A PHENOMENOLOGICAL MUSCLE MODEL TO ASSESS HISTORY DEPENDENT EFFECTS IN HUMAN MOVEMENT

1Craig P. McGowan, 1Richard R. Neptune and 2Walter Herzog
1Department of Mechanical Engineering, University of Texas at Austin, Austin, TX, USA
2Faculty of Kinesiology, University of Calgary, Calgary, AB, Canada
email: cpmcgowan@mail.utexas.edu, web: www.me.utexas.edu/~neptune/

INTRODUCTION
In a recent study, we developed and validated a modified Hill-type muscle model that included shortening induced force depression based on the relationship with mechanical work [1]. The model was able to accurately reproduce in-situ experimental data when incorporated into a forward dynamics computer simulation and was used to examine the influence of force depression on dynamic cyclic movements. The results showed that in maximal power pedaling, force depression has the potential to substantially reduce the amount of muscle power produced. However, during pedaling, muscle contractions are predominately concentric. In contrast, in many activities muscles undergo repeated stretch-shorten cycles. It is not clear to what extent stretch induced force enhancement effects mechanical output, nor is it known to what degree force depression and force enhancement may offset one another during dynamic cyclic movements.

Therefore, the aims of this study were to 1) develop and validate a muscle model that includes stretch induced force enhancement, and 2) combine this model with our previous model of force depression to validate the cumulative effects during controlled stretch-shorten and shorten-stretch cycles. The model’s ability to accurately reproduce force enhancement on the descending limb of the force-length curve and its ability to characterize the differences in cumulative effects between stretch-shorten and shorten-stretch cycles were evaluated by comparing the outputs from simulated in-situ experiments with actual experimental data from isolated cat soleus muscles [2, 3].

METHODS
A previously described muscle ergometer model was used to simulate the in-vivo experiments [1]. Briefly, the model consisted of two blocks mounted horizontally on a frictionless surface with a muscle governed by Hill-type intrinsic properties mounted between them. One block underwent prescribed linear motion in which position and velocity was controlled. Values for the optimal muscle fiber length (36 mm), tendon slack length (74 mm, including aponeurosis), maximum shorting velocity (3.3 lengths/sec) and maximum isometric force (28.6 N) were set to the approximate average values for a cat soleus muscle.

Simulations were developed to match a subset of the protocol from the experimental study [2]. The experiment was designed to compare the isometric force following constant velocity stretches of fully active muscles with the isometric force of a muscle that was not stretched. Individual stretches were made for three lengths (3mm, 6mm and 9mm) at three different velocities (3mm/s, 9mm/s and 27mm/s) for a total of nine stretches. To account for force-length effects, isometric contractions and all stretches ended at the same length (9 mm greater than optimal). A second set of simulations was developed to examine the model’s ability to reproduce experimental data in stretch-shorten and shorten-stretch cycles. Stretch-shorten cycles consisted of a 4 mm contraction preceded by active stretches of 0 mm, 2 mm and 4 mm. Similarly, shorten-stretch cycles consisted of a 4 mm stretch preceded by contractions of 0 mm, 2 mm and 4 mm. All length changes occurred at 4 mm/s and ended at the muscle’s optimal length. Results from these simulations were compared to data in the literature [e.g., 3].

Based on experimental data from cat soleus muscles [2], when the muscle was actively stretched on the descending limb of the force-length curve, the relationship between force enhancement (FE) and
muscle length change (ΔL) was best described by a second order polynomial equation ($R^2 > 0.99$). On the ascending limb of the force velocity curve, FE was considered to be independent of length change based on data from the literature [4]. Shortening induced force depression was included based on our previously described model [1]. Force enhancement was abolished as soon as the muscle began shortening such that the effects were not cumulative in stretch-shorten cycles. Whereas, force depression was maintained until the muscle was deactivated and the effects were cumulative in shorten-stretch cycles.

**RESULTS AND DISCUSSION**

On the descending limb of the force length curve, the simulations of single muscle active stretches accurately reproduced the experimental data for all conditions (e.g., 9 mm/s; Fig. 1). The average root mean square error (RMSE) between the simulations and experimental data while the muscle was active was 0.59 N (range: 0.45 – 0.85 N) for 3 mm/s stretches, 0.60 N (range: 0.36 – 1.05 N) for 9 mm/s stretches and 0.98 N (range: 0.68 – 1.42 N) for 27 mm/s stretches. Across all of the simulations on the descending limb, the average RMSE was 0.72 N.

**Experimental**

Simulations of stretch-shorten and shorten-stretch cycles were consistent with experimental data from the literature [e.g., 3]. The results also show the model was able to capture the cumulative effects of force depression and enhancement when the muscle underwent shorten-stretch cycles and the non-cumulative effects during stretch-shorten cycles (Fig. 2).

**CONCLUSIONS**

The results of this study show that a relatively simple phenomenological muscle model can accurately reproduce experimentally measured stretch induced force enhancement. When the model was combined with our previously described shortening induced force depression model, the combined model was able to reproduce the non-linear cumulative effects of force enhancement and force depression during stretch-shorten and shorten-stretch cycles. In future studies, the model will be incorporated into more complex musculoskeletal models to examine the influence history dependent effects have on human movement such as running.

**REFERENCES**