The limits of running performance

By Jason R. Karp

The highest level of performance that human beings will ever be able to reach is of interest to fans, athletes, coaches, physiologists, evolutionary biologists, and anthropologists. This article starts with a discussion of evolution's effect on the structural and functional design of humans, the comparison of maximal oxygen consumption across animal species and identification of factors that affect running performance. These include metabolism, oxygen diffusion in the lungs, oxygen delivery to the working muscles, and the range of motion of the hip joint. The second part of the article is a discussion of attempts to predict the limits of human running performance using mathematical modelling. From the predictions examined, it can be suggested that humans are closer to their theoretical potential in the sprint events than in the distance events.

ABSTRACT

Athletic performance is ultimately limited by the quantities of useful force and mechanical power that can be generated and sustained. Force and power are functions of neuromuscular co-ordination, skeletal muscle mechanics and energy utilisation, efficiency of converting metabolic power into mechanical power, and aerobic and anaerobic metabolic capacities of skeletal muscle. The site of force generation in skeletal muscle is the actin-myosin cross-bridge. Interestingly, the maximal stress that the cross-bridge can produce is nearly constant for all vertebrate animals. A.V. HILL calculated that the maximal muscular work (per kg of body mass) per contraction should thus be the same for all mammals and concluded that all mammals should be capable of nearly the same maximal running velocity. Obviously, this is not the case. Therefore, factors other than cross-bridge cycle work must influence speed. Since running velocity equals the product of stride rate and

Introduction

It was not long after participating in my first track meet in junior high school that I became interested in athletic performance. There was something exciting about running faster than the guy in the lane next to you and something intriguing about how to do it. Sport, after all, is engaging.
stride length, increasing either or both of these variables will increase velocity. Relatively fast mammals, such as the cheetah and pronghorn antelope, move their limbs through a larger angle than is predicted for their size\textsuperscript{16}. The greater the angle through which the limbs move (i.e., the range of motion), the greater the stride length. Thus, the limiting factor of maximal running velocity in humans may be their range of motion at the hip joint, which will be influenced by both hip extension and hip flexion.

An organism’s structural design is regulated by its functional demand\textsuperscript{27,29} such that “…the quantity of structure incorporated into an animal’s functional system is matched to what is needed: enough but not too much”\textsuperscript{28}. Since demand drives the change in structure, the limits of human performance can only be exceeded if the demand becomes greater. Given that modern man’s lifestyle is more sedentary than that from which he evolved, it may be expected that the limits of human performance will decrease with further evolution.

The evolution of human physiology was inherently dependent on efficient oxygen delivery and on the development of aerobic metabolic pathways, with a relatively minor dependence on anaerobic (oxygen-independent) metabolic systems to sustain whole body performance. The ancestors of Homo sapiens evolved in African highlands at altitudes of 1,000m to 2,000m\textsuperscript{11}. Therefore, natural selection would have favoured those with enhanced aerobic abilities. It is not surprising that the physiological traits underlying tolerance to altitude in modern humans are similar to those associated with greater endurance performance\textsuperscript{11,12}. Humans are aerobic animals.

As far as their ability to consume oxygen at a fast rate, however, humans do not fare well against many other animals, as their maximal rate of oxygen consumption (\(\text{VO}_2\text{max}\)) is equal to that of the pig and the rat, about half that of the horse and the dog, and only one-third that of the hunting fox\textsuperscript{8}. While dogs, wolves, foxes, and coyotes can sustain up to 32 times their resting metabolic rate during short-term aerobic exercise\textsuperscript{23}, humans can only sustain up to about 25 times their resting metabolic rate. Among all animals, flying insects have the highest rate of oxygen consumption relative to their size\textsuperscript{22}. The \(\text{VO}_2\) of a hummingbird flapping its wings 80 beats per minute is 40 milliliters/gram/hour, which, in human terms, is equivalent to 666 milliliters/kilogram/minute (ml/kg/min)! As if this were not impressive enough, the flight muscles of worker honeybees, flapping their wings 250 beats per minute, consume 6ml of oxygen/gram/minute, equivalent to 6,000ml/kg/min in human terms\textsuperscript{23,31}. By comparison, the best human endurance athletes have a \(\text{VO}_2\text{max}\) of 85-90ml/kg/min.

As far as sprinting capability is concerned, humans lag well behind other species, as the fastest speed recorded for a human is 23.2 miles per hour (Michael Johnson’s world record of 19.32 seconds for 200 meters). The cheetah, by contrast, can run at nearly 70 miles per hour\textsuperscript{16} while antelopes, gnus, horses, foxes, rabbits, and many other animals can also reach speeds much faster than any human.

There is a large degree of variation in running performance among humans, even among trained individuals. Although evolution has given humans an exceptional ability to adapt, our capacity has limits\textsuperscript{5}. For example, it is well known that mitochondrial density is highly modifiable and that the number of mitochondria in skeletal muscle increases in response to endurance training\textsuperscript{11,13}. However, there is a threshold, above which further increases in training volume do not result in further increases in mitochondrial density\textsuperscript{4}. Since athletic performance has a high genetic component, and since the ability to improve performance with training is limited, it seems as if genetics (human variation) outweighs training (human adaptation). A person with a lot of talent will almost always outperform a person with little talent and a lot of training.
In examining the uppermost limit of humans to perform aerobically, PETERSON and colleagues came up with an interesting concept termed the “metabolic ceiling”, which they define as the highest ratio of sustained metabolic rate (the metabolic rate that can be sustained indefinitely while remaining in energy balance by consuming food) to resting metabolic rate. As a primary example of a metabolic ceiling, these researchers use cyclists in the Tour de France, whose average power output over the race is five times resting metabolic rate, despite consuming large quantities of food. The limiting factors of sustained metabolic rate and the metabolic ceiling include the small intestine’s ability to absorb nutrients, the liver’s ability to process absorbed nutrients, and the skeletal muscles’ ability to metabolise nutrients. A metabolic ceiling may exist because metabolism may have evolved only to those limits that an animal’s food supply is likely to be able to fuel without wasting energy. In addition, a greater sustained metabolic rate may come at the cost of an increased resting metabolic rate to support the extra metabolic machinery needed.

Since VO\(_2\)\(_{\text{max}}\) is inversely proportional to body mass\(^2\), it has been suggested that the factors that set the upper limit to VO\(_2\) must also be involved in setting the lower limit to body mass\(^4\). Since many other aspects of running performance, including stride rate, maximal velocity of slow-twitch muscle fibre shortening, muscle cross-sectional area, distance over which muscle contracts, enzyme activity, and metabolic cost of running, are also related to body mass\(^2\), the limits to human performance may ultimately be dependent on body mass. For example, relative VO\(_2\)\(_{\text{max}}\) and aerobic enzyme activity are inversely related to body mass, while muscle cross-sectional area and the enzymes of glycolysis are positively related to body mass\(^4\). In other words, as mammals increase in size, their aerobic capabilities worsen while their anaerobic capabilities improve. Thus, if human aerobic performance is to improve beyond what training can accomplish, it may be expected that the next species of human, Homo futuralis, will be smaller. Conversely, if improvements are to be seen in human anaerobic performance, Homo futuralis will be bigger.

While it is generally agreed that cardiovascular factors (cardiac output, blood flow) represent the main limitation for humans, as individuals, to perform endurance exercise, the lungs may set the limit for humans, as a species. The lungs, unlike the cardiovascular or skeletal muscle systems, do not alter their structural or functional capacity in response to functional demand. In effect, the lungs can limit performance by “lagging behind” other, more readily adaptable characteristics. Thus, humans seem to be limited by the genetic potential of the lungs to provide for adequate diffusion of oxygen into the blood. In addition, many elite athletes reach the lungs’ mechanical limit of generating airflow during intense exercise—said to be “flow-limited”—and simply cannot breathe enough to match their high metabolic demand, leading to an inadequate pulmonary gas exchange.

**Predictions of Running Performance**

What’s the fastest that humans will ever be able to run? A few attempts have been made to predict running performance. Using previously recorded values for the three main variables influencing distance running performance—VO\(_2\)\(_{\text{max}}\) (the maximal rate of oxygen consumption), lactate threshold (the speed above which lactate and associated acidosis begins to increase exponentially), and running economy (the oxygen cost to run at a given speed)—JOYNER predicted that the marathon could be run in 1:57:58\(^1\). This prediction is seven minutes faster than Paul Tergat’s current world record (2:04:55).

With a mathematical model based on anaerobic capacity, maximal aerobic power, and the reduction in aerobic power with race duration, PÉRONNET and THIBAULT...
### Table 1 - Predictions of men's and women's world running records  
(Data from PÉRONNET and THIBAULT\(^4\))

<table>
<thead>
<tr>
<th>Distance</th>
<th>2000</th>
<th>2028</th>
<th>2040 (2033 for women)</th>
<th>Ultimate Performance</th>
<th>Current World Record (2005)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 metres</td>
<td>9.74</td>
<td>9.57</td>
<td>9.49</td>
<td>9.37</td>
<td>9.77</td>
</tr>
<tr>
<td></td>
<td>10.66</td>
<td>10.46</td>
<td>10.44</td>
<td>10.15</td>
<td>10.49</td>
</tr>
<tr>
<td>200 metres</td>
<td>19.53</td>
<td>19.10</td>
<td>18.92</td>
<td>18.32</td>
<td>19.32</td>
</tr>
<tr>
<td></td>
<td>21.46</td>
<td>20.95</td>
<td>20.90</td>
<td>20.25</td>
<td>21.34</td>
</tr>
<tr>
<td>400 metres</td>
<td>43.44</td>
<td>42.12</td>
<td>41.59</td>
<td>39.60</td>
<td>43.18</td>
</tr>
<tr>
<td></td>
<td>46.85</td>
<td>45.34</td>
<td>45.18</td>
<td>44.71</td>
<td>47.60</td>
</tr>
<tr>
<td>800 metres</td>
<td>1:39.88</td>
<td>1:36.18</td>
<td>1:34.71</td>
<td>1:30.86</td>
<td>1:41.11</td>
</tr>
<tr>
<td></td>
<td>1:51.16</td>
<td>1:46.95</td>
<td>1:46.53</td>
<td>1:42.71</td>
<td>1:53.28</td>
</tr>
<tr>
<td>1,500 metres</td>
<td>3:25.45</td>
<td>3:17.45</td>
<td>3:14.27</td>
<td>3:04.27</td>
<td>3:26.00</td>
</tr>
<tr>
<td></td>
<td>3:47.93</td>
<td>3:38.91</td>
<td>3:38.00</td>
<td>3:26.95</td>
<td>3:50.46</td>
</tr>
<tr>
<td>Mile</td>
<td>3:41.96</td>
<td>3:33.29</td>
<td>3:29.84</td>
<td>3:18.87</td>
<td>3:43.13</td>
</tr>
<tr>
<td></td>
<td>4:10.79</td>
<td>4:00.83</td>
<td>3:59.82</td>
<td>3:43.24</td>
<td>4:12.56</td>
</tr>
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<td>3,000 metres</td>
<td>7:22.54</td>
<td>7:03.91</td>
<td>6:56.87</td>
<td>6:24.81</td>
<td>7:20.67</td>
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<tr>
<td></td>
<td>8:11.98</td>
<td>7:50.61</td>
<td>7:48.46</td>
<td>7:11.42</td>
<td>8:06.11</td>
</tr>
<tr>
<td>5,000 metres</td>
<td>12:42.72</td>
<td>12:09.39</td>
<td>11:56.19</td>
<td>11:11.61</td>
<td>12:37.35</td>
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<tr>
<td></td>
<td>14:19.33</td>
<td>13:41.56</td>
<td>13:37.75</td>
<td>12:33.36</td>
<td>14:24.68</td>
</tr>
<tr>
<td>10,000 metres</td>
<td>26:43.63</td>
<td>25:32.27</td>
<td>25:04.01</td>
<td>23:36.89</td>
<td>26:17.53</td>
</tr>
<tr>
<td></td>
<td>1:05:27</td>
<td>1:02:28</td>
<td>1:02:11</td>
<td>57:59</td>
<td>1:06:44</td>
</tr>
<tr>
<td></td>
<td>2:18:43</td>
<td>2:12:19</td>
<td>2:11:40</td>
<td>2:00:33</td>
<td>2:15:25</td>
</tr>
</tbody>
</table>
predicted performances in running events from 100m to the marathon. Using the men’s and women’s world running records from 1987 to test the accuracy of their model, they predicted that men would run the 100m in 9.74s by the year 2000, 9.57s by 2028, and 9.49s by 2040, while the women would run 10.66s by 2000, 10.46s by 2028, and 10.44s by 2033 (see Table 1). Thus, the current men’s world record—9.78s—is slightly slower than the prediction, while the current women’s world record—10.49s—far surpasses the prediction. In light of both past and recent evidence of the use of illegal performance-enhancing substances, it must be acknowledged that some of the performances initially studied by Péronnet and Thibault, as well as some current performances, may be artificially inflated. How fast the 100m can be run is determined largely by the phosphagen system's ability to regenerate ATP, which is itself influenced by the amount of creatine phosphate and ATP stored in skeletal muscles, as well as the activity of the ATP-regenerating enzymes, creatine kinase and adenylate kinase. It seems as if humans can produce better performances than what is predicted for them, as 12 of the 22 current world records listed in the table are faster than what was predicted just five years ago. Notable exceptions are the middle distance events—800m, 1,500m and the mile—for which both men and women are slower than their 2000 prediction. This observation may be more than happenstance since, compared to pure sprint and endurance performance, much less is known about training for events that require both a large aerobic and anaerobic contribution.

From these predictions, it can be suggested that humans are closer to their theoretical potential in the sprint events than in the distance events. For example, the difference between the current men’s world record and the “ultimate performance” in the 100m (9.78s and 9.37s, respectively) is 4.4%, while the difference between the respective times in the marathon (2:04:55 and 1:48:25) is 15.2%. For women, the percent differences in performance are less (3.3% and 12.3% for the 100m and marathon, respectively), a surprising observation given that men have been competing for much longer than women, especially in the marathon. While comparisons between actual and predicted performances lends some insight into how close (or how far) humans are to the limits of running performance, conclusions based on these comparisons are subjected to a certain naiveté, as the use of performance-enhancing substances by both sprinters and distance runners have made it seem that runners are closer to their potential than is likely the case.

Using a less scientific method, Roger Bannister, the first man to run a mile in less than four minutes, gave his own prediction for how fast humans can run the mile:

“At what point will record-breaking for the mile end? Clearly there is a limit determined by the structure of the human body. In 1981... I predicted that a 3:30 mile is not impossible... the record has fallen on average by about 0.3 seconds per year. At this rate, the 3:30 mile might be run in the year 2044.”

Interestingly, Bannister’s prediction, based solely on the average rate of progression, is close to that of Péronnet and Thibault, who predicted that the mile will be run in 3:29.84 by 2040.

It has been said that the best athletes make what they do look easy. This is certainly true of the African male distance runners, who hold every world record from 800m to the marathon. What makes these runners able to run so fast? Until we find out, coaches like me will continue to shake their heads in disbelief at what these athletes can do with their skinny little legs.

Please send all correspondence to:
Jason R. Karp
jason@runcoachjason.com.
REFERENCES