Physiology and Performance Prospects of a Women’s Sub-4-Minute Mile

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When will women run a sub-4-minute mile? The answer seems to be a distant future given how women’s progress has plateaued in the mile, or its better studied metric placeholder, the 1500 m. When commonly accepted energetics principles of running, along with useful field validation equations of the same, are applied to probe the physiology underpinning the 10 all-time best women’s mile performances, insights gained may help explain the present 12.34-second shortfall. Insights also afford estimates of how realistic improvements in the metabolic cost of running could shrink the difference and bring the women’s world record closer to the fabled 4-minute mark. As with men in the early 1950s, this might stir greater interest, excitement, participation, and depth in the women’s mile, the present absence of which likely contributes to more pessimistic mathematical modeling forecasts. The purpose of this invited commentary is to provide a succinct, theoretical, but intuitive explanation for how women might get closer to their own watershed moment in the mile.

Keywords: middle-distance running, elite female athletes, running economy, sex differences in performance

In the era of ratified world records, Svetlana Masterkova’s 1996 world record of 4:12.56 in the mile came 81 years after Norman Taber ran 4:12.6.1 Roger Bannister’s watershed moment of becoming the first man to eclipse the fabled 4-minute barrier came famously in 1954. Might women do the same 81 years after Bannister in the year 2035? Even some elite women runners believe that the proposition is “far-fetched.”2 It does seem unlikely at first given how women’s progress has mathematically plateaued in the mile, or its better studied metric placeholder the 1500 m.3–6 Although Sifan Hassan bettered Masterkova’s mark in 2019,7 her time of 4:12.33 represents an improvement of just 00:00:23 seconds over 23 years. How could an additional 12.34 seconds be chipped away in the next 13 years? The purpose of this invited commentary is to provide a succinct, theoretical, but intuitive explanation for how women might get closer to their own watershed moment in the mile.

Limitations to Forecasting Future Performance

Various models have been proposed projecting ultimate running performance limits. One of these, a physiological model, projects the possibility of a sub-four-minute mile for women in 2033.8 However, most quantitative mathematical forecasts of world records3–5 project incremental improvements like those observed for the women’s mile between 1996 and 2019, thus making a Roger Bannister moment for women a credulity-straining proposition until well after 2100.9 Importantly, any predictive model will be biased if the data being modeled contains participation bias, whether for social, economic, or other reasons.9–11 The odds of an athletic woman choosing to become a miler seem far worse today than the odds of being born with the phenotype required to be a successful miler. Numerous factors8–11 create differential participation in running between men and women, resulting in a decrease in the depth of track running talent among the latter12,13 that may help explain why women are not closer to the 4-minute mile today. Participation disparity is a known confounder for comparing performances between the sexes or when forecasting future trends.5,6,9,11 A closer look at what is required physiologically to go sub-four, juxtaposed against the documented best performances of women, offers a different and potentially more optimistic outlook.

Physiology and Energetics of Running Sub-4

The energetics required for a 51.3-kg woman (Table 1) to run a sub-four-minute mile can be described by the product of body mass, running distance (1609 m), and the estimated energy cost when racing outdoors (4.53 J·kg⁻¹·m⁻¹).14 All calculations (see Appendix for details) assume that the consumption of 1 mL of oxygen yields 20.92 J of energy (ie, a respiratory exchange ratio of 1.0). The mile elicits a maximal rate of sustainable aerobic energy utilization and exhausts nonsustainable energy reserves.15 If approximately 80% (75%–85%) of the sustainable energy requirements in the mile are oxidative,15–18 then the required oxygen uptake is 3.58 L·min⁻¹ or 69.7 mL·kg⁻¹·min⁻¹. The remaining 20% of unsustainable energy required accumulates an oxygen deficit equivalent to 1458 J·kg⁻¹. The above estimates are entirely consistent with values measured or estimated for elite women runners.8,18–20 Distance divided by time yields an average required running velocity of 6.7 m·s⁻¹, which is 112% of the estimated velocity at maximal oxygen uptake (vVO₂max) or 6.0 m·s⁻¹.21 The required maximal sprint speed (MSS) must be well above 6.7 m·s⁻¹. Based upon recent research with 800- and 1500-m runners21–23 combined with the above 6.0 m·s⁻¹ estimate of vVO₂max, we may estimate the required MSS of the above 4-minute miler to be >8 m·s⁻¹ (ie, MSS/ vVO₂max >1.36),24 which looks attainable even for subelite women middle-distance runners.23 The above estimates are also strikingly...
similar to the actual v\(\text{VO}_2\text{max}\), MSS, and 1500 m equivalent sub-four-minute mile performances of men (approximately 219 s).\(^{23}\)

Table 1 lists in descending order the ten fastest legal times ever run by women in the mile.\(^{25}\) The top 10 individual performers, rather than the top 10 performances overall, were selected to remove potential overrepresentation by exceptional performers. Body mass data were obtained from personal information available within athlete Wikipedia profiles. The average required running velocity was calculated using distance divided by personal best time. The energy cost of racing\(^{14}\) and v\(\text{VO}_2\text{max}\)\(^{23}\) were calculated as above, and the assumption concerning the energy yield of oxygen was held constant with the 4-minute example. Compared with the requirements calculated for a 4-minute mile at the same average body mass, the average energy cost of racing was higher (4.76 J·kg\(^{-1}\)·m\(^{-1}\)) and the lower average running velocity (6.3 m·s\(^{-1}\)) reflected a higher percentage (125%) of a lower v\(\text{VO}_2\text{max}\) (5.05 m·s\(^{-1}\)). The overall average finishing time was 15.51 s outside the 4-minute barrier. The average rate of oxygen consumption was, however, quite close to the estimated requirement for a 4-minute mile (3.53 L·min\(^{-1}\); 68.8 mL·kg\(^{-1}\)·min\(^{-1}\)), as was the average accumulated oxygen deficit (1533 J·kg\(^{-1}\)). It appears that the minimum necessary “fitness” needed to eclipse 4 minutes is present even when averaged among all ten women (Table 1). Since the unsustainable energy reserve is implicated in the instantaneous control of running speed above v\(\text{VO}_2\text{max}\),\(^{15}\) the faster depletion of said reserves, partially indexed as racing velocity minus v\(\text{VO}_2\text{max}\),\(^{21,22}\) may help explain slower than expected performances (in this example). Clearly, both the higher energy costs of racing\(^{14}\) and a larger difference between race velocity and v\(\text{VO}_2\text{max}\)\(^{15,21,22,26}\) combine to produce a finishing time slower than 4 minutes. There are many ways in which improvements in the women’s mile might be targeted. It is presumed that elite runners are already taking advantage of similar, appropriate, and widely available training techniques aimed at optimal middle-distance performances,\(^{24,27}\) which requires bioenergetics and neuromuscular characteristics and constraints unique to all-out efforts of <4-min duration.\(^{23}\) Based upon the arguments presented above, one key\(^{14}\) to achieving sub-four-minute glory sooner than later may be to focus on reducing the metabolic cost of running.

**Prospects for Improving Performance**

**Drafting and Body Weight**

Forward propulsion and the support of body mass explain approximately 80% of the metabolic cost of running on level ground.\(^{28}\) In the second example above, a 4-minute mile requires that running velocity increases 0.4 m·s\(^{-1}\), which increases the net energy cost of running due to added air resistance by 1.6% (0.2%).\(^{29}\) The energy saving benefits of drafting are well known to runners. Roger Bannister utilized cooperative drafting behind pacemakers Chris Brasher and Chris Chataway for more than 3 laps en route to the world’s first sub-four-minute mile. The current men’s world record by Hicham El Guerrouj was also set with the aid of multiple pacemakers over more than 3 laps. If we assume a pacemaker for women at 6.7 m·s\(^{-1}\) through only 2 laps of the race, the additional 1.6% energy cost is reduced to 1.2% (0.1%), assuming that drafting itself is imperfect and reduces the energy cost of air resistance by 50%.\(^{29}\) The remaining disadvantage could be offset by reducing body mass by 1 kg; simply apply the same calculations above using 50.3 kg and the total metabolic cost for the effort is reduced by −1.9% (0.2%). An acute loss of 1 kg (1 L) of body water could be considered,\(^{30}\) but this is probably not feasible for maximizing performance.\(^{31}\) The strategic loss of 1 kg of body fat, lost gradually over a season, is common among both men and women runners either through purposeful periodization feedback techniques\(^{32}\) or through the result of heavier training.\(^{33}\) Sufficient fat mass is important for health, while any surplus represents mass that must be carried without benefits toward propulsion. Estimates of body fat percentages in elite women middle-distance runners average approximately 15%.\(^{19,32,33}\) For the 51.3 kg woman in this example, a loss of 1-kg body fat would reduce the percentage body fat to approximately 13%. Although natural seasonal fluctuations and relative percentage changes in body fat on this order have been reported for elite female middle-distance runners,\(^{32}\) any potential benefits of weight loss to performance must always be uniquely evaluated against any unintended health consequences of the same. Runners will be fastest at the right weight, not the lowest weight. If body fat is already optimized, strategies such as...
reducing shoe mass can have proportionally smaller, but still profound, effects on metabolic energy costs and middle-distance running performance, owing in part to the distal location of the added mass. However, track spikes are already near their lower mass limits. Perhaps the most promising strategy of all for getting closer to a sub-four-minute mile is a deliberate assault on improving running economy.

### Running Economy

Improved running economy can be achieved using a variety of training techniques, the discussion of which goes well beyond the purposes of this paper. Improved running economy is defined by a lower oxygen cost of running at a prescribed running velocity, usually 4.4 to 5.5 m·s⁻¹, which is well below the racing velocity required for a 4-minute mile. However, the metabolic cost of racing outdoors can be quantified. Runners with the lowest energy costs when racing achieve the fastest finishing times, a characteristic common in elite middle-distance runners. The top ten women include faster vVO₂max estimates. The vVO₂max combines translates to mathematically faster performance calculations to running economy, considered independently of other factors, which is 96% of the variance in middle-distance running performance. A 2.5% improvement in running economy, considered independently of other factors, translates to mathematically faster performance calculations to include faster vVO₂max estimates. The vVO₂max combines maximal oxygen uptake (VO₂max) and running economy into a single factor demonstrated to be critical for successful mile performance.

Ingham et al. for example, report that the proportional curvilinear ratio of VO₂max divided by running economy explains almost 96% of the variance in middle-distance running performance. A 2.5% improvement in running economy translates into a mathematically proportional ~2.5% reduction in the energy cost of running (when considered in isolation). Larger improvements in running economy of 5% within 1 year were reported for American miler Steve Scott along with new record setting performances. Similarly, former 1500-m runner turned marathon record holder, Paula Radcliffe, improved her running economy by 11% over 4 years en route to many new personal bests. It is also worth noting that male runners who possess exceptional running economy alongside VO₂max values on par with elite women (approximately 65 mL·kg⁻¹·min⁻¹) have achieved mile times well under 4 minutes.

### Integrated Physiology and Performance Prospects

The impact of the independent factors discussed above on the energy cost of running can be integrated to produce the performance forecasts in Table 2. It can be demonstrated that the combination of small but realistic reductions in the metabolic cost of running could substantially improve mile times in Table 1 to near 4-minute glory. In Table 2, calculations are anchored to the assumption that the capacity for sustaining high rates of oxidative ATP turnover remains unchanged (i.e., VO₂ = 3.53 L·min⁻¹, Table 1) for there is no good reason to doubt this assumption. The lower total energy cost of running (~3.2% [0.2%]), divided by the original energy provision rate, results in mathematically faster performances and affords extrapolations among other parameters. An approximate 8-second average improvement from 4:15.51 to 4:07.30 is observed for the group (Table 2), corresponding to a new average running velocity of 6.51 m·s⁻¹, which is 118% of the newly estimated vVO₂max (5.54 m·s⁻¹), 83% of sustainable oxidative metabolism and 1513 J·kg⁻¹ of oxygen deficit. The current world record holder lowers her mark to 4:03.59. Importantly, the estimates in Table 2 integrate the added cost of overcoming air resistance (+0.4 m·s⁻¹) with conservative improvements from drafting (50% efficiency for 2 laps only), mass loss (1 kg), and improved running economy (2.5%). Larger individual or combined improvements calculate to even faster times. However, while the field validation equations used for estimating the energy cost of racing and vVO₂max were derived from outdoor 1500-m races in competitive male runners for whom performance times encompass those of elite women milers (5.8–6.9 m·s⁻¹), they do not necessarily reflect the competitive circumstances in which the record performances in Table 1 were achieved, circumstances which inevitably include energy expended running wide on a turn, surging, jostling, or jockeying for position with or without the direct benefits of drafting from a pacemaker. The results in

### Table 2 Forecasted Improvements in the All-Time Top 10 Women’s Mile Performances Through Integrated Reductions in the Metabolic Costs of Running

<table>
<thead>
<tr>
<th>Name</th>
<th>Weight, kg</th>
<th>Mile time, s</th>
<th>Race velocity, m·s⁻¹</th>
<th>vVO₂max, m·s⁻¹</th>
<th>Racing economy, a J·kg⁻¹·m⁻¹</th>
<th>Oxygen uptake, L·min⁻¹</th>
<th>Oxygen deficit, J·kg⁻¹</th>
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</thead>
<tbody>
<tr>
<td>S. Hassan</td>
<td>48.0</td>
<td>243.59</td>
<td>6.61</td>
<td>5.77</td>
<td>4.65</td>
<td>3.38</td>
<td>1495.91</td>
</tr>
<tr>
<td>S. Masterkova</td>
<td>58.0</td>
<td>244.46</td>
<td>6.58</td>
<td>5.71</td>
<td>4.65</td>
<td>4.07</td>
<td>1495.70</td>
</tr>
<tr>
<td>G. Dibaba</td>
<td>51.2</td>
<td>246.02</td>
<td>6.54</td>
<td>5.61</td>
<td>4.68</td>
<td>3.60</td>
<td>1506.27</td>
</tr>
<tr>
<td>P. Ivan</td>
<td>56.1</td>
<td>247.80</td>
<td>6.49</td>
<td>5.51</td>
<td>4.70</td>
<td>3.93</td>
<td>1512.77</td>
</tr>
<tr>
<td>G. Tsegay</td>
<td>48.9</td>
<td>247.90</td>
<td>6.49</td>
<td>5.50</td>
<td>4.71</td>
<td>3.43</td>
<td>1516.55</td>
</tr>
<tr>
<td>H. Obiri</td>
<td>48.9</td>
<td>248.88</td>
<td>6.49</td>
<td>5.50</td>
<td>4.71</td>
<td>3.43</td>
<td>1516.38</td>
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<tr>
<td>M. Slaney</td>
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<td>5.45</td>
<td>4.72</td>
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</tr>
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<td>41.2</td>
<td>247.88</td>
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<td>5.50</td>
<td>4.73</td>
<td>2.90</td>
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<td>S. O’Sullivan</td>
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<td>249.52</td>
<td>6.45</td>
<td>5.40</td>
<td>4.73</td>
<td>3.64</td>
<td>1523.01</td>
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<td>J. Simpson</td>
<td>49.0</td>
<td>249.26</td>
<td>6.46</td>
<td>5.42</td>
<td>4.73</td>
<td>3.43</td>
<td>1523.10</td>
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<tr>
<td>Mean</td>
<td>50.3</td>
<td>247.30</td>
<td>6.51</td>
<td>5.54</td>
<td>4.70</td>
<td>3.53</td>
<td>1513.09</td>
</tr>
</tbody>
</table>

Abbreviation: vVO₂max, velocity at maximal oxygen uptake.

*Integrated energy cost of running (Equation 8 in the Appendix); all calculations performed out to 6 decimal places; numbers in table truncated to nearest 10th or 100th place using common rounding rules; please see text for detailed assumptions and the Appendix for calculations.
Table 2 may therefore be overly optimistic for some competitive circumstances.

**Conclusions**

When will women run a sub-four-minute mile? This invited commentary argues that, among the many ways in which women might target improvements in the mile,24,27 small but realistic improvements in the energy cost of running could bring the women’s world record closer to the fabled mark sooner than later. As with men in the early 1950s, this might stir greater interest, excitement, participation, and depth in the women’s mile, the present absence of which likely contributes to more pessimistic mathematical modeling forecasts.5,6,9,11 The extrapolation of metabolic cost savings to forecast performance improvements is sound,34 but not without limitations,39 particularly for running events like the mile which require significant unsustainable energy sources.24,40 The concepts and conclusions presented herein are theoretical—but they are also reasonable. Although prospective studies of VO2max, vVO2max, MSS, and other variables in elite women milers are needed to substantiate the hypotheses put forth herein, it is plausible that the first woman capable of running a sub-four-minute mile is alive today. The future will speak for itself.

**References**


(Ahead of Print)
Appendix: Running Energetics Calculations

**Equation 1: running economy**\(^{14}\)

\[-0.16 \times \text{(race velocity, km·h}^{-1}) + 8.39 = \text{J·kg}^{-1}·\text{m}^{-1}\]

**Equation 2: running velocity at VO_2\text{max}\(^{21}\)**

\[[(\text{race velocity, km·h}^{-1} - 14.921)/0.4266] \times 0.2778 = \text{vVO}_2\text{max, m·s}^{-1}\]

**Equation 3: total energy expended**

Equation 1 \times \text{body mass (kg)} \times 1609 \text{ m} = \text{Joules}

**Equation 4: added cost of air resistance**\(^{26}\)

\[\text{[Du Bois SA} \times 0.266 \times 0.00354 \times (6.7 \text{ m·s}^{-1})^3] - \text{[Du Bois SA} \times 0.266 \times 0.00354 \times \text{(race velocity, m·s}^{-1})^3] \times 4 \text{ min} \times 20920 = \text{Joules}\]

**Equation 5: added cost of air resistance with drafting**\(^{26}\)

\[(\text{Equation 4} \times 0.5) + (\text{Equation 4} \times 0.5 \times 0.5) = \text{Joules}\]

**Equation 6: total independent energy expended at reduced body mass**

Equation 1 \times \text{(body mass, kg} - 1) \times 1609 \text{ m} = \text{Joules}

**Equation 7: total independent energy expended with improved economy**

Equation 1 \times \text{body mass (kg)} \times 1609 \text{ m} \times 0.975 = \text{Joules}

**Equation 8: integrated energy cost of running**

\[\text{[Equation 1} \times \text{(body mass, kg} - 1) \times 1609 \text{ m} \times 0.975 + \text{Equation 5, J] / [(body mass, kg} - 1) \times 1609 \text{ m] = J·kg}^{-1}·\text{m}^{-1}\]

**Equation 9: improved time**

\[\text{[Equation 8} \times \text{(body mass, kg} - 1) \times 1609 \text{ m, J] / (Equation 3 original metabolic cost, J·s}^{-1}) = \text{s}\]

**Equation 10: time savings**

Equation 9 – \text{original race time, s} - \text{ s}