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Short communication

What gives Bolt the edge—A.V. Hill knew it already!

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ABSTRACT

The 100 m is the blue ribboned event of world athletics competitions, with the winner crowned as the fastest human on Earth. Currently that fastest human is Usain Bolt, who covers 100 m in 9.58 s, achieving an average velocity of 10.43 m s^{-1}. Bolt is a phenomenal athlete, but what is his trick? Using Hills model, relating muscle force and heat liberation to shortening velocity, we propose that Bolt is at an advantage in relative power development and biomechanical efficiency compared to his contemporaries.

Between 1968 and 2007 it took seven exceptional athletes to reduce the 100 m sprint world record, defining the so called fastest man on Earth, from 9.95 to 9.74 s (http://www.olympic.org). Since 2007 Usain Bolt has bettered this mark by 0.16 s and has speculated that he could even improve the world record which he holds at 9.58 s (http://www.welt.de; Official programme of the 12th IAAF World Championship, 2009). What is his trick?

Obviously Bolt is very tall compared to previous championship finalists (Brüggemann et al., 1997) who were approximately 1.81 m in height with body masses of approximately 77 kg (http://www.iaaf.org). Measuring 1.96 m and 96 kg (Charles and Bejan, 2009; Usian Bolt interview http://www.youtube.com/) Bolt does not look overly massive related to his exceptional stature but his step length (in absolute terms) is much longer than his opponents after the acceleration phase of the race. Therefore, he runs the 100 m with fewer steps (41 steps in the 2009 Berlin World Championship final) than previous championship finalists (approximately 45 steps (Brüggemann et al., 1997)). Bolt's steps were counted from TV coverage and 100 m times from official results (http://berlin.iaaf.org) allowed calculation of step frequency for the whole race. This means that he wins even though he is moving his limbs more slowly at an average step rate of 4.28 Hz compared to his competitors in Berlin (4.54 ± 0.20 Hz) or previous world championship and olympic finalists (4.54 ± 0.16 Hz (Brüggemann et al., 1997)).

We propose that A.V. Hill would have already known at least some of the tricks through consideration of the inherent properties of muscle fibres, which he described as functions relating muscle force and heat liberation to shortening velocity (Hill 1938, 1964). Hill's definition of the general force velocity relationship can be transformed into general terms of power and biomechanical efficiency related to relative cross sectional area of fast and slow twitch fibres where constants depending on muscle size are eliminated (Kohler and Boutellier, 2005), Fig. (1A and B).

World class sprinters are a breed characterised by a high percentage (approximately 75%) of fast twitch muscle fibres compared to the average population who present approximately a 50% composition (Wilmore et al., 2004). Because of this greater percentage of fast twitch fibres, sprinters can generate propulsive power at remarkably high step rates of above 5.0 Hz on flat terrain (Zaciorskij, 1987). To what extent this step frequency could be furthermore increased if the force that needs to be overcome is decreased by conditions like downhill running is unknown.

Assuming similar fractions of fast twitch fibres of 75% in world class sprinters, Bolt's reduced step rate of 4.28 Hz compared to the average of 4.54 Hz seen for other world class sprinters suggests an increase in mechanical power development per muscle fibre from 0.36 to 0.42 maximum fast twitch fibre power, equivalent to an advantage in the magnitude of approximately 17% (Fig. 2A). Furthermore, this is combined with a substantially better biomechanical efficiency of approximately 10% compared to 8% in the other world class sprinters (Fig. 2B). Sprinters who prefer higher step rates would require the unlikely fraction of 90% fast twitch fibres to compensate for Bolt's advantages in power generation (Fig. 2A). However, even this super fast muscle fibre profile would not yet match Bolt's efficiency advantage (Fig. 2B).

The idea that an approximate 6% reduction in step rate combined with an approximate 17% increase in power per step may be one relevant factor of Bolt's success is supported by findings that human runners reach faster top speeds by applying greater support forces to the ground than by faster repositioning of their limbs (Weyand et al., 2000). The assumption that world class sprinters have comparable fractions of fast and slow twitch fibres and a muscle mass close to their individual maximum, may limit the possibility to apply higher forces during similar ground contact times. If a 6% reduction in step rate is used to increase ground contact time and the corresponding distance travelled during this fraction of a step within a naturally elongated step this

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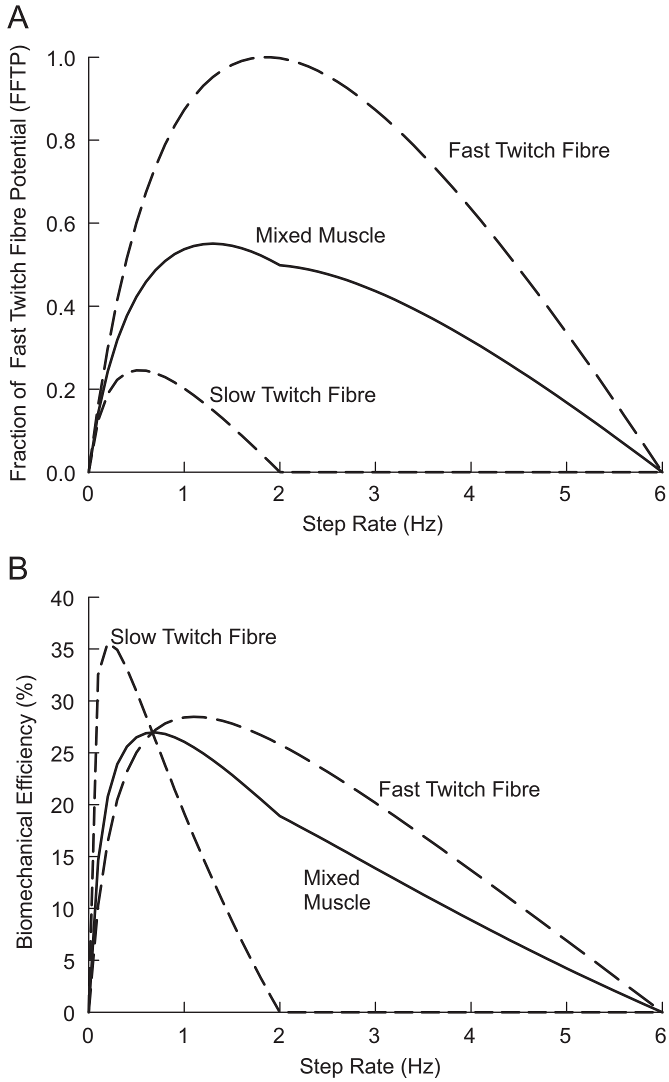

Fig. 1. (**A**) Power and biomechanical efficiency (**B**) related to step rate assuming a maximum step rate of fast twitch muscles fibres of 6 Hz during unloaded running, maximum shortening velocity of type II fibres of thrice that of type I fibres (Faulkner et al., 1986), factors defining static force related to specific fibre cross section area for fast and slow twitch fibres (Faulkner et al., 1986), and the rates of maintenance heat and shortening heat (Hill, 1964) for an average person with 50% fast and slow twitch fibres each (for details see Kohler and Boutellier, 2005).

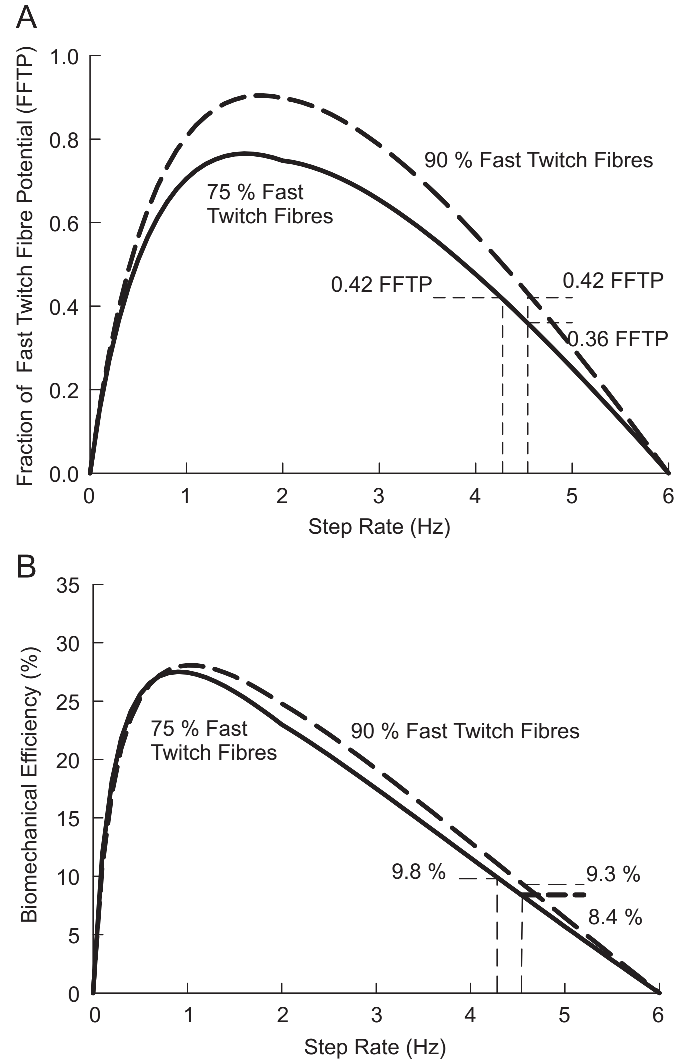

Fig. 2. (**A**) Power and biomechanical efficiency (**B**) related to step rate according to fibre characteristics applied in Fig. 1**A** and **B** assuming 75% and 90% fast twitch fibres in sprinters, respectively. Fractions of fast twitch fibre potential and biomechanical efficiency increase with lower sprinting step rate.

would enable the application of a higher ground force during a longer ground time with higher biomechanical efficiency.

Estimation of the metabolic power above rest per unit of body mass by describing the 100 m sprint as a transition from up hill running during the acceleration phase to running on flat terrain thereafter (di Prampero et al., 2005) gives an average power difference of approximately 6% between a 9.96 and a 9.58 s 100 m sprint, which is mainly required during the acceleration phase (Fig. 3). This results in overall metabolic costs of approximately 722 and 735 J kg^{-1}, for the 9.96 and 9.58 s sprint, respectively. Assuming that a ground contact time of 0.092 s per step during a 9.96 s sprint at 4.54 Hz step rate increased to 0.106 s during a 9.58 s sprint at 4.28 Hz step rate (Weyand et al., 2000) this would result in a metabolic power of 174 and 169 W kg^{-1} per ground contact respectively, which are close to the limits of human performance (Beneke and Böning, 2008). Considering the differences in body mass the latter reflects a total metabolic power above rest of 16.2 kW for Bolt and 13.4 kW for previous championship finalists respectively. An increase in biomechanical efficiency from 8.4% to 9.8% (Fig. 2B) gives a difference in mechanical power of approximately 14% if power is related to body mass in Bolt's favour, which is comparable to the difference in power estimates as shown in Fig. 2A. In terms of absolute power the corresponding difference is approximately 42%. The difference between absolute power and power related to body mass suggests that Bolt's advantage can be attributed to three factors (a) his exceptional physique (approximately 60%) which (b) additionally enables him to lengthen his ground contact time without negative effects on gait characteristics and therefore a higher impulse (approximately 10%) and (c) lower step rate combined with inherent properties of muscles and increased mechanical power (30%).

However, the present considerations imply that step rate and muscle shortening velocity can be transformed into one another. This is a highly speculative assumption. Nevertheless the present concept is consistent with theories that (a) sprint performance depends on the force generated during ground contact (Weyand et al., 2000), (b) the time needed to reposition the limbs is individually almost running speed invariant and not limited by mechanical power chemically generated within the muscle

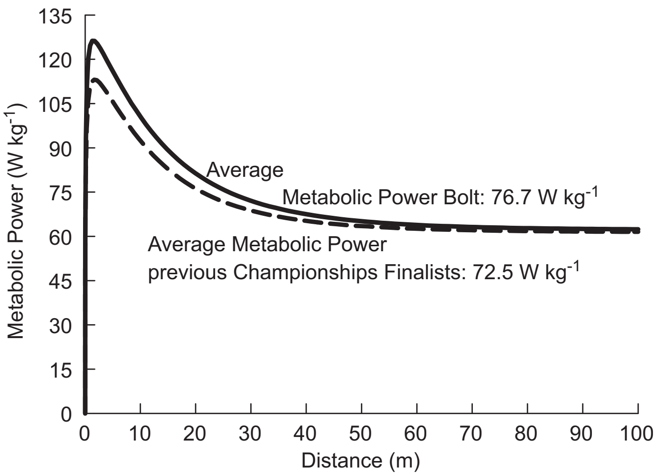

Fig. 3. Metabolic power above rest per unit of body mass of 100 m sprints with a finishing time of 9.58 s and Bolt's stature vs. 9.96 s and corresponding stature of previous championship finalists based on modeling the 100 m sprint as a transition from up hill running during acceleration phase to running on flat terrain thereafter (for details see di Prampero et al., 2005).

(Weyand et al., 2000), and (c) an optimum time needed to apply the large, mass-specific forces necessary (Weyand et al., 2010); these are all consistent with (d) estimates of the energy cost of sprint running calculated from overall acceleration resulting from forward acceleration and gravity, and speed dependent air resistance (di Prampero et al., 2005) and (e) metabolic limits of human performance (Beneke and Böning, 2008).

Therefore the inherent properties of muscles described by the force–velocity relationship (Hill, 1938) and heat release (Hill, 1964) seem to uncover relevant factors of how stature and a corresponding advantage in relative power development and biomechanical efficiency seem to do a trick for the currently fastest man on Earth.

Conflict of interest statement

There is no conflict of interest.

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