This article was downloaded by: [185.55.64.226]
On: 17 March 2015, At: 12:11
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954
Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK

International Journal of Occupational Safety and Ergonomics
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tose20

Force-Velocity Characteristics of Individual Human Skeletal Muscles: TBClat and TBClong. Outline of the Method

Stefan Kornecki[a] & Adam Siemieński[a]
[a] Academy of Physical Education, Wroclaw Poland

Published online: 08 Jan 2015.

To cite this article: Stefan Kornecki & Adam Siemieński (1998) Force-Velocity Characteristics of Individual Human Skeletal Muscles: TBClat and TBClong. Outline of the Method, International Journal of Occupational Safety and Ergonomics, 4:1, 75-83

To link to this article: http://dx.doi.org/10.1080/10803548.1998.11076381

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the “Content”) contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at http://www.tandfonline.com/page/terms-and-conditions

INTERNATIONAL JOURNAL OF
OCCUPATIONAL SAFETY AND ERGONOMICS 1998, VOL. 4, NO. 1, 75–83

Force–Velocity Characteristics of Individual Human Skeletal Muscles: TBClat and TBClong. Outline of the Method

Stefan Kornecki
Adam Siemieński

Academy of Physical Education, Wrocław, Poland

The aim of the work is to outline a procedure of finding force–velocity (F–V) characteristics (F = f(V)) of individual skeletal muscles of the human locomotor system. The presentation is based on an example concerning extensors of the elbow joint: the lateral and long heads of triceps brachii (TBClat and TBClong). The experimental part of the procedure involves a natural movement of using the upper extremity to push an external object of variable, adjustable load, engaging both the elbow and shoulder joint.

Five men aged 23 took part in the experiment. Their task was to push the handle of a physical pendulum whose moment of inertia could be adjusted within the range of 58 $\mathrm{kg \cdot m^2}$–450 $\mathrm{kg \cdot m^2}$, so as to give it maximum angular velocity. During each trial the movement of the trunk, of the upper extremity and of the pendulum was video recorded and the force applied with the hand to the handle of the pendulum was measured.

In order to find the F–V characteristics a simulation model SHOULDER was used, which is capable of solving the synergy problem for muscles of the arm and the shoulder girdle.

It was found that despite considerable dispersion of experimental points the respective regression lines revealed a clear tendency of decreasing muscle force for increased shortening velocity of the monoarticular head (TBClat) and of increasing muscle force for increased lengthening velocity of the biarticular head (TBClong) of the triceps brachii muscle.

force–velocity chracteristics   modeling of the locomotor system   muscle synergy problem   iteration procedure

1. INTRODUCTION

Modern views on how to formally describe force–velocity (F–V) properties of skeletal muscle were formed by the famous paper of A.V. Hill published in 1938. It brought together results of the classical isotonic quick release test with measurement of the amount of heat released during activation and contraction of the muscle *in vitro*. These mechanical and thermodynamical considerations resulted in the formulation of

---

This work was carried out within statute projects 53/0201/S and 53/0202/S of the Wrocław Academy of Physical Education during the years 1995–1996.

Correspondence and requests for reprints should be sent to Stefan Kornecki, Unit for Biophysics of Motion, Academy of Physical Education, al. I.J. Paderewskiego 35, 51-612 Wrocław, Poland. E-mail: <kornecki@netra.awf.wroc.pl>.

the equation describing the relationship between the force produced by maximally activated muscle F and the velocity of isotonic shortening V at the rest length of muscle L. This equation corresponds to a hyperbola (its downward convex branch) and is now known as Hill's characteristic equation. Beside his equation, Hill proposed a macroscopic muscle model containing two elements connected in series as in its predecessor—the Levin–Wyman model (1927). The first element is a nonlinear spring with length and stiffness determined by the momentary force developed by the muscle. The second one, called the contractile element, is responsible for transforming free chemical energy into mechanical work. The separation of elasticity and contractility into two phenomenologically different units is thus the specific feature of Hill's model. This structure became the most popular and influential model representing the specific, dynamical properties of skeletal muscle.

The force–velocity characteristics published by Hill (1938) are a branch of the hyperbola corresponding to positive shortening velocities, that is, to concentric muscle action. It was complemented with the negative shortening velocity branch, typical of eccentric muscle action, by Katz (1939), who applied the isotonic quick release test to frog and turtle muscles. This part of the F = f(V) curve turned out to be the upward convex branch of a hyperbola, which means that increasing forces produced by the muscle correspond to increasing lengthening velocities of activated muscle.

Although, as can be deduced from the review of literature (Winters & Woo [eds.], 1990), the phenomenological Hill model is nowadays generally accepted in biomechanists' community, at least two important questions remain to be answered. How faithfully does it represent muscle dynamics *in vivo*? Is it equally adequate for all the muscles of the locomotor system? In practical terms, these two questions reduce to whether Hill's model is capable of describing adequately force–velocity properties of muscles as elements of contemporary models of the human locomotor system. Due to essential differences in construction, static and dynamic models should be considered separately. Static models of the locomotor system are based on the assumption that muscular force depends only on muscle excitation level and its physiological cross sectional area. Supplemented with faithfully reproduced geometry of the musculoskeletal system, this is quite enough to estimate individual muscle forces, especially under static conditions. Dynamical models, on the other hand, can be divided into two categories depending on whether they include internal muscle dynamics, which seems to correspond physiologically to the rate of Ca^{2+} ions transfer from the sarcotubular system to the endoplasma of the muscle fibre. Besides, any dynamical model must consider the fact that the force produced by a muscle is determined not only by its physiological cross section and excitation level but also by its current length and contraction velocity. If, therefore, a simulation model is to be able to reliably calculate the force exerted by a given muscle on the bone, the corresponding F–V characteristics should be found experimentally for the same muscle. For technological and humanitarian reasons, however, this can not be achieved under natural conditions of human movement. For lack of a better solution, the F–V characteristics found by A.V. Hill (1938) *in vitro* for m. sartorius of the frog are commonly used with the tacit assumption that its general form is representative for all the skeletal muscles of the vertebrates. Consequently, it is assumed that differences between F–V characteristics of different muscles are due only to the differences between their maximum isometric forces and lengths of the contractile portions (for maximum contraction velocities depend on these lengths). The form of the F–V relationship is thus fitted for the muscle under consideration by an appropriate scaling of one of the branches of a hyperbola, which means that characteristics are allocated to a muscle for which most probably no Hill type nor any other characteristics have ever been obtained experimentally.

The question whether Hill's hyperbola is a faithful representation of the force–velocity properties of all skeletal muscles of vertebrates should, therefore, be posed again. The answer appears to be negative both theoretically and experimentally. Firstly, in Hill's physical model elastic and contractile properties are treated separately, which contradicts the generally accepted role of myosin cross bridges as contributing to both elasticity and contractility. Secondly, it was shown experimentally by Joyce and Rack (1969) that for some skeletal muscles the hyperbolic relationship between force and contraction velocity does not hold during isotonic contraction. This all leads to the conclusion that although the $F = f(V)$ characteristics influence significantly the reliability of the results obtained by means of dynamical models of the human musculoskeletal system, their present form cannot be considered satisfactory.

There seems to exist, however, a reasonable way of solving this important problem of biomechanics. Identification of F–V characteristics of individual skeletal muscles by solving the muscle force distribution problem using optimisation methods may help in this respect.

The aim of the work is to illustrate a procedure of obtaining the $F = f(V)$ characteristics of individual skeletal muscles by an example involving the extensors of the elbow joint: the lateral head and the long head of the triceps brachii muscle (TBClat and TBClong). The experiment is based on a natural movement of pushing an external object with the hand, engaging both the elbow and shoulder joint, against a variable, adjustable load.

2. MATERIAL AND METHOD

Five healthy male students of physical education aged 23 with body mass and body length equal to 79.8 ± 19.9 kg and 1.84 ± 0.12 m, respectively, took part in the experiment.

The main element of the measuring stand (Figure 1) was a 3.12 m long physical pendulum, which was treated as a rigid body with one rotational degree of freedom with respect to immovable basis (1). The moment of inertia of the pendulum could be made equal to the following five values: 58, 150, 252, 352, and 453 $\mathrm{kg \cdot m^2}$.

The task of the participant, whose trunk was fixed to the seat back, was to push (without counter movement) the handle (2) of the pendulum using maximum force in order to give it highest possible angular velocity. Each participant performed five trials for each of the five adjustable loads. During each trial the movement of the trunk and of the upper extremity was recorded and a motion analysis system VIDANA (Germany) was used to obtain the time histories of the pendulum deflection angle α and the elbow (β) and shoulder (γ) joint angles in sagittal plane.

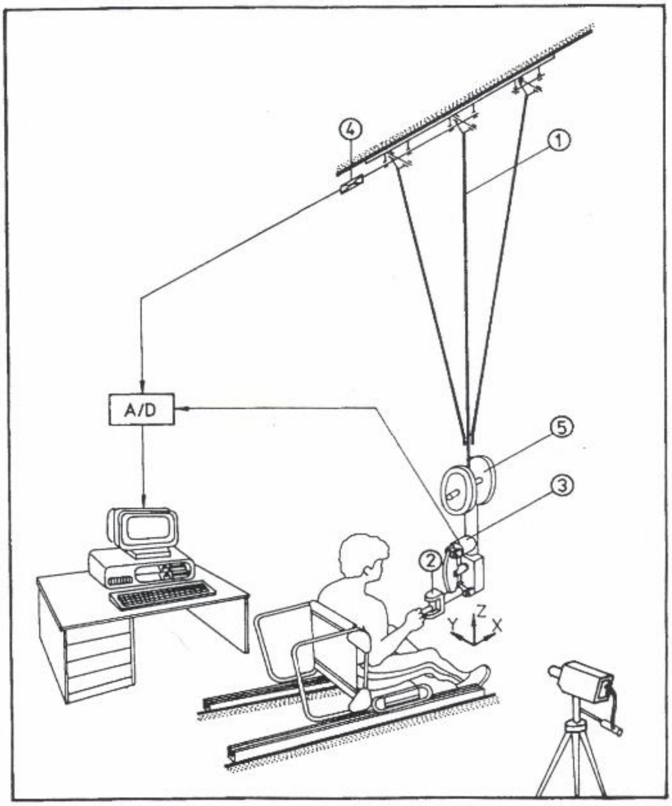

Figure 1. Measuring stand: 1—pendulum, 2—handle, 3—dynamometer, 4—potentiometer, 5—additional mass.

Simultaneously, a dynamometer (3) was used to measure the force applied to the pendulum F_p, and a potentiometer (4)—to measure the pendulum's deflection angle α. Although the force thus measured does not take into account the influence of inertia of the forearm and the arm, it seems, however, to properly reflect the load of the upper extremity, which is due to the negligibility of the masses and moments of inertia of its segments as compared with the inertial parameters of the pendulum even at the lowest value of its moment of inertia. Measuring the angle α by both the VIDANA system and the potentiometer enabled synchronisation of the time courses of the angles β and γ with that of the force F_p (Figures 2 and 3). For each instant of a given trial source information was obtained which, supplemented with geometrical and inertial data of the participants, enabled the solution of the muscle force distribution problem for the muscles of the upper extremity responsible for setting in motion an external object.

In order to solve the muscle force distribution problem and, consequently, find the F–V characteristics of m. TBClat and m. TBClong, a simulation package SHOULDER capable of simulating synergy of 38 muscles of the arm, forearm, and the shoulder girdle was used (Karlsson & Peterson, 1992). The calculations were carried out for eight instants around the point in time when the elbow angle equalled

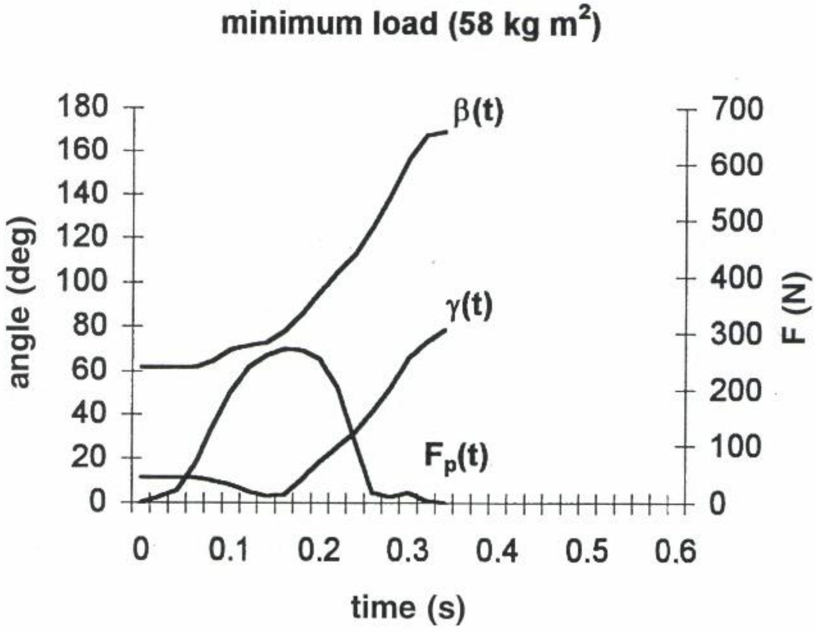

Figure 2. An example (for 1 participant) of experimental courses of the force $F_p(t)$ applied with the hand to the pendulum handle, of the elbow joint angle $\beta(t)$ and of the shoulder joint angle $\gamma(t)$ for the minimum load (moment of inertia of the pendulum).

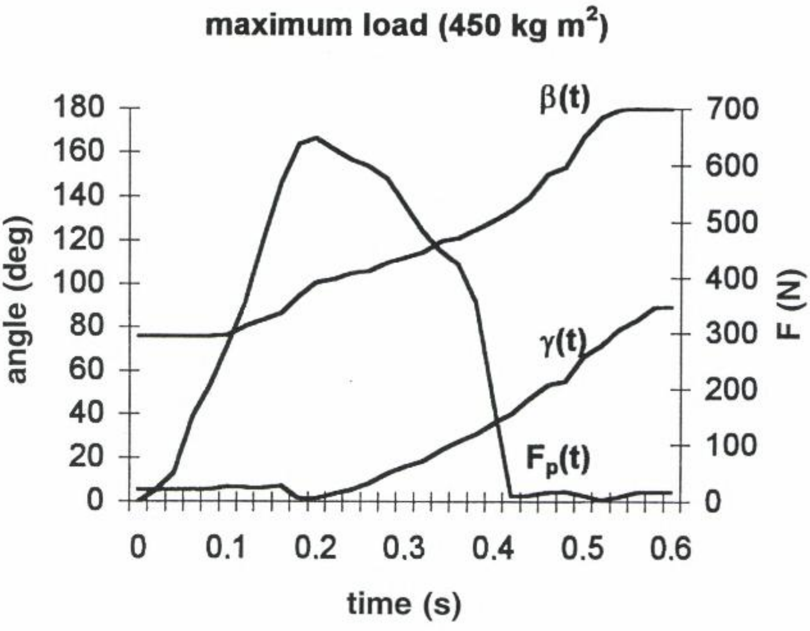

Figure 3. An example (for 1 participant) of experimental courses of the force $F_p(t)$ applied with the hand to the pendulum handle, of the elbow joint angle $\beta(t)$ and of the shoulder joint angle $\gamma(t)$ for the maximum load (moment of inertia of the pendulum).

105° (four instants before and four after), which implied the optimum lengths of the muscles under consideration (Bober & Hay, 1990). (These eight instants were enough to calculate contraction velocities of the muscles.)

The solution of the muscle force distribution problem gave lengths and contraction velocities of the two heads of the triceps muscle for each of those eight instants of each trial. The method of finite differences of the first order was used to calculate contraction velocities of those heads and then, by interpolation, a pair of values of force and velocity (F, V) was found corresponding exactly to the moment when the elbow angle equalled 105°. In this way 125 pairs (F, V) giving rise to F–V characteristics were obtained for each of the two heads under consideration. It was not possible to perform the calculations by using the SHOULDER program in nine cases, so the real number of points of each characteristic was 116.

3. RESULTS

The identification of the F–V characteristics of individual skeletal muscles, exemplified by m. TBClat and m. TBClong, was carried out for a natural movement of the upper extremity consisting in setting an external object in motion. It required simultaneous engagement of all the major joints of the extremity, and not only a single joint with mobility reduced to one degree of freedom as it is the case when using an isotonic (or isokinetic) device. It is thanks to this fact that the muscles actuating the elbow and shoulder joints worked naturally, that is, some at positive, whereas some at negative contraction velocities. Moreover, it can be assumed that the muscles under consideration produced force at a constant, nearly maximum stimulation. The experiment, aimed at finding the $F = f(V)$ function for the extensors of the elbow joint, was thus carried out under isotonic conditions implying a negligible influence of the internal muscle dynamics on the results of the experiment.

The obtained results took the form of two sets containing pairs (F, V) for each of the trials—the two F–V characteristics. The experimental F–V characteristics for m. TBClat were approximated by a straight line defined by the equation

$$F = aV + b,$$

where, $$a = -1335.05\left[\frac{N\cdot s}{m}\right],\quad b = 599.35\ [\mathrm{N}]$$

The F–V characteristics for m. TBClong were approximated following Pierrynowski and Morrison (1985) by a hyperbola defined by the equation

$$F = a\left(1 - \frac{bV}{c - V}\right),$$

where, $a = 175.65$ [N], $b = 2.94$, $c = 0.031$ [m/s].

Parameters in both equations were fitted by using the least squares method.

The analysis of the time courses of the lengths of the extensors of the elbow joint enabled the statement that for each trial at the instant corresponding to the rest length of the muscles the monoarticular head (m. TBClat) was shortening, whereas the biarticular head (m. TBClong) was lengthening. That is why the first of the two F–V characteristics (Figure 4) correspond to the branch of positive contraction velocities of m. TBClat (concentric work), and the second—to the branch of negative contraction velocities of m. TBClong (eccentric work, Figure 5).

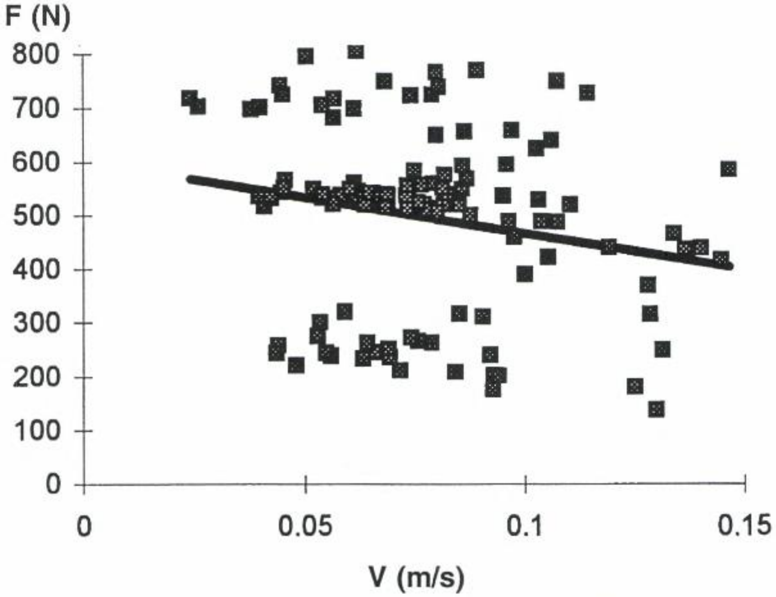

Figure 4. Force–velocity characteristics of the TBClat muscle.

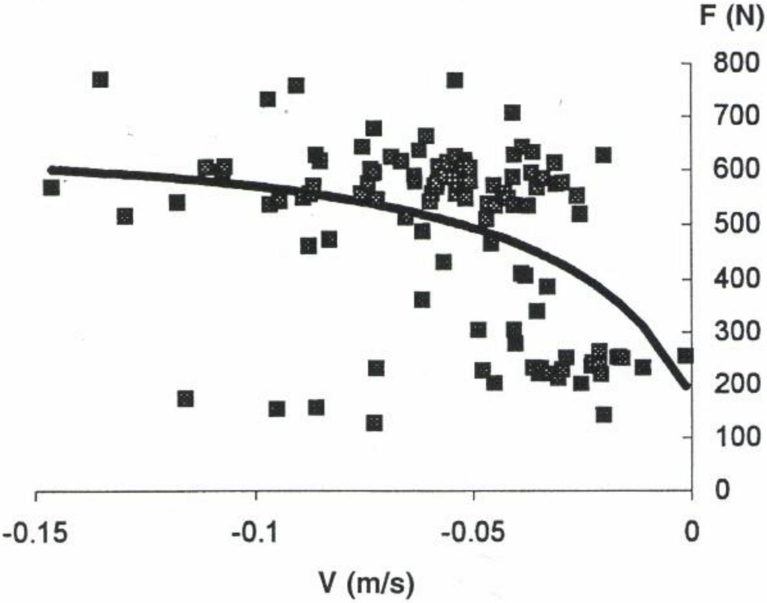

Figure 5. Force–velocity characteristics of the TBClong muscle.

4. DISCUSSION

The SHOULDER package is a static model. On its basis, forces of individual muscles were evaluated for appropriately selected instants of a push against an external object. This was possible thanks to previously video recording the instantaneous positions of the upper extremity and the trunk. Strictly speaking, the muscle force distributions thus obtained should be understood as corresponding to the positions comprised in the movement under consideration but realised statically, that is, as if stopped at each position for a while. Thanks to these quasidynamic properties of the SHOULDER package, the F–V characteristics of individual skeletal muscles were found, but they should be treated as merely the first approximation of the real characteristics, although possibly not differing much from them.

Future research will be focused on finding those real F–V characteristics. This can be accomplished by introducing the first approximation to the SHOULDER model making it more (but not yet fully) adequate for dynamic conditions. Thus modified model, containing improved force–velocity characteristics of all the muscles involved in the movement and not only those considered in this paper, will be used to calculate the second approximation of the F–V characteristics, which will be again used to modify the model. This iteration procedure will result in a sequence of models more and more adequate for work under dynamic conditions and a sequence of F–V curves more and more faithfully representing the true force–velocity characteristics of individual cross-striated muscles. The iteration procedure will transform a decent three-dimensional but static simulation package SHOULDER into a dynamic model, thus making it a universal tool capable of solving the muscle synergy problems in the upper extremity under dynamic conditions. Future research will cover many human motion tasks, and not only those studied here experimentally. Moreover, the incorporation of individualised F–V characteristics into the dynamical model will enable more precise calculation of the forces applied by individual muscles to the bones, which belong to the real forces acting within the locomotor system. Making the method of finding individual muscle forces more strict should facilitate ergonomic optimisation of the work place and contribute to designing more functional prostheses and more durable endoprostheses. More efficient injury prevention during work and sport activities and individualisation of the movement rehabilitation process could be possible. Realising fully the iteration procedure (this work presents merely the first step) will make the method of finding F–V characteristics of individual skeletal muscles a convenient tool for investigating real human force–velocity properties. The method will thus become a reasonable alternative of a wide class of muscle experiments *in vitro*.

5. CONCLUSIONS

It was found that despite considerable dispersion of experimental points the respective regression lines reveal a clear tendency of decreasing the muscle force for increased shortening velocity of the monoarticular head and of increasing the muscle force for increased lengthening velocity of the biarticular head.

The F–V characteristics shown in Figure 4 and Figure 5 do not seem to contradict the well established experimentally fact that the maximum force produced by a given muscle under concentric conditions is smaller than the isometric force, and the force produced by it under eccentric conditions exceeds the isometric force.

REFERENCES

Bober, T., & Hay, J. (1990). Topografia siły mięśni kończyn człowieka [Topography of strength of human extremities muscles]. *Wychowanie Fizyczne i Sport, 3*, 3–23.

Hill, A.V. (1938). The heat of shortening and dynamic constants of muscle. In *Proceedings of Royal Society, B 126*, 136–195.

Joyce, G.C., & Rack, P.M.H. (1969). Isotonic lengthening and shortening movements of cat soleus muscle. *Journal of Physiology, 204*, 475–591.

Karlsson, D., & Peterson, B. (1992). Towards a model for force predictions in the human shoulder. *Journal of Biomechanics, 2*, 189–199.

Katz, B. (1939). The relation between force and speed in muscular contraction. *Journal of Physiology, 96*, 45–64.

Levin, A., & Wyman, J. (1927). The viscous elastic properties of muscle. In *Proceedings of Royal Society, B 101*, 218–243.

Pierrynowski, M.R., & Morrison, J.B. (1985). A physiological model for the evaluation of muscular forces in human locomotion—Theoretical aspects. *Mathematical Biosciences, 75*, 69–101.

Winters, J.M., & Woo, S.L-Y. (Eds). (1990). *Multiple muscle systems. Biomechanics and movement organization.* New York: Springer.