CLOSED-FORM MODELING OF THE SOLEUS MUSCULOTENDON UNIT

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Introduction

Hill-type muscle-tendon unit (MTU) models, Fig. 1, are widely used in a variety of applications while maintaining an appropriate balance between model complexity and accuracy. Throughout the literature there are models of the MTU that use Splines and other conditional statements for modeling the hill-type muscle [1]. Finding a closed-form equation for this system enables to implement different controllers for controlling the MTU force in closed-loop fashion.

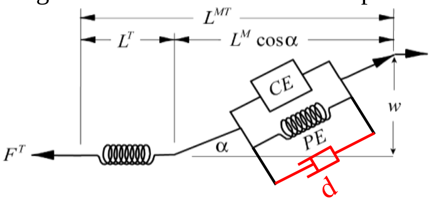

Figure 1: The pennate hill-type muscle model that is modified using a parallel damping element (in red)

Methods

There were some attempts in the literature to obtain the closed-form equation for the MTU [2]. The tendon force equation is derived by the following equation:

$$\dot{F}^T = k^T\left(\dot{L}^{MT} - \dot{L}^M \cos\alpha + L^M \sin\alpha . \dot{\alpha}\right) \quad (1)$$

where, F^T and k^T are the tendon force and stiffness, respectively. The MTU length, L^{MT}, and the pennation angle, α, are derived by the limb kinematics but the muscle fibre length, L^M is derived by the integral of the following equation's inverse:

$$\tilde{F}_V^M\left(\dot{L}^M\right) = \frac{\dfrac{F^T}{\cos\alpha} - \tilde{F}^{PE}}{a(t)\cdot F_o^M \cdot \tilde{F}_L^M\left(L^M\right)} \quad (2)$$

In this equation, F_O^M F_L^M, F_V^M, and F^{PE} represent the optimal muscle force, muscle force-length, force-velocity, and the parallel element force, respectively. Since the muscle activation, $a(t)$, is in the denominator of equation (2), the Clay Anderson's muscle model with optimal parameters becomes unstable when $a(t) \cong 0$:

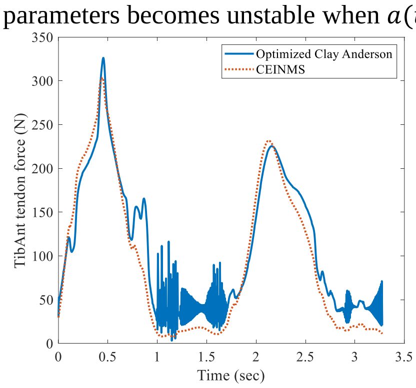

Figure 2: Tibialis Anterior tendon force during plantar/dorsiflexion using a dynamometer

Two strategies were used to solve this issue. First, different $\dot{L}^M$s were tested using optimization and regression. Since in this strategy the optimization should be done for every muscle and gait separately, a second strategy was developed. In this strategy, equation (2) was simplified to a linear model, $\tilde{F}_V^M = a\dot{\tilde{L}}^M + b$, and damping was added to the hill-type muscle model (Fig. 1). The linearized model assumption is valid while $\left|\dot{L}^M\right| \leq 0.5$ which is almost always the case for walking and running gaits [3].

Results

Using the new formulation, the model conforms to the results obtained by the neuromusculoskeletal modeling toolbox, CEINMS [4], for different gaits and muscles.

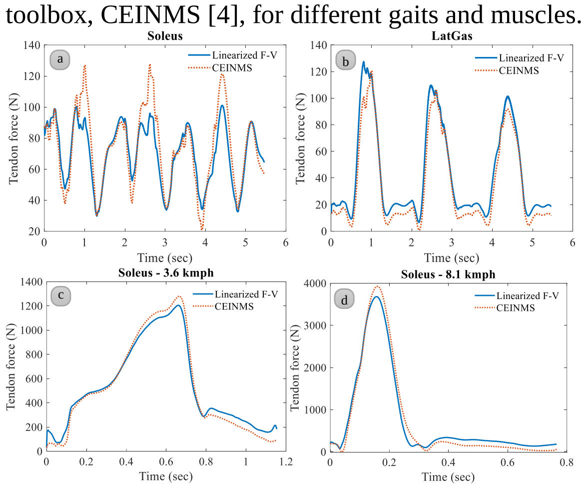

Figure 3: Comparison of the tendon forces obtained by the proposed MTU modeling technique with CEINMS toolbox for: a/b) Soleus and latGas using dynamometer, c/d) Soleus in gaits with various speeds

As a result, equation (1) can now be written in closed-form, ideal for designing different closed-loop controllers for lower-limb muscles (e.g., Soleus).

References

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