Accuracy of Three Mathematical Models vs. Human Trained Paralyzed Muscle

Laura A. Frey Law and Richard K. Shields
Graduate Program in Physical Therapy & Rehabilitation Science, The University of Iowa
1-252 MEB, Iowa City, IA 52242 USA; email: laura-freylaw@uiowa.edu

INTRODUCTION

Paralysis due to chronic spinal cord injury dramatically decreases physical function, can induce transformation towards fast fatigable muscle fibers [1], and can result in life threatening musculoskeletal deterioration (e.g. pressure ulcers, osteoporosis). Electrical stimulation may be able to improve function of paralyzed muscle and isometric muscle training may attenuate various neuromuscular and skeletal adaptations. Previous work has demonstrated that several mathematical muscle models can represent chronically paralyzed human muscle (untrained) to assist in the development of optimal activation strategies for specific muscle force doses [2]. However, no previous studies have evaluated the ability of mathematical muscle models to represent altered muscle contractile properties resulting from repetitive activation (training) in paralyzed muscle. The purpose of this study was to compare the force predictions of three available muscle models (one linear and two nonlinear) versus human trained (> 1 year) paralyzed muscle.

METHODS

Isometric soleus forces were obtained from 4 individuals with complete spinal cord injury (SCI, 1.5 to 4.2 yrs) who had been continually training their left soleus muscles since the acute injury stage (~6 weeks post injury). Three models of varying complexity, a Hill based nonlinear (Hill NL, [3]), a 2nd order nonlinear (2nd Ord NL, [4]), and a simple 2nd order linear model (Linear), were parameterized using a single force train resulting from a variable ramp of increasing and decreasing stimulation frequencies [4]. The optimal parameter values were then used to predict forces for 9 trains (5, 10, and 20 Hz constant, CT, doublet, DT, and dual doublet, DDT, trains) for each model. Model errors were determined relative to the experimental results for each subject (Matlab 6.0) as an overall error (% error) and specific force property errors: peak force (PF), force time integral (FTI), time to peak tension (TPT), half-relaxation time (HRT), relative fusion index (RFI), and doublet difference (DDiff) to estimate the "catch-like" property of muscle. Model comparisons were made using repeated measures ANOVA, alpha = 0.05, with follow-up tests using Bonferroni correction for multiple comparisons.

The simplest model was the Linear model (3 parameters), followed by the 2nd Ord NL model (6 parameters) and the most complex was the Hill NL model (6 parameters). The Hill NL model was more complex than the 2nd Ord NL model because one of its differential equations had no analytical solution. Numerical analysis techniques (e.g. Runge-Kutta) were required adding to the computational complexity and processing time necessary for optimal convergence.

RESULTS AND DISCUSSION

All three models provided reasonable estimates of force (< 20% mean error), but to varying degrees. Overall, human trained soleus muscle forces were best predicted by the Hill NL, followed by the 2nd Ord NL, and lastly the Linear model (Table 1). However, the 2nd Ord NL model often produced similar errors ($p > 0.05$) as the Hill NL model (e.g. PF, FTI, and DDiff). The 2nd Ord NL model had the greatest difficulty predicting TPT accurately, consistently under predicting contraction times. The simplest Linear model produced the greatest overall error, but had similar errors as the NL models for unfused constant frequencies (5 Hz CT). The relative degree of force fusion (RFI) was best predicted by the nonlinear models, but the Linear model provided reasonable predictions. All three models had difficulty predicting the "catch-like" property of muscle.

CONCLUSIONS

The 2nd Ord NL model produced nearly equivalent force predictions as the Hill NL model, but with less model complexity. Further, the Linear model was the simplest model, producing reasonable force predictions for select force trains. These three models can provide reasonable estimates of human trained paralyzed muscle force, but the 2nd Ord NL model produced the best estimates most simply.

REFERENCES

1. Shields RK. *J Neurophysiol* **73**, 2196-2206, 1995.
2. Frey Law LA, et al. *Proceedings of ACSM*, Nashville, 2005.
3. Ding J, et al. *Muscle & Nerve* **26**, 477-485, 2002.
4. Bobet J, et al. *IEEE Biomed Eng* **45**, 1010-1016, 1998.

ACKNOWLEDGEMENTS

Support was provided by NIH grant RO1 HD39445 (RKS) and The Foundation for Physical Therapy (LAFL).

Table 1: Mean (SEM) errors associated with each mathematical muscle model for predicting human, trained paralyzed muscle forces across stimulation patterns: 5, 10, and 20 Hz: CT and DDT patterns - % error, PF and FTI; CT only – HRT, RFI; 5 Hz CT only – TPT; and mean difference between DDT – DT and DT – CT at 5, 10, and 20 Hz = DDiff.

Model	% error (%)	PF (%)	FTI (%)	TPT (ms)	HRT (ms)	RFI (%)	DDiff (%)
Hill NL	7.8 (0.4)	7.5 (0.7)	9.0 (1.3)	3.0 (2.3)	5.8 (2.0)	3.0 (0.8)	24.9 (2.0)
2nd NL	10.0 (0.8)	7.3 (0.5)	9.3 (2.0)	22.0 (1.8)	11.0 (3.4)	6.6 (1.6)	21.6 (1.6)
Linear	15.8 (1.2)	20.0 (1.1)	17.5 (2.2)	2.8 (1.4)	33.8 (4.8)	12.1 (1.1)	61.6 (8.1)