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

Dr. Enrico Chiovetto

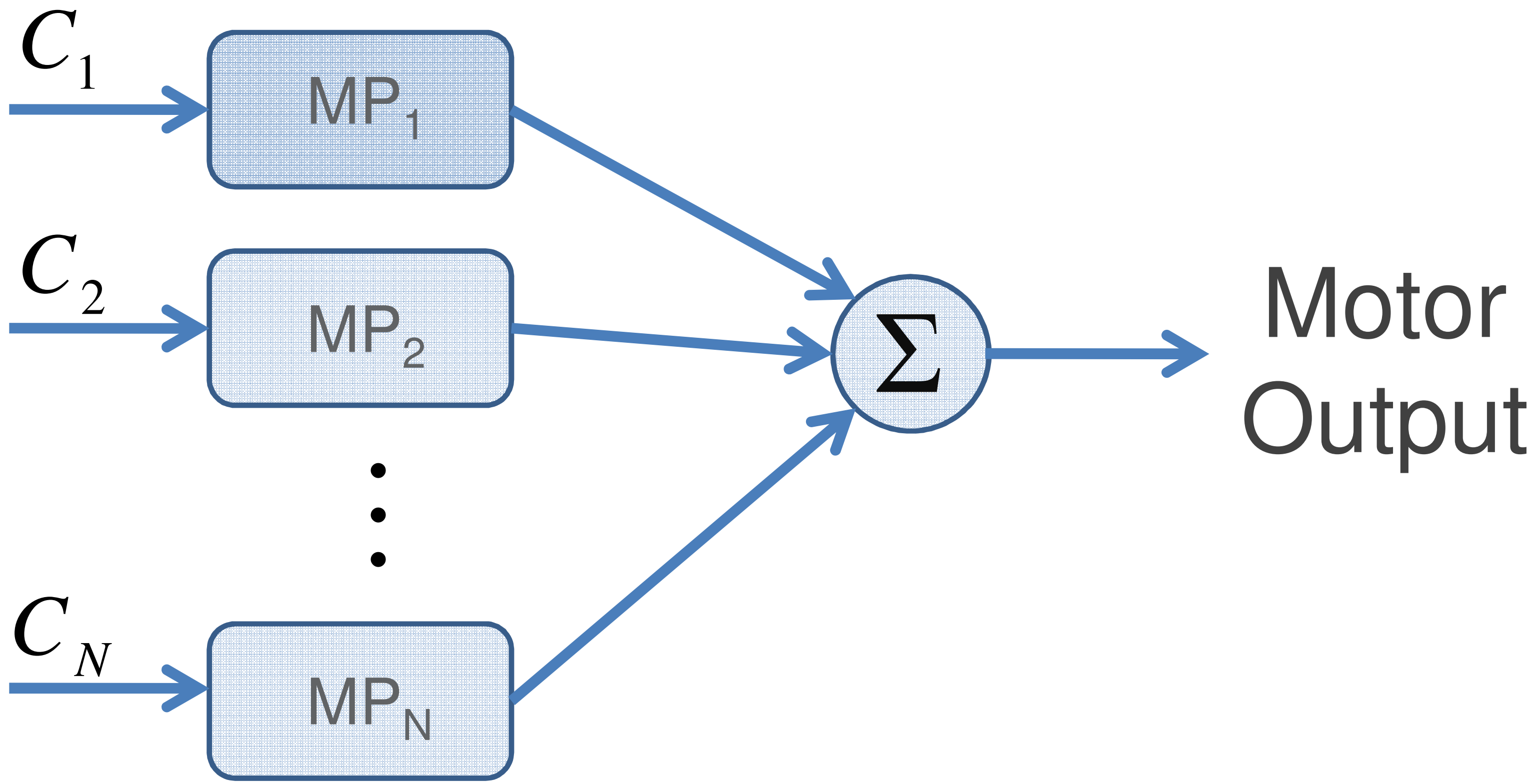
Section for Computational Sensomotorics, Department of Cognitive Neurology, Hertie Institute for Clinical Brain Research, Centre for Integrative Neuroscience, University Clinic Tübingen, Tübingen, Germany.

Redundancy in motor control

A large number of joints implies a high level of redundancy

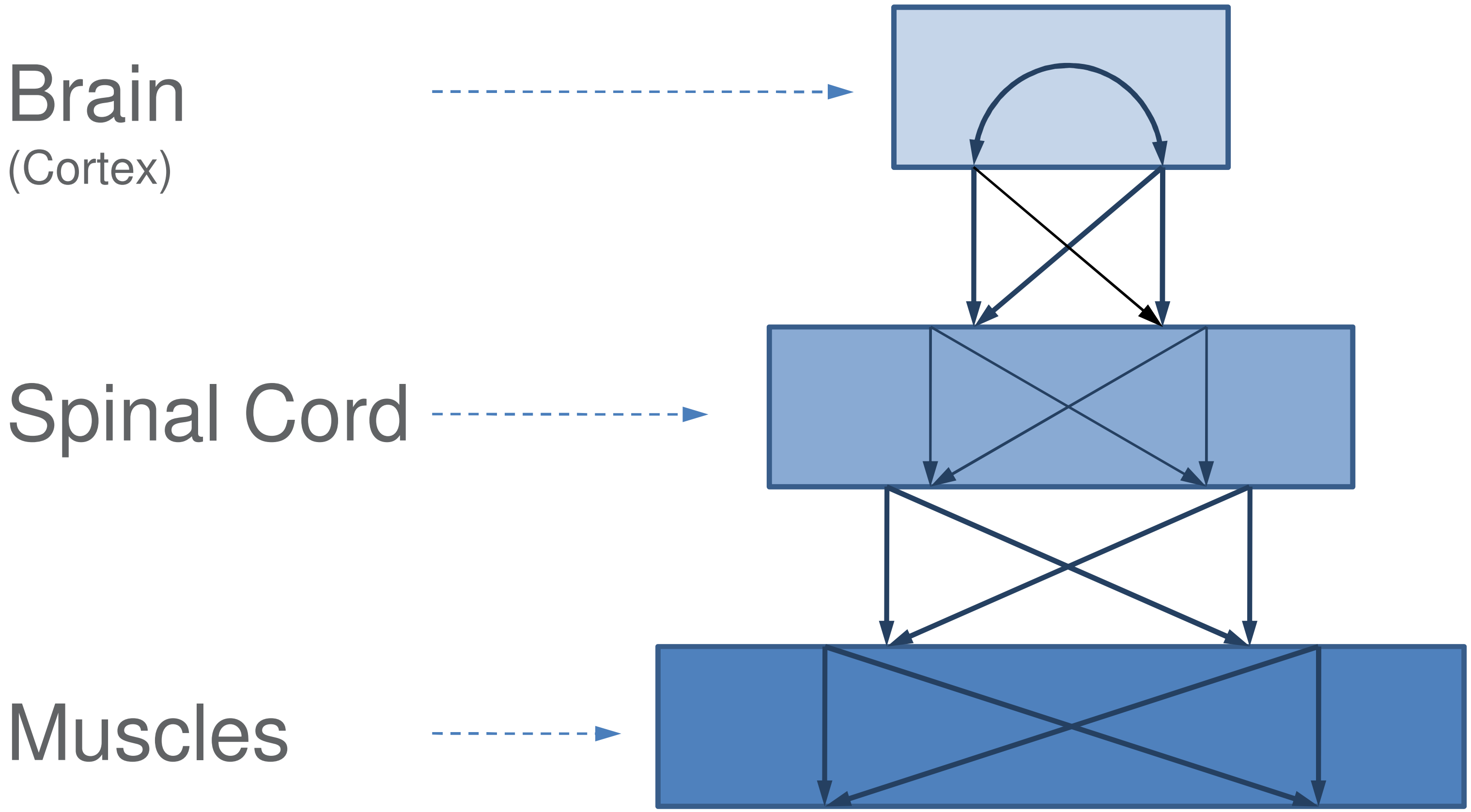
Redundancy in motor control

Motor primitives (MPs)



Redundancy in motor control

Hierarchical organization of motor control



Redundancy in motor control

Questions:

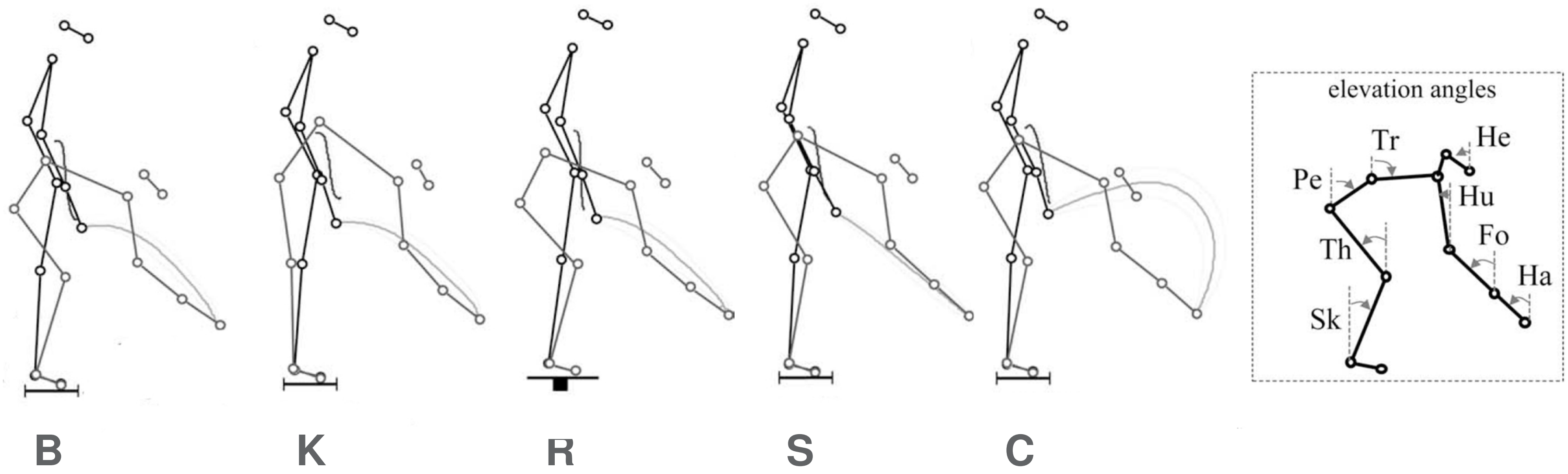
- What is, at each level, the minimum number of motor primitives necessary?
- How do motor primitives of different levels relate to one another?

Redundancy in WBP movements

Two motor sub-tasks:

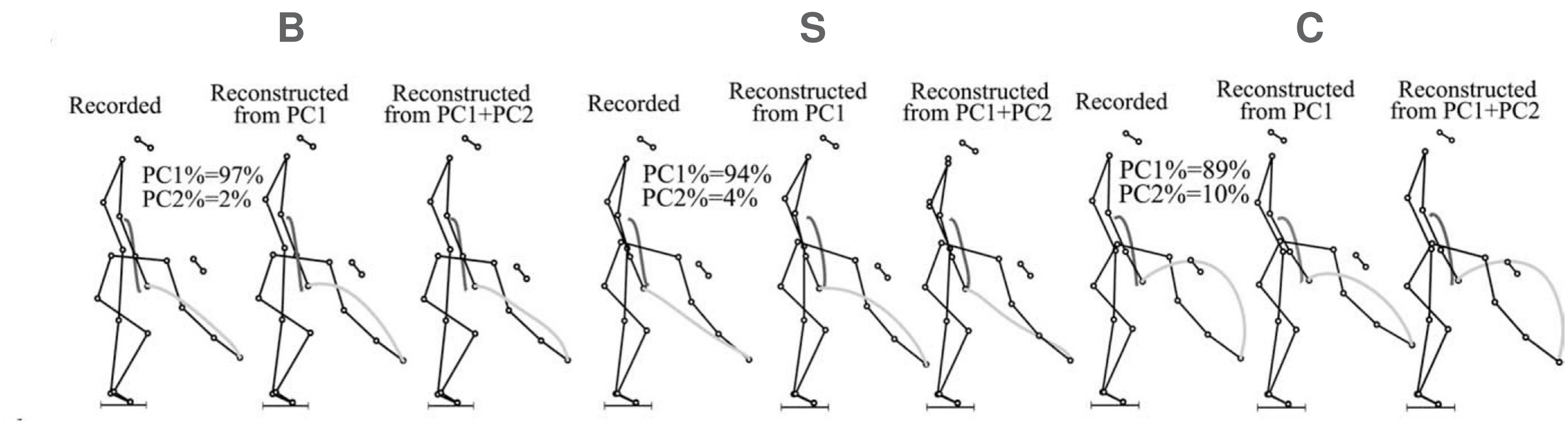
- Pointing at a target
- keeping the balance

Kinematic modularity of WBP



(Berret et al. 2009)

Kinematic modularity of WBP



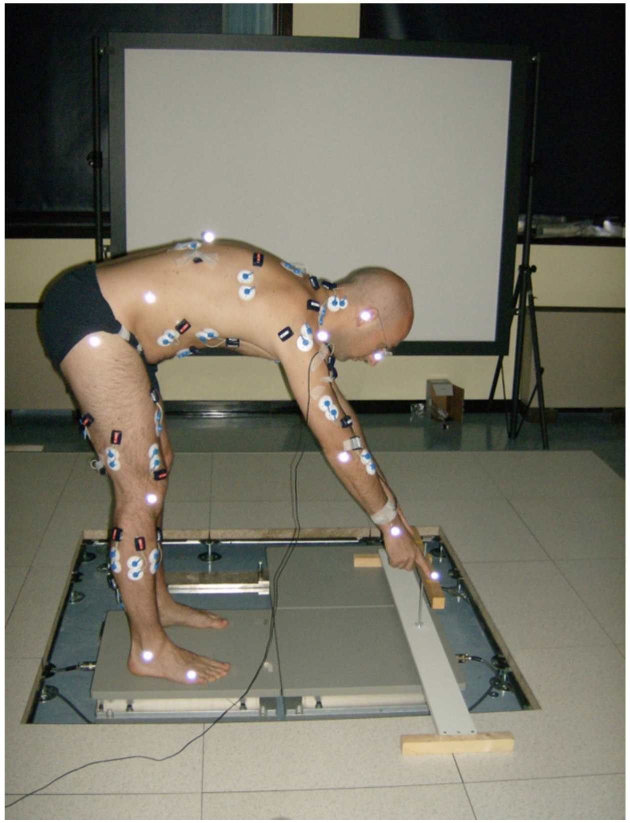
From PCA on the elevation angles the existence of **two** flexible modules was found:

- 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)

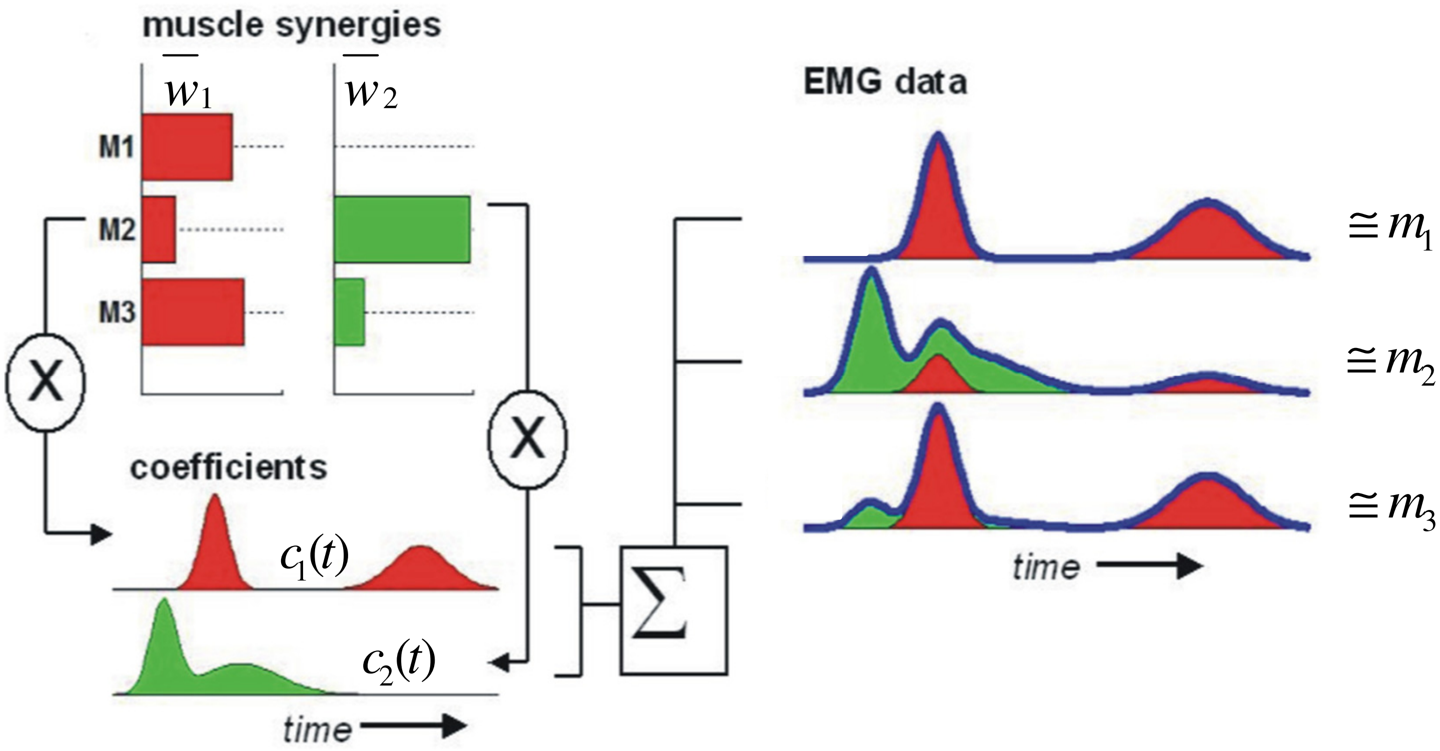
Muscle organization of WBP

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

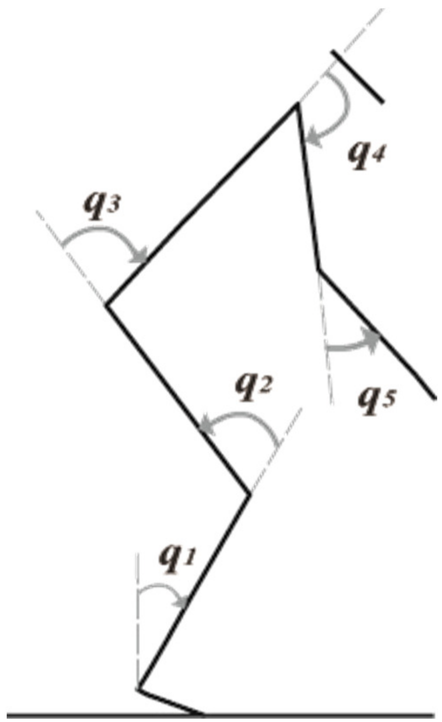
Muscle organization of WBP



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

Muscle organization of WBP

Inverse dynamic analysis + muscle dynamics modelling



$$\boldsymbol{\tau} = M(\boldsymbol{q})\cdot d^2\boldsymbol{q}/dt^2 + C(\boldsymbol{q},d\boldsymbol{q}/dt)\cdot d\boldsymbol{q}/dt+N(\boldsymbol{q})$$

$$d\boldsymbol{\tau}/dt = (\boldsymbol{\varepsilon}-\boldsymbol{\tau})/\sigma$$

$$d\boldsymbol{\varepsilon}/dt = (\boldsymbol{\alpha}-\boldsymbol{\varepsilon})/\sigma$$

$\boldsymbol{q}$ = vector of the generalized coordinates

$\boldsymbol{\tau}$ = vector of the joint torques

$\boldsymbol{\varepsilon}$ = EMG signal

$\boldsymbol{\alpha}$ = muscle activation signal

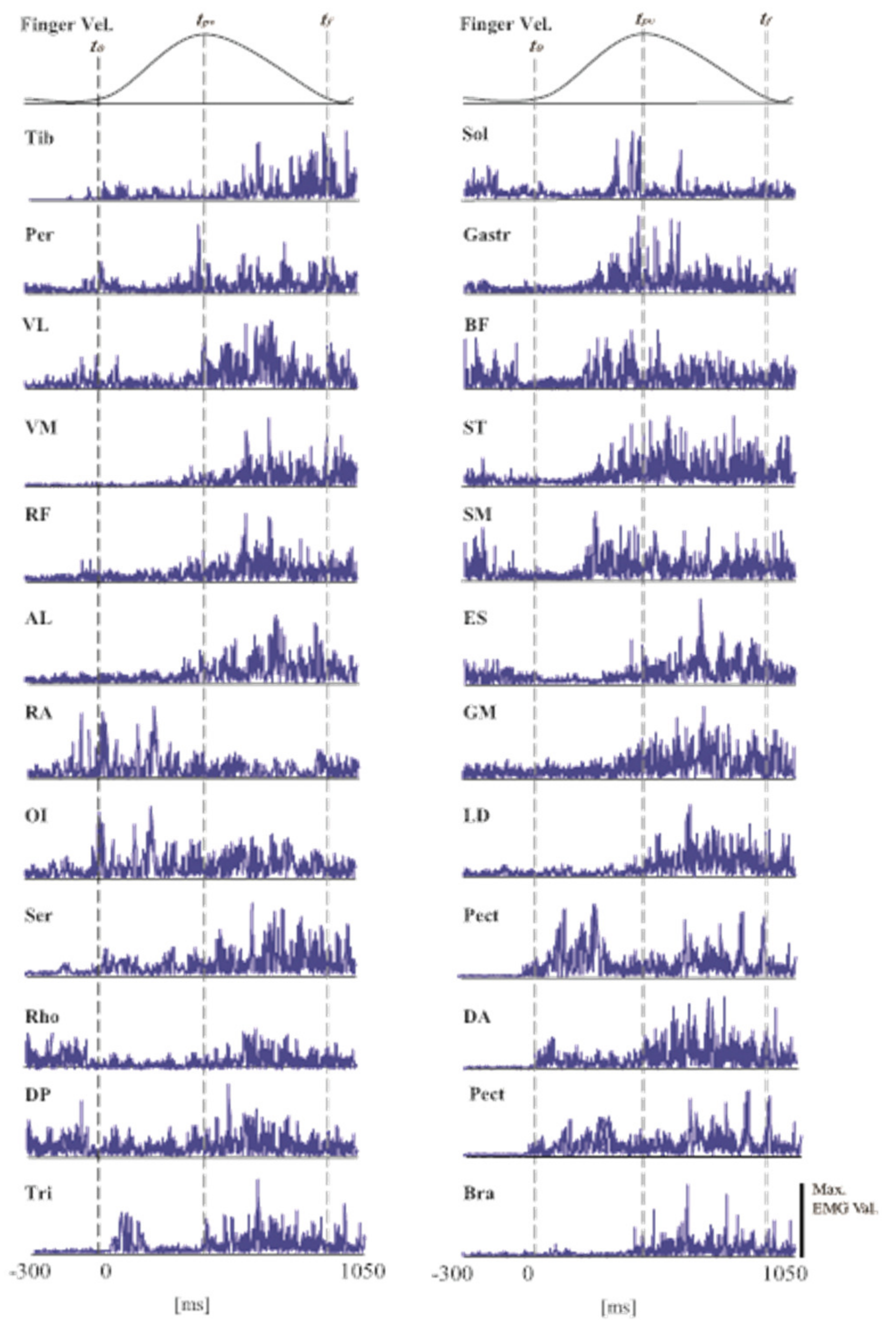
σ = constant

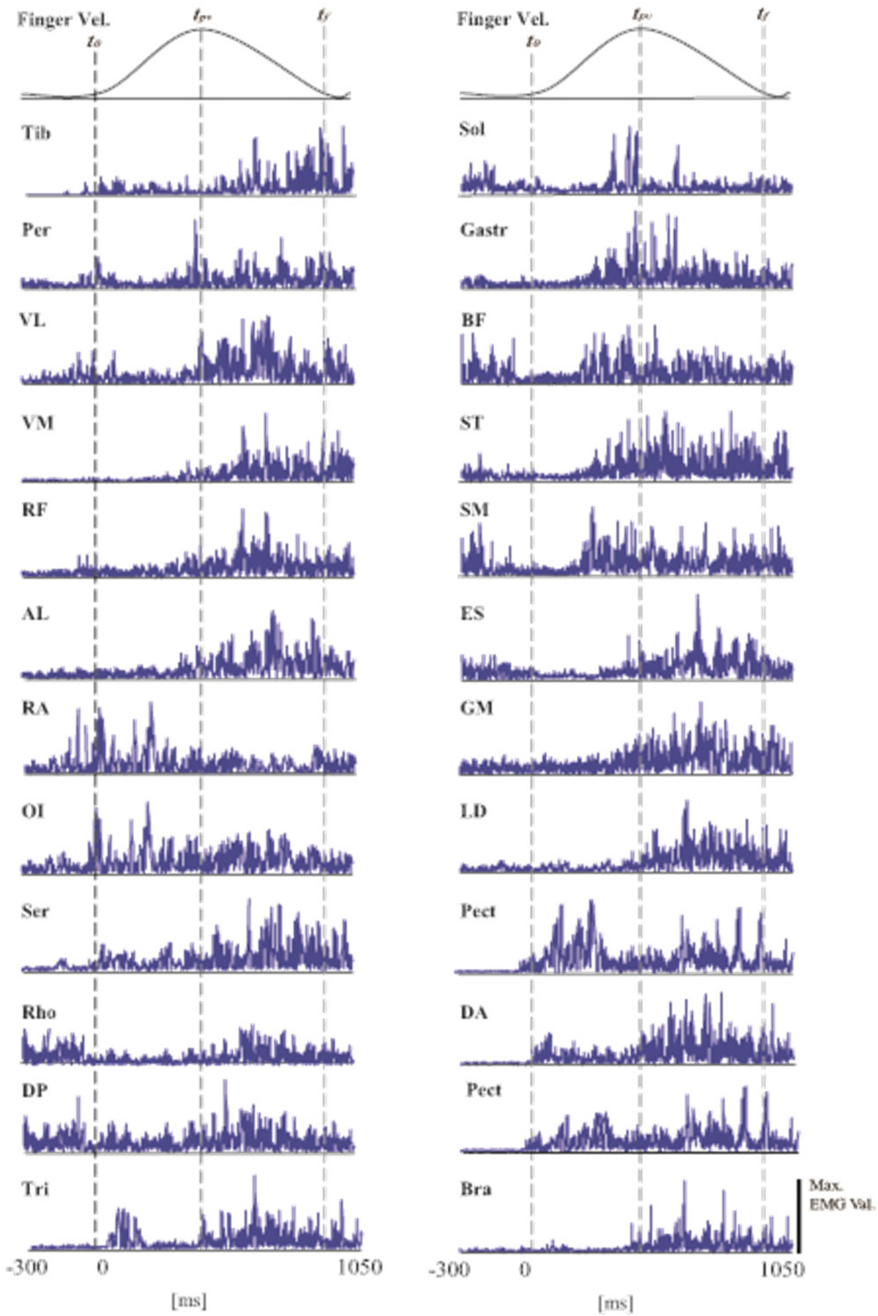
Muscle organization of WBP

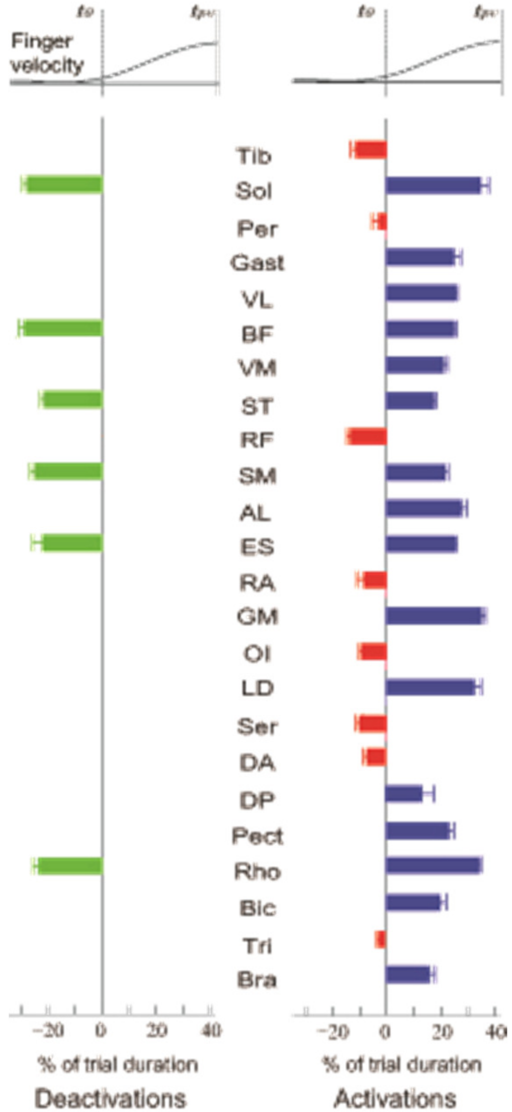
Results

Typical muscle activity recorded during one trial

(Chiovetto et al. 2008, 2010)



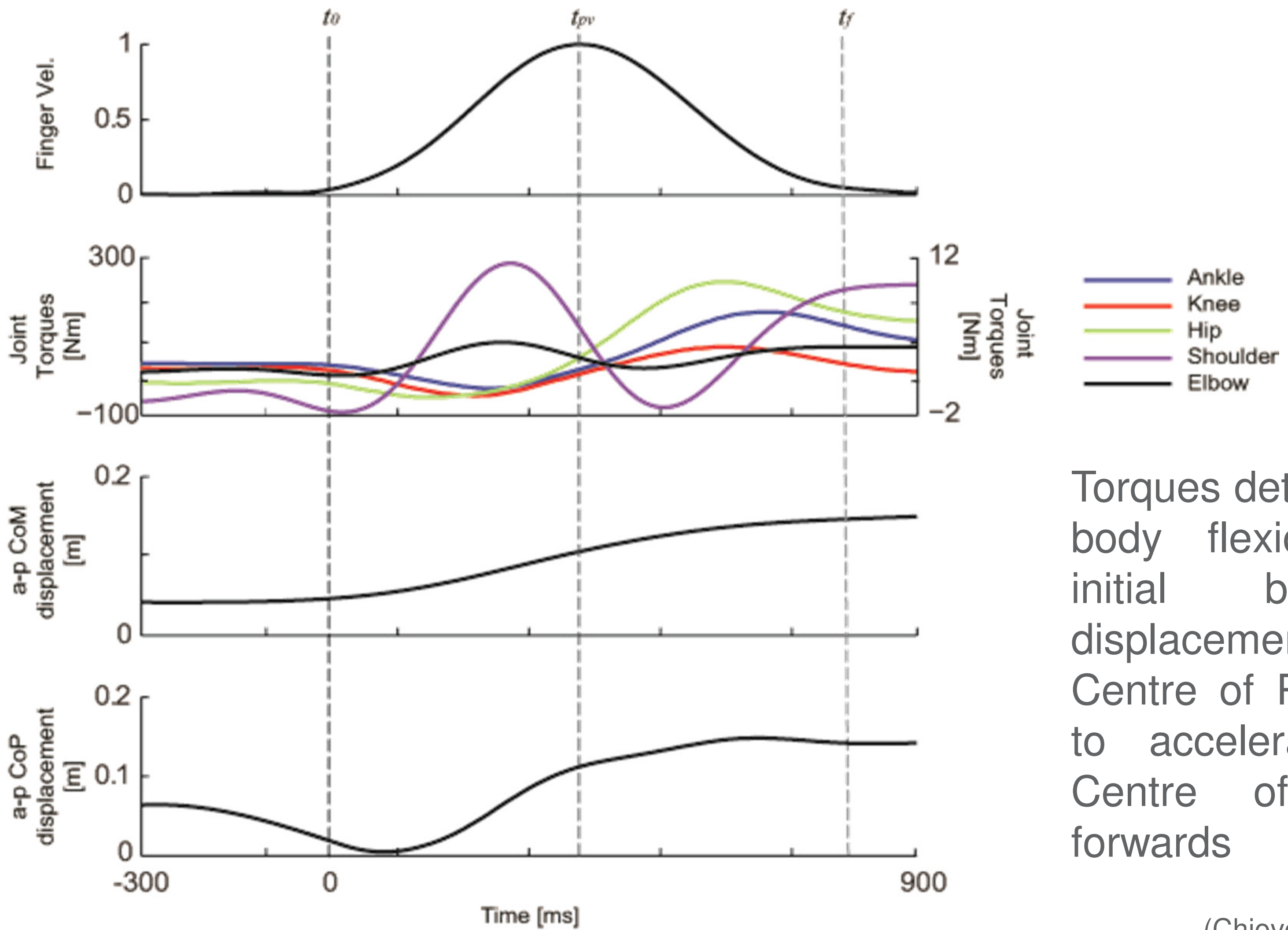




Deactivation-Activation onset delays

(Chiovetto et al. 2008, 2010)

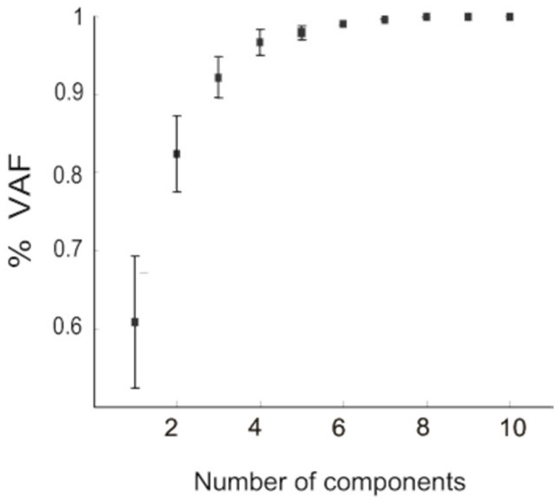
Muscle organization of WBP

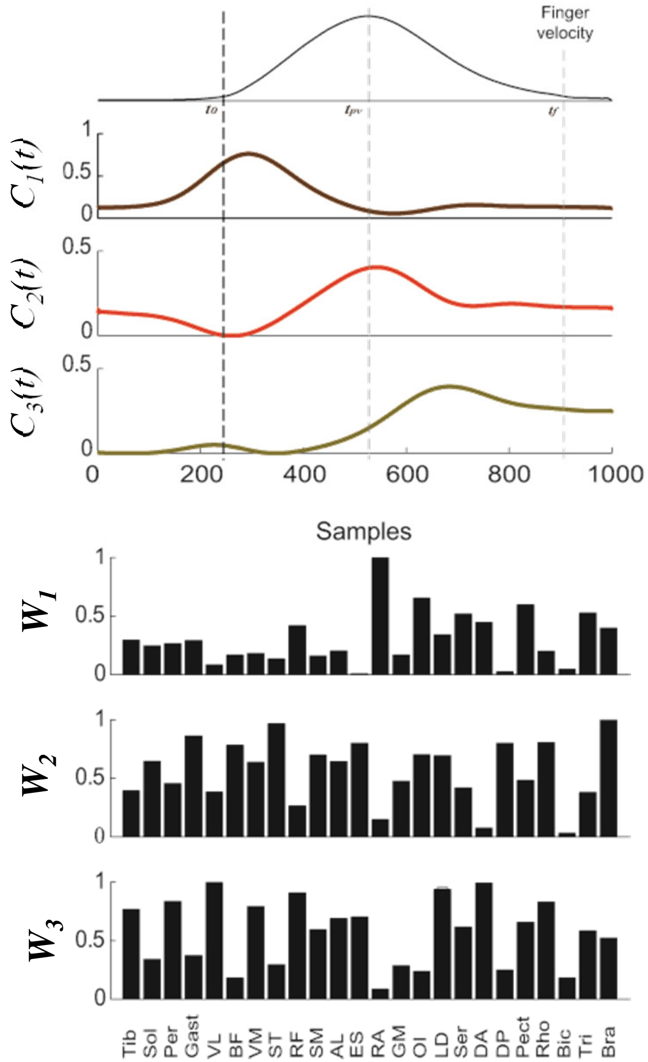


Torques determined body flexion and initial backward displacement of the Centre of Pressure to accelerate the Centre of Mass forwards

(Chiovetto et al. 2009)

Muscle organization of WBP





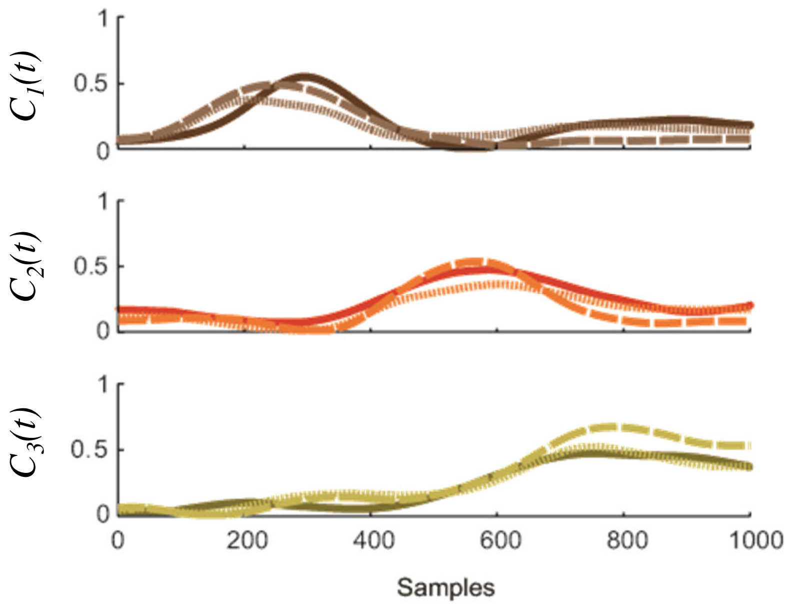
$$E^2 = \sum_{k=1}^{T} \left\| \overline{m}(t_k) - \sum_{i=1}^{N} c_i(t_k) \cdot \overline{w_i} \right\|^2$$

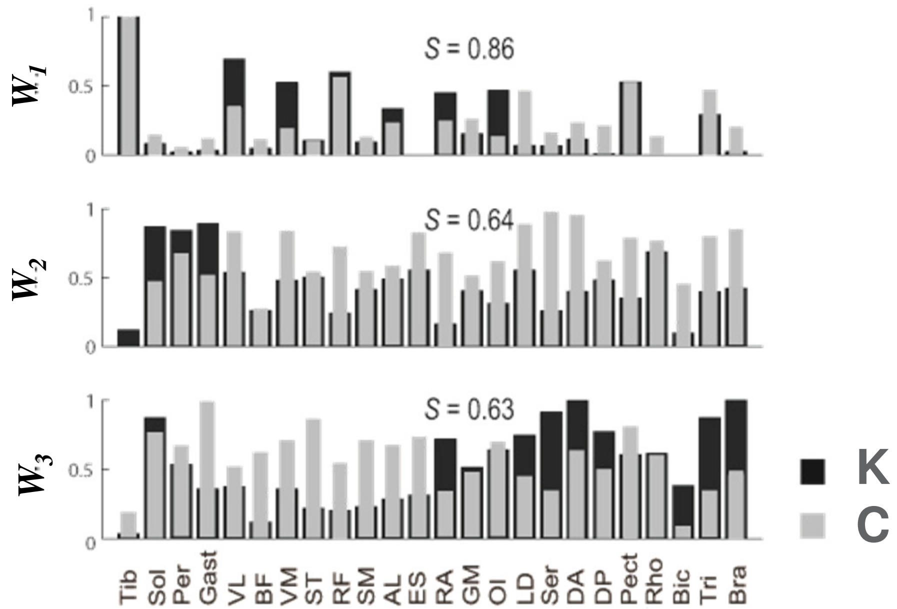
NNMF Cost Function

(Chiovetto et al. 2010)

Muscle organization of WBP

K and C



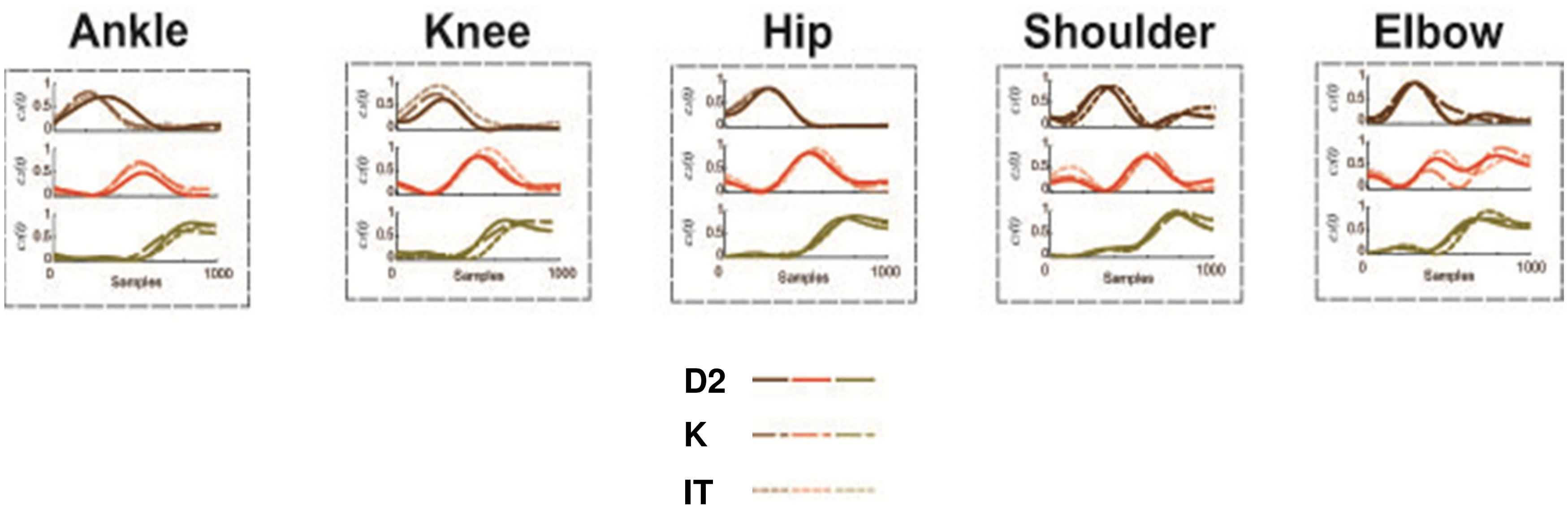


K and **C** are the dashed lines, **B** the solid one.

(Chiovetto et al. 2010)

Muscle organization of WBP

Results
(local analysis)



(Chiovetto et al. 2010)

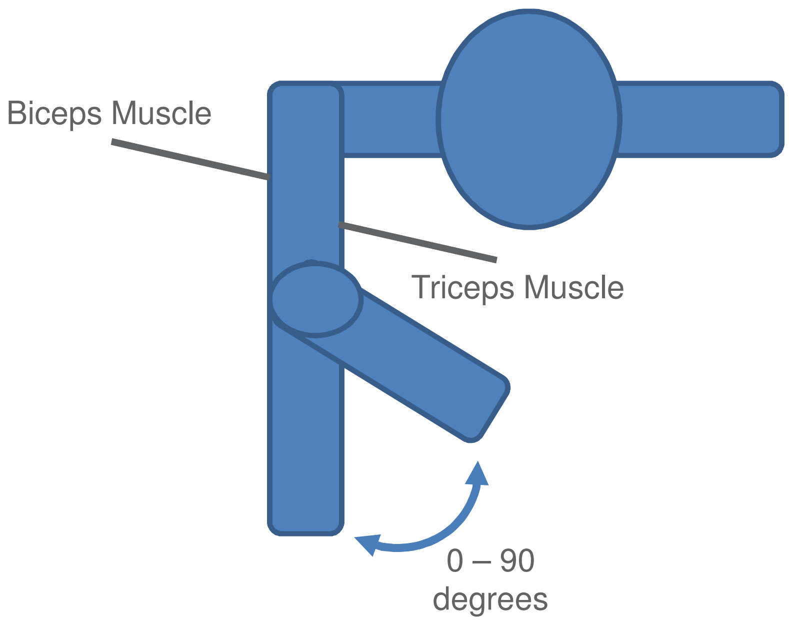
Take home message

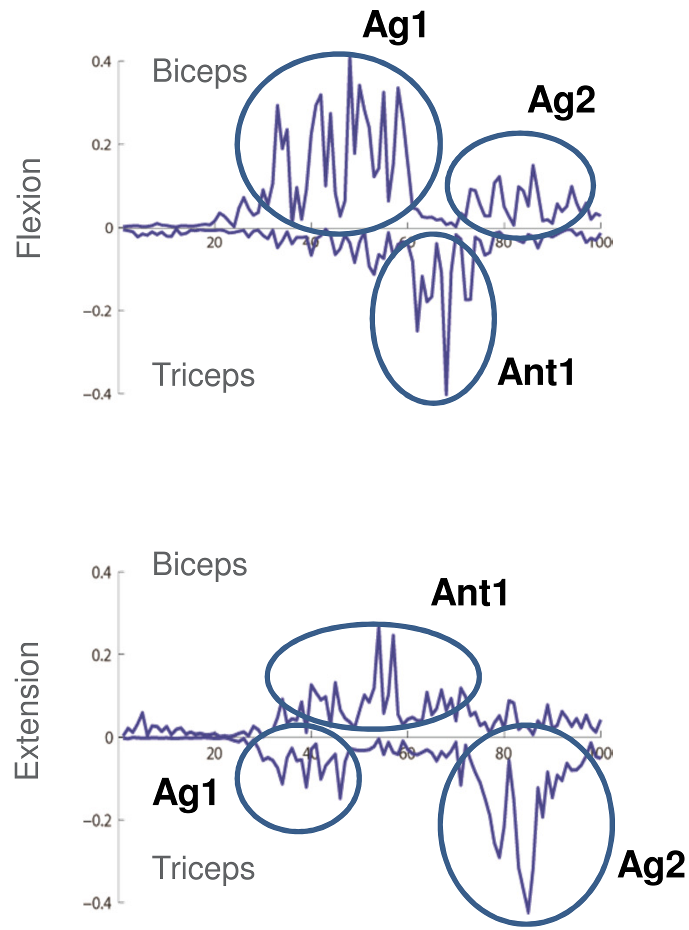
- 24 muscle → 3 temporal components (TRIPHASIC PATTERN)

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

- 3 components also at local level (single joints)

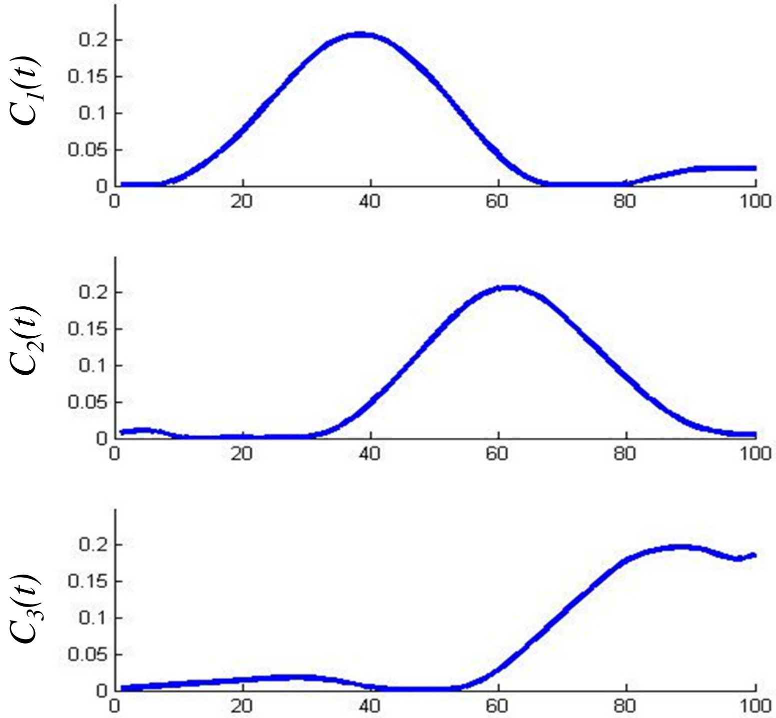
Elbow Flexion and Extension





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

Elbow Flexion and Extension



Standardized time

2 muscles → 3 functional components

Take home message

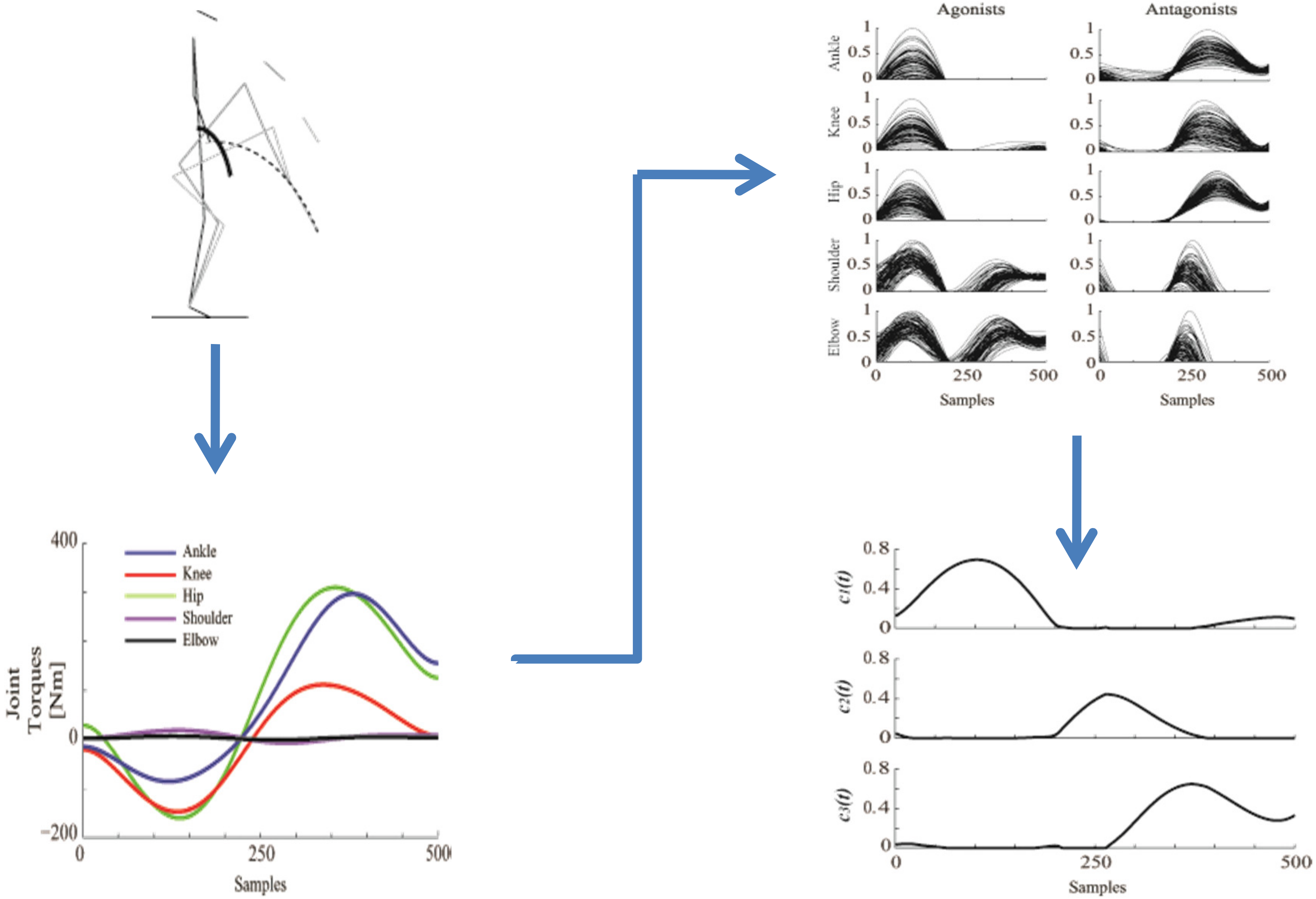
- 24 muscles → 3 components (TRIPHASIC PATTERN)

- 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 → 3 components (TRIPHASIC PATTERN)

- 3 components also when postural and focal constraints were introduced

- 3 components also at local level (single joints)

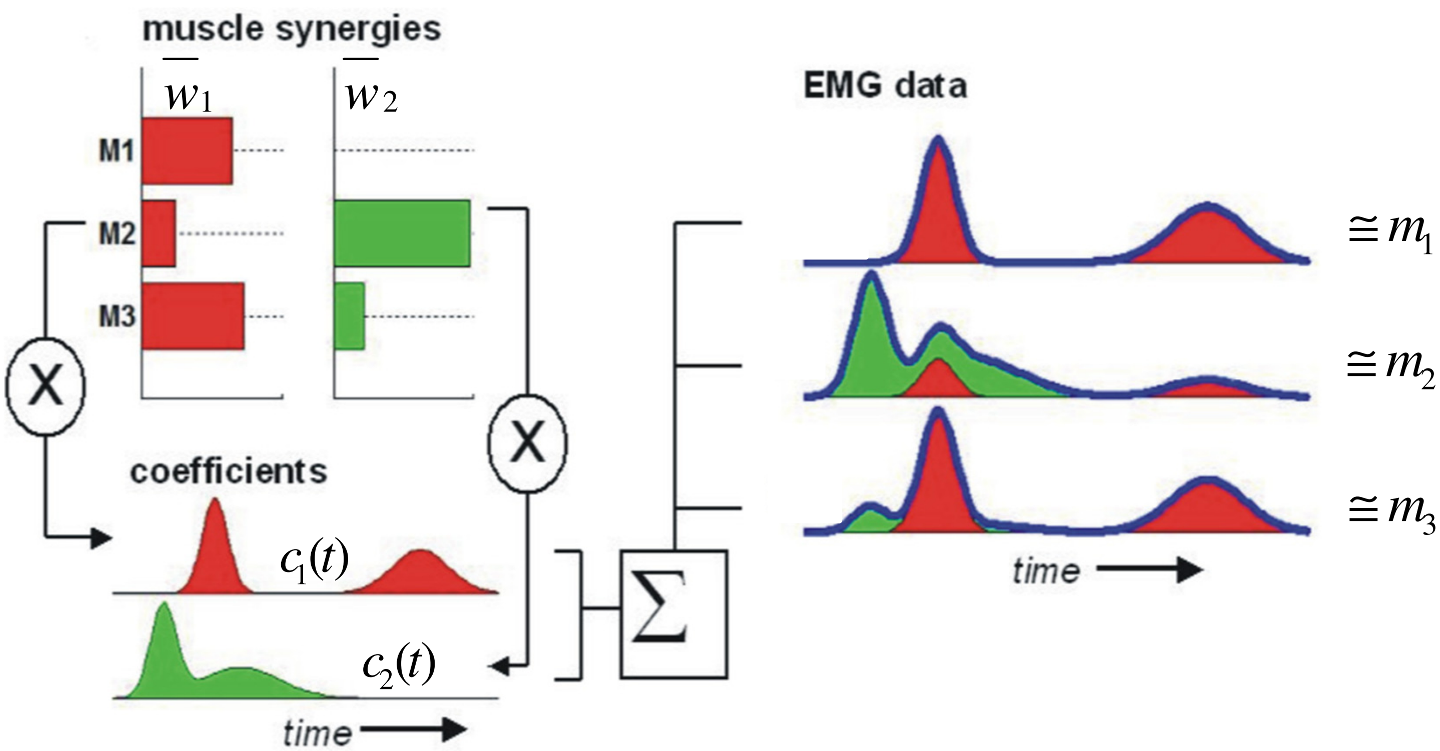
- The triphasic pattern is independent of the number of muscles and might represent a standard mode to generate movement

- 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



$$\boldsymbol{m}(t) = \sum_{i=1}^{n} c_i(t) \cdot \boldsymbol{w}_i$$

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

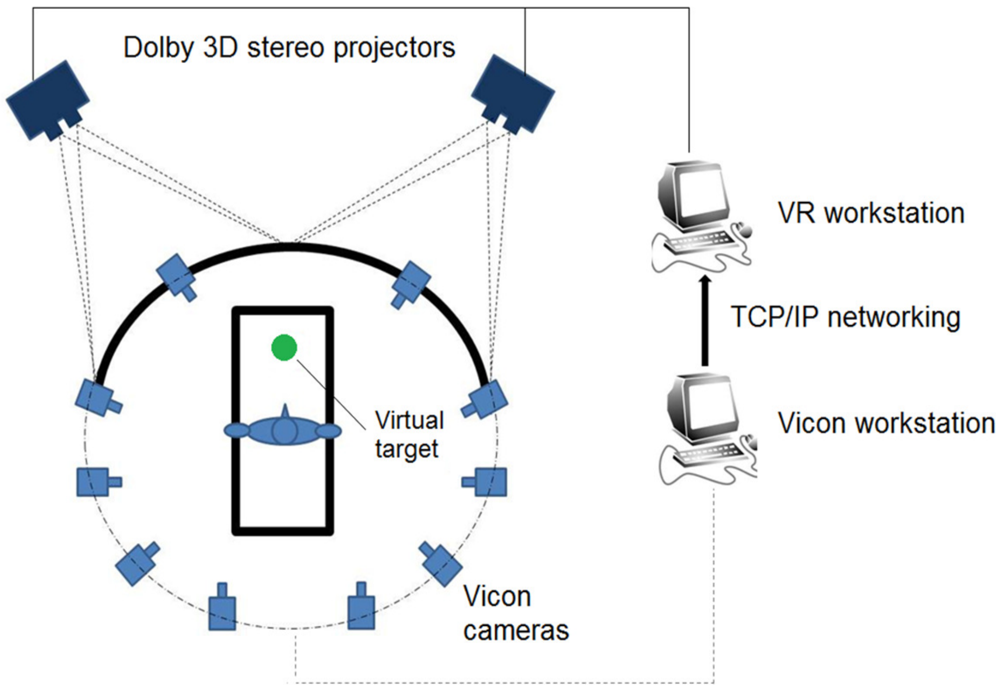
The previous equation is redundant -> computation of a set of projections onto lower dimensional spaces that specify the same information as the original problem. Solution comes the iterative solution of the following two equations:

$$\left|Fx_i(\omega)\right|^2 = \sum_j \left|a\right|_{ij}^2 \left|Fs_j(\omega)\right|^2$$

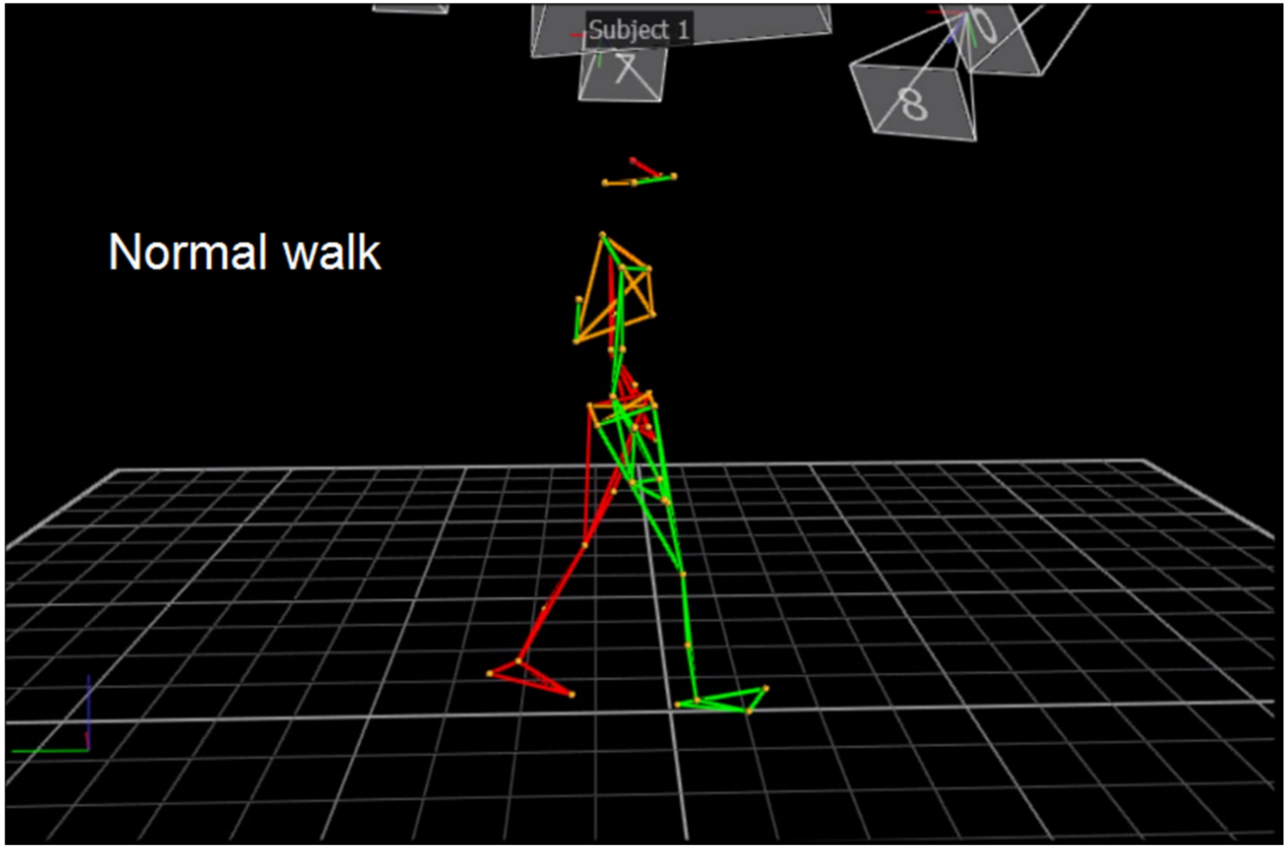
$$\left|Fx_i(\omega)\right|^2 \frac{\delta}{\delta\omega} \arg\left\{Fx_i(\omega)\right\} = \sum_j \left|a\right|_{ij}^2 \left|Fs_j(\omega)\right|^2 \left[\frac{\delta}{\delta\omega} \arg\left\{Fs_j(\omega)\right\} + \tau_{ij}\right]$$

where *Fx* and *Fs* indicate the Fourier transformations of the trajectory data and the sources.

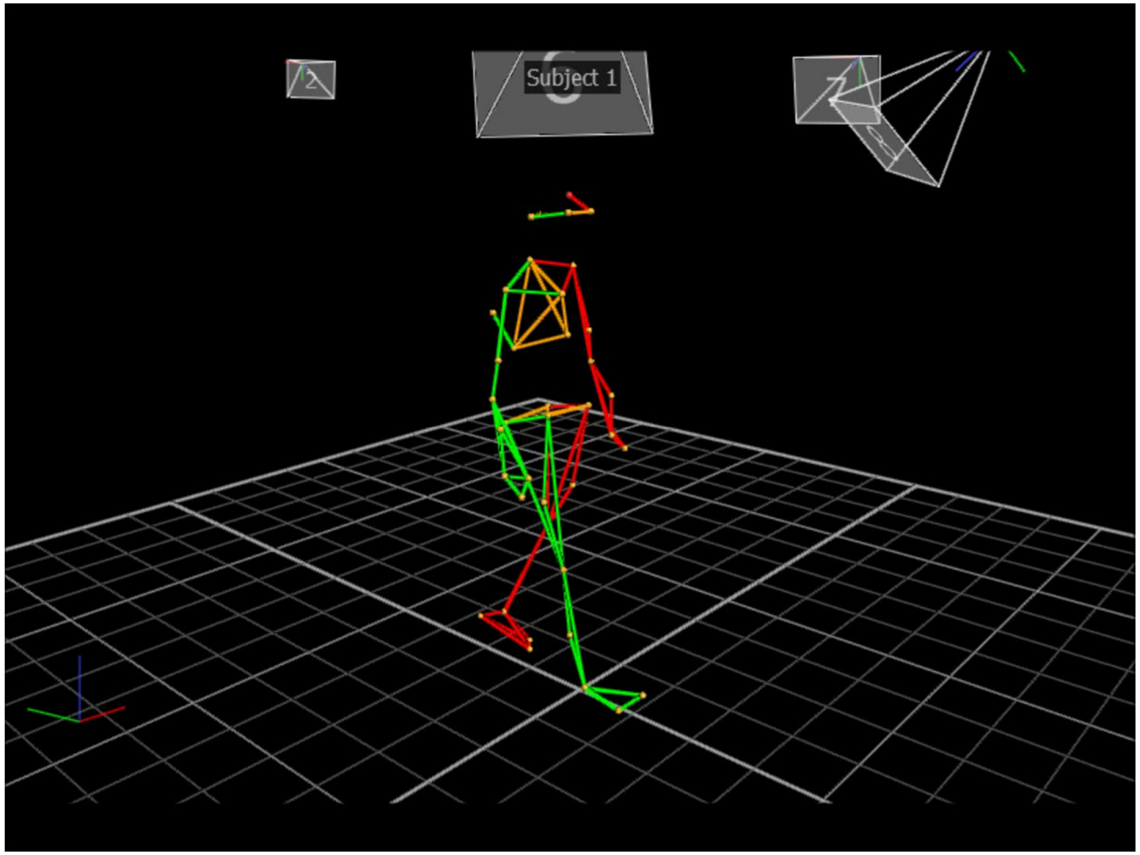
Dynamic coupling of periodic and non-periodic motor primitives: experimental setup



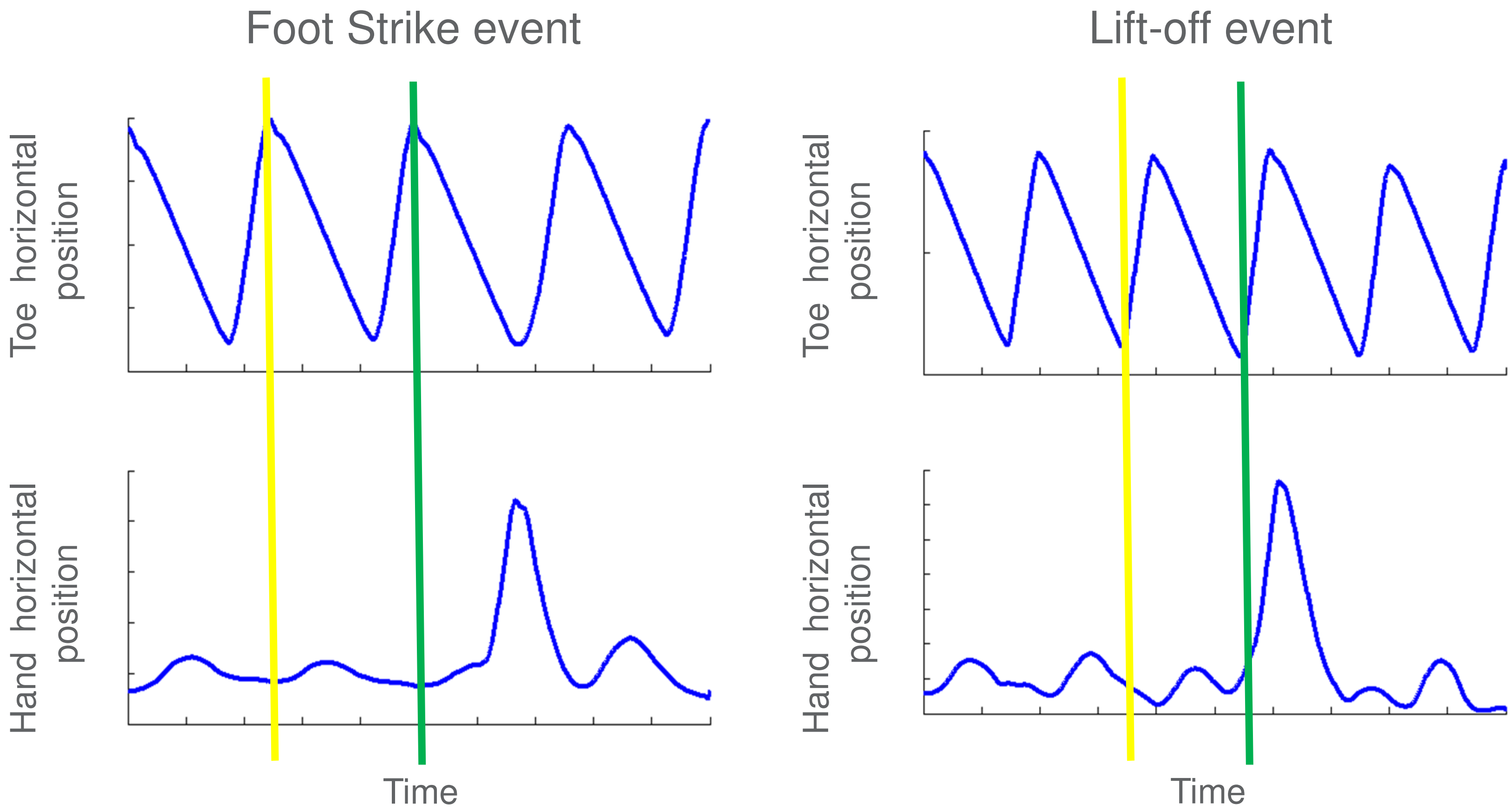
Dynamic coupling of periodic and non-periodic motor primitives: experimental setup



Dynamic coupling of periodic and non-periodic motor primitives: experimental setup



Setup to study walking and reaching in virtual reality



My collaborators

Compsens Lab, Hertie Institute (Tuebingen)

Prof. Martin Giese
Dr. Lars Omlor
Mr. Albert Mukovskiy

RBCS Lab, Italian Institute of Technology (Genova)

Prof. Thierry Pozzo
Dr. Bastien Berret
Dr. Francesco Nori

Neuromotor Lab, Fondazione Santa Lucia (Roma)

Dr. Andrea d'Avella

Thank you
Questions?

www.compsens.uni-tuebingen.de