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Sensitivity of maximum sprinting speed to characteristic parameters of the muscle force–velocity relationship

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ABSTRACT

An accumulation of evidence suggests that the force–velocity relationship (FVR) of skeletal muscle plays a major role in limiting maximum human sprinting speed. However, most of the theories on this limiting role have been non-specific as to how the FVR limits speed. The FVR is characterized by three parameters that each have a different effect on its shape, and could thus limit sprinting speed in different ways: the maximum shortening velocity V_{max}, the shape parameter A_R, and the eccentric plateau C_{ecc}. In this study, we sought to determine how specifically the FVR limits sprinting speed using forward dynamics simulations of human locomotion to examine the sensitivity of maximum speed to these three FVR parameters. Simulations were generated by optimizing the model's muscle excitations to maximize the average horizontal speed. The simulation's speed, temporal stride parameters, joint angles, GRF, and muscle activity in general compared well to data from human subjects sprinting at maximum effort. Simulations were then repeated with incremental and isolated adjustments in V_{max}, A_R, and C_{ecc} across a physiological range. The range of speeds (5.22–6.91 m s^{-1}) was most sensitive when V_{max} was varied, but the fastest speed of 7.17 m s^{-1} was attained when A_R was set to its maximum value, which corresponded to all muscles having entirely fast-twitch fibers. This result was explained by the muscle shortening velocities, which tended to be moderate and within the range where A_R had its greatest effect on the shape of the FVR. Speed was less sensitive to adjustments in C_{ecc}, with a range of 6.23–6.70 m s^{-1}. Increases in speed with parameter changes were due to increases in stride length more so than stride frequency. The results suggest that the shape parameter A_R, which primarily determines the amount of muscle force that can be produced at moderate shortening velocities, plays a major role in limiting the maximum sprinting speed. Analysis of muscle force sensitivity indicated support for previous theories on the time to generate support forces in stance (Weyand et al., 2000, Journal of Applied Physiology, 89, 1991–1999) and energy management of the leg in swing (Chapman & Caldwell, 1983, Journal of Biomechanics 16, 79–83) as important factors in limiting maximum speed. However, the ability of the knee flexors to slow the rotational velocity of the leg in preparation for footstrike did not appear to play a major role in limiting speed.

1. Introduction

A central question in the study of sprint running is how modifiable factors such as muscular properties limit the maximum steady-state speed. In a previous study (Miller et al., 2011a), we identified the force–velocity relationship of muscular force production (Hill, 1938) as the most critical muscle contractile property in maximum sprinting speed, supporting a similar conclusion drawn 85 years ago by Furusawa et al. (1927) and later assessed by Fenn (1930a,b). In the present study, we ask how specific features of the force–velocity relationship limit maximum sprinting speed.

The force–velocity relationship described by Hill (1938) and by Katz (1939) includes constants A and B that define the shape of the concentric limb. The ratio B/A specifies the maximum shortening velocity V_{max}. On the eccentric limb, the plateau force F_{ecc} is typically scaled by the maximum isometric force F_o to give the dimensionless parameter C_{ecc}. Independent changes in these parameters have different effects on the shape of the force–velocity relationship. A primarily affects the shape at moderate velocities, V_{max} (or B) the shape at fast concentric velocities, and C_{ecc} the height of the eccentric limb (Fig. 1). These characteristic parameters can potentially constrain the maximum sprinting speed by limiting the amount of force muscles can produce during particular points in the stride. Two theories on how the

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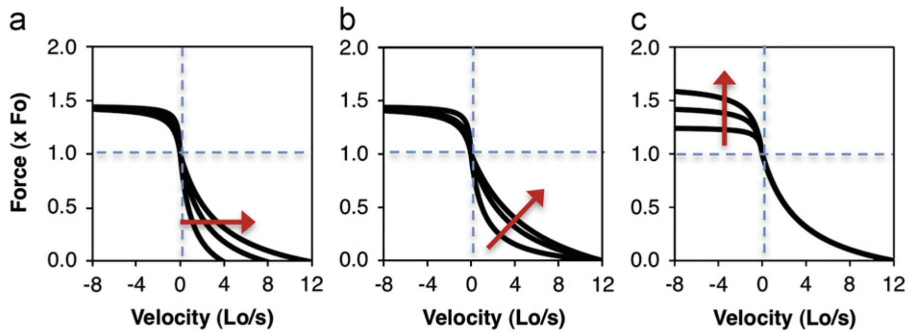

Fig. 1. Sensitivity of the muscle force–velocity relationship to incremental adjustments in (a) the maximum shortening velocity, (b) the dynamic constant *A*, and (c) the eccentric plateau force. Arrows indicate trend directions for increasing parameter magnitude. Axes are scaled by the optimal contractile component length (L_o) and the maximum isometric force (F_o). The crosshair indicates zero velocity and maximum isometric force. Graphs were constructed using the equations of van Soest and Bobbert (1993).

force–velocity relationship limits maximum sprinting speed have been proposed. The stance-based "time to generate force" theory of Weyand et al. (2000, 2010) states that speed is limited by the rate at which muscles can develop sufficient forces to support the body weight while the large extensor muscles are rapidly shortening, implicating the concentric force–velocity relationship. The swing-based "energy management" theory of Chapman and Caldwell (1983) poses that speed is limited by the ability of the knee flexors to reduce the kinetic energy of the lower limb while they lengthen in late swing, implicating the eccentric force–velocity relationship. These two theories are not necessarily in conflict, but it is unknown if one or the other plays a predominant role in limiting maximum sprinting speed. Analyses of muscle forces produced in stance and swing while the characteristic force–velocity parameters are manipulated should help clarify this issue.

Therefore, our purpose was to examine the sensitivity of maximum sprinting speed to adjustments in the characteristic force–velocity parameters. The force–velocity relationship in human muscle is sensitive to training status (e.g. Thorstensson et al., 1977; Andersen et al., 2005), but it is impossible to modify selected parameters *in vivo*, or to account for other confounding training effects such as increased muscle strength. We therefore used computer simulations to determine the effects of incremental adjustments in force–velocity parameter values on maximum sprinting speed. We expected that increasing the parameter values of *A*, V_{max}, or C_{ecc} would increase maximum sprinting speed, and hypothesized that maximum speed would be most sensitive to adjustments in V_{max} because sprinting presumably requires muscles to shorten at fast velocities. Finally, we assessed the simulation results in the context of the Weyand et al. (2000, 2011) and Chapman and Caldwell (1983) theories to elucidate their respective roles in limiting maximum sprinting speed.

2. Methods

2.1. Experimental data

Kinematic, ground reaction force (GRF), and muscle electromyographic (EMG) data were collected from 12 adult females (mean ± SD: age = 27 ± 6 years, height = 1.66 ± 0.05 m, mass = 61.0 ± 4.7 kg) as they sprinted at maximum effort along a level 40-m runway (Miller et al., 2011a). Subjects were fit and recreationally active but were not competitive sprint athletes. Data were measured from one stride near the center of the runway, ~20 m from the starting point.

Reflective marker positions were smoothed at 12 Hz and processed into 2D histories of sagittal plane joint and segment kinematics (Robertson et al., 2004). Raw EMG signals were processed into linear envelopes by sequentially applying a bandpass filter (20–300 Hz), full-wave rectification, and a lowpass filter (10 Hz), with amplitudes scaled to maximum isometric contractions. All data were averaged over strides (five per subject), then over subjects.

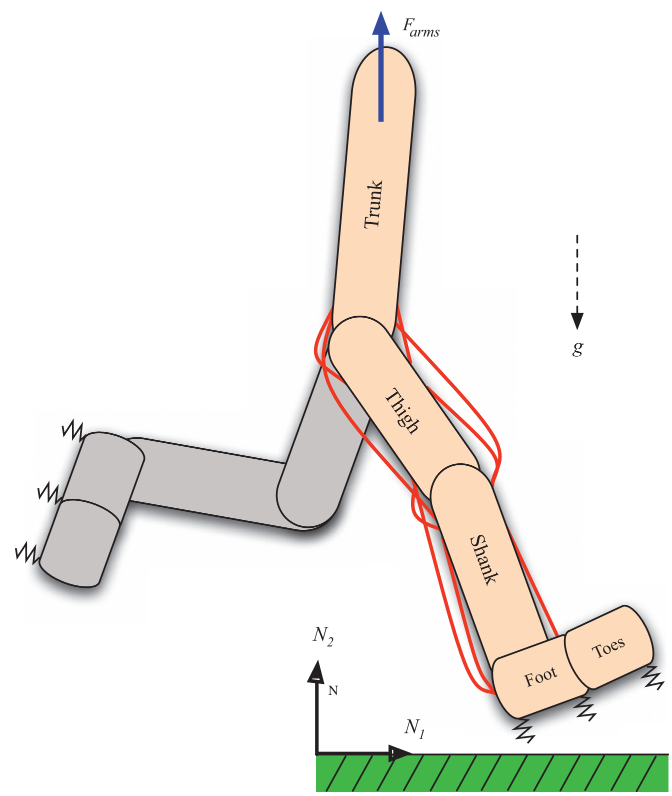

Fig. 2. Diagram of the 2D computer model used to simulate sprinting.

2.2. Computer model

A previously described 2D model was used to simulate sprinting (Fig. 2; Miller et al., 2011a,b). The model included nine rigid segments (trunk and bilateral thighs, shanks, feet, and toes) actuated by 18 Hill-based muscle models (bilateral iliopsoas, glutei, vasti, biceps femoris (short head), tibialis anterior, soleus, rectus femoris, hamstrings, and gastrocnemius), each with a contractile component (CC) in series with an elastic component (SEC). The muscle model parameters (Table 1) were derived from isovelocity joint strength tests on the female runners. The muscle force–velocity equations of van Soest and Bobbert (1993) were used, with the dimensionless Hill constants A_R and B_R defined according to Winters and Stark (1985, 1988)

$$A_R = \frac{A}{F_o} = 0.1 + 0.4FT \tag{1}$$

$$B_R = \frac{B}{L_o} = A_R V_{max} \tag{2}$$

where *FT* is the proportion of fast-twitch muscle fibers, F_o is the maximum isometric muscle force, and L_o is the optimal CC length. Eq. (2) is used to calculate B_R given values for A_R and V_{max}. Non-linear spring/frictional elements on the feet