Muscle synergies and neuromotor recovery

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Outline

- Why muscle synergies?
- Muscle synergy models and identification
- Evidence for muscle synergies
- How are muscle synergies affected by neurological lesion?
- Potential applications to neurorehabilitation

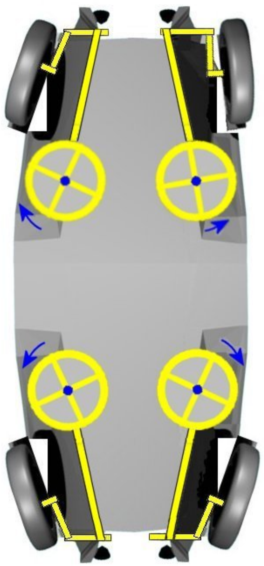
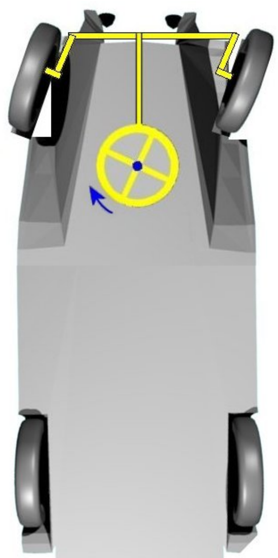
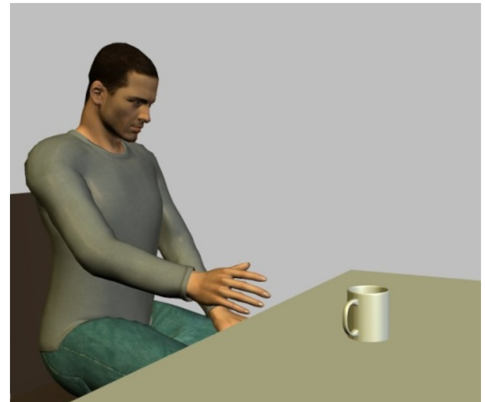
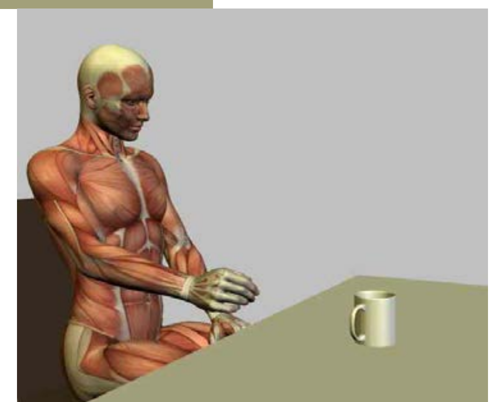
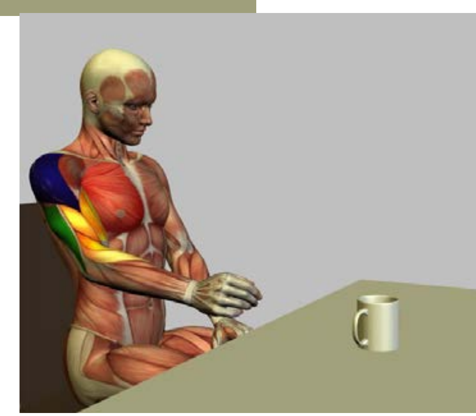
http://www.youtube.com/watch?v=pSMq_P-4wXw

http://www.shadowrobot.com/
http://www.youtube.com/watch?v=_k5iQfjM1DI

http://www.youtube.com/watch?v=Dk3dsLJOPxQ

Motor control challenges

- Dimensionality
  - Many joints and muscles (complex dynamics of a redundant musculoskeletal system)
- Versatility
  - Many different motor skills
- Optimality
  - Motor task performance with minimal effort and/or error

Hypothesis: synergies simplify control

- Control can be simplified by grouping muscles into functional units (muscle synergies) and using them as <u>building blocks</u>
- A goal can be achieved by selecting a <u>small number</u> of synergy-specific <u>control signals</u>
- Synergies incorporate <u>a priori knowledge</u> of the musculoskeletal system and of the task that
  - can be reused across task conditions
  - allow to find quickly and efficiently adequate but possibly suboptimal solutions

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Viewpoints on muscle synergies

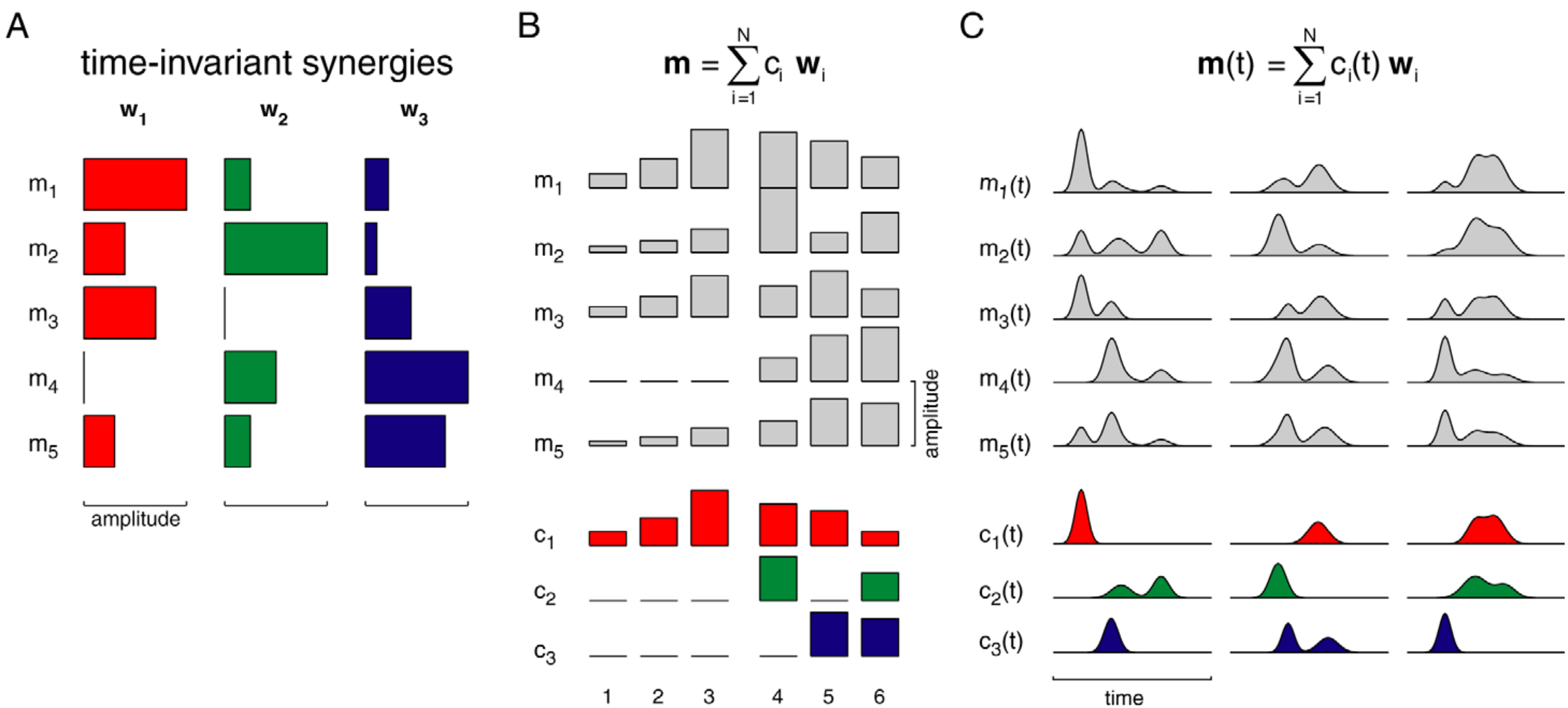
- *Neuroscience*: coordination of muscle recruitment by the central nervous system to simplify control (reduction of DoF -> positive!)

- *Neuro-rehabilitation*: stereotyped muscle activation patterns due to loss of independent control (abnormal coupling -> negative!)

Muscle synergies models

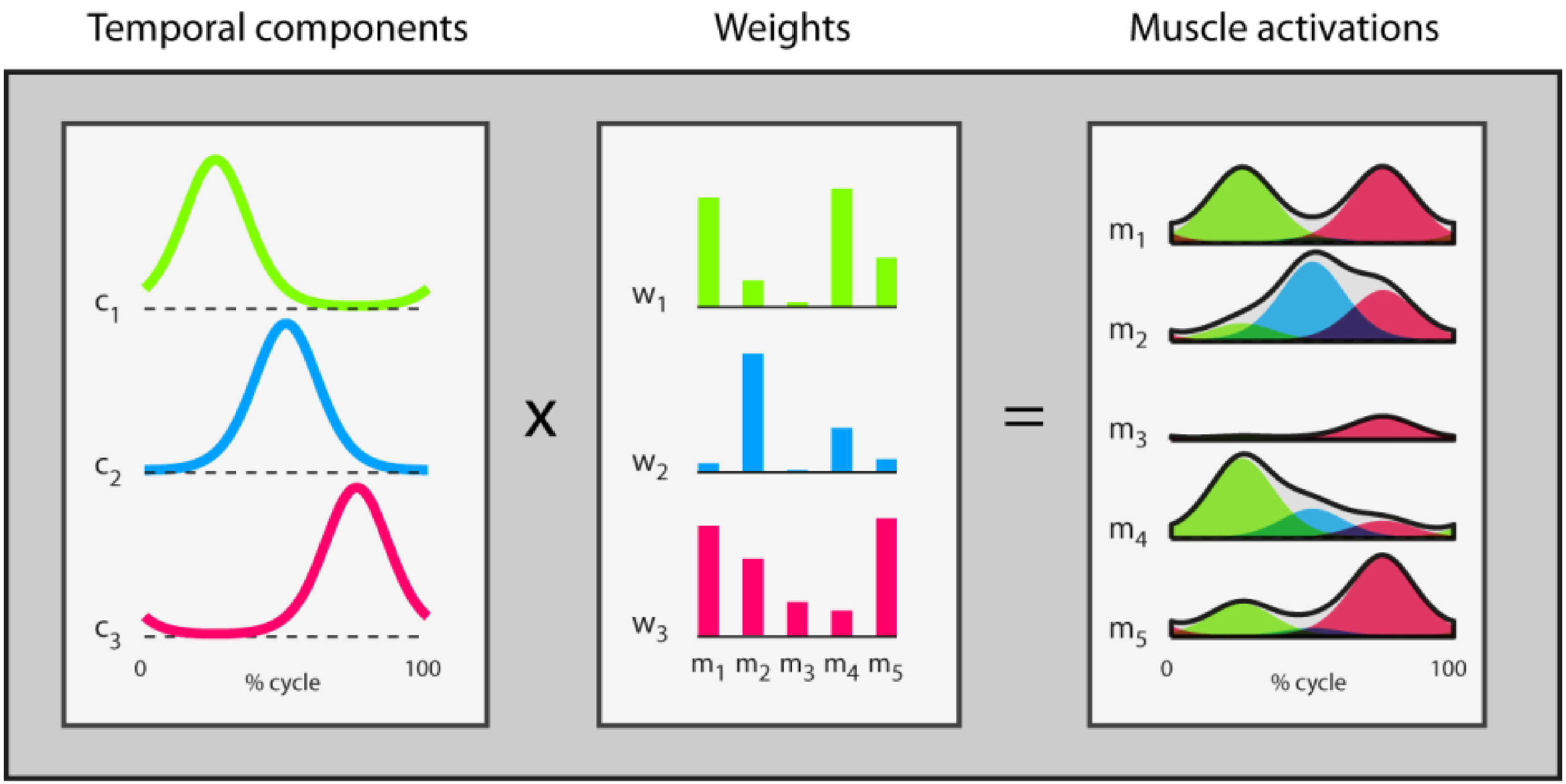
- Muscle synergy = coordinated recruitment of a group of muscles with
  - a balance of muscle activation that does not change over time (<u>time-invariant</u> synergies)
  - an activation waveform shared across muscles (invariant <u>temporal components</u>)
  - a collection of different activation waveforms for different muscles (<u>time-varying</u> synergies)

Time-invariant muscle synergies



Time-invariant synergies capture spatial regularities in the motor output

Temporal components



$$\mathbf{m}(t) = \sum_{i=1}^{N} c_i(t)\,\mathbf{w}_i$$

Temporal components capture temporal regularities in the motor output

Temporal components vs. synergies

- Invariance across task conditions (k = 1…K)

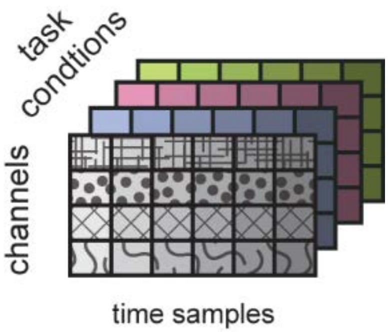
$$\mathbf{m}^{k}(t) = \sum_{i=1}^{N} c_i^{k}(t)\,\mathbf{w}_i$$

$$\mathbf{m}^{k}(t) = \sum_{i=1}^{N} c_i(t)\,\mathbf{w}_i^{k}$$

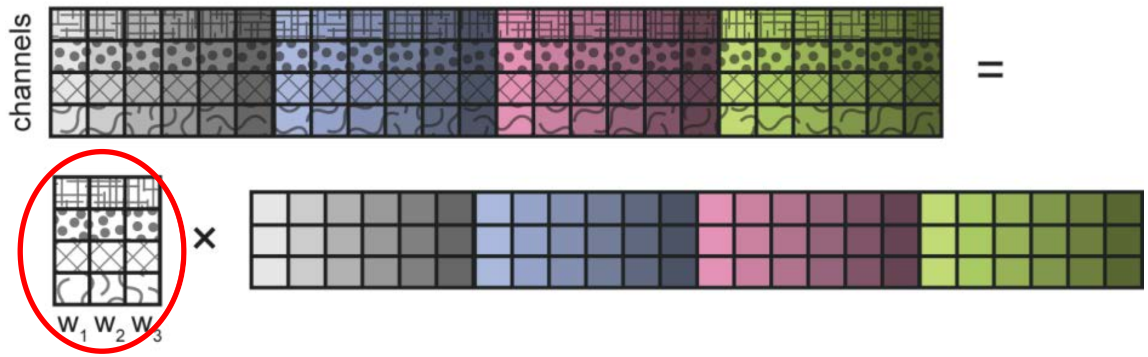
<u>synergies</u> ($\mathbf{w}_i$)
invariant
across
conditions

<u>temporal components</u> ($\mathbf{c}_i$)
shared across
conditions

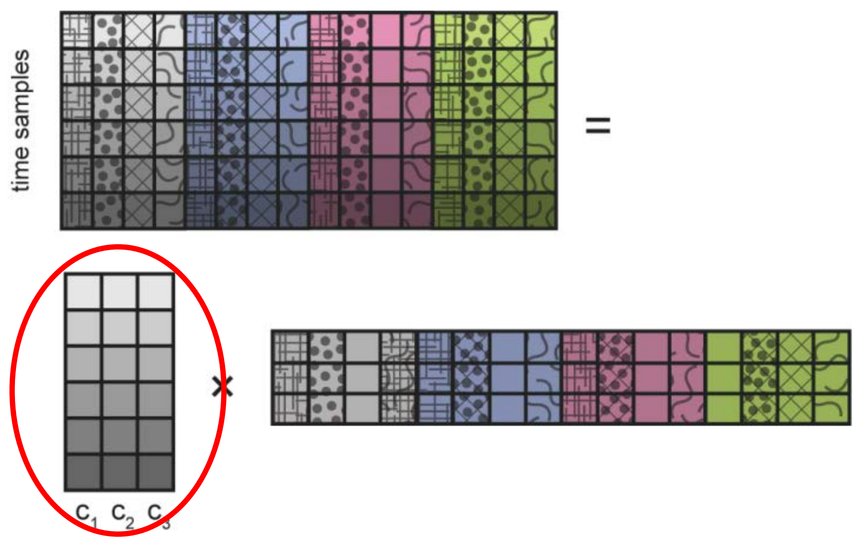
EMG DATA



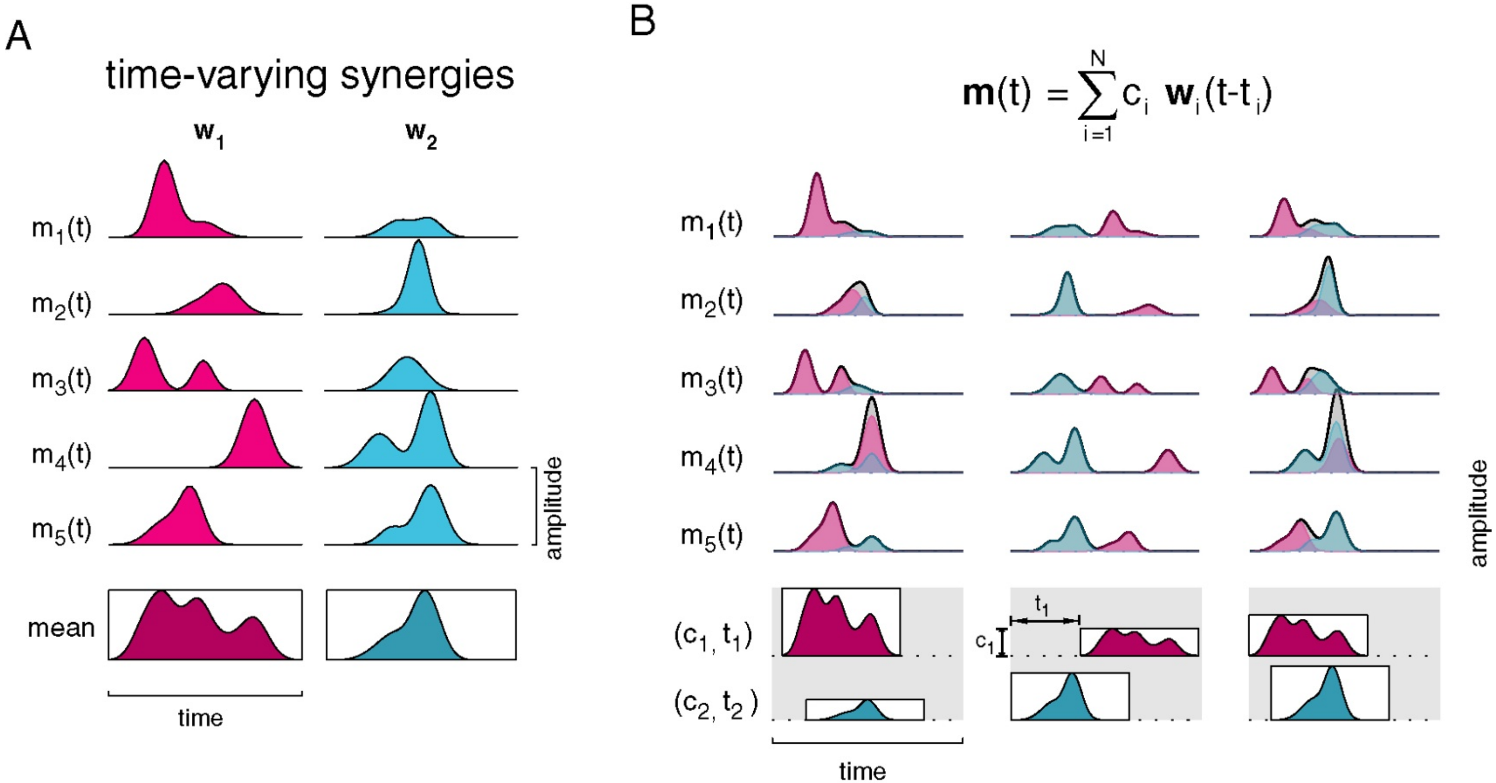
TIME-INVARIANT SYNERGIES



TEMPORAL COMPONENTS



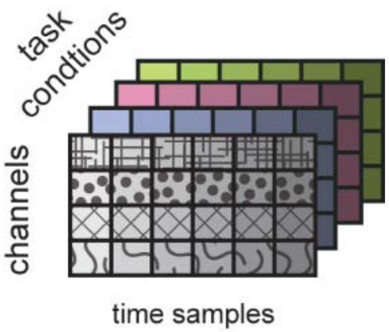
Time-varying muscle synergies

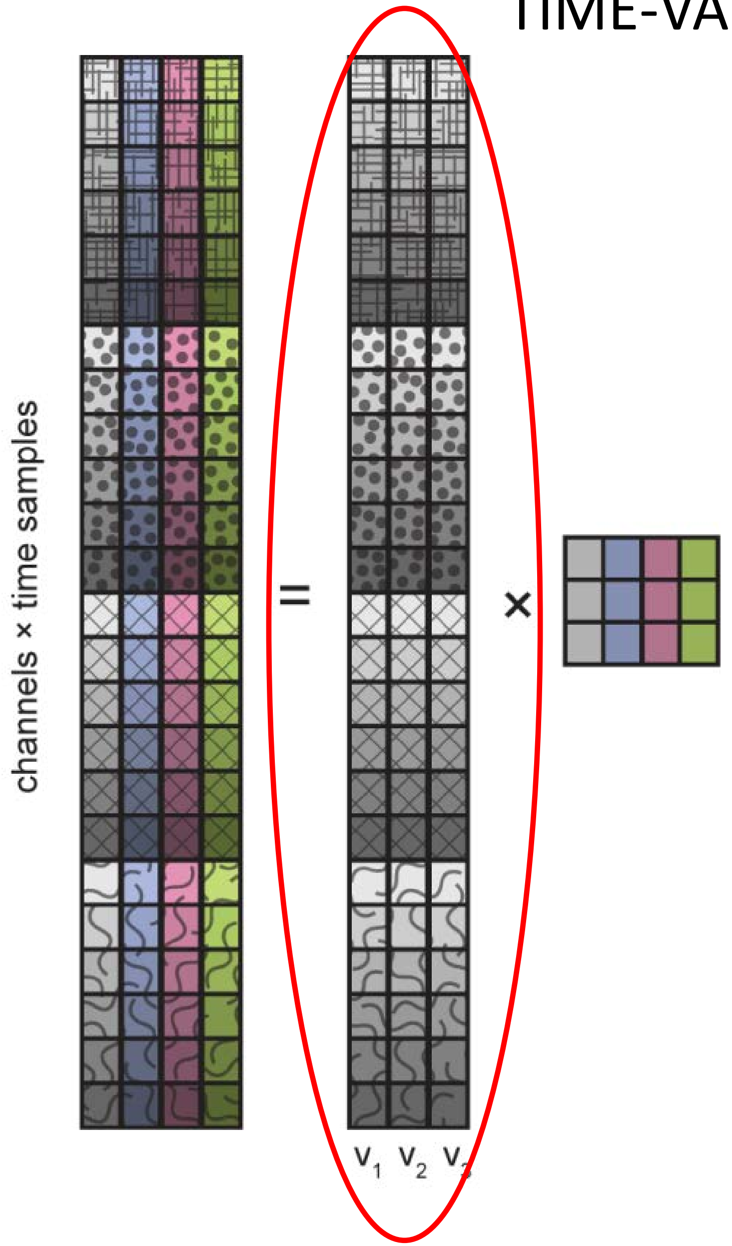


Selection of a small number of combination coefficients allows generating different muscle patterns

TIME-VARYING SYNERGIES

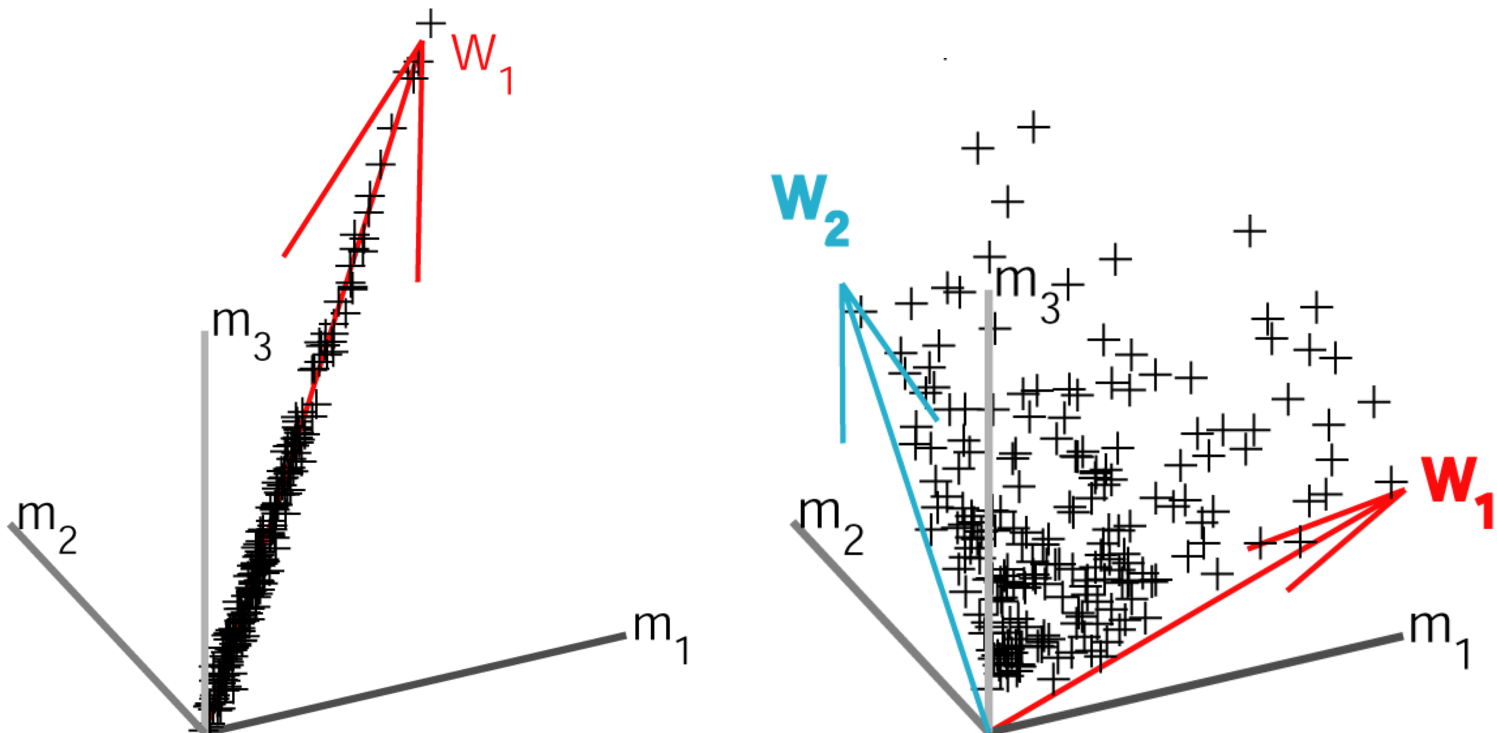
EMG DATA





EMG decomposition algorithms

- Standard multidimensional factorization algorithms (PCA, FA, ICA, NMF) can be used to identify time-invariant synergies, temporal components, and time-varying synergies (without delays)
- Iterative optimization algorithms have been developed to identify time-varying synergies (with delays) [d’Avella et al. 2002, 2003, 2005; Omlor and Giese 2011]



W1
m3
m2
m1
W2
m3
W1
m2
m1

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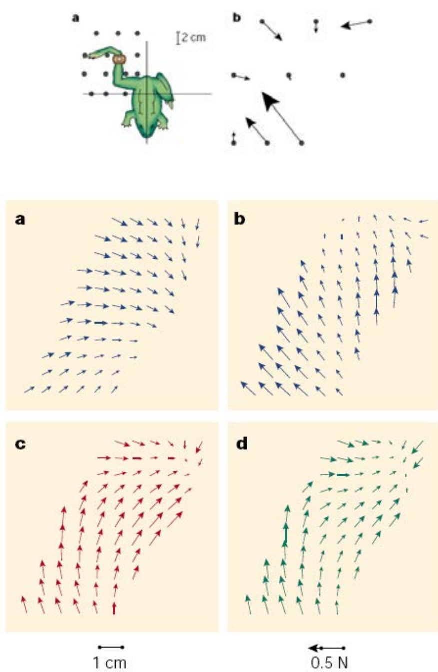
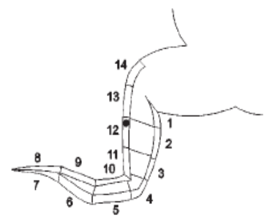
Evidence from EMG decomposition

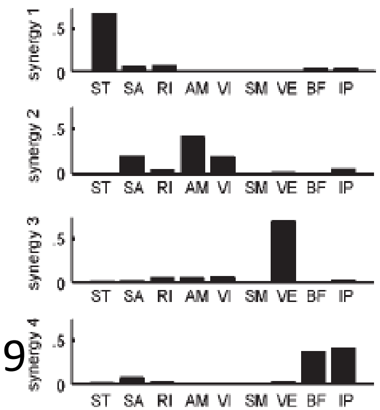
- A small number of muscle synergies captures the variations of the muscle patterns across behavioral and task conditions
  - Frogs
  - Cats
  - Monkeys
  - Healthy humans
    - Postural control
    - Locomotion
    - Reaching
    - Isometric force generation

Defensive reflexes in the frog

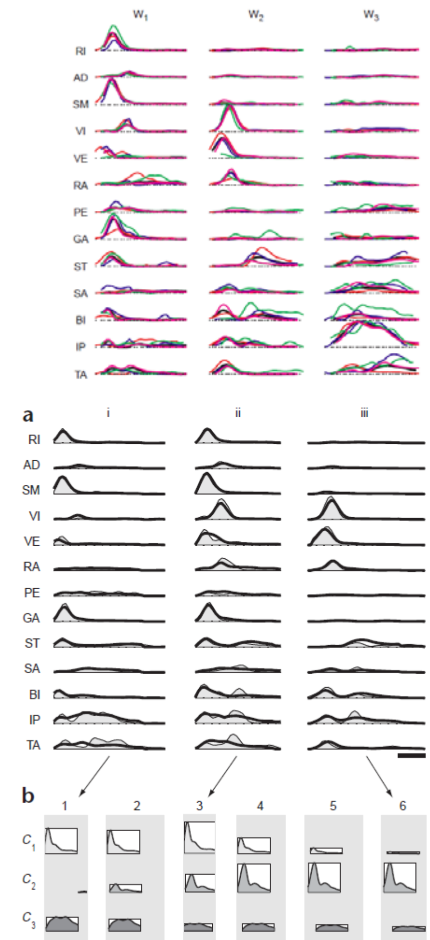


Giszter et al. 1993
Mussa-Ivaldi et al. 1994



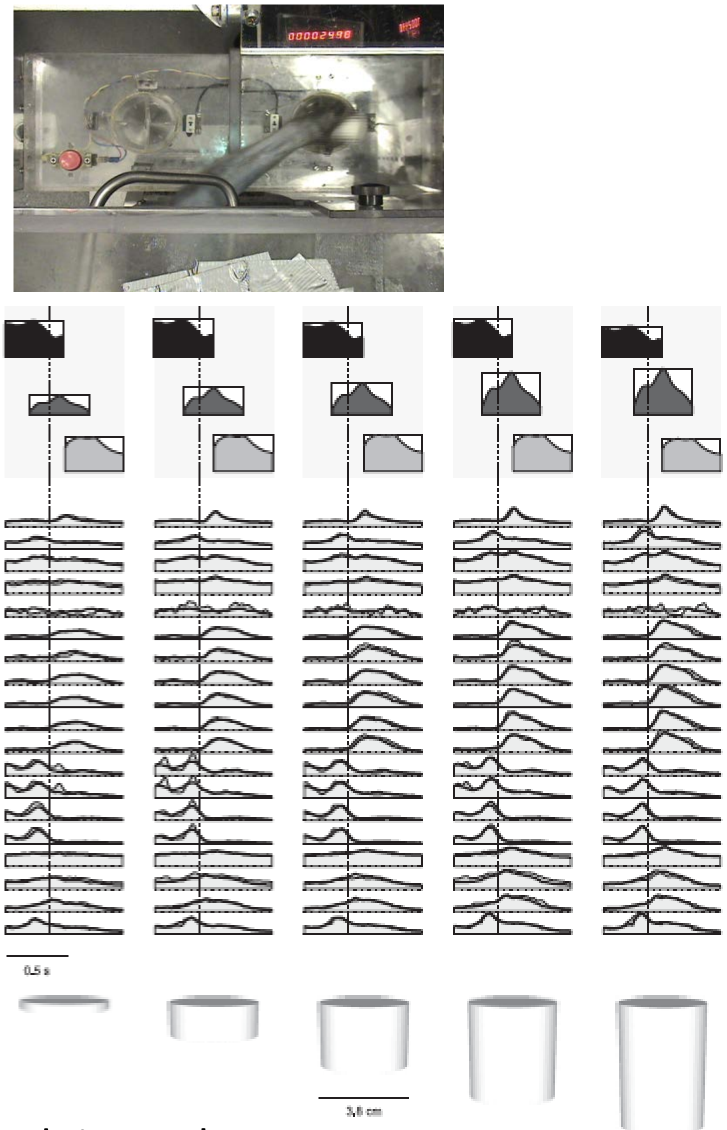


Tresch et al. 1999

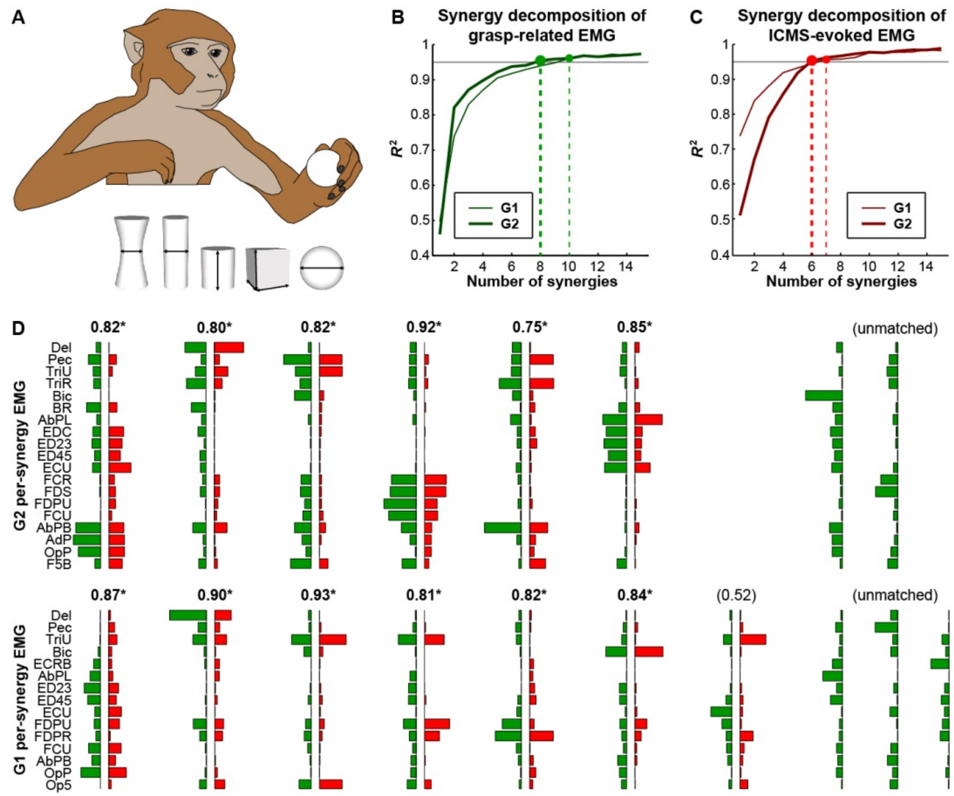


d’Avella et al. 2003

Reaching and grasping in monkeys

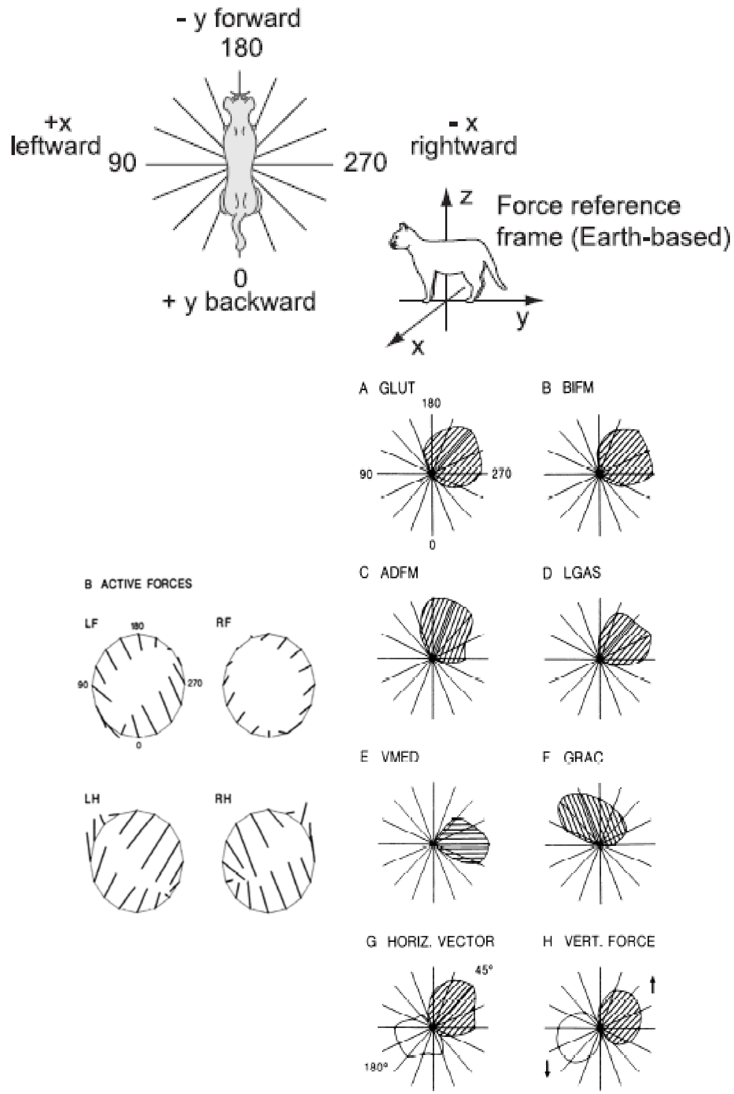


Overduin et al. 2008

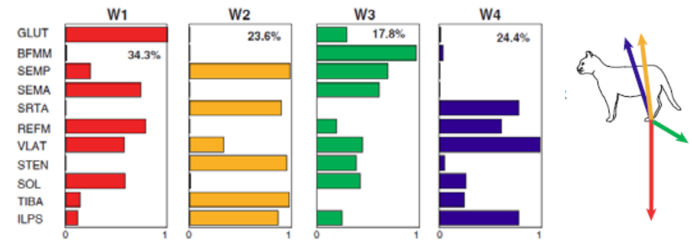


Overduin et al. 2012

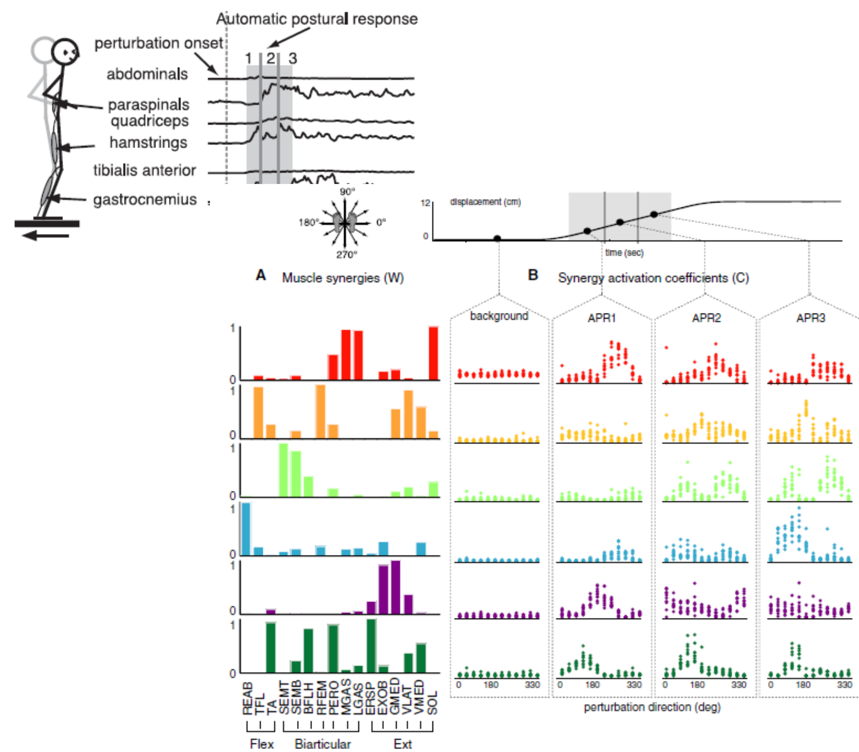
Postural control



Macpherson 1988

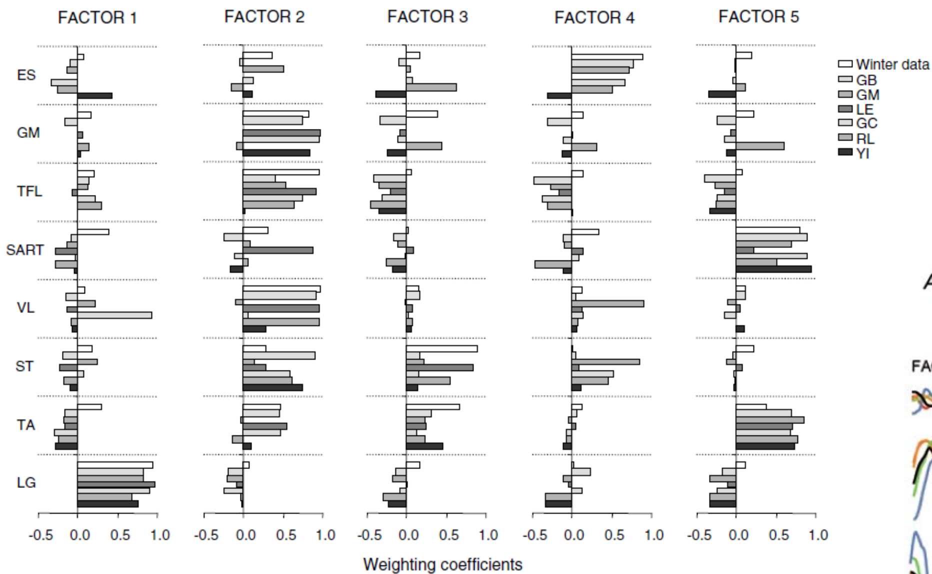


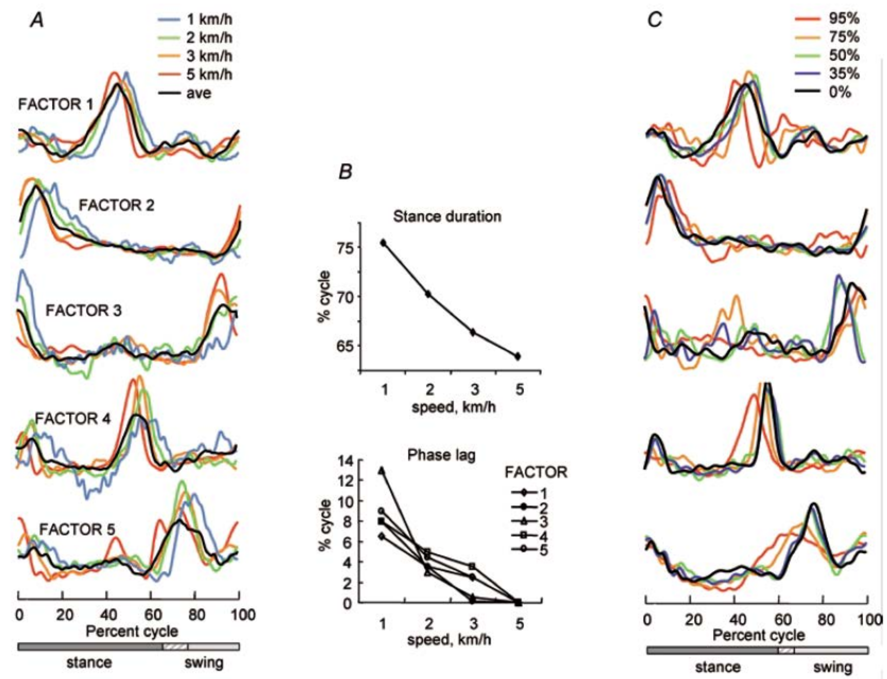
Ting & Macpherson 2005



Torres-Oviedo et al. 2007

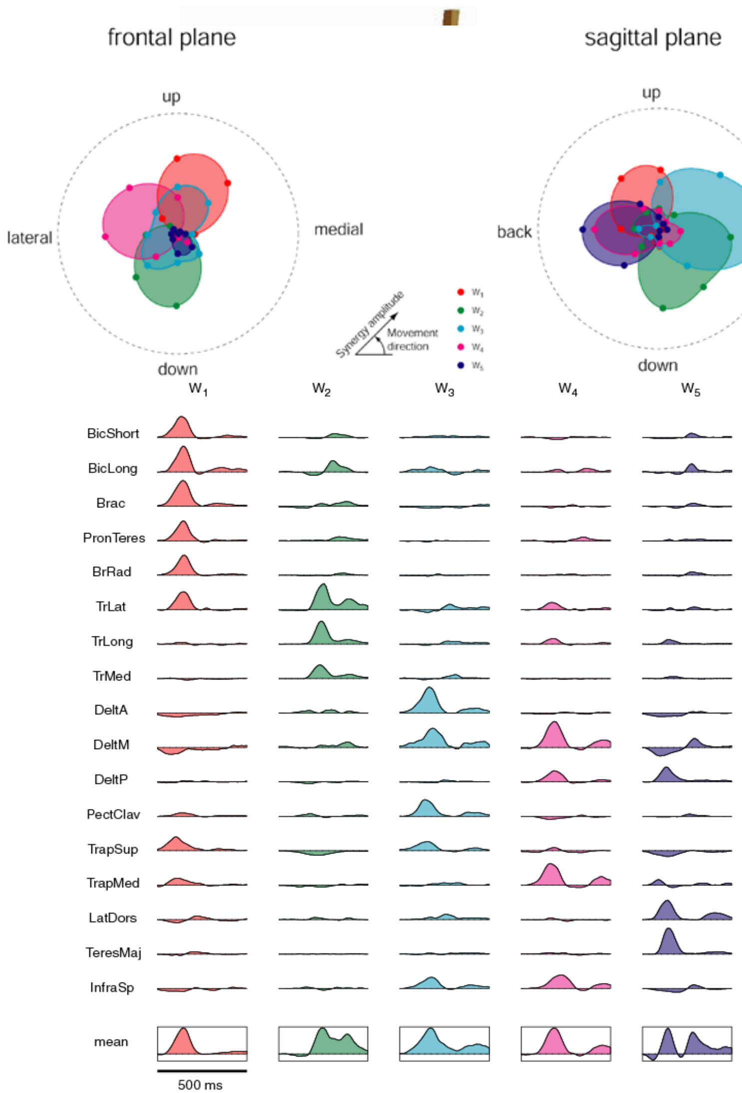
Human locomotion

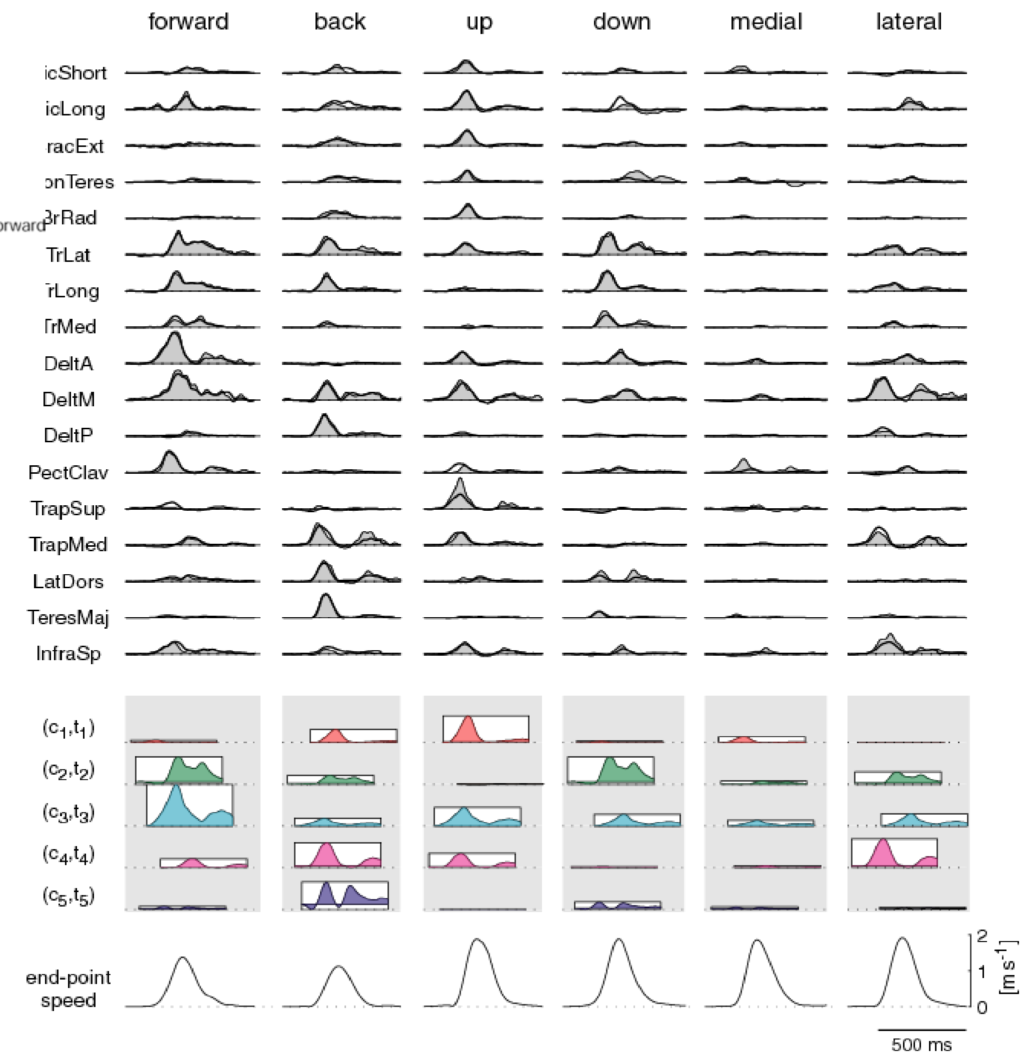




Ivanenko et al. 2004

Human reaching





d'Avella et al. 2006

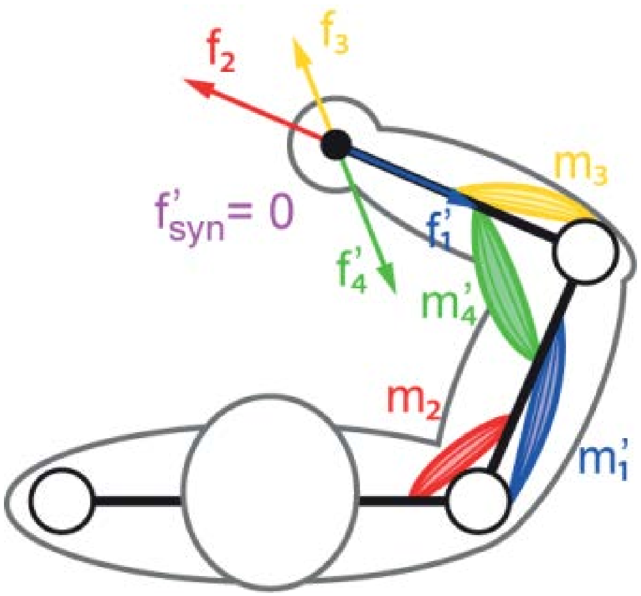
Are muscle synergies a neural strategy or data fitting?

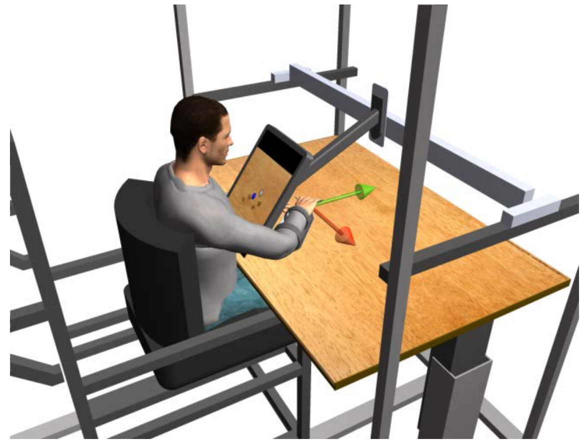
- Muscle synergy decomposition provides a parsimonious <u>descriptive model</u> of the statistical regularities in the motor commands
- To test modularity as a <u>causal model</u> it is necessary to test predictions on the outcome of experimental interventions affecting the organization of the controller

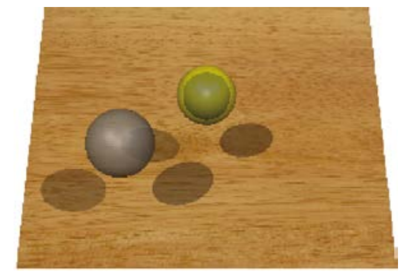
Adaptation as a probe of modularity

- As modularity allows efficient learning by reducing the number of parameters it also constrains what can be learned with the modules
- Prediction: in truly modular architecture there must be some perturbation that are harder to compensate because they are incompatible with the modules

Adaptation to “virtual surgeries”







- Subjects generate isometric forces with the hand inserted in a hand-wrist splint
- They displace a cursor (virtual sphere) according to recorded forces or EMGs (<u>myoelectric control</u>)

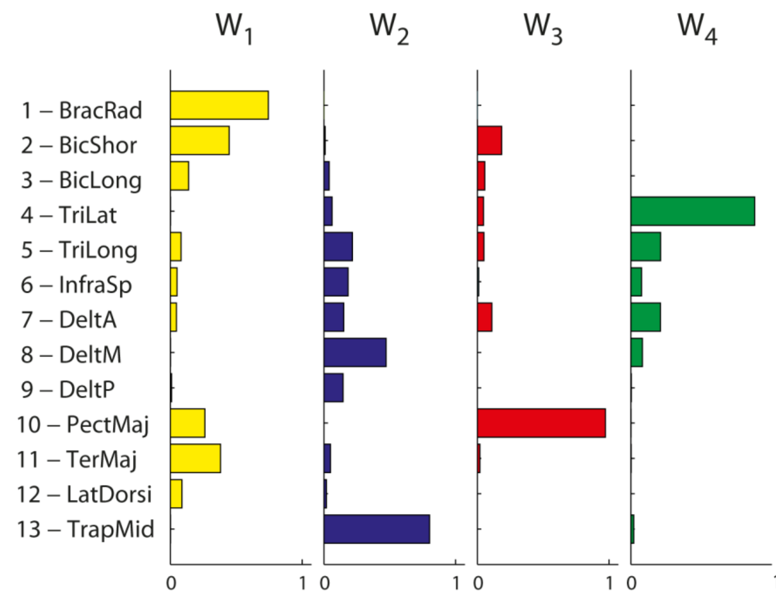
EMG-to-force and muscle synergies

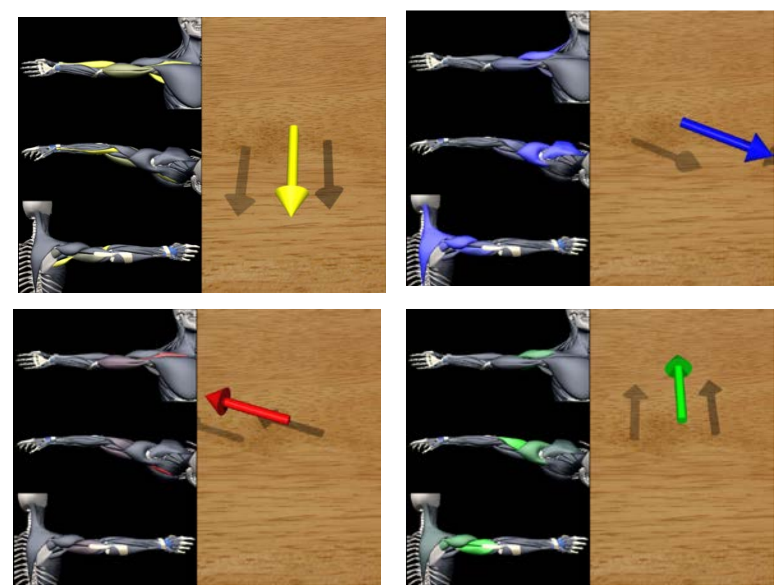
- EMG-to-force: linear mapping esitimated by multiple regression of force by EMG

$$f = H\,m$$

- Muscle synergies: identified from EMGs using NMF

$$m = W\,c$$





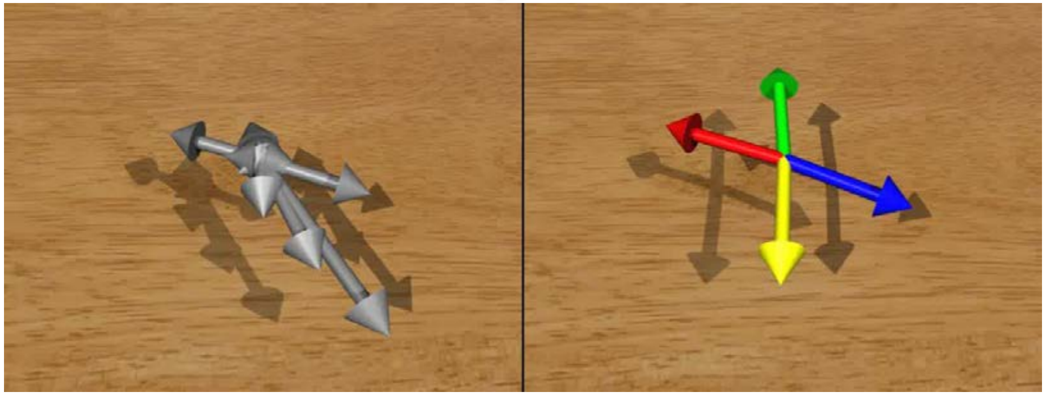
Virtual surgeries

- Muscle space rotations altering muscle-to-force mapping

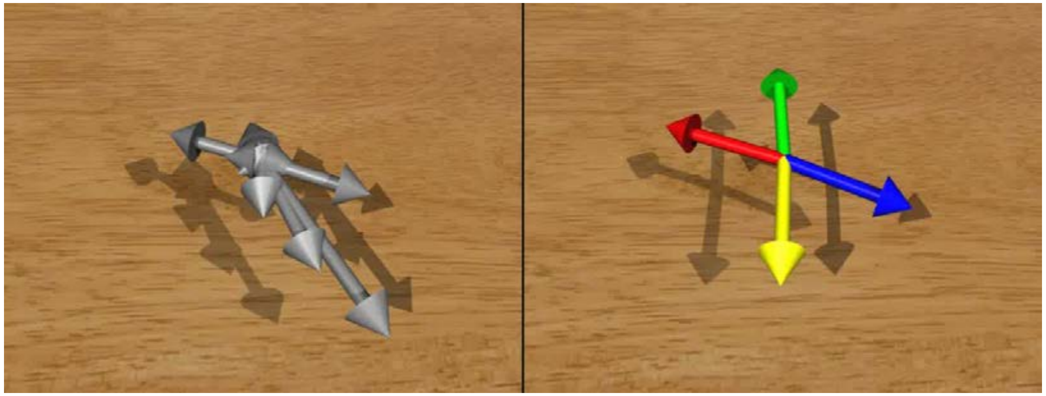
  $$m' = T\,m$$

- Given a set of synergies involved in the task, surgeries can be either compatible or incompatible with them

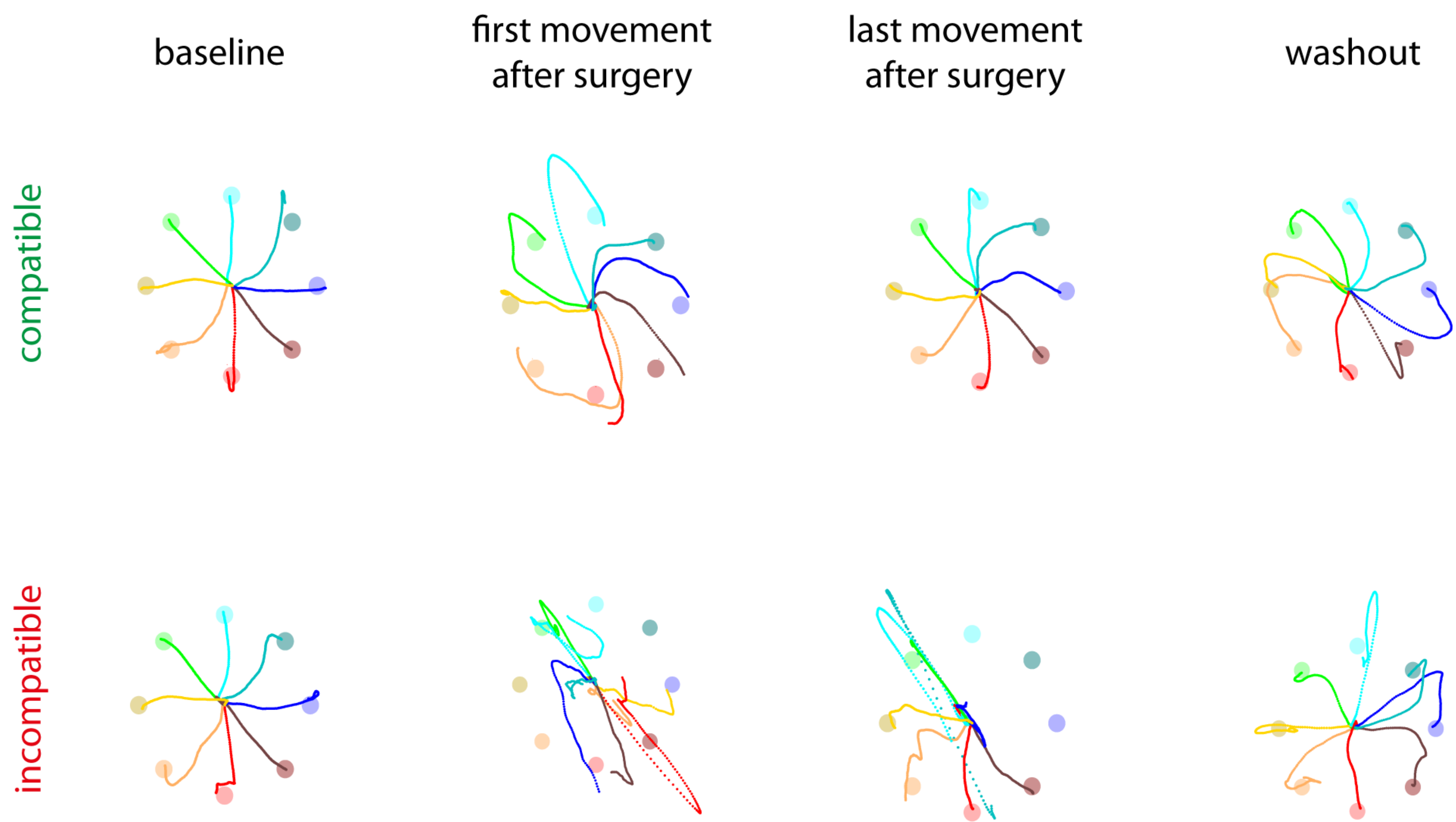
compatible



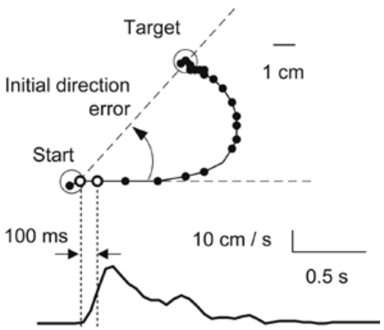
incompatible

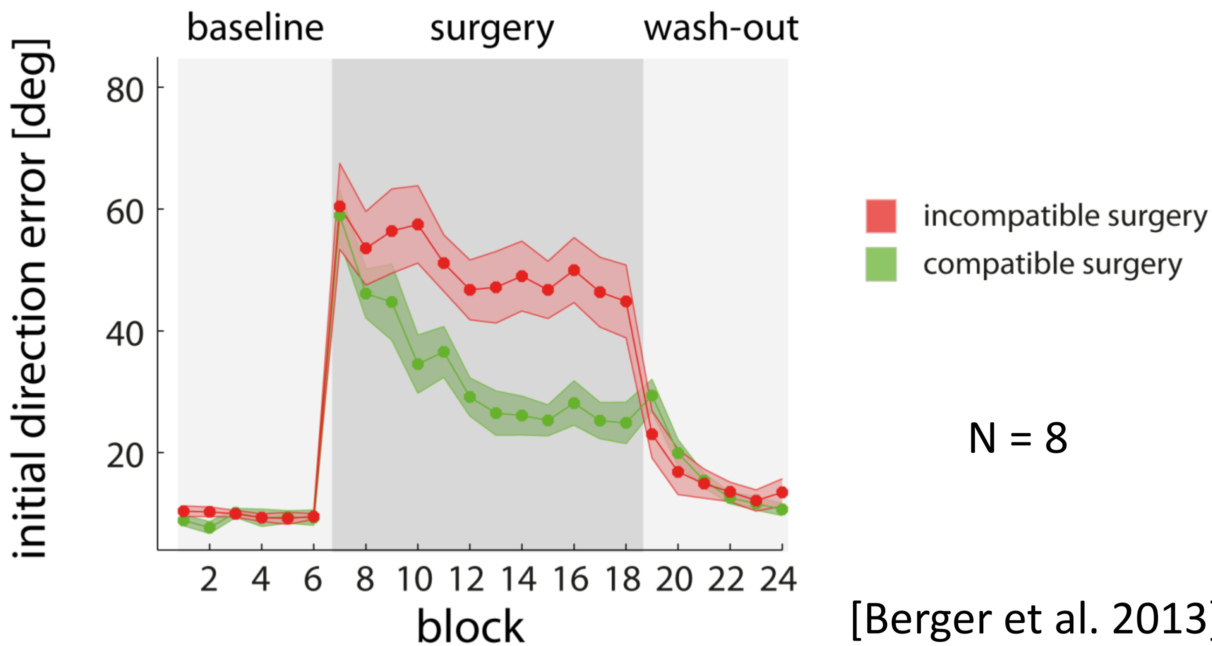


Cursor trajectories in myocontrol



Adaptation is slower after incompatible surgeries





N = 8

[Berger et al. 2013]

- No difference in 1st block after surgery
- Larger errors in last incompatible block
- New direct evicence for modularity

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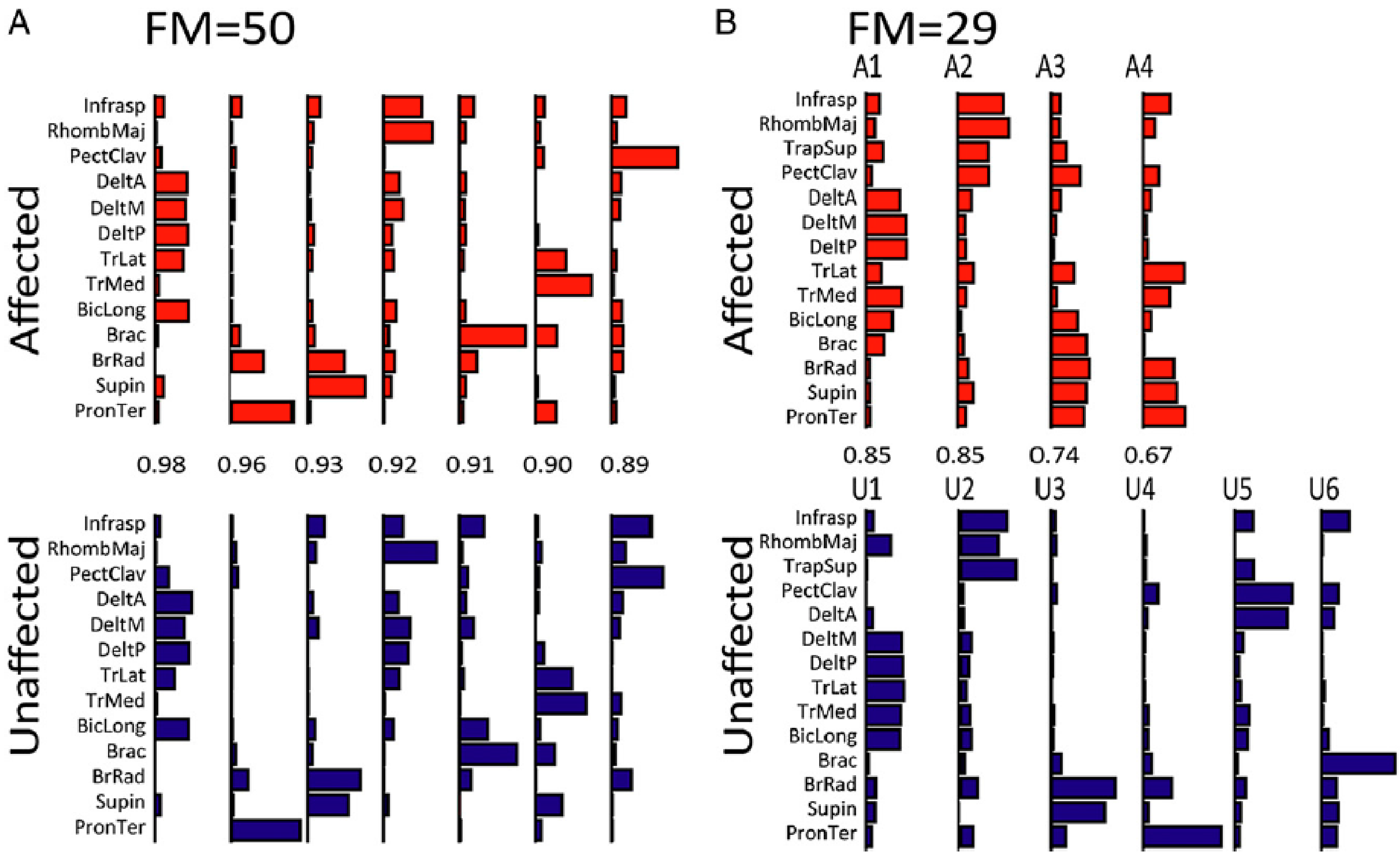
Synergistic organization after injury

- Changes of synergies and coefficients for arm movement and force generation post-stroke
    - [Cheung et al. 2009, 2012, Roh et al. 2013]
- Effect of robot-aided training on synergies
    - stroke [Salman et al. 2010, Tropea et. al 2013]
- Changes of synergies and coefficients for locomotion
    - stroke [Clark et al. 2010, Gizzi et al. 2011]
    - spinal cord injury [Ivanenko et al. 2003]

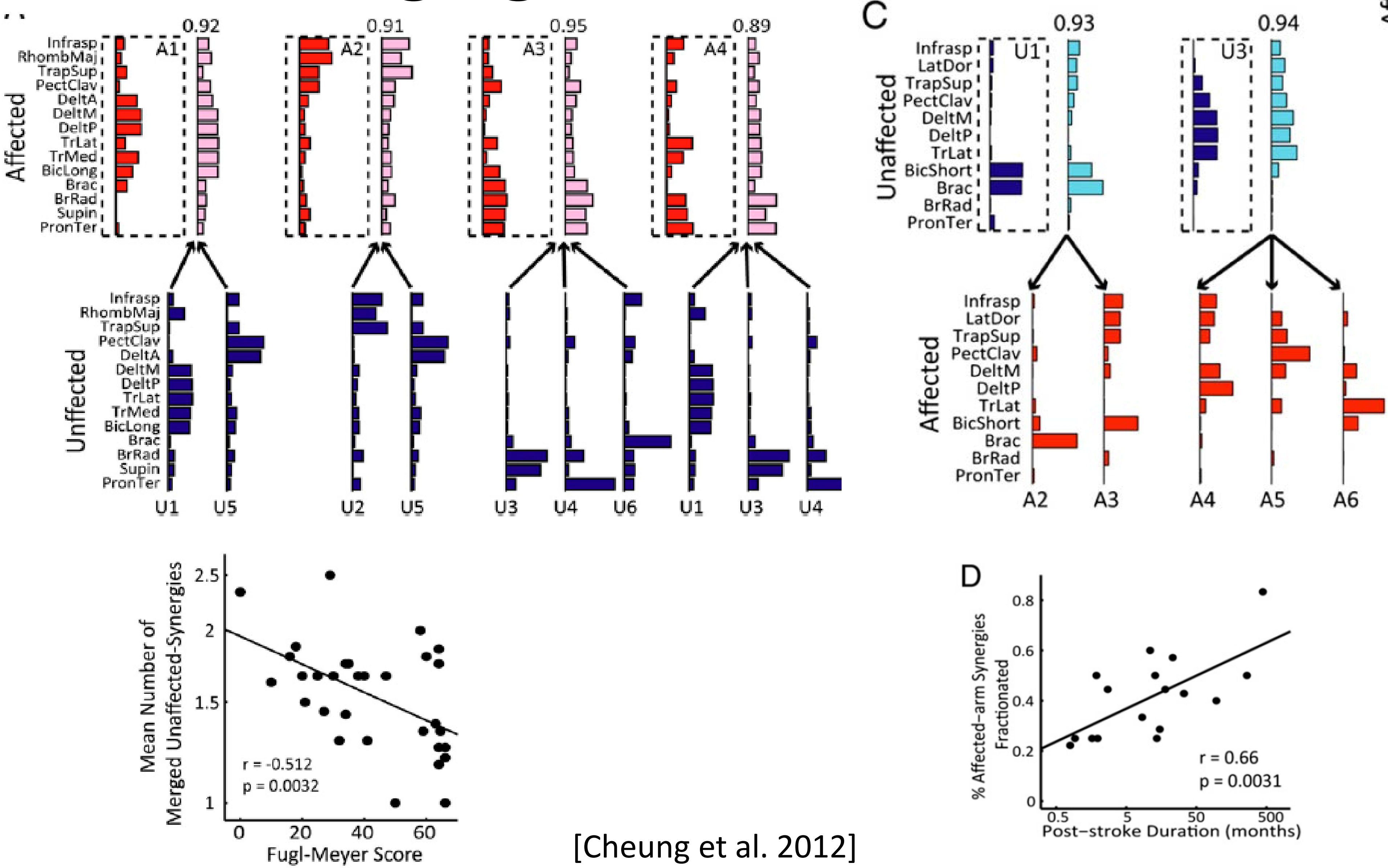
Reaching muscle synergies after stroke



[Cheung et al. 2009]

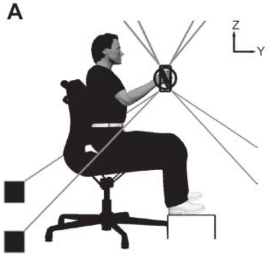
[Cheung et al. 2012]

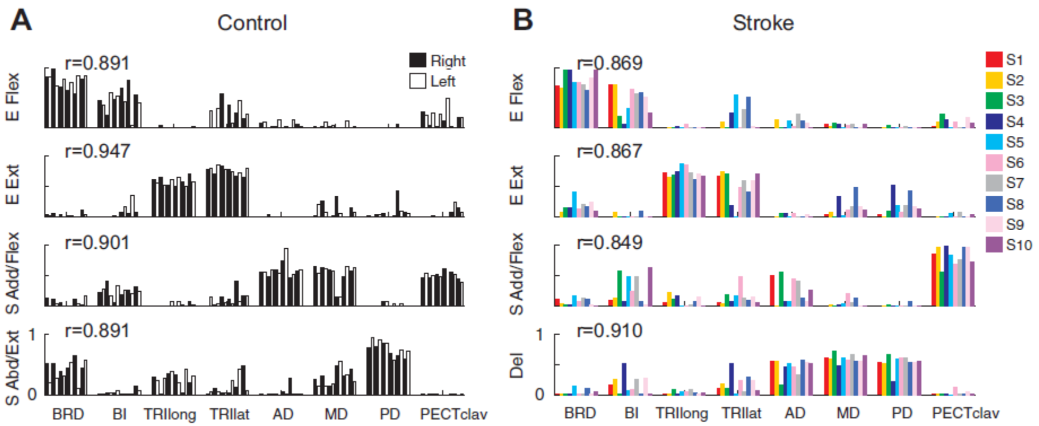
Merging and fractionation

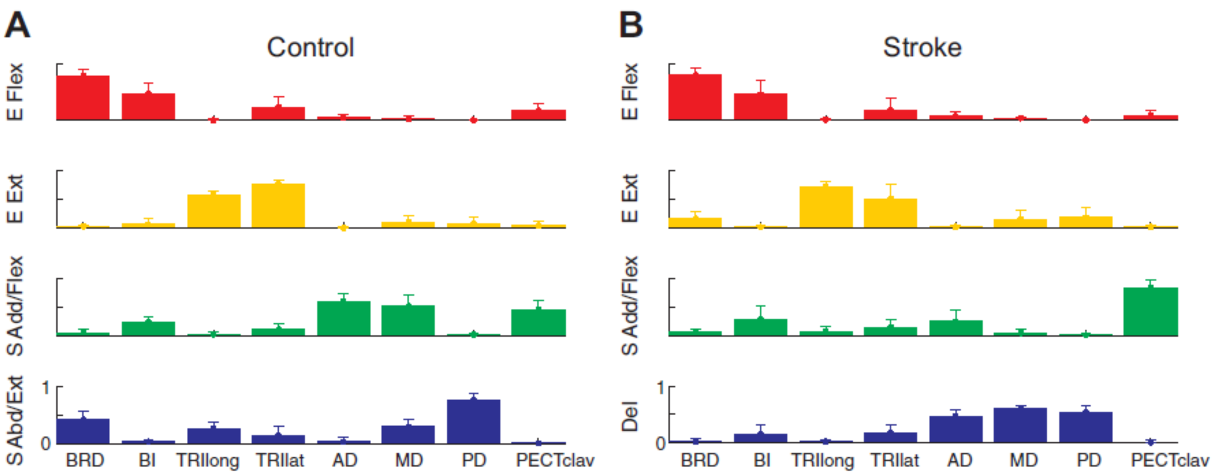


[Cheung et al. 2012]

Force generation synergies after stroke

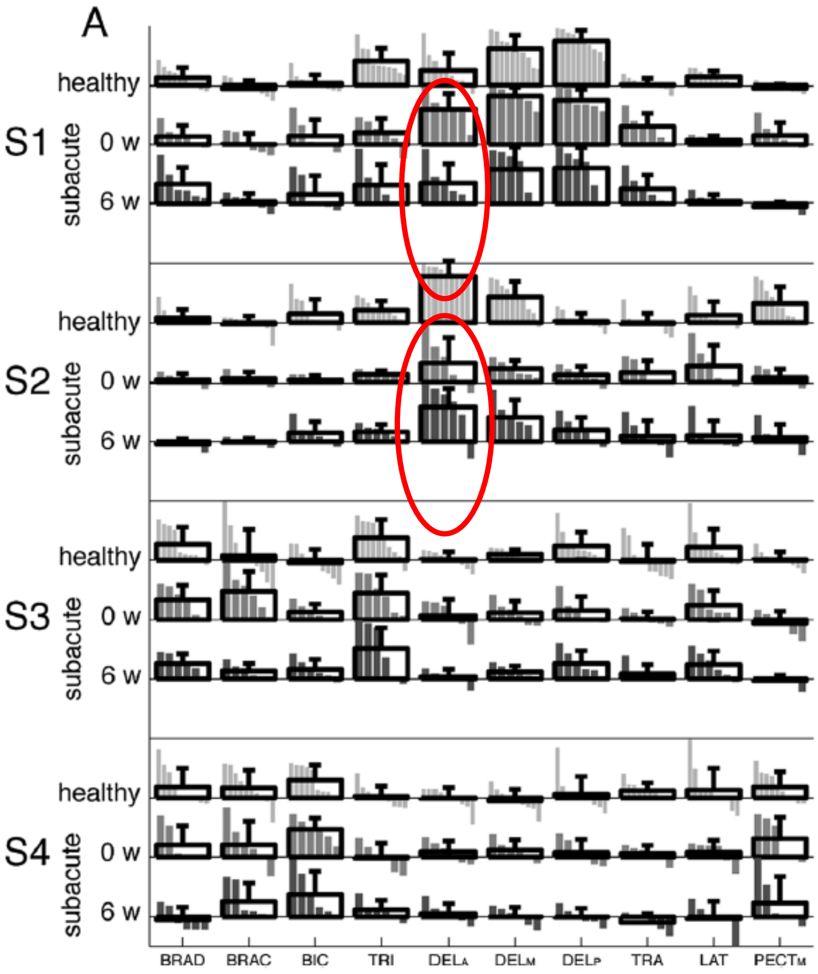


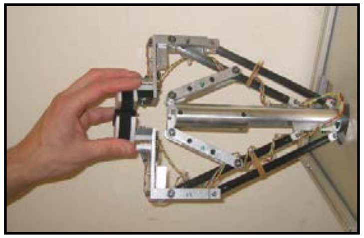


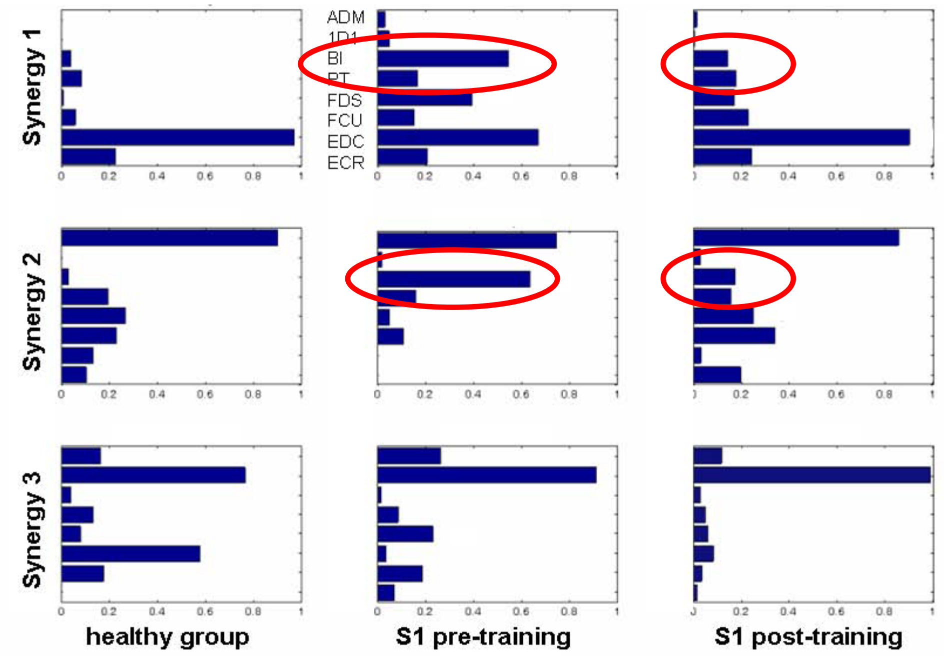


[Roh et al. 2013]

Effect of robot-therapy



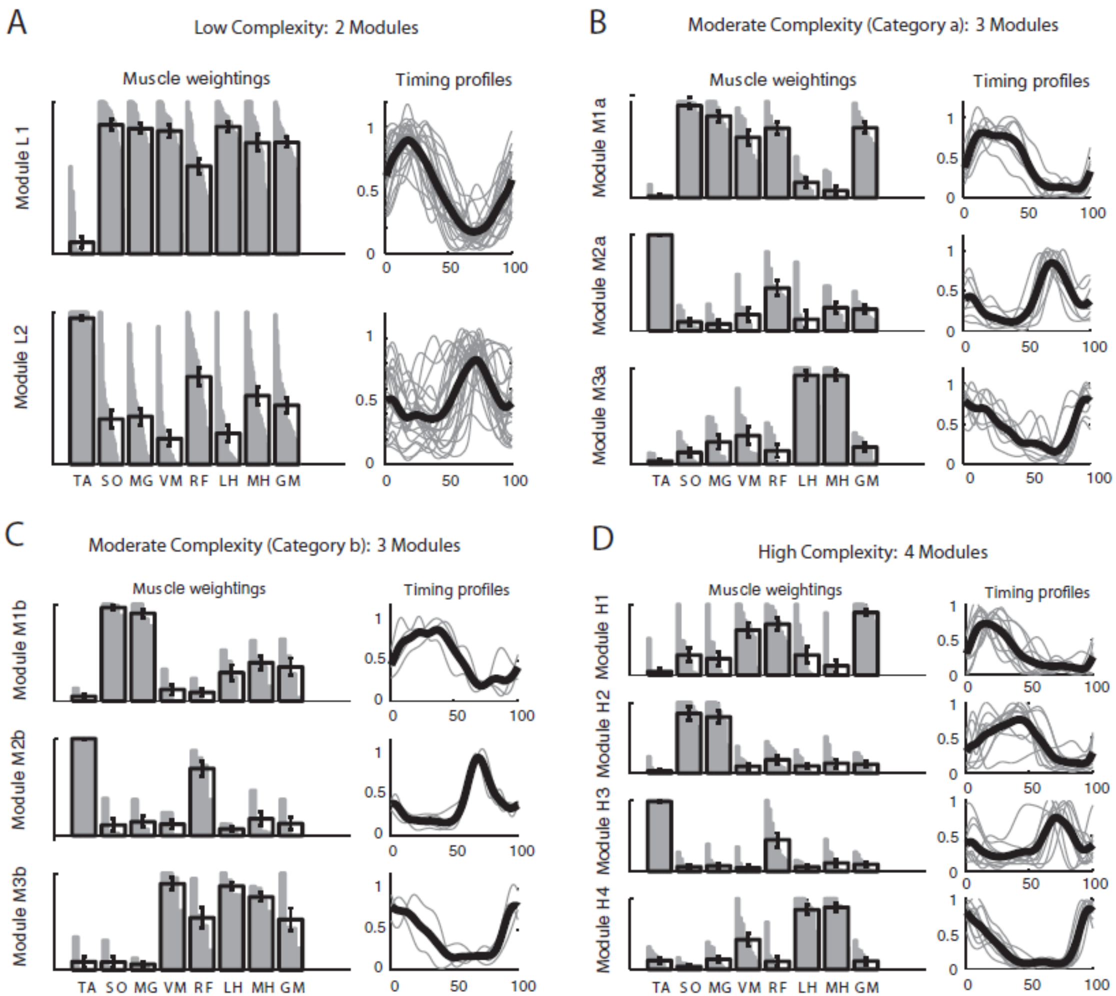


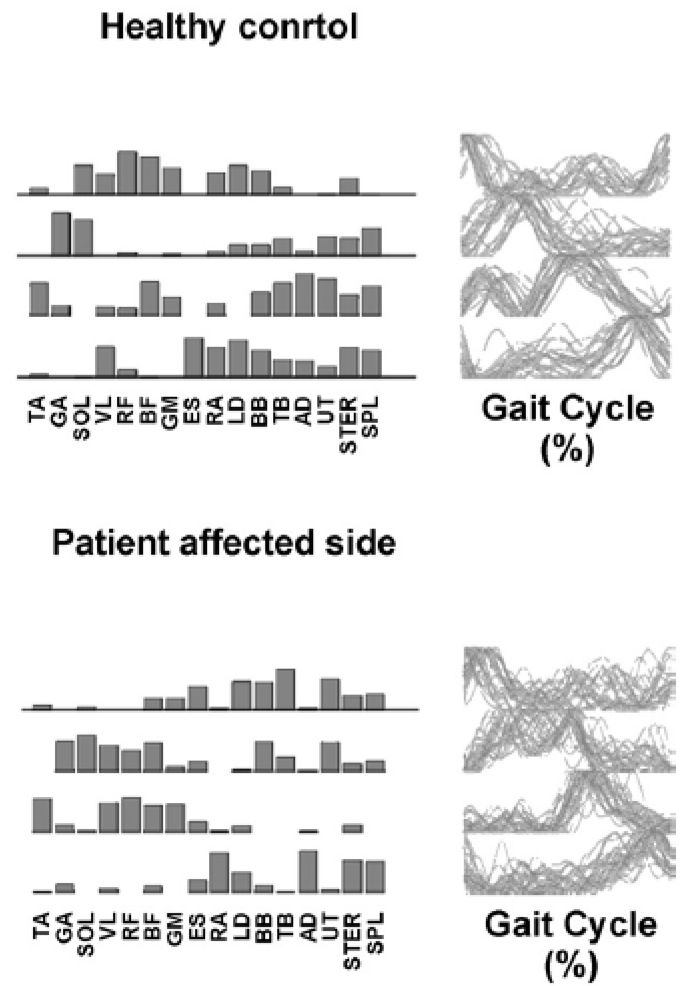


[Salman et al. 2010]

[Tropea et al. 2013]

Locomotor synergies after stroke





[Clark et al. 2010]

[Gizzi et al. 2011]

Many issues remain open…

- Motor impairment after stroke may be due to:
  - dysfunctional synergy recruitment
  - merging of muscle synergies
  - disruption of synergy structure
- Neuromotor recovery might involve:
  - recovery of appropriate synergy recruitment
  - re-organization of original synergies
  - organization of new compensatory synergies

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Muscle synergies for neurorehabilitation

- Diagnostic: synergy structure and recruitment as quantitative indicators of functional impairment and of efficacy of rehabilitation treatments
- Therapeutic: rehabilitation exercises using subject-specific synergy-based feedback

Synergy-based functional assessment

- Clinical tests evaluate motor output at behavioral or kinematic levels
- Muscle coordination patterns may provide a better understanding of neural dysfunction
  - Different muscle patterns may underlie similar motor deficits
- Characterization of the changes in the muscle synergy organization (structure and number) and in their recruitment after injury and during treatment may allow for a quantitative and informative assessment of functional recovery or compensatory strategies

Synergy-based rehabilitation

- Hypotheses
  - muscle synergies are preserved after stroke but their recruitment is impaired
    - [Cheung et al. 2009]
  - Faster recovery of functional synergy recruitment may be obtained by providing synergy-based feedback during training
- Myoelectric control to provide real-time, individualized synergy-based feedback

Synergy-based feedback

- Assuming “healthy” synergies (**W**) are available, the “dysfunctional” muscle pattern for a given task is due to “dysfunctional” coefficients (**c**)

$$\mathbf{m} = \mathbf{W}\,\mathbf{c}$$

- Synergy coefficient “error” with respect to healthy coefficients ($\mathbf{c}^*$)

$$\mathbf{e} = \mathbf{c} - \mathbf{c}^*$$

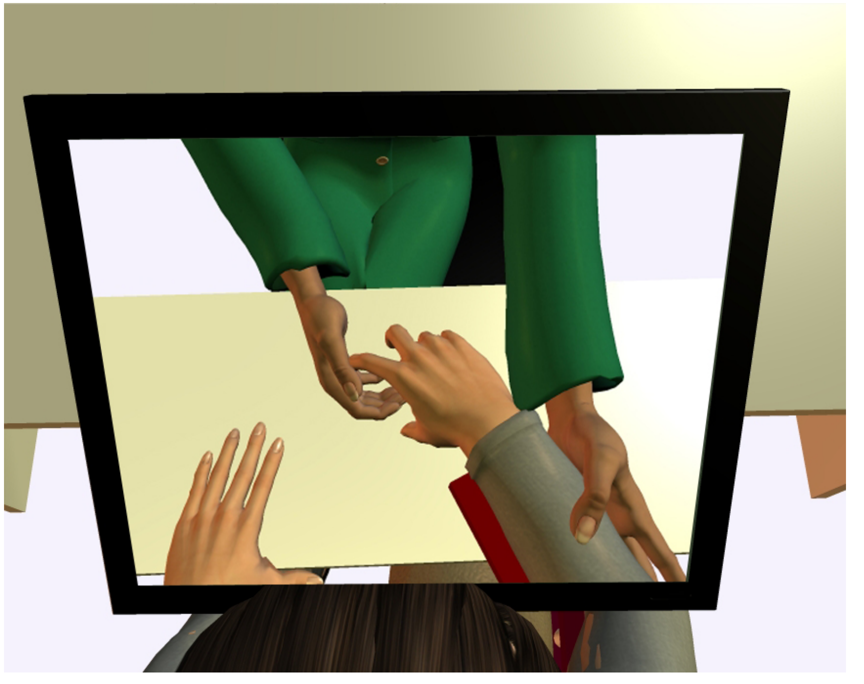
- Error feedback by “correcting” muscle patterns

$$\mathbf{m}' = \mathbf{W}\,\mathbf{c}' = \mathbf{W}\,[\mathbf{c} - \alpha\,\mathbf{e}]$$

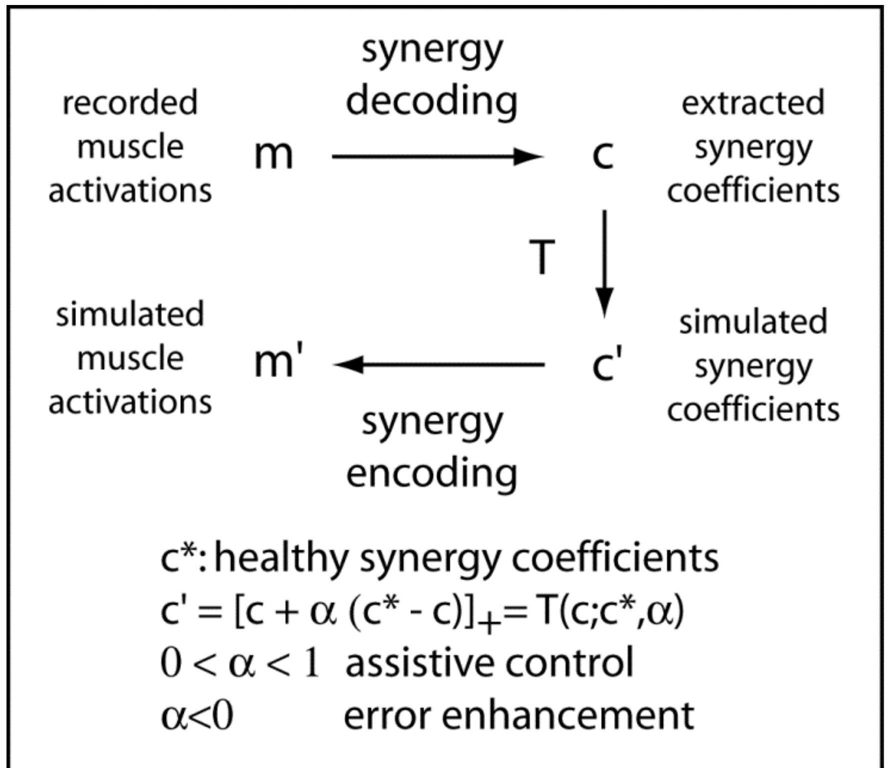
  – $\alpha = 1 \rightarrow$ full correction; $\alpha = 0 \rightarrow$ no correction

Myoelectric control in virtual rehabilitation environment

- Patient (and possibly a remote therapist) avatars in a desktop virtual environment setup
- EMGs recorded from patient arm are used to simulate “corrected” muscle patterns and animate in real-time the patient avatar’s arm
- Alternatively, EMG-driven FES and/or exoskeleton device

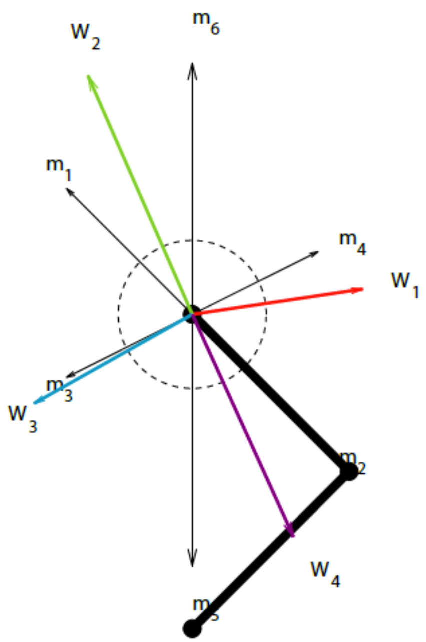


Feedback by synergy decoding and encoding

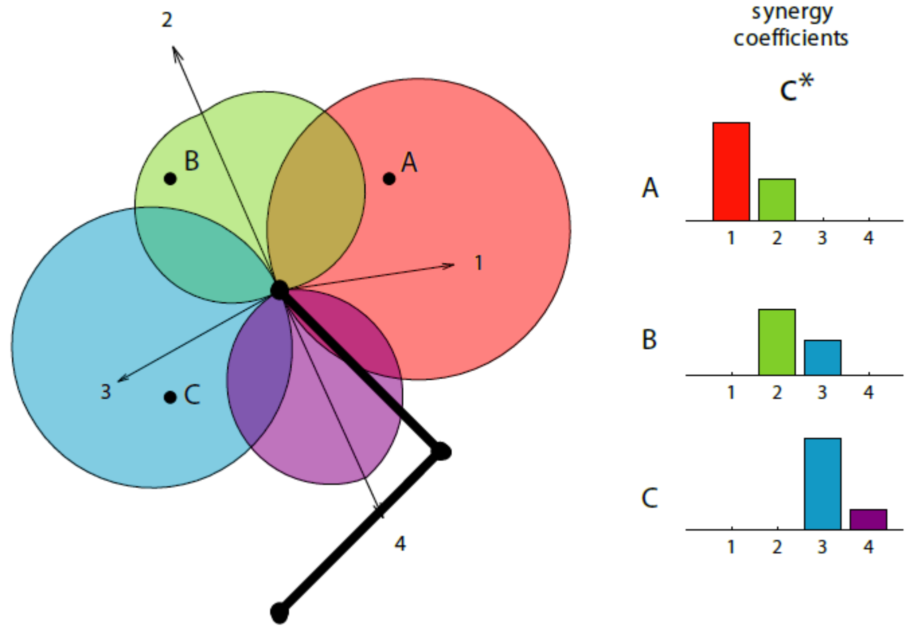


Synergy coefficient decoding

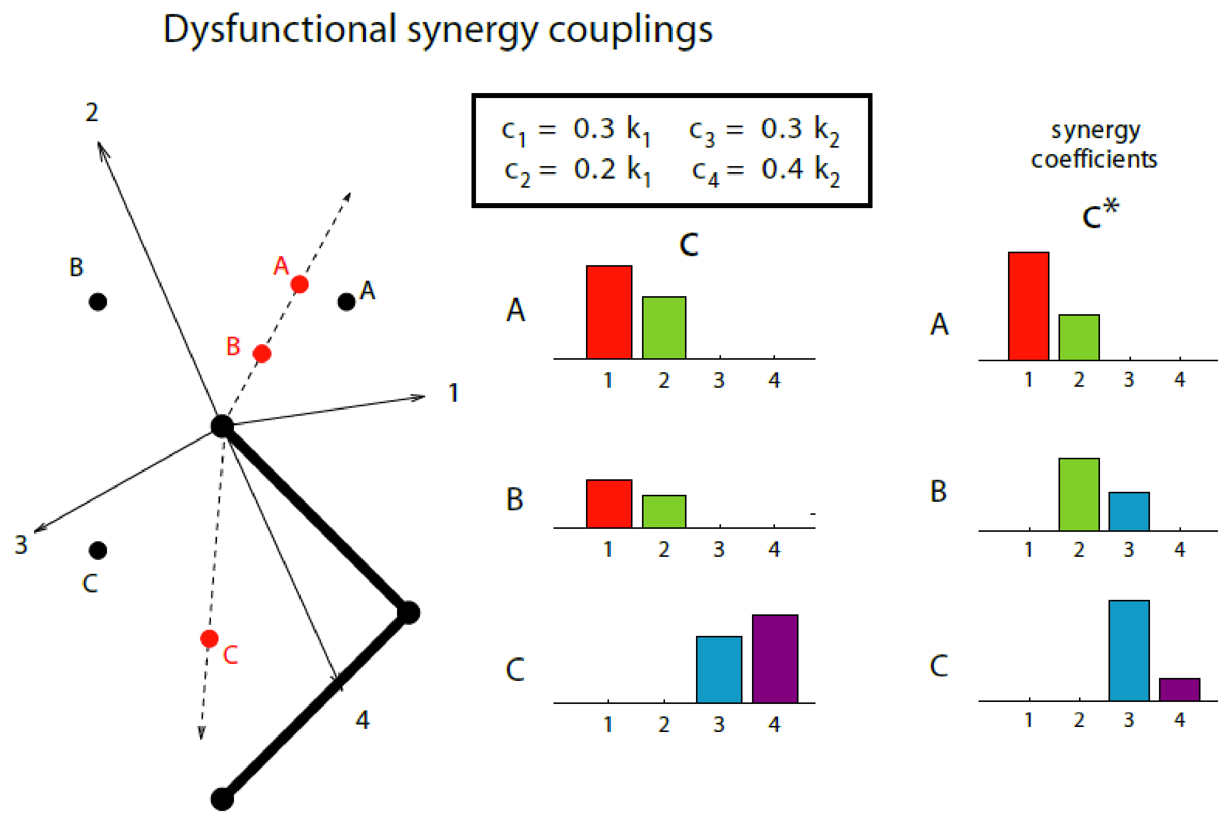
Muscle and synergy forces



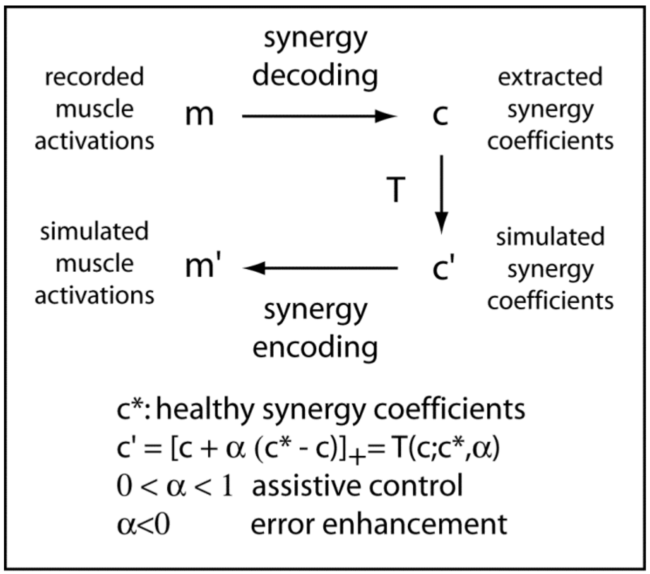
Healthy synergy activation

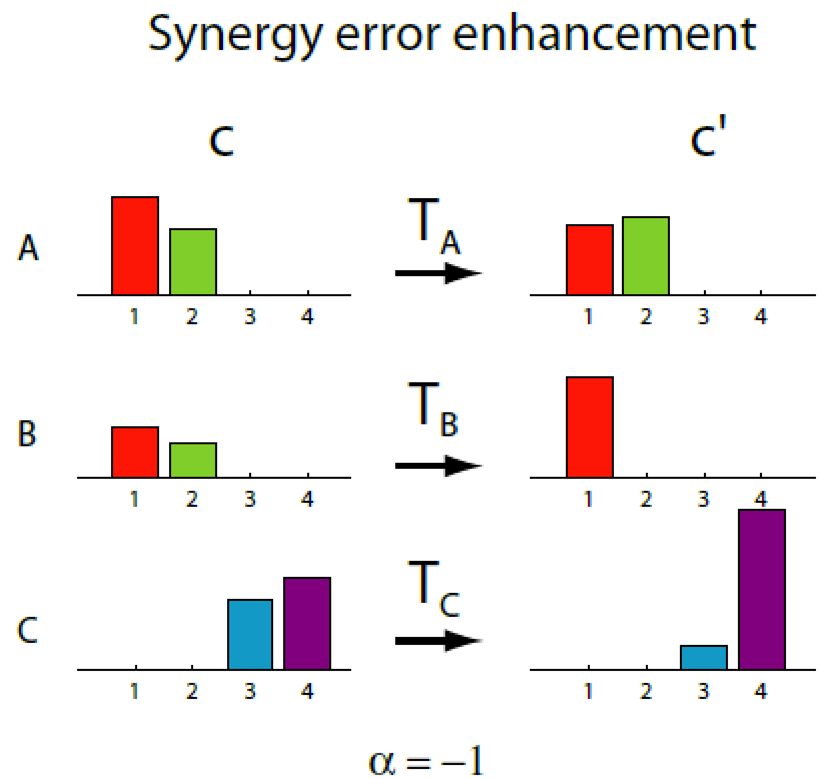


Dysfunctional synergy coefficients



Assistive and error-enhancing therapies





Summary

- Muscle synergies may simplify control in healthy individuals
- Evidence for muscle synergies comes from low-dimensionality of EMG patterns and from adaptation difficulty
- Motor impairment after lesion may be due to abnormal synergy structure and/or recruitment
- Therapy based on personalized, synergy-based feedback may enhance neuromotor recovery

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