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 would enable 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 (Ding et al., 2000). The force model has been expanded to predict force in non-isometric contractions (Perumal et al., 2006), but a fatigue model for these contractions has not been developed. This study’s objectives were to 1) determine whether modifications to the fatigue model are necessary to predict fatigue in non-isometric contractions, 2) if so, then incorporate necessary modifications into the fatigue model, and 3) test the predictive accuracy of the modified model on human subjects.

METHODS AND PROCEDURES

The force model (Perumal et al., 2006) incorporates muscle activation and contraction dynamics. The input is stimulation timing. The output is torque, angle, and angular velocity as functions of time. The isometric fatigue model (Ding et al., 2000) predicts changes in force model parameter during fatigue. The input is force predicted by the force model and the outputs are three of the force model parameters, $A_0$, $K_m$, and $\tau_1$, as functions 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; force was measured at the ankle. The pulse duration was 600 $\mu$s and the amplitude was set to produce maximal excursion of the leg with 9.1 kg applied to the distal leg. Three non-isometric 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 non-isometric non-fatiguing leg extension tests to identify the force model parameters (Perumal et al., 2006). During the non-isometric 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. Angular velocity and three parameters were
added. The new parameters are functions of the other 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 (Figure 1).

![Figure 1](image1.png)

**Figure 1.** Average relative angular displacements in response to 33 Hz pulse trains. Every 6th contraction is shown and is normalized to first contraction (deg1).

![Figure 2](image2.png)

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

Average $r$-squared values for the maximum angular velocity for all applied loads were > 0.65 (Figure 2). The average $r$-squared values for the maximum angular displacement for the 4.5 kg and 9.1 kg loads were 0.7 (Figure 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.

The RMSE values were low compared to the initial and final angular velocities and displacements. For angular displacement, the maximum initial values ranged from 68 to 58 deg, and minimum final values ranged from 59 to 31 deg, for 0 and 9 kg, respectively. Average RMSE values were 7.5, 5.5, and 7.0 deg for 0, 4.5, and 9 kg, respectively.

**DISCUSSION**

Others have shown that a decrease in force and a decrease in maximum velocity are consequences of non-isometric fatigue (De Ruiter et al, 1999). When our force-fatigue model was modified to account for angular velocity, fatigue was reasonably well predicted. 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**


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