Study of the modular organization of motor control: experimental and modeling approaches

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Redundancy in motor control

A large number of joints implies a high level of redundancy
Redundancy in motor control

Motor primitives (MPs)

$C_1 \rightarrow MP_1$

$C_2 \rightarrow MP_2$

$\vdots$

$C_N \rightarrow MP_N$

$\Sigma \rightarrow \text{Motor Output}$
Redundancy in motor control

Hierarchical organization of motor control

Brain
(Cortex)

Spinal Cord

Muscles
Redundancy in motor control

Questions:

• What is, at each level, the minimum number of motor primitives necessary?
• How do motor primitives of different levels relate to one another?
Redundancy in WBP movements

Two motor sub-tasks:
- Pointing at a target
- Keeping the balance
Kinematic modularity of WBP

(Berret et al. 2009)
Kinematic modularity of WBP

From PCA on the elevation angles the existence of two flexible modules was found:

- A **postural** one, responsible of the co-variation of trunk plus lower-limbs joint-angles
- A **pointing** one, more dedicated to finger trajectory formation

(Berret et al. 2009)
Muscle organization of WBP

Experimental setup

- Twelve male subjects
- Kinematic data
- Force platform under the feet (forces, torques and centre of pressure)
- Twenty-four muscles activation (EMG) recorded
- 3 conditions: one basic normal pointing (B), one postural condition with no knee flexion (K) and one reaching condition with imposed curved finger trajectory (C)
Muscle organization of WBP

Non-Negative Matrix Factorization (Lee and Seung, 1999) was applied to the EMGs data

\[ E^2 = \sum_{k=1}^{T} \left\| \mathbf{m}(t_k) - \sum_{i=1}^{N} c_i(t_k) \cdot \mathbf{w}_i \right\|^2 \]

- \( w_{ij} > 0, c_i(t) > 0 \)
- \( T \) is the total number of time samples
- \( N \) is the dimensionality of the muscle space
Muscle organization of WBP

\[ E^2 = \sum_{k=1}^{T} \left\| m(t_k) - \sum_{i=1}^{N} c_i(t_k) \cdot w_i \right\|^2 \]
Muscle organization of WBP

Inverse dynamic analysis + muscle dynamics modelling

\[ \tau = M(q) \cdot d^2q/dt^2 + C(q, dq/dt) \cdot dq/dt + N(q) \]

\[ d\tau/dt = (\varepsilon - \tau)/\sigma \]

\[ d\varepsilon/dt = (\alpha - \varepsilon)/\sigma \]

\( q = \) vector of the generalized coordinates

\( \tau = \) vector of the joint torques

\( \varepsilon = \) EMG signal

\( \alpha = \) muscle activation signal

\( \sigma = \) constant
Muscle organization of WBP

Results

Typical muscle activity recorded during one trial

(Chiovett et al. 2008, 2010)
Deactivation-Activation onset delays
(Chiovetto et al. 2008, 2010)
Muscle organization of WBP

Torques determined body flexion and initial backward displacement of the Centre of Pressure to accelerate the Centre of Mass forwards

(Chiovetto et al. 2009)
Muscle organization of WBP

\[ E^2 = \sum_{k=1}^{T} \left\| m(t_k) - \sum_{i=1}^{N} c_i(t_k) \cdot w_i \right\|^2 \]

NNMF Cost Function

(Chiovetto et al. 2010)
Muscle organization of WBP

$K$ and $C$

$K$ and $C$ are the dashed lines, $B$ the solid one.

(Chiovetto et al. 2010)
Muscle organization of WBP

Results
(local analysis)

(Chiovetto et al. 2010)
Take home message

• 24 muscle $\rightarrow$ 3 temporal components (TRIPHASIC PATTERN)

• 3 components also when postural and focal (reaching) constraints were introduced

• 3 components also at local level (single joints)
Elbow Flexion and Extension

For both F and E same strategy: Ag1 burst, followed by Ant1 and then Ag2
Elbow Flexion and Extension

2 muscles $\rightarrow$ 3 functional components
Take home message

• 24 muscles $\rightarrow$ 3 components (TRIPHASIC PATTERN)

• 3 components also when postural and focal constraints were introduced

• 3 components also at local level (single joints)

• The triphasic pattern is independent of the number of muscles and might represent a standard mode to generate movement
Relationship between modularity in kinematic and muscle space
Take home message

• 24 muscles $\rightarrow$ 3 components (TRIPHASIC PATTERN)

• 3 components also when postural and focal constraints were introduced

• 3 components also at local level (single joints)

• The triphasic pattern is independent of the number of muscles and might represent a standard mode to generate movement

• In a hierarchical view of motor control the triphasic muscle organization would ensure co-variation at kinematic level
Adaptive Modular Architectures for Rich Motor Skills

www.amarsi-project.eu
Muscle synergies

\[ m(t) = \sum_{i=1}^{n} c_i(t) \cdot w_i \]
Anechoic algorithm

An mixture

\[ x_i(t) = \sum_{j=1}^{n} a_{ij} s_j(t - \tau_{ij}) \]

Wigner-Ville Spectrum (WVS)

\[ W_{x_i}(t, \omega) := \int E \left\{ x_i(t + \frac{\tau}{2}) \overline{x_i(t - \frac{\tau}{2})} \right\} e^{-2\pi i \omega \tau} d\tau \]
Anechoic algorithm

An mixture

\[ x_i(t) = \sum_{j=1}^{n} a_{ij} s_j(t - \tau_{ij}) \]

WVS applied to \( x_i(t) \)

\[ W_{x_i}(t, \omega) := \sum_{j} a_{ij}^2 W_{s_j}(t - \tau_{ij}, \omega) \]

under the assumption that the sources are statistically independent

(Omlor and Giese, 2010)
Anechoic algorithm

The previous equation is redundant -> computation of a set of projections onto lower dimensional spaces that specify the same information as the original problem. Solution comes the iterative solution of the following two equations:

\[
|F x_i(\omega)|^2 = \sum_j |a_{ij}|^2 |F s_j(\omega)|^2
\]

\[
|F x_i(\omega)|^2 \frac{\delta}{\delta \omega} \text{arg}\{F x_i(\omega)\} = \sum_j |a_{ij}|^2 |F s_j(\omega)|^2 \left[ \frac{\delta}{\delta \omega} \text{arg}\{F s_j(\omega)\} + \tau_{ij} \right]
\]

where $Fx$ and $Fs$ indicate the Fourier transformations of the trajectory data and the sources.
Dynamic coupling of periodic and non-periodic motor primitives: experimental setup
Dynamic coupling of periodic and non-periodic motor primitives: experimental setup

Normal walk
Dynamic coupling of periodic and non-periodic motor primitives: experimental setup
Setup to study walking and reaching in virtual reality
My collaborators

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Thank you
Questions?

www.compsens.uni-tuebingen.de