Muscle synergies and neuromotor recovery

Andrea d’Avella
Laboratory of Neuromotor Physiology
Fondazione Santa Lucia, Rome, Italy
a.davella@hsantalucia.it

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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
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 building blocks
• A goal can be achieved by selecting a small number of synergy-specific control signals
• Synergies incorporate a priori knowledge 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 (time-invariant synergies)
  – an activation waveform shared across muscles (invariant temporal components)
  – a collection of different activation waveforms for different muscles (time-varying synergies)
Time-invariant muscle 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 ($k = 1...K$)

\[
m^k(t) = \sum_{i=1}^{N} c_i^k(t) w_i
\]

**synergies** ($w_i$)
- invariant
- across conditions

**temporal components** ($c_i$)
- shared across conditions
EMG DATA

TIME-IN VARIANT SYNERGIES

TEMPORAL COMPONENTS
Time-varying muscle synergies

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

\[ m(t) = \sum_{i=1}^{N} c_i w_i(t-t_i) \]
TIME-VARYING SYNERGIES

EMG DATA

channels × time samples = x

v₁, v₂, v₃
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]
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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

Tresch et al. 1999

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

d’Avella et al. 2003
Reaching and grasping in monkeys

Overduin et al. 2008

Overduin et al. 2012
Postural control

Ting & Macpherson 2005

Macpherson 1988

Torres-Oviedo et al. 2007
Human reaching

d’Avella et al. 2006
Are muscle synergies a neural strategy or data fitting?

• Muscle synergy decomposition provides a parsimonious descriptive model of the statistical regularities in the motor commands

• To test modularity as a causal model 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 (myoelectric control)
EMG-to-force and muscle synergies

- **EMG-to-force**: linear mapping estimated 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.
Cursor trajectories in myocontrol

baseline  first movement after surgery  last movement after surgery  washout

compatible

incompatible
Adaptation is slower after incompatible surgeries

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

[Berger et al. 2013]
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Synergistic organization after injury

• Changes of synergies and coefficients for arm movement and force generation post-stroke
• 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

[Tropea et al. 2013] [Salman et al. 2010]
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 ($c$)

$$m = W \cdot c$$

• Synergy coefficient “error” with respect to healthy coefficients ($c^*$)

$$e = c - c^*$$

• Error feedback by “correcting” muscle patterns

$$m' = W \cdot c' = W \cdot [c - \alpha \cdot e]$$

  $\alpha = 1$ → full correction; $\alpha = 0$ → 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

\[ \begin{align*}
    c^* &: \text{healthy synergy coefficients} \\
    c' &= [c + \alpha (c^* - c)]_+ = T(c;c^*,\alpha) \\
    0 < \alpha < 1 &: \text{assistive control} \\
    \alpha < 0 &: \text{error enhancement}
\end{align*} \]
Synergy coefficient decoding

Muscle and synergy forces

Healthy synergy activation

Synergy coefficients
Dysfunctional synergy coefficients

Dysfunctional synergy couplings

\[ c_1 = 0.3 \ k_1 \quad c_3 = 0.3 \ k_2 \]
\[ c_2 = 0.2 \ k_1 \quad c_4 = 0.4 \ k_2 \]
Assistive and error-enhancing therapies

\[ c' = [c + \alpha (c^* - c)]_+ = T(c; c^*, \alpha) \]

- \( 0 < \alpha < 1 \) assistive control
- \( \alpha < 0 \) error enhancement

\[ \alpha = -1 \]
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
References

• Review papers on motor control modularity


• **Neurophysiological evidence**


• **Effect of lesion**

• **Synergies and neurorehabilitation**