MODELS FOR FORCE-VELOCITY RELATIONS IN CALF MUSCLES INJURIES

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In biomechanics, force-velocity relation and its computational models are important to study muscle behavior, muscle fatigue, muscle pathophysiology, or in the development of therapeutic approaches. We propose here two mechanical approaches linked with Hill's standard equation, considering additional resistant forces, modeling minor and moderate injuries. We focused on calf muscles, including two classes: muscles with high and low cross-sectional areas. The results show a decrease in shortening velocity range, especially for muscles with low area. Comparing muscle class in terms of developed power under identical conditions, low cross-section area muscles have a decrease in maximum power approximately 5 times greater than high cross-section area muscles.

Keywords: skeletal muscles, fatigue, cross-section area, shortening velocity, numerical models, maximum power

1. Introduction

The relation between force and the shortening velocity to describe contractions in skeletal muscle was experimentally established by Hill for normal conditions [1], as hyperbolic dependence. This relation reflects the cyclic interaction between myosin heads and myosin-binding sites in actin filaments, linked with ATP hydrolysis [2], with the effect of producing muscle contraction. To mimic the muscle fiber, spring arrangements have been proposed: a contractile spring in series with a non-linear spring element and in parallel with another non-linear spring element [3]. Active force in the contractile element is generated by the actin and myosin cross-bridges at the sarcomere level. The parallel element is responsible for the muscle passive behavior and the series element represents the tendon.

The Hill equation indicates also the energy output rate, i.e. the power ($P = F \cdot \mathrm{v}$, *where* F *is the muscle shortening load and* v *is the shortening velocity of muscle contraction*) in a contracting muscle, and that is why it is widely investigated in the field of exercise physiology, to determine the effects of exercise

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training [4,5]. In recent years, several studies have investigated the force-velocity relation in an attempt to describe muscle function in complex tasks in elite sports (e.g., performance in vertical jumping, sprinting, or rowing) [6-9] or daily living standard activities in older adults (e.g., walking or the ability to get up from a chair) [10]. Training methods in the elite contact sports required continually quality improvements on scientific basis from force-velocity-power assessment [11].

Another field where the Hill equation is useful is to study muscles under fatigue/injuries resulted from disorders in ion concentrations [12,13] or other mechanisms that inhibit the force generation capacity [14,15]. High intracellular levels of Inorganic phosphate (Pi), hydrogen ions (H^+) and low levels of calcium ions (Ca^{2+}) are likely responsible for the reduction in the maximum contraction force the muscle can develop (F_{max}) during fatigue [16]. At low pH, myosin ATPase activity is reduced [17], likely due to a slower release of ADP from the myosin head [18], which has been shown to decrease F_{max}. It has been demonstrated that small decreases in F_{max} may occur during the initial phase of muscle fatigue, without a significant change in the maximum contraction velocity the muscle can reach (v_{max}) [19].

In this context, for targeted situations, mathematical models of the relation between developed force and shortening velocity of the muscle have also been proposed in the literature: linear, double hyperbolic [20], multiscale [21]. The double-hyperbolic pattern may be a direct consequence of the kinetic properties of myofilament cross-bridge formation. A multiscale model was proposed to predict muscle force, stiffness, and power behavior in fatigue muscles due to reduction in active calcium ions [21].

In this study we propose models for force - velocity relation applicable to muscles affected by fatigue and, even more, by injuries, primarily responsible for the reduction of muscle functions. These have consequences on developed force and on ranges for shortening velocity possible to develop by the affected muscle. Therefore, we introduced resistance forces proportional to velocity and squared velocity, modeled in MATLAB as additional terms to the Hill equation [1]. We applied these models for two classes of skeletal muscles: with high/low values for cross-sectional areas, characterized by two pairs of muscle constants (A_H, B_H and A_L, B_L), specifically, triceps surae, tibialis anterior and peroneus longus, important for locomotion.

They are fundamental for propulsion during walking and running, allowing standing on toes and maintain balance. They also support the ankle and knee joints [22]. In essence, the primary function of the triceps surae is to execute plantar flexion of the foot at the ankle joint [23]. The tibialis anterior is a fusiform dorsiflexor muscle that primarily has a crucial role for the walking cycle [24]. The peroneus longus muscle is responsible for flexing the ankle [25].

We worked in the intervals for low velocities because we considered muscles with injuries. Our results show how resistance forces affect the range for shortening velocities and the maximum power developed by the affected muscles. Proposed models allow a comparative study of the behavior of these three muscles subjected to the same conditions.

2. Models for force-velocity relation
2.1 Normal conditions

The mechanical performance of a muscle is often assessed in terms of how quickly the muscle shortens in response to a range of external loads. A highly simplified biomechanical muscle model considers two spring elements in series (one elastic and one contractile) with one spring element in parallel(Fig. 1).

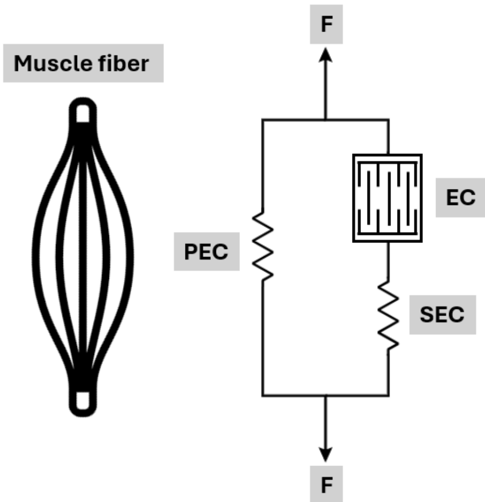


Fig. 1. Hill muscle model

Fig. 1. shows the schematic of Hill's model consisting of a contractile element (CE), serial elastic element (SEC) and parallel elastic element (PEC). The elements in the schematic have specific roles for each component of the muscle cell as follows: the CE is equivalent to thick and thin filaments, so if it has length and velocity of contraction, it can generate a force; the PEC corresponds to the fibre structures and other connective tissues that support muscle mechanics, and the SEC represents the clusters of tendons and actin and myosin links. During isometric contraction, their length varies with the same value but in opposite sense, the total length of the muscle remaining constant. Contraction force has the same magnitude as shortening force, and both are proportional with the length (Hooks law). A. V. Hill [1]

proposed a mathematical relationship based on his detailed extensive experiments measuring the length, velocity, force and the energy released during muscle contractions. Mathematically, for skeletal muscles, in standard conditions, Hill proposed the relationship between force F and shortening velocity v, as hyperbolic dependence:

$$F_{Hill}(\mathrm{v}) = \frac{(F_{max}+A)B}{\mathrm{v}+B} - A \quad (1)$$

where F_{Hill} is the tension (or load) in the muscle in normal physiological conditions, F_{max} is the maximum tension (or load) generated in the muscle and has specific values for each muscle, v is the shortening velocity, and A, B are two constants depending on the muscles size (A_H, B_H for high and A_L, B_L for low cross-sectional areas). Hill-type models for force-velocity relation are attractive for their low computational time and easy link with experimentally measured parameters [26]. The empirical force-velocity relationshipis was explained [2] based on the dynamics of the repeated interactions between myosin cross-bridges and actin filaments in the muscle's contractile units. Subsequent models have been developed to better account for the intricate behavior of muscle during both transient and steady conditions. The force of a muscle is largely determined by its size; thus, on the basis of the cross-section of the human muscle (physiological cross-section), it is known that one square centimeter of cross-section can exert a traction maximum force between 49 ÷ 78.5 N [27].

Performing a quantitative comparison between muscles in terms of their architectural properties, Lieber and Friden [28] introduced two force-velocity curves for high/low cross-sectional area. Considering values from these experimental curves, we computed the values for constants A_H, B_H and A_L, B_L (Table 1).

2.2 Resistant forces

Starting from Hill's model, multiple others have been proposed, each designed to accomplish specific objectives. For example, models for fatigue and injured muscles take into account the reduction in power to perform certain movements and to develop the necessary forces. The benefits of one of the proposed models [21] go beyond predicting the force in different conditions as it can also predict muscle stiffness and power, demonstrating that maximum decrease can be on the order of 40% and 6.5%, respectively.

In another approach, A. F. Pereira's [29] model integrates a Hill-type muscle model into a multibody system dynamics framework to simulate muscle contraction, fatigue, and performance. The model is composed of two critical components: the Hill-type muscle model for forward and inverse dynamic analysis, and a dynamic muscle fatigue model.

The Munich Consensus statement on muscles injuries [30] categorized strain severity as minor (involves only a small number of fibers in the muscle), moderate (involves a significant number of muscle fibers) and severe (rupture of the muscle).

For minor injuries, we propose a physical model of resistance forces proportional with shortening velocity, v. In this case, we denote this force F_{mi}, described by the equation:

$$F_{mi}(\mathrm{v}) = -r\mathrm{v} \tag{2}$$

The moderate injuries were associated in our proposal by physical model of force proportional with squared velocity and muscle cross-sectional area. In this case, we denote this force F_{mo}, described by the equation:

$$F_{mo}(\mathrm{v}) = -CS\mathrm{v}^2 \tag{3}$$

In these equations, *r* is the resistance coefficient, *C* is the drag coefficient, S is the cross-sectional area of the muscles. This form of the resistance force is a general one, used in many fields to describe dynamic systems, allowing analysis on a scaled models by its proportionality to the area [31].
In these conditions, standard Hill equation (1) is completed with one additional term for each analyzed case, and we have named the two new forces $F_{Hill+mi}$ and $F_{Hill+mo}$, described by the equations:

$$F_{Hill+mi}(\mathrm{v}) = \frac{(F_{max} - r\mathrm{v}_{max} + A)B}{\mathrm{v}+B} - A - r\mathrm{v} \tag{4}$$

for muscles with minor injuries or fatigue,

$$F_{Hill+mo}(\mathrm{v}) = \frac{(F_{max} - CS\mathrm{v}_{max}^2 + A)B}{\mathrm{v}+B} - A - CS\mathrm{v}^2 \tag{5}$$

for muscles with moderate injuries.

The constant v_{max} represents the maximum shortening velocity developed by one muscle, computed as $\mathrm{v}_{max} = B\frac{F_{max}}{A}$.
The above approaches are applied in the case of a group of calf muscles (triceps surae, tibialis anterior and peroneus longus). In our physical model proposal, the values for constants are summarized in Table 1 for each investigated muscle. We

tested some values for resistance constant *r*, starting from the values for muscles in standard conditions [32].

Table 1

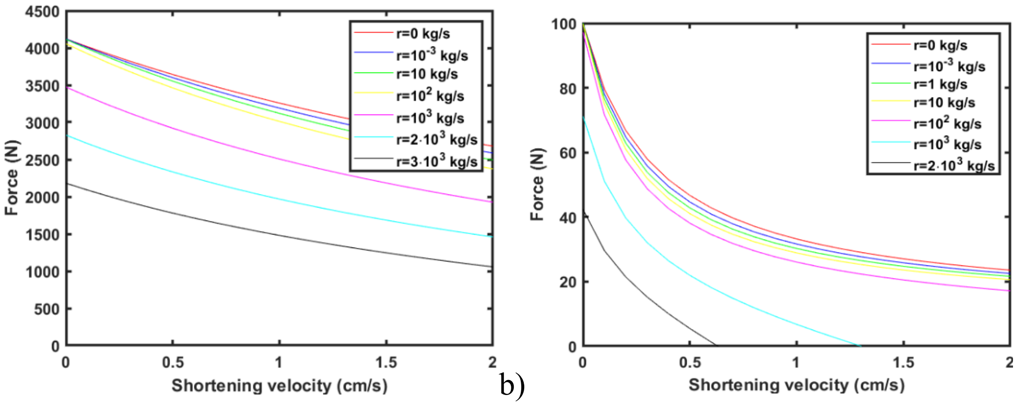
Constants for each investigated muscle

Muscles	*S* (cm^2)	A_H (N)	B_H (m/s)	A_L (N)	B_L (m/s)	*r* (kg/s)	*C* (kg/m^3)
Triceps surae	82	260	0.0408	-	-	10^{-3}-10^{3}	10^{2}-10^{6}
Peroneus longus	7	-	-	95.38	0.0338	10^{-3}-10^{3}	10^{2}-10^{6}
Tibialis anterior	4						

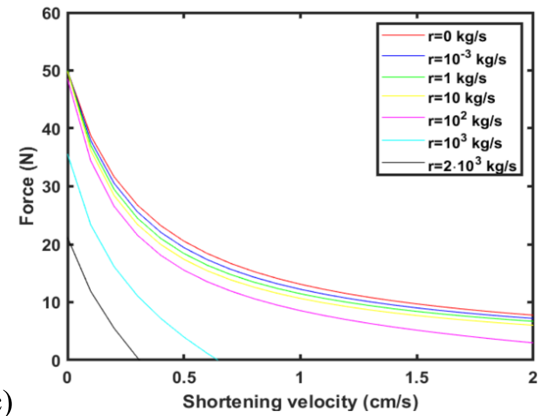
3. Results and discussions

3.1 Resistance force proportional with velocity

In Fig. 2 are reprezented the developed forces by each investigated muscle (triceps surae, peroneus longus, tibialis anterior) for shortening velocities between 0 and 2 cm/s in the case of developed model for minor injuries. We investigated the case for standard Hill equation 1 for r=0 and also for muscles with fatigue or minor injuries according to eq. 4 for r values from TABLE 1. The simulations are considered for values of F_{max} in normal conditions attributed for each muscle class: 4120 N for triceps surae [27], 100 N for peroneus longus [33] and 50N for tibialis anterior [34].



a) b)



c)

Fig. 2. Force-velocity dependence for a) triceps surae, b) peroneus longus, c) tibialis anterior in the case of resistant force proportional with velocity (minor injuries).

It can be seen that is preserved the hyperbolical dependence between force and the shortening velocity, but with a decrease in the F_{max} values and also in the interval for developed shortening velocities, indicating that for both classes of muscles studied it is more difficult to develop high shortening velocities. The rate of force decrease is steeper for muscles with low cross-sectional area.

F_{max} values decrease as the resistance coefficient increases; comparing the two classes of muscles, under identical conditions, it is observed that for those with high area (triceps surae) F_{max} decreases by 1.9 times, and for those with low cross-sectional area (peroneous longus and tibialis anterior), F_{max} decreases by 2.5 times.

Our model predict that muscles with high cross-sectional area can develop shortening velocities up to 2 cm/s even in conditions of resistance forces, while those with low cross-sectional area reduced their shortening velocity range: peroneus longus only for $r > 10^2$ kg/s can achieve all shortening velocity range. This effect is even more pronounced for the tibialis anterior.

3.2 Resistance force proportional with squared velocity

In Fig. 3 are reprezented the developed forces by each investigated muscle (triceps surae, peroneus longus, tibialis anterior) for shortening velocities between 0 and 2 cm/s in the case of developed model for moderate injuries. We investigated the case for standard Hill equation (1) for C=0 and also for muscles with moderate injuries according to eq. 5 for C values from TABLE 1. The simulations are performed for the same values of F_{max} as in the case for minor injuries.

It is observed that for drag coefficients up to 10^3 kg/m^3, our proposed model approximately overlaps with the classical Hill equation, for both classes of muscles studied. At higher values of the drag coefficient ($C>10^5$ kg/m^3), the resistance force term predominates, and the hyperbola turns into a parabola for muscles with high cross-sectional area.

In these conditions, of moderate injuries, both classes of muscles reduced their intervals for shortening velocities and also the values for F_{max}. Comparing all muscles, under identical conditions, it is observed that for triceps surae F_{max} decreases by 5.15 times, for peroneous longus by 3.3 times and for tibialis anterior F_{max} decreases by 2.5 times.

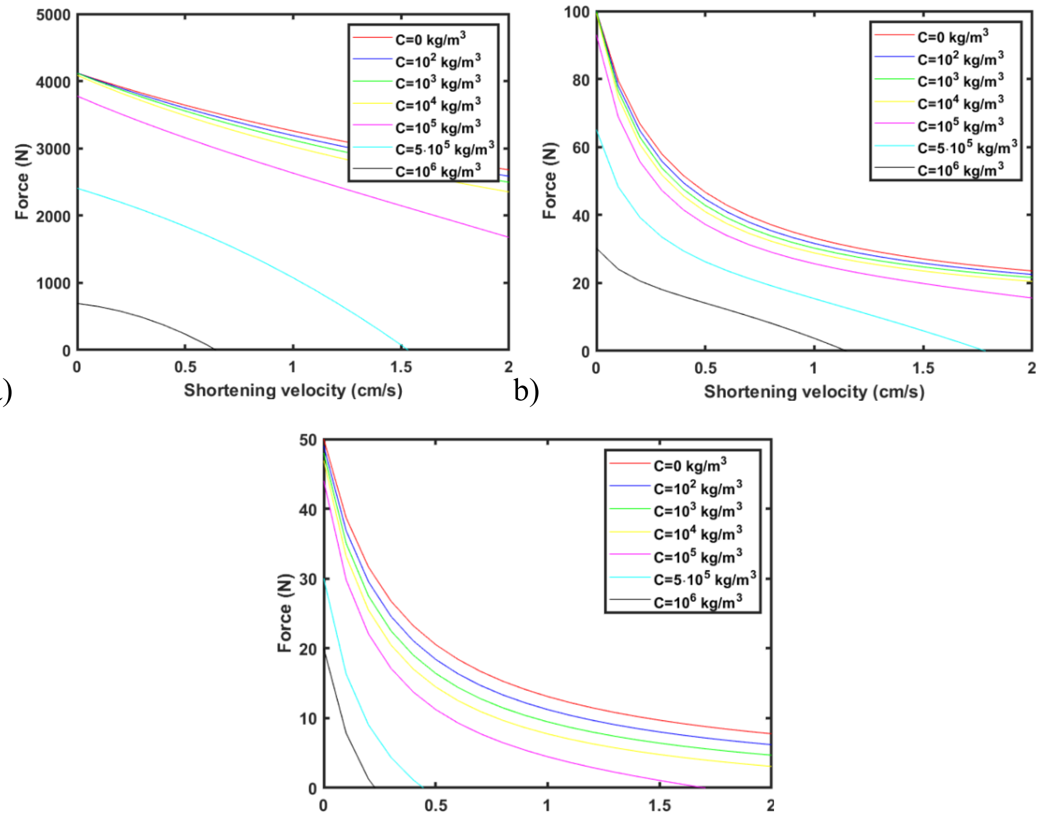


Fig. 3. Force-velocity dependence for a) triceps surae, b) peroneus longus, c) tibialis anterior in the case of resistant force proportional with squared velocity and cross-sectional area (moderate injuries).

Comparing the two kinds of models proposed to describe minor and moderate injuries, we can say that they reduce the ranges for possible shortening velocities and also the values for F_{max}, the slope of the decline increases as the values of the resistance and drag coefficients increase. We can assimilate these

models with viscous forces inside muscles, in agreement with previous studies in the literature [32] that indicated the viscous force required is 10^4 times the hydrodynamic estimate, close to recent experimental measurements, themselves 10^2–10^3 times the hydrodynamic estimate.
Also, the observed reduction in both the F_{max} and the shortening velocities values for both models are in agreement with experimental results [35] where it was noticed that an important aspect of muscle performance changes during fatigue, is a progresive decline in F_{max} values and a notable shortening velocity reduction.
It was demonstrated that triceps surae power is the most useful metrics for maximal-effort accelerations and sprint performances in hard sports [36]. Experimental measurements indicate that maximum power developed by muscles is limited and diminished in cases of minor/moderate injuries. For our proposed models, these values are in Table 2. We mention the maximum power for standard model (eq. 1) in the case of three studied muscles: 53.584 W for triceps surae, 0.478 W for peroneus longus and 0.155 W for tibialis anterior.

Table 2

Maximum power developed by triceps surae, peroneus longus, tibialis anterior in all above studied cases

P_{max} [W]	$r=10^{-3}$ kg/s	$r=10^2$ kg/s	$r=10^3$ kg/s	$r=2\cdot10^3$ kg/s	$C=10^2$ kg/m^3	$C=10^3$ kg/m^3	$C=10^4$ kg/m^3	$C=10^5$ kg/m^3	$C=10^6$ kg/m^3
Triceps surae	51.712	47.462	29.178	21.127	51.707	49.905	47.033	33.620	14.94
Peroneus longus	0.450	0.342	0.109	0.0456	0.453	0.432	0.409	0.311	0.037
Tibialis anterior	0.144	0.0854	0.033	0.012	0.123	0.096	0.077	0.056	0.011

It is observed that the maximum power possible to be developed by each muscle decreases with increasing resistance and drag coefficients, as it is expected in the case of tired or injured muscles. Comparing muscles under our analysis, for minor injuries, under similar conditions proposed by our models, the maximum power decreases by 2.5 times in the case of triceps surae, by 10.5 times in the case of peroneus longus and by 12.6 times in the case of tibialis anterior. In moderate injuries, in the case of the model proposed by us, the maximum power decreases by 3.5 times for triceps surae, by 12.8 times in the case of peroneus longus and by 14.1 times in the case of tibialis anterior. These values for triceps surae are in agreement with experimental studies on calf muscles [37].

4. Conclusions

Models for resistance forces are useful to study fatigued-injured muscle and the effect of various shortening velocities on developed forces. In this regard, we proposed two categories of resistance forces: F_{mi}, proportional to the velocity and

F_{mo}, proportional to the square velocity in a comparative analysis of two classes of muscles: with high and low cross-sectional area. The already known fact that muscles shorten faster against light loads than they do against heavy loads, is preserved also when we consider supplementary resistance forces inside fatigue or injured muscles.

In the case of the proposed model with F_{mi} force for the conditions considered in this study, the range of shortening velocities is narrowed for all muscles, but the effect is more visible in the case of muscles with low cross-section area. For model with F_{mo} force, all studied muscles narrow their range for shortening velocities from C above specific thresholds. The specific hyperbolic decrease is turned into parabolic one for triceps surae and peroneus longus after threshold values of drag coefficient.

The maximum force decreases progressively for all cases studied: for triceps surae and peroneus longus more in the case of F_{mo}, and for tibialis anterior this decrease is approximately similar for the two resistance forces considered. The maximum power decreases for all cases studied, as is natural; a similar decrease is observed for both kinds of forces. Comparing muscle classes under similar conditions, maximum power is much more reduced for low cross-section area muscles.

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