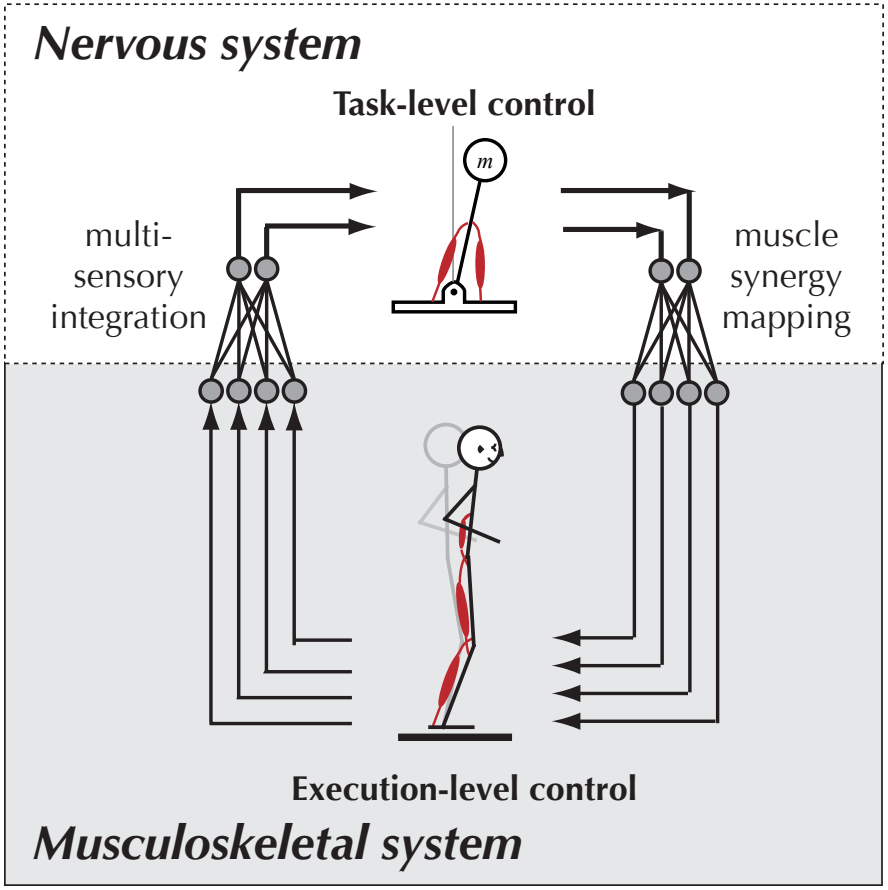
Neuromechanical constraints and optimality for balance

J. Lucas McKay, Sc.M.
Lena H. Ting, Ph.D., advisor

Georgia Tech

EMORY

We would like to understand how people maintain standing balance.



Ting and McKay, Curr Opin Neurobiol 2007

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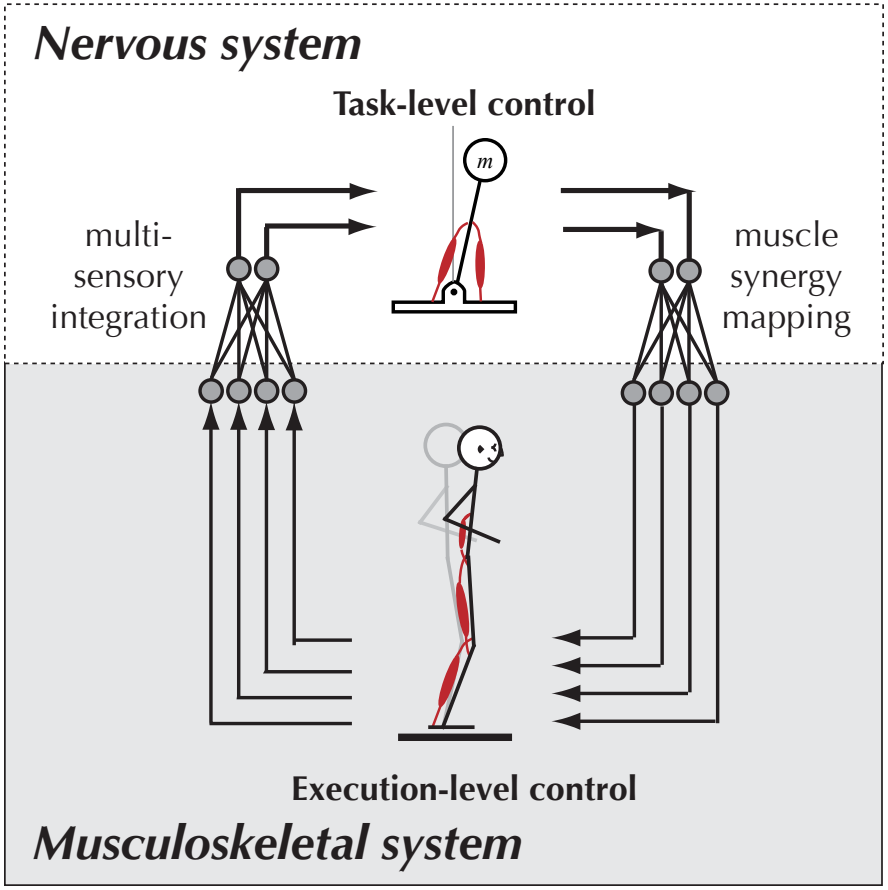
many sensory inputs



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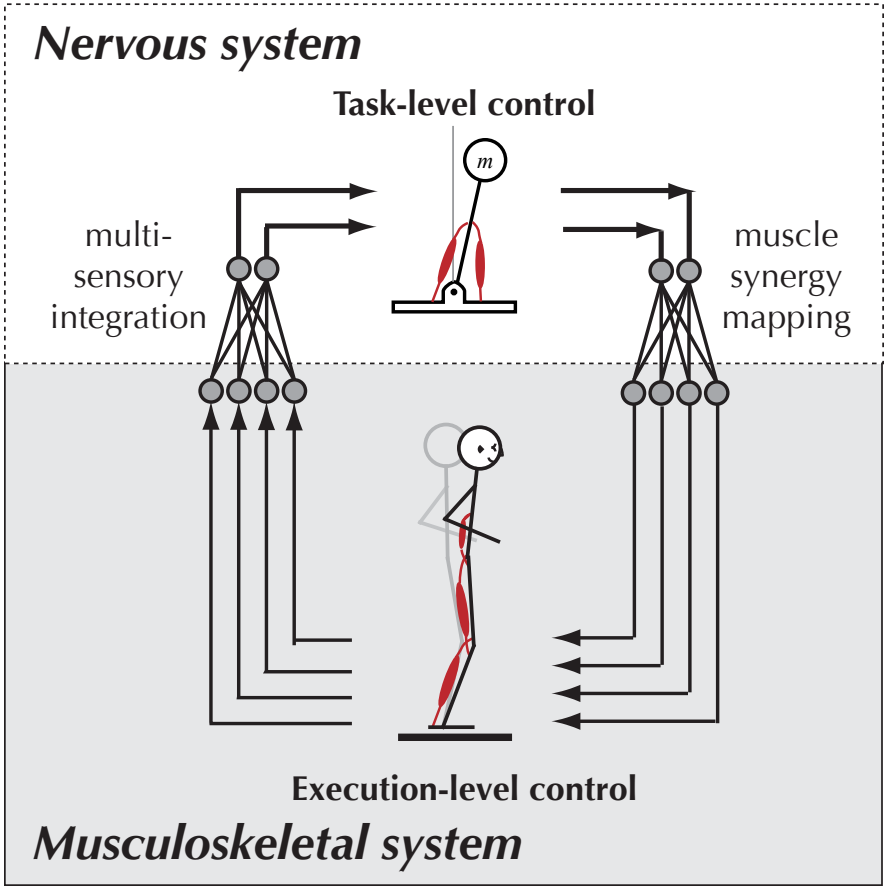
transform

task-level motor command

many sensory inputs



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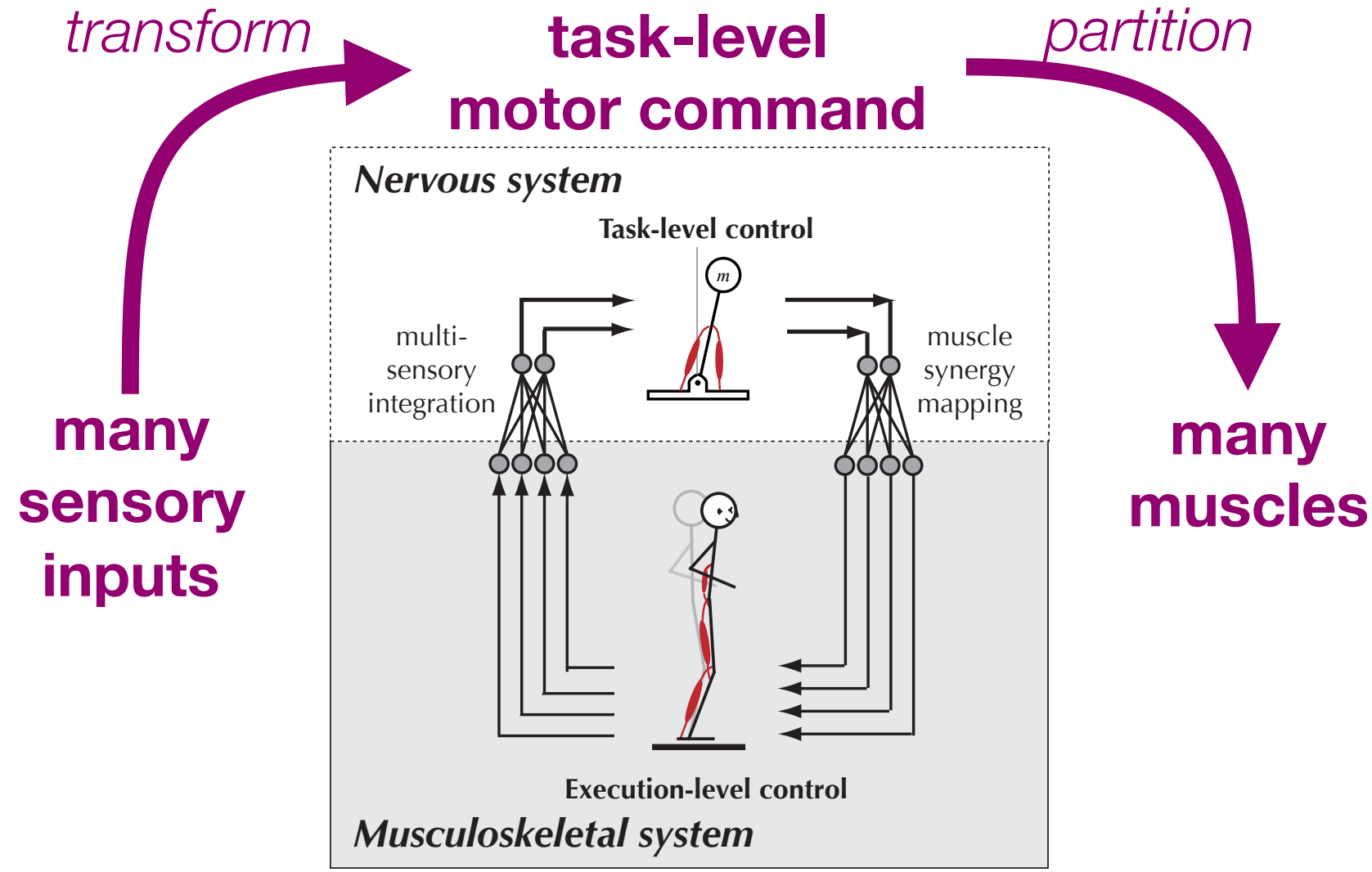

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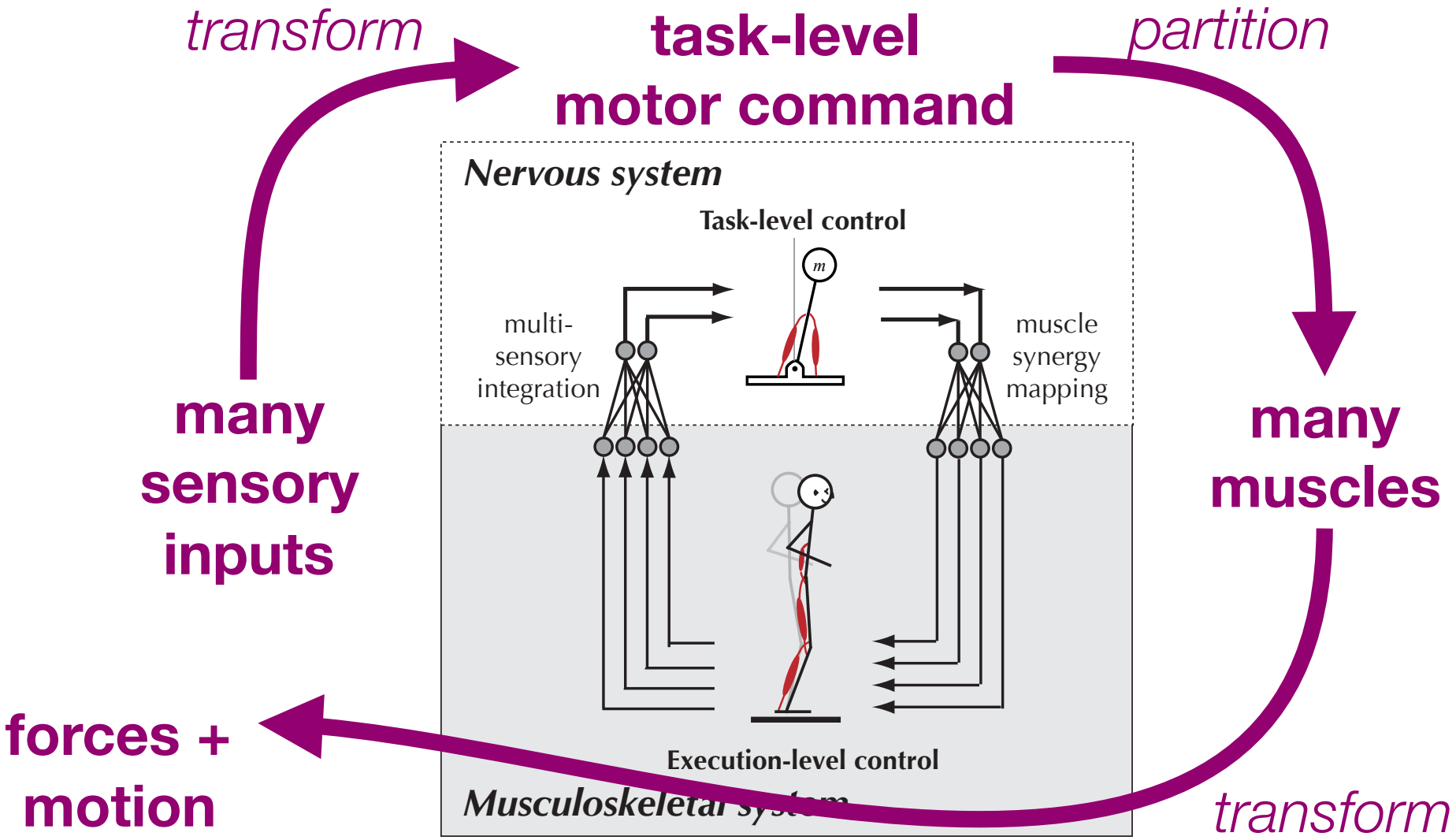

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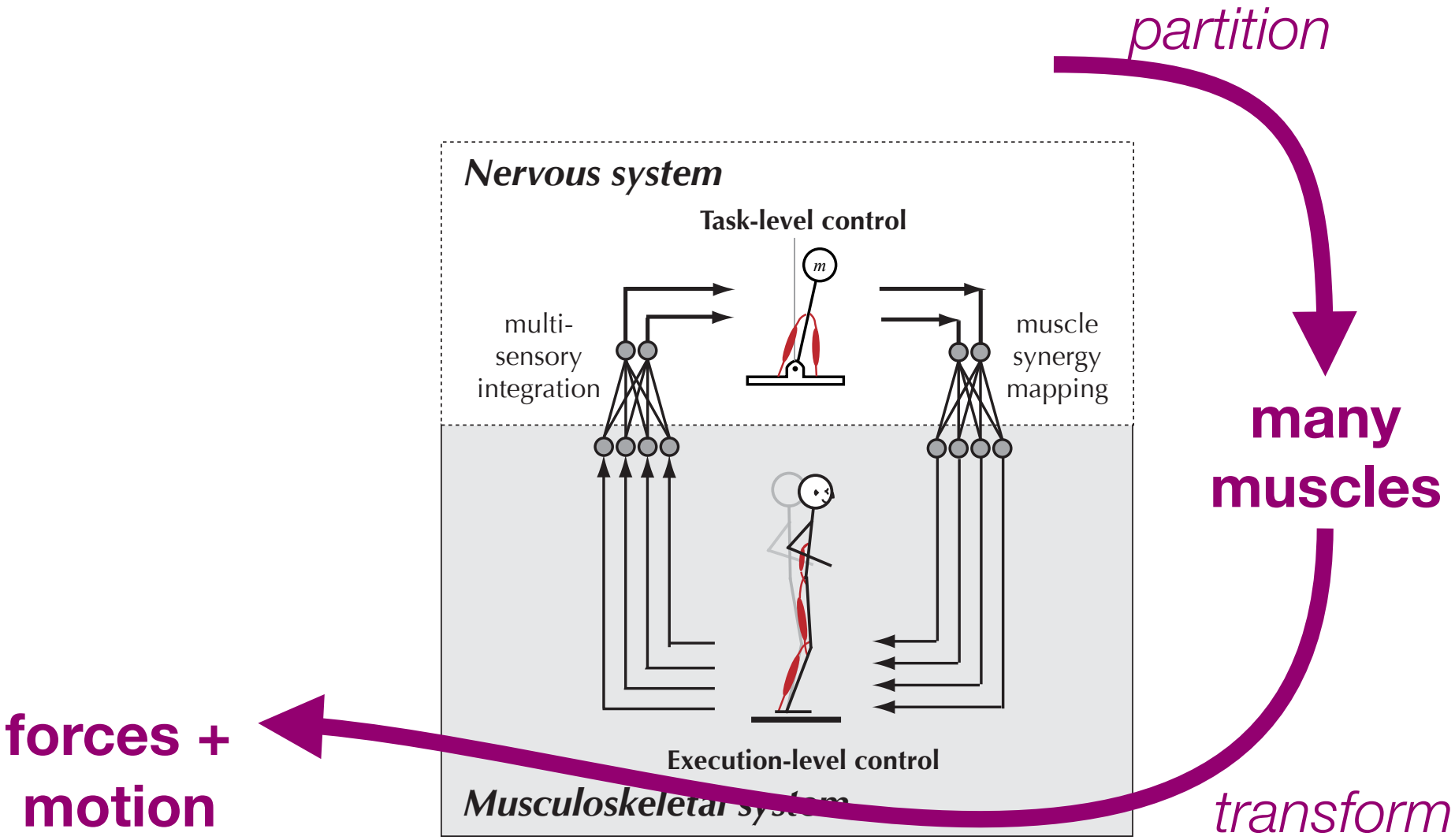

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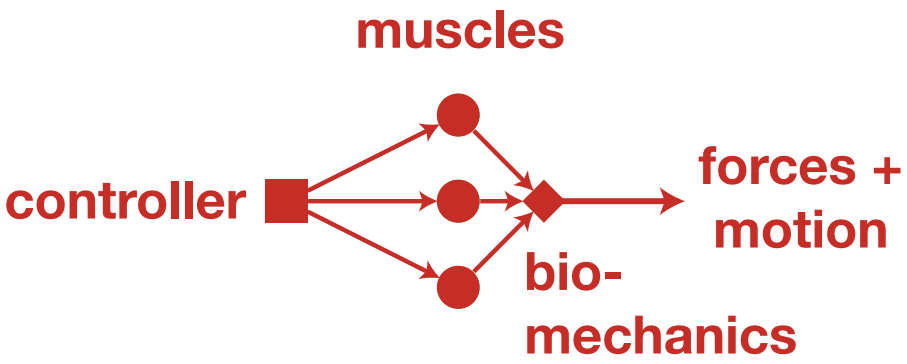
How are motor commands partitioned among the muscles?

individual muscle control?



Harris and Wolpert 1998; Todorov and Jordan 2002; Fagg et al., 2002; Kurtzer et al., 2006; others

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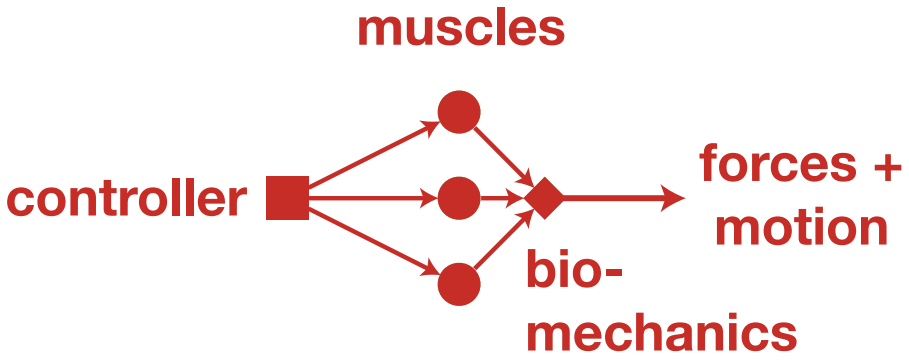

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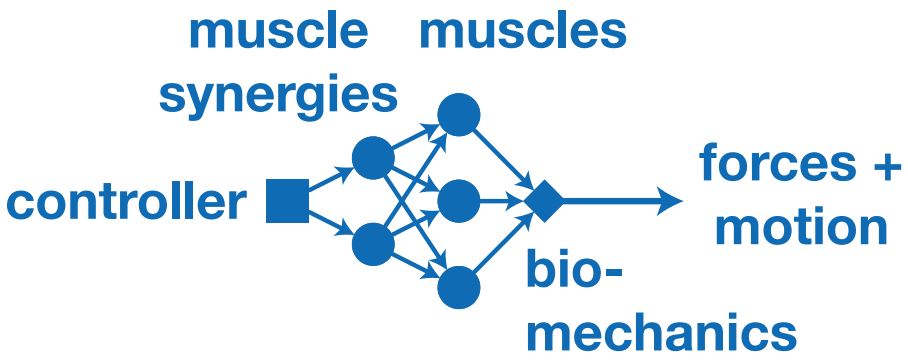
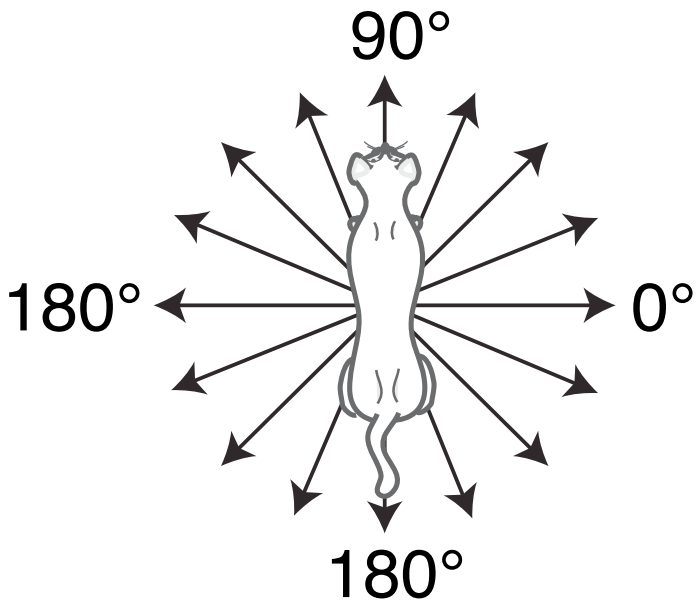
muscle synergy control?



Tresch et al., 1999; Krishnamoorthy et al., 2003; d'Avella et al., 2006; Cheung et al., 2009; Clark et al., 2010; others

Low-dimension muscle activity and forces are observed during balance in cats.

perturbation experiments



Macpherson, 1988

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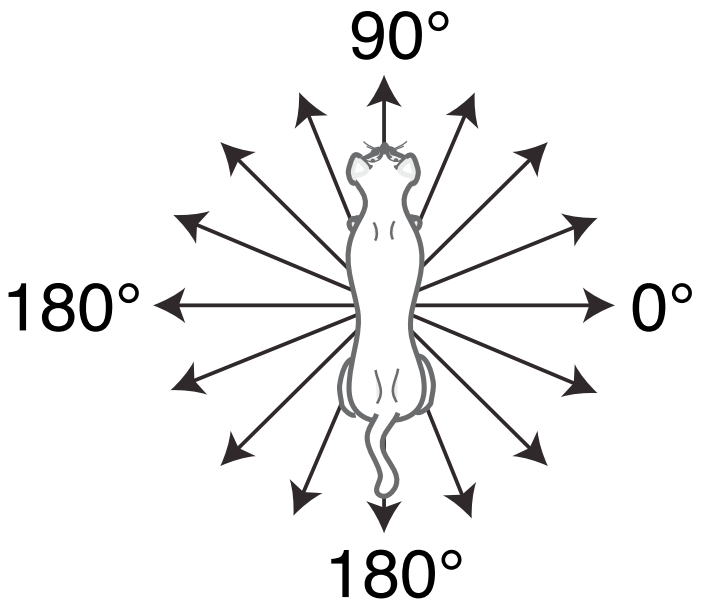

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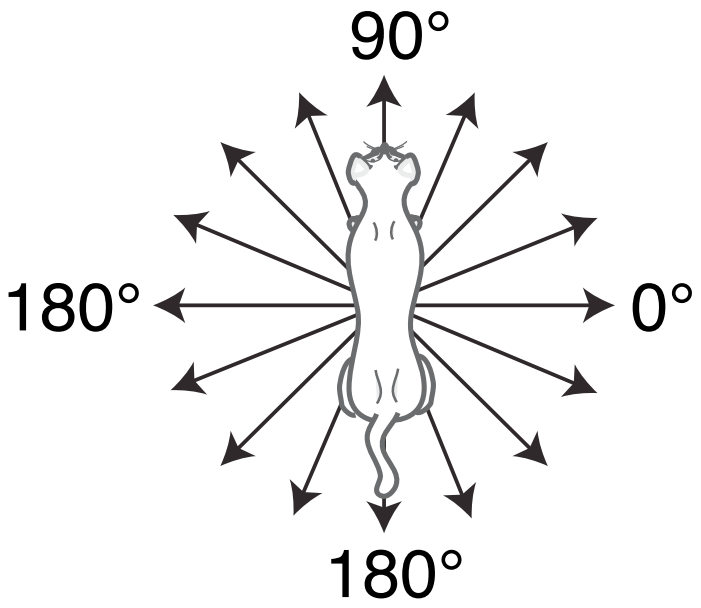

Macpherson, 1988

- **We identified five functional muscle synergies** *(Torres-Oviedo, Macpherson, and Ting, 2006)*.
- **Composed of a muscle activation pattern and a unique force vector at the ground.**

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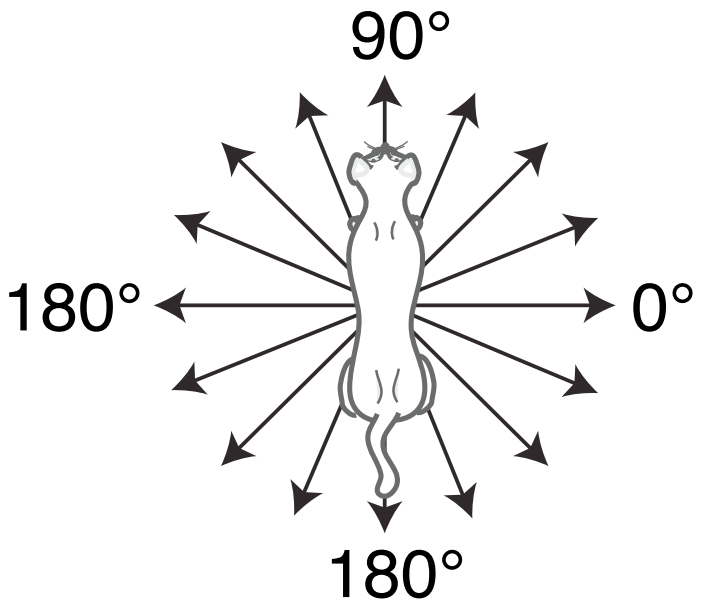

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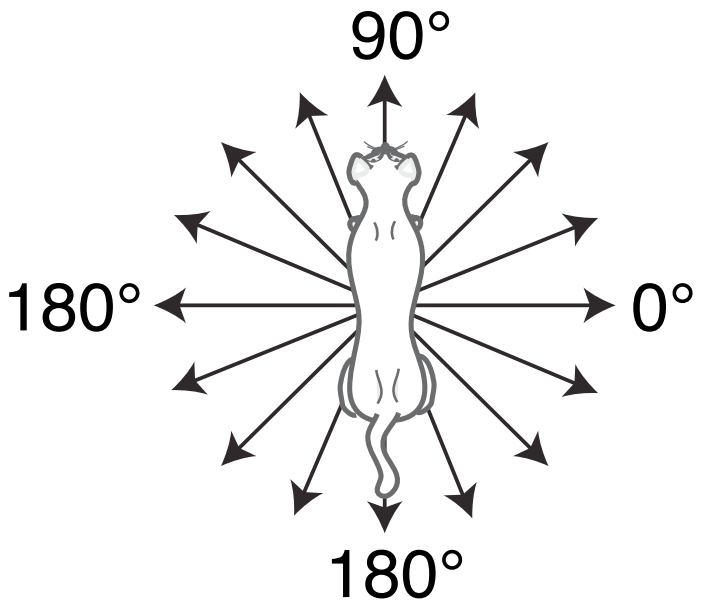

Macpherson, 1988

What is the source of low-dimension muscle activity and forces during balance?

Low-dimension muscle activity and forces are observed during balance in cats.

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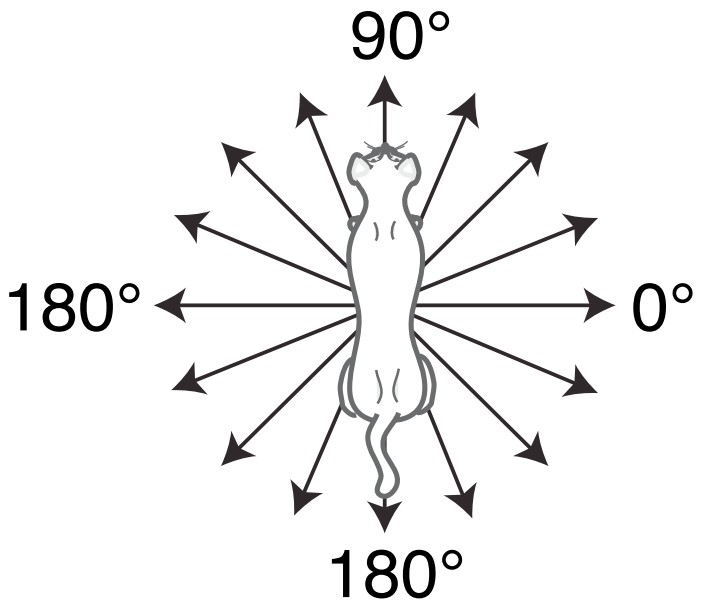

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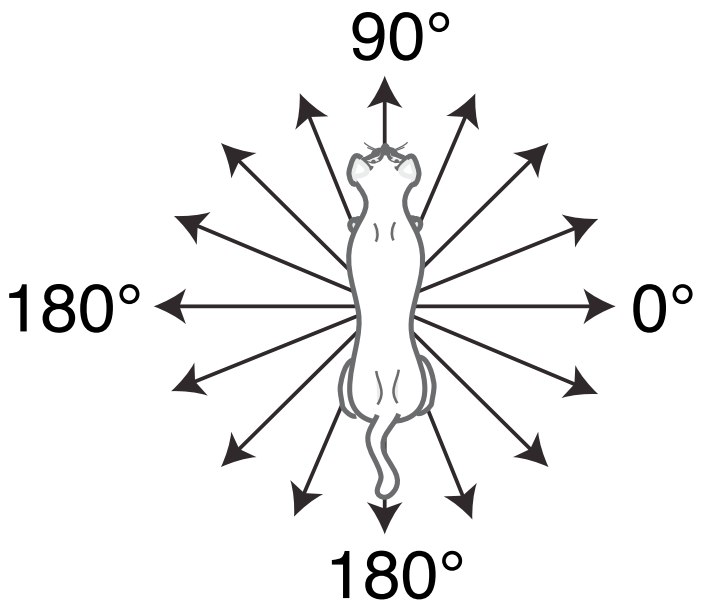

Macpherson, 1988

- **Nervous system constraints on muscle activation?**

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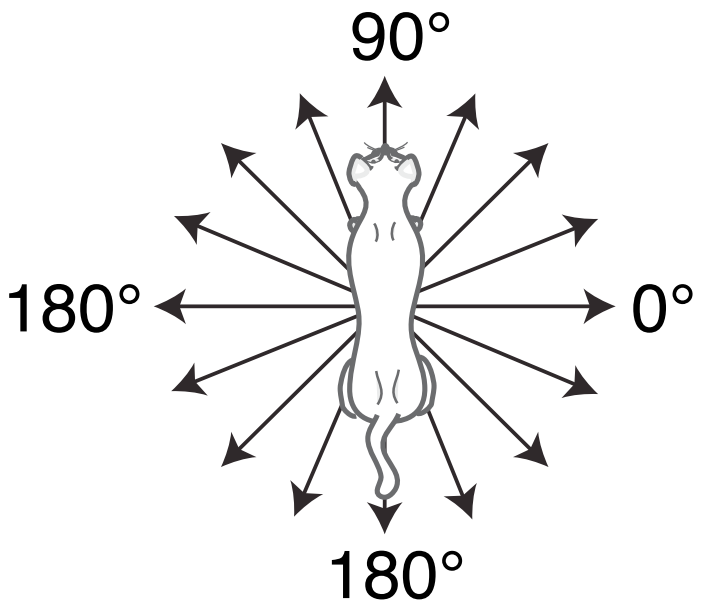

Macpherson, 1988

- **Nervous system constraints on muscle activation?**
- **Musculoskeletal constraints on force production?** *(Valero-Cuevas et al., 1998)*

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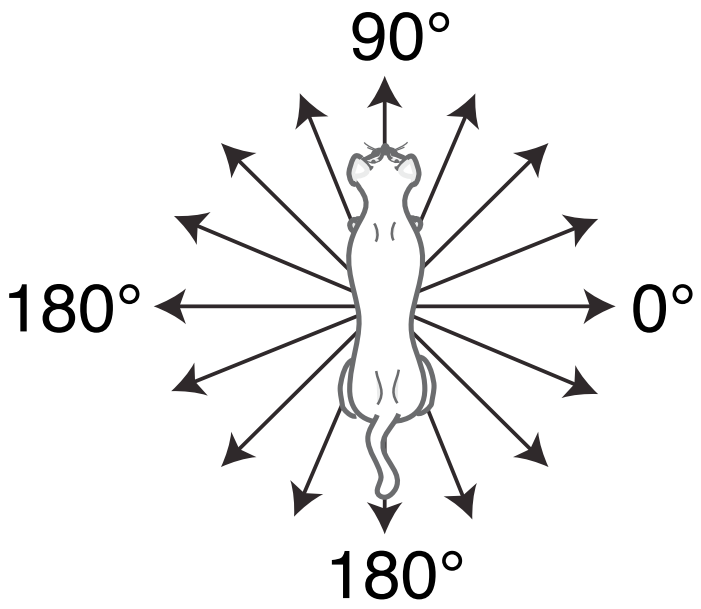

Macpherson, 1988

- **Nervous system constraints on muscle activation?**
- **Musculoskeletal constraints on force production?** *(Valero-Cuevas et al., 1998)*
- **Optimal control of individual muscles during the task?** *(Todorov and Jordan, 2002)*

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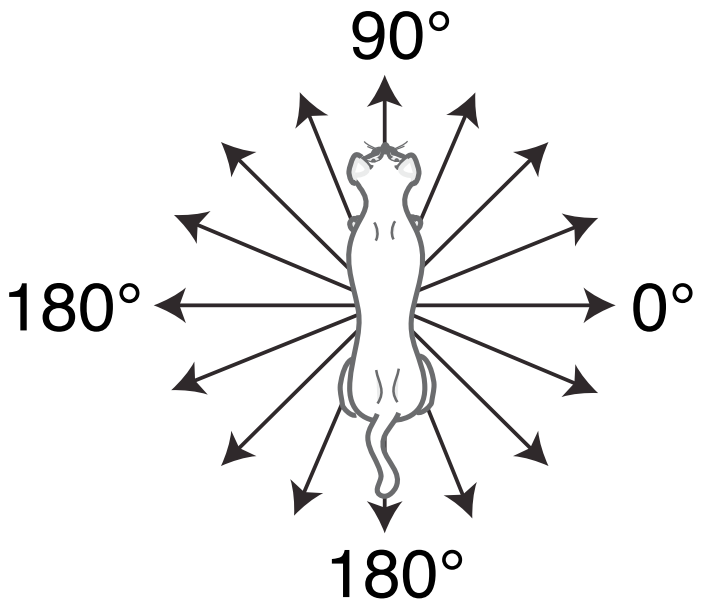
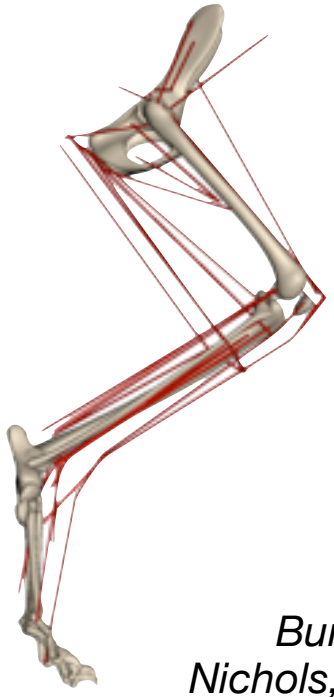
perturbation experiments



Macpherson, 1988

- identify functional muscle synergies to reconstruct muscle activity and forces.

neuromechanical simulations



Burkholder and Nichols, 2000; 2004

- simulate control of muscles or muscle synergies to predict forces.

What is the source of low-dimension muscle activity and forces during balance?

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Muscle synergies constrain hindlimb force production capability during balance

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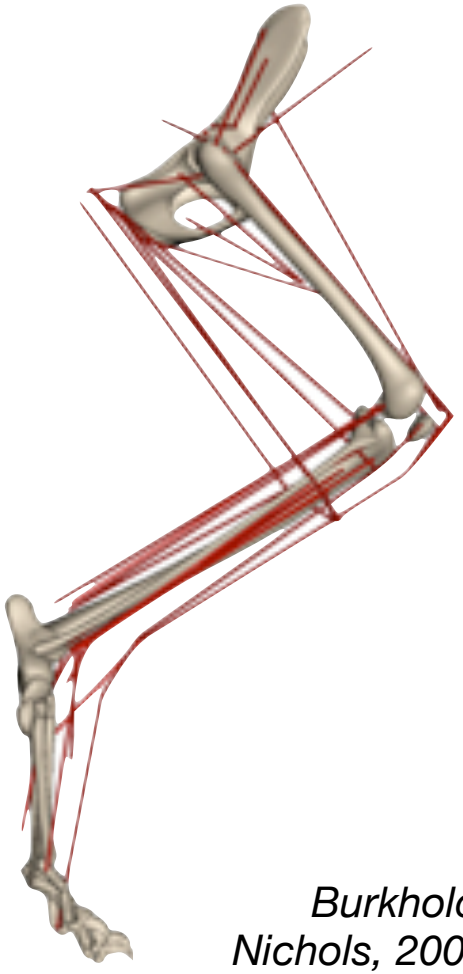
Muscle synergies constrain hindlimb force production capability during balance

We compared musculoskeletal and muscle synergy constraints on force production.



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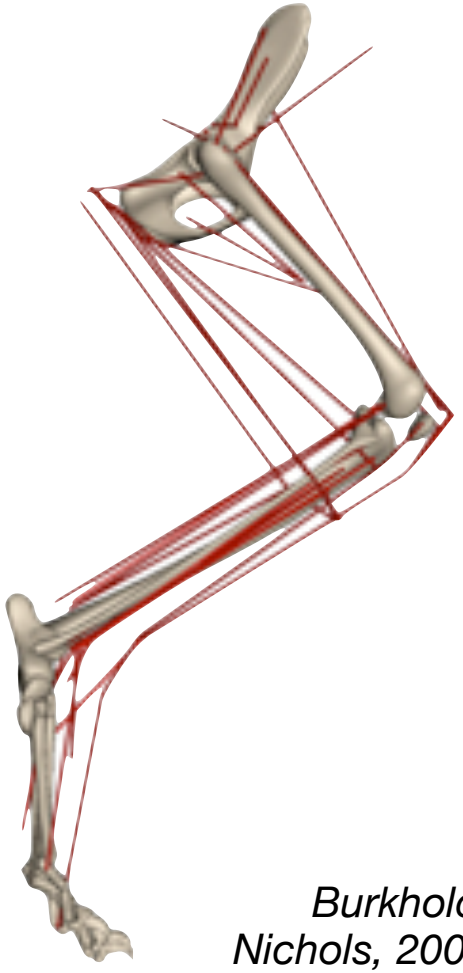

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- **Hypothesis:** muscle synergy control provides a more limited behavioral repertoire than individual muscle control.

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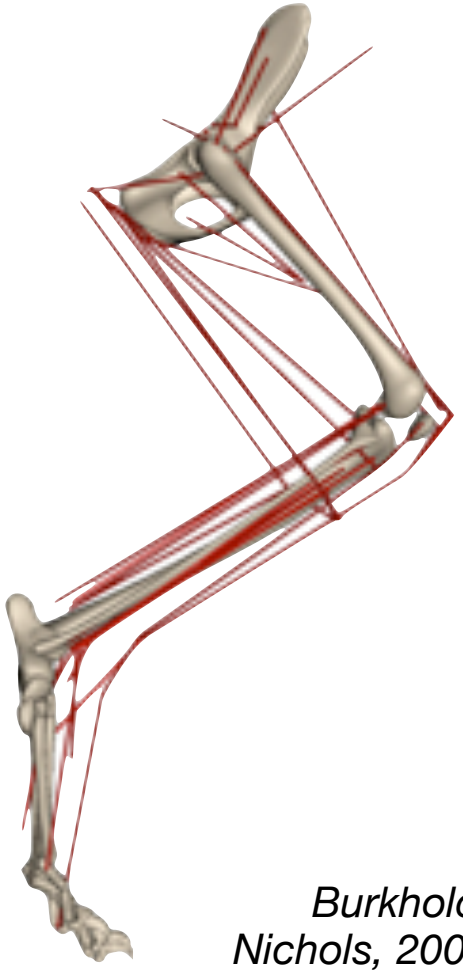
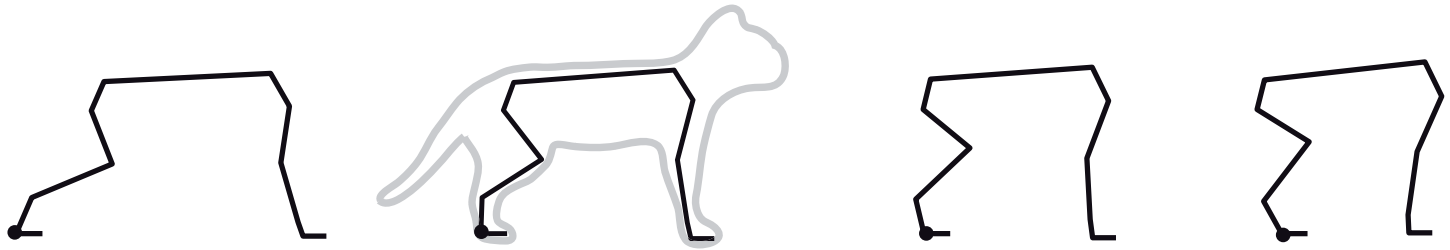


Burkholder, and Nichols, 2000; 2004

- **Hypothesis:** muscle synergy control provides a more limited behavioral repertoire than individual muscle control.
- **Prediction:** the range of feasible forces that the hindlimb can produce will be decreased in the presence of muscle synergy constraints.

Modeled muscle synergy force vectors rotate with the limb axis.



McKay and Ting, 2008

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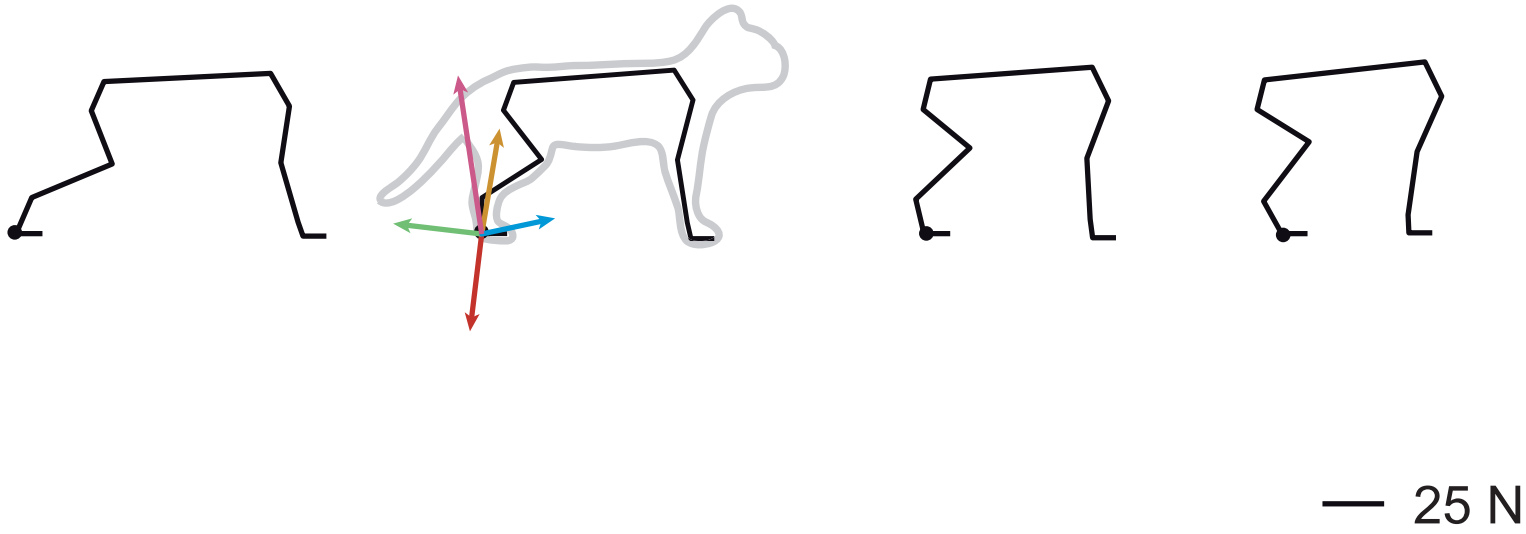

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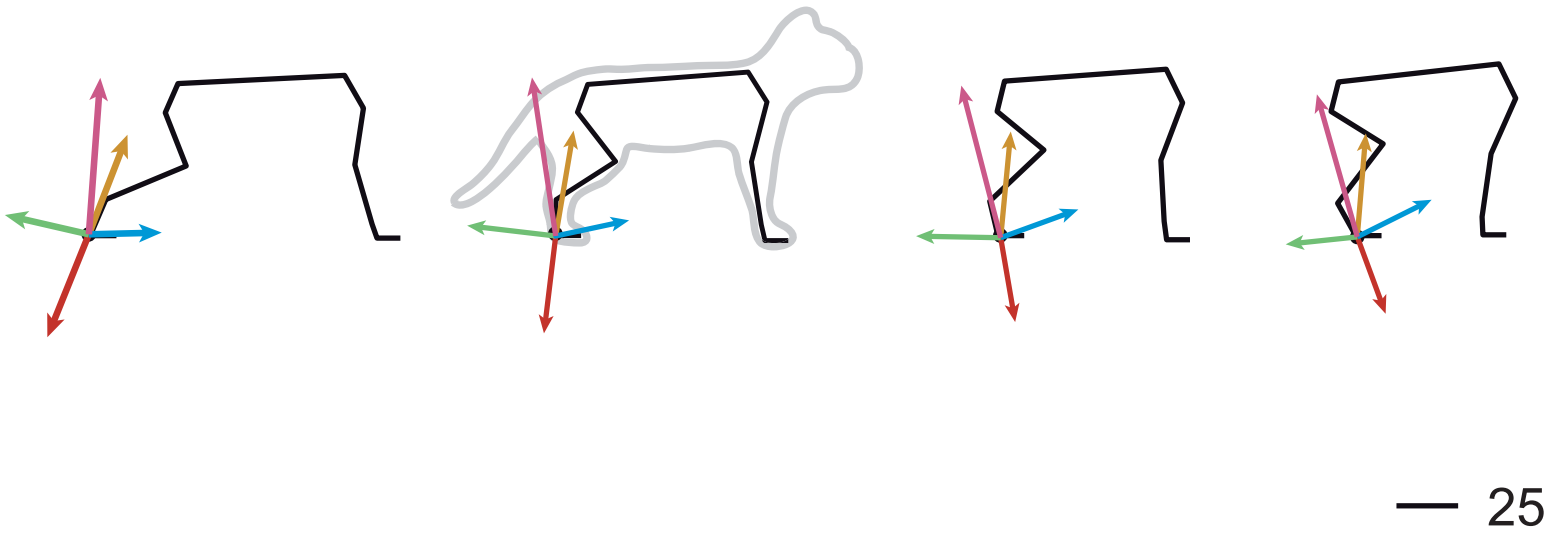

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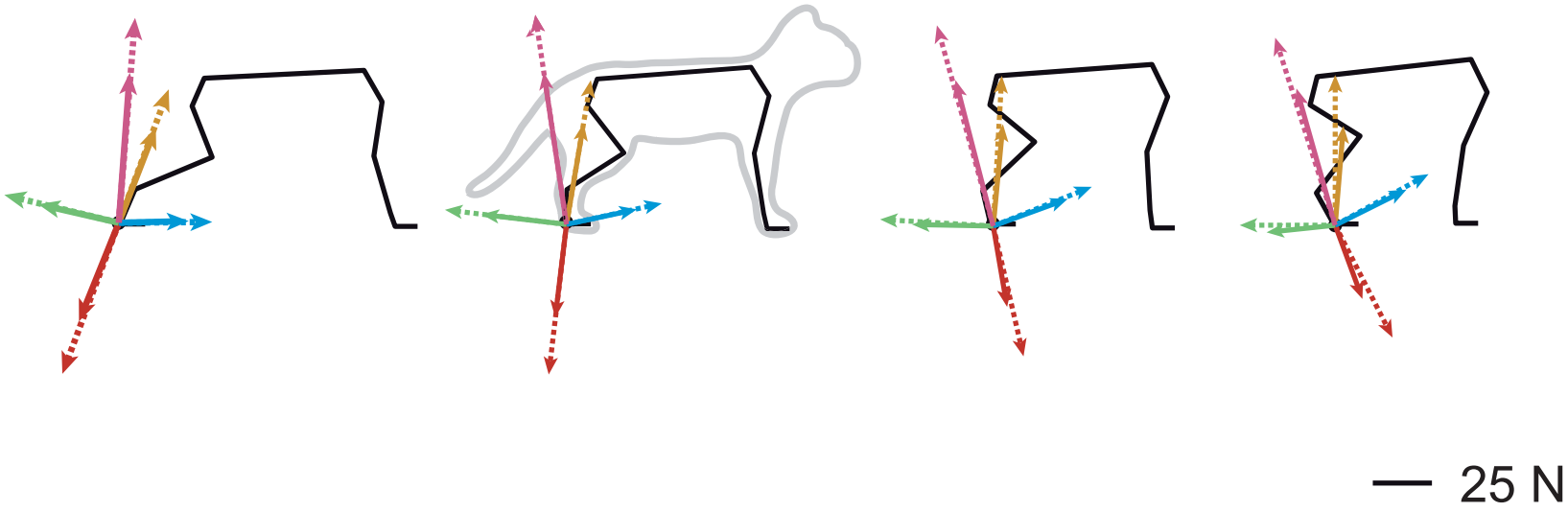


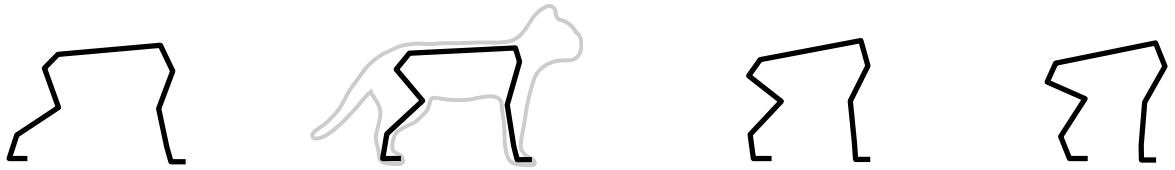
McKay and Ting, 2008

We calculated force production capability of the hindlimb assuming either:

1. musculoskeletal constraints
2. musculoskeletal constraints + muscle synergy constraints

Kuo and Zajac 1993; Valero-Cuevas et al., 1998; Schmidt et al. 2003

Functional muscle synergies constrain hindlimb force production capability.



preferred

McKay and Ting 2008

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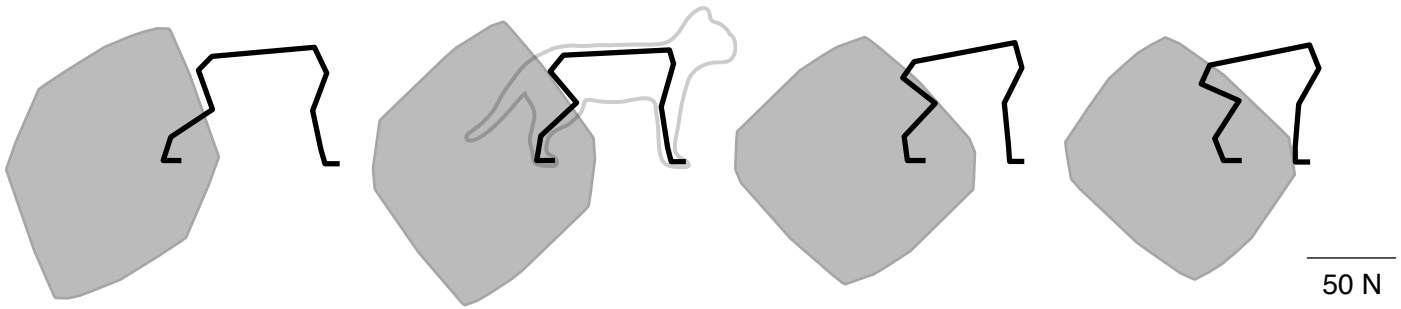

musculoskeletal constraints

- **Musculoskeletal constraints do not vary with configuration.**

McKay and Ting 2008

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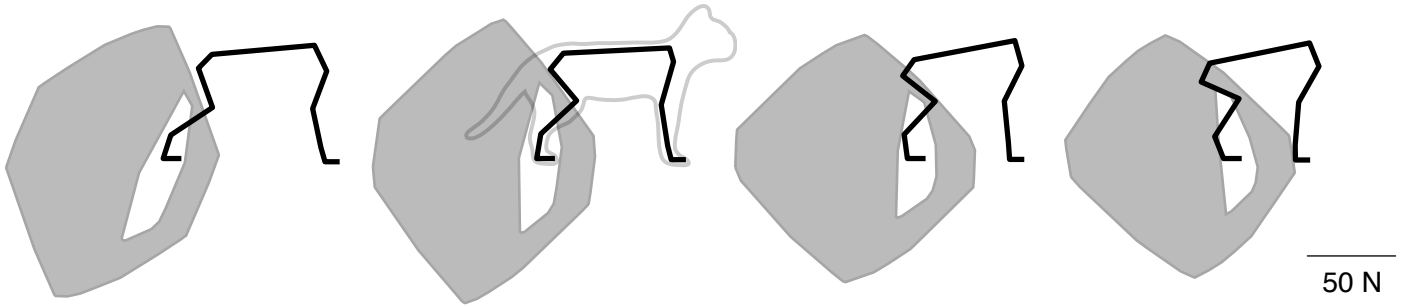

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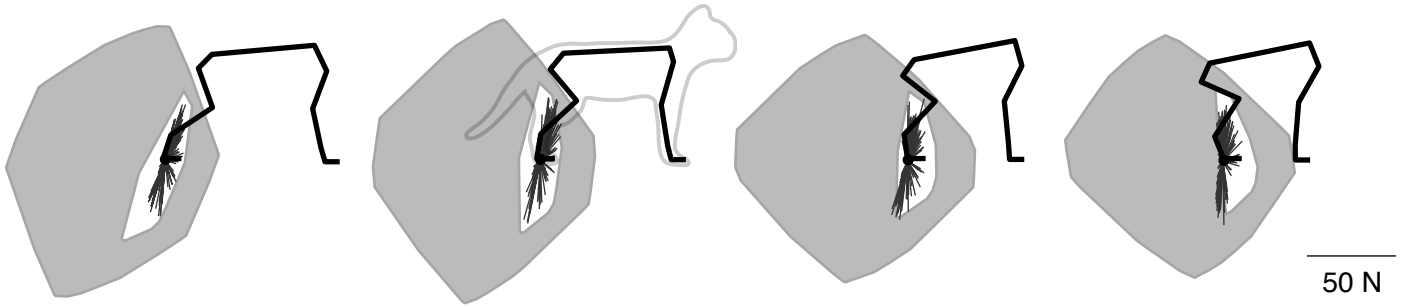

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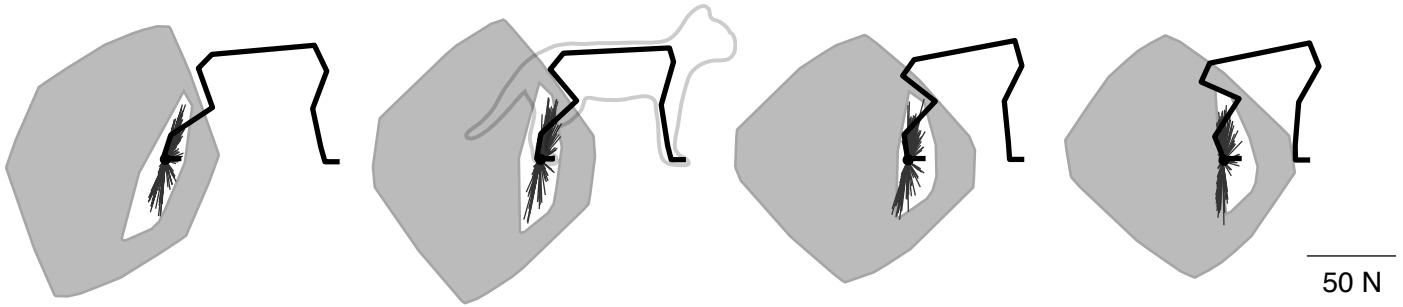

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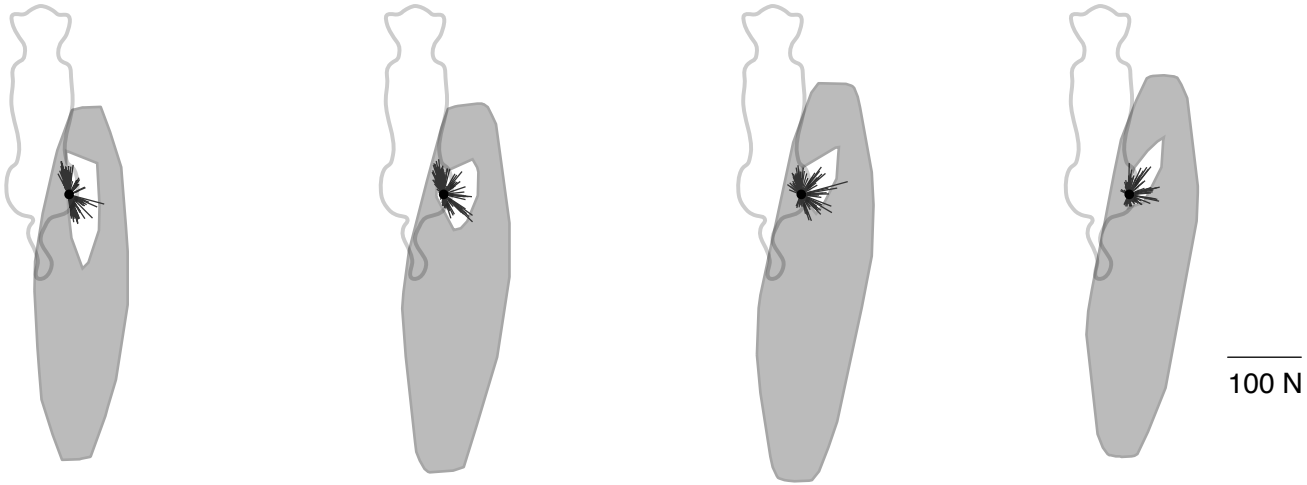

McKay and Ting 2008

- **Musculoskeletal constraints do not vary with configuration.**
- **Muscle synergy constraints rotate with the limb axis.**
- **Horizontal-plane forces not well-represented.**

Functional muscle synergies constrain hindlimb force production capability.

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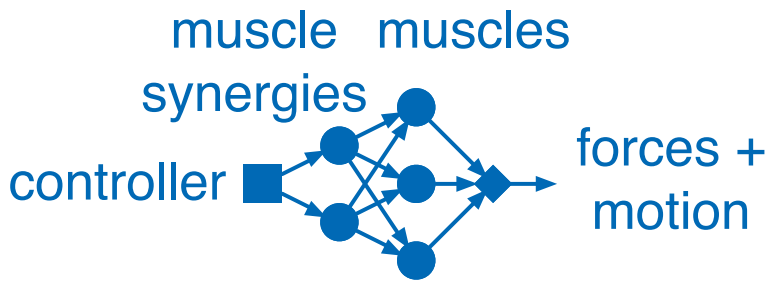
What is the source of low-dimension muscle activity and forces during balance?

- **Muscle synergy constraints on muscle coordination?**
  (Tresch et al., 1999; Ting and Macpherson 2005)

muscle synergy control



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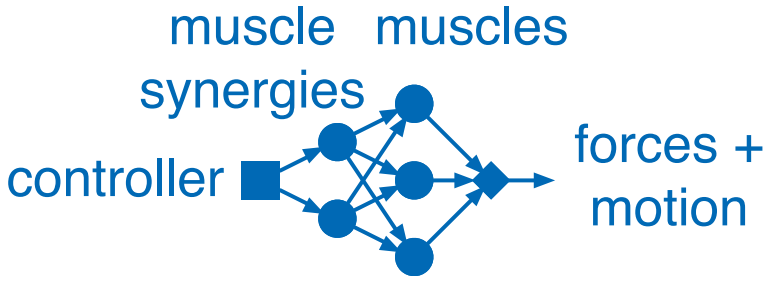
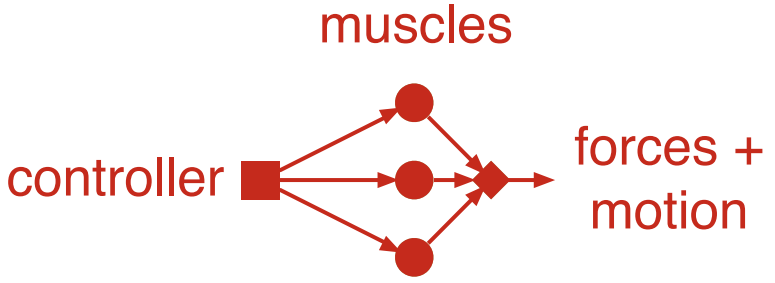


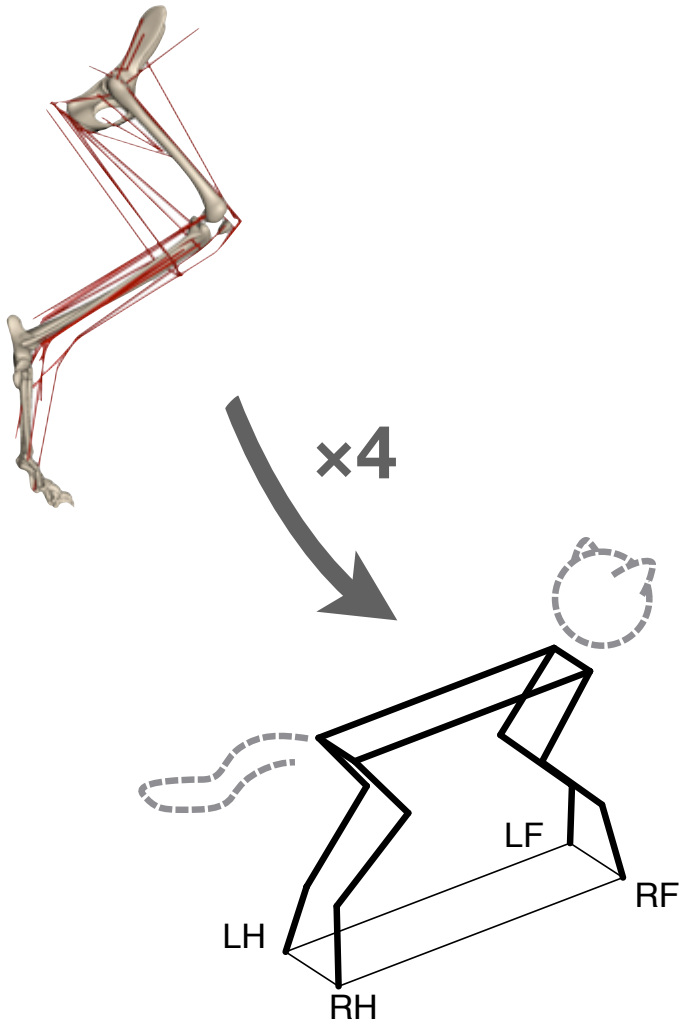
optimal muscle control

- **Optimal muscle coordination pattern?**
  (Todorov and Jordan 2002; Fagg et al., 2002)



$$\min \sum e_i^2$$

We compared optimal muscle control and muscle synergy control in four limbs.



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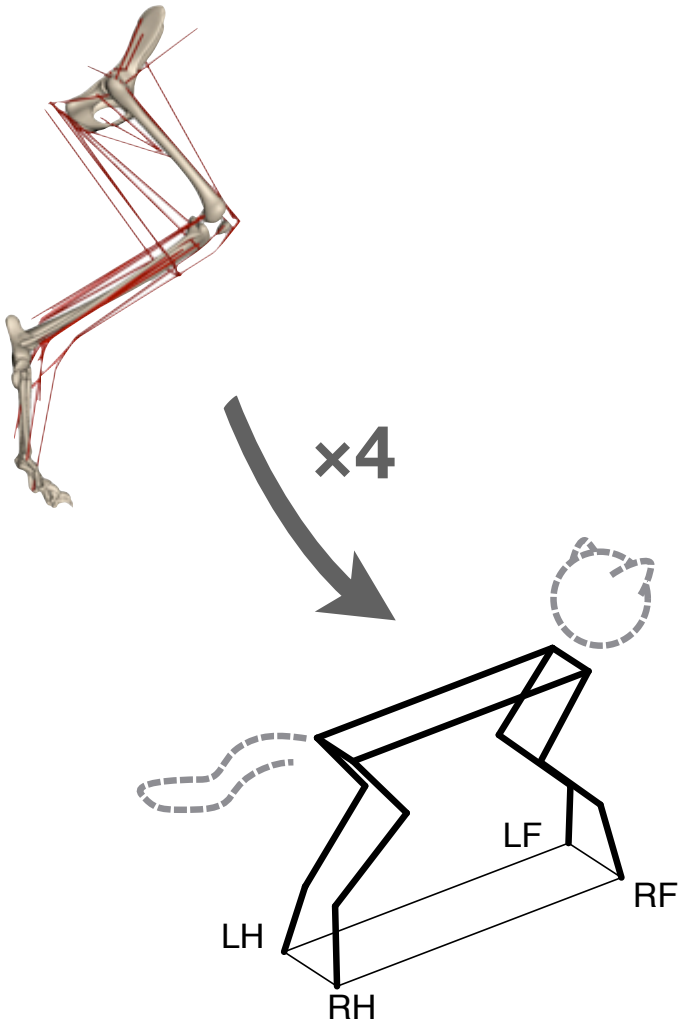

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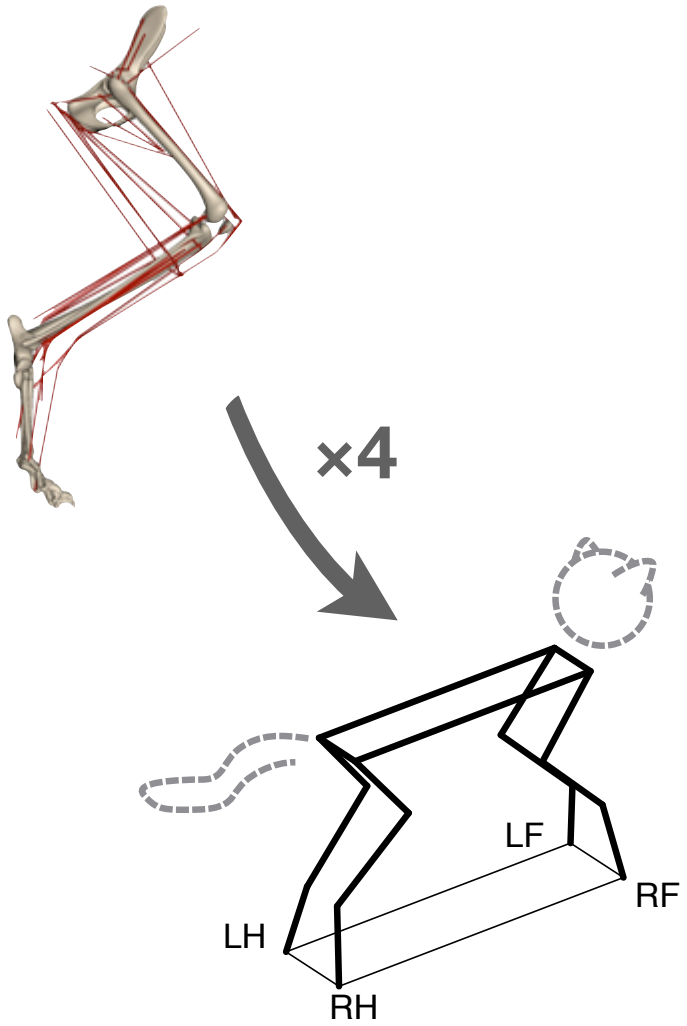
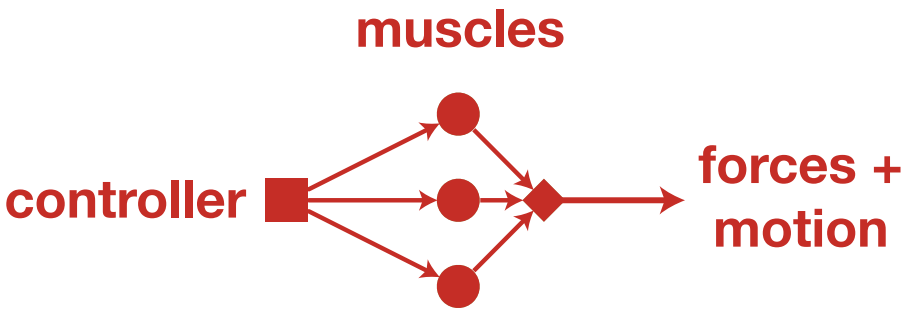


- **Hypothesis:** muscle synergies are generalized across postural configurations, biasing motor performance and increasing control cost compared to optimal muscle control.

- **Prediction:** forces generated by muscle synergy control will vary with postural configuration as in data; forces generated by optimal muscle control will not.

We simulated two ways of generating net forces and moments at the CoM.

1. optimal muscle control



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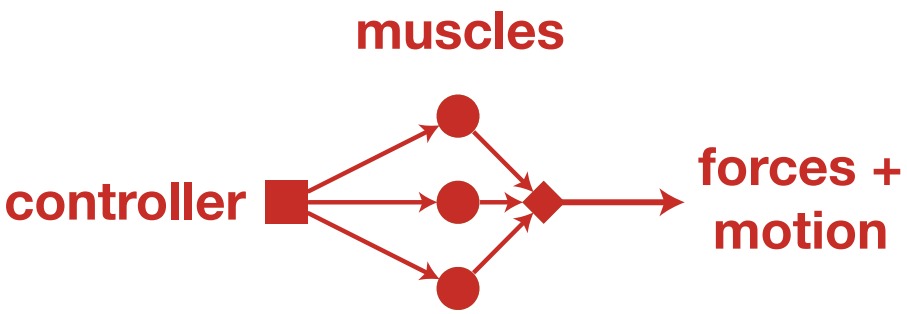

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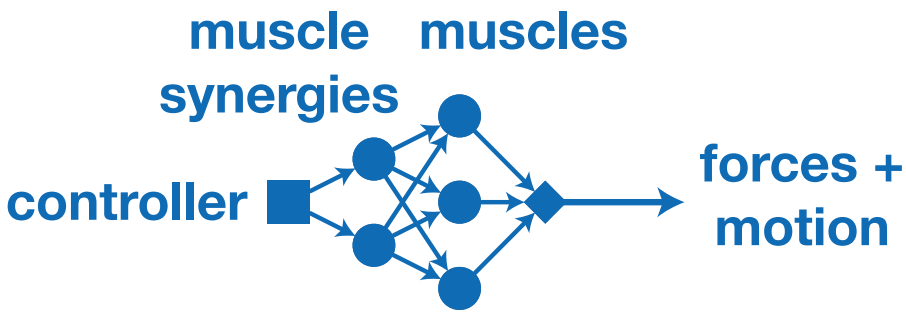
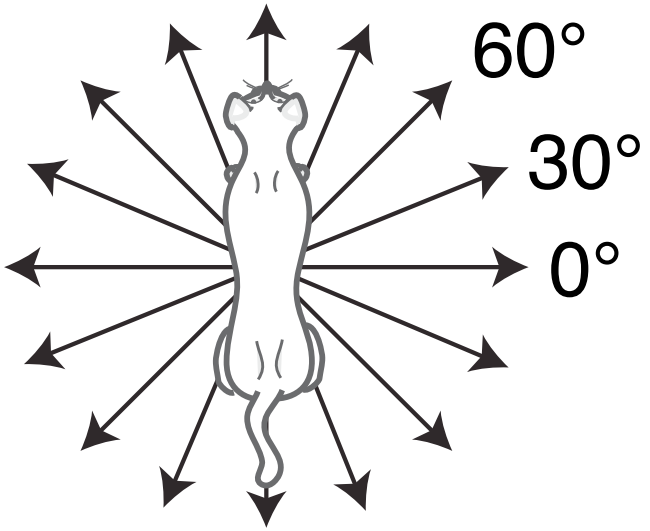
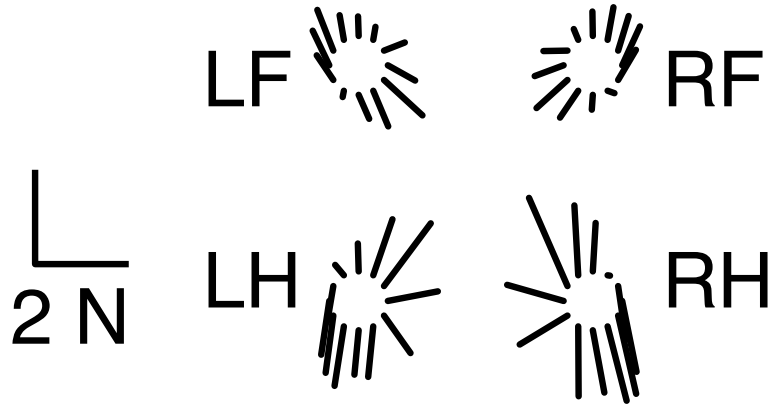
2. muscle synergy control

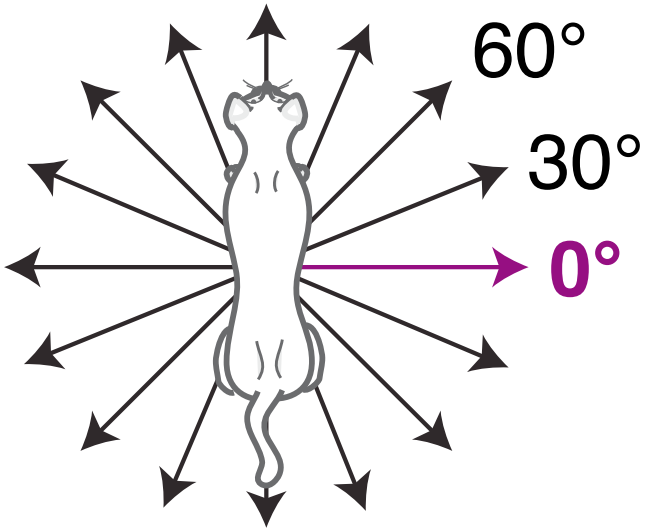


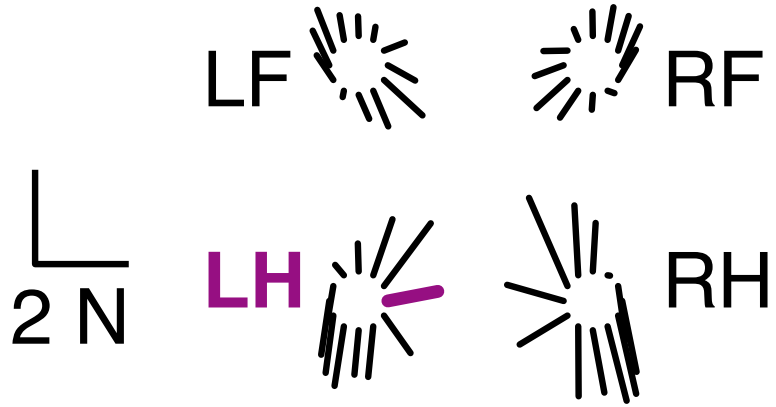
$$\min \sum c_i^2$$





Macpherson, 1988





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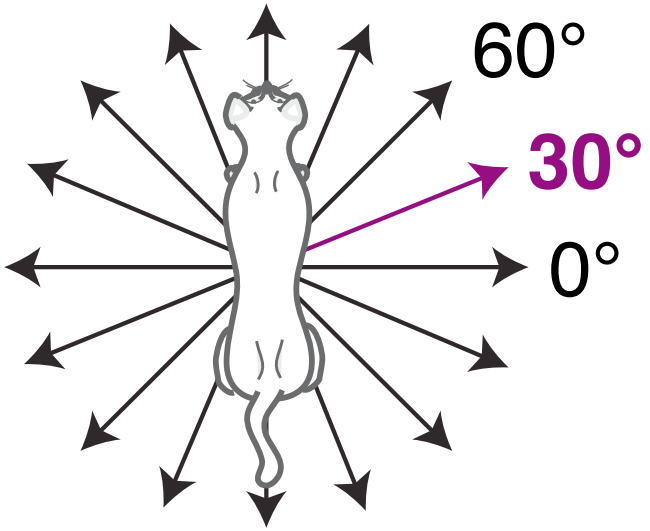
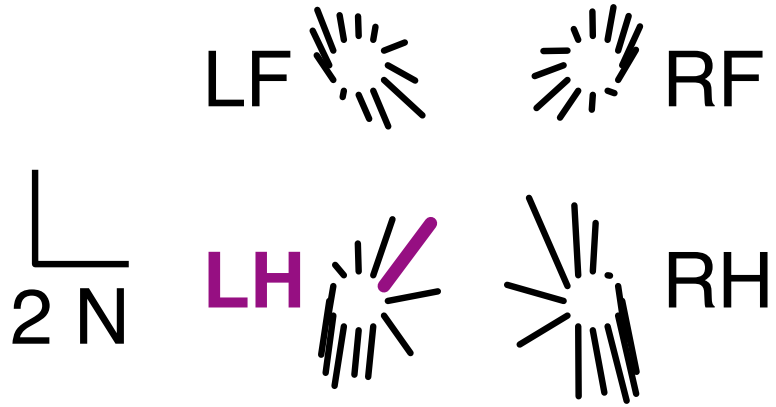
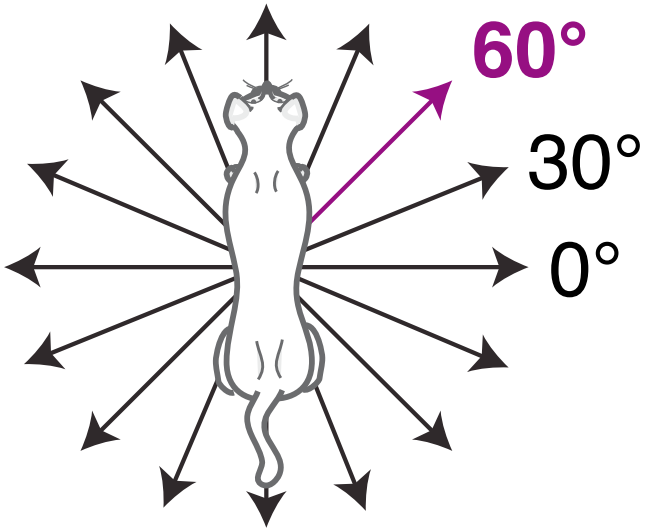
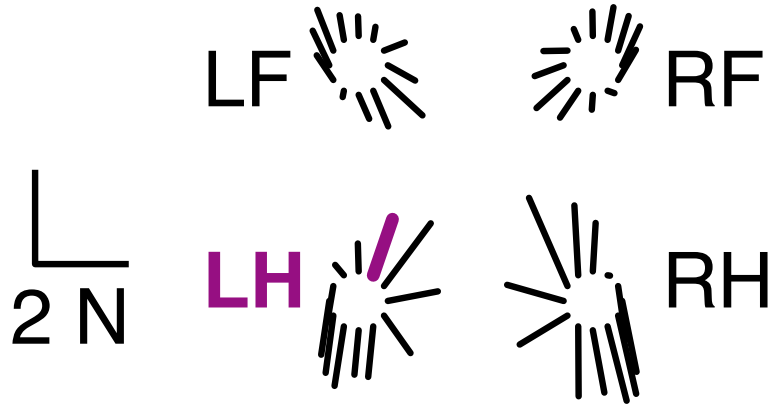


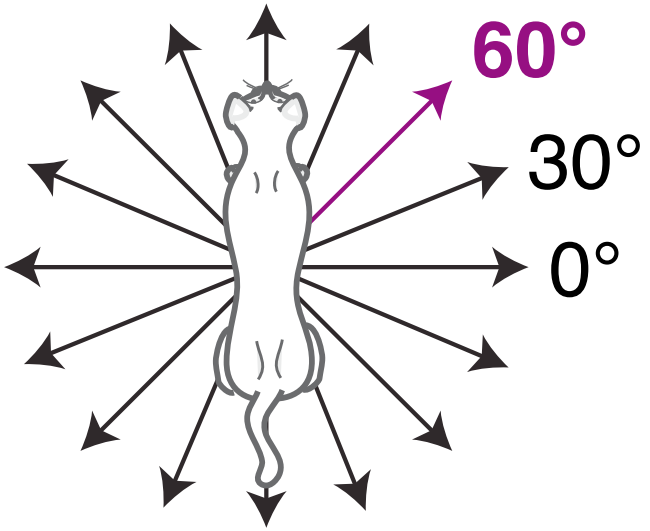


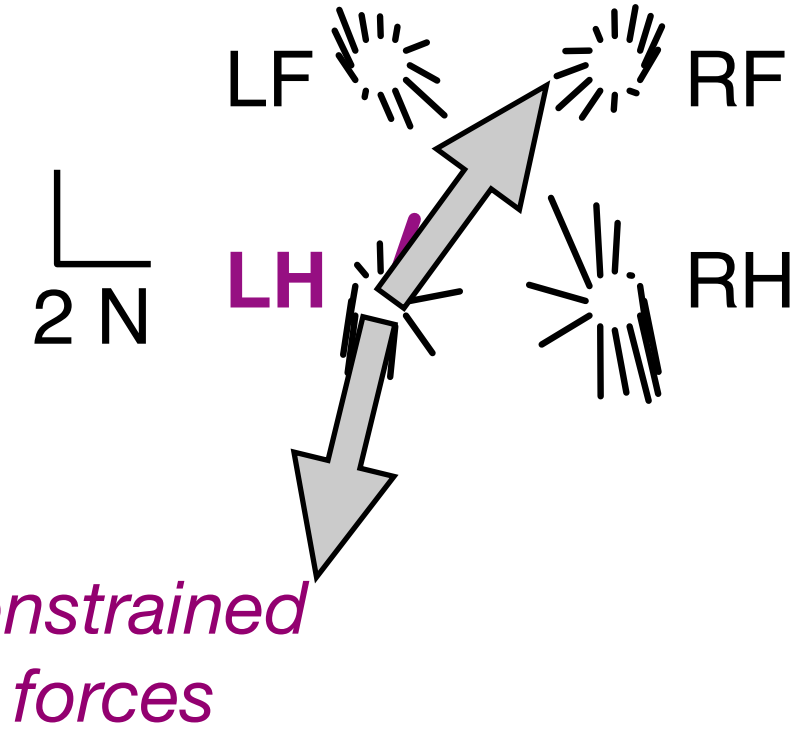
Macpherson, 1988



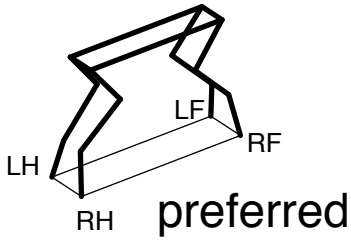


Macpherson, 1988



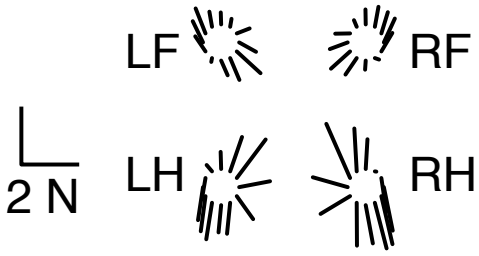


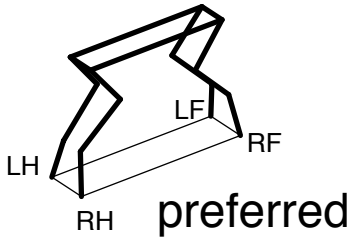
Macpherson, 1988



preferred

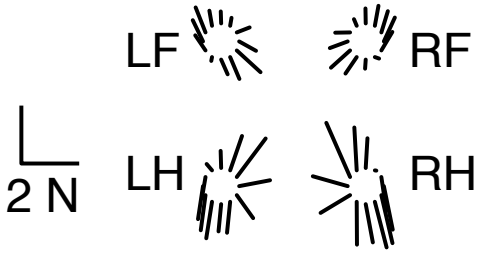
translation perturbation data



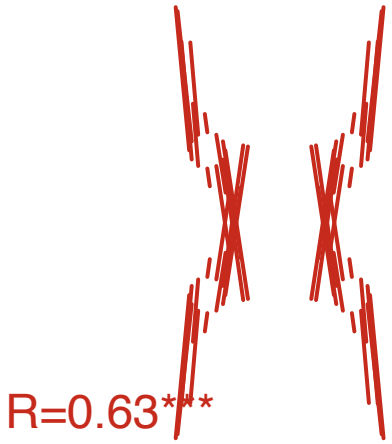


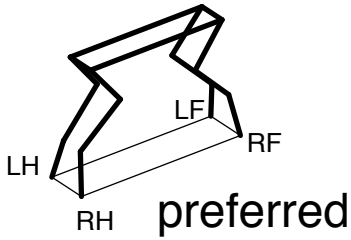
preferred

translation perturbation data

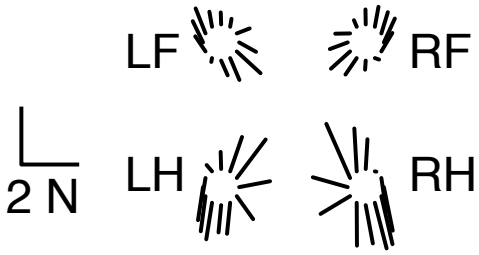


optimal muscle control

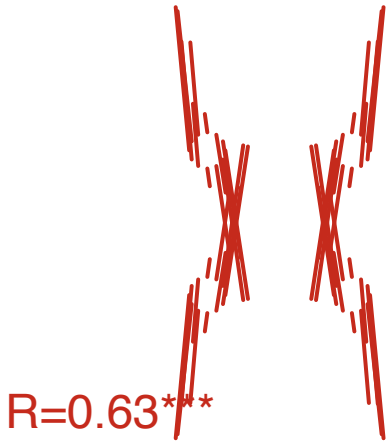




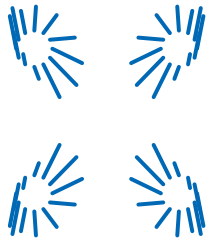
translation perturbation data

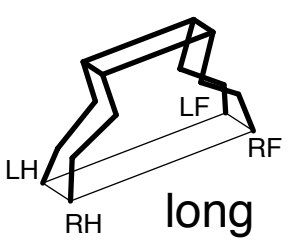


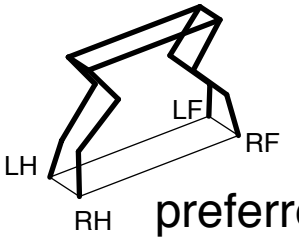
optimal muscle control

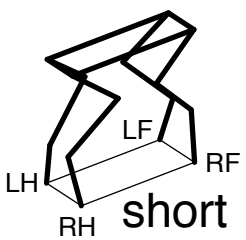


muscle synergy control









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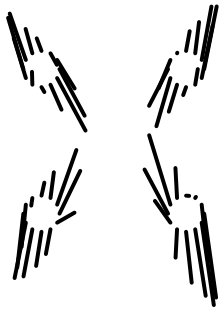
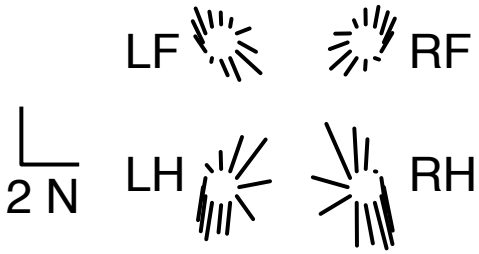
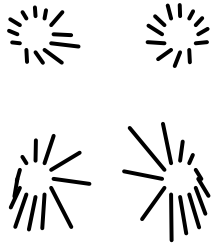
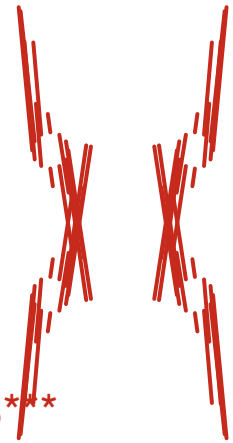




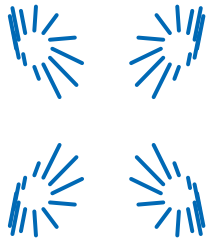


optimal muscle control

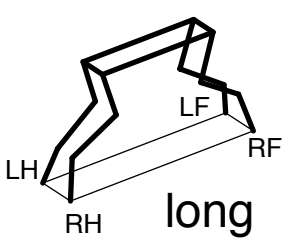


R=0.63***

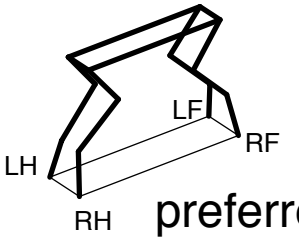
muscle synergy control



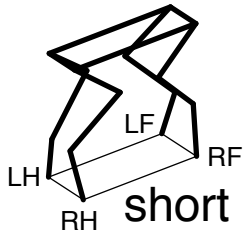
R=0.89***



long

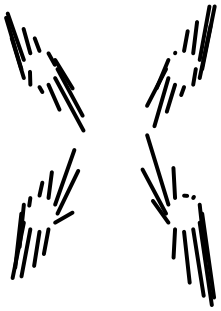


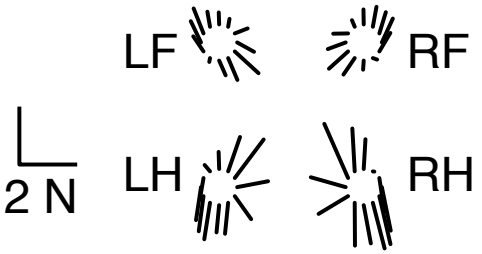
preferred

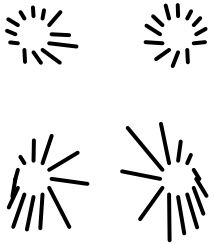


short

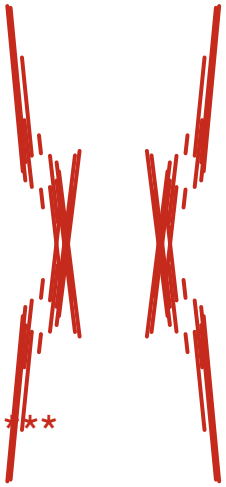
translation perturbation data



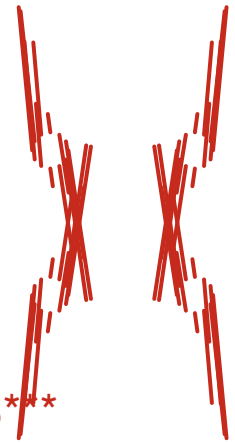




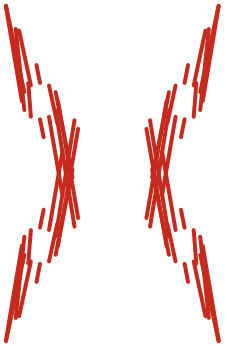
optimal muscle control



R=0.91***

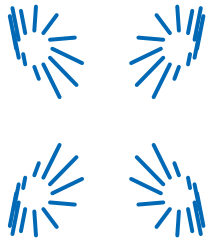


R=0.63***

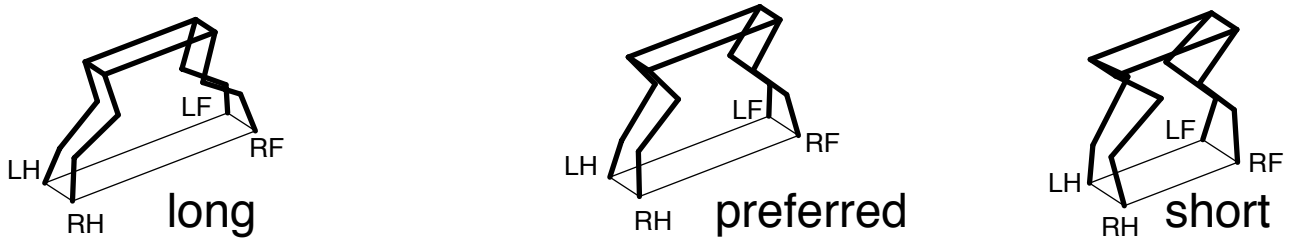


R=0.32**

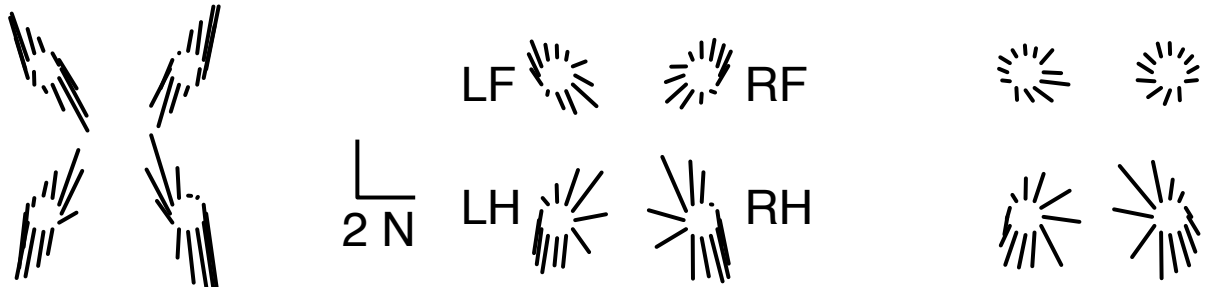
muscle synergy control



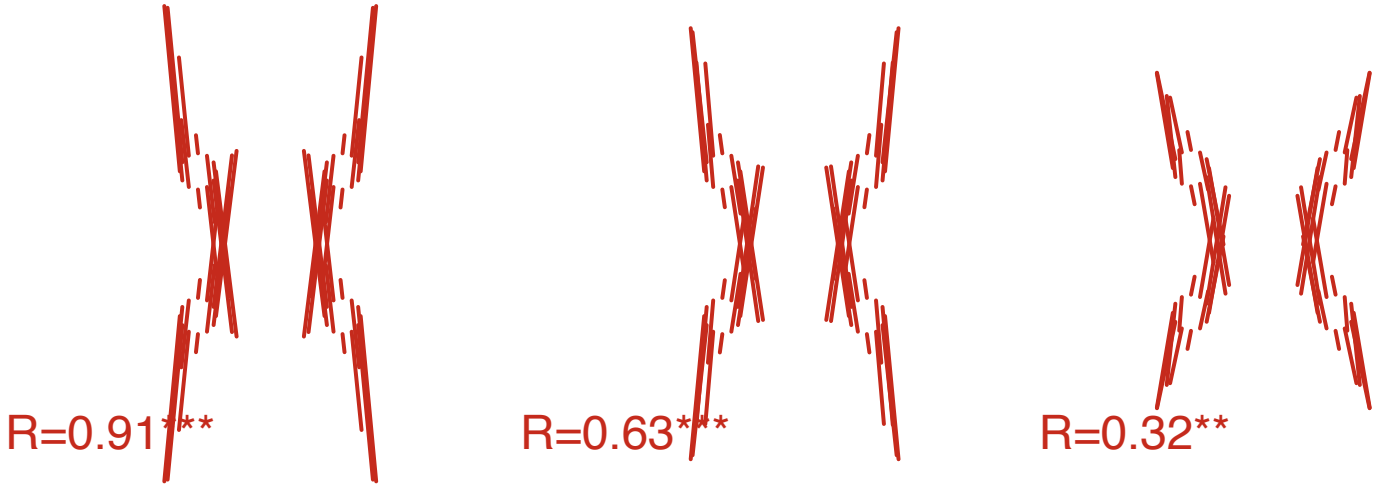
R=0.89***



translation perturbation data

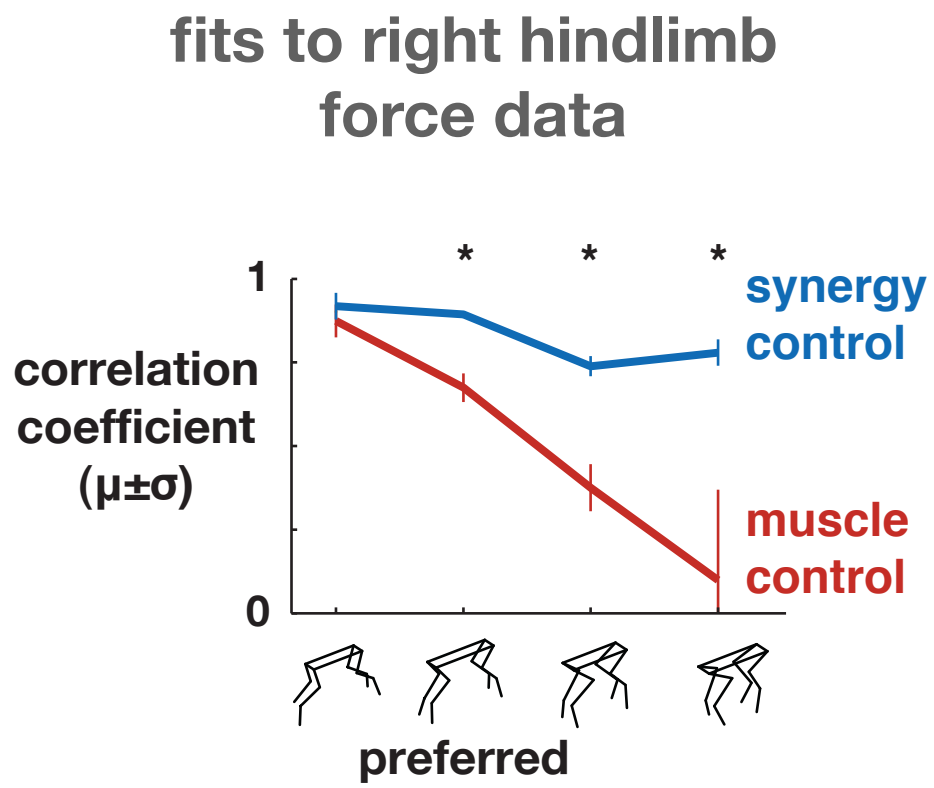


optimal muscle control



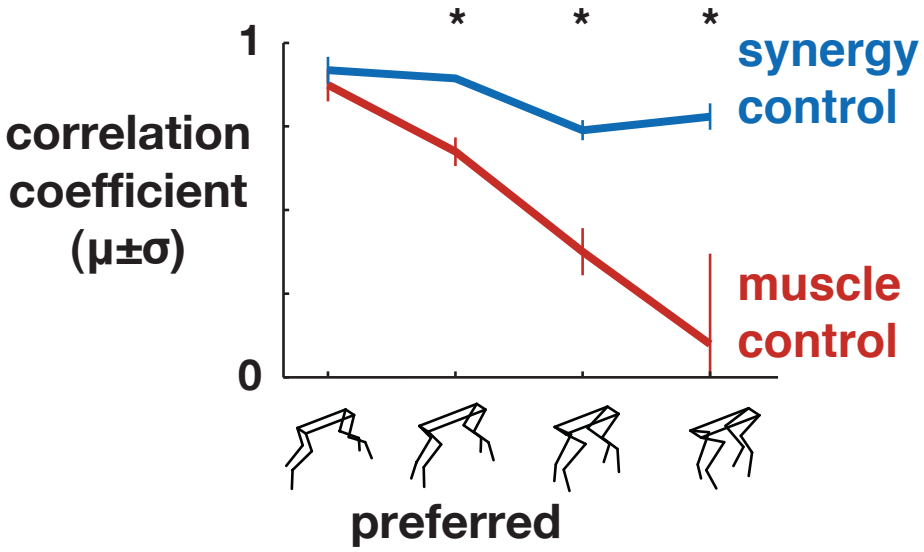
muscle synergy control

Muscle synergy control predicts data better than optimal muscle control.

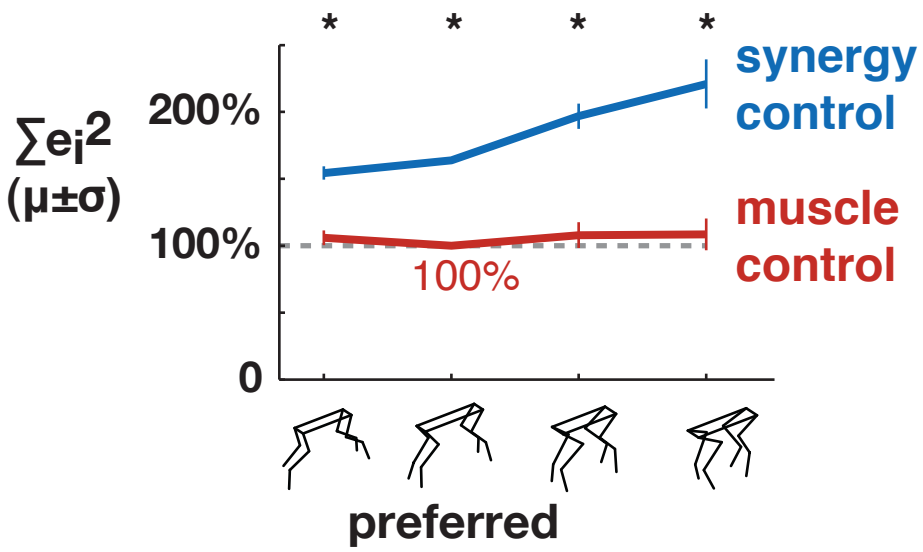


Muscle synergy control predicts data better than optimal muscle control. ... but costs more.

fits to right hindlimb force data

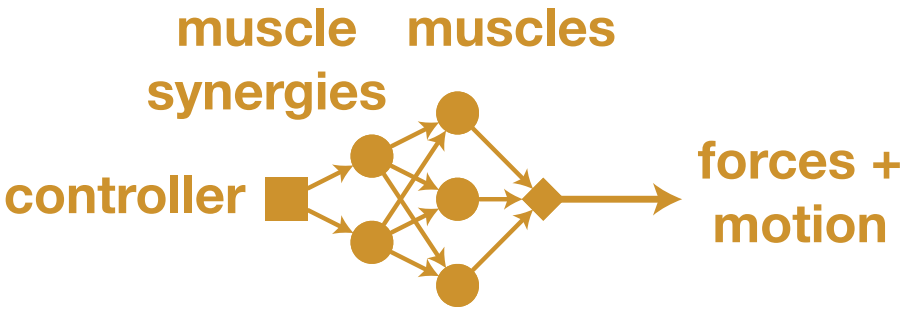


simulated muscle activation



We also minimized muscle activation within muscle synergy constraints.

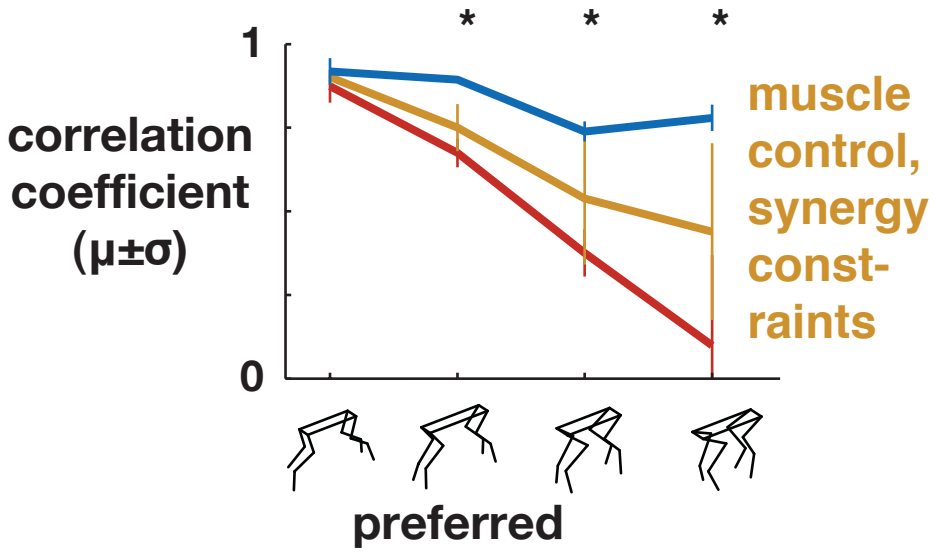
3. optimal muscle control, muscle synergy constraints



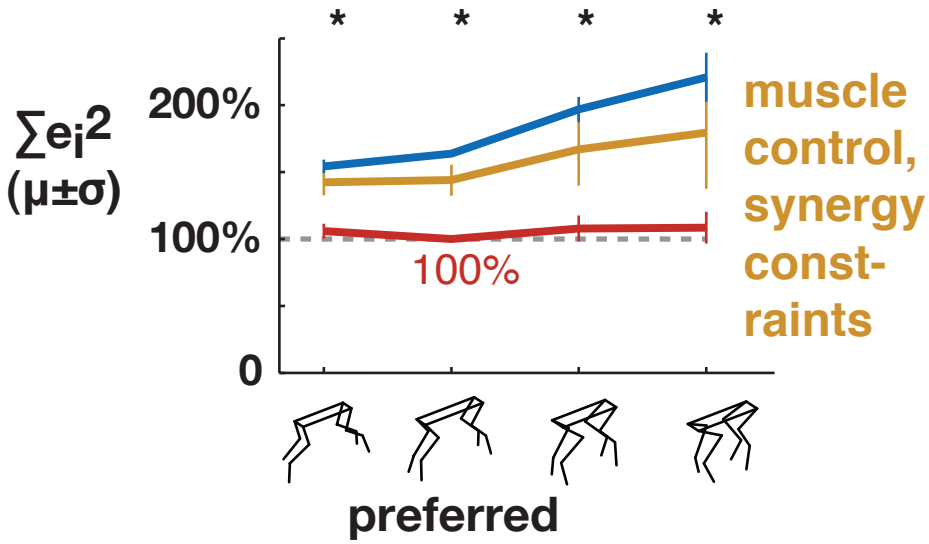
$$\min \sum e_i^2$$

Minimizing muscle activation within muscle synergy constraints splits the difference.

fits to right hindlimb force data

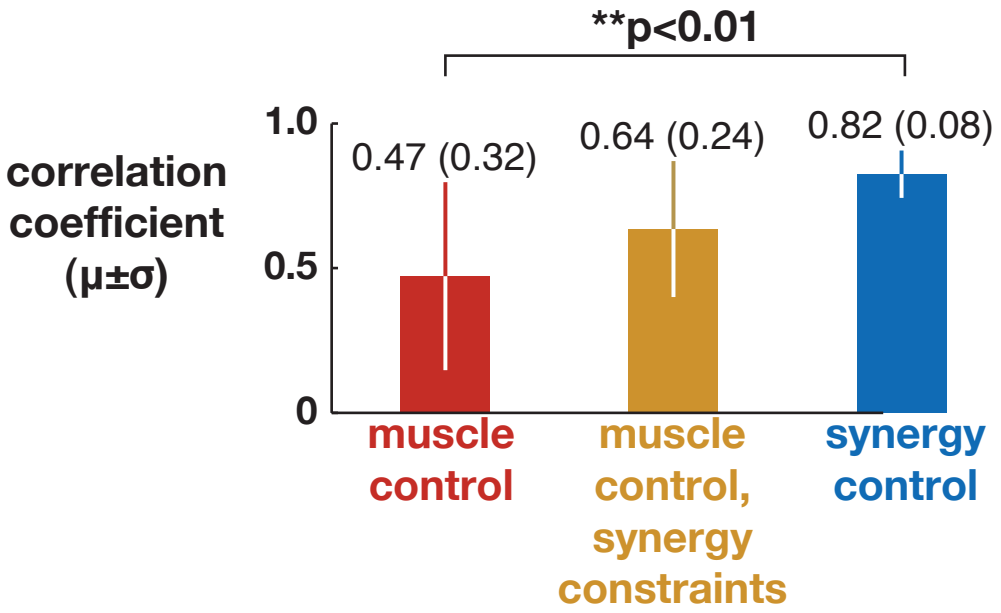


simulated muscle activation

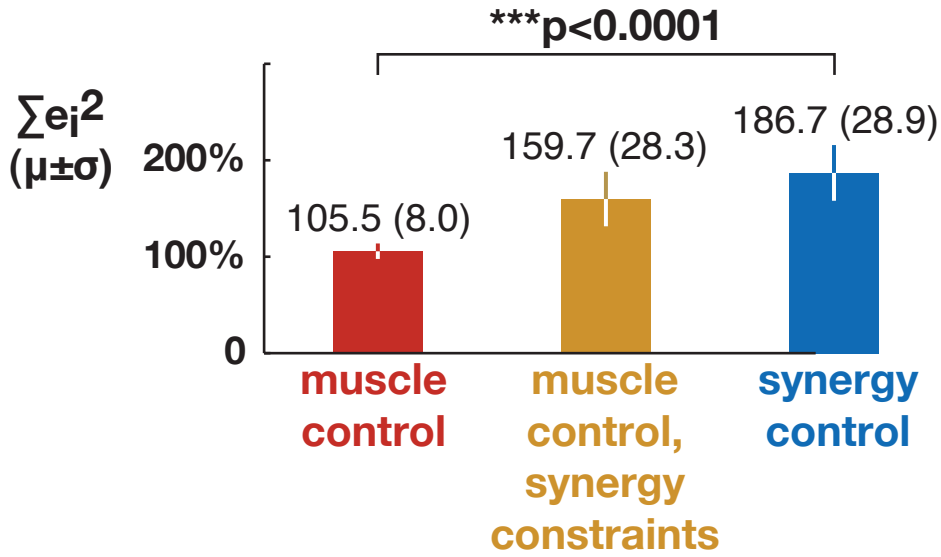


Muscle synergy control predicts data better than optimal muscle control but costs more.

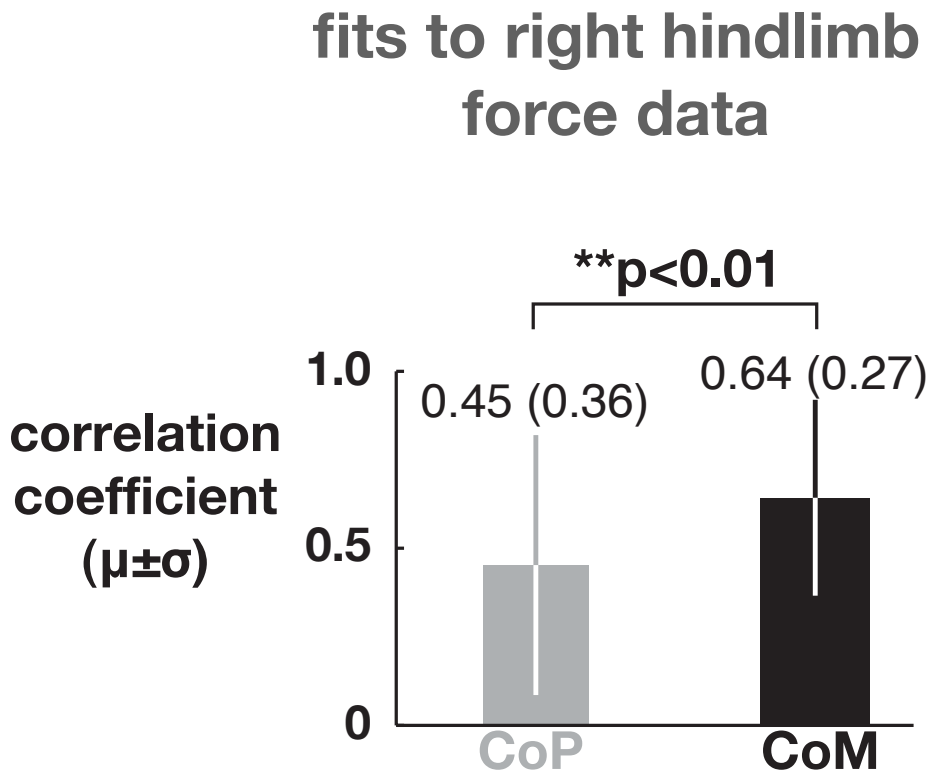
fits to right hindlimb force data



simulated muscle activation



Coordinating the CoP, rather than the CoM, doesn't work.



CoM: *Lockhart and Ting, 2007; Welch and Ting, 2009;* ***CoP:*** *Winter, 1995*

Muscle synergies produce expensive behavioral biases during postural control

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  - **May be near optimal overall.**

What is the source of low-dimension muscle activity and forces during balance?

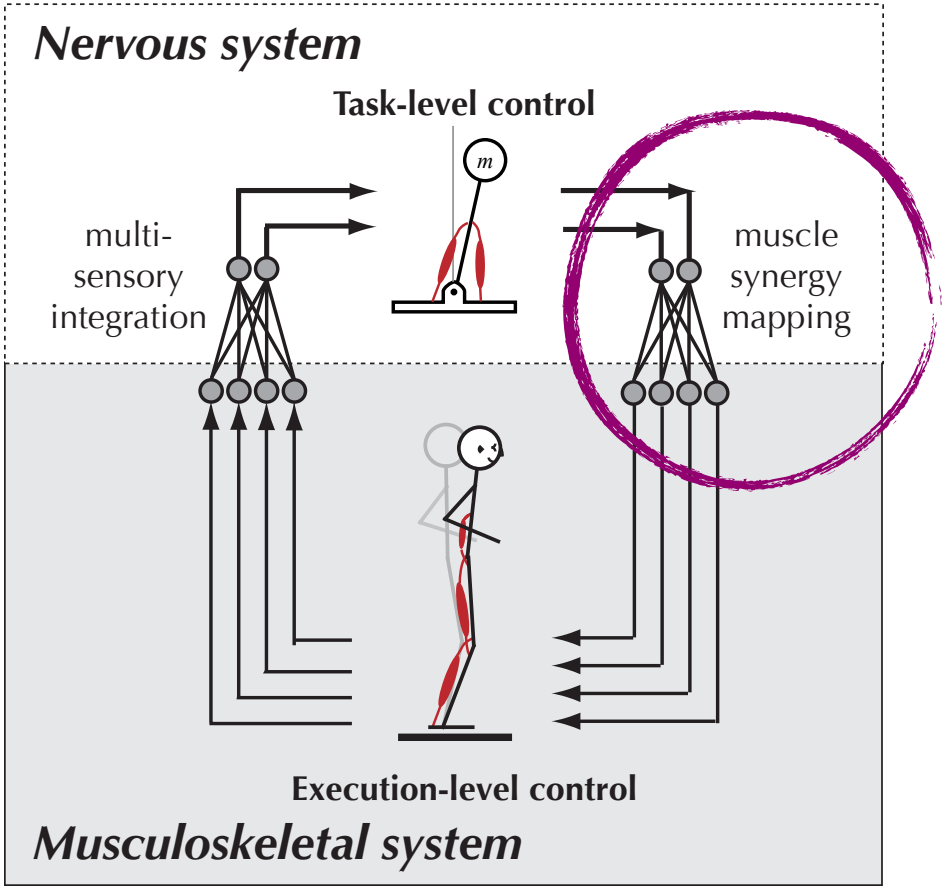
PART 1

Muscle synergies constrain hindlimb forces during balance

PART 2

Optimal control of muscle synergies, not individual muscles, reproduces balance forces across postural configurations

What is the source of low-dimension muscle activity and forces during balance?



muscle synergy mapping

Ting and McKay, Curr Opin Neurobiol 2007

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- **Mechanical constraints are critical to understanding first order motor behaviors** *(Collins et al., 2001)***.**
- **Neural constraints are required to explain patterns of generalization** *(Shadmehr and Mussa-Ivaldi, 1994)***.**

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Muscle synergies can facilitate understanding both normal and impaired movement.

- **We use muscle synergies to characterize healthy cats and college students.**
- **Muscle synergies can also serve as a diagnostic tool.**
  - **Hemiplegic stroke patients exhibit fewer muscle synergies that are merged versions of healthy modules** *(Clark et al, 2010; Dewald et al., 1995)*.

Muscle synergies can facilitate understanding both normal and impaired movement.

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- **Muscle synergies can also serve as a diagnostic tool.**
  - **Hemiplegic stroke patients exhibit fewer muscle synergies that are merged versions of healthy modules** *(Clark et al, 2010; Dewald et al., 1995)*.
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  - **Pathological muscle synergies after stroke can be escaped with focused training and understanding of muscle synergy function** *(Ellis et al., 2005)*.

Publications resulting from this work

PART 1

- **McKay JL, Burkholder TJ, and Ting LH.** Biomechanical capabilities influence postural control strategies in the cat hindlimb. *J Biomech* **40**: 2254-2260, 2007.
- **McKay JL, and Ting LH.** Functional muscle synergies constrain force production during postural tasks. *J Biomech* **41**: 299-306, 2008.
- **Ting LH, and McKay JL.** Neuromechanics of muscle synergies for posture and movement. *Curr Opin Neurobiol* **17**: 622-628, 2007.

PART 2

- **McKay JL, and Ting LH.** Muscle synergies produce expensive behavioral biases during postural control. *in prep*.

not shown

- **McKay JL, and Ting LH.** The nervous system reduces the dimension of sensory inflow during responses to postural perturbations. *in prep.*

Thank you!

- Jane Macpherson, Ph.D.
- Tom Burkholder, Ph.D.
- Gelsy Torres-Oviedo, Ph.D.
- NIH HD46922

Georgia Tech

EMORY

“I used to think that the brain was the most wonderful organ in my body. Then I realized who was telling me this.”

Emo Philips

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