The degree of freedom problem

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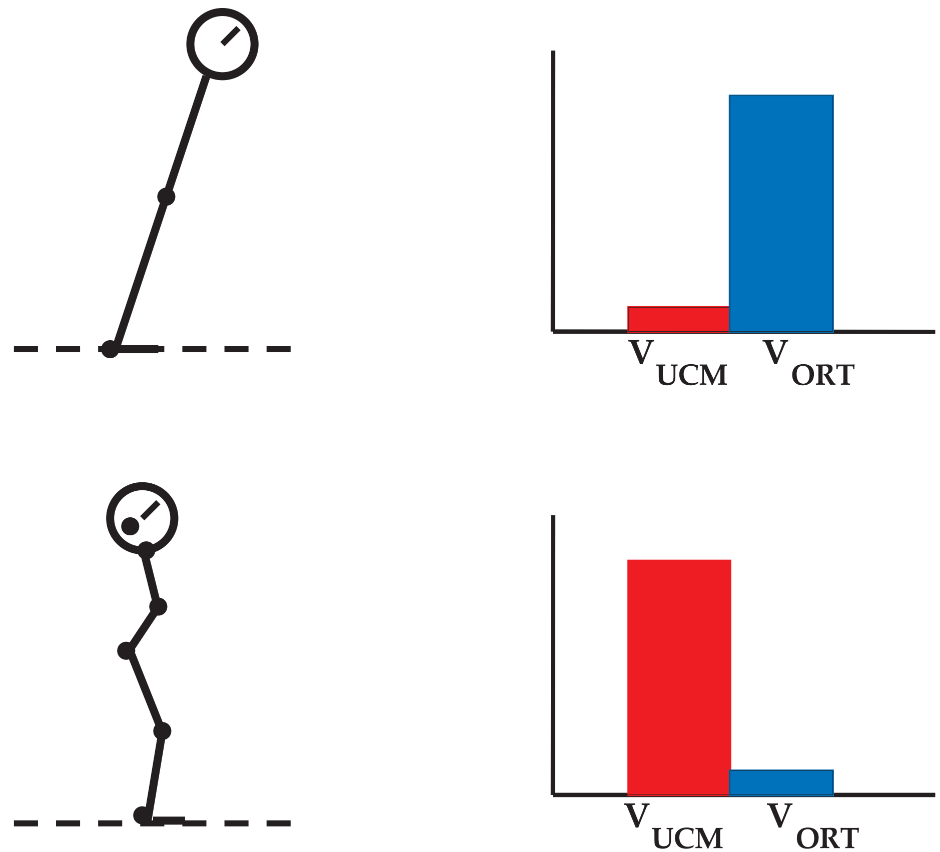
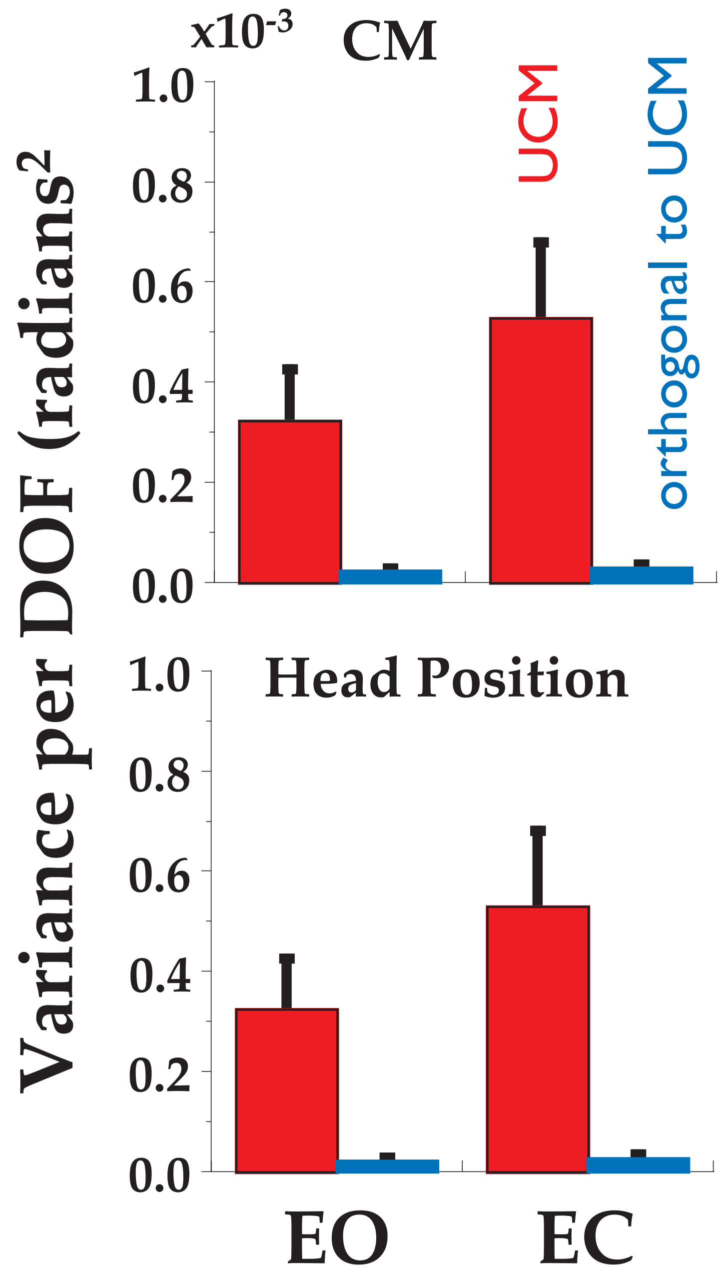
Example 3: posture

- Inverted pendulum hypothesis predicts the opposite than UCM



Example 3: posture

- but: find signature of UCM synergy



Hsu, Scholz, Schöner, Jeka, Kiemel, 2007

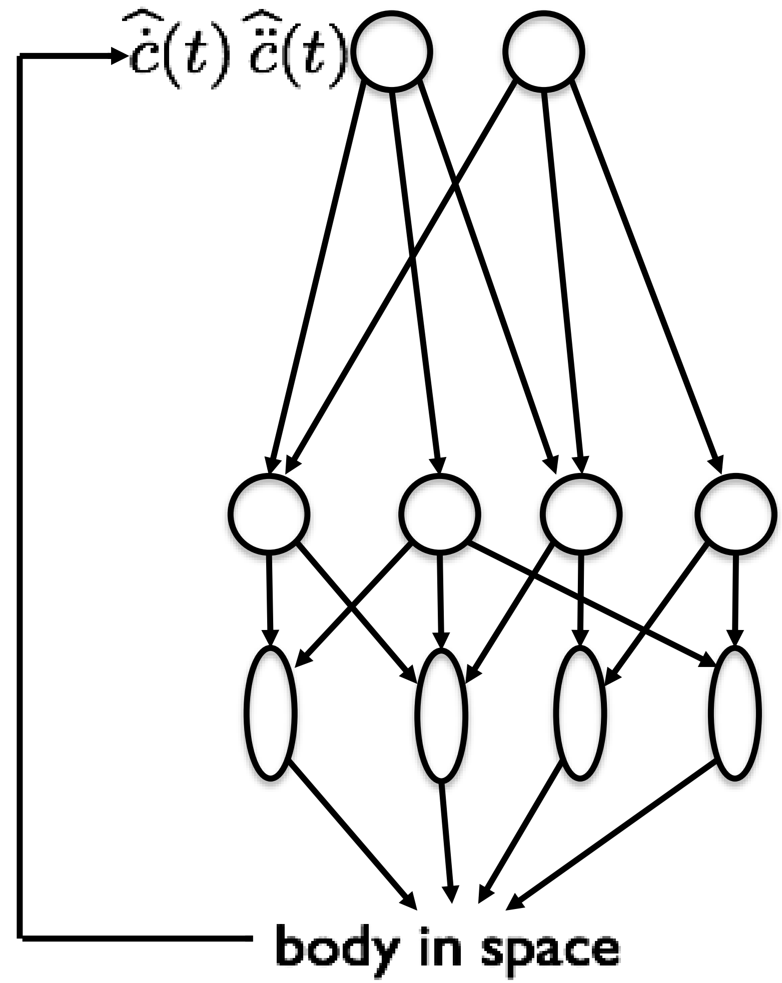
UCM synergy: from feedback

leads to change here

passes this to other DoF

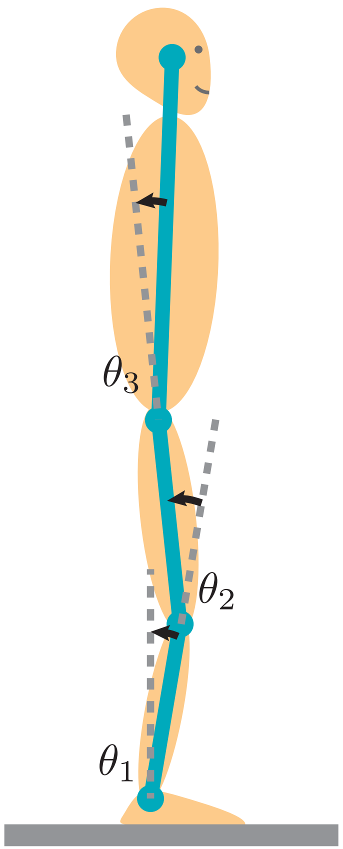
insert a perturbation here

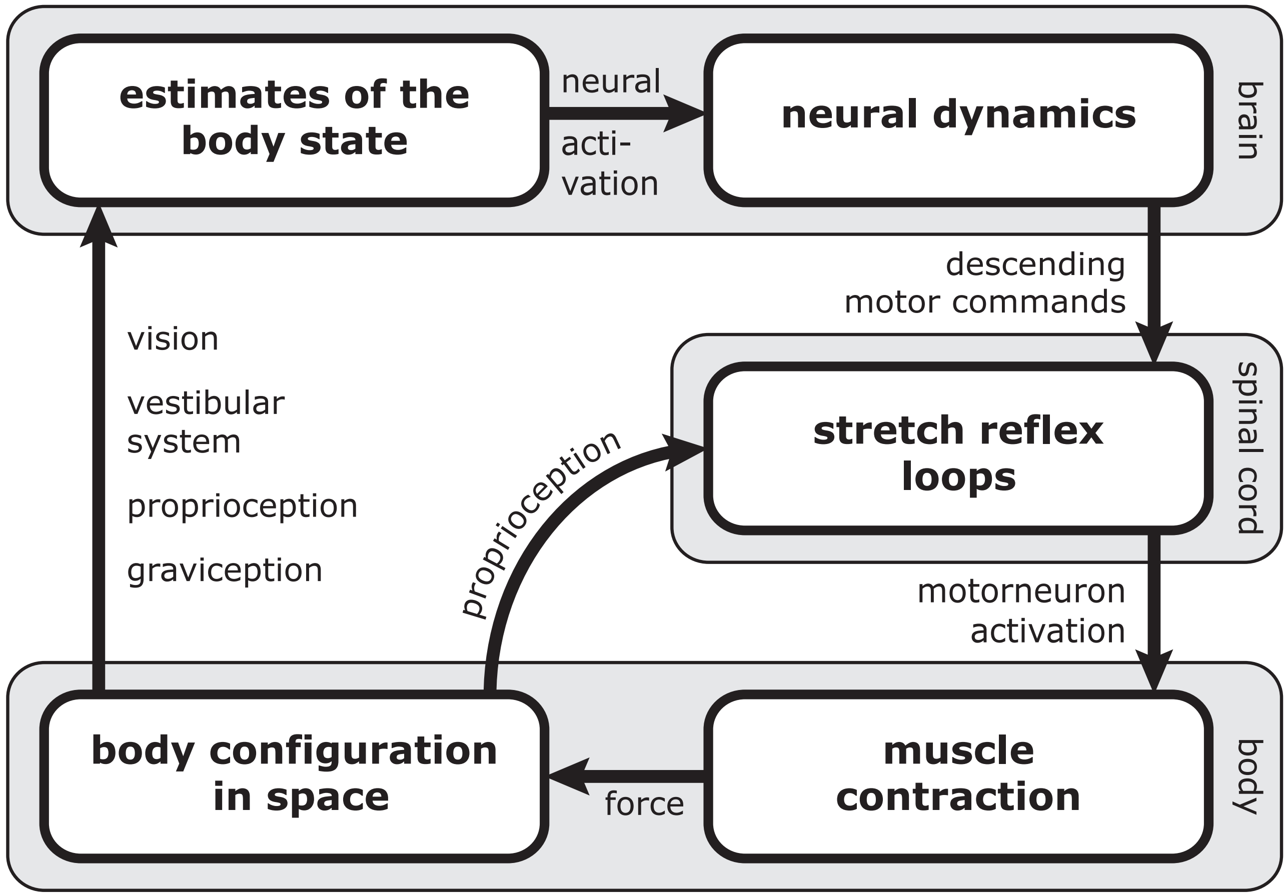
compensatory change here



Reimann, Schöner, Biological Cybernetics 2017

Multi-segment postural control model



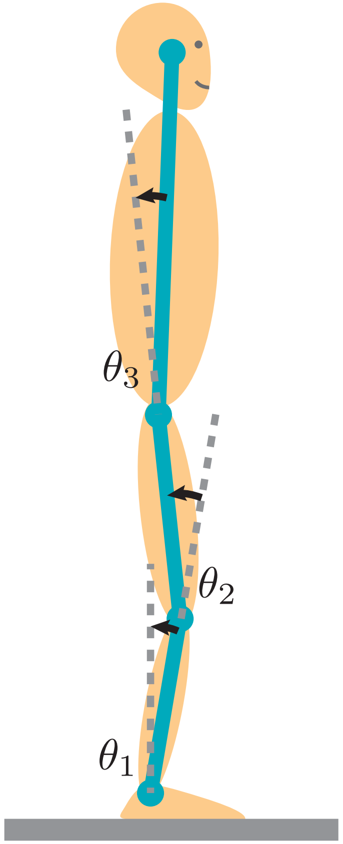


PhD thesis Hendrik Reimann

Reiman, Schöner, Biol Cybernetics 2017

Multi-segment postural control model

- bio-mechanical dynamics

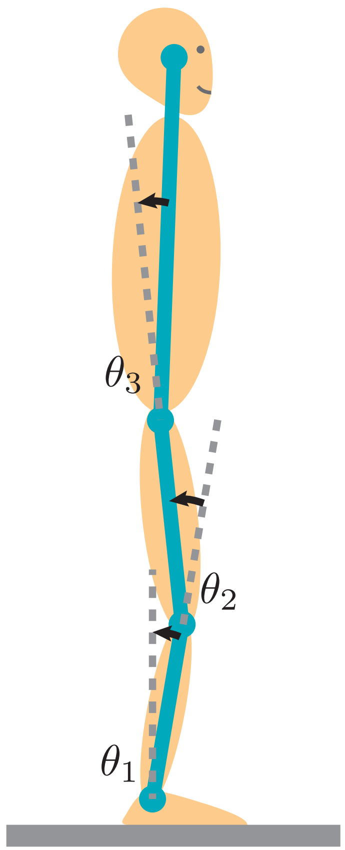


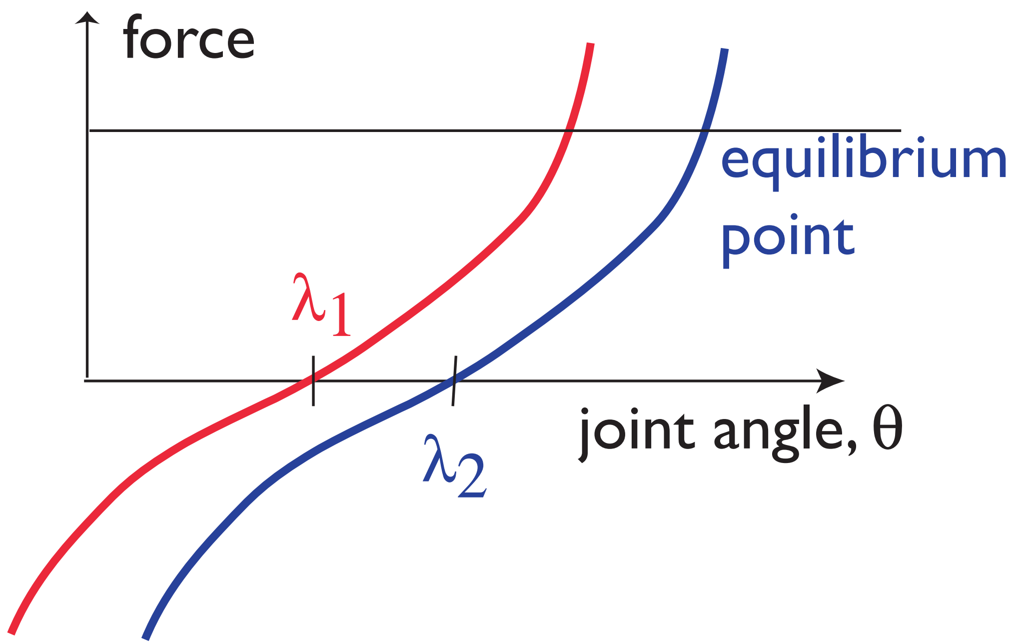
$$M(\theta)\ddot{\theta} + C(\theta, \dot{\theta})\dot{\theta} + N(\theta) = T$$

[Reiman, Schöner, Biol Cybernetics 2017]

Multi-segment postural control model

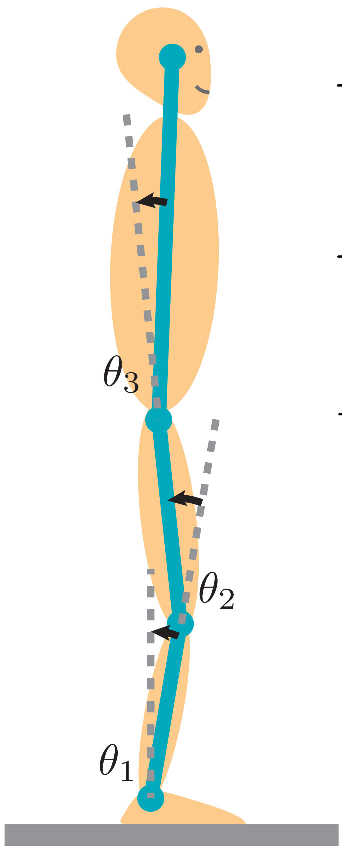
muscle model





Multi-segment postural control model

- muscle model



$$E_{\mathrm{AG}} = e^{\left[\alpha_E\left(\widehat{\theta}-\lambda+\rho+\mu(\dot{\widehat{\theta}}-\dot{\lambda})\right)\right]^{+}} - 1,$$

$$E_{\mathrm{AN}} = e^{\left[-\alpha_E\left(\widehat{\theta}-\lambda-\rho+\mu(\dot{\widehat{\theta}}-\dot{\lambda})\right)\right]^{+}} - 1.$$

muscle activation

$$E = \left(-E_{\mathrm{AG}} + E_{\mathrm{AN}}\right)\eta_m$$

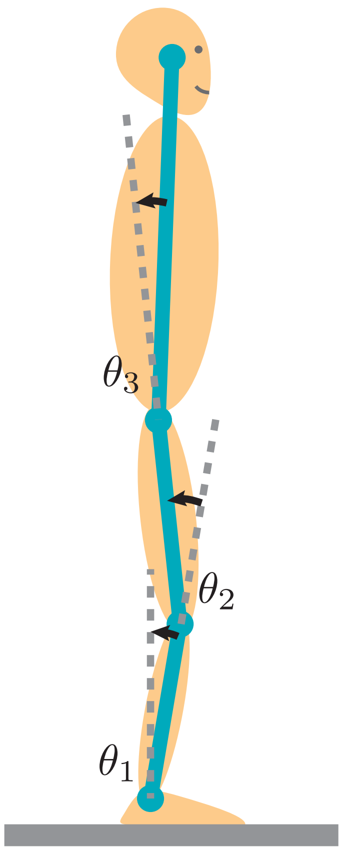
$$\widetilde{T}_{\mathrm{act}} = AE$$

$$\tau_m^2 \ddot{T}_{\mathrm{act}} + 2\tau_m \dot{T}_{\mathrm{act}} + T_{\mathrm{act}} = \widetilde{T}_{\mathrm{act}}$$

active muscle torque

Multi-segment postural control model

- muscle model



$$T_{\mathrm{ela},j} = \exp(a_{j0} + \sum_{i=1}^{3} a_{ji}\theta_i) - \exp(b_{j0} + \sum_{i=1}^{3} b_{ji}\theta_i) + c_{ji}$$

$$T_{\mathrm{vis}} = -B\dot{\theta}$$

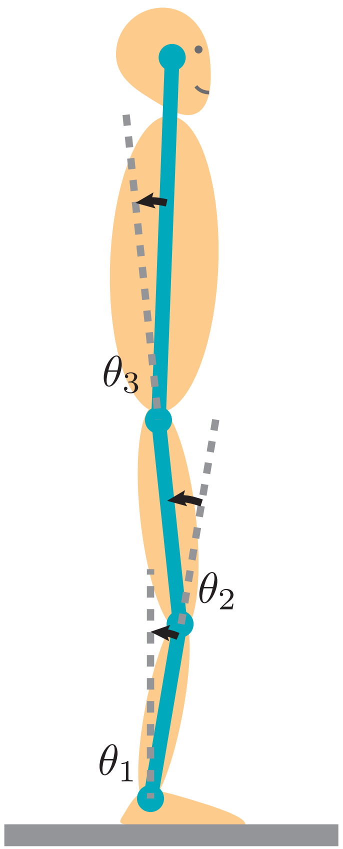
← passive torques

$$T = T_{\mathrm{act}} + T_{\mathrm{ela}} + T_{\mathrm{vis}}$$

← total muscle torque

Multi-segment postural control model

- sensor model



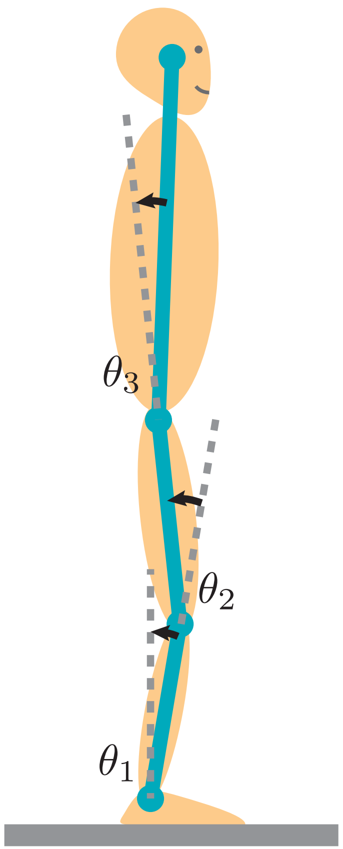
$$\widehat{\dot{c}}(t) = \dot{c}(t - d_c) + \eta_{\dot{c}},$$

$$\widehat{\ddot{c}}(t) = \ddot{c}(t - d_c) + \eta_{\ddot{c}},$$

body in space

Multi-segment postural control model

- control model



$$\dot{\lambda} = F_c = R^{-1}A^{-1}MJ_c^{+}\left(-\alpha_{\dot{c}}\widehat{\dot{c}} - \alpha_{\ddot{c}}\widehat{\ddot{c}}\right)$$

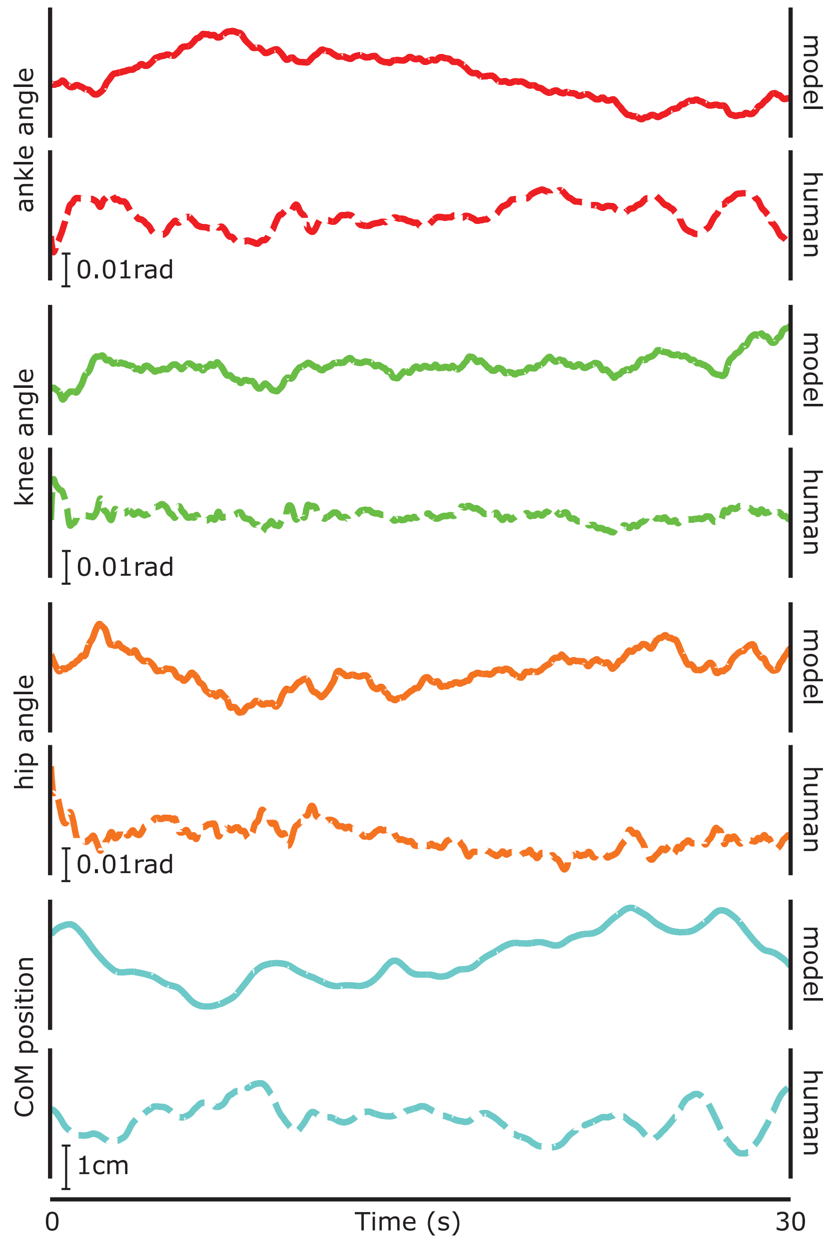
active stiffness

inertial tensor

kinematic pseudo-inverse

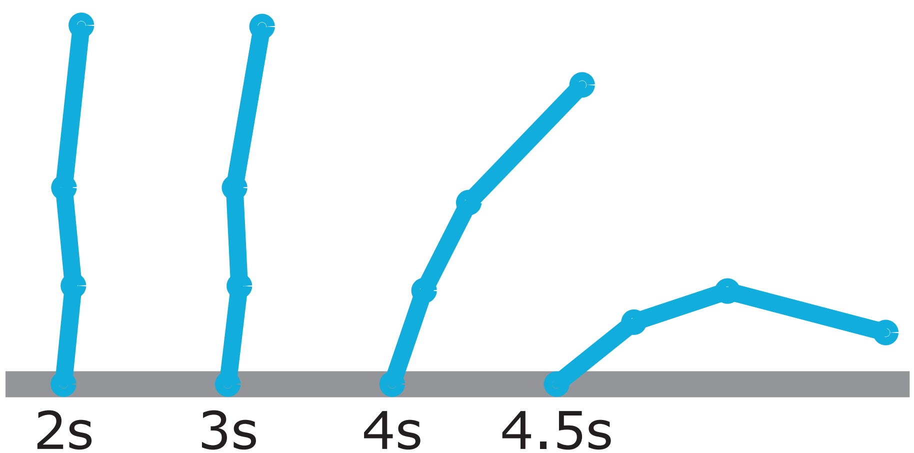
sensory estimate body in space

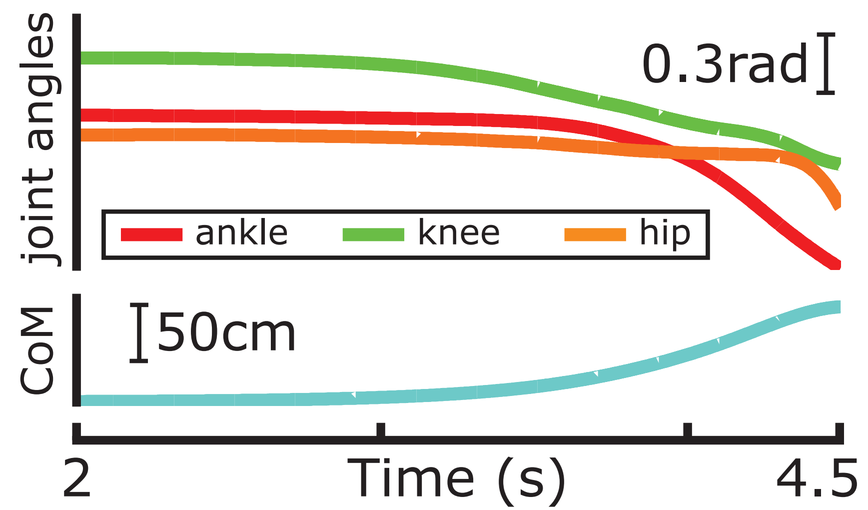
Results: model stands



Results: model falls

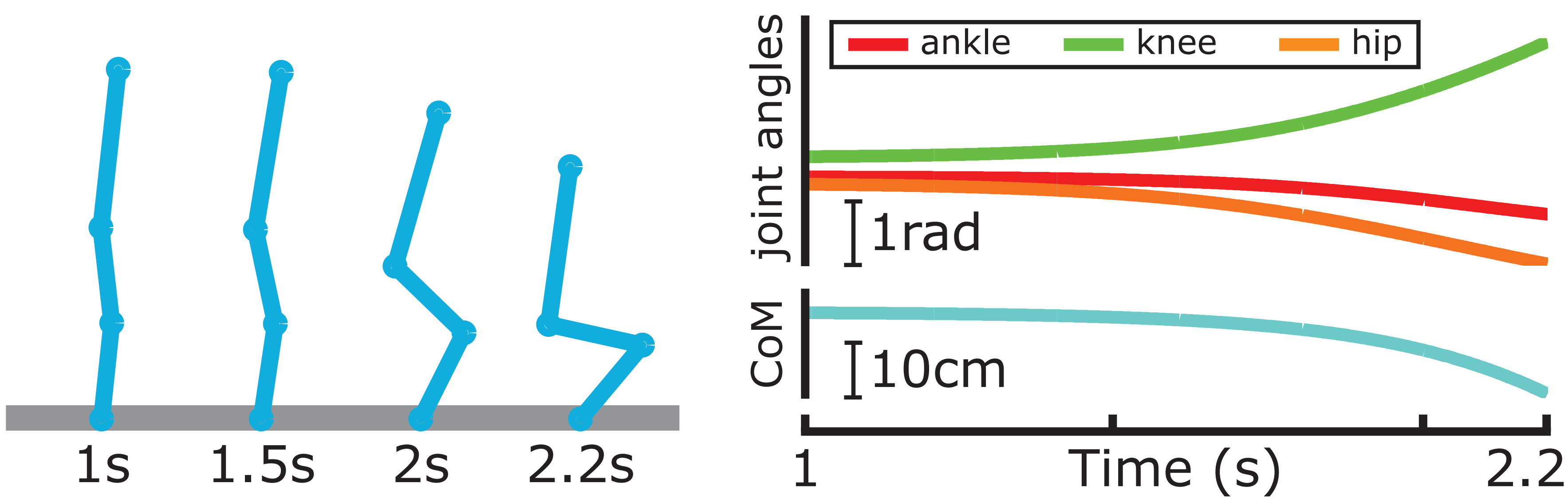
- when the sensory feedback loop about the body in space is removed



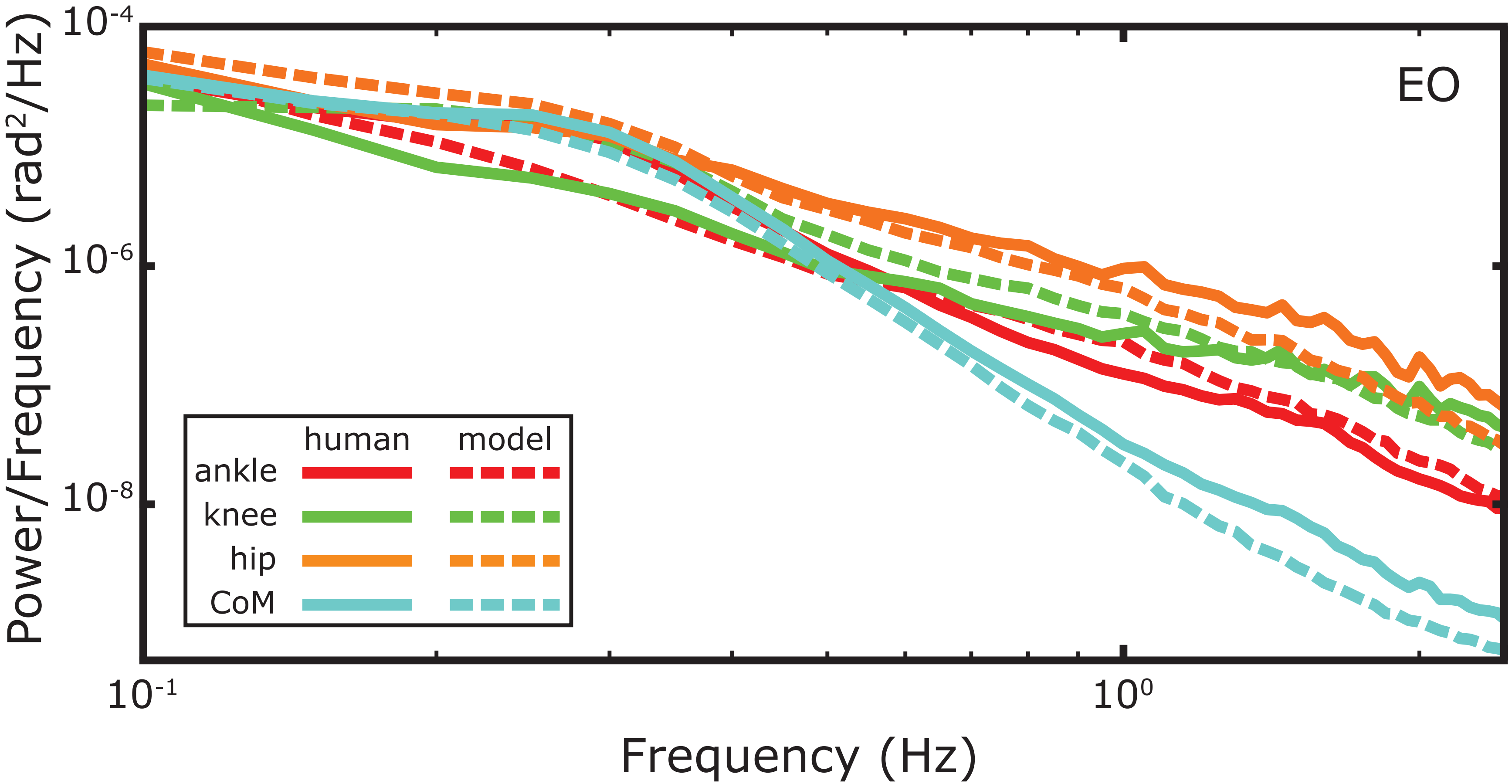


Results: model falls

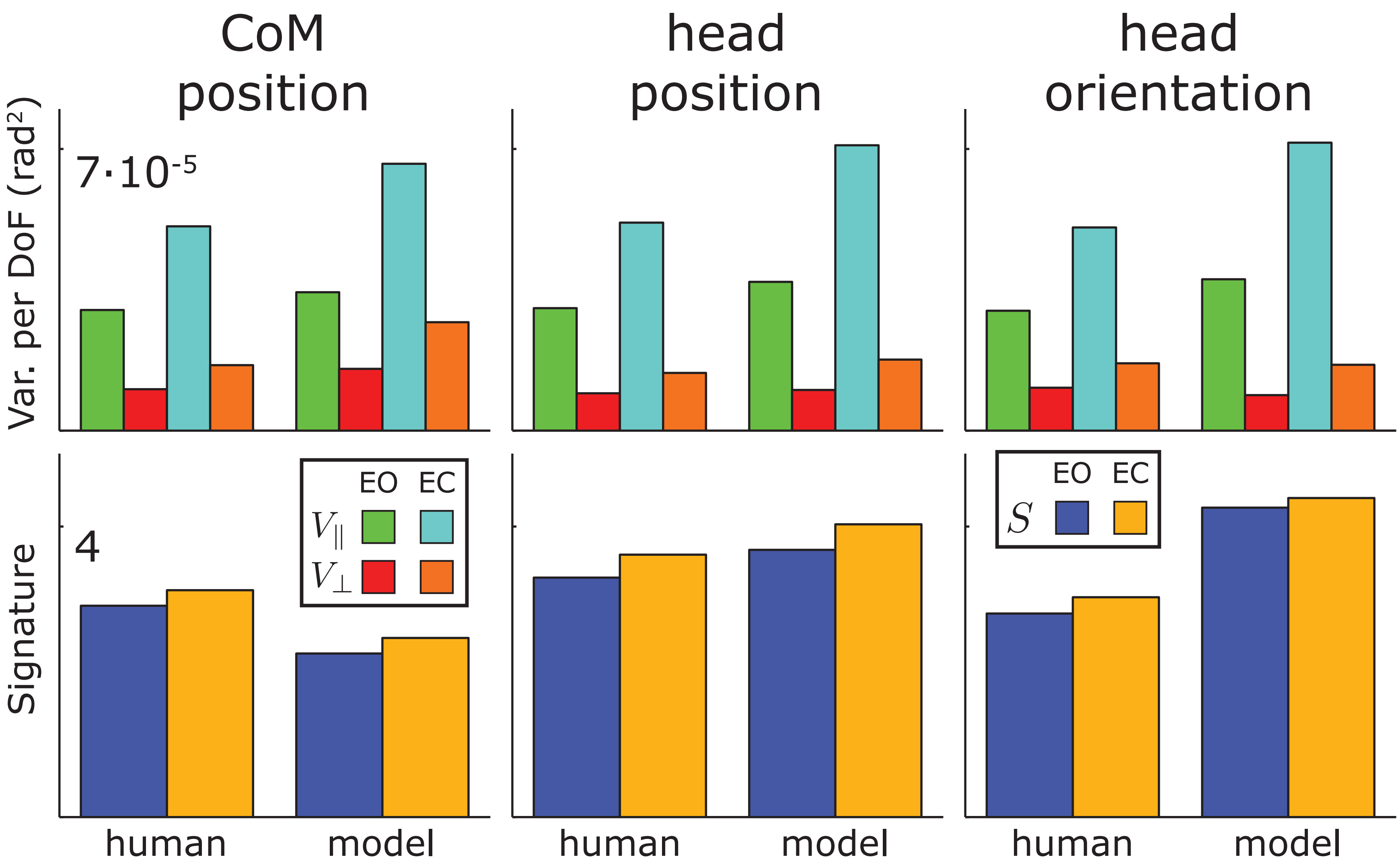
- when the spinal reflex loop within muscle model is removed (constant activation level of motor neurons)



Results: model predicts joint spectra



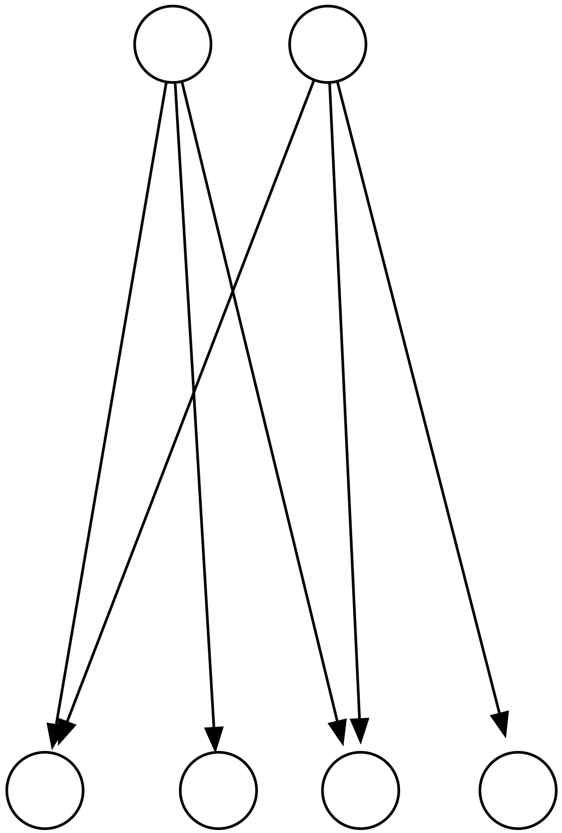
Results: model predicts UCM signature



Why does this work?

$$\dot{\lambda} = F_c = R^{-1}A^{-1}MJ_c^{+}\left(-\alpha_{\dot{c}}\widehat{\dot{c}} - \alpha_{\ddot{c}}\widehat{\ddot{c}}\right)$$

$\widehat{\dot{c}}(t)\ \widehat{\ddot{c}}(t) \rightarrow$ motor commands

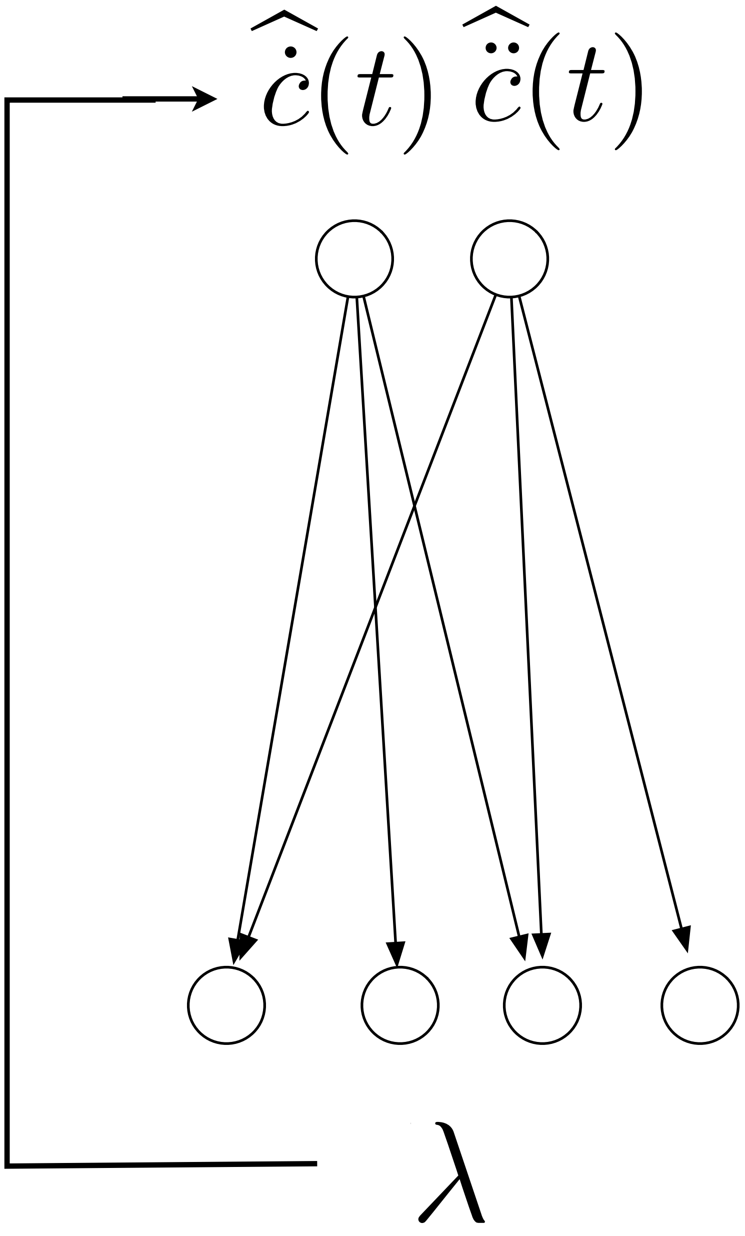


- model looks like a feed-forward neural network
- => should not have a UCM signature: classical synergy?

$\lambda \rightarrow$ DoF/muscles

Why does this work?

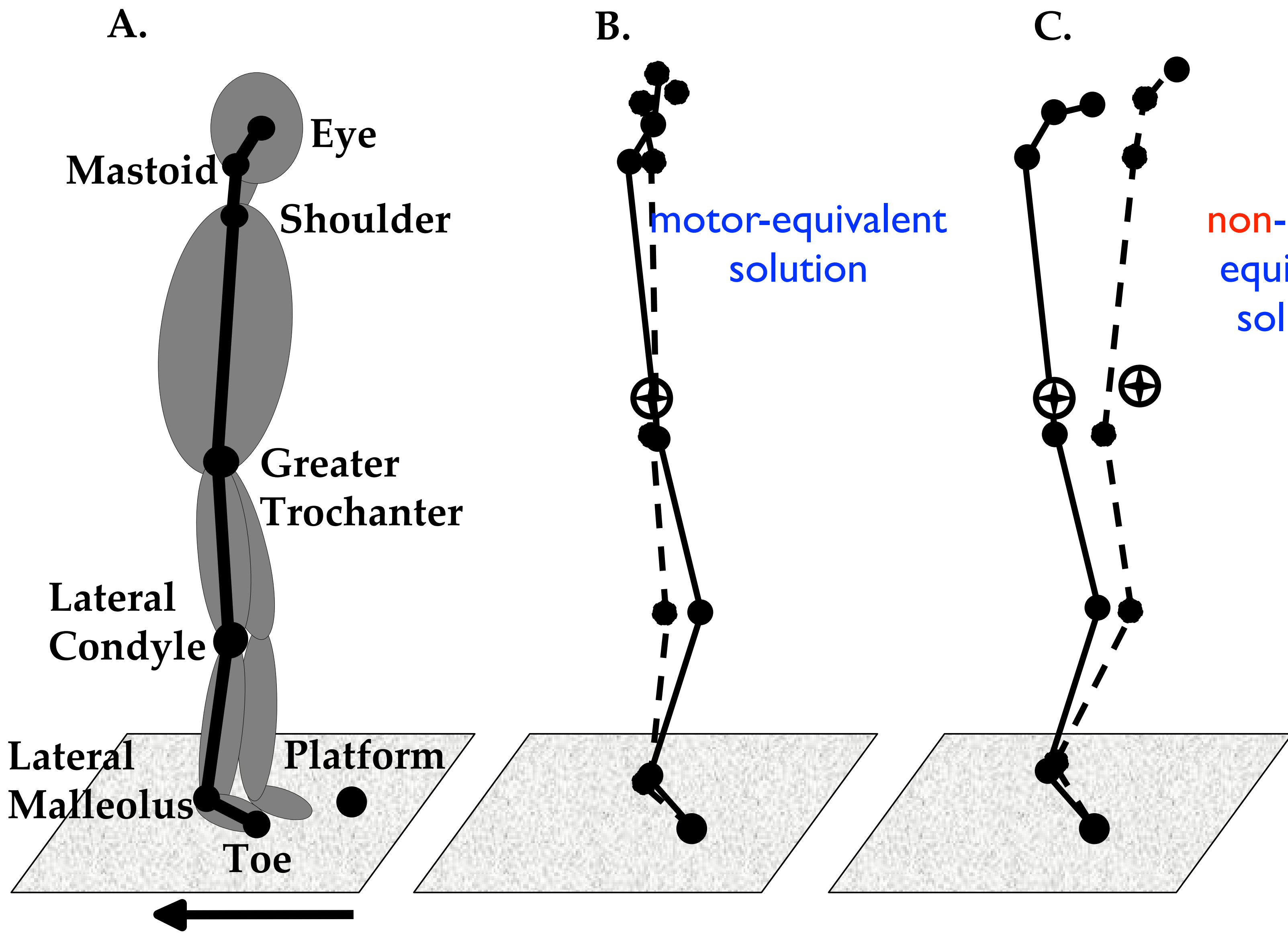
- feedback loop through the world stabilizes configuration in ORT space
- DoF are effectively coupled through that loop to generate the compensatory signature



Motor equivalence

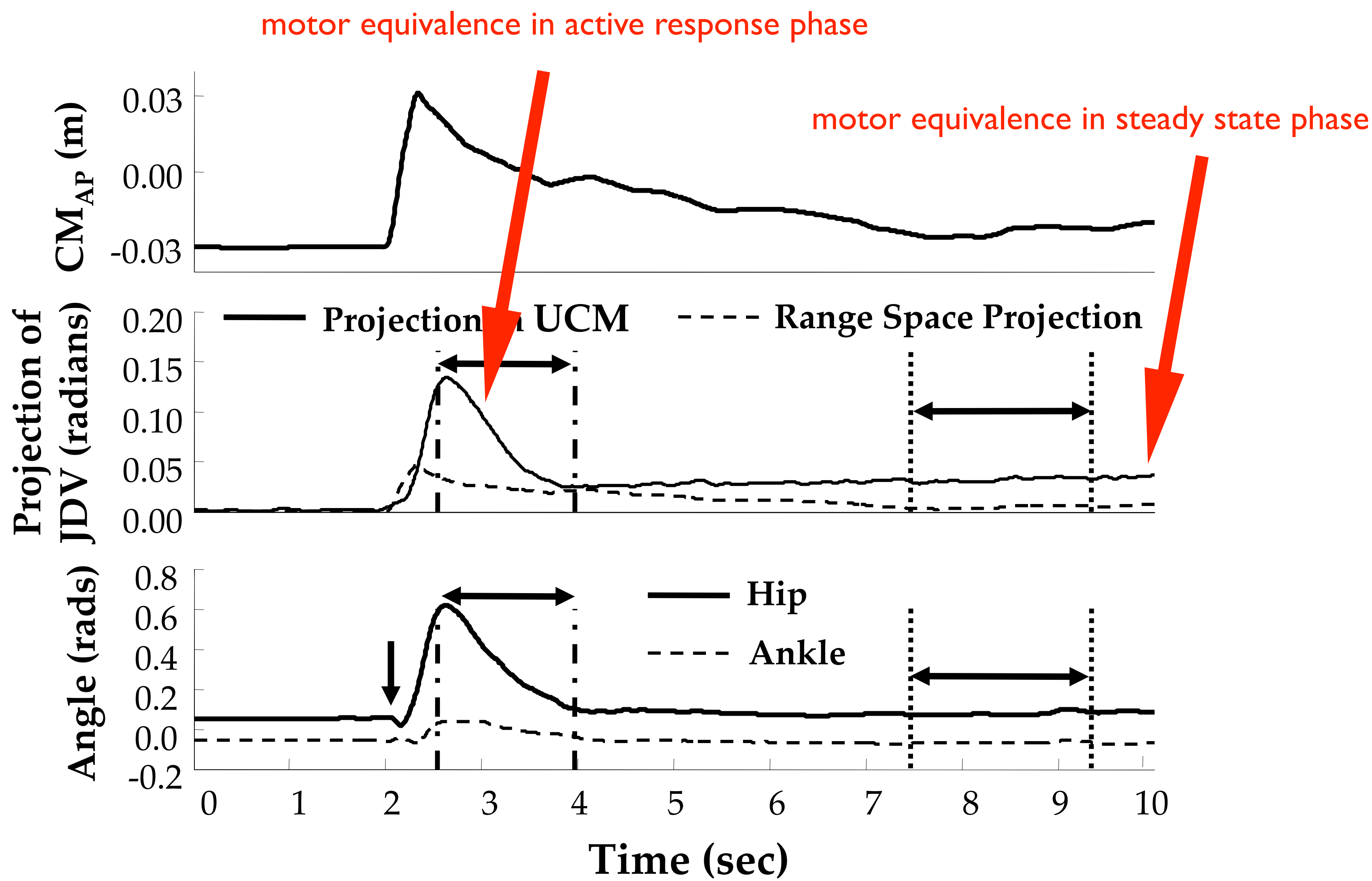
- Perturbation rather than noise:
- “following perturbation, different initial condition, or changed conditions, the task achieved with a new joint configuration”
- But: the task is never achieved 100 percent => how much error at the task level compared to how much error at the joint level?
- => error lies more within UCM than orthogonal to it

Motor equivalence in quiet stance



[Scholz, Schöner, Hsu, Jeka, Horak, Martin. *Exp Brain Res* (2007)]

Motor equivalence in quiet stance



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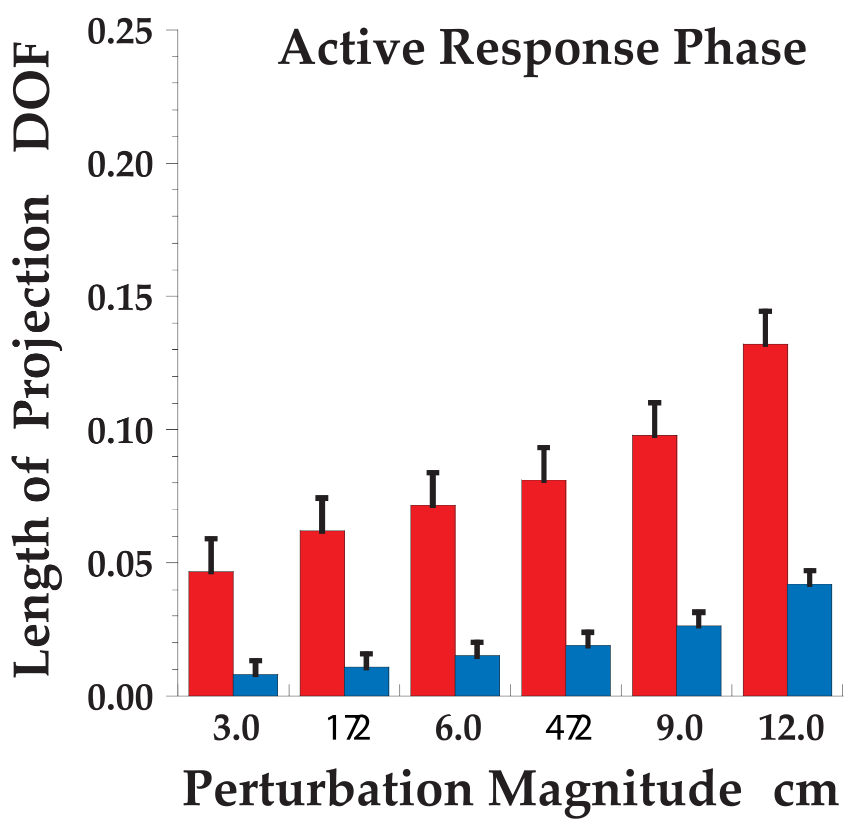
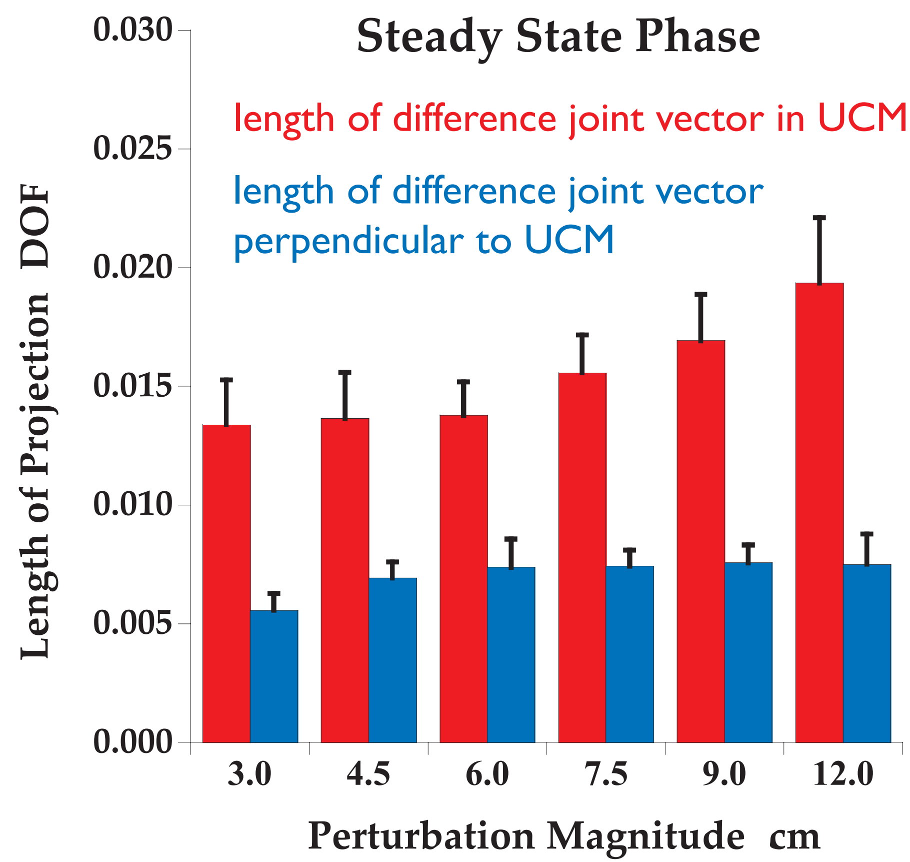
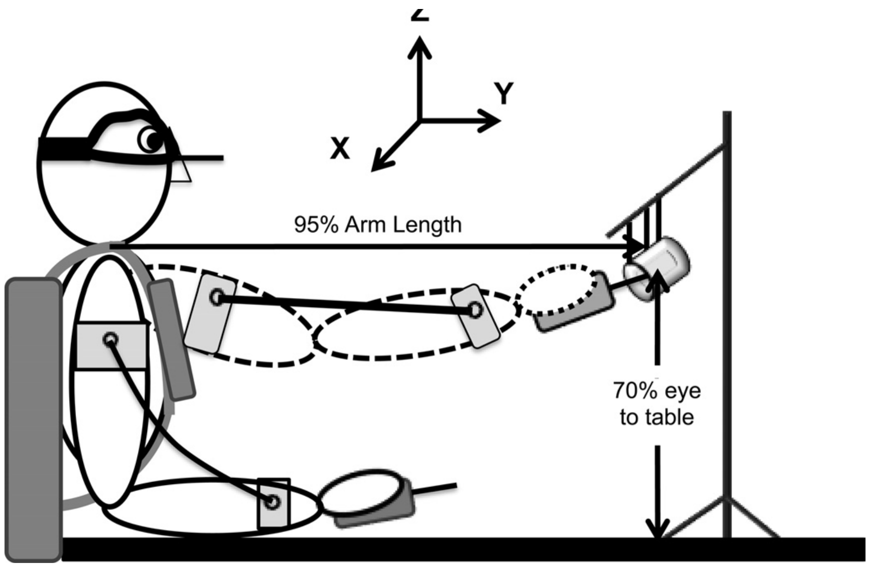
Motor equivalence in quiet stance

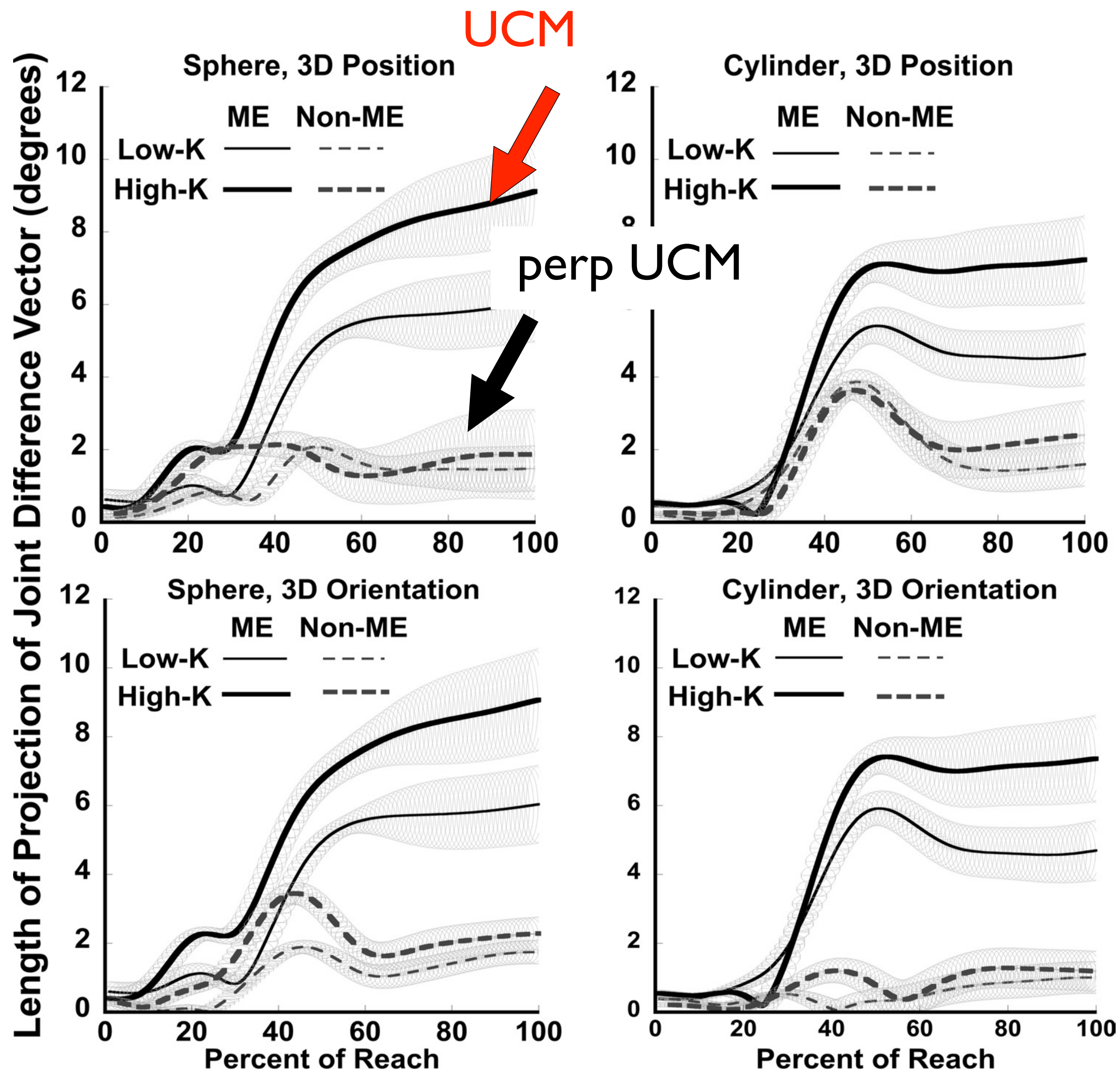




[Scholz, Schöner, Hsu, Jeka, Horak, Martin. *Exp Brain Res* (2007)]

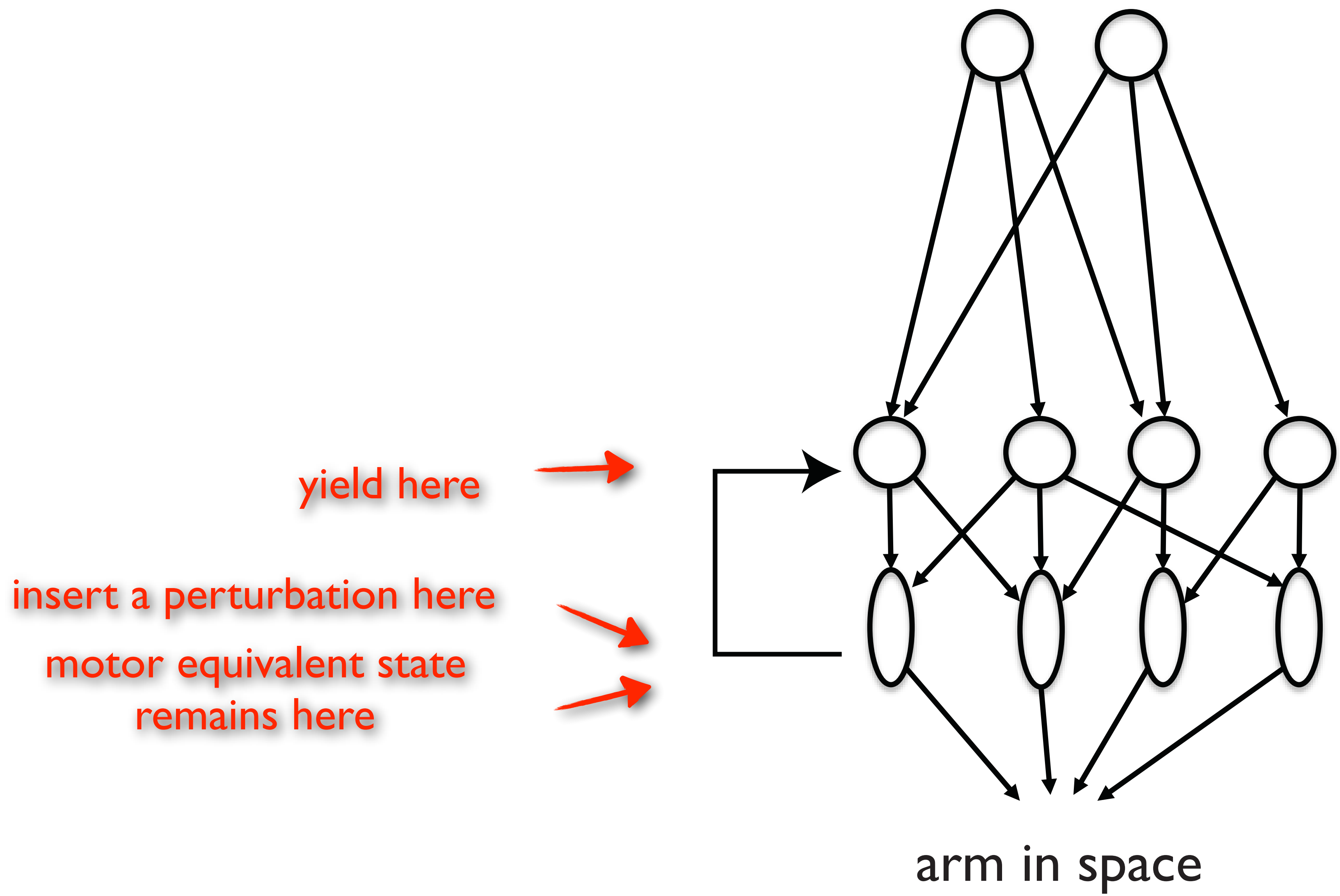
Motor equivalence in reaching





[D. J. S. Mattos, M. L. Latash, E. Park, J. Kuhl, J. P. Scholz J Neurophysiol 106:1424 (2011)]

UCM synergy: back-coupling

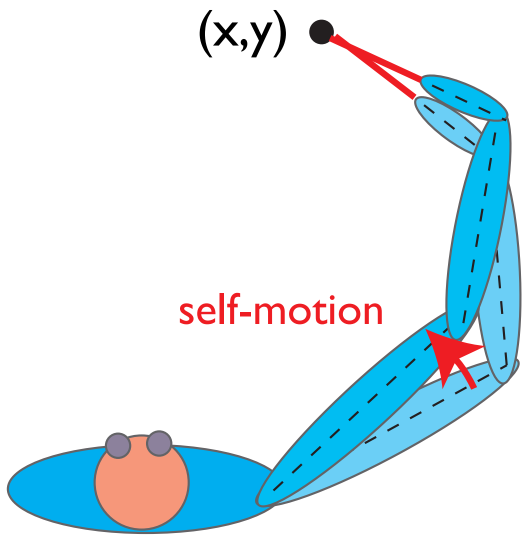


[Martin, Scholz, Schöner: Neural Computation 2009]

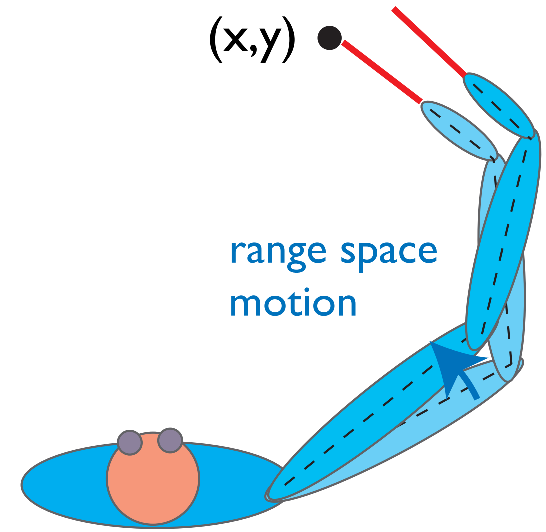
Self-motion

- Beyond variation or response to perturbation…
- Does the mean movement trajectory reveal the DoF problem and its solution?
- => self-motion

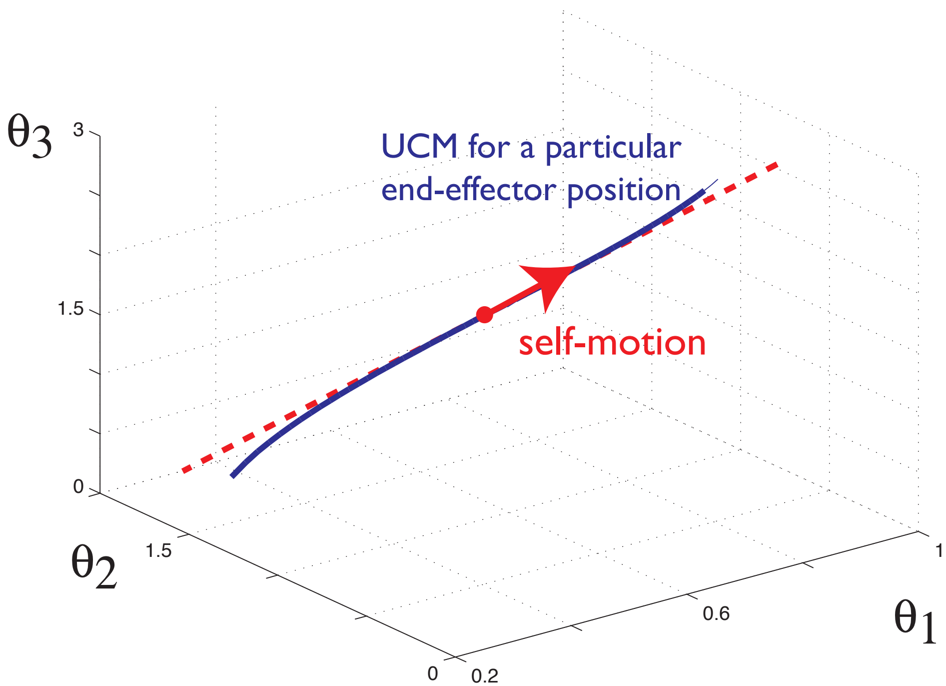
Self motion



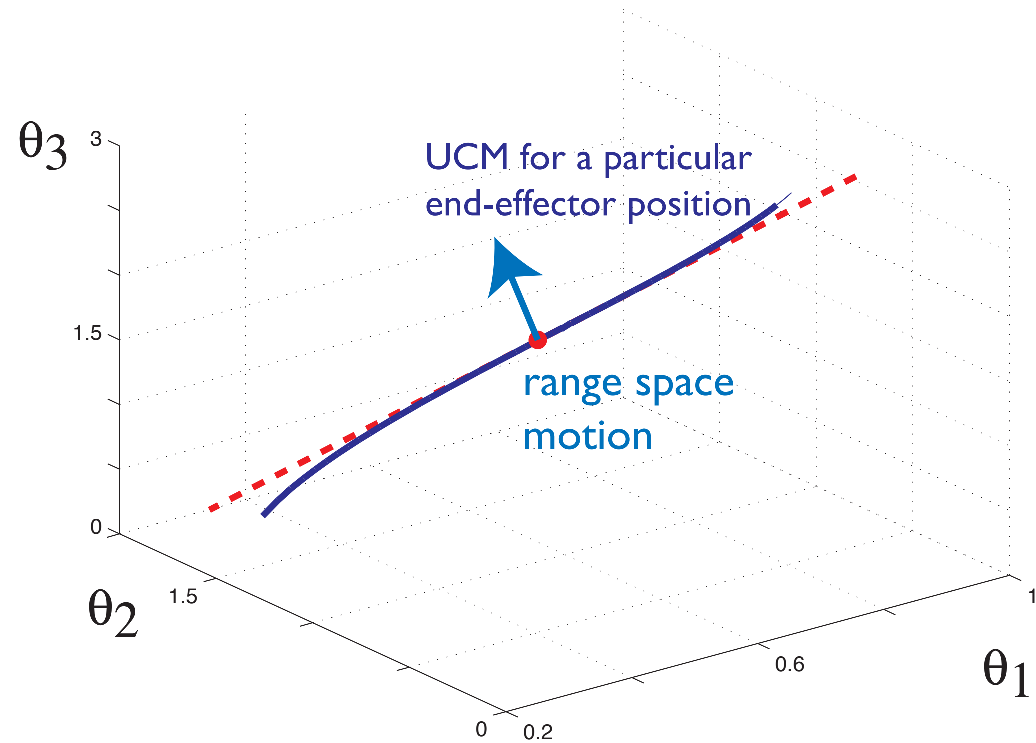
(x,y)
self-motion



(x,y)
range space
motion

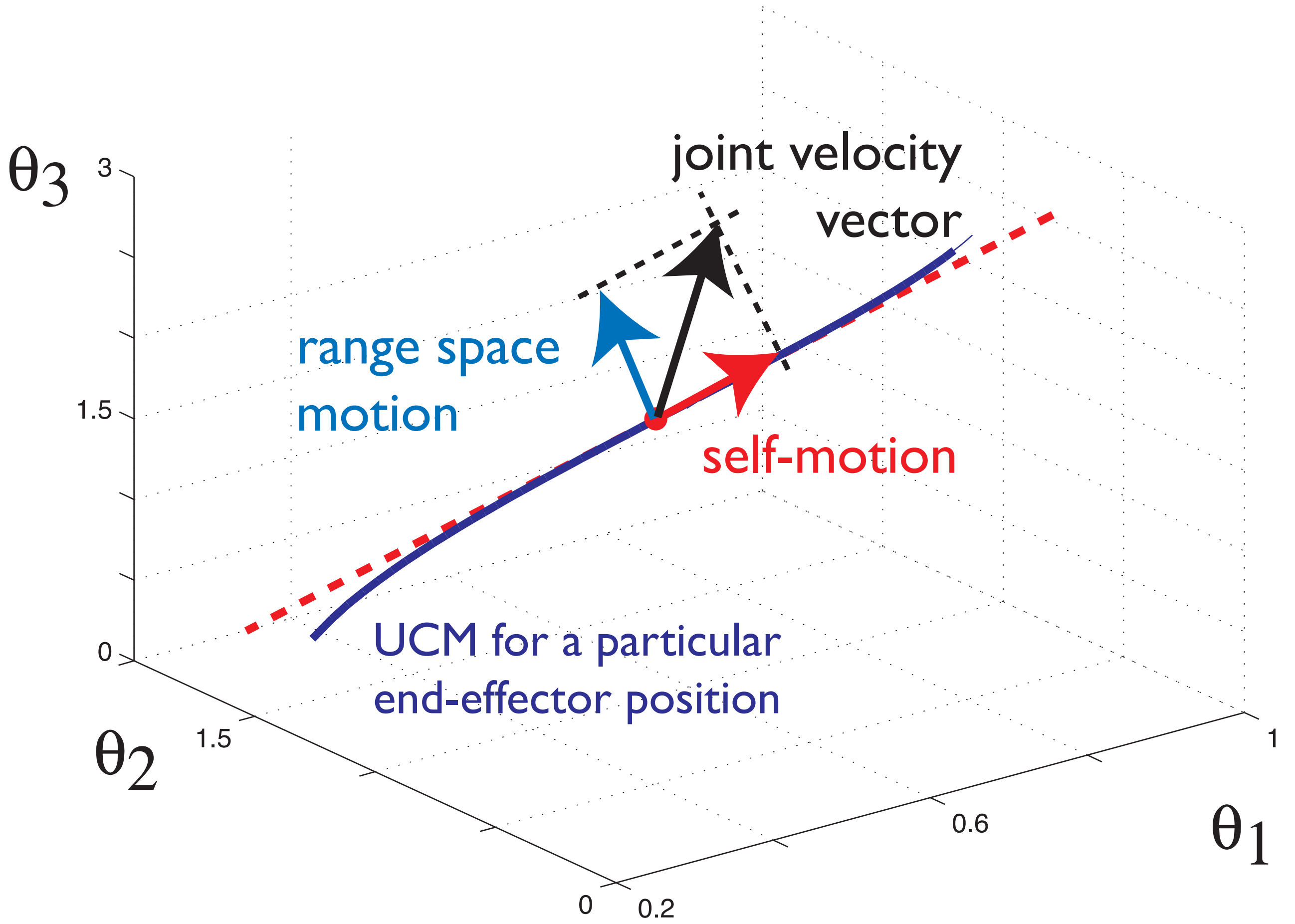


θ_3
3
1.5
0
UCM for a particular
end-effector position
self-motion
θ_2
1.5
0
0.2
0.6
1
θ_1

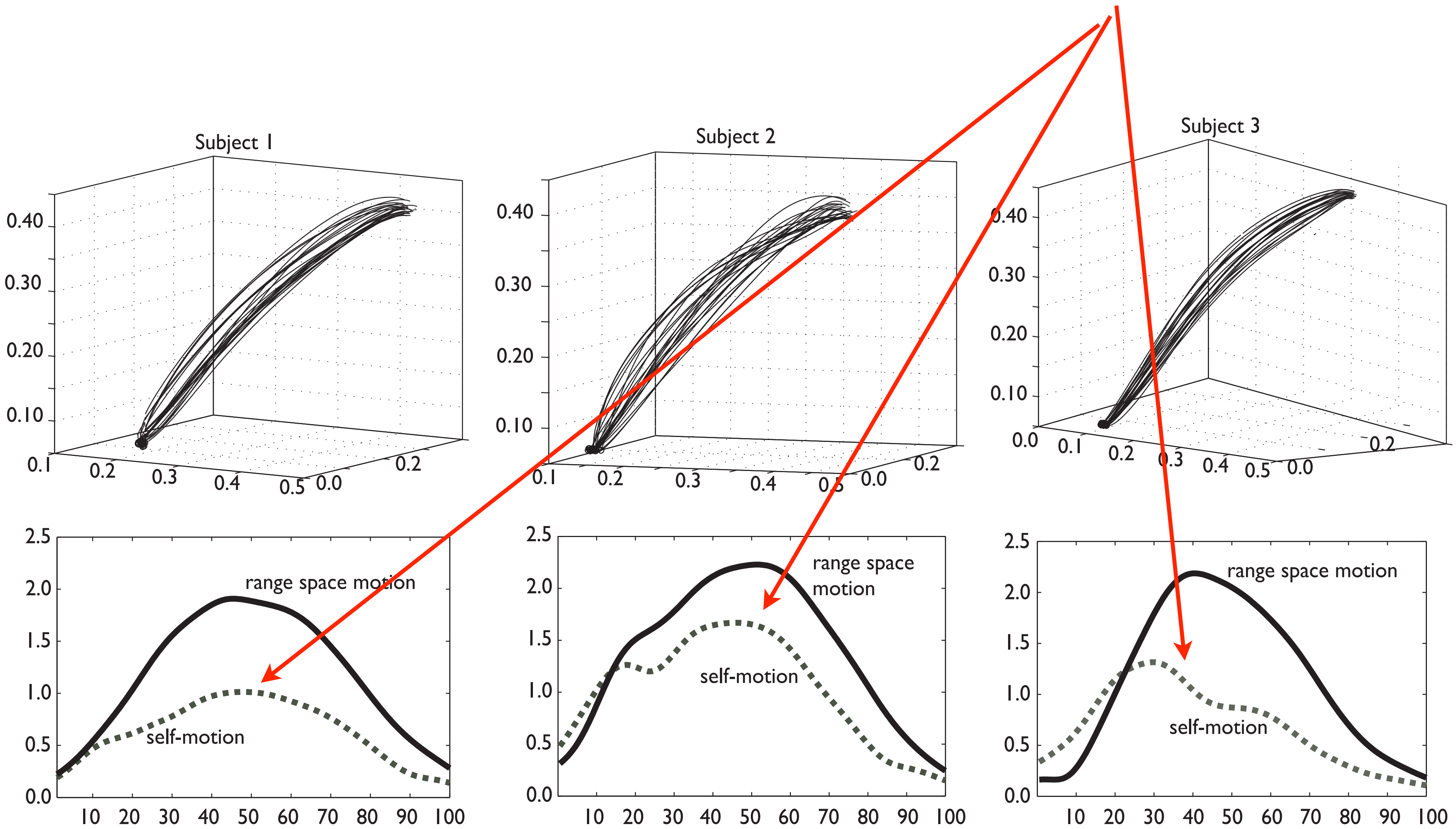


θ_3
3
1.5
0
UCM for a particular
end-effector position
range space
motion
θ_2
1.5
0
0.2
0.6
1
θ_1

Self-motion


joint velocity vector
range space motion
self-motion
UCM for a particular end-effector position
θ3
3
1.5
0
θ2
1.5
0
θ1
0.2
0.6
1

Reaching movement in 3D with 10 DoF shows considerable amount of self-motion



[Martin, Scholz, Schöner. *Neural Computation* 21, 1371–1414 (2009)]

Conclusion: DoF problem

- Studying the structure of the end-effector path and the variation of movement with task through synergies is not informative about the degree of freedom problem.
- The degree of freedom problem can be studied directly through the structure of variance at iso-task, iso-command conditions: the UCM structure of variance.

Conclusion: DoF problem

- The degree of freedom problem can also be studied by inserting perturbations and looking for motor-equivalence
- Self-motion is a direct signature of the DoF problem at the level of the mean trajectory.