The analysis of the force-velocity (F-V) relationship in skeletal muscles and the possible mechanisms that modulate its behavior is still a major point of interest in the field of muscle physiology. The force-velocity (F-V) relationship is a fundamental property of the neuromuscular system that consists in the premise that when all the other variables are kept constant (e.g. neural activation and type of muscle action), the concentric force that a muscle can produce at given muscle length is higher the lower the velocity at which it shortens and vice versa. The shape of this relationship per se has important implications for different aspects of
muscle physiology. For example, fast twitch muscle fibers exhibit an increased intrinsic mechanical power because of their decreased curvature of the F-V relation when compared with slow twitch muscle fibers. In addition, maximal mechanical power is more severely reduced with fatigue due to the concomitant enhancement of the curvature of the F-V relation. Another relevant point is that the shape of the F-V relationship has historically been indispensable for the development of theories of muscle contraction, and thus it reflects the main characteristics of cross-bridge kinetics.

The most widely accepted and used F-V model has traditionally been the one proposed by A. V. Hill. According to Hill’s experiments, the F-V relationship followed a rectangular hyperbola that can be fitted by a hyperbolic equation (Supplementary material 1).

However, first in isolated single muscle fibers, and recently in the in situ medial gastrocnemius muscle of the rat, the F-V relationship was demonstrated to deviate from the rectangular hyperbola at forces close to the maximal isometric force. In 1988, K. A. P. Edman reported the appearance of a breakpoint at a certain level of force (78% of maximal isometric force or $P_0$) that divided the F-V relation in two different hyperbolic segments. Thus, the F-V relationship was found to be better fitted by a double-hyperbolic equation (Supplementary material 2). Edman essentially introduced in the original hyperbolic equation a ‘correction term’ that reduces velocity values in the high-force/low-velocity region of the F-V relation.

There are only two previous studies that have analyzed the F-V relationship in humans with a specific focus on the high-force/low-velocity portion of the F-V relation. In the study of Harris et al., the high-force/low-velocity portion of the F-V relationship obtained from either voluntary or electrically evoked muscle actions might correspond very well with a double-hyperbolic pattern. On the other hand, the results obtained by Seger et al., also from voluntary and
electrically evoked muscle actions, are consistent with the sigmoidal pattern observed by Edman\textsuperscript{7} for the transition from the concentric to the eccentric portion of the F-V relationship, which is not compatible with a hyperbolic function. However, the two previous studies did not test the hypothesis of the double-hyperbolic nature of the F-V relationship. Therefore, we wanted to determine whether the double-hyperbolic F-V relationship was also present in the \textit{in situ} F-V relationship of humans. Due to the substantial differences in force production across distinct angles over the same joint, the measurement of high enough forces (>0.8 $P_0$) before reaching muscle failure is challenging. To cope with this limitation, we conducted a series of experiments in which force and velocity were evaluated during a lower-body multi-joint exercise (leg press) in ten resistance-trained young men performing unilateral maximal isometric and concentric repetitions over a partial range of movement close to the optimal joint angle (i.e. the joint angle yielding the maximal force). Using this procedure, we were able to register concentric peak force values as high as 89-96\% of the measured $P_0$ at corresponding velocities as low as 1-4\% of the estimated maximal unloaded shortening velocity ($V_{\text{max}}$). The results of these experiments showed that the \textit{in situ} F-V relationship in humans followed a double-hyperbolic pattern with a breakpoint found at 0.90±0.03 $P_0$ and 0.05±0.02 $V_{\text{max}}$, above which measured force and velocity values deviated downwards in regard to the classical rectangular hyperbola (Figure 1).

Consequently, maximal isometric force values were significantly overestimated by 12.5±11.1\% when using the hyperbolic equation ($p = 0.023$), in comparison with the maximal isometric force values measured at the beginning of the test.

Collectively, the observations made, first in isolated single muscle fibers,\textsuperscript{7} later in whole muscles,\textsuperscript{6} and finally in electrically evoked muscle actions in humans,\textsuperscript{8,9} suggest that the double-hyperbolic F-V relationship observed in our subjects during voluntary muscle actions might reflect the behavior of the contractile elements of skeletal muscles. In addition, our results
regarding the location of the breakpoint agree with those presented by Devrome and MacIntosh in mammalian whole skeletal muscles at physiological temperatures (0.90 $P_0$ and 0.05 $V_{max}$, and 0.88 $P_0$ and 0.07 $V_{max}$, respectively).

Furthermore, in order to consider the F-V relationship as a rectangular hyperbola, three previous assumptions regarding cross-bridge kinetics should be accepted: 1) the detachment rate is linearly proportional to the shortening velocity and reaches zero at $P_0$; 2) the attachment rate is independent of shortening velocity; and 3) force per cross-bridge declines linearly with shortening velocity. In contrast, all these assumptions have been partially or totally rejected based on recent evidence: 1) the detachment rate decreased linearly with decreasing shortening velocity, but it never reached zero; 2) the attachment rate increased with shortening velocity until ~0.5 $P_0$, below which it stabilized and remained constant for faster shortening velocities; and 3) the force exerted per cross-bridge was not found to merely decrease with shortening velocity, but it was nearly constant at intermediate and low velocities. Therefore, it seems that serious discrepancies between the original assumptions made for a hyperbolic F-V relationship and recent evidence on cross-bridge kinetics in the high-force/low-velocity region of the F-V relationship exist, which in fact matches with the double-hyperbolic F-V relationship.

Regarding the mechanism responsible for the biphasic pattern of the F-V relationship, Edman demonstrated that the proportion of active cross-bridges increases above the breakpoint disproportionally to the production of force, and thus that the force per cross-bridge is reduced above the breakpoint. This phenomenon would explain the lower force values observed in the high-force/low-velocity portion of the F-V relationship compared with those expected from a truly hyperbolic F-V relationship.

The functional benefit derived from a double-hyperbolic F-V relationship has been speculated to be the improvement of the mechanical stability of the myofilament system at high forces. The
sigmoidal pattern observed in the transition from the concentric to the eccentric portion of the F-V relationship, and the relatively flat region observed at forces around the maximal isometric force would let the muscle remain nearly isometric within a relative wide range of forces. This might be considered as an advantage in situations where the muscle is suddenly overloaded close to its limit of maximal isometric force, since the active muscle fibers could support the extra load with very little change in length, acting as an almost instantaneous protective mechanism. However, what might be the real impact of the double-hyperbolic F-V relationship on different specific areas of exercise physiology and aging regarding physical performance is not known. In addition, whether the degree of departure from the rectangular hyperbola or the location of the breakpoint can be modified by different training regimens or disuse situations remain to be elucidated. The answer to these and other relevant questions might help in the advance of the knowledge about the functioning of skeletal muscles and their adaptations to training, disuse and/or aging.

**Conflict of interest**

The authors declare no conflicts of interest.

**References**

Figure 1. Average force-velocity relationship obtained from the participants during the leg press exercise. Standard deviations were not presented in order to make the figures clearer. Velocity values obtained from Hill’s (white circles and black line) and the Edman’s equations (blue circles and blue line) were plotted at 0.05 $P_0$ intervals. The whole force-velocity relationship is displayed in A, while only the high-force/low velocity portion of the force-velocity relationship is shown in B.