Response-Surface Mapping to Generate Distributions of Forward Dynamic Simulations

Matt J. Camilleri

Sacramento City College, Sacramento, CA, USA
E-mail: camillm@scc.losrios.edu

INTRODUCTION

Muscle quantities such as force and work are estimated using forward dynamic simulations because forces cannot be measured readily. Input muscle excitations are transformed into forces that act on the body segments to produce a simulated motion. Minimizing the error between experimental and simulated data is typically implemented to compute a solution.

However, optimizing (minimizing) a single simulation to represent a distribution is problematic for several reasons. First, a single simulation provides no standard deviations with which to establish statistical confidence. Second, current simulation methods generate few quantities that can be validated against experimental data. Third, a simulation method whose explicit objective is to minimize tracking errors also tends to obscure potential manifestations of inaccuracies (tracking errors) in the neuro-musculo-skeletal model, potentially generating false confidence in the results.

Therefore the objectives of this work were to: 1) develop a method, designated the descent-ascent distributor, for generating a distribution of feasible simulation results, 2) demonstrate quantities by which to validate the distribution, and 3) demonstrate any manifestations of inaccuracies in the underlying models, revealed by the method.

METHODS

To achieve these objectives, pedaling was used as a demonstration task. Fifteen subjects pedaled at 90 rpm and 250 W. Intersegmental moments were computed by inverse dynamics. Onset angles of the leg muscles were computed from EMG data. A forward dynamic model of pedaling was used to simulate the input muscle excitations and output inter-segmental moments (Camilleri et al., in press).

The distributor had similarities to gradient-based optimization methods. A vector-valued objective function was defined by error terms (difference been simulated and experimental data), including the intersegmental moments. The distribution direction, **d**, ("descent direction" in gradient-based methods) was defined by the Jacobian, **J**, of the objective function:

$$\mathrm{d}_n = f\left(-\sum_{f=1}^{\mathrm{F}} \mathbf{J}_{nf}\right),$$

where F is the number of objective function components and n is the index of the control parameter. The Jacobian, computed from regression of the previous 20 simulations (steps), and distribution direction, were updated every 20 simulations. The use of 1) a vector-valued objective function, in which all components would unlikely be minimized simultaneously, and 2) a constant number of steps between updates of the distribution direction, ensured that new and different simulations would be generated. These simulation results were sequentially included in a distribution until it stabilized.

Statistical analyses of coordination behaviors included: 1) standard deviations of the intersegmental moments, and 2) cadence/onset-timing-angle relationships.

RESULTS AND DISCUSSION

The control parameters varied about regions of small errors (Figure 1), with associated variations in the simulated intersegmental moments (sim., Figure 2). Phasing of the pedaling frequency of the intersegmental-moment standard deviations was similar between simulations and experiments. Ninety percent of the simulated onset angles advanced and retarded with the cadence in accordance with the experimental data. A distribution of simulation results generated by the random and independent perturbation of control parameters (e.g. Monte Carlo methods) would not generate such a realistic solution.

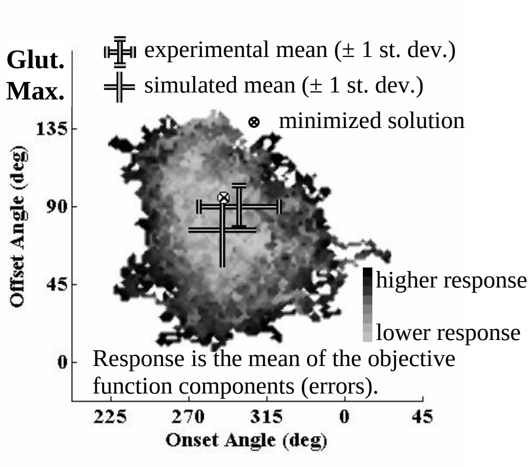

Figure 1: Minimum response surface.

Because the distributor did not explicitly minimize errors, it manifested a known inaccuracy in the model, whereas a minimized solution (tracking errors minimized; Camilleri et al., in press) obscured the inaccuracy. Pedaling is asymmetric between left and right sides (Smak et al., 1999). However, a symmetric model was implemented, as is typically done, and the distribution solution demonstrated an overestimation of the average crank power from the tracked leg, which manifests as a tracking error at the knee (Figure 2). Because of this manifestation, and the differences in simulated muscle work (Figure 3), modeling volitional pedaling as asymmetric is appropriate to generate simulations with greater confidence.

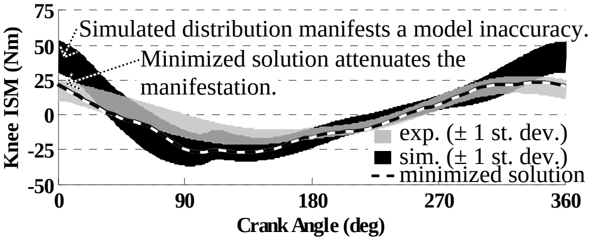

Figure 2: Knee intersegmental moment.

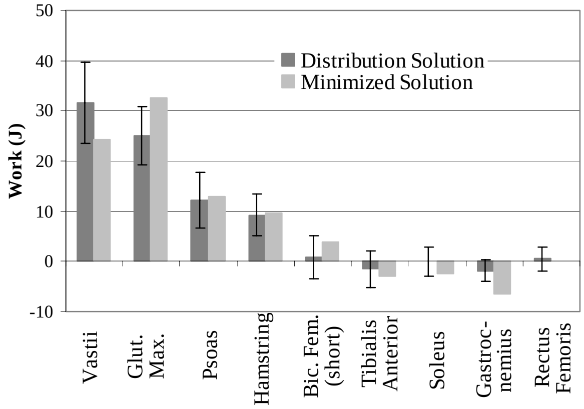

Figure 3: Muscle work per crank cycle.

SUMMARY

Implementing the descent-ascent distributor: 1) provides means and deviations for computing statistical confidence, 2) demonstrates a solution that replicates some of the coordination behaviors of pedaling, and 3) is more apt to reveal model inaccuracies. These findings support the use of the descent-ascent distributor to increase confidence in conclusions drawn from analyses of forward dynamic simulations.

REFERENCES

Camilleri, M.J. et al., *J Biomechanics*, in press.

Smak, W. et al., (1999). *J Biomechanics*, **32**, 899-906.