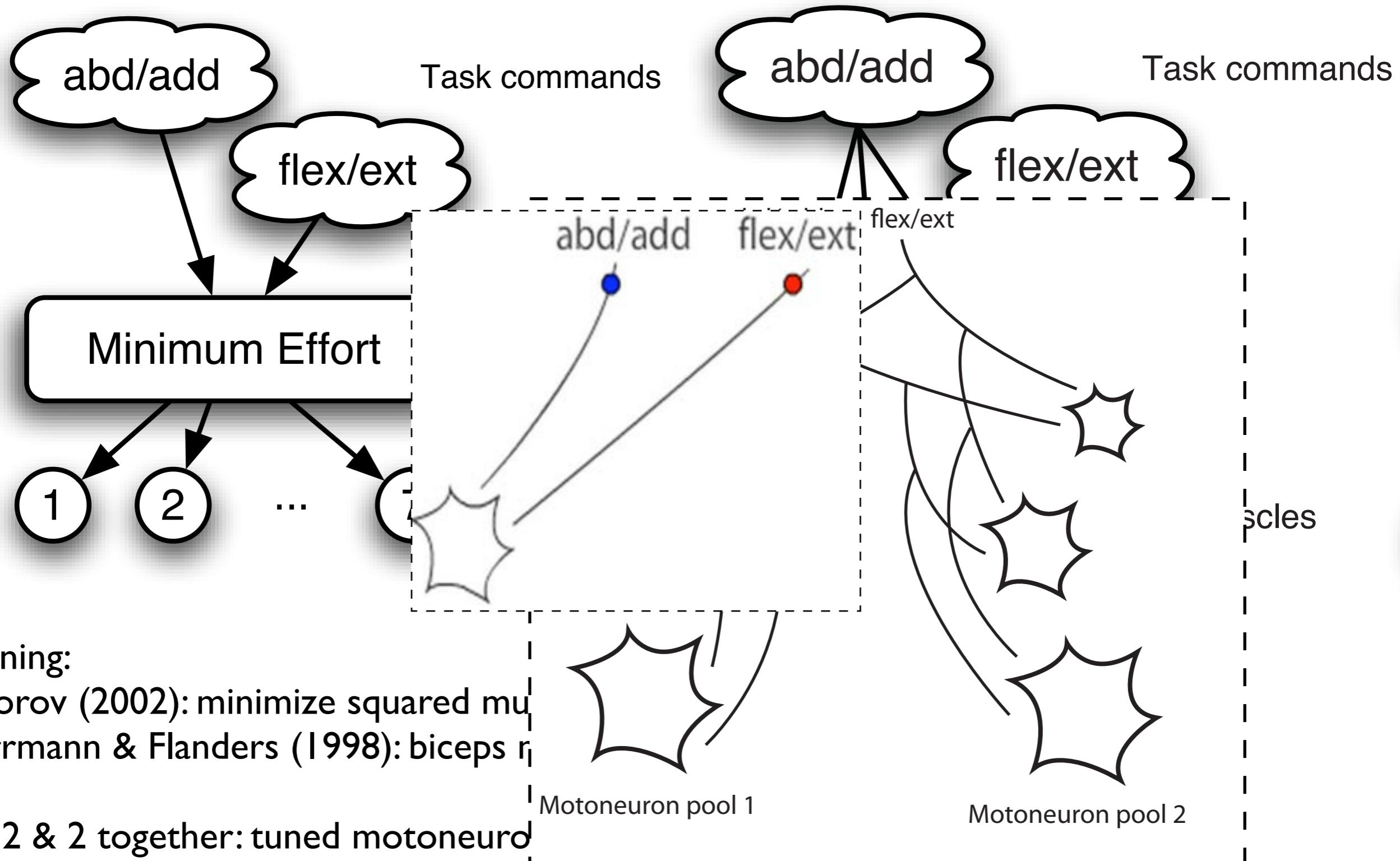
Motoneuron pool 1

Motoneuron pool 2

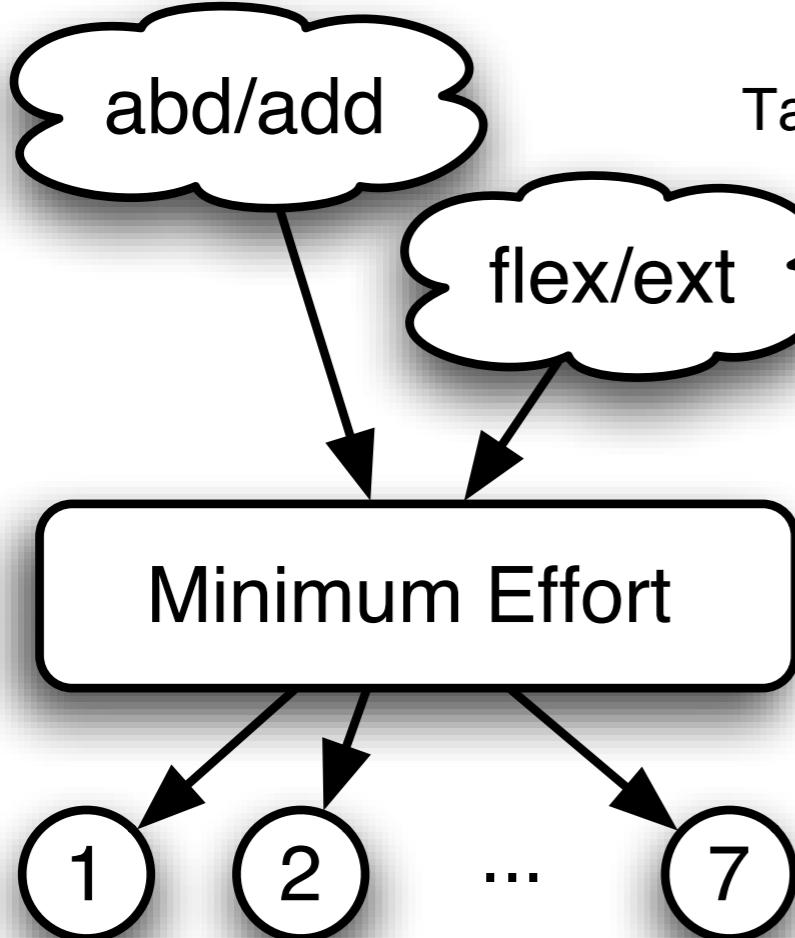
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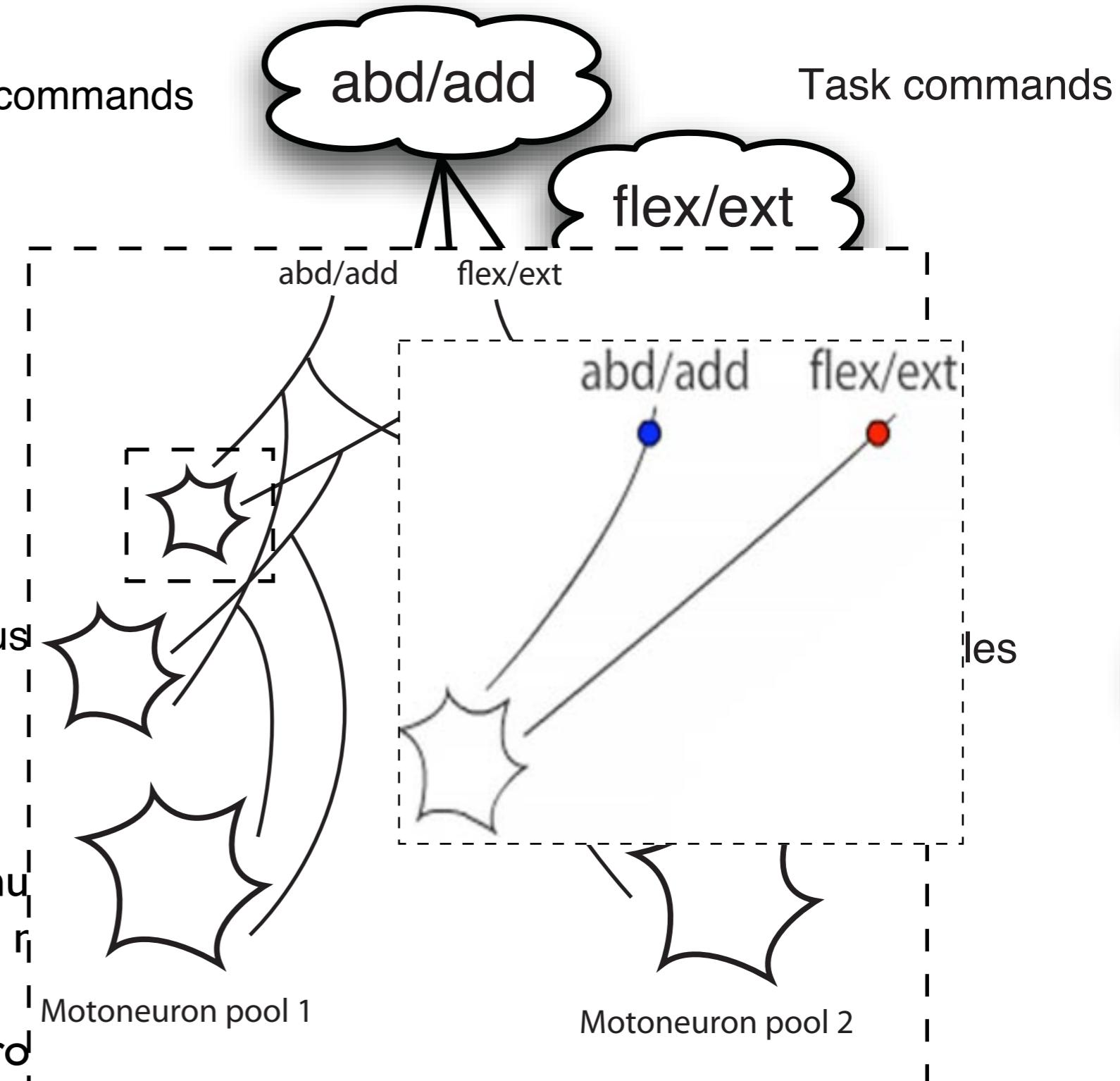


Task commands

...  
Mus

Reasoning:

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- ...  
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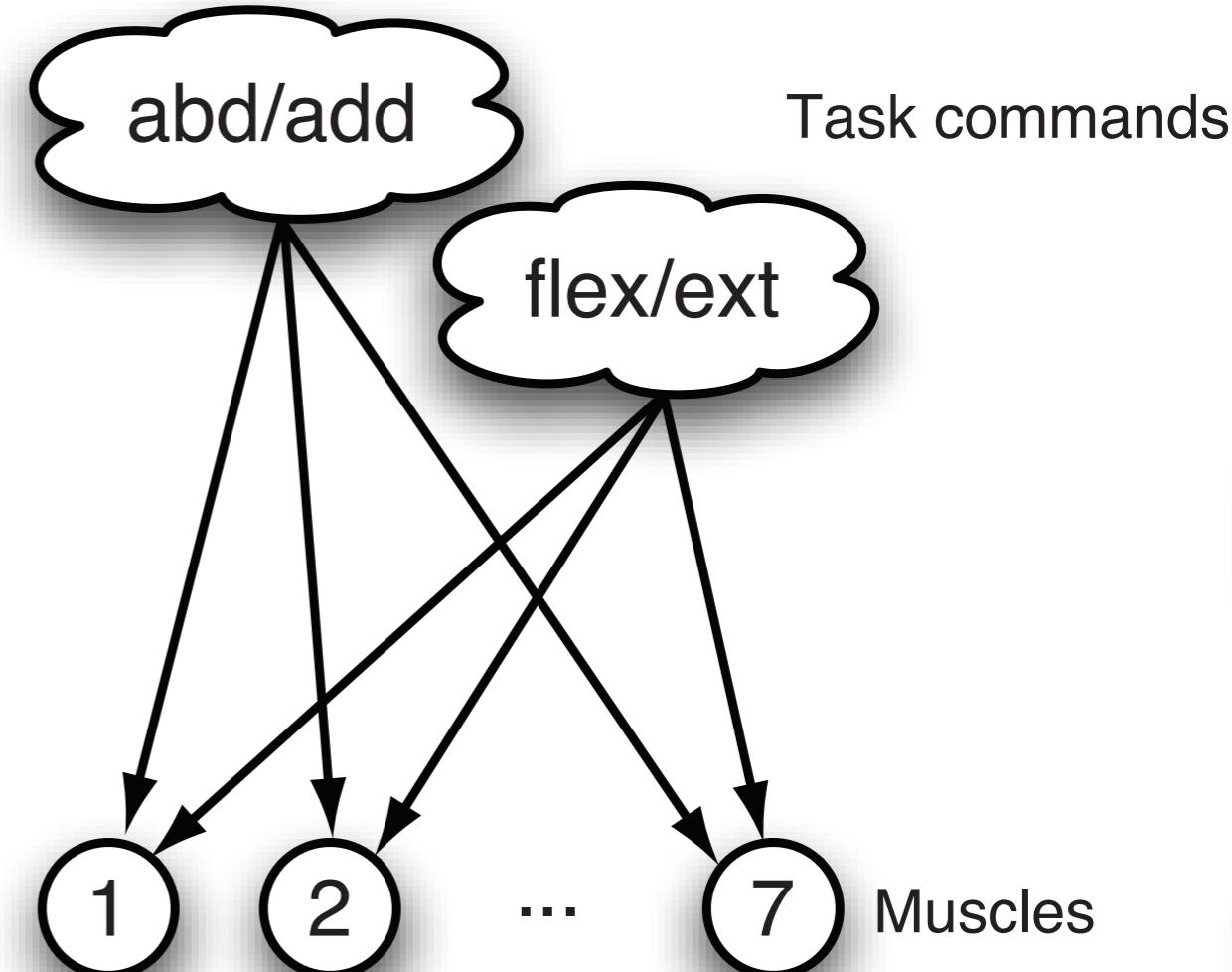
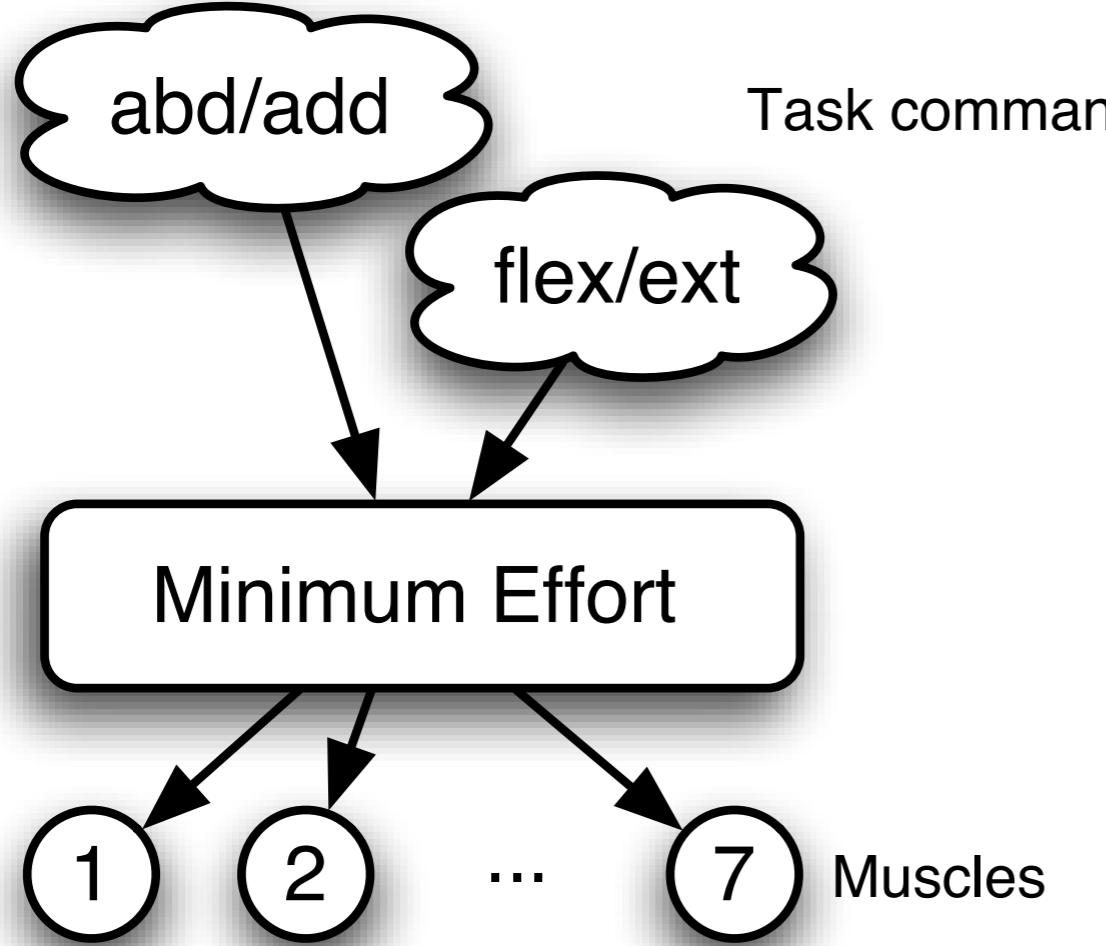
Task commands

...  
les

Motoneuron pool 1

Motoneuron pool 2

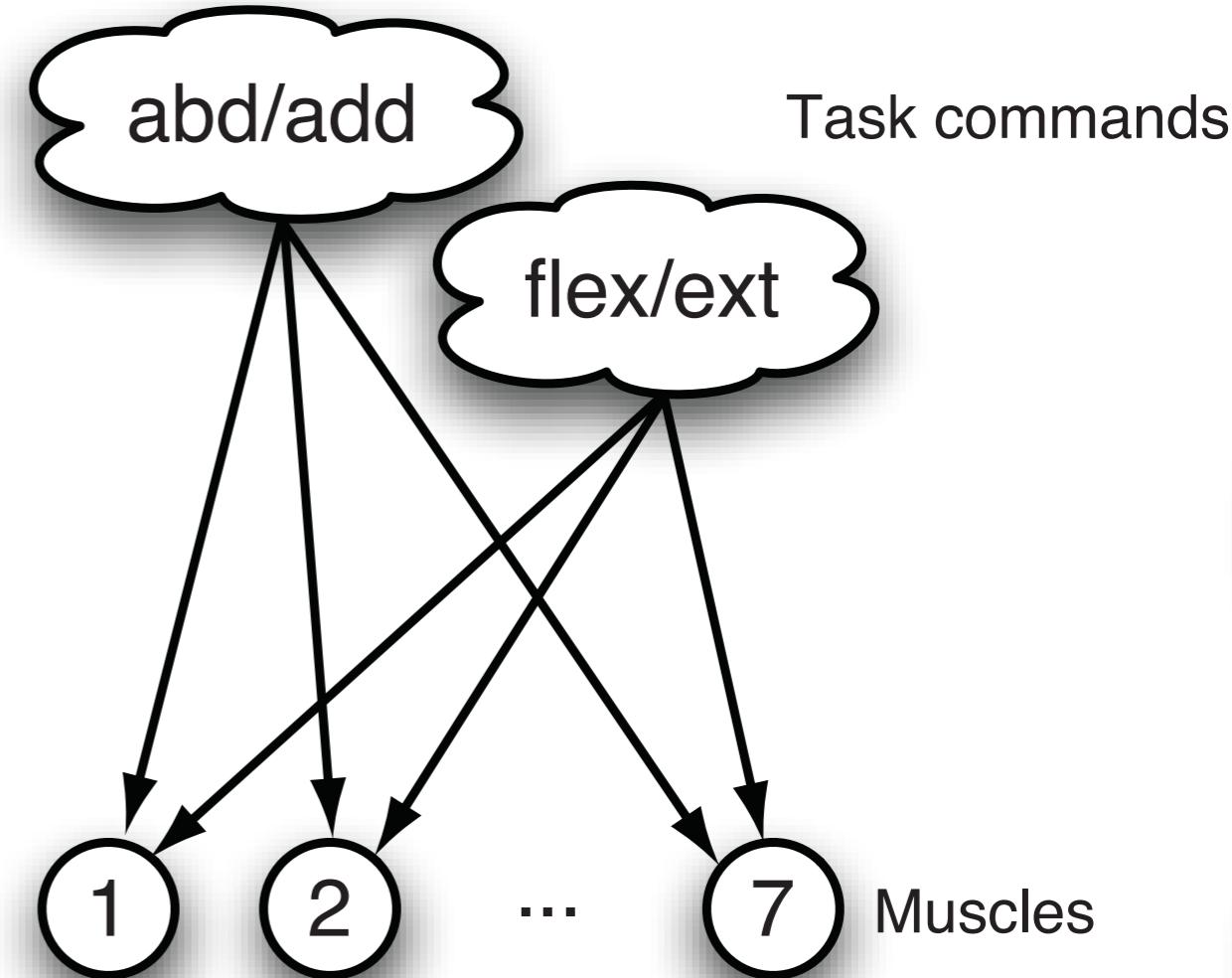
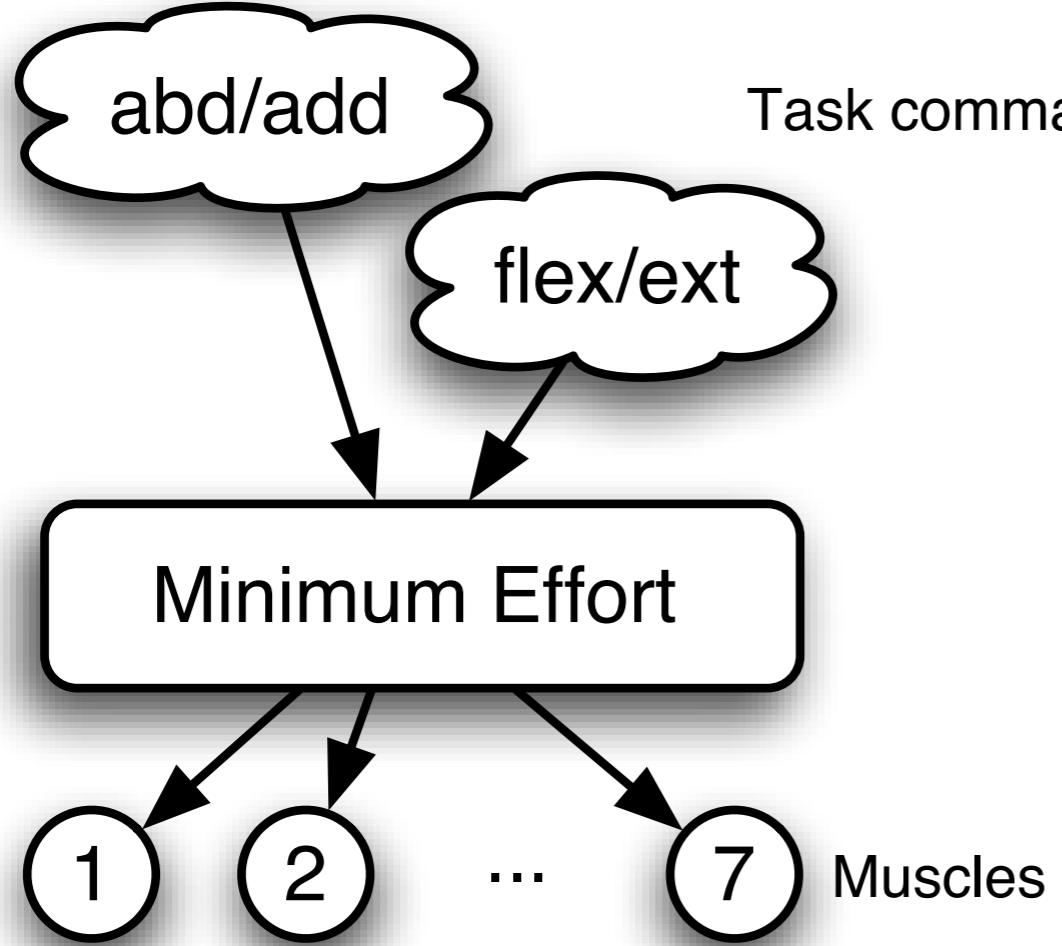
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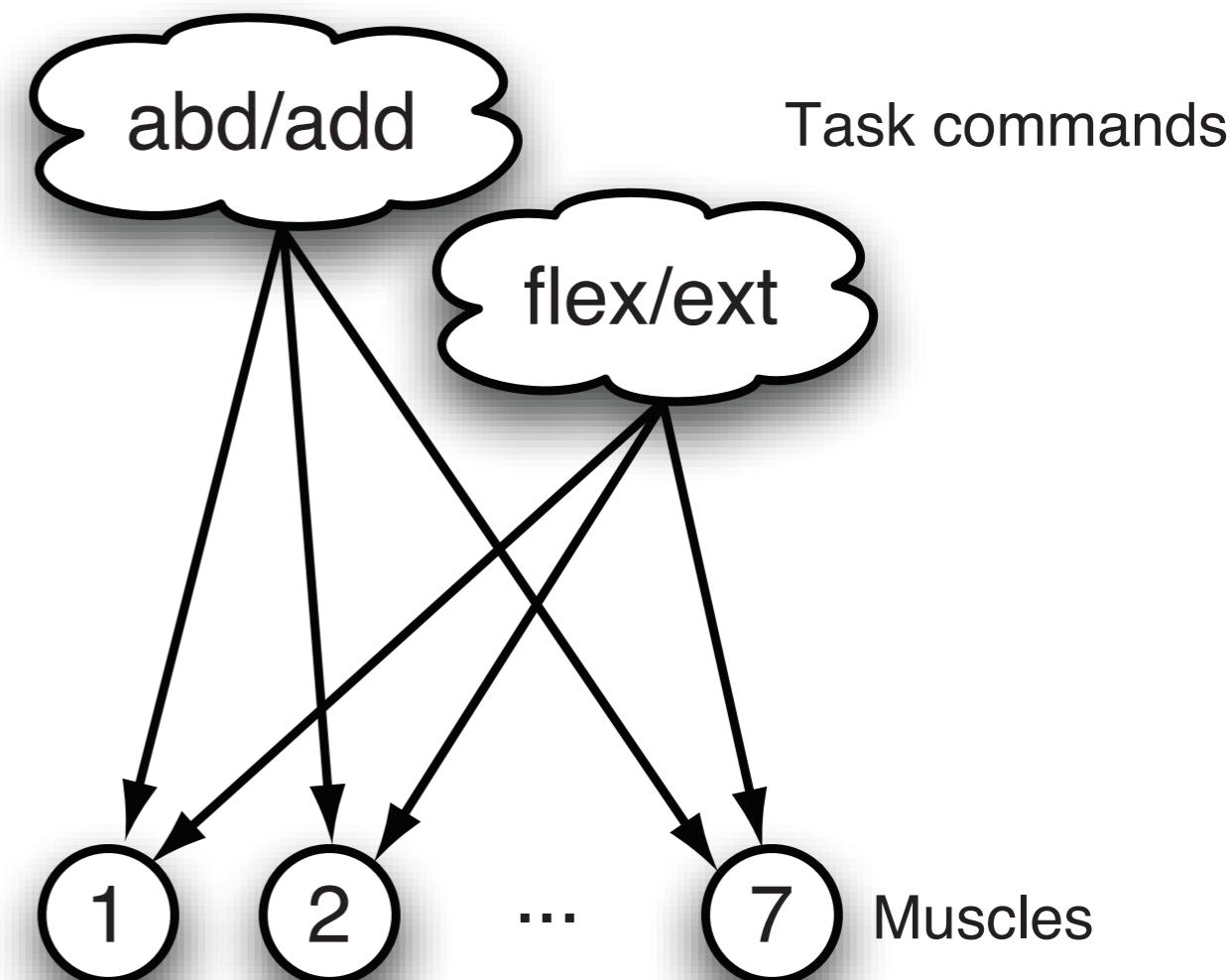
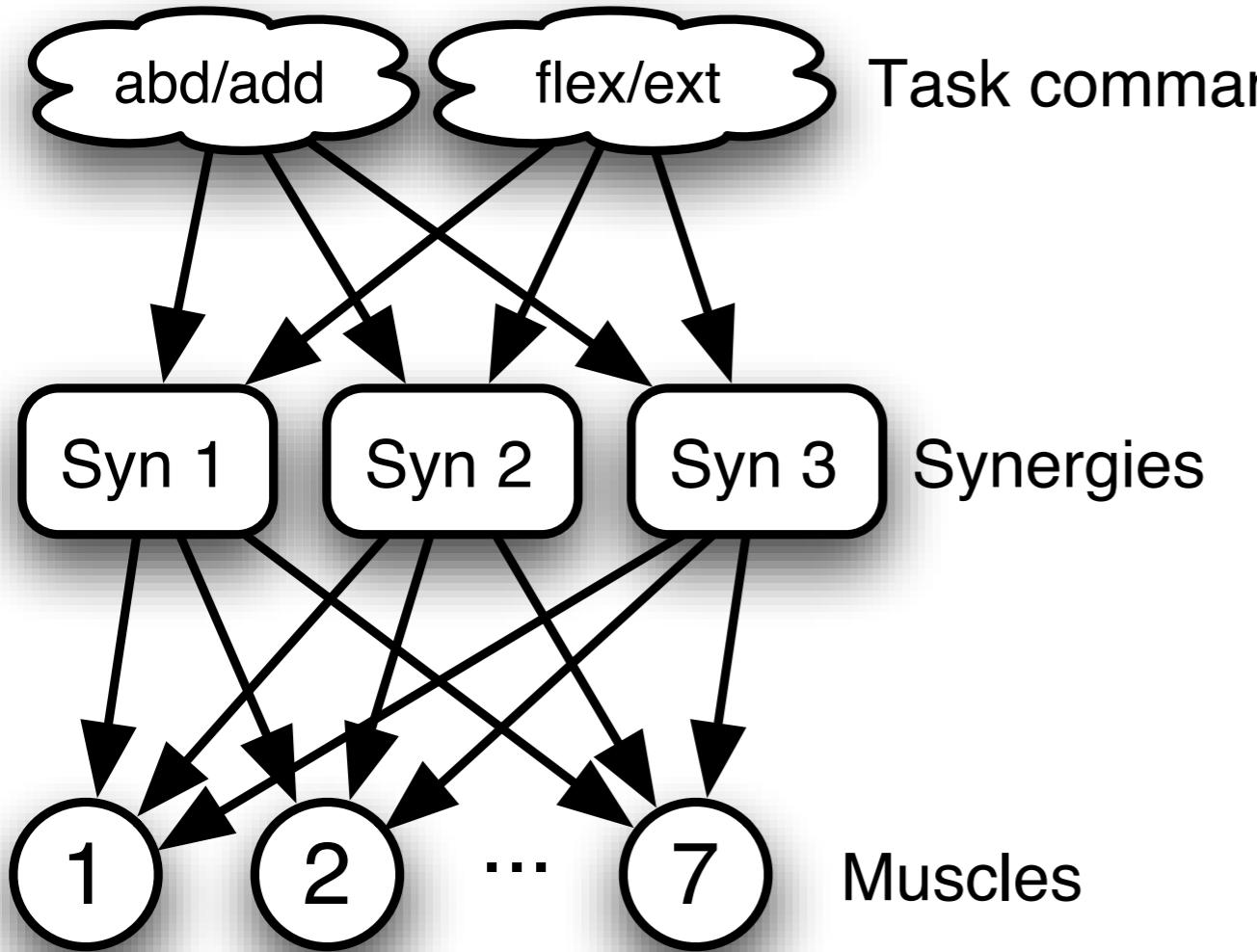


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**Minimum effort solution with simpler neural network than synergies.**

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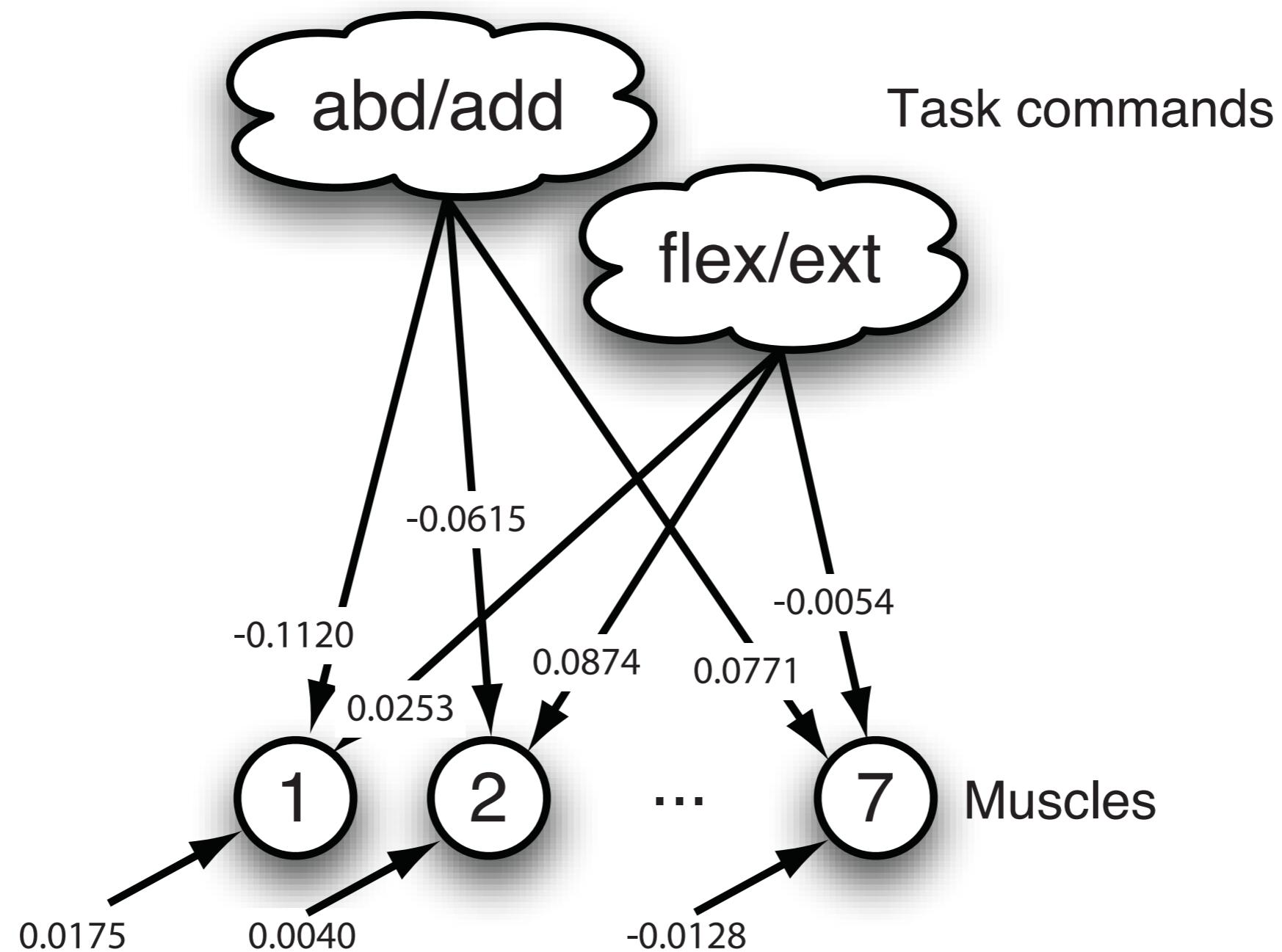


Reasoning:

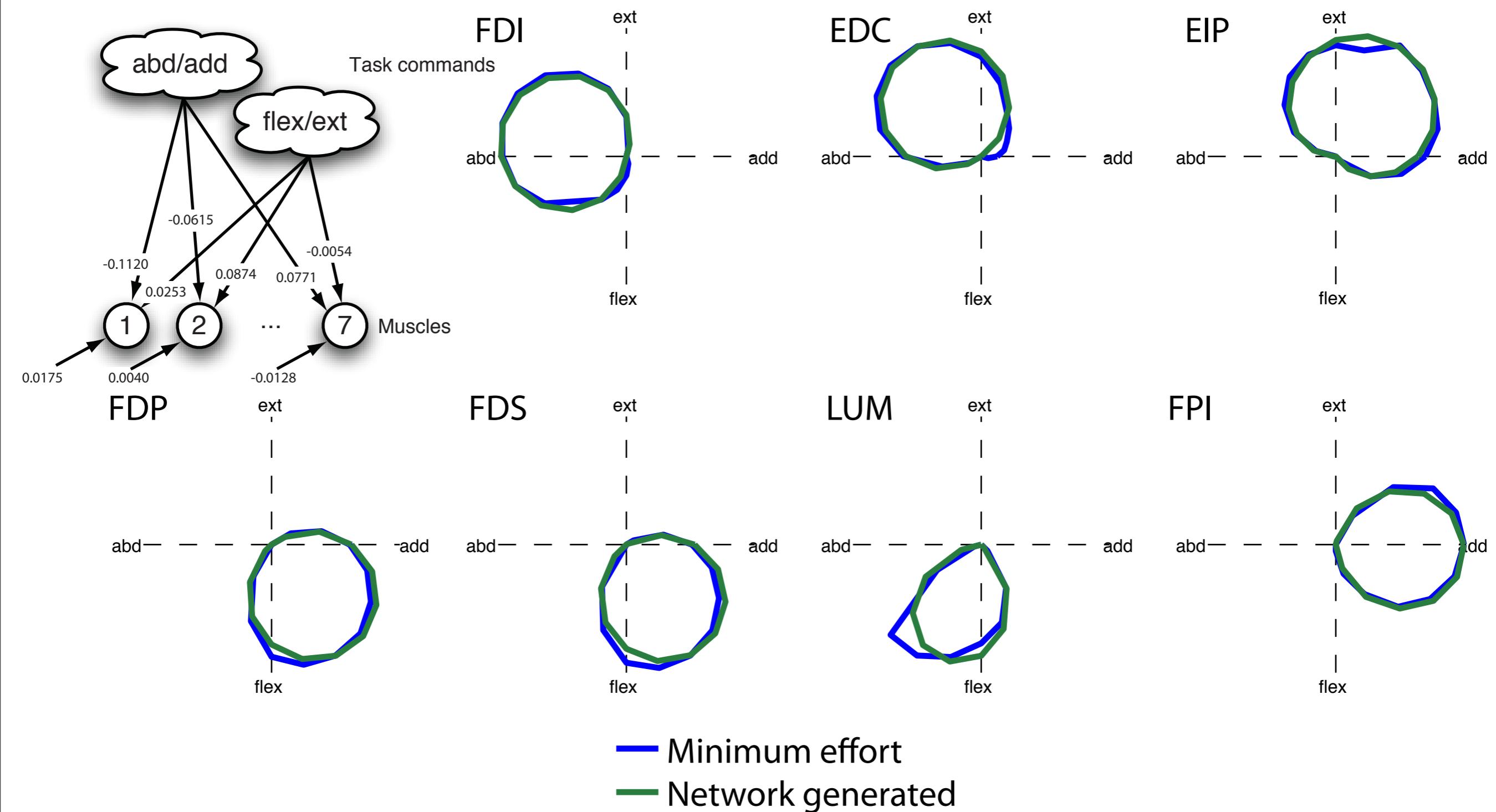
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The problem with simplification

No synergies for finger muscles

Flexible activity noise vs synergy noise

Muscle synergies may not be necessary

Towards clinical application

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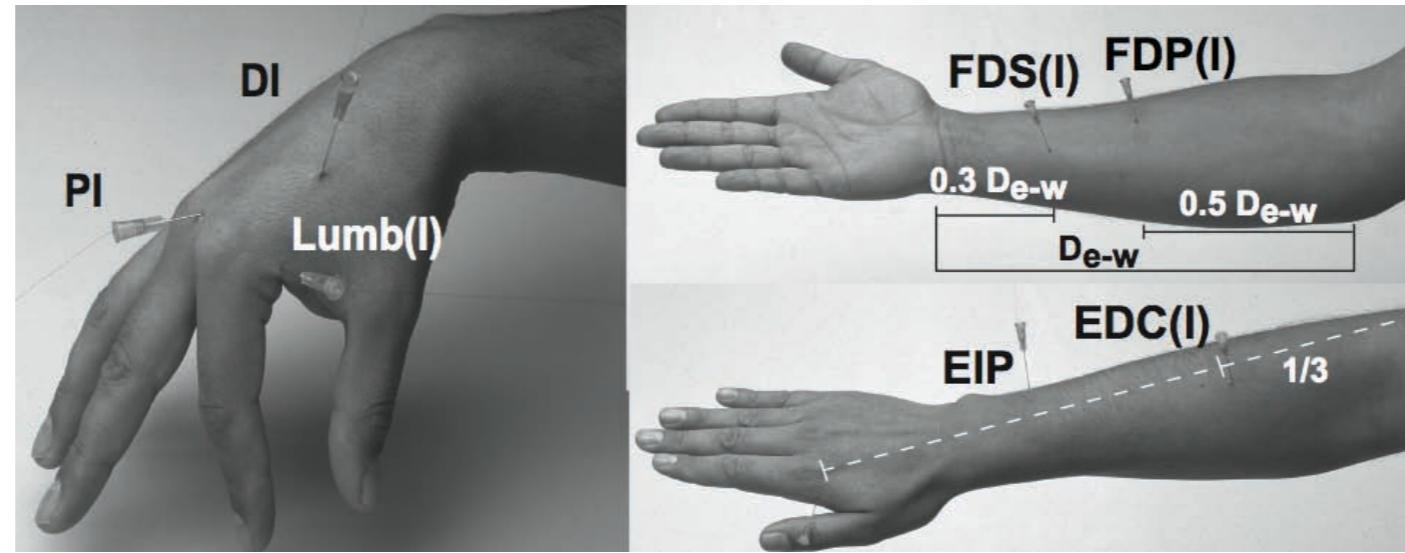
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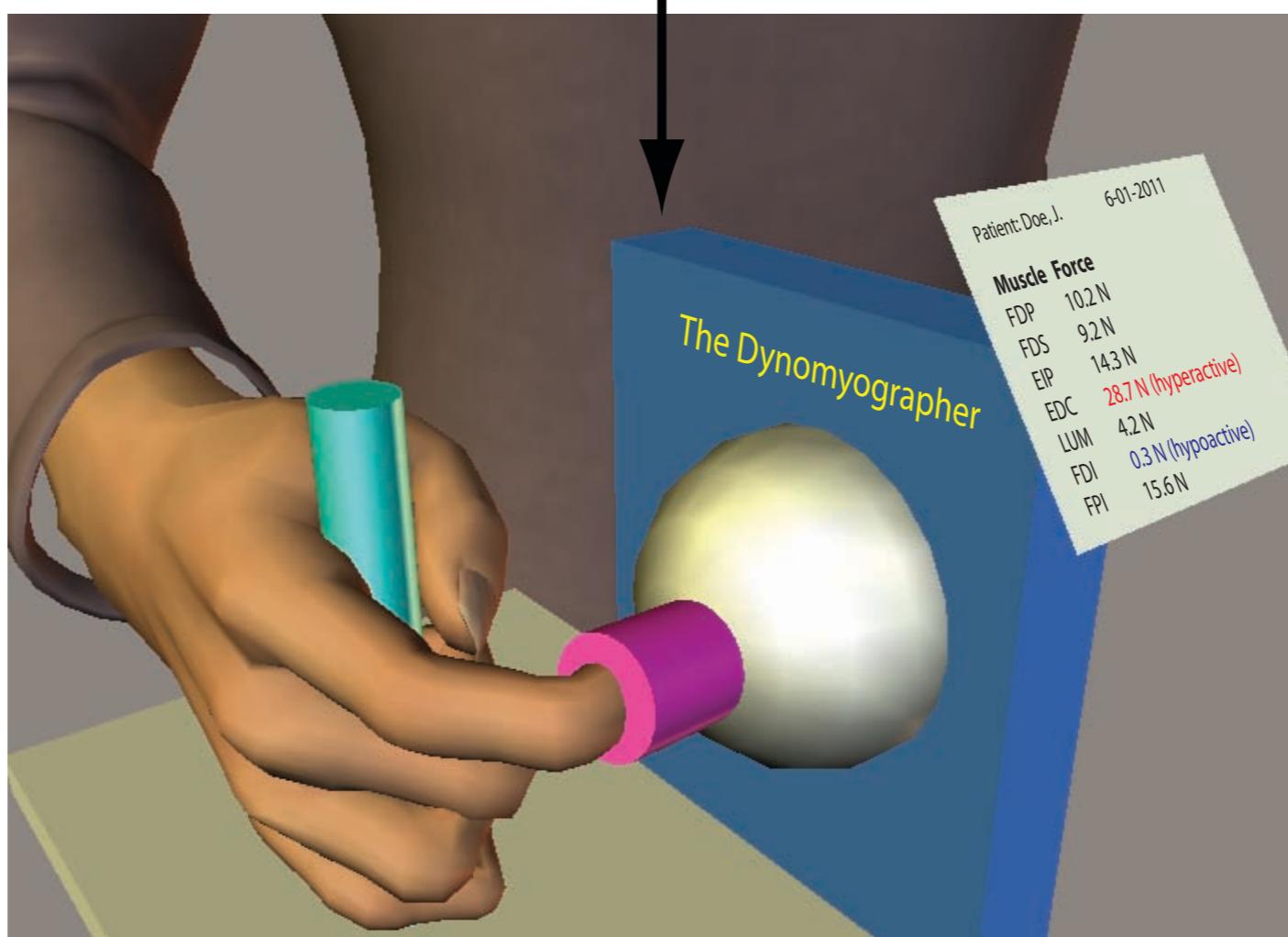
Towards clinical application

# Towards clinical application

# Towards clinical application



The Challenge: Dispense with needles and intramuscular electrodes



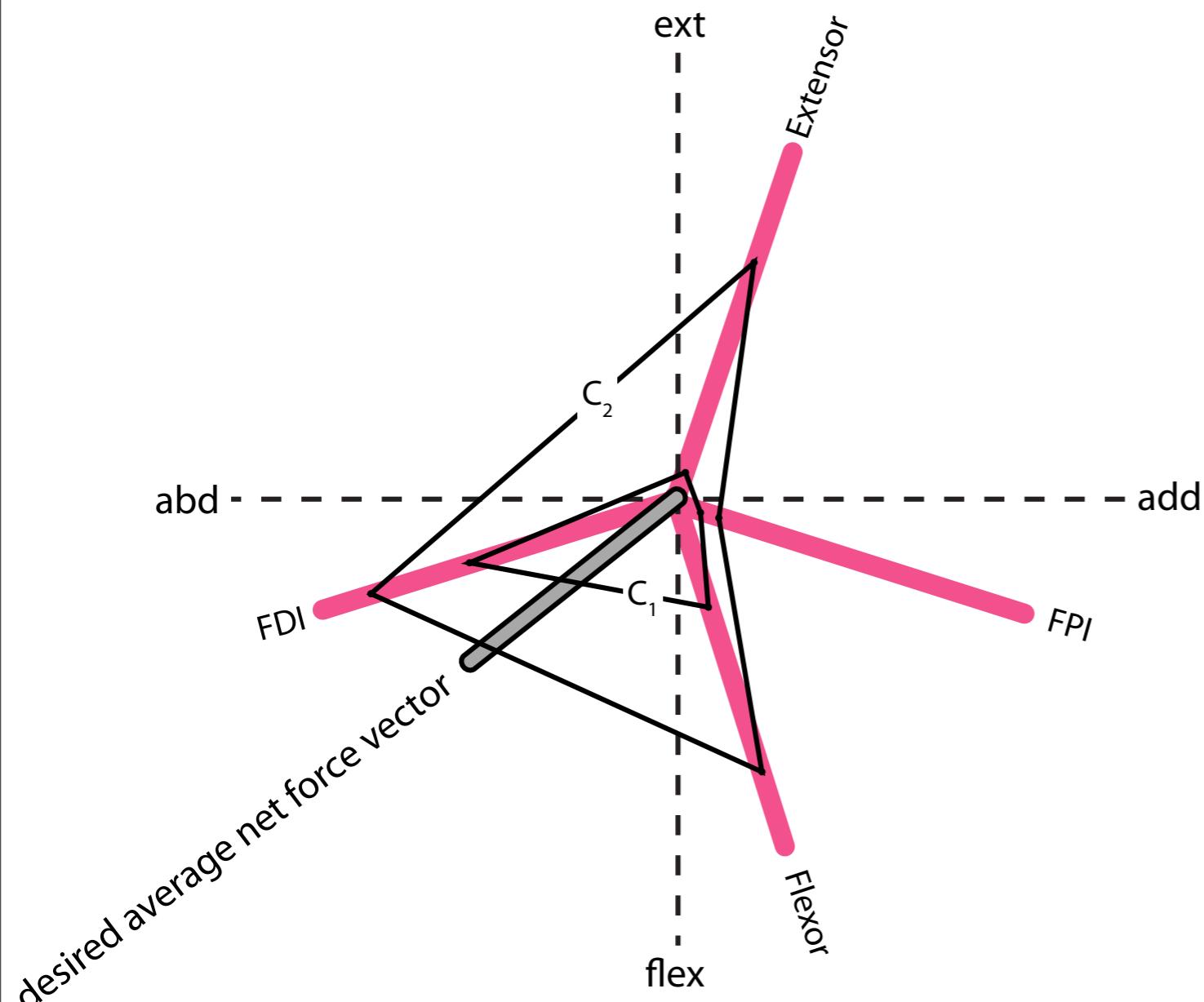
# Towards clinical application

## Dyno-myography:

# Towards clinical application

## Dyno-myography:

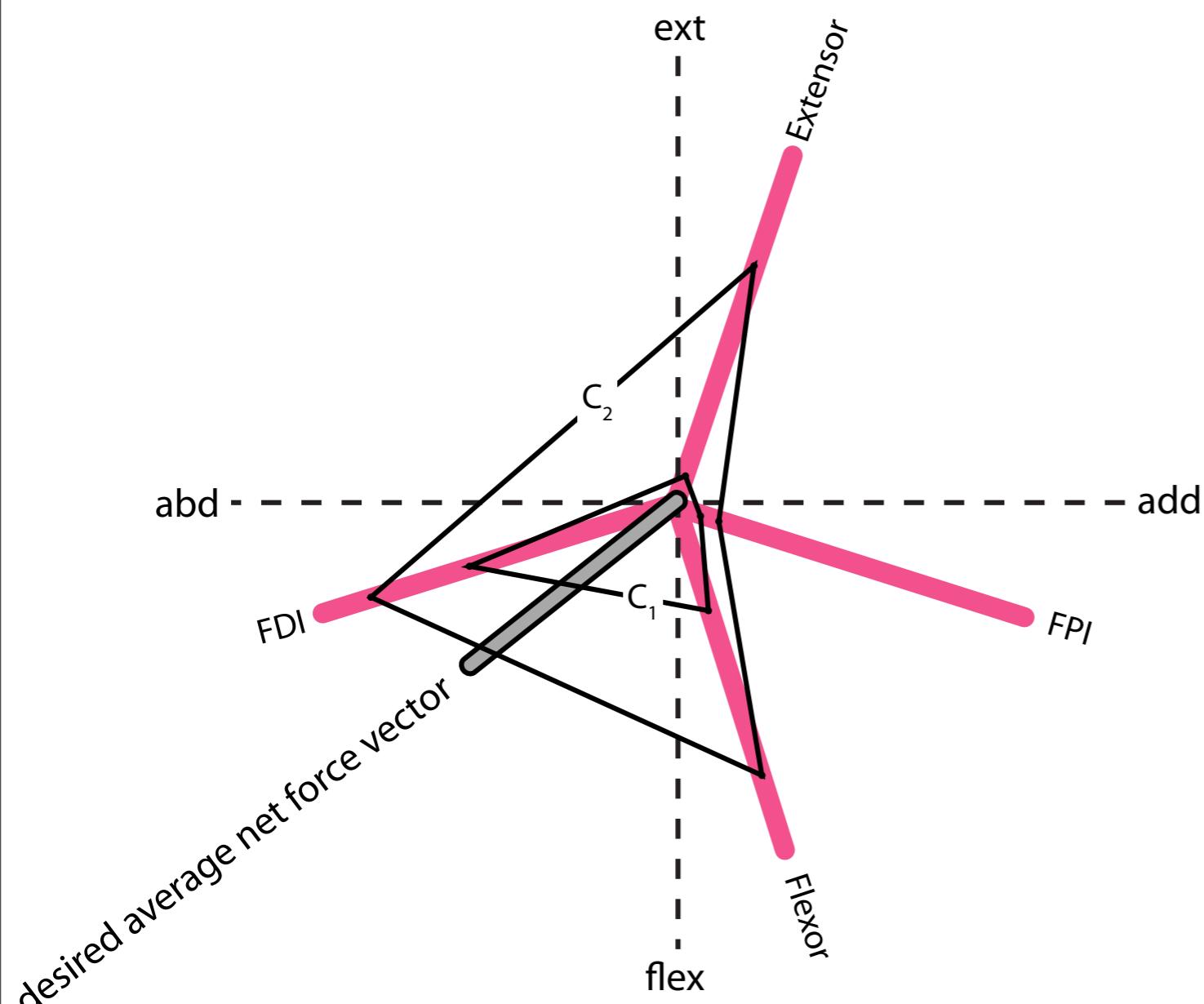
- A. Many different muscle activity combinations produce the same desired average net force vector



# Towards clinical application

## Dyno-myography:

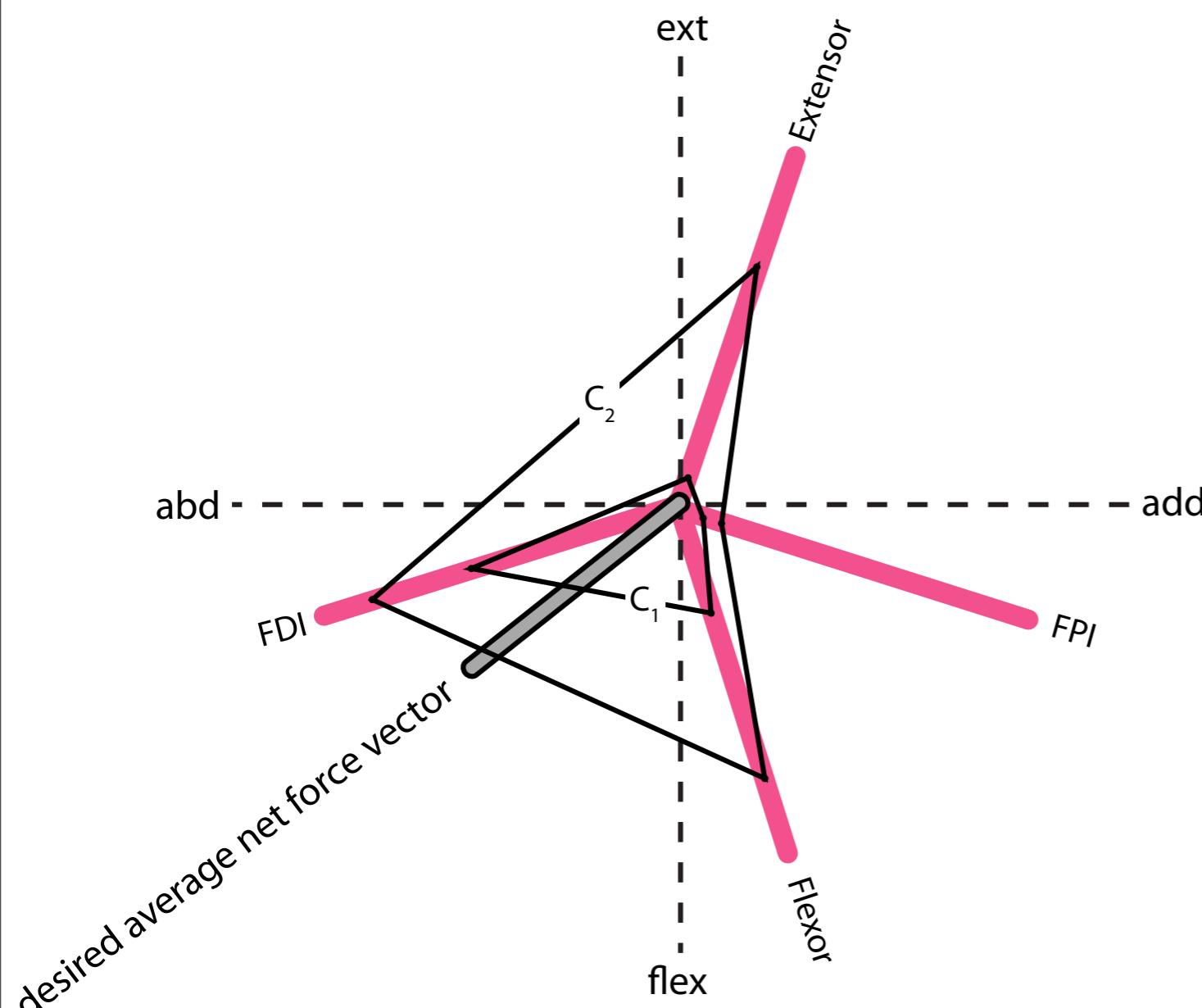
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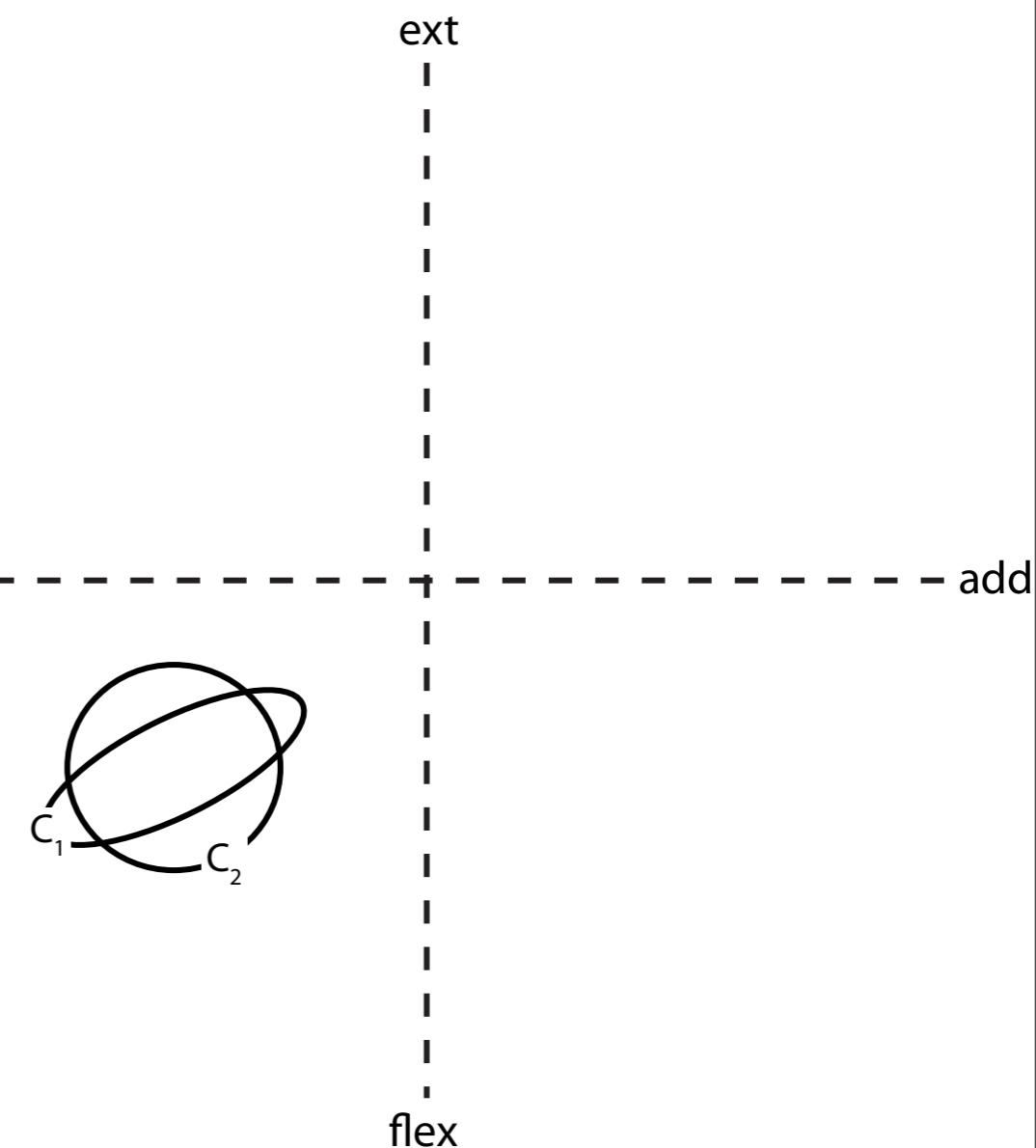
# Towards clinical application

## Dyno-myography:

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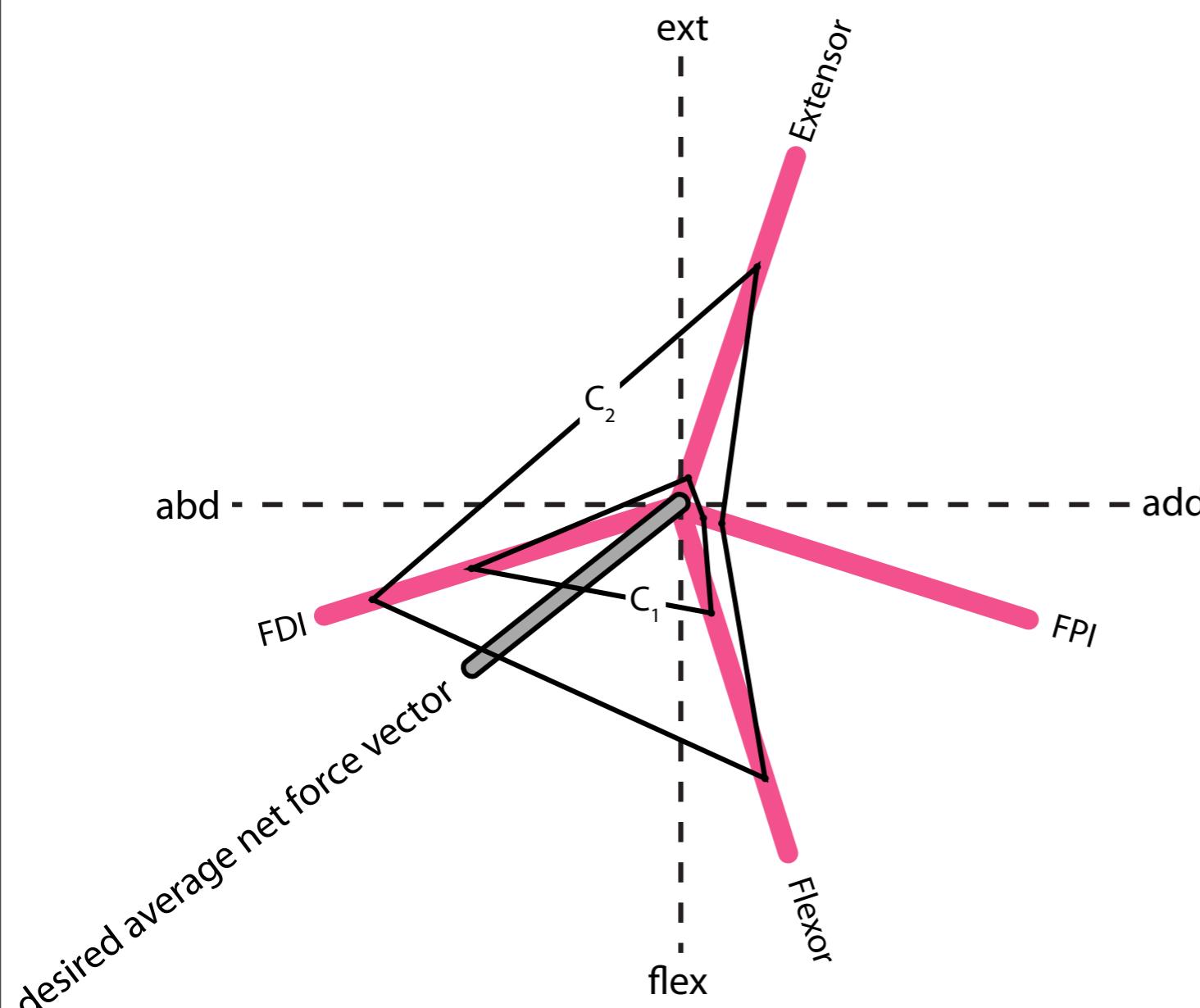
B. But different muscle activity combinations produce different force covariance ellipses



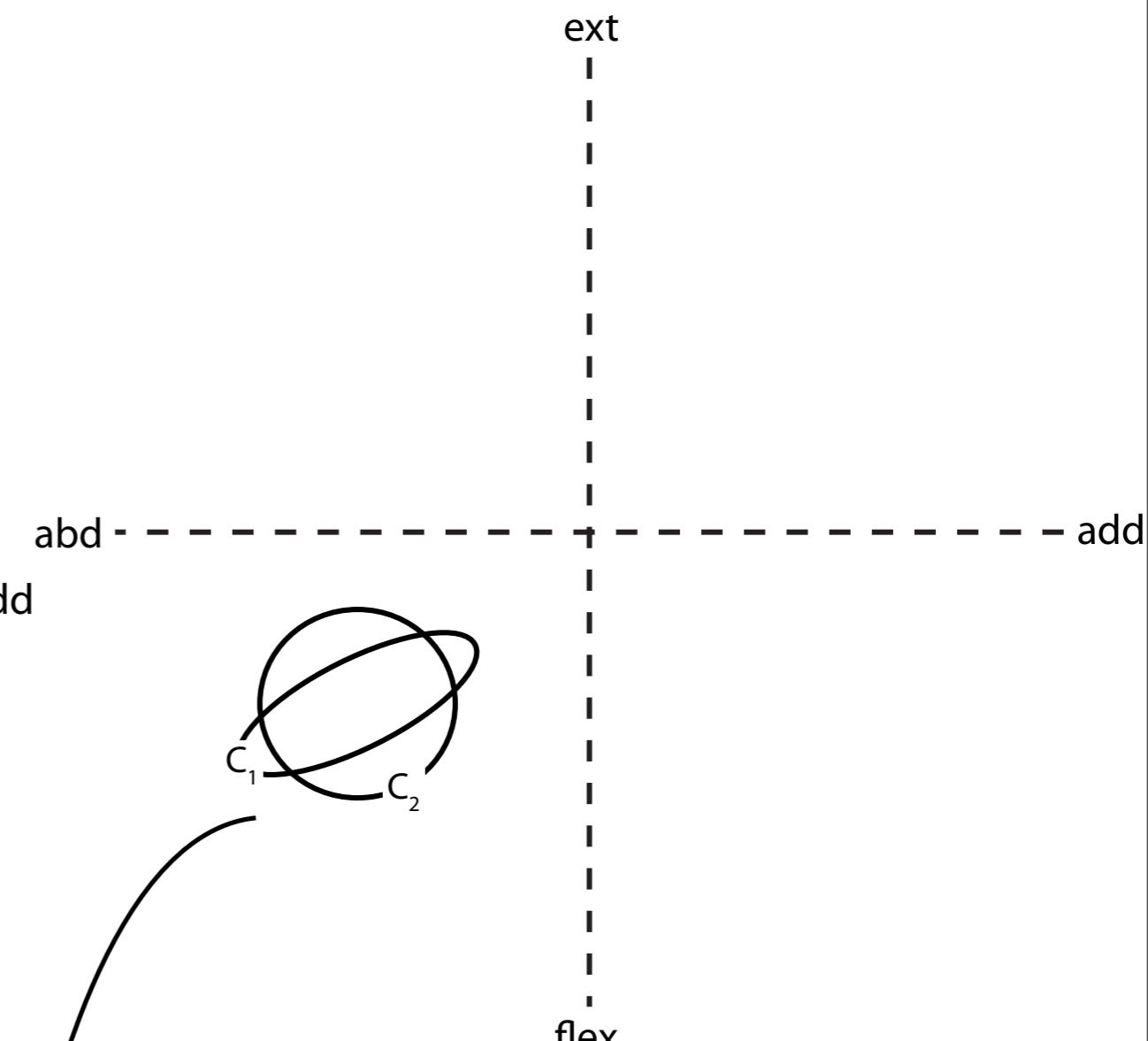
# Towards clinical application

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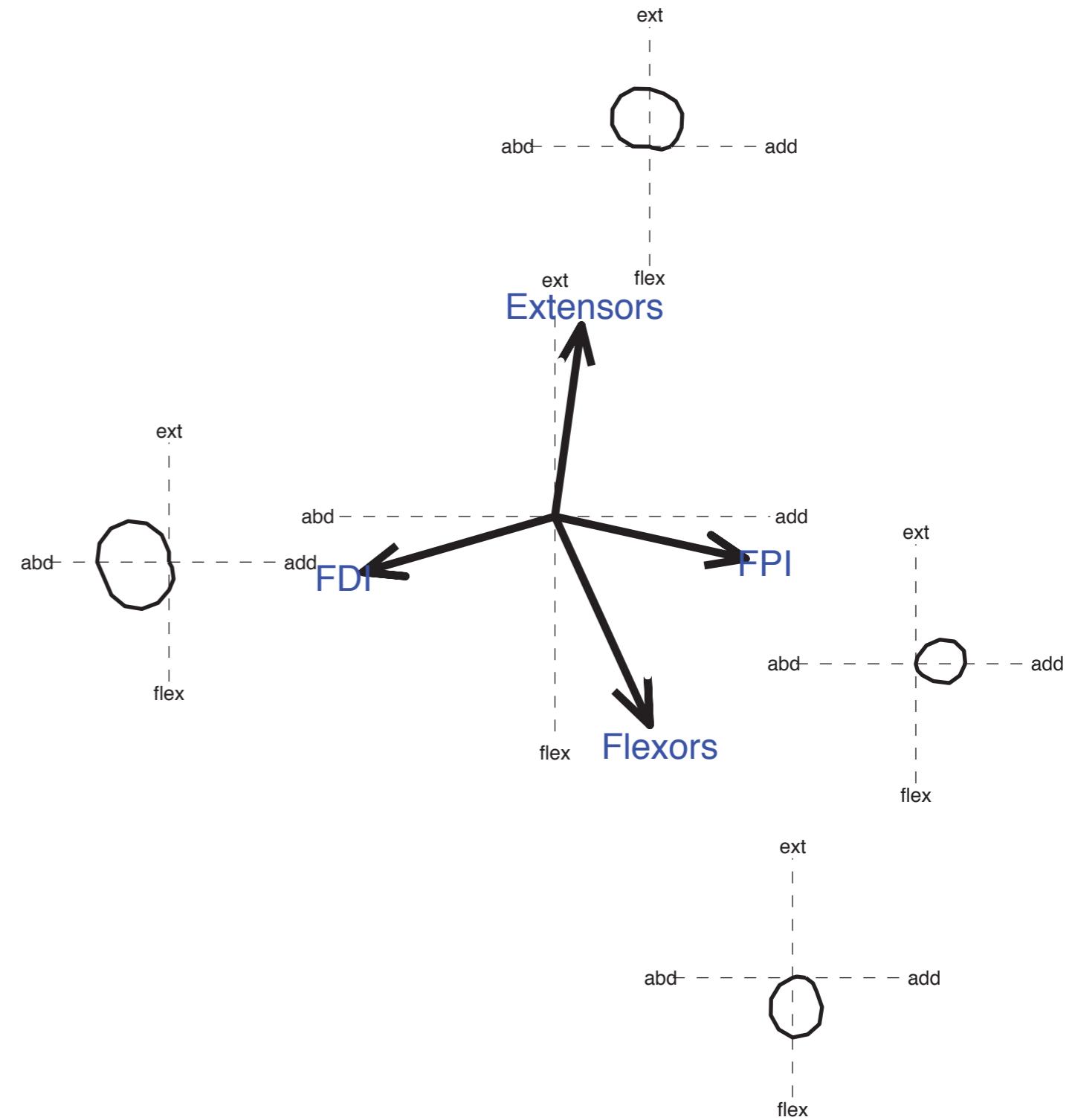
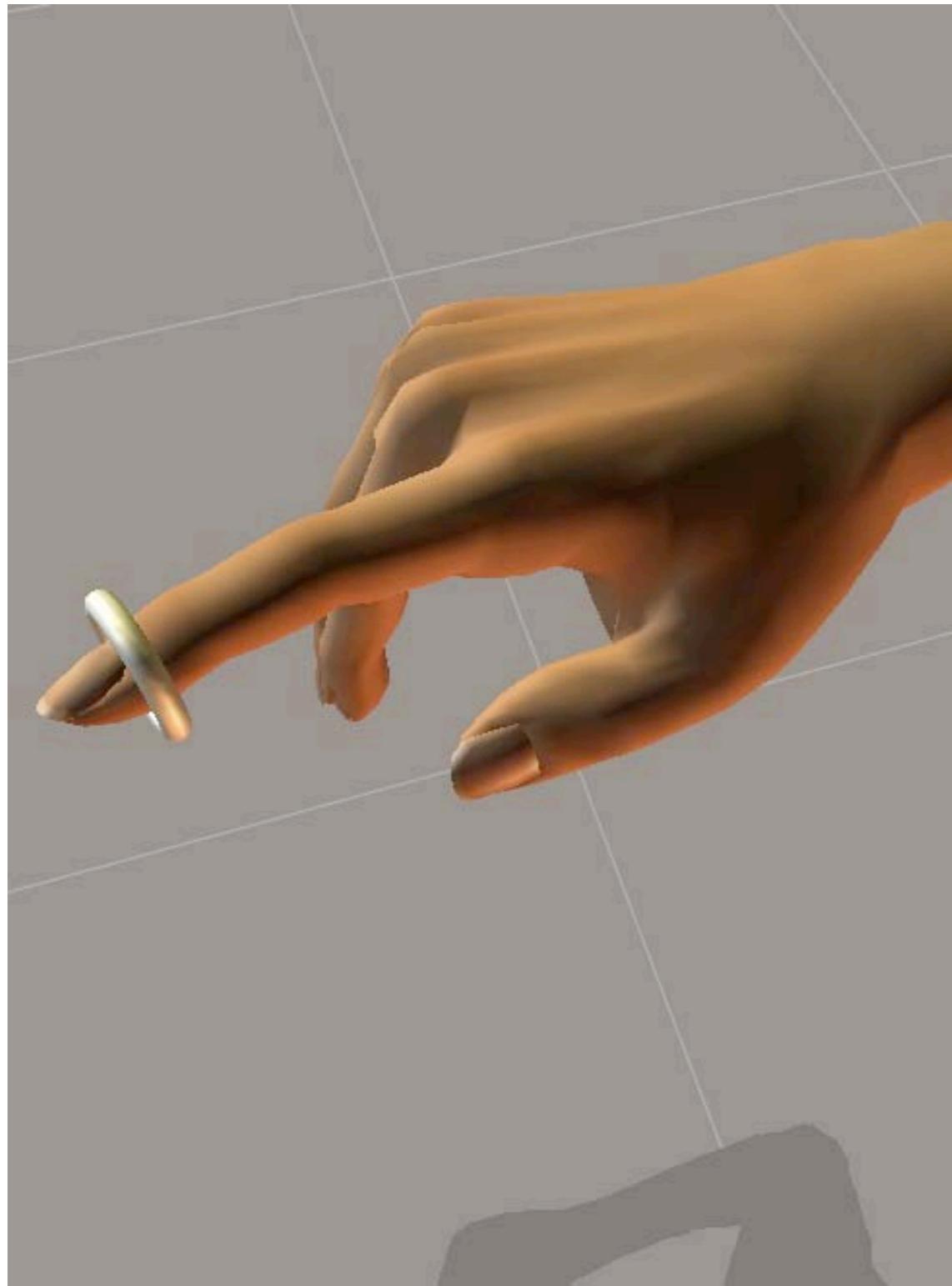
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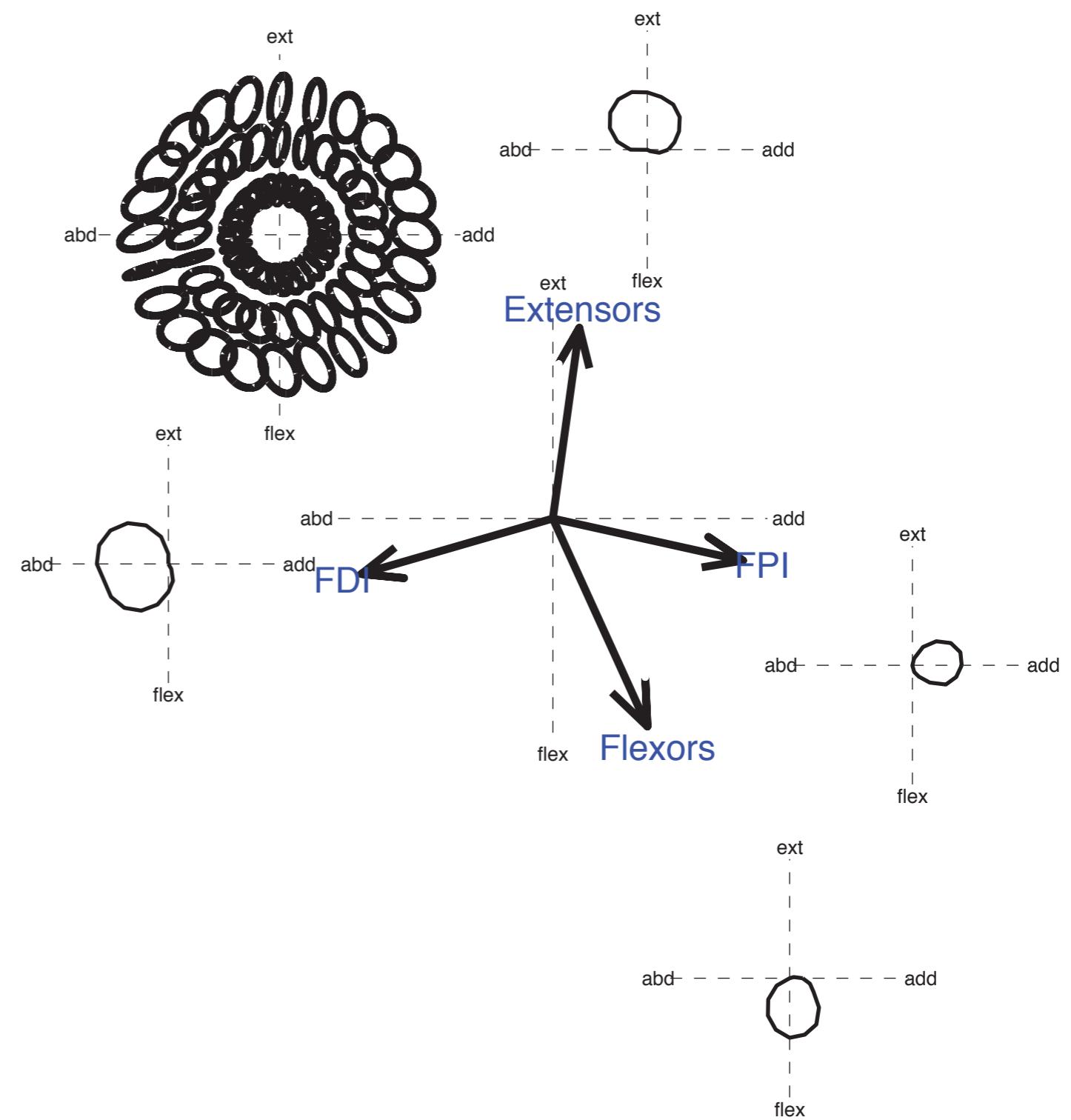
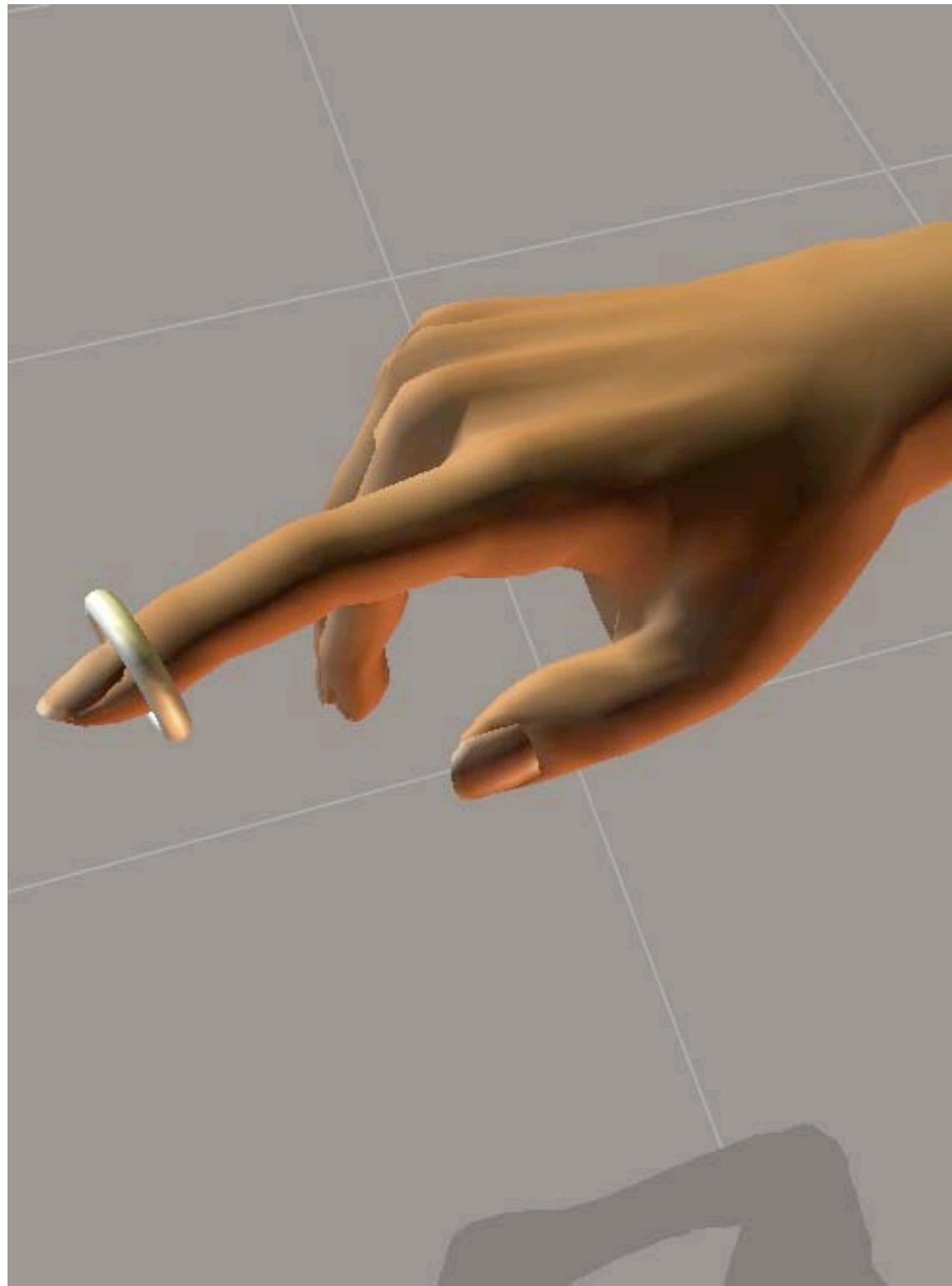
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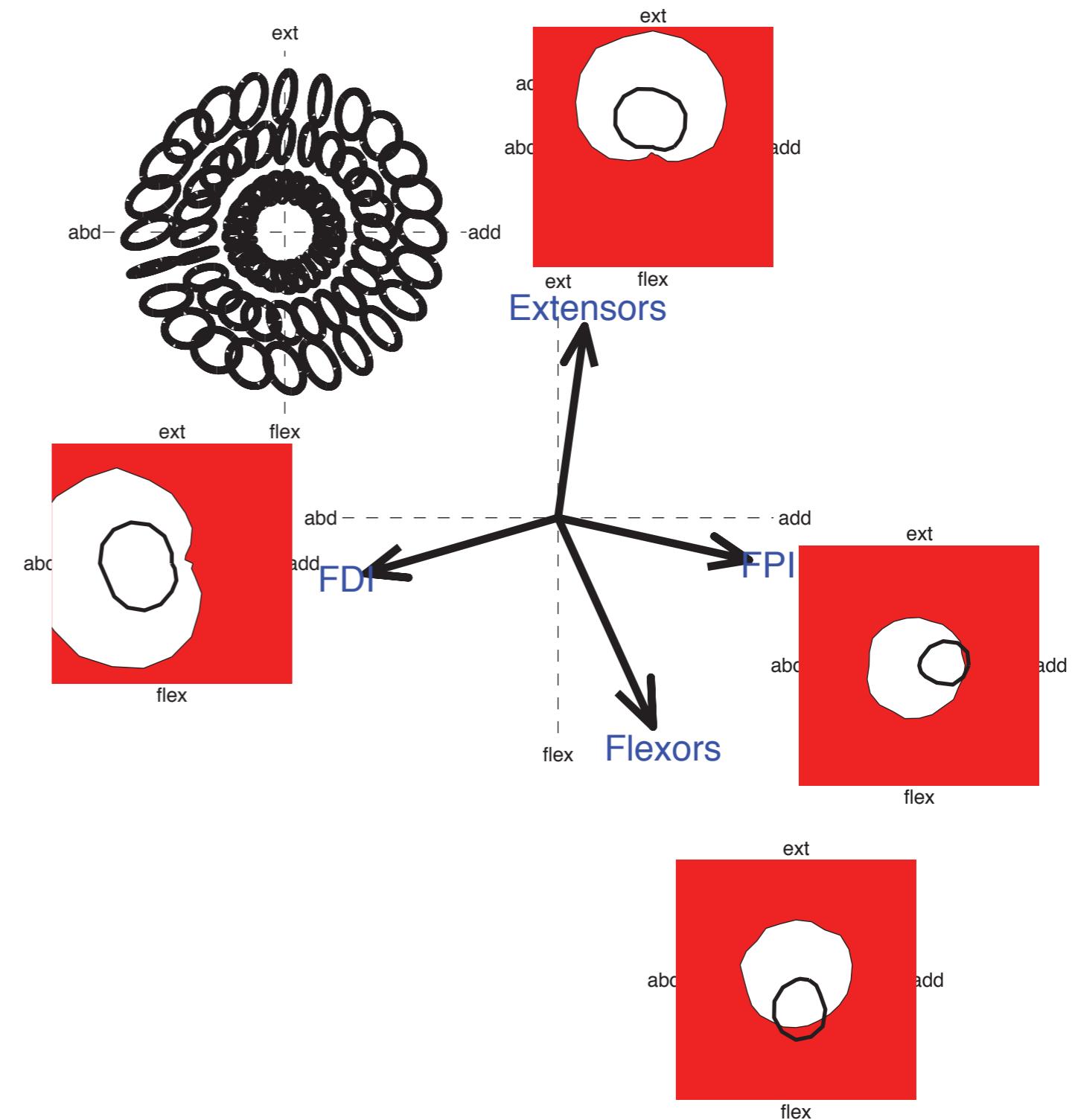
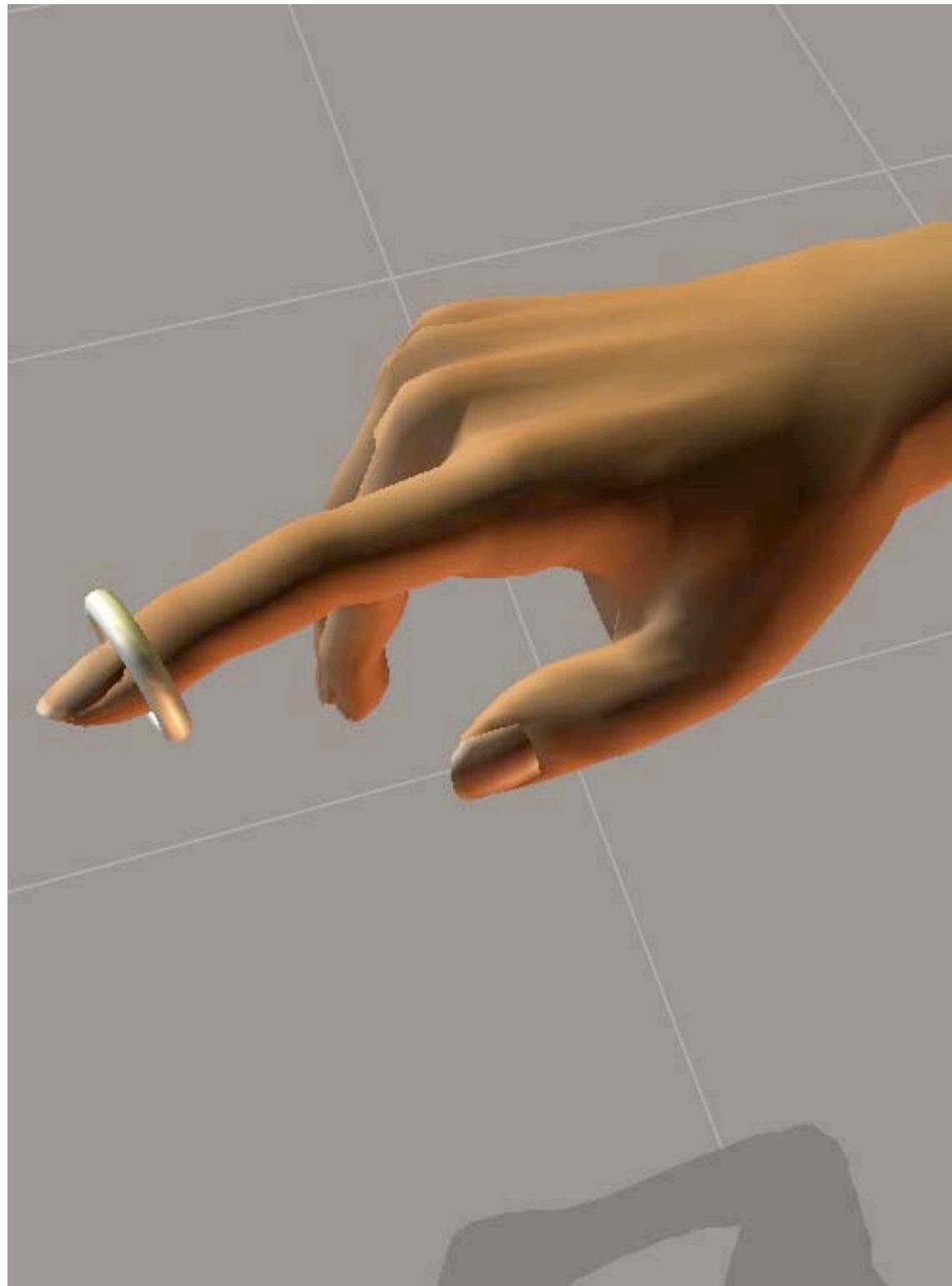
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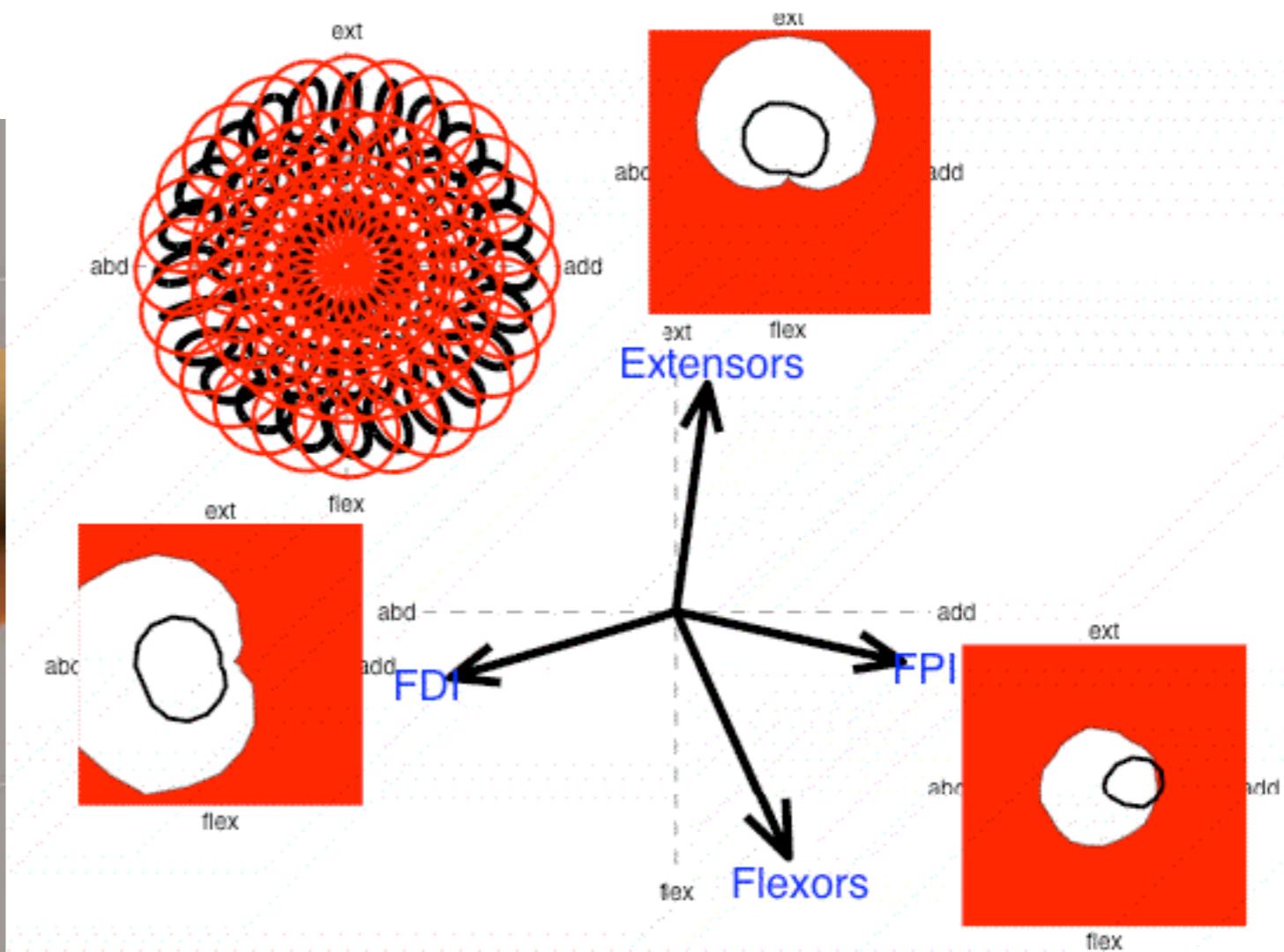
# Towards clinical application



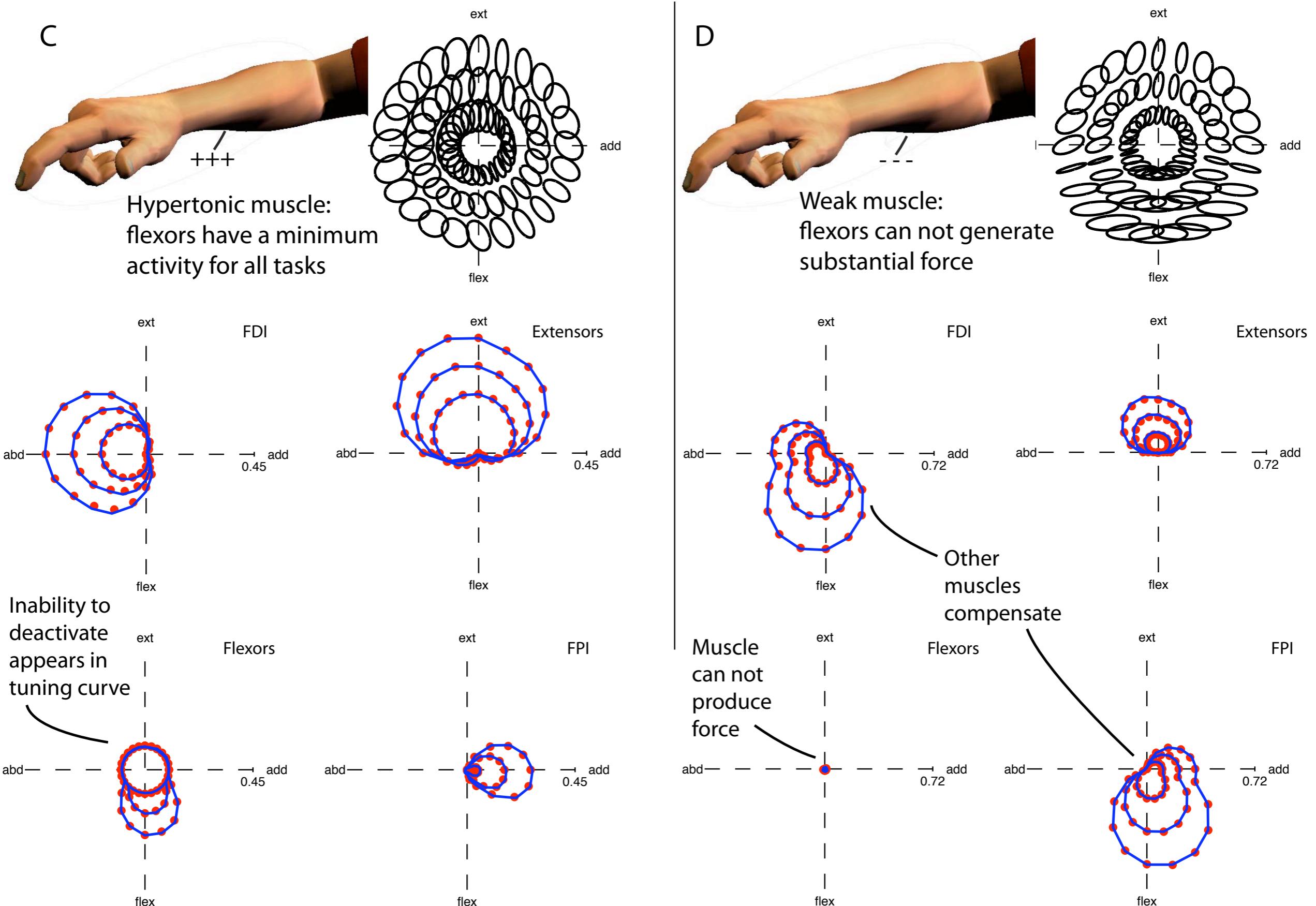
# Towards clinical application



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# Conclusions

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I. Muscle synergies can interfere with good mechanical choices

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2. Noise: “index finger redundancy not resolved muscle synergy”

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## Conclusions

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4. Simple neural network can give minimum effort for all tasks
5. Future: non-invasive study of multiple muscle systems

# Acknowledgments



UNIVERSITY  
OF SOUTHERN  
CALIFORNIA

ANNO 1817

THE UNIVERSITY OF MICHIGAN



# Acknowledgments



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Manish Kurse  
Heiko Hoffmann

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Nina Suresh  
Carol Mottram  
Matthieu Chardon  
Stan Chikando  
Ben Sinder

Hand surgeons:  
Isabella Fassola (USC)  
V. Rod Hentz (Stanford University)  
Caroline Leclercq (L'institut de la Main, Paris)

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Francisco Valero-Cuevas

DMS-0604307 and CMS-0408542  
to Tony Bloch

# Flexible activity noise vs. synergy noise

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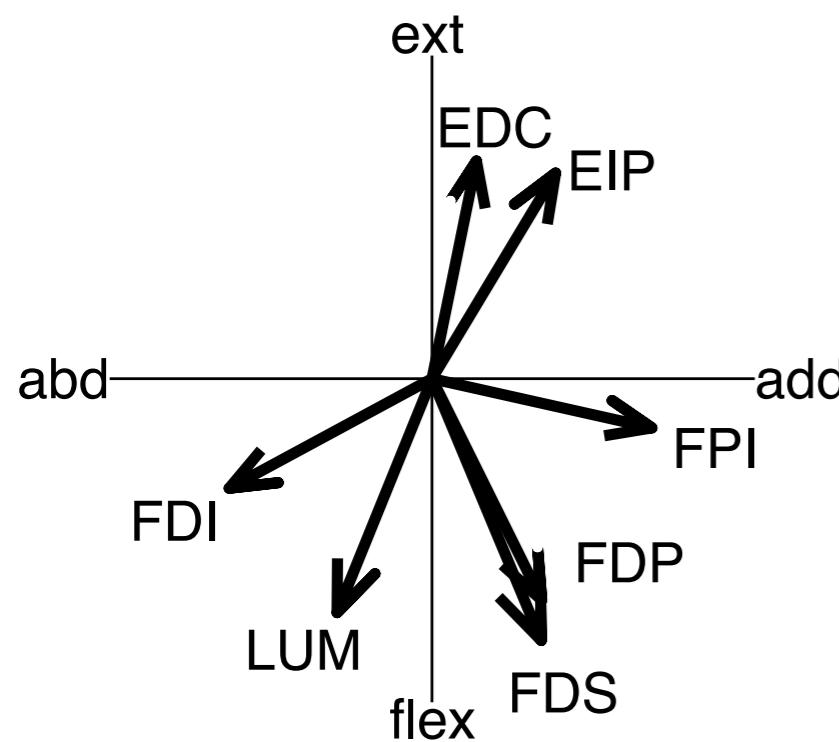
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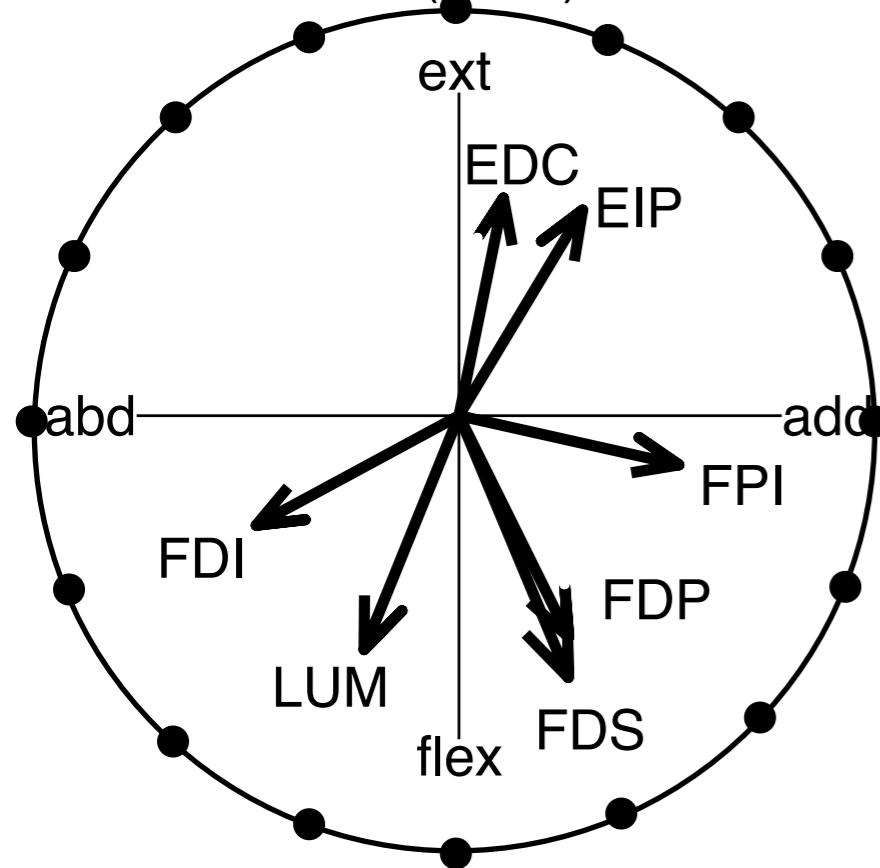
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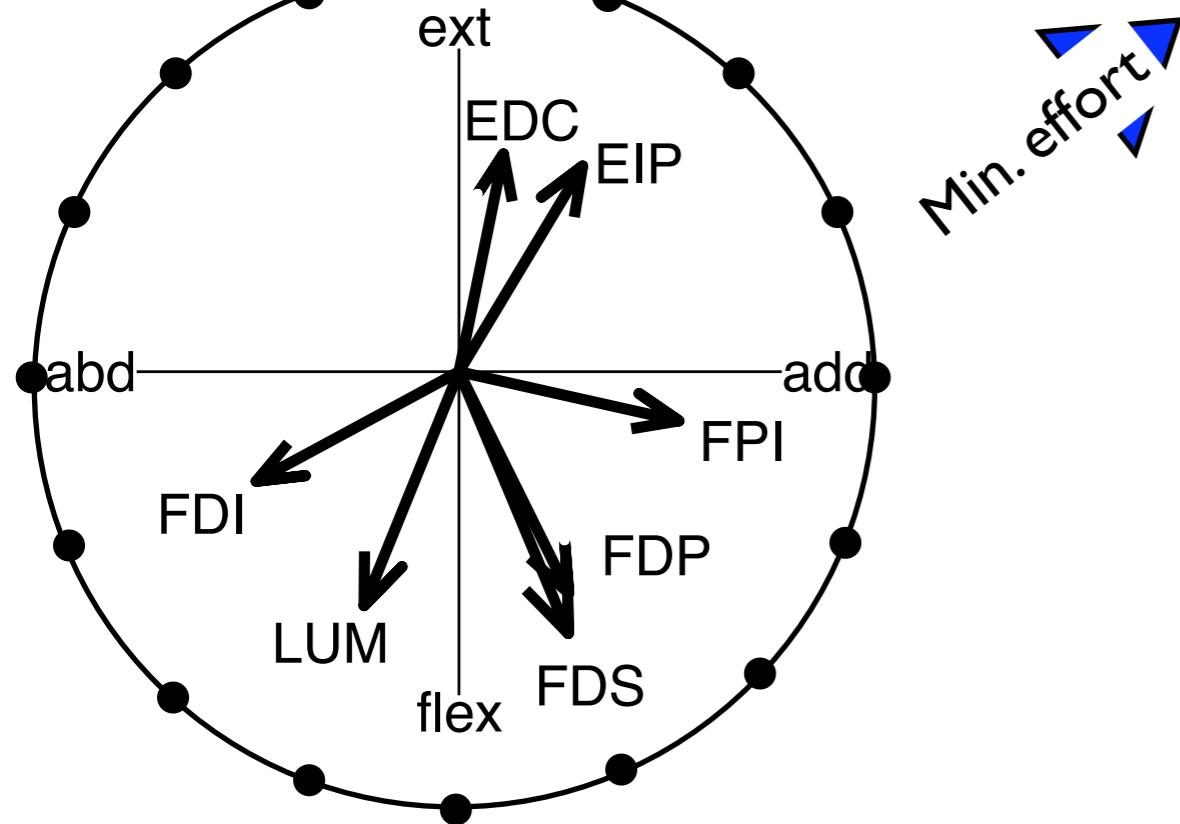
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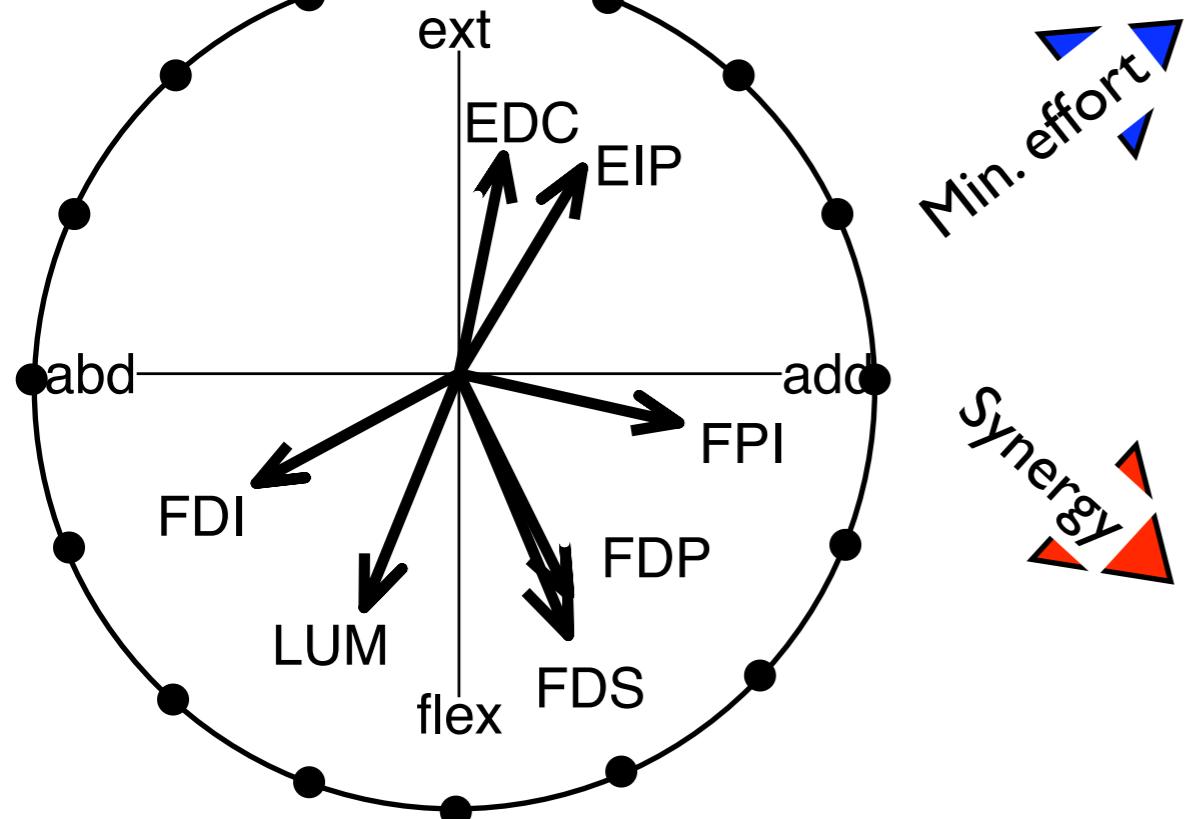
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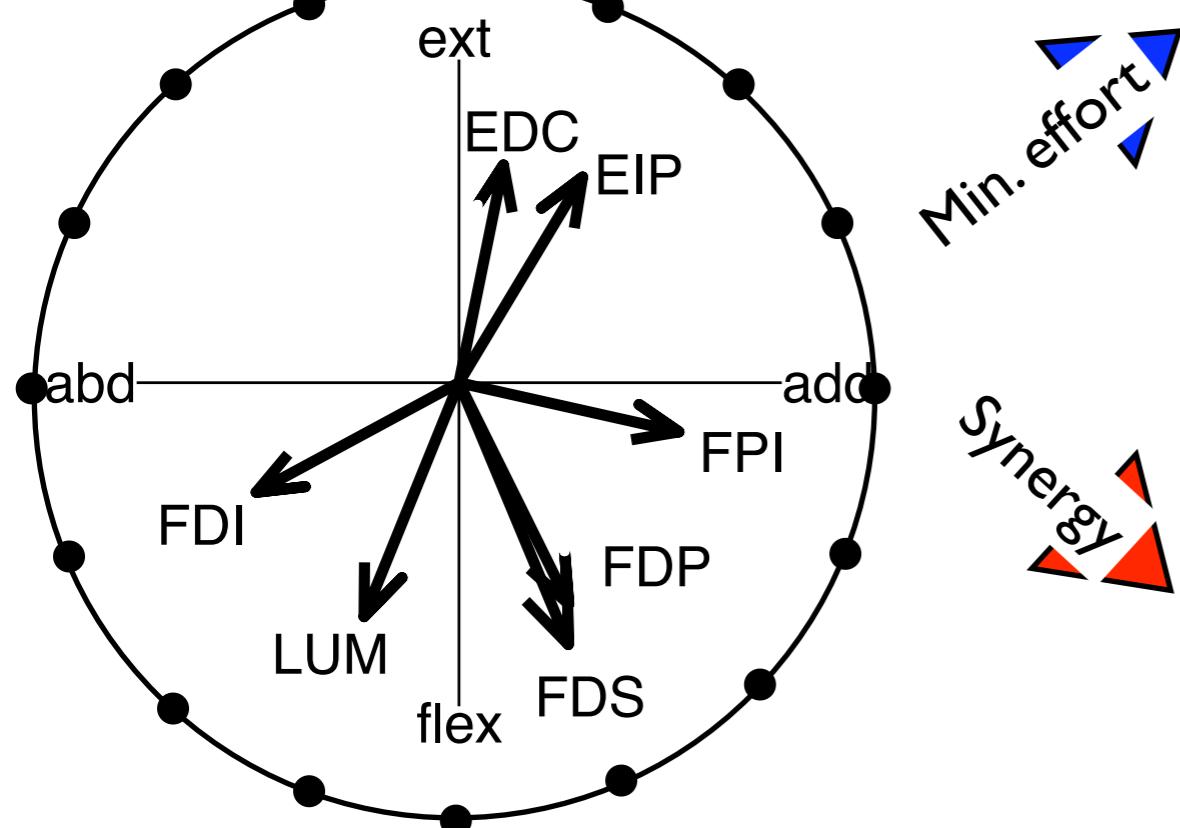
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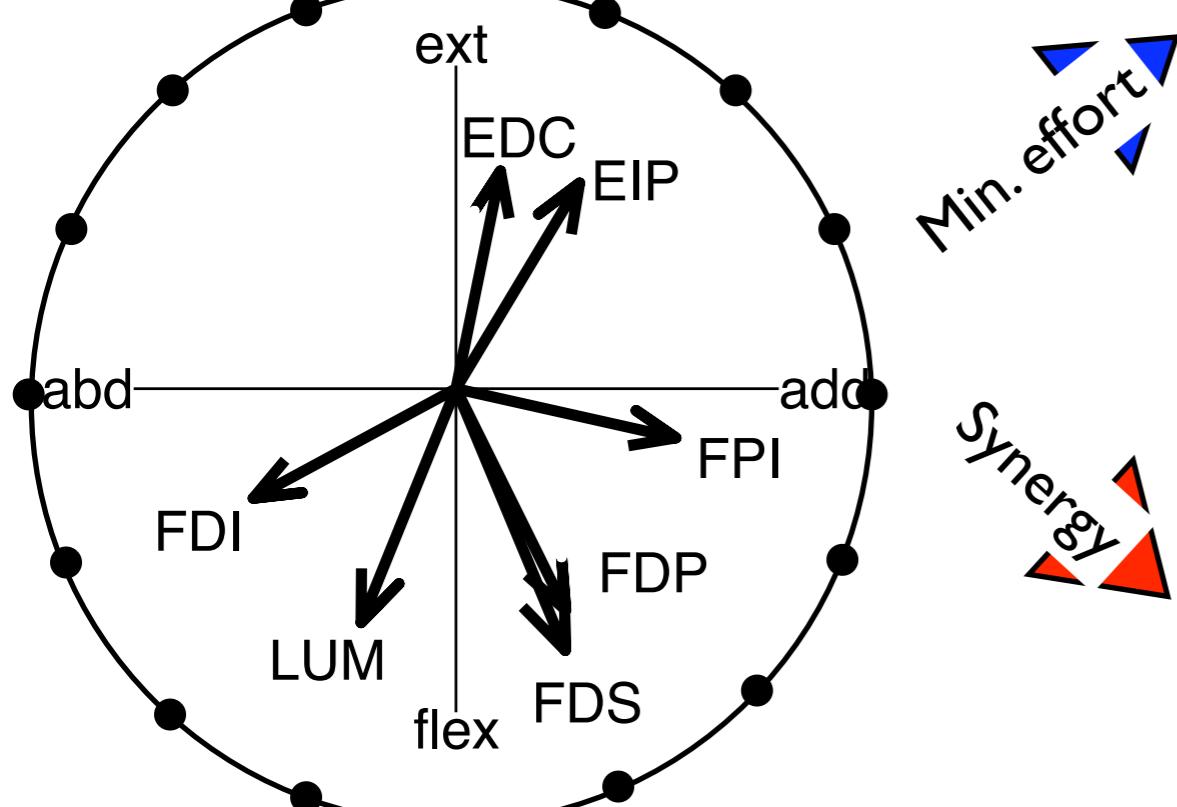
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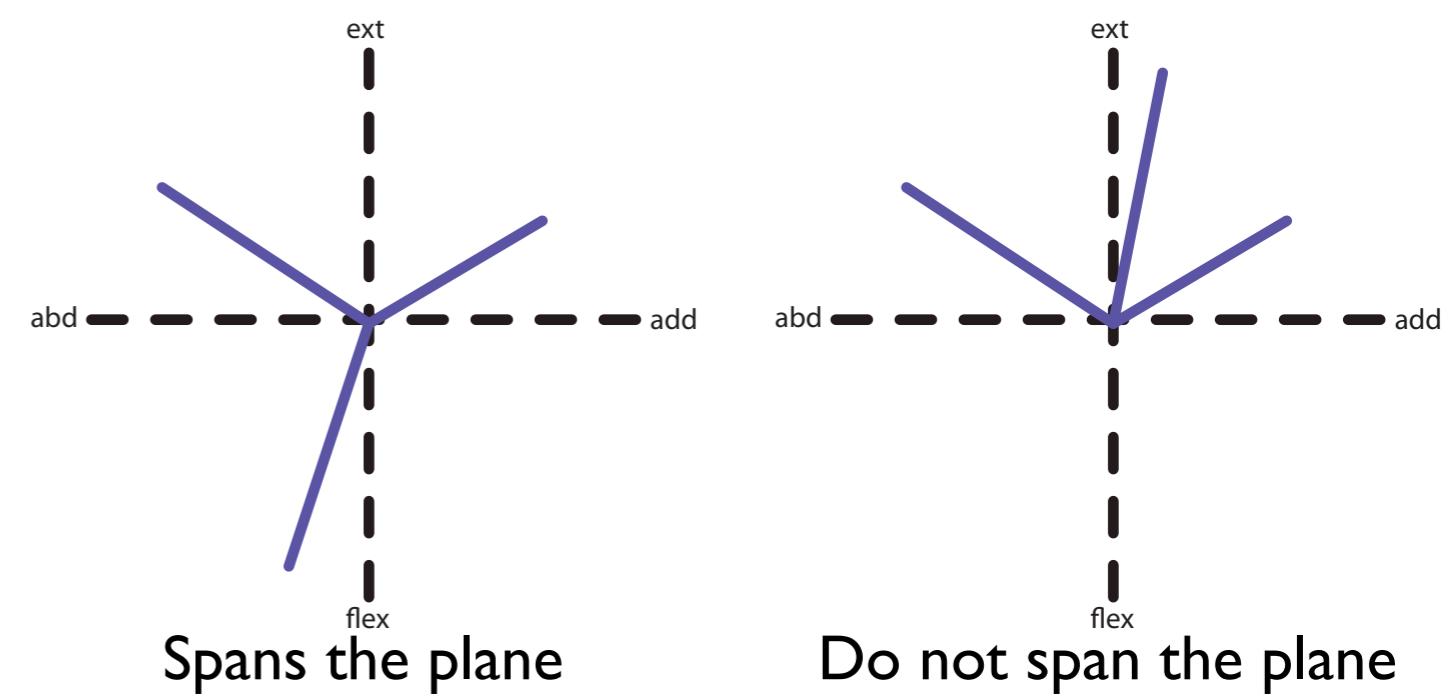
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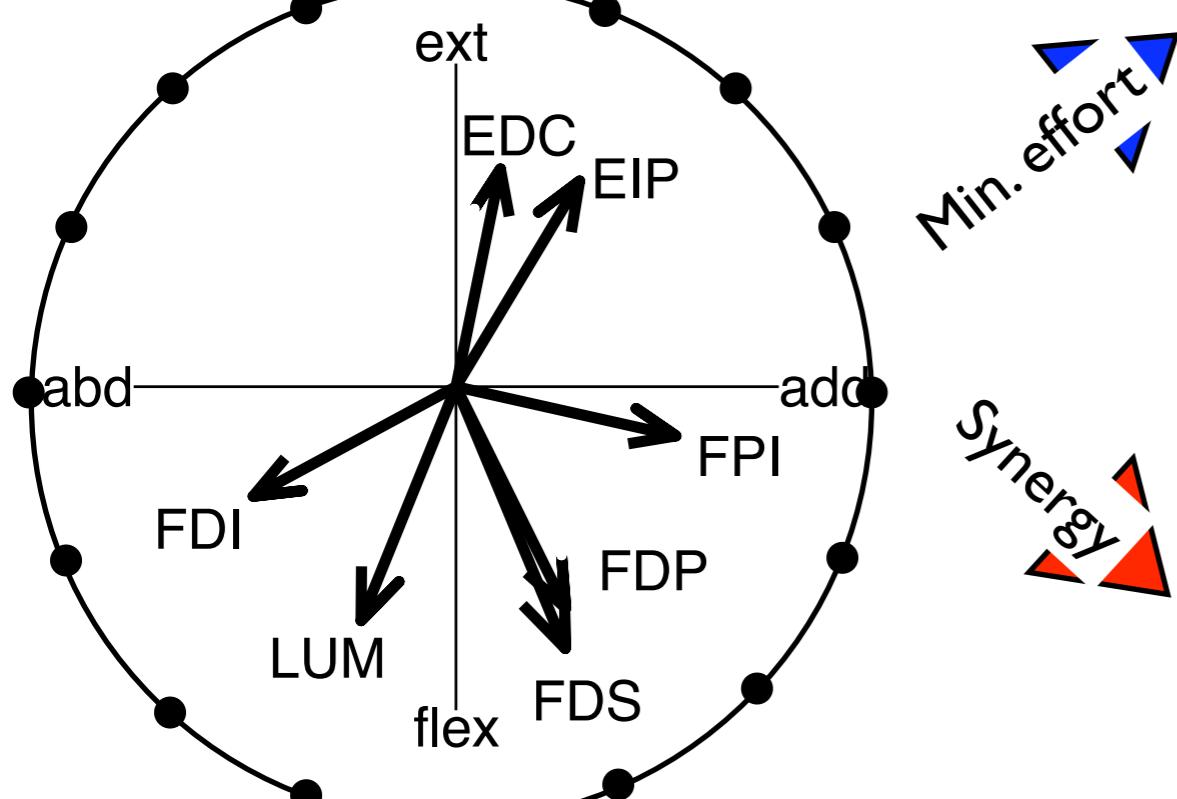
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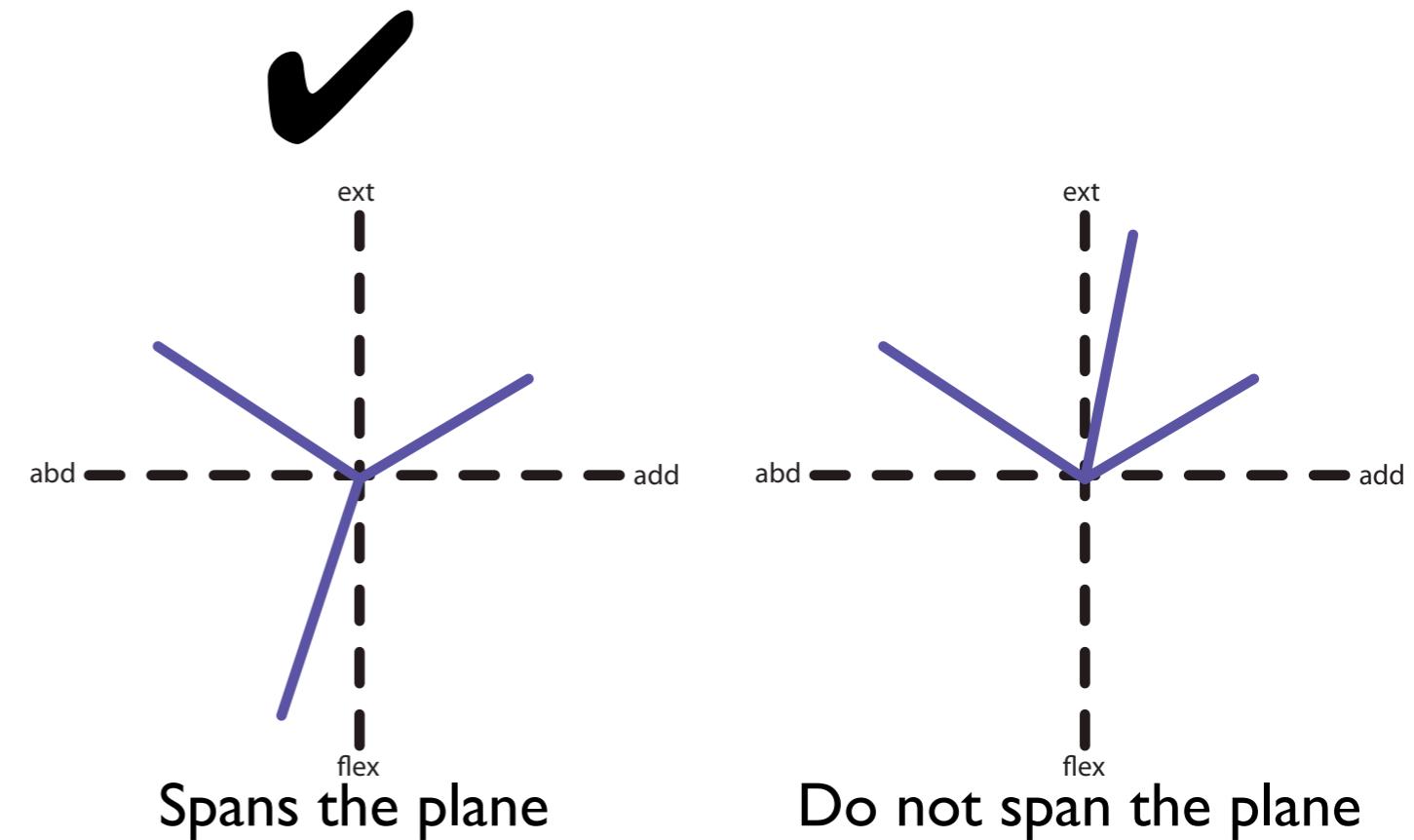
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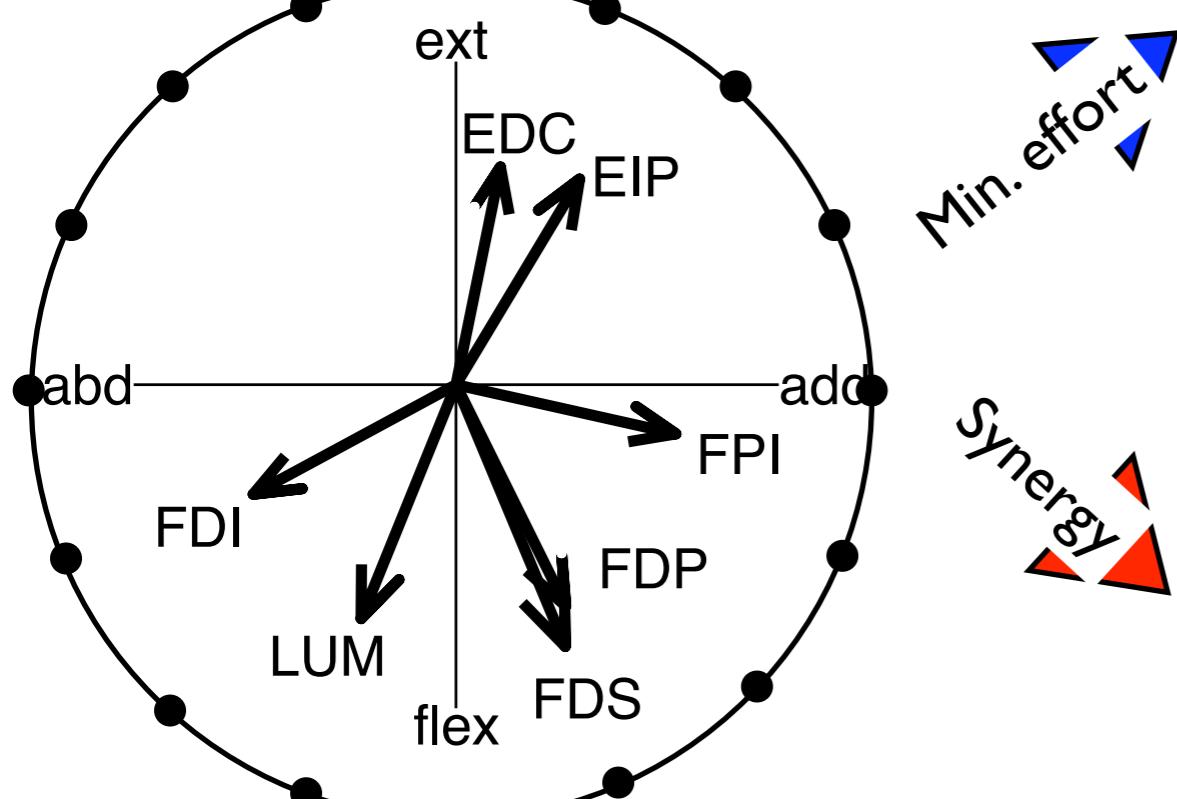
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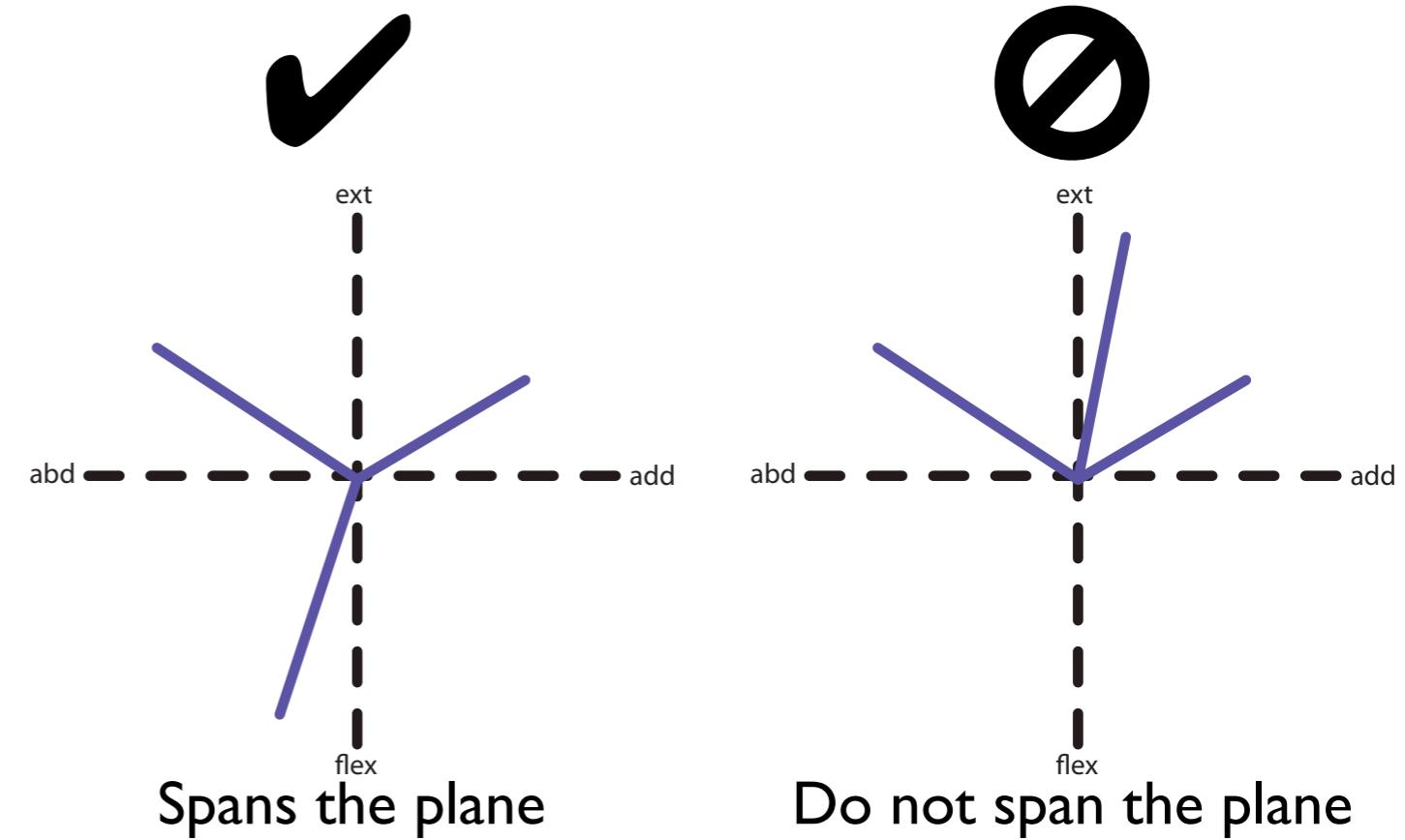
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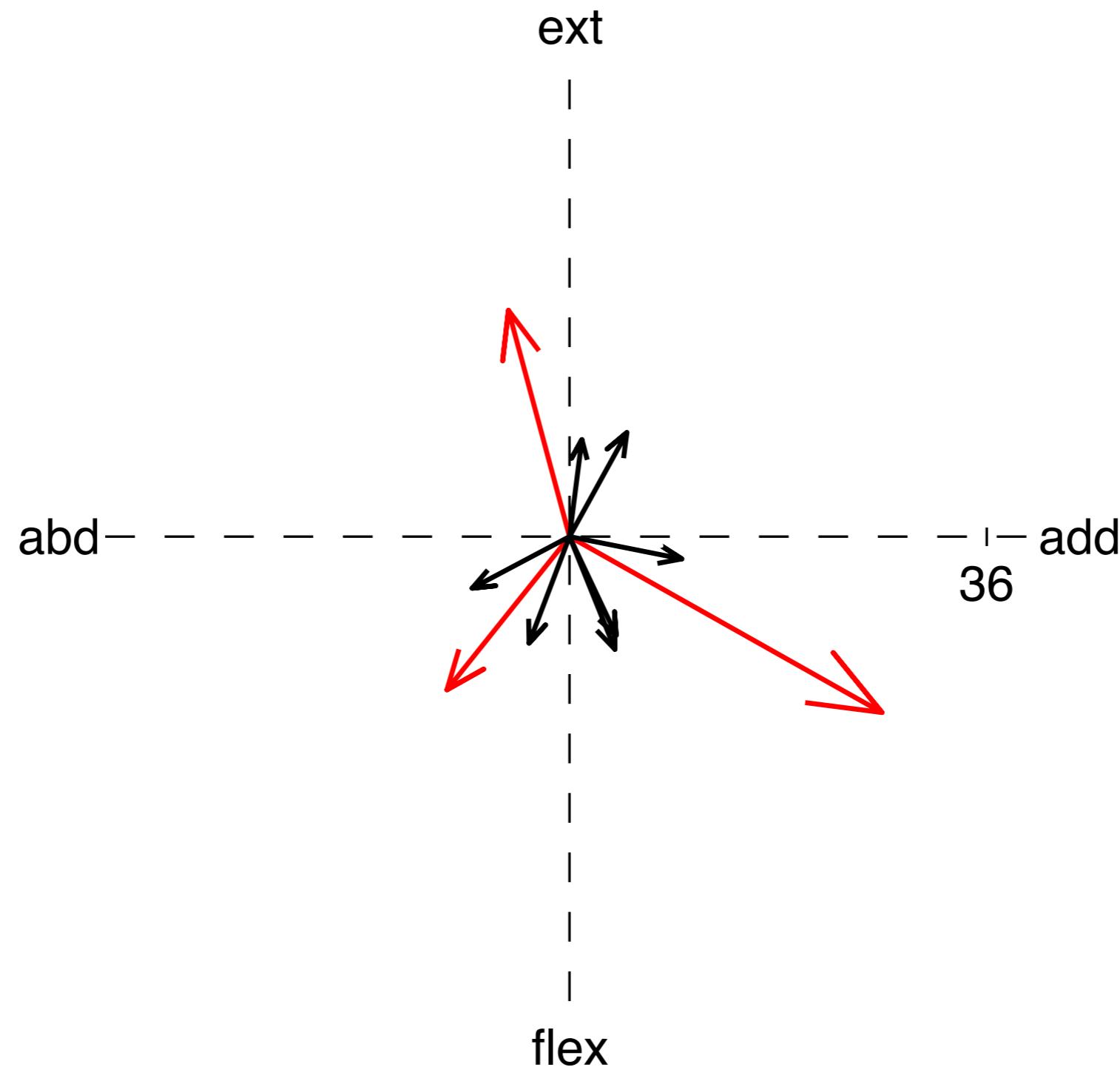
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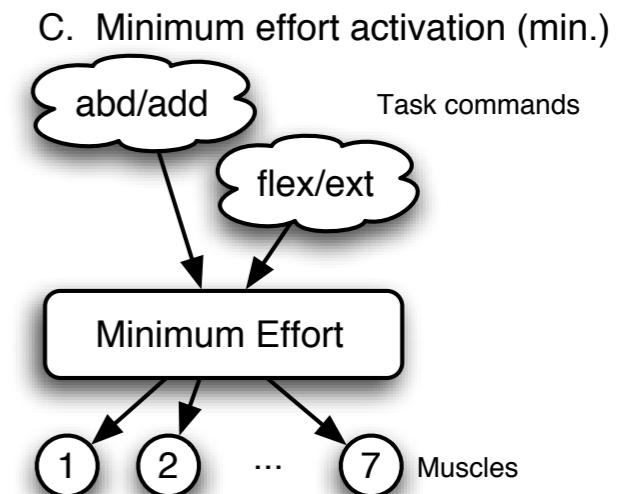
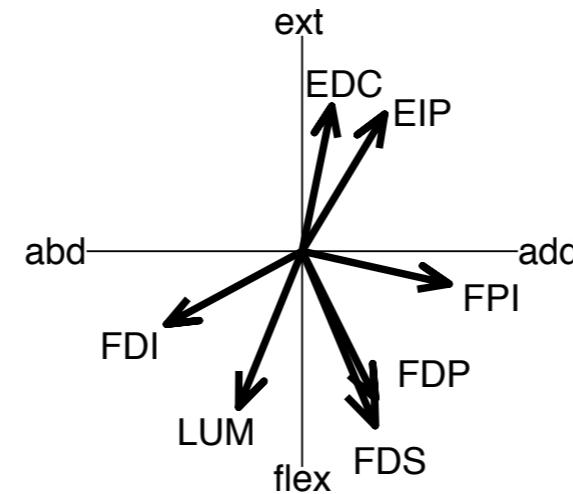
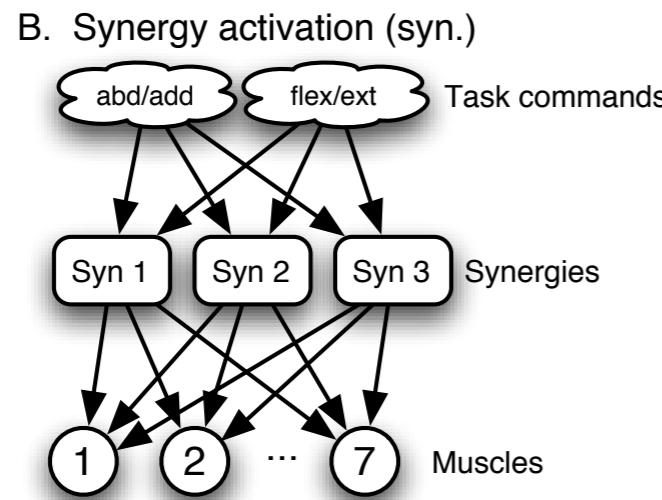


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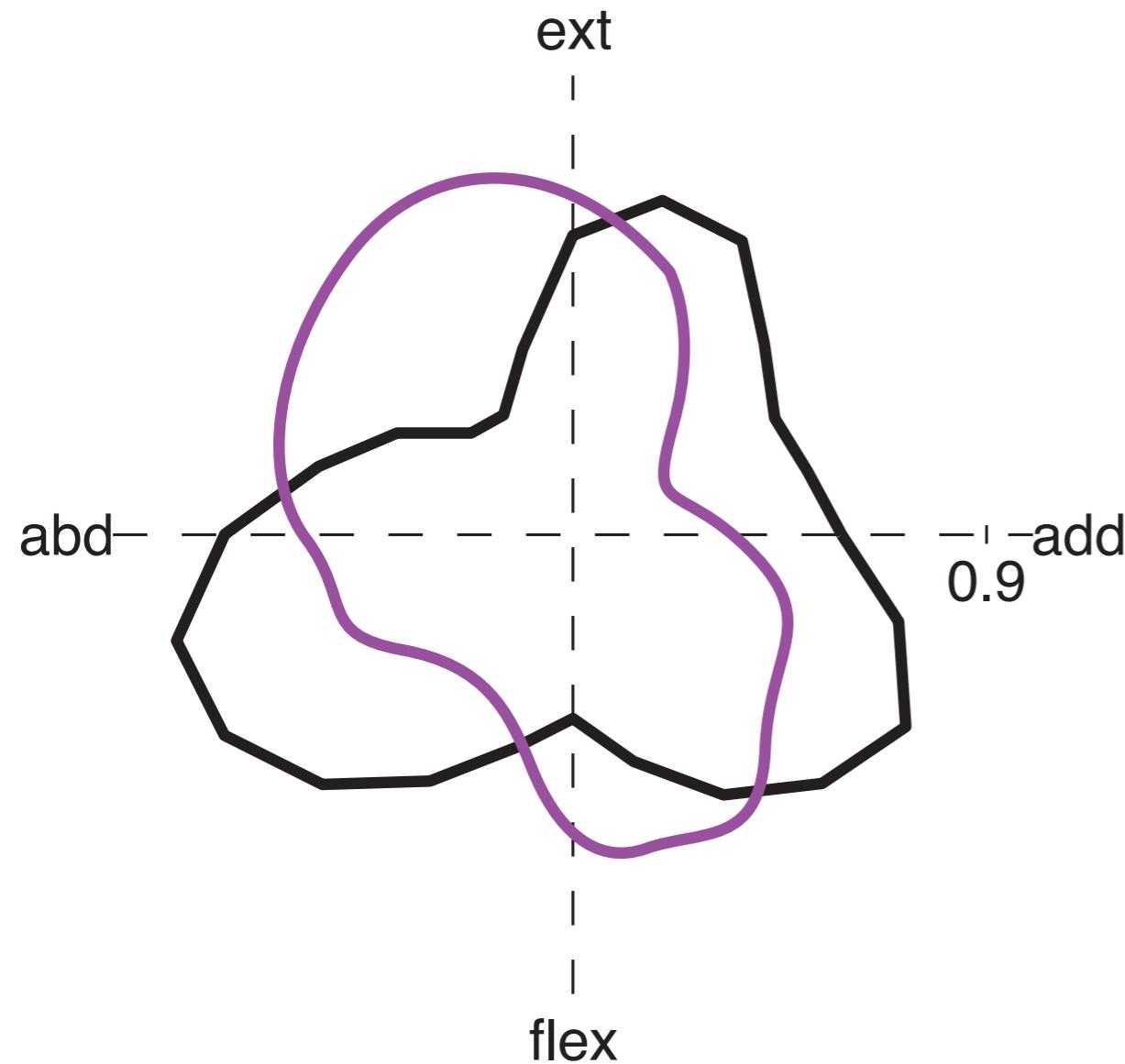
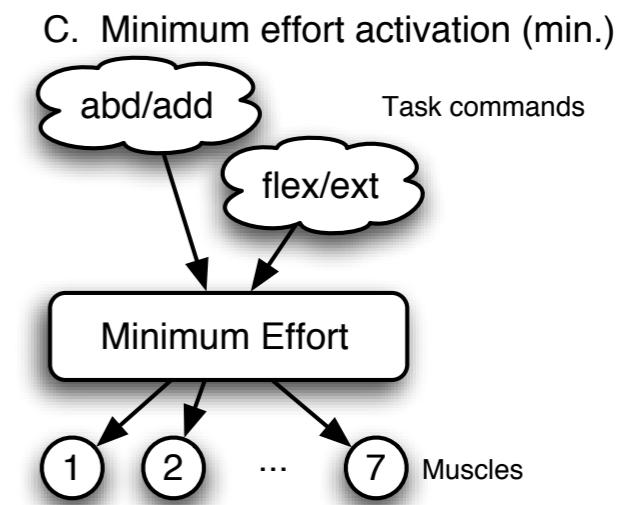
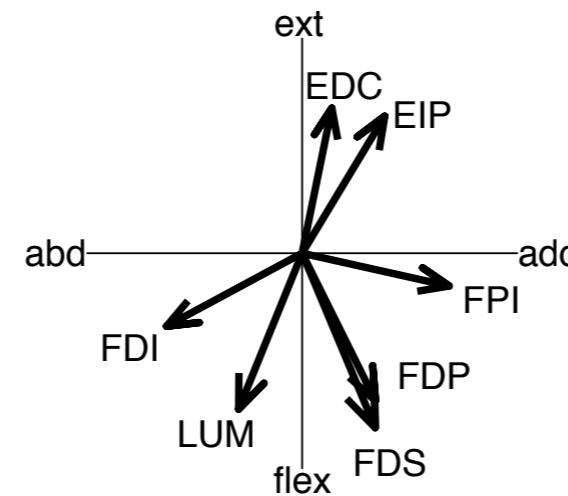
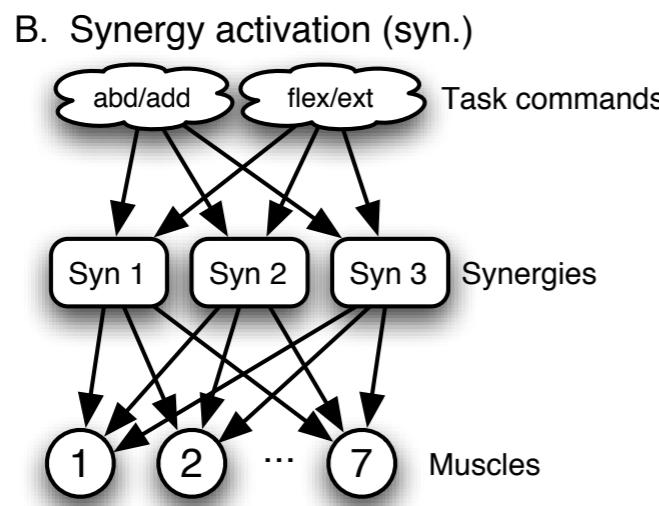
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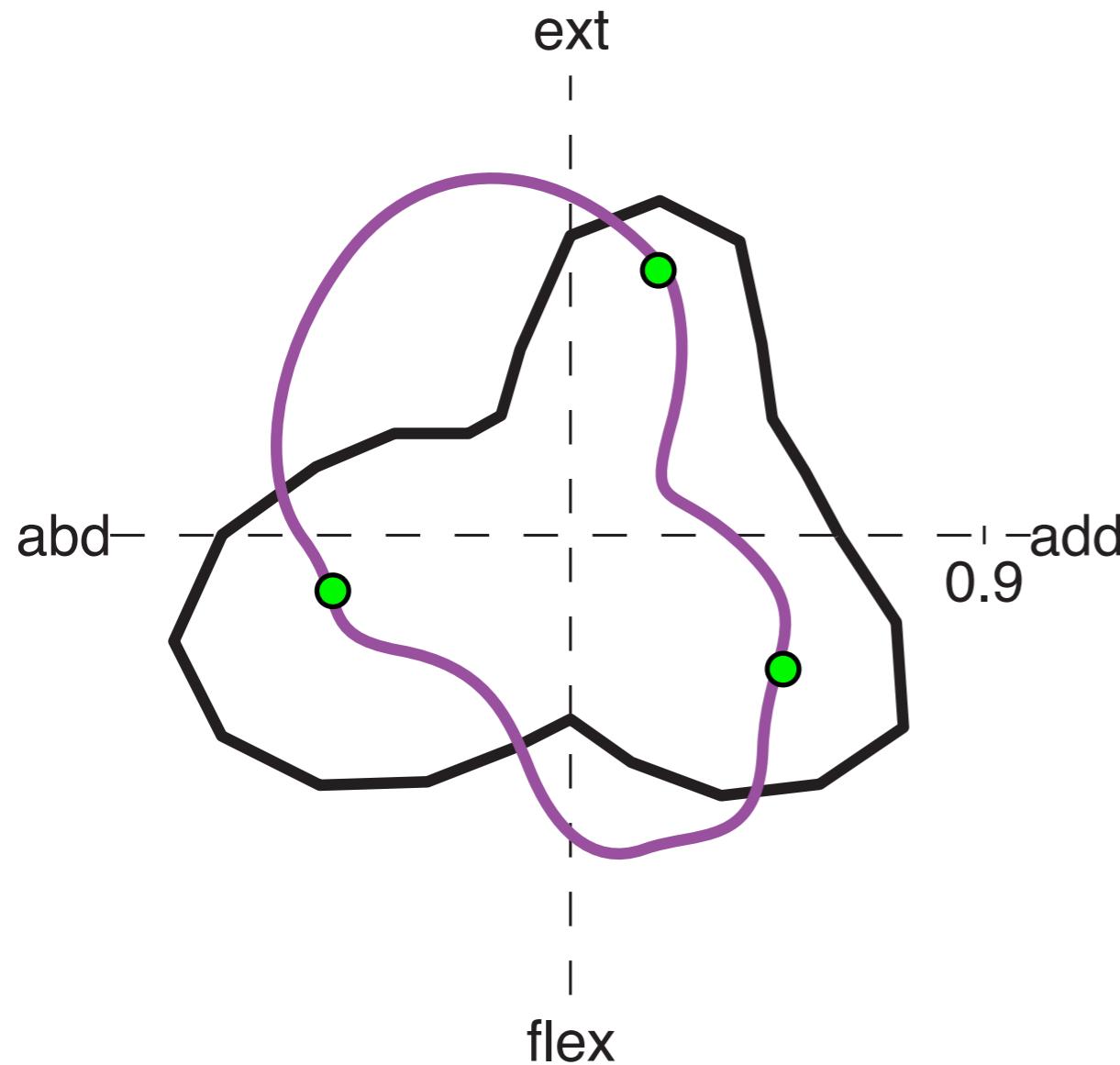
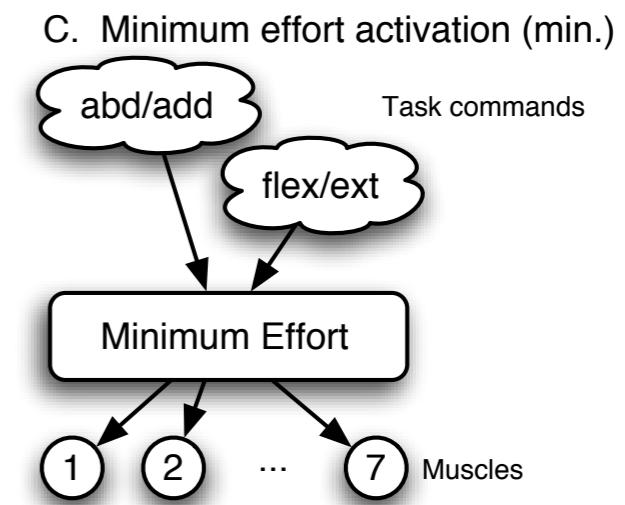
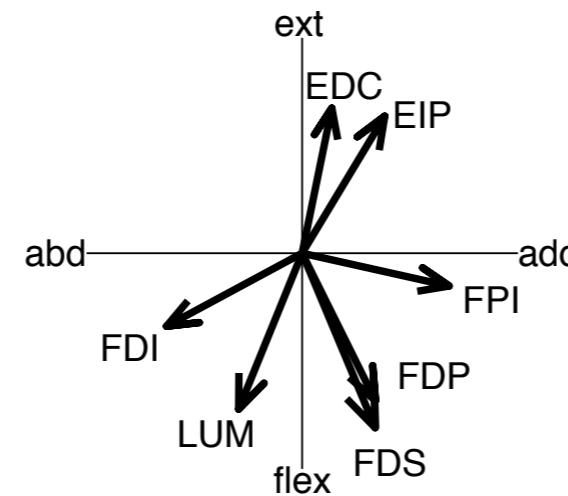
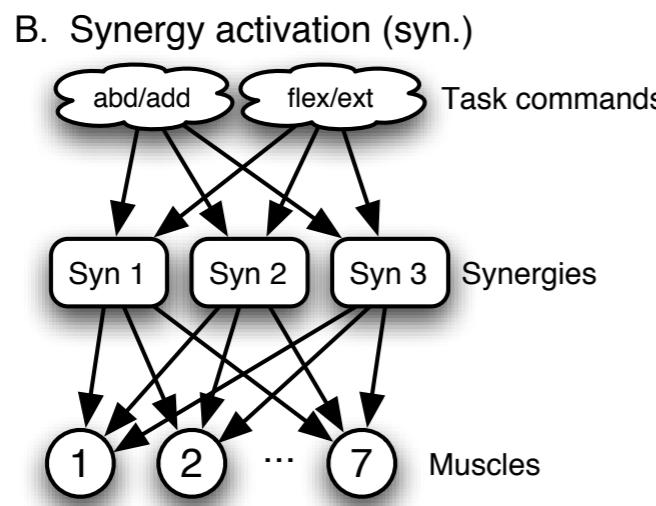
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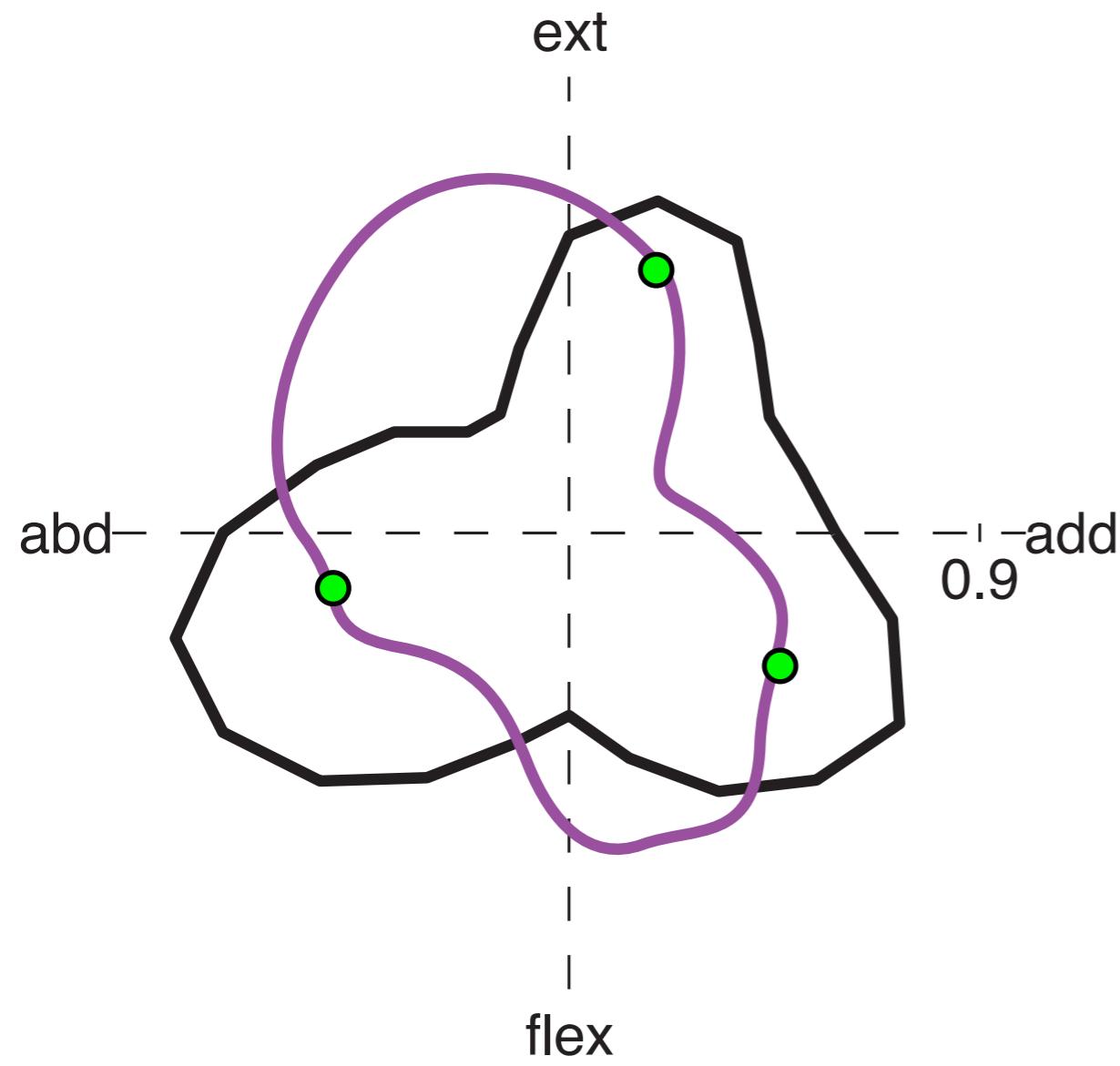
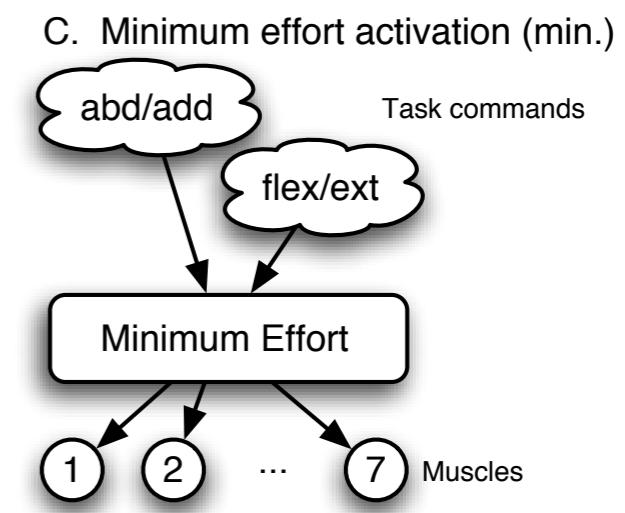
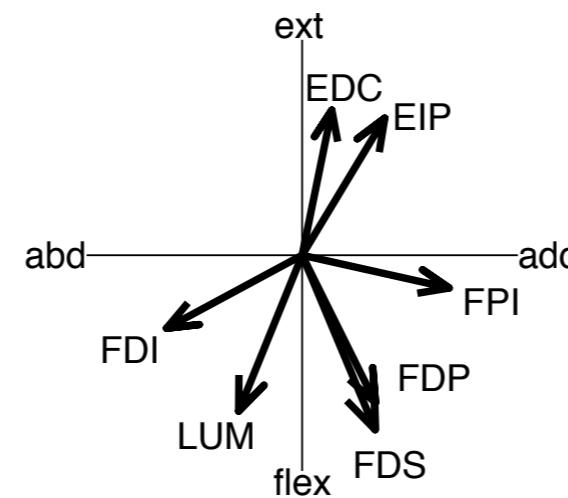
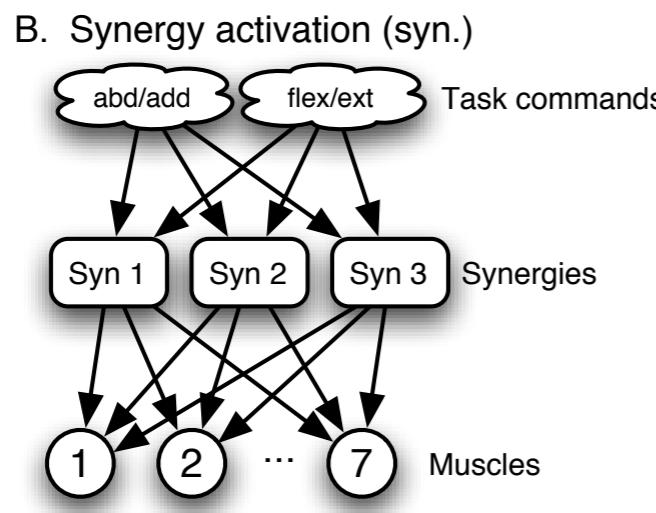
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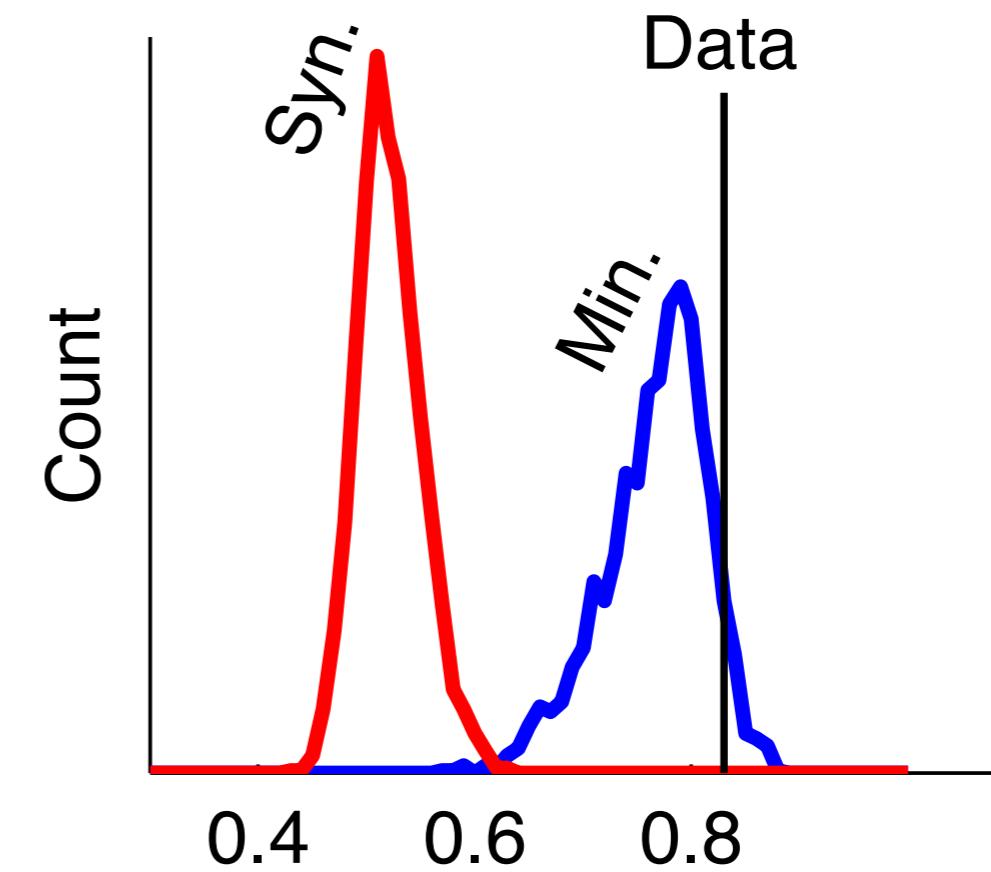


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H. Random search histograms



Average  $\eta$  in peak data directions

C. Dyno-myography estimates muscle tuning curves by only selecting muscle activity combinations consistent with the force covariance ellipse

