A minimum transition hypothesis to account for motor synergies

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NCM
Naples, Florida
April 2002

Question:

How does the brain control many muscles simultaneously?

Answer: (by Harvey)

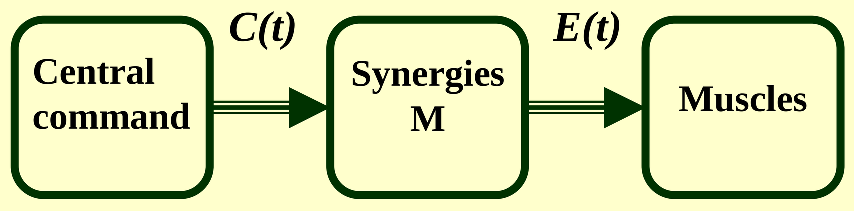
"Nature sets in motion by signs and watchwords, which are made with little momentum…. Just as in the army the soldiers are set in motion by one word as if by a given signal and continue to move until they receive another signal to stop, so the muscles move in order and harmony from established custom."

William Harvey (1578-1657)

Synergies as filters

- We define muscle synergy by a group of filters that receive the same motor command and transform it to activation signals for certain muscles.
- In the matrix notation below, each column represents one synergy.

1 Synergies as a matrix of filters



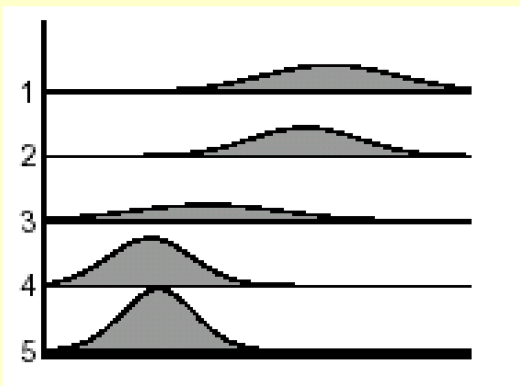
$$\begin{bmatrix} e_1(t) \\ e_2(t) \\ \vdots \\ e_K(t) \end{bmatrix} = \begin{bmatrix} \mu_{11} & \mu_{12} & \cdots & \mu_{1N} \\ \mu_{21} & \mu_{22} & \cdots & \mu_{2N} \\ \vdots & \vdots & & \vdots \\ \mu_{K1} & \mu_{K2} & \cdots & \mu_{KN} \end{bmatrix} \begin{bmatrix} c_1(t) \\ c_2(t) \\ \vdots \\ c_N(t) \end{bmatrix}$$

μ_{ij} is a general filter with input signal $c_j(t)$ and output signal $e_i(t)$

For linear time invariant filters: $E(s) = M(s) \cdot C(s)$

For static time invariant filters: $E(t) = M \cdot C(t)$

With simple filters, a single command and a single synergy could generate typical time varying muscle activation (see d'Avella and Tresch, NIPS 2001)



THE HYPOTHESIS

- We hypothesize that the bare control command consists of finite number of transitions, i.e., combination of steps:

$$c_i(t) = \sum_{j=1}^{J_i} k_{ij} \cdot u(t - t_{ij})$$

- The Minimum transitions hypothesis asserts that the synergies evolved to minimize the number of transitions:

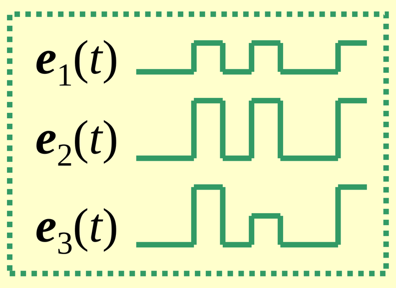
$$M^* = \arg\min_{M \in \mathrm{M}} \sum_{t=1}^{T} \sum_{i=1}^{N} \Delta C_i^M(t)$$

$$\Delta C_i^M(t) = \begin{cases} 0 & C_i^M(t) = C_i^M(t-1) \\ 1 & C_i^M(t) \neq C_i^M(t-1) \end{cases}$$

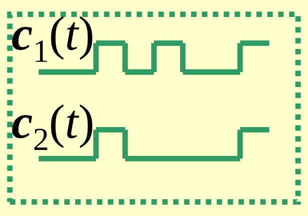
$$\mathrm{M} = \left\{ M \middle| \exists C^M \middle| E(t) = M \cdot C^M(t) \right\}$$

- The signals $E(t)$ should represent the expected behavior of the animal

2 A toy example for possible static synergies

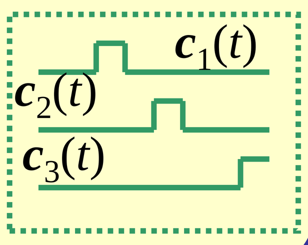


$$M^1 = \begin{bmatrix} 1 & 0 \\ 2 & 0 \\ 1 & 1 \end{bmatrix}$$



M	Transitions
I	15
M^1	8
M^2	5

$$M^2 = \begin{bmatrix} 1 & 1 & 1 \\ 2 & 2 & 2 \\ 2 & 1 & 2 \end{bmatrix}$$



PREDICTIONS

I. The muscles activation signals could be well described as a sum of filtered commands consists of pulses. (i.e., better than other descriptions with equivalent complexity.)

II. The number of transitions in the actual synergies should be smaller than in any equivalent synergies. (This is the definition of M^*)

III. For static synergies, the number of transitions in the command signal per transition in the muscles' signal should be smaller in actual signals than the number in shuffled signals. (shuffling generates signals that are not physiologically plausible but could be represented by the same synergies).

Analysis of Multiple EMG

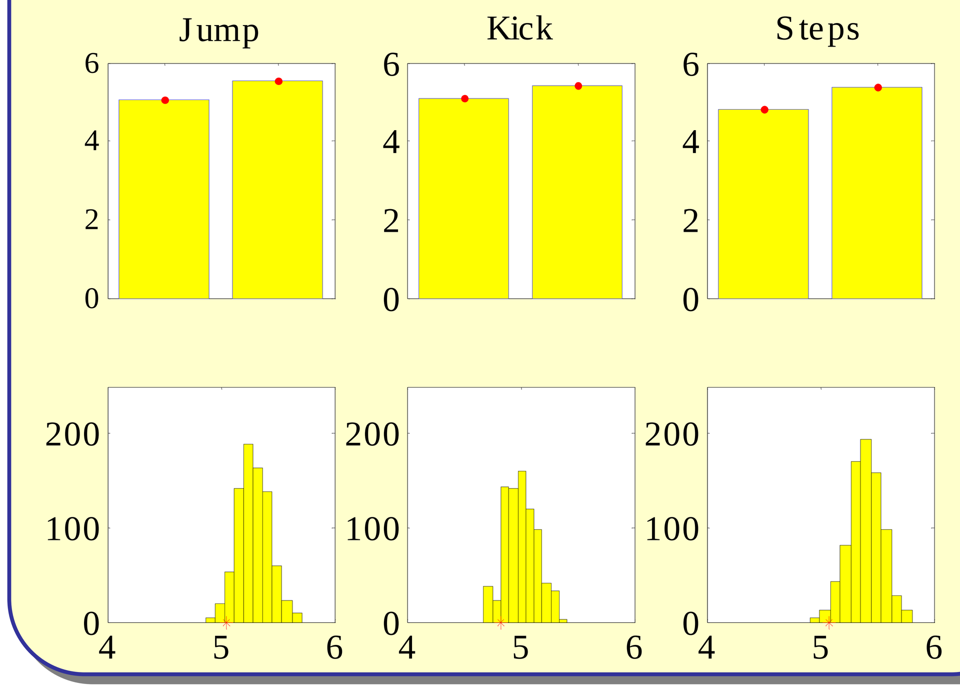
- Indications for small number of synergies and for dynamic filters could be found in previous studies (d'Avella and Tresch NIPS 2001).
- In order to test the second and third predictions we have analyzed the EMG signals of 13 muscles in behaving frogs.
- We did a preliminary test for the linear static synergies extracted with a non-linear least squares algorithm (Tresch et al. Nature Neuroscience 2,1999; Saltiel et al. J. Neurophysiol. 85,2001).
- The first test compared the transition number with the original and shuffled EMG.
- The second test compared the number of transitions with equivalent synergies:

$$E(t) = MAA^{-1}C(t) \Rightarrow MA \in \mathrm{M}$$

4 Testing the predictions:

First raw: Transitions in control signal per transitions in emg. (shuffled right)

Second raw: number of transitions with extracted (star) and equivalent synergies.



DISCUSSION

- We present a new hypothesis and a mathematical framework for synergies.
- Preliminary data analysis supports the predictions of the hypothesis
- In order to prove the hypothesis the complete distribution of the muscles activations needs to be estimated and the actual filters and connectivity of the synergies have to be found.
- The MTH provide new tools for the ongoing investigation of the superb dexterity in motor behavior

Supported by: NIH 5 P50 MH48185

Multiple Electromyography Recordings of Behaving Frogs

- 13 electrodes were placed in the muscles that control the hind limb of a frog.
- The EMG was recorded and averaged every 25 milliseconds as the frog was engaged in natural behavior such as kick or swim (Andrea d'Avella, PhD Thesis, MIT, 2000)

3 EMG Analysis

The figure depict one trace of 13 EMG signals during kick

The signal does not appear like pulses and steps, but it might be a smoothed version of pulses and steps. In the data analysis we considered only significant changes in the norm of the EMG. Significant was defined as change over two time steps in the norm of the EMG.