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Predicting Quadriceps Fatigue during Electrically Stimulated Non-Isometric Contractions

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ABSTRACT

Introduction. Functional electrical stimulation (FES) is increasingly used by individuals with paralysis to regain functional movement, but muscle fatigue can limit the applicability of this technology. The ability to predict FES-induced muscle fatigue enables design of control strategies for producing functional limb movements repetitively. An existing force model together with a fatigue model can predict isometric fatigue in the quadriceps [1]. The force model has been expanded to predict non-isometric contractions [2], but a fatigue model for these contractions has not been explored. This study's objectives were to 1) determine whether modifications to the fatigue model are necessary to predict fatigue in response to non-isometric contractions, 2) if so, incorporate angular displacement or angular velocity into the fatigue model, and 3) test the predictive accuracy of the expanded model on human subjects.

Methods. The force model [2] describes muscle activation and contraction dynamics. The input is stimulation timing. The output is force, angle, and angular velocity as function of time. The isometric fatigue model [1] predicts force model parameter changes during fatigue. The input is force predicted by the force model and the outputs are three of the force model parameters, A_θ, Km and τ_1, as a function of time.

Experiments were conducted using a computer-controlled stimulator that sent trains of pulses to surface electrodes on the thighs of seven able-bodied subjects; forces were measured at the ankle. The pulse duration was 600 μs and the amplitude was set to produce 20% of the subject's maximum voluntary isometric contraction. Three dynamic and one isometric fatiguing leg extension sessions per subject were required to identify the fatigue model parameters and to assess the model accuracy. Each session was separated by >48 hours. All sessions included both isometric and dynamic non-fatiguing leg extension tests to identify the force model parameters [2]. During the dynamic leg extensions, either 0, 4.5, or 9.1 kg was applied to the freely swinging distal leg.

Model parameters were identified by minimizing the sum of squares error between the model and observations. Predictive accuracy was determined from linear regression analyses and RMSE of the maximum angular displacement and angular velocity.

Results. The fatigue model required modification. Two first order differential equations were added, one each for parameters A and τ_1. Angular displacement from the

initial angle was added to the forcing function in all equations. Three parameters were added to the fatigue model, but none require identification. All are functions of parameters within the existing force-fatigue model.

The predictive accuracy of the force-fatigue model was relatively high. Increasing the applied load, increased both the measured and predicted fatigue, as determined by the reduction in angular velocity and angular displacement (Fig. 1). The average r-squared values for the maximum angular velocity for all applied loads were > 0.65 (Fig. 2). The average r-squared values for the maximum angular displacement for the 4.5 kg and 9.1 kg loads were 0.7 (Fig. 2), however the average r-squared value for 0 kg was 0.54. In general, at least 65% of the variability in the measurements was explained by the model.

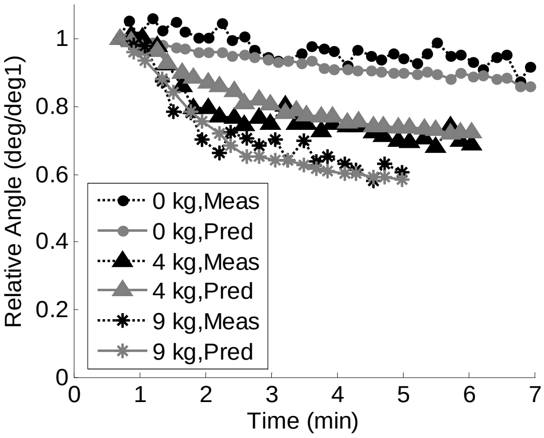

Figure 1. Average relative angular displacements in response to 33 Hz trains. Every 6th contraction is shown and is normalized to first contraction.

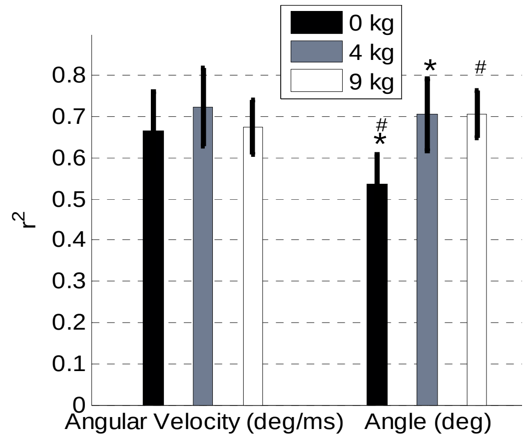

Figure 2. Average linear regression coefficients of determination (r^2; $\pm$ 95% confidence limit). Matching symbols significant at p = 0.0005.

In general, the RMSE values were low compared to the initial and final angular velocities and displacements. For angular velocity, in response to the 33 Hz trains, the maximum initial values ranged from 0.38 to 0.18 deg/ms, and the minimum final values ranged from 0.27 to 0.11 deg/ms, for 0 and 9 kg, respectively. The average RMSE values were 0.052, 0.028, and 0.023 deg/ms for 0, 4.5, and 9 kg, respectively. For angular displacement, the maximum initial values ranged from 68 to 58 deg, and the minimum final values ranged from 59 to 31 deg, for 0 and 9 kg, respectively. The average RMSE values were 7.5, 5.5, and 7.0 deg for 0, 4.5, and 9 kg, respectively.

Discussion and Conclusions. Dynamic fatigue was reasonably well predicted by the force-fatigue model when it was modified to account for angular displacement. Day-to-day differences in the number and types of muscle fibers recruited, in the initial conditions, and in the resting position of the freely swinging leg before each contraction may have contributed to the random error.

REFERENCES

[1] J. Ding, A. S. Wexler, and S. A. Binder-Macleod, "A predictive model of fatigue in human skeletal muscles," *J Appl Physiol*, Vol. **89**, pp. 1322-32, (2000).

[2] R. Perumal, A. S. Wexler, and S. A. Binder-Macleod, "Mathematical model that predicts lower leg motion in response to electrical stimulation," *J Biomech*, Vol. **39**, pp. 2826-36, (2006).