Whole-body motor strategies for balancing on a beam

when changing the number of available degrees of freedom

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Introduction

- How the central nervous system controls the excessive number of degrees of freedom (dof) to accomplish complex movements remains still an open question.
- A possible solution to the problem might be provided by a modular architecture that is composed from invariant control modules (motor primitives or synergies), which are linearly combined to generate the desired motor output [1,2,3,4,5].
- Although many studies have focused on the identification of such primitives, less attention has been given to adaptive mechanisms that allow the system to deal flexibly with varying constraints or situations when specific dof become unavailable [6,7]. A previous study from our groups have shown that freezing of dof improves task performance [8].
- In this study, we investigated how complex motor coordination patterns vary during a highly redundant whole-body task, in both constrained and unconstrained conditions.

Experiments

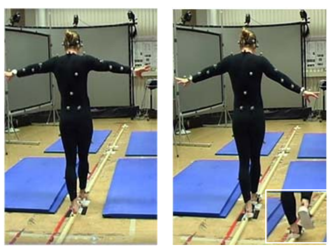
Experiment 1 (arms constrained)

- 9 participants were asked to walk on a narrow beam (3.5cm wide, 5m long) at a self-selected speed.
- Three sessions (free, constrained, free).
- In each session, participants performed as many trials as necessary to complete 20 successful trials.
- A trial was deemed successful, if the participant remained on the beam for its entire length.
- In the constrained condition elbow and wrist joints were fixated by rigid tubes.

Free Constrained

Experiment 2 (feet constrained)

- 7 participants were asked to perform the same walking task as in experiments 1, but in the second session the feet, instead of the arms, were constrained.
- In the constrained condition the flexion of the feet was prevented by having participants wearing special sandals with rigid soles.



Free Constrained

Analysis

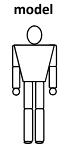
Angular momentum (x-axis direction)

- Motion of a 14-segment rigid body model was fit to the 3D motion capture data.
- Angular momenta (AM) about the x-axis (beam direction) around the body's COM were calculated for each segment i.
- For each subject, the contribution of each link to the total angular momentum was computed.

$$\mathbf{L}_i = (\mathbf{r}^i_{CM} - \mathbf{r}_{CM}) \times m_i(\mathbf{v}^i_{CM} - \mathbf{v}_{CM}) + \mathbf{I}^i\boldsymbol{\omega}_i$$

$\mathbf{L}_i$ = angular momentum
M = total mass
$\mathbf{r}_{COM}$ = COM position
$\mathbf{v}_{COM}$ = COM velocity
$\mathbf{r}^i_{COM}$ = COM position *i-th* segment
$\mathbf{v}^i_{COM}$ = COM velocity *i-th* segment
m_i = mass *i-th* segment
$\mathbf{I}_i$ = moment of inertia *i-th* segment
$\boldsymbol{\omega}_i$ = angular velocity *i-th* segment

Segmental body model



PCA

- Principal component analysis (PCA,[9]) was performed on the matrix $\mathbf{L}$, each row $\mathbf{L}_i$ being the angular momentum contribution provided the *i-th* segment.
- PCA on the covariance matrix.
- PCA factorization: $\mathbf{L{=}WH}$

each column of W being a principal component (PC). Each PC consists of a 14-component vector, corresponding to the 14 body segments of the human model. $\mathbf{L} \in \mathbb{R}^{14xT}$, $\mathbf{W} \in \mathbb{R}^{14xN}$, $\mathbf{H} \in \mathbb{R}^{NxT}$, with N<<T.

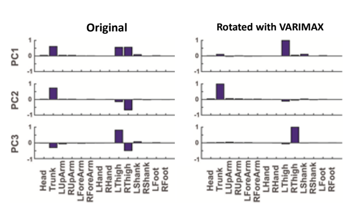
VARIMAX rotation

- Only N principal components (PCs), each explaining at least 5% of variance, were retained for each participant. PCs were rotated using VARIMAX rotation [10], as done in Factor Analysis, to improve sparness of components.
- VARIMAX maximizes the sum of the variances of the squared loadings (squared correlations between variables and PCs):

$$\nu = \sum (w_{ij}^2 - \overline{w}_{ij}^2)^2$$

- with w_{ij}^2 being the squared loading of the *i-th* variable on the *j-th* PC and $\overline{w}_{ij}^2$ being the mean of the squared loadings. VARIMAX keeps the components orthogonal to each other.

Representative example of VARIMAX rotation of the PCs

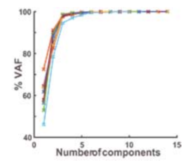


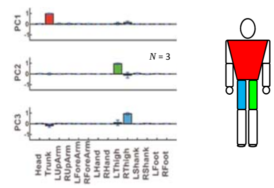
The main outcome of VARIMAX is **sparsification** of the PCs.

Results

Experiment 1

Session 1 (free, control)

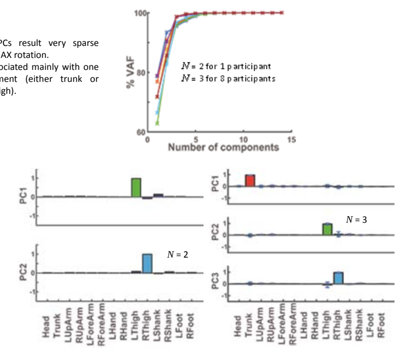




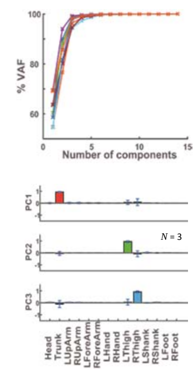
- Identified PCs result very sparse after VARIMAX rotation.
- Thy are associated mainly with one single segment (either trunk or left\right thigh).

Experiment 2

Session 1 (free, control)

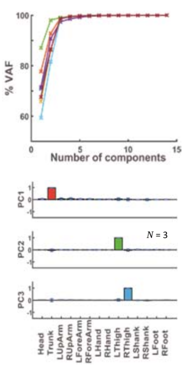


Session 2 (arms constrained)

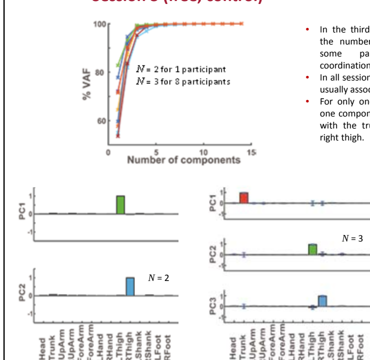


- In both the constrained sessions three PCs were always considered.
- "Elbows" in the % VAF curves seem to be qualitatively more pronounced for some subjects with respect the first session.

Session 2 (feet constrained)

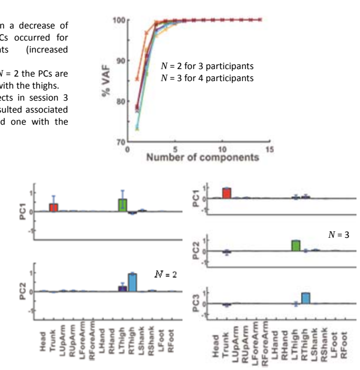


Session 3 (free, control)



- In the third session a decrease of the number of PCs occurred for some participants (increased coordination).
- In all sessions, for N = 2 the PCs are usually associated with the thighs.
- For only one subjects in session 3 one component resulted associated with the trunk and one with the right thigh.

Session 3 (free, control)



Conclusions

- Only few PCs are needed to account for the majority of the AM variation along the walking direction.
- Despite of their large kinematic variability along the frontal plane [8], arms do not contribute substantially to the total whole-body AM. Rather, AM seems determined by the segments that are the most proximal to the whole-body COM.
- Freezing the dof did not cause significant differences in the low-dimensional organization of the AM.

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