# Objective Function Choice Influences Muscle Force Predictions During Human Walking

Elijah C. Kuska[1] and Allison L. Kinney[1]

[1]Department of Mechanical & Aerospace Engineering, University of Dayton, Dayton, OH, USA

"Doctors have long known that **people differ in susceptibility to disease and response to medicines.** But, with little guidance for understanding and adjusting to individual differences, **treatments developed have generally been standardized for the many, rather than the few."**

- National Academy of Engineering

## Introduction

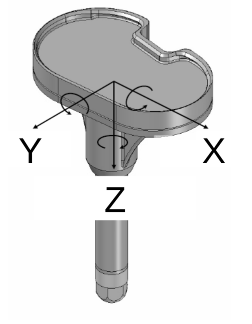
- Musculoskeletal disorders can limit mobility; level of impairment between individuals with a disorder varies
- Current rehabilitation techniques generalized for the many rather then the few
- Knowledge of patient-specific muscle forces may help to design personalized rehabilitation
- Muscle forces are impractical to measure and the musculoskeletal system is redundant (# muscles >> # degrees of freedom): optimization is needed to predict muscle forces
- Previous studies have looked at use of objective functions and their effect on muscle force predictions [1]
- Validation is limited because *in vivo* muscle force measurements are rare; however, validation of simulation results may be improved with comparison to *in vivo* joint contact forces [2]

**The purpose of this study was to investigate the influence of objective function choice on muscle force predictions during walking.**

## Methods

**Data from 3rd Grand Challenge Competition [2]:**

- Single subject with force-measuring knee implant (female, left knee, age 68 years, mass 79 kg, height 1.63 m)
- Leg left CT images
- Motion capture data
- Ground reaction data
- *in vivo* contact data measured from subject's knee implant
- Electromyography (EMG) data




Force-measuring implant coordinate system

**Musculoskeletal model:**

- Full leg model containing patient's bones and implant components created in OpenSim [3]
- Muscle geometry and parameters for the 44 Hill-type muscles obtained from generic model [4].

**Muscle dynamic optimizations:**

- One complete gait cycle
- Inverse skeletal dynamics
- Forward activation/contraction dynamics
- Solving with direct collocation optimal control techniques using MATLAB, GPOPS-II [5], and ADiGator [6].
- All optimizations performed with constraints such that sum of muscle force contributions to inverse dynamics torques matched experimental inverse dynamic torques (also while tracking of *in vivo* knee contact data)
- Muscle forces optimized while minimizing 16 unique objective functions of simulation time $T$ with generic form:
  - $u$ - category of muscular effort (excitation, activation, force, or stress)
  - $m$ - number of muscles
  - $p$ - exponent (1, 2, 3, or 4)

$$J = \int_0^T \sum_{i=1}^{m} u_i^p \, dt$$

- After optimization, compared convergence time and muscle element predictions

## Results

**Convergence times**

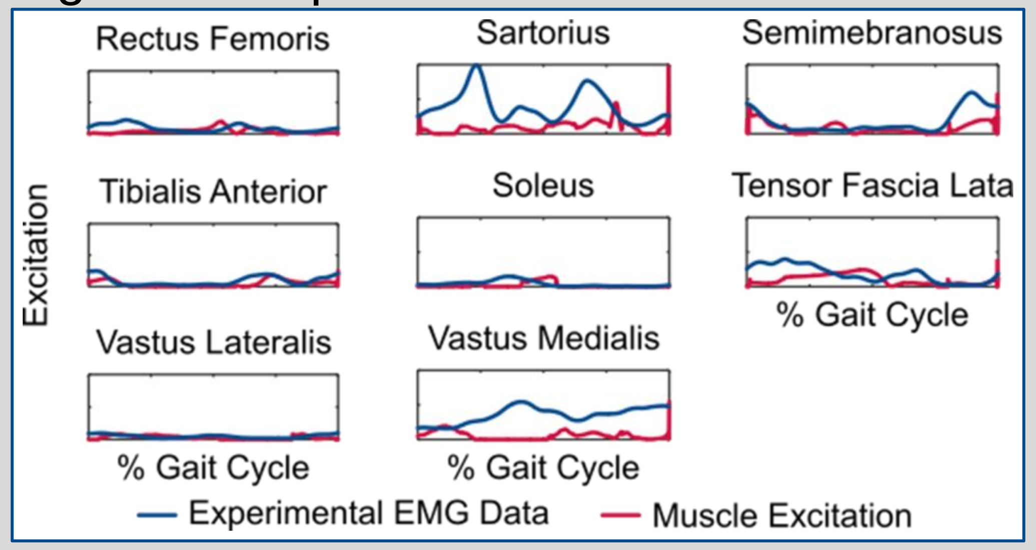
- All converged in less than 16 minutes
- Excitation functions and functions raised to second power converged the fastest
  - Excitation squared fastest converging (4.8 minutes)

| | | Power | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1st | 2nd | 3rd | 4th | Average | S.D. |
| Category | Excitation | 9.88 | 4.80 | 7.75 | 15.57 | **9.50** | 3.94 |
| | Activation | 13.20 | 8.16 | 7.67 | 10.69 | 9.93 | 2.21 |
| | Force | 8.88 | 8.73 | 15.50 | 10.29 | 10.85 | 2.75 |
| | Stress | 14.19 | 9.75 | 11.70 | 11.85 | 11.87 | 1.57 |
| | Average | 11.54 | **7.86** | 10.66 | 12.10 | 10.54 | |
| | S.D. | 2.21 | 1.86 | 3.24 | 2.08 | | |

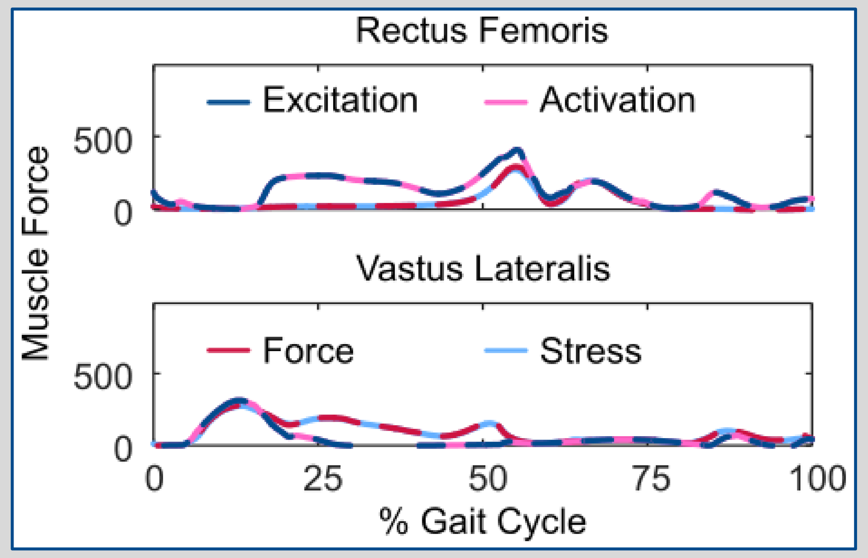
Test matrix of objective functions ran with their convergence time in minutes

**Muscle force prediction comparisons**

- Excitation predictions vs. experimental EMG data
  - Results bound to qualitative analysis due to difficulties with processing and interpretation of EMG data




- Muscle force tradeoff between categories of muscular effort
  - Tradeoff occurs with objective functions either containing force (force/stress) or not (excitation/activation)
  - Excitation/Activation function favor biarticular (performs two functions) such as Rectus Femoris (extends knee and flexes thigh at hip joint)
  - Force/Stress favor uniarticular muscles such as Vastus Lateralis (extends knee) that have larger cross-sectional areas and maximum isometric forces




## Discussion

**All objective functions can be considered valid and feasible for use in muscle force optimization during walking**

- All tracked knee contact force data, matched inverse dynamics, and converged
- Limitation: results are based on a gait cycle from a subject

**Best objective function identified**

- Excitation squared fastest converging function
- Could be used by clinicians to allow for most efficient use of time with their patient

**The results of this study provide insight into the muscle coordination strategies used during walking. Future studies should investigate other motions and subjects.**

## References and Acknowledgments

1. Ackermann M, van den Bogert, AJ. *J Biomech* **43**, 1055-1060, 2010.
2. Fregly BJ, et al. *J Orthop Res* **30**, 503-513, 2012.
3. Delp SL, et al. *IEEE Trans Biomed Eng* **54**, 1940-1950, 2007.
4. Arnold EM, et al. *Ann Biomed Eng* **38**, 269-279, 2010.
5. Patterson MA, Rao AV. *ACM Trans Math Soft* **41**, Article 1, 2014.
6. Patterson MA, et al. *ACM Trans Math Soft* **39**, Article 17, 2013.

Funding for this research provided by the University of Dayton Research Council Seed Grant.