Daily variability in running economy among well-trained male
Research Quarterly for Exercise and Sport: Mar 1994; 65, 1; Health Module
pg. 72

Daily Variability in Running Economy
Among Well-Trained Male and Female Distance Runners

Don W. Morgan, Mitchell W. Craib, Gary S. Krahenbuhl, Keri Woodall, Shawn Jordan, Kristen Filariski, Cathy Burleson, and Tracy Williams

Key words: running economy, variability, aerobic, gender

Running economy, defined as the aerobic demand (VO₂) at a given submaximal running speed, is an important determinant of distance-running performance among well-trained individuals exhibiting comparable values of maximal aerobic power (VO₂ max) (Conley & Krahenbuhl, 1988; Daniels, 1988; Morgan, Baldini, Martin, & Kohrt, 1989). While numerous studies have reported interindividual economy differences ranging from 15 to 30% among competitive distance runners (Conley & Krahenbuhl, 1988; Daniels, 1974; Daniels, Krahenbuhl, Foster, Gilbert, & Daniels, 1977), relatively few studies have documented the magnitude of intraindividual VO₂ variation in this population.

In a recent investigation of moderately trained male distance runners (MVO₂ max = 61.7 mL·kg⁻¹·min⁻¹; M 10-km race time = 41.7 min) who were tested 5 days a week over a 4-week period, Williams, Krahenbuhl, and Morgan (1991) noted that the average coefficient of variation (CV) in running economy ranged from 2.60 to 3.08%. Likewise, Morgan, Martin, Krahenbuhl, and Baldini (1991) reported a CV of 1.32% in recreationally trained male distance runners (M VO₂ max = 58.8 mL·kg⁻¹·min⁻¹) who were tested on 2 days. In both studies (Morgan et al., 1991; Williams et al., 1991), subjects were tested at the same time of day and in the same pair of shoes, engaged in 60 min of treadmill accommodation prior to testing, refrained from competitive racing, and maintained their normal training routine (consisting of endurance runs at a fixed pace) or reduced the intensity and duration of normal workouts.

While testing constraints in the aforementioned studies (Morgan et al., 1991; Williams et al., 1991) served to minimize VO₂ variability among moderately trained male distance runners, it is not known whether highly trained athletes of both genders following demanding training and racing regimens would exhibit less stability in submaximal VO₂. Quantification of within-subject economy differences in highly trained male and female distance runners would yield important baseline data necessary to evaluate the efficacy of manipulations designed to perturb running economy in these cohorts. Documenting intraindividual variation in the aerobic demand of running among athletes of both genders would also aid in determining the number of test sessions required to obtain accurate and stable exercise VO₂ measures. Given these rationales, the purpose of this study was to assess daily intraindividual variability in running economy of well-trained male and female distance runners engaged in a rigorous program of training and competitive racing.

Method

Subjects

Four male (M age = 32 ± 7 years; M mass = 68.8 ± 4.4 kg; M height = 177.7 ± 2.3 cm) and four female (M age = 25 ± 4 years; M mass = 54.0 ± 2.5 kg; M height = 165.1 ± 0.9 cm) distance runners volunteered to participate in this study. The average duration of participation in run training for the male group was 11.7 ± 2.2 years, while the female group averaged 5.7 ± 1.2 years.
Questionnaire data revealed that all subjects had garnered high overall or age-group finishes in track or road races in the year prior to data collection. As an indication of the athletic ability of the cohort, mean 10-km performances for men and women were 33.8 ± 1.0 min and 37.7 ± 2.3 min, respectively (see Note 1). Daily logs completed during the study indicated that subjects engaged in various combinations of long-distance running, tempo runs, and interval workouts. Because the focus of the investigation was to document typical variation in VO₂ in this cohort, no attempt was made to alter subjects' training regimens or curb race participation. Weekly running mileage for the males and females, including races (3 km to 161.3 km) but excluding treadmill running, averaged 69.5 ± 23.1 km-week⁻¹ and 48.2 ± 15.2 km-week⁻¹, respectively. Prior to the study, subjects were asked to maintain their normal dietary regimen during the data collection period.

Experimental Procedure

**Determination of pretesting VO₂ max.** After obtaining written informed consent, VO₂ max was assessed using a constant-speed, grade-incremented protocol modified after Bransford and Howley (1977). Following a short period of treadmill accommodation, subjects began running at 0% grade at either 3.33 m·s⁻¹ (females) or 3.83 to 4.02 m·s⁻¹ (males). During the first minute of running, a photoelectric cell mounted above the treadmill belt and connected to an electronic timer counted the elapsed time required for 10 treadmill belt revolutions to establish and verify treadmill belt speed. At 2-min intervals, treadmill grade was raised 2.5% until subjects reached volitional exhaustion. During the latter portion of the test, expired gas was collected into meteorological balloons at 1-min intervals and analyzed for carbon dioxide (CO₂) and oxygen (O₂) content using electronic gas analyzers (Ametek) calibrated previously with primary standard gases. The O₂ and CO₂ content of the primary standard gases was determined using the micro-Scholander technique. Expired ventilation was measured by evacuating the meteorological balloons into a Rayfield dry gas meter calibrated previously against a 120-L Tissot. The standard criterion of a plateau or drop in VO₂ in response to an increased workload was used to determine VO₂ max (Taylor, Buskirk, & Henschel, 1955). Of the 16 tests performed (8 pre- and 8 posttests), 11 met the aforementioned criterion. In the remaining cases, the highest VO₂ measured was taken as VO₂ max.

**Treadmill accommodation.** Two to 3 days following the VO₂ max test, subjects performed the first of two level treadmill running sessions at the test speeds. A second identical session was conducted within 2 days of the initial run. During each session, subjects ran for 10 min at 3.57, 4.02, and 4.47 m·s⁻¹ (males) or 3.13, 3.57, and 4.02 m·s⁻¹ (females). Hence, subjects ran a total of 60 min over the 2-day period. Ten-minute rest periods separated each running bout, and a short warm-up preceded the first bout. The purpose of these sessions was to allow subjects to accommodate to treadmill running at the test speeds prior to the daily measurement of VO₂. Based on previous research (Cavanagh & Williams, 1982; Martin, 1985; Morgan & Craib, 1992; Schieb, 1986), 60 min of treadmill running practice is sufficient for trained runners to establish reliable and representative economy values and a consistent treadmill running pattern.

**Daily measurement of VO₂.** Approximately 3 to 4 days following the second treadmill accommodation session, subjects began a 5-week period of testing. Five days a week (Monday through Friday), subjects performed 6-min level treadmill runs at each test speed. Five-min rest periods separated each run, and a 3-min warm-up at the first test speed preceded the initial run. Using previously described procedures, the aerobic demand of running at each speed was determined by analyzing a 2-min expired gas sample collected during the last 2 min of running.

Although it was not possible to eliminate all extraneous variation in measuring submaximal VO₂, attempts were made to account for or minimize known contributions to this source of variability. To assess measurement error associated with gas analysis, the stability of the gas analyzers was quantified during a randomly chosen test session by recording changes in O₂ and CO₂ content occurring in serial, 1-min time segments during a 10-min sampling period in which the meteorological balloons were in line with the analyzers. Oxygen demand values calculated from these measurements were analyzed to derive a CV value for analyzer drift for each subject. These data were then used to compute the percent variation in the total CV accounted for by gas analyzer drift. Additionally, the influence of circadian variation and footwear on VO₂ variability (Morgan & Craib, 1999) was eliminated by having subjects perform economy sessions at the same time of day and in the same pair of shoes.

**Determination of posttesting VO₂ max.** Within a week following the last daily measurement of submaximal VO₂, subjects performed a second VO₂ max test identical in protocol to the VO₂ max test completed prior to testing. The rationale for having subjects perform VO₂ max tests at the beginning and end of the study was to evaluate whether daily variability in VO₂ might be related to changes in VO₂ max occurring across the 5-week testing period.

**Statistical Analysis**

Pre- and posttest values for VO₂ max were analyzed...
for both genders using a paired $t$ test. A $3 \times 4$ (Speed x Subject) repeated measures ANOVA was performed for males and females separately across running speeds to evaluate differences in VO$_2$ CV values. Because the sphericity assumption was not violated, no degrees of freedom adjustments were necessary. When an overall speed effect was observed, the Tukey HSD test was used to locate significant pairwise differences. Statistical significance was established at the .05 level.

Reliability analyses of submaximal VO$_2$ data, conducted following the approach described by Williams et al. (1991), were used to determine the percent variation in running economy accounted for by different combinations of consecutive and nonconsecutive testing days. To elaborate, testing sessions were grouped into the following aggregations: 2 nonconsecutive days (e.g., Monday, Wednesday), 2 consecutive days (e.g., Monday, Tuesday), 3 nonconsecutive days (Monday, Wednesday, Friday), 3 consecutive days (e.g., Monday, Tuesday, Wednesday), 4 consecutive days (e.g., Monday, Tuesday, Wednesday, Thursday), and 5 consecutive days (Monday, Tuesday, Wednesday, Thursday, Friday). For a given running speed, Cronbach’s alpha coefficients were determined for each aggregation of days across the 5-week testing period. Because correlation coefficients are not normally distributed, the individual coefficient values were converted to Fisher Z scores and averaged to derive a mean Fisher Z score for each aggregation of days. Mean Fisher Z values were then converted to correlation coefficients and entered into the Spearman-Brown formula (Ferguson, 1981):

$$r_{kk} = \frac{kr_{xx}}{1 + (k-1)r_{xx}},$$  \hspace{1cm} (1)

wherein $r_{xx}$ is the correlation coefficient for a particular aggregation of days and $k$ is equal to the groupings (i.e., 2, 3, 4, or 5) identified previously. The resultant reliability coefficient, or $r_{kk}$, represents the percent variation in mean VO$_2$ from all observations (at a given speed) accounted for by measures obtained from subsets of the data formed from various combinations of testing days, as described above.

**Results**

The average of pre- and posttest VO$_2$max values for the male and female runners was 69.3 ± 3.7 and 59.2 ± 0.9 mL·kg·min$^{-1}$, respectively. No significant difference in VO$_2$max across time was observed for either gender [males: $t(3) = -0.60$, $p < .59$; females: $t(3) = 0.71$, $p < .53$].

Individual and mean running economy and CV measures for males and females at each speed are shown in Table 1. The relative contribution of gas analyzer drift to total VO$_2$ variability was 3.92%. The mean percentages of VO$_2$max utilized at the three speeds were 56, 64, and 73% for males and 58, 66, and 77% for females. While repeated measures ANOVA indicated that mean CV values remained constant across speeds for males, $F(2, 6) = 3.40$, $p < .10$, an overall difference in mean CV values for the female runners was observed, $F(2, 6) = 5.94$, $p < .04$. Follow-up analysis using the Tukey HSD test revealed that variability in VO$_2$ was lower at the fastest speed compared to the slowest speed.

Reliability coefficients representing the percent variation in mean VO$_2$ values at each speed accounted for by various combinations of consecutive and noncon-

<table>
<thead>
<tr>
<th></th>
<th>Subjects</th>
<th>VO$_2$ (mL·kg·min$^{-1}$)</th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Speed 1</td>
<td>Speed 2</td>
</tr>
<tr>
<td>Male</td>
<td>1</td>
<td>39.5</td>
<td>44.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>39.2</td>
<td>43.4</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>36.0</td>
<td>40.8</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>41.1</td>
<td>46.9</td>
</tr>
<tr>
<td></td>
<td>$M$</td>
<td>38.9</td>
<td>43.9</td>
</tr>
<tr>
<td>Female</td>
<td>1</td>
<td>32.0</td>
<td>36.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>37.1</td>
<td>42.4</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>35.4</td>
<td>40.5</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>33.8</td>
<td>37.9</td>
</tr>
<tr>
<td></td>
<td>$M$</td>
<td>34.6</td>
<td>39.3</td>
</tr>
</tbody>
</table>

*Note.* Speeds for male subjects were 3.57, 4.02, and 4.47 m·s$^{-1}$. Speeds for female subjects were 3.13, 3.57, and 4.02 m·s$^{-1}$.  

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
secutive testing days are shown for male and female runners in Figures 1 and 2, respectively. These data indicate that, while slightly more variation in mean VO$_2$ values was accounted for as the number of observations increased, about 97 to 99% of the total variation in VO$_2$ was captured in 2 consecutive or nonconsecutive days of testing.

Discussion

The maximal aerobic power of the subject pool is consistent with findings obtained for elite or highly trained male (Bransford & Howley, 1977; Conley & Krahenbuhl, 1980; Davies & Thompson, 1979; Sjödin & Svendehag, 1985) and female (Daniels et al., 1977; Pate, Sparling, Wilson, Cureton, & Miller, 1987) subjects. The absence of change in VO$_2$max across time for either gender suggests that intraindividual variability in running economy was not influenced by changes in aerobic fitness.

Running economy data obtained in this study are similar to values reported previously for well-trained male and female distance runners displaying comparable VO$_2$max values (Conley & Krahenbuhl, 1980; Costill, Thomason, & Roberts, 1973; Daniels et al., 1977; Daniels, Scardina, & Foley, 1984). The mean percentages of VO$_2$max used at the three speeds provide evidence that the VO$_2$ data reflect steady-state conditions and should reflect true aerobic demands because they fall well below the mean relative workload (88% VO$_2$max) associated with a lactate threshold of 4 mmol·L$^{-1}$ in good and elite distance runners (Sjödin & Svendehag, 1985).

The small intraindividual variability in VO$_2$ displayed by the subjects is in agreement with that documented in nonfatigued, moderately trained distance runners who performed fixed pace endurance runs and refrained from competitive racing (Morgan et al., 1991; Williams et al., 1991). The marked stability in body mass across the 5-week testing period for all subjects ($SD = 0.29$–$0.73$ kg) implies that body mass fluctuations did not account substantially for observed variation in VO$_2$. The day-to-day stability in VO$_2$ reported in the current study also agrees with data revealing no short-term change in economy following 30 min of fatiguing/exhaustive running (Morgan, Martin, Baldini, & Krahenbuhl, 1990; Morgan et al., 1992) and suggests that serial measurements of running economy in well-trained athletes are relatively unaffected by demanding training and performance regimens. The small relative

![Graph showing variation in VO$_2$ over days](image)

**Figure 1.** Percent variation in mean VO$_2$ values accounted for by various aggregations of testing days in well-trained males running at 3.57, 4.02, and 4.47 m·s$^{-1}$. (VO$_2$ = aerobic demand; non = nonconsecutive; cons = consecutive.)

ROES: March 1994

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
The contribution of gas analyzer drift to VO₂ variability measured in this investigation (3.92%) is virtually identical to the value of 3.95% calculated from running economy data obtained on male runners who performed four exercise trials (Armstrong & Costill, 1985).

The finding that a lower mean CV value was observed for female runners at the fastest speed compared to the slowest speed suggests that variability in VO₂ in this group may reflect a more constant metabolic response as the relative exercise intensity approaches that typically employed during training and racing. It is also possible that exposure to the initial workloads aided these subjects in achieving a greater metabolic stability at the highest exercise intensity. While mean CV values also decreased at faster speeds for the male runners, no significant difference was observed.

Data portrayed in Figures 1 and 2 suggest that an extremely large proportion of variation in mean VO₂ measured in well-trained male and female distance runners is accounted for in 2 consecutive or nonconsecutive days of testing. Moreover, little additional gain is obtained as the number of test sessions increase, which indicates that prolonging the assessment period with additional repeated tests would yield little additional benefit. Our findings are also consistent with data reported for moderately trained male distance runners who abstained from competitive racing and whose training featured constant-speed endurance runs or reductions in the intensity and duration of daily workouts (Morgan et al., 1991; Williams et al., 1991).

In conclusion, results from this investigation indicate that the CV in running economy is small (~1 to 2%) among well-trained male and female distance runners following a demanding regimen of training and competitive racing. From a practical standpoint, this finding suggests that large changes in submaximal VO₂ may not be required to demonstrate the effectiveness of a particular intervention aimed at perturbing running economy in these cohorts. Moreover, if proper attention is paid to methodological concerns such as length of treadmill accommodation, time of testing, and footwear, an acceptably stable measure of the aerobic demand of running measured in highly trained subjects can be secured by averaging two consecutive or nonconsecutive VO₂ values.

Note

1. Mean 10-km performance was derived from 10-km times or, in two cases, from 5-km and 12-km times using the conversion table of Daniels and Gilbert (1979).
References


Authors' Note

Address correspondence to Don W. Morgan, PhD, 237D HHP Building, Department of Exercise and Sport Science, The University of North Carolina at Greensboro, Greensboro, NC 27412.