Frequency Response Characteristics of Numerical Muscle Models

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Summary

This study compared the frequency response of the Thelen (TMM) and Millard (MMM) muscle models using Bode plots. TMM exhibited a higher resonant frequency and a wider bandwidth than MMM at all muscle length conditions, suggesting its greater applicability for musculoskeletal simulations that involve rapid dynamic movements.

Introduction

Numerical muscle models, such as Hill's muscle model, play a crucial role in musculoskeletal simulations for replicating human movements. The implementations by Thelen [1] and Millard et al. [2] are widely used for such simulations, as they effectively capture the time-domain characteristics of experimental muscle data. However, few studies have evaluated how these models respond to rapid changes in movement dynamics through frequency-domain analysis. The objective of this study is to compare the frequency response characteristics of the Thelen [1] and Millard [2] models at multiple muscles lengths under near-zero velocity conditions.

Methods

TMM and MMM (Equilibrium model) were implemented in MATLAB for single musculotendon unit simulations (Figure 1). In both models, muscle force is modeled as a nonlinear function of muscle length, velocity, and activation level. We adopted soleus muscle parameters from a previous study [3].

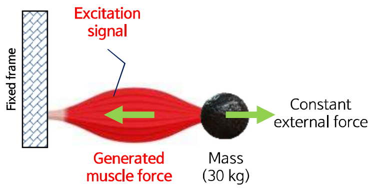

Figure 1: Musculotendon unit simulation schematics

In this study, we employed an FFT-based multi-sine approach to evaluate the frequency response of muscle force relative to the excitation signal, modeling the muscle-tendon complex with muscle length windows set at ± 0.05 around normalized lengths of 0.6, 0.8, 1.0, 1.2, and 1.4. Velocity was controlled to remain within ± 0.05 normalized velocity by adjusting the excitation signal's magnitude. Under these conditions, we investigated the system's response to excitation signals ranging from 0.49 to 0.51 at 1,000 distinct frequencies spanning 0.1 to 100 Hz. Within each length window, piecewise linearization was used to treat the muscle-tendon system as a linear time-invariant model, and we constructed Bode plots for both magnitude and phase from the measured force output. This method enables us to compare how the Thelen [1] and Millard [2] muscle models capture dynamic changes across a broad frequency range.

Results and Discussion

Resonant frequencies of both models were within the measured activation frequency range (19.9 ± 7.3 Hz [4]) for maximum force generation in the soleus muscle, as determined by electromyogram. This indicates that both models reflect actual physiological behavior. In our simulation, TMM exhibited approximately 4 Hz higher resonant frequency and 5 Hz wider bandwidth than the MMM (Figure 2). These findings suggest that TMM's broader bandwidth could enable more rapid responses and faster movements compared to MMM.

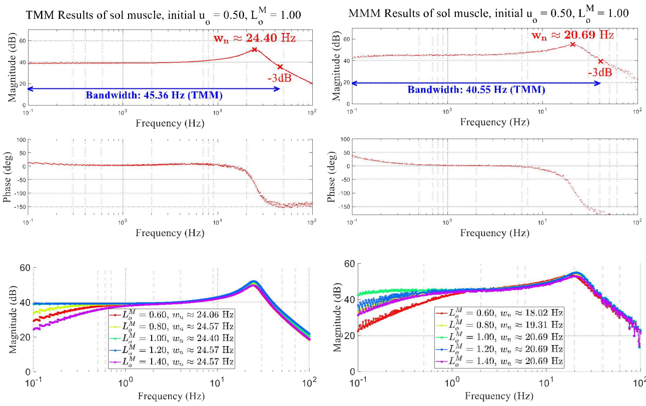

Figure 2: Bode plots of TMM, MMM in soleus muscle at length 1.0 condition (top) and five different length conditions (bottom)

As the muscle length changed, both models exhibited variations in magnitude within the low-frequency range. Under all muscle length conditions, the TMM demonstrated a wider bandwidth and higher resonant frequency. The MMM showed a decreasing resonant frequency at muscle lengths of 0.6 and 0.8 (Figure 2).

Conclusions

This study successfully estimated the frequency response of numerical muscle models through simulations and compared the responsiveness of the two models. The TMM is expected to provide faster responses to input excitation signals during rapid dynamic movements under all muscle length conditions.

Acknowledgments

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