Using Distributions of Forward Dynamic Simulations to Investigate Model Inaccuracies

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INTRODUCTION

Muscle forces 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. Solutions may be generated by optimizing (minimizing) the error between experimental and simulated data, or by generating a distribution of simulation results (Camilleri, 2006).

However, large tracking errors exist in the total intersegmental moments in both the distribution and optimization solutions (Figure 1). The tracking errors are a result of high frequencies in the total simulated intersegmental moments that are not evident in the experimental data. This indicates an inaccuracy in the neuro-musculo-skeletal model. Identifying the source of this inaccuracy and correcting it would provide more confidence in the neuro-musculo-skeletal model and the attendant forward simulation results.

The muscle velocities affect the intersegmental moments and demonstrate little variability across simulations. Thus, it is reasonable to assume that particular muscle velocities are associated with the high frequencies. The objective of this work was to determine any such associations.

METHODS

To achieve these objectives, pedaling was used as a demonstration task. Fifteen subjects pedaled at 90 rpm and 250 W. Inverse dynamics were used to compute the intersegmental moments. A forward dynamic model of recumbent pedaling was implemented to simulate the input muscle excitations and output intersegmental moments. Specifically, the descent-ascent distributor was used to simulate an experimental distribution (Camilleri, 2006).

Muscles that demonstrated high frequencies in their contribution to the total intersegmental moments, over the same region that the total intersegmental moment demonstrated high frequencies (“error region”, Figure 1), indicated that these muscles contributed to the high frequencies. The muscle velocities were extracted from each simulation, for each of these muscles, over the corresponding error region, and averaged. The averaged velocities were normalized to both the optimal fiber length (i.e., rest length) and the unloaded maximum shortening velocity.

Frequency histograms of the averaged and normalized velocities were plotted with the frequency histograms of the normalized velocities over the crank cycle. Histograms of the averaged velocities, producing a mean value consistent across muscles, indicated that the mean value was associated with the high frequencies in the intersegmental moments.

RESULTS AND DISCUSSION

Muscles that demonstrated high frequencies in their contribution to the total intersegmental moment were the psoas (PSO) and gluteus maximus (GMAX) for the hip (Figure 1), soleus and gastrocnemius for the ankle, and vastii for the knee. The high frequencies were associated with muscle velocities near zero (Figure 2).

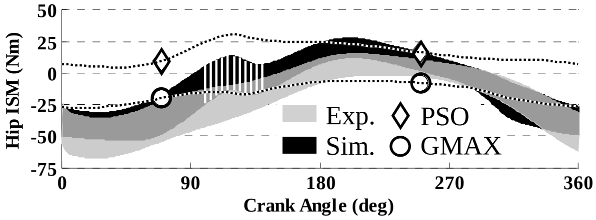

Figure 1. Intersegmental (ISM) hip moments (Exp. is total experimental and Sim. is total simulated, ± 1 st. dev.). Hatched region is the error region.

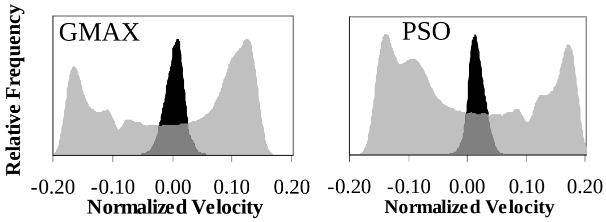

Figure 2. Relative frequencies of the normalized velocities. Black distributions are the frequencies for the error region, and gray distributions are the frequencies over the crank cycle.

This association is readily explained when the sensitivity of muscle force to velocity in the muscle model is considered. As is common, a Hill-type force-velocity relationship was used in the forward model. This relationship demonstrates the greatest sensitivity of muscle force to velocity (Δforce/Δvelocity) at zero velocity (Figure 3). This sensitivity causes rapidly changing muscle forces and thus high frequencies.

The finding of higher frequencies in the simulated versus experimental intersegmental moments is consistent with experimental results and the implemented muscle model. In-vivo experiments demonstrate that for a particular shortening velocity and length, the force is depressed with preceding shortening (‘force depression’), and that the depression is magnified when the amplitude of the preceding shortening is increased (Herzog, 2004). The opposite effects are demonstrated for lengthening muscle (‘force enhancement’). If history effects had been included in the forward dynamic model, then the high frequencies in the simulated intersegmental moments may have been diminished. This is because during both muscle shortening and lengthening, the force depression and enhancement, respectively, should cause the sensitivity of force to velocity, near zero velocity, to decrease with respect to the conventional model (Figure 3).

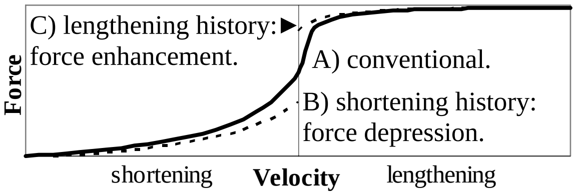

Figure 3. The force velocity relationship from a conventional Hill-type equation (A) and the hypothetical effects of history on the relationship (B and C, dashed). In both B and C, sensitivity of force to velocity, at zero velocity, is less than that of A.

SUMMARY

High frequencies in the simulated intersegmental moments: 1) were associated with muscle velocities near zero, 2) resulted in part from the simulated high sensitivity of muscle force to velocity at zero velocity, and 3) may be reduced if the history of the muscle velocity is included within the muscle model. These findings support the use of distributions of simulation results to diagnose simulation errors and address inaccuracies in the underlying models, to increase confidence in conclusions drawn from simulation analyses.

REFERENCES

Camilleri, M.J. (2006). *Ph.D. Dissertation,* **Chapters 2 and 3**.

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