

# NEUROMECHANICAL MODELING OF FUNCTIONAL MUSCLE SYNERGIES FOR POSTURAL CONTROL IN THE CAT

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## INTRODUCTION

In a recent study, we demonstrated that EMG and kinetic data from the automatic postural response in cats could be decomposed into five “functional” muscle synergies, each specifying a pattern of hindlimb muscle activation and a correlated “synergy force vector” at the ground (Torres-Oviedo et al., 2006). The analysis showed that these functional muscle synergies could explain both muscle activation patterns and endpoint forces in a range of postural configurations that alter the biomechanical conditions of the task. However, this generalization was apparent only when we expressed the kinetic data in a coordinate system that rotated with the sagittal hindlimb axis. This suggests that muscle synergies provide the nervous system with a simple mechanism to generate forces consistent in the reference frame of the limb.

Here, we used a static 3D musculoskeletal model of the cat hindlimb (McKay et al. 2006) to test the hypothesis that muscle synergies could produce endpoint force vectors across a range of postural configurations corroborating our experimental observations. We then examined the neuromechanical implications of the functional muscle synergy architecture by examining changes in the feasible force set (FFS; Valero-Cuevas 2006) after a synergy organization was imposed.

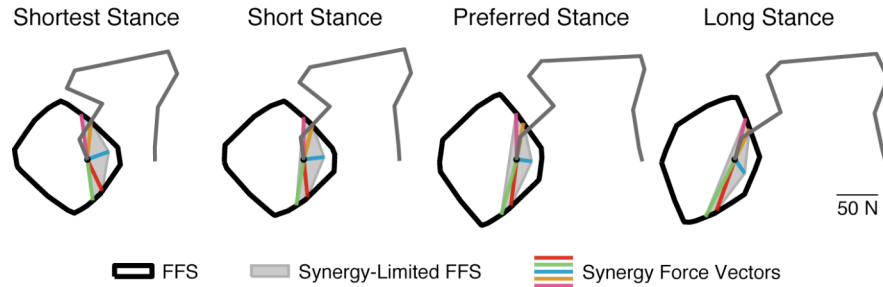
## METHODS

First, we tested whether muscle synergies could produce endpoint forces that were consistent with respect to the sagittal hindlimb axis in a range of postural configurations. For each of three animals, we generated five simulated muscle synergies that could reproduce the experimentally derived synergy force vectors in the nominal postural configuration. We then examined the endpoint forces generated by these muscle synergies in the three other postural configurations using kinematic data from each cat (Torres-Oviedo et al., 2006).

We investigated whether the simulated muscle synergies limited or spanned the force-production capabilities of the hindlimb. We calculated FFSs for all conditions as in (McKay et al. 2006); first assuming individuated control of muscles and later assuming individuated control of only the simulated synergies.

## RESULTS AND DISCUSSION

Consistent with our hypothesis, simulated synergies produced force vectors that rotated monotonically with the limb axis in the sagittal plane as postural configuration varied (Figure 1, colored lines). Synergy force vector orientation was highly correlated to limb axis angle in the sagittal plane ( $r^2 = 0.94 \pm 0.08$ ,  $\mu \pm \sigma$ ), and less so in the dorsal plane ( $0.75 \pm 0.3$ ), confirming the quasi-planar variation we observed



**Figure 1:** Rotation of synergy force vectors and feasible force sets with hindlimb axis when the animal stands using various postural configurations.

experimentally. This result suggests that postural forces can be coordinated by the nervous system throughout the workspace with a relatively simple polar transformation from intrinsic to extrinsic coordinates. This is consistent with the encoding of limb orientation in sensory signals traveling from the spinal cord to higher brain centers (Bosco et al. 1996).

When compared with the nominal FFS (Figure 1, thick black lines), the synergy-limited FFS (Figure 1, gray shaded areas) varied much more acutely with postural configuration, particularly in the sagittal plane ( $r^2 = 0.92 \pm 0.05$  vs.  $0.77 \pm 0.2$ ). The synergy-limited FFS was also considerably more elongated at all postures. We have previously demonstrated that the nominal FFS is a weak determinant of postural force, due to its generally isotropic shape (McKay et al, 2006) – taken together, these results suggest that the synergy-limited FFS may be a much stronger determinant of force magnitude in the hindlimb, particularly as postural configuration changes.

Our results illustrate that the muscle synergies recruited for postural control do not span the force-producing capabilities of the limb, so that only a limited range of forces are available for the postural task. Similar reductions in FFS volume occur in conditions of neural deficit (cf. Valero-Cuevas 2006). Based on these results, we

predict that tasks like locomotion will recruit additional synergies to reach the remainder of the FFS (e.g., d'Avella and Bizzi 2005).

Muscle synergies appear to limit the biomechanical outputs of the limb based on a parsimonious control strategy rather than musculoskeletal constraints. Our results suggest that it may be valuable to consider the changes to the FFS associated with muscle synergies when predicting muscle coordination and biomechanics for some natural behaviors, as opposed to “maximal” tasks where coordination is determined uniquely by biomechanical limitations (e.g., Valero-Cuevas 2006).

## REFERENCES

- Bosco, G., et al. (1996). *J. Neurophys*, **76**, 715-726.  
d'Avella, A., Bizzi, E. (2005). *PNAS*, **102**, 3076-3081.  
McKay, J.L., et al. (2006). *J. Biomech*, doi:10.1016/j.jbiomech.2006.10.013.  
Torres-Oviedo, G., et al. (2006). *J. Neurophys*, **96**, 1530-1546.  
Valero-Cuevas, F. (2006). *Progress in Motor Control V*, in press.

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