Feasible Ranges of Muscle Activity Quantify Musculoskeletal Redundancy in Human Walking

Cole Simpson¹, M. Hongchul Sohn¹, Jessica Allen², and Lena H. Ting¹,²

¹School of Mechanical Engineering, Georgia Tech  ²Department of Biomedical Engineering, Georgia Tech and Emory University

Introduction

Musculoskeletal redundancy allows for an infinite number of combinations of muscle activation patterns for performing a task and is frequently resolved in musculoskeletal modeling using optimization techniques. Optimization methods select a single set of muscle activations from the entire range of possible solutions to satisfy physiologically based criteria, such as minimizing muscle stress. However, such techniques do not account for the variability that is commonly observed in many motor tasks such as walking, both within and across individuals. Accordingly, optimal muscle activation solutions frequently deviate from experimentally recorded patterns. How does the nervous system select these variable muscle activations? Are consistent trends in the deterministic result of biomechanics or common neural strategies? In order to better understand the role that biomechanical versus neural constraints play in shaping muscle activation patterns for movement, the full range of possible muscle activation patterns based on biomechanics must first be defined. Several methods for computing biomechanical limitations have been explored in static simulations. Our objective was to identify biomechanical limitations on muscle activation during a dynamic human walking task.

Biomechanical Constraints on Variability:

Redundant System: Leg with two opposing muscles, one large (m1) and one small (m2), acting on a knee with 1 degree of freedom

Objective: Produce a flexion torque equal to half of the maximum torque producible by the system

Optimization yields one solution from many possibilities:

- Minimum muscle stress solution (Q): 50% m1 and 0% m2
- Measured muscle activities (X) may vary significantly from Q

Upper and lower bounds define limits of variation (Feasible Range):

- Upper bound (maximum possible activation) limited by relative strength of the antagonistic muscles
- Lower bound (minimum possible activation) determined by necessity for the task

Feasible limits can be determined for each measured time point during a dynamic task:

- Upper bound indicates whether muscle is constrained (<1) or unconstrained (=1)
- Lower bound indicates whether a muscle is optional (0=) or necessary (>0)
- Time point B shows a narrow feasible range, which does not permit a lot of variability
- Time point A shows a wide feasible range, which permits a large amount of variability

Results

Feasible ranges were generally wide

- Most muscles (73%) were not limited by their biomechanics at any time during the gait cycle (upper bound = 1, lower bound = 0)
- Only two muscles were necessary (lower bound > 0 at any time point): the left TA and the left GMED1
- Most muscles (76%) were unconstrained (upper bound = 1 for every time point)

Differences were observed in the feasible ranges of the right and left legs

- The musculoskeletal model is symmetric
- Differences were observed between the feasible ranges of the right and left legs (ex: GMED2)
- Differences in feasible ranges between right and left legs are due to variations in joint angles and joint torques between the legs

Experimental variability was much less than that permitted by the biomechanics

- Experimental EMG data was superimposed on the feasible ranges for available muscles
- Variability in experimental EMGs was much less than that allowed by the biomechanics (ex: RF)

Conclusions

- Wide feasible ranges suggest that the selection of muscle activations is not the deterministic result of biomechanical considerations for this submaximal task
- Large amounts of variability are permitted in a redundant system (compared to finger model)
- Additional neural constraints are needed to select unique muscle activations
- Sensitivity of feasible ranges to biomechanical variations is consistent with previous studies
- Small variations in experimental data compared with feasible ranges suggest that consistent neural strategies are used
- Feasible ranges quantify the redundancy of muscle activations during a dynamic task
- This method reveals the complete range of biomechanically allowed variability in muscle activity during a dynamic task
- Additional constraints will further reduce the feasible ranges (ex: muscle synergies) to more closely predict experimental muscle activation ranges

Methods

Experimental Data - John et al. 2012

Musculoskeletal Model - OpenSim 2.3 (©

Model Outputs

Computing Feasible Ranges

Linear Programming - linprog.m, Matlab

Acknowledgments

References


Contact: csimpson37@gatech.edu