Running economy of elite male and elite female runners

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ABSTRACT
DANIELS, J. and N. DANIELS. Running economy of elite male and elite female runners. Med. Sci. Sports Exerc. Vol. 24, No. 4, pp. 483-489, 1992. Twenty female and 45 male middle and long-distance runners, in training for the U.S. Olympic Trials, served as subjects. Ninety percent of both men and women subjects reached the Trials; eight women and 12 men qualified for the Olympic Games and five won medals. Each subject completed a VO_{2max} and a series of submax treadmill runs, for the purpose of comparing heart rate (HR), VO_{2}, and blood lactate (HLA) among men and women and among runners of various event specialties. Results showed the men to be taller, heavier, to have a lower six-site skinfold sum and a higher VO_{2max}, than the women (P < 0.05); there was no difference in age. When compared in running economy, men used less oxygen (ml·min^{-1}·kg^{-1}) at common absolute velocities, but VO_{2} (ml·km^{-1}·kg^{-1}) was not different between men and women at equal relative intensities (%VO_{2max}). When men and women of equal VO_{2max} were compared, the men were significantly more economical, using any method of comparison. Also, when comparisons of men and women of equal economy were made, it was found that the men had an even greater advantage over the "matched" women subjects than the mean VO_{2max} comparison using all subjects. In looking at the SD (800-/1500-m runners), MD (3-K/5-K/10-K runners) and LD (marathon runners), it was found that the SD runners used the least oxygen (ml·min^{-1}·kg^{-1}) at speeds of marathon race pace and faster, but not at slower speeds. Men and women responded similarly in this regard. Running economy data for speeds slower than typical race paces, tended to show the LD runners to be most economical, suggesting that the speeds over which runners are tested plays an important part in determining which subjects are the most economical. It was concluded that at absolute running velocities, men are more economical than women, but when expressed in ml·km^{-1}·kg^{-1} there are no gender differences at similar relative intensities of running. Also, when men and women of equal VO_{2max} or equal economy are matched, the men show a better aerobic profile. It is recommended that economy data be collected up to speeds equal to 90% VO_{2max}.

RUNNING ECONOMY, VO_{2SUBMAX}, ECONOMY OF EXERCISE, ELITE RUNNERS, ELITE ATHLETES, OXYGEN CONSUMPTION

Although the aerobic demands of submaximal running have been investigated for many years, VO_{2max} has generally been the factor that has received most attention relative to identifying talented endurance athletes. Among a heterogeneous group of runners, VO_{2max} does, indeed, correlate highly with distance-running perform-

ance. However, when a homogeneous group of runners is studied, VO_{2max} becomes poorly correlated with, and running economy, highly correlated with performance. Running economy is defined as the relationship between oxygen consumption (VO_{2}) and velocity (v) of running, or as the aerobic demands of running.

The number of factors that affect running economy are many; indeed, age (11), training (5), stride rate and frequency (17), shoe weight (15), wind (13,20) and air resistance, including the lower density found at altitude (8,13), have all been shown to affect the VO_{2} related to submaximal running intensities. Furthermore, clothing, footing, terrain, and possibly fatigue are additional factors that can change the "cost" of running.

The differences in running economy that may exist between males and females has also been investigated, but with mixed findings. Some investigators have reported no difference in running economy, based on gender (10,14,16,18); others have found males to be more economical (1,2). Often, comparisons have been made with untrained or unequally trained subjects, or between different studies involving only male or only female runners. In addition, speeds utilized in most studies have been slower than typical race pace for the individuals involved. The present study was designed to evaluate running economy over a range of submax velocities, among elite female and elite male middle- and long-distance runners.

METHODS AND PROCEDURES

Subjects. Male and female runners, sponsored by NIKE, Inc. Shoe Company, volunteered to be subjects. Twelve of the 20 female subjects and 36 of the 45 male subjects were members of Athletics West (AW), NIKE's elite-athlete track club, which was housed in Eugene, OR. The remaining 17 subjects were either Americans (N = 5) training in Eugene or NIKE-sponsored foreign runners who were visiting Eugene prior to the 1984 Olympic Games. Eighteen of the 20 women and 41 of

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the 45 men qualified for the Olympic Trials. Eight women and twelve men reached the Olympic Games; two women and three men won medals.

AW athletes were all tested on more than one occasion, between 1983 and 1986; non-AW runners were tested one or more times during the same period. When more than one set of data were available for any athlete, the mean of all tests was used to represent that subject.

Economy and VO_{2max} tests. Each test session included a series of submax, level-grade treadmill runs, followed by a constant-speed, increasing-grade treadmill run, to determine VO_{2max}. Submax test velocities used were 248 m·min^{-1} (starting speed for most female subjects), 268 m·min^{-1} (initial speed for all men and some women), 290, 310, 330, and 350 m·min^{-1}. Some men also ran 370, even 390 m·min^{-1}.

For the submax tests, the treadmill was set at the desired speed, then, once the subject was running, 10 revolutions of the treadmill belt were timed and any necessary adjustments made during the first 30 s of each test. If the pace was not exactly as planned (it was always within 2 m·min^{-1}), the actual velocity was recorded for the test being run. Each submax test lasted 6 min, with expired-air samples collected in meteorological balloons during the final 2 min of each run. Low-resistance breathing valve and collection valve were used in all tests. Heart rates, palpated the first 10 s after each run, and post-run lactates taken 30 s after the completion of each run were also recorded for each subject. A blood-lactate accumulation of 4.0 mmol·L^{-1} was used to terminate the submax series of runs. There was a 5-min recovery period between submax tests. All female subjects reached 310 m·min^{-1} (many reached 330); all males ran at least 330 m·min^{-1}, and most did 350 m·min^{-1} before achieving a blood lactate concentration of 4.0 mmol·L^{-1}.

Five to 10 min following the final submax run, a VO_{2max} test was performed, using each subject’s final submax treadmill velocity (but not faster than 350 m·min^{-1}) as the test speed for the max test. The first 2 min of each max test were at 0% grade; 1% grade was added to the treadmill each subsequent minute starting with minute 3. The test was terminated when the subject decided he/she could not complete another minute. Consecutive, 30-s bags were collected, starting at the 3.5-min point in each test, and continued until the test ended, which was usually 6–7 min, total test time. The highest VO_{2} recorded was accepted as VO_{2max}.

Gas volumes were measured with a Collins 350-l gasometer; expired fractions of CO_{2} and O_{2} were determined by a Lloyd-Gallenkamp volumetric gas analyzer. Blood lactates were measured with a YSI Blood Lactate Analyzer, using a 25-μl sample taken from a separate finger stick following each test.

RESULTS

General characteristics of the subjects are presented in Table 1. There was no difference between the males and females in age or in maximum heart rate; the men were taller, heavier, had a lower six-site skinfold sum and a higher VO_{2max}, than did the women.

Table 2 shows the mean data for the females, broken down into three categories—800-/1500-m specialists, 3000-m/5000-m/10-km runners and marathon runners. The marathoners were older, but not significantly so (P > 0.05); the mean age of this group was greater mainly due to one of the subjects being in her late 30s at the time of testing. The 800/1500 runners had a significantly lower VO_{2max}, both when expressed in absolute terms (l·min^{-1}) and in relative terms (ml·min^{-1}·kg^{-1}), as shown in Table 2. Table 3 presents the same data for men as shown in Table 2 for women. As with the females, no differences existed among the male event groups in age, height or skinfold thickness (P > 0.05). However, the 800-/1500-m specialists were heavier than either of the other groups, and the 3-km/5-km/10-km runners had a higher VO_{2max} in ml·min^{-1}, kg^{-1} than did the 800-/1500-m runners. It should be pointed out that the 800-/1500-m men had the highest VO_{2max}, expressed in l·min^{-1}, but because of their greater body weight, did not have a VO_{2max} advantage, expressed in relative terms.

Running economy. By plotting VO_{2} data against running velocity, “economy curves” were generated for each subject. These resulting individual regression equations were then used to generate VO_{2} values for the exact common speeds strived for in the submax tests—248, 268, 290, 310, 330, and 350 m·min^{-1}. The economy curves, VO_{2max} and vVO_{2max} (velocity related to VO_{2max}), for both men and women, are depicted in Figure 1. At the three common test velocities (268, 290, and 310 m·min^{-1}), the male runners were more economical (consumed less oxygen) than their female

<table>
<thead>
<tr>
<th>Age (yr)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>SP (mm)</th>
<th>VO_{2max} (ml·min^{-1}·kg^{-1})</th>
<th>HR_{max} (b·min^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female</td>
<td>20</td>
<td>166</td>
<td>52.2</td>
<td>47.3</td>
<td>68.2</td>
</tr>
<tr>
<td>Male</td>
<td>45</td>
<td>180</td>
<td>65.4</td>
<td>35.4</td>
<td>75.4</td>
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</tbody>
</table>

* Six-site sum.
* Different from females, P < 0.05.

<table>
<thead>
<tr>
<th>Group</th>
<th>Age (yr)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>SP (mm)</th>
<th>VO_{2max} (ml·min^{-1}·kg^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>800-/1500-m</td>
<td>8</td>
<td>25.5</td>
<td>166</td>
<td>51.8</td>
<td>48.1</td>
</tr>
<tr>
<td>3K/5K/10K</td>
<td>5</td>
<td>26.2</td>
<td>165</td>
<td>51.3</td>
<td>45.5</td>
</tr>
<tr>
<td>Marathon</td>
<td>7</td>
<td>28.4</td>
<td>167</td>
<td>53.2</td>
<td>47.6</td>
</tr>
</tbody>
</table>

* Six-site sum.
* P < 0.05.
counterparts \((P < 0.05)\). The combination of a higher \(V_{\text{O}2_{\text{max}}}\) (Table 1 and Fig. 1) and better economy (Table 1) also resulted in a significantly higher \(v\text{VO}_{2_{\text{max}}}\) (381 vs 332 \text{ m} \cdot \text{min}^{-1}) for the men \((P < 0.05)\). The \(v\text{VO}_{2_{\text{max}}}\) difference is 14%, suggesting that the men have a 14% advantage in aerobic capabilities (\(\text{VO}_{2_{\text{max}}}\) and economy, combined).

If the men and women are compared at relative intensities of effort (common percentages of \(\text{VO}_{2_{\text{max}}}\), including \(v\text{VO}_{2_{\text{max}}}\)), rather than at absolute velocities of running, then the differences in economy are only 1–2%, which is not significant \((P > 0.05)\). This, relative-intensity comparison, expressed in \text{ml} \cdot \text{kg}^{-1} \cdot \text{km}^{-1}, is presented in Figure 2 and only favored the men at 70% \(\text{VO}_{2_{\text{max}}}\) and slower, which is below race intensity, even for marathon runners.

Additional evidence that the women were equal to the men in running economy, when expressed in terms of relative intensity of effort, was found in the results of the blood lactate data. A lactate concentration of 4.0 mmol \cdot l^{-1} corresponded to a \(\text{VO}_{2}\) representing 87.1% of \(\text{VO}_{2_{\text{max}}}\) for the women and 85.5% of \(\text{VO}_{2_{\text{max}}}\) for the men \((P > 0.05)\). Also, at a 4.0 mmol \cdot l^{-1} blood lactate accumulation, the women were at 90.8% of \(\text{HR}_{\text{max}}\), the men at 89.3% of their \(\text{HR}_{\text{max}}\), again, no significant difference existed \((P > 0.05)\). At any common, absolute running velocity, the women were always at a higher HR and higher blood lactate concentration than were the men, just as they were at a higher \(\text{VO}_{2}\), as shown in Figure 1.

**DISCUSSION**

The characteristics of the present subjects are similar to those reported for elite runners in other studies (7,12,19). The single highest \(\text{VO}_{2_{\text{max}}}\), for women (78.6 ml \cdot min^{-1} \cdot kg^{-1}) has been reported earlier (12), and was that of an Olympic Gold Medalist in the marathon. For the men, the highest \(\text{VO}_{2_{\text{max}}}\) was 81.0, reached by a non-Olympian. The highest \(\text{VO}_{2_{\text{max}}}\) of an Olympic, from the present group of male subjects, was 79.3; of the Olympic Medalists, the highest \(\text{VO}_{2_{\text{max}}}\) was 72.1 ml \cdot min^{-1} \cdot kg^{-1}. This medalist, and another of the male subjects, who was a Gold Medalist, were both 800-m specialists, an event which is as highly anaerobic in nature as it is aerobic, and a high \(\text{VO}_{2_{\text{max}}}\) is obviously not a necessity. Both the male and female 800-/1500-m specialists in the current study were lower in \(\text{VO}_{2_{\text{max}}}\) (ml \cdot min^{-1} \cdot kg^{-1}) than were the longer-distance specialists (Tables 2 and 3), but the 800-/1500-m men were also the largest and had a 5.01 \cdot min^{-1} absolute \(\text{VO}_{2_{\text{max}}}\).

The six-site skinfold sums are particularly low; the low and high values for men were 24.9 and 48.6 mm. The extremes for women were 36.4 and 59.7 mm. Previously reported sums for the same six sites for females averaged 54.9 mm (12). For elite males, the 35.4 mm sum is comparable to the seven-site values reported by Pollock (19) in 1977. Rather than attempt to convert the skinfold data to a representative percentage of body fat, it is these investigators’ opinion that the raw skinfold data are more useful among elite runners. In fact, a simple two-site sum (umbilical plus

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**TABLE 3. Characteristics of elite male runners.**

<table>
<thead>
<tr>
<th>Group</th>
<th>Age (yr)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>SP (mm)</th>
<th>(\text{VO}<em>{2</em>{\text{max}}}) (ml \cdot min^{-1} \cdot kg^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>800/1500-m</td>
<td>13</td>
<td>182</td>
<td>69.0\textsuperscript{a}</td>
<td>35.6</td>
<td>72.5</td>
</tr>
<tr>
<td>3K/5K/10K</td>
<td>23</td>
<td>176</td>
<td>63.4</td>
<td>35.3</td>
<td>77.4\textsuperscript{b}</td>
</tr>
<tr>
<td>Marathon</td>
<td>9</td>
<td>181</td>
<td>65.3</td>
<td>35.4</td>
<td>74.4</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Six-site sum.

\textsuperscript{b} \(P < 0.05\) relative to other groups.

\textsuperscript{c} \(P < 0.05\) relative to shorter distances.

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**Figure 1:** Aerobic profiles of elite female (\(N = 20\)) and elite male (\(N = 45\)) runners. Significant differences favor the males in \(\text{VO}_{2_{\text{max}}}\), \(v\text{VO}_{2_{\text{max}}}\), and running economy at all common absolute running velocities \((P < 0.05)\).
anterior thigh, which are both easy to obtain on both
females and males) has proved to be very useful with
delites runners and correlates well with the six-site
sums (R = 0.80 for women, 0.91 for men). For the two-site
sum referred to, elite male runners typically fall between
10 and 15 mm (equal to 30.6 to 40.5 six-site sum) and
the elite females, between 15 and 20 mm (42.7 to 52.3
six-site sum). The two-site means for the men and
women elite runners tested were 12.4 and 17.1 mm,
respectively.

The mid-to upper-20s average age of the subjects
is not surprising since membership in Athletics West
is restricted to athletes who do not have any remaining
collegiate eligibility. Also, the fact that there has become
greater financial support for runners, beyond their col-
gegiate days, leads to more athletes remaining active in
sport. The age of the current male subjects was not
greater than reported by Pollock in 1977 (19), but was
significantly older than in Daniels’ study of elite males
in 1968 (7). Also, the age of the current females was
greater than reported by Daniels et al. (12) in 1984, for
an equally impressive group of elite female distance
runners.

The running economy data, shown in Figure 1, agree
with some previous investigators (1, 2) that males are
more economical than females when compared at com-
mmon running velocities. Certainly, economy is an im-
portant factor in distance-running performance, and
even though the males have a much greater advantage
in VO2max (Table 1), than in economy (Fig. 1, which
shows a 6–7% economy advantage for the males),
economy can and does often determine the difference in
performance between individuals with equal or near
equal VO2max, as shown earlier by Conley and Krahen-
buhl (4). An example of two of the current subjects
dramatizes this quite well. One of the current male
subjects holds the American record in a long-distance
race; one of the females, the American record for
women in the same event. Their respective VO2max
values are 78.7 and 78.6 ml·min⁻¹·kg⁻¹. Based on the
male’s economy curve, and if he were to race his event
at 83.7% of his VO2max, as determined by Daniels and
Gilbert (9), his time would be within a few seconds of
his record. The comparable female record holder, based
on her economy and an intensity of 83.1% VO2max (9),
would run a marathon within a few seconds of her
record, and more than 12 minutes slower than would
the man, who has no VO2max advantage at all. Differ-
ences in economy can clearly explain differences in
performance when VO2max data are equal, as can they
explain equal performances among individuals of vastly
different VO2max. Two of the current female subjects
(subject A and subject B) have 10-km bests within 20 s
of each other; both are among the best in the world.
Their respective VO2max are 66.4 and 71.2, both well
below the value displayed by the marathoner referred
to above, whose 10-km time is also quite comparable
to subjects A and B. Actually, the fastest 10-km time is
held by subject A, who is also an Olympic Silver Med-
alist in the marathon. In examining the economy data
of these two athletes, and if both were to race a 10-km
in 32.00, A would be at 95.4% of her VO2max. B would
be at 96.5% of her VO2max. Clearly, at an equal intensity
of effort, A should win, as she has on many occasions.

The reference to relative intensity is an important
one, because it is the authors’ belief that well-trained
runners all perform at near-equal percentages of their
respective VO2max for various durations of time, as
described by Daniels and Gilbert earlier (9). In support
of this contention, is the fact that eight of the subjects
in the current study, all of whom raced marathons
within a few weeks of being tested, performed at an
average of 84.6% of VO2max, with six of the eight
between 84.0 and 84.9% of VO2max (the other two were
at a calculated 82.8 and 88.2% VO2max).

Because of the importance of relative intensity, the
current males and females were compared in economy
at equal percentages of their respective VO2max. Units
of measure used for this comparison was ml·kg⁻¹·
km⁻¹, since running velocities were not the same. Figure
2 presents these findings and shows that none of the
intensities typically used in races up through the mar-
thon, produced significant differences between the
males and females in running economy (P > 0.05).
Figure 2 also suggests that the aerobic demand, and
energy demand, of running is not necessarily independ-
tent of speed as has been earlier suggested (3). However,
from among the current pool of 65 subjects, there were
16 who showed equal aerobic demands over all speeds
tested and six who had lower VO2 at higher speeds
than at slower paces. Those who fit into the latter
category, and most of the subjects in both of these two
categories were 800-/1500-m specialists, who spend
a great deal of time training at higher velocities relative
to what is spent at slow running speeds. So, it is certainly

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**Figure 2**—Aerobic demands of running (per kilometer) for elite female
and elite male runners. No differences exist (P > 0.05) within the
range of most race intensities (80–110% VO2max).
measures from submax tests is that the test speeds are not fast enough to reflect race intensities. VO₂ at 268 m·min⁻¹ (6:00 per mile pace) is a typical test intensity, often because a heterogeneous group of subjects can all attain this speed within their aerobic capacities, often because a treadmill is not capable of faster speeds. When possible, submax data should be collected to an intensity which represents 95% of each individual’s VO₂max. If final test speeds prove to be too close to VO₂max, producing a flattening of the economy curve, then the final speed should be discarded; however, higher speeds should be attempted. A 95% VO₂max effort allows the athlete to reach 10-km race pace and usually

possible to collect data either supporting or refuting the claim that the “cost” of running is independent of speed, depending upon the type of subjects tested.

In an attempt to clarify the relationship between VO₂max and running economy, and why the average male is faster than the average female runner, eight women who had the highest VO₂max were closely matched with eight male runners of equal VO₂max. The running economies for these VO₂max-matched subjects are presented in Figure 3. It appears that the women with the highest VO₂max have economies that are not as good as the overall average for women, as presented in Figure 1. It also appears that the “matched” males are better than the average of all males in economy, and worse than average in VO₂max by design. The resulting vVO₂max data, shown in Figure 3, give the males a 7–8% performance advantage were both to run at VO₂max.

Figure 4 takes the male/female comparison a step farther. In this case, the eight most economical female runners were matched with eight males of equal running economy, at comparable absolute running velocities. The result gives the males a 14% VO₂max advantage and a 14% vVO₂max advantage. One thing seems quite clear—elite male runners have a decided aerobic advantage over elite female runners; they have a better aerobic profile.

Velocity at VO₂max (vVO₂max) appears to be a more desirable predictor of running success than VO₂max or economy, alone, since vVO₂max gives some insight as to how fast an individual can run when operating at VO₂max or at any fraction of that VO₂max. As shown in Figure 1, VO₂max and economy, are each only part of the performance difference between males and females. Also, as shown in Figures 3 and 4, having equal VO₂max or equal economy does not guarantee equal performance, even in a purely aerobic sense.

One danger of comparing runners based on economy
to exceed a 4.0 mmol·l⁻¹ blood lactate accumulation, as referred to above.

Figures 5 and 6 demonstrate how having economy data to high intensities and projections to or even beyond VO₂max can give additional insight into differences that may or may not exist at race intensities. To generate Figures 5 and 6, the eight best 800-m runners (which included some 1500-m runners also) were compared with the eight best marathon runners (including some who also specialized in 10-km races). Among the women, there was no difference in economy at marathon race pace, although it appears that tests slower than 268 m·min⁻¹ may have suggested an advantage for the longer-distance specialists, as has been suggested by others (6,19). In the case of the men, the marathon runners were more economical at 6:00 pace (268 m·min⁻¹), and presumably at all slower speeds, but by marathon race pace the two groups were equal. Projection of the economy curves to and beyond VO₂max (up to 1500-m race pace) shows that the shorter-distance specialists have a decided advantage in running economy (P < 0.05). It is very possible that the range of velocities over which runners are tested can determine whether it is concluded that one runner, or type of runner, has an economy advantage over another. In the case of Figures 5 and 6, when the slopes of the regression curves are compared (0.209 vs 0.243, for women and 0.205 vs 0.254 for men), a significant difference occurs between the shorter and longer distance runners (P < 0.05). However, at common test speeds, just about any conclusion can be reached relative to running economy comparisons.

CONCLUSION

Relative to elite male and elite female runners the following is concluded. 1) Males are more economical than are females at common velocities of running. 2) No difference exists in running economy between males and females at typical, relative (% VO₂max) race intensities. 3) Among males and females of equal VO₂max, males are more economical, both at common velocities and at common relative intensities of running. 4) Among males and females of equal running economy, males have a greater VO₂max and a greater vVO₂max. 5) Marathon runners have a greater VO₂max than 800-/1500-m specialists. 6) Due to a flatter regression curve (relating VO₂ and running velocity), 800-/1500-m specialists are more economical at 800-/1500-m race pace, but not at marathon race pace. 7) Males and females both run at the same intensity (approximately 86% VO₂max) when at a blood lactate accumulation of 4.0 mmol·l⁻¹. 8) When runners are tested for comparative purposes, VO₂submax (economy) data, which should be collected at speeds ranging up to 95% VO₂max, as well as VO₂max and vVO₂max data, present the clearest possible "aerobic profile" for each individual.

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