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Short communication

Hill-type muscle model with serial damping and eccentric force–velocity relation

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ABSTRACT

Hill-type muscle models are commonly used in biomechanical simulations to predict passive and active muscle forces. Here, a model is presented which consists of four elements: a contractile element with force–length and force–velocity relations for concentric and eccentric contractions, a parallel elastic element, a series elastic element, and a serial damping element. With this, it combines previously published effects relevant for muscular contraction, i.e. serial damping and eccentric force–velocity relation. The model is exemplarily applied to arm movements. The more realistic representation of the eccentric force–velocity relation results in human-like elbow-joint flexion. The model is provided as ready to use Matlab ® and Simulink ® code.

1. Introduction

Hill-type muscle models are commonly used in biomechanical simulations to predict passive and active muscle forces during various movements. They predict muscle forces on an organ level and are therefore considered macroscopic muscle models. In mechanics, Hill-type muscle models are classified as 0-d elements due to the lack of mass and inertia. Such a model's output is a one-dimensional force, which is applied to skeletal models between origin and insertion points, or sometimes as moments by means of (constant) lever arms. The models' inputs are muscle length, or more precisely muscle–tendon-complex (MTC) length, MTC contraction velocity, and neural muscle stimulation. Typically, Hill-type muscle models consist of three elements: a contractile element incorporating force–length and force–velocity dependencies, a serial and a parallel elastic element in diverse configurations (Zajac, 1989; Winters, 1990; van Soest and Bobbert, 1993; Günther and Ruder, 2003; Houdijk et al., 2006; Kistemaker et al., 2006; Siebert et al., 2008). Various extensions account for physiologically observable effects, such as contraction history effects (Meijer et al., 1998; Rode et al., 2009; McGowan et al., 2013), recruitment patterns of slow- and fast twitch fibers (Wakeling et al., 2012), high frequency oscillation damping (Günther et al., 2007; Siebert et al., 2003), or force in eccentric contractions (van Soest and Bobbert, 1993; Cole et al., 1996; Till et al., 2008). The model presented here combines the latter two.

In eccentric contractions the muscle is elongated due to external forces exceeding the force the muscle is currently generating. In contrast to the extensively studied concentric contractions, considerably less data has been published on eccentric contractions – presumably due to the experimental difficulties. It has, however, been observed that during eccentric contractions single muscle fibers and whole muscles produce forces exceeding those of isometric (at constant length) contractions (Katz, 1939; Joyce and Rack, 1969; Rijkelijkhuizen et al., 2003; Till et al., 2008). Furthermore, the eccentric muscle force depends on the contraction velocity. For small lengthening velocities, the force rapidly increases with increasing velocities (Katz, 1939; Joyce and Rack, 1969; Rijkelijkhuizen et al., 2003; Till et al., 2008). For higher lengthening velocities (where the experimental difficulties increase, e.g., due to fiber damage) some studies report force saturation (Joyce and Rack, 1969), a slower increase in force (Till et al., 2008), or even a slow reduction with increasing lengthening velocity, depending on the experimental setup. van Soest and Bobbert (1993) proposed a muscle model where the eccentric force–velocity relation is described by a hyperbolic relation. The advantages of this approach are the possibility to use similar equations for concentric and eccentric force–velocity relation and the good approximation of the experimental data.

The biomechanical function of the eccentric force–velocity relation has also been examined. Seyfarth et al. (2000) showed

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in a simulation study that the jumping performance of long jumps is greatly influenced by the eccentric force–velocity relation. Here, a key feature is the relatively low metabolic energy required for relatively high eccentric forces (Lindstedt et al., 2001). Also, the increased muscle force in eccentric contractions together with the reduced force in concentric contractions can have an effect similar to a mechanical damper. With this, the muscle can dissipate movement energy, e.g. during down-hill walking (Lindstedt et al., 2001), and provide rapid stabilizing reactions to perturbations in hopping (Haeufle et al., 2010).

Günther et al. (2007) found that the low but significant damping within the passive tendinous tissue (Ker, 1981; Alexander, 2001) is responsible for the dampening of high-frequency oscillations. Considering such a damping in the series elastic structure of a Hill-type muscle model predicts muscle forces more realistically. Otherwise, unrealistic high frequency oscillations may occur when simulating contractions against a mass (Günther et al., 2007).

For complex biomechanical simulations of human movement, both series elastic damping and the characteristic eccentric force–velocity relation have to be considered. Here, we propose a Hill-type model based on van Soest and Bobbert (1993), Günther et al. (2007), and Mörl et al. (2012), which models both effects. Furthermore, we propose a robust method to find the initial conditions for the muscle model's internal state. With these extensions, the muscle model can be used in multi-body simulations of many different human and animal movements. We provide the model implemented in Matlab ®/Simulink ® as electronic supplementary material and hope that this facilitates the biomechanical research on biological movement.

2. Muscle model

The model of the muscle tendon complex (MTC) consists of four elements (see Fig. 1): the contractile element (CE) modeling the active force production, the parallel elastic element (PEE) arranged in parallel to the CE, the serial elastic element (SEE) in series to the CE (length l_{SEE}), and the serial damping element (SDE) in parallel to the SEE. The four elements fulfill the force equilibrium:

$$F_{CE}(l_{CE}, \dot{l}_{CE}, q) + F_{PEE}(l_{CE}) = F_{SEE}(l_{CE}, l_{MTC}) + F_{SDE}(l_{CE}, \dot{l}_{CE}, \dot{l}_{MTC}, q). \quad (1)$$

In this equation, the force dependencies are also specified. l and $\dot{l}$ with the respective subscripts symbolize length and contraction velocity of the respective elements. $q_0 \le q \le 1$ represents the muscles activity with $q = q_0 = 0.001$ for minimally activated muscle and $q = 1$ for maximally activated muscle. The lower limit $q_0 > 0$ captures the fact that in a whole muscle with it's vast number of contractile proteins some cross bridges will always generate force even in the absence of neural stimulation. Additionally, the model's equations generate a singularity for $q = 0$ – the lower limit is thus a precondition for the simulation. The elements' forces in Eq. (1) will be explicitly formulated in the following paragraphs. The kinematic relations between the elements are $l_{SEE} = l_{SDE}$, $l_{PEE} = l_{CE}$, and $l_{MTC} = l_{SEE} + l_{CE}$.

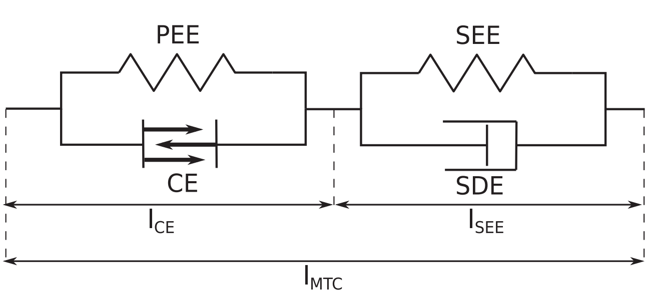

Fig. 1. The structure of the MTC model. l_{MTC} is the sum of the length of the contractile element (CE) l_{CE} plus the length of the serial elastic element (SEE) l_{SEE}. The length of the parallel elastic element (PEE) equals l_{CE}. The serial damping component SDE was introduced by Günther et al. (2007).

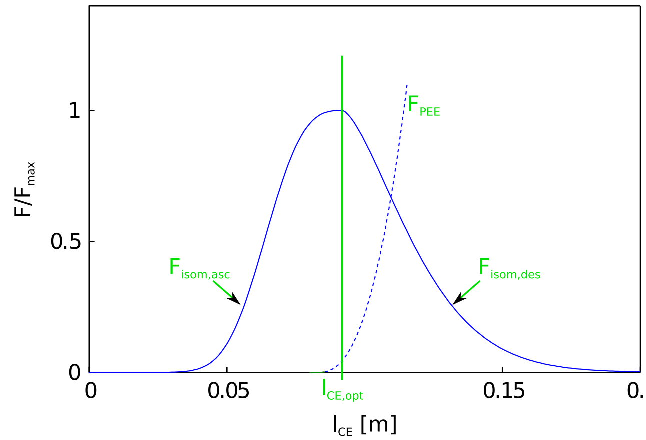

Fig. 2. Force–length relation of the contractile element (CE, solid line) and the parallel elastic element (PEE, dashed line) starting at $0.95 \cdot l_{CE,opt}$.

2.1. Contractile element CE

The contractile element CE represents the active fiber bundles in the muscle. The CE force depends on the current length of the muscle fibers. This *force–length relation* (Fig. 2) is modeled as

$$F_{isom}(l_{CE}) = \exp\left\{ -\left| \frac{l_{CE}/l_{CE,opt} - 1}{\Delta W_{limb}} \right|^{\nu_{CE,limb}} \right\} \quad (2)$$

Here, $l_{CE,opt}$ is the optimal fibre length for which $F_{isom}(l_{CE,opt})$ reaches a maximum. ΔW_{limb} depicts the width of the normalized bell curve in the respective limb (ascending or descending) and $\nu_{CE,limb}$ its exponent.

Furthermore, the CE force depends on the current fiber contraction velocity $\dot{l}_{CE}$ (with $\dot{l}_{CE} < 0$ for concentric contractions, indicated by the index "c"). This *force–velocity relation* (Hill, 1938) is modeled as a hyperbola (see Fig. 3a):

$$F_{CE,c}(\dot{l}_{CE} \le 0) = F_{max} \left(\frac{q F_{isom} + A_{rel}}{1 - \dfrac{\dot{l}_{CE}}{B_{rel} l_{CE,opt}}} - A_{rel} \right). \quad (3)$$

The parameters A_{rel} and B_{rel} are the normalized Hill "parameters" (Hill, 1938). $F_{\max}$ is the maximum isometric force.

As shown by experiments and previously described (Winters, 1990; van Soest and Bobbert, 1993; Günther et al., 2007), the Hill parameters depend on length l_{CE} and activation q: $A_{rel}(l_{CE}, q) = A_{rel,0} L_{A_{rel}}(l_{CE}) Q_{A_{rel}}(q)$ and $B_{rel}(l_{CE}, q) = B_{rel,0} L_{B_{rel}}(l_{CE}) Q_{B_{rel}}(q)$. The dependencies are modeled as

$$L_{A_{rel}}(l_{CE}) = \begin{cases} 1, & l_{CE} < l_{CE,opt} \\ F_{isom}(l_{CE}), & l_{CE} \ge l_{CE,opt} \end{cases} \quad (4)$$

$$L_{B_{rel}}(l_{CE}) = 1. \quad (5)$$

and

$$Q_{A_{rel}}(q) = \tfrac{1}{4}(1 + 3\,q) \quad (6)$$

$$Q_{B_{rel}}(q) = \tfrac{1}{7}(3 + 4\,q). \quad (7)$$

In the previously published versions of this model (Günther et al., 2007; Mörl et al., 2012), the force–velocity relation as described above was not explicitly modeled for eccentric contractions ($\dot{l}_{CE} > 0$,