Running Economy: Comparison of Body Mass Adjustment Methods

Michael J. Davies, Matthew T. Mahar, and Lee N. Cunningham

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Gender differences have been reported with conflicting results for running economy, defined as submaximal oxygen uptake (VO₂submax) for a given speed (Morgan, Martin, & Krakhenbuhl, 1989). Daniels and Daniels (1992) compared VO₂submax of 20 female and 45 male elite middle- and long-distance runners. Male runners reportedly displayed more economy (lower VO₂submax) than their female counterparts at common speeds of 268, 290, and 310 m·min⁻¹. Within the same study, maximal oxygen uptake (VO₂max)-matched males still had a lower aerobic demand for running than VO₂max-matched females at the aforementioned speeds. Bransford and Howley (1977) reported that VO₂submax at 200 m·min⁻¹ for 10 trained males was significantly less than for 10 trained females. They postulated that the differences were attributed to biomechanical and training variables.

Conversely, Daniels, Krakhenbuhl, Foster, Gilbert, and Daniels (1977) observed no significant differences in VO₂submax with highly trained male and female distance runners at 202, 215, 241, and 268 m·min⁻¹. Similar findings were reported for adolescent cross-country runners (Cunningham, 1990a), collegiate cross-country runners (Maksud, Cannistra, & Dubinskis, 1976), 24.2 km performance-matched distance runners (Pate, Barnes, & Miller, 1985), and nonelite marathon runners (Wells, Hecht, & Krakhenbuhl, 1981).

An explanation for conflicting results in running economy may be in the statistical adjustment methods which may not adequately control for body size differences between genders. Ratio standards of running economy have yielded negative relationships between relative VO₂submax (ml·kg⁻¹·min⁻¹) and body mass (Bergh, Sjödin, Forsberg, & Swedenhag, 1991; Williams & Cavanagh, 1986), indicating that the independent effects of body mass may not be completely controlled within and between groups (Nevill, Ramsbottom, & Williams, 1992). Nevill (1994) and Bergh et al. (1991) suggested that an allometric scaling exponent be used to normalize oxygen uptake for body size differences.

Moreover, Winter (1992) suggested that to properly control for body size differences, analysis of covariance (ANCOVA) should be used instead of ratio standards. Unlike ratio standards, ANCOVA does not rely on a y-intercept of zero between the covariate and the criterion variable. Simply, ANCOVA compares groups by adjusting the criterion variable (i.e., absolute VO₂submax) for the linear relationship between the covariate (i.e., body mass) and the criterion variable with a regression-based approach (Pedhazur, 1982).

Due to the conflicting running economy results and differing statistical adjustment methods used among studies, the present study was designed to compare absolute VO₂submax at 215 m·min⁻¹ between male and female runners, while controlling body mass with three statistical adjustment methods (ratio standards, allometric scaling, and ANCOVA).

Method

Twelve male and 12 female distance runners between the ages of 18 and 34 years volunteered to participate in this study. Runners were recruited from local track clubs and collegiate track teams. Those selected for the study were averaging at least 24 km·wk⁻¹ of running training for at least 1 year.

Participants reported to the laboratory rested, without having exercised within 24 hours of the test. All provided written informed consent and completed medical history forms before the start of any testing. A calibrated physician’s scale was used to obtain height and weight.
information for each participant. Participants wore running shoes while their weight was recorded.

Metabolic and ventilatory data for submaximal and maximal testing were collected every 20 s using a calibrated Sensormedics metabolic cart (Sensormedics, Model 2900, Anaheim, CA). Heart rates (HR) were assessed with a Polar Vantage XL Heart Rate Monitor (Polar CIC, Inc., Port Washington, NY). Ratings of perceived exertion (RPE) were recorded at the end of each stage using the modified Borg Scale (0–10) (Borg & Linderholm, 1967).

All participants had expressed familiarity with treadmill running and were allowed to adjust to using the treadmill before any gas collection apparatus was used. After a brief rest, participants completed a modified Cunningham (1990b) protocol for VO₂submax and VO₂peak. VO₂submax was measured at 160, 215, and 267 m·min⁻¹ stages on a level treadmill (Marquette Electronics, Model QA1018, Milwaukee, WI). During the last minute of each 6-min stage, HR, RPE, and absolute VO₂submax were obtained and used for subsequent analyses. After the 267 m·min⁻¹ submaximal stage, speed was held constant, and the treadmill grade was increased by 2% every 2 min until volitional exhaustion.

Before any analysis of VO₂submax data was conducted, allometric scaling exponents were calculated for men and women separately and compared to each other and to the ratio standard exponent of 1 for differences, using 95% confidence intervals. An extensive statistical explanation of allometric scaling is provided in a review by Smith (1984). Calculation of scaling exponents is briefly outlined below:

1. log-transform equation 1; \( Y = a \times X^b \) (1) to \( \log Y = b \times \log X + \log a \) (2)
   where \( Y \) is absolute VO₂submax (ml·min⁻¹), and \( X \) is body mass (kg);
2. slope (b; equation 2) is calculated with regression analysis, where b in the regression output is equal to the scaling exponent (b) and the inverse of log a is equal to the constant (a) in equation 1; and
3. scaled VO₂submax is calculated by dividing absolute VO₂submax by body mass raised to scaling exponent.

Scaled VO₂submax and relative VO₂submax were compared for gender differences using independent \( t \) tests. ANCOVA was used, with absolute VO₂submax at 215 m·min⁻¹ as the criterion variable and body mass as the covariate. Multiple \( t \) tests were used to examine gender differences for physical and anthropometric characteristics, training histories, and selected submaximal and maximal test data. A Bonferroni adjustment was implemented to reduce Type I errors which may occur with multiple \( t \) test comparisons. All statistical analyses were performed with a software package (Statistical Pack-

age for Social Sciences, Version 6.0, Chicago, IL). The experimental alpha level of significance was set at .01.

Results

One female participant had to be eliminated, because she was an outlier in terms of weight, which fell almost 2.75 standard deviations above the mean for the female runners. The physical characteristics and training histories are summarized in Table 1 for the 12 male and 11 female participants. During the maximal portion of the treadmill test, all but one female participant achieved a maximal effort during the 267 m·min⁻¹ stage. Consequently, the highest recorded VO₂ value was used as VO₂peak for all participants. Selected maximal test variables are also presented in Table 1.

Because all but one female participant achieved a maximal effort during the 267 m·min⁻¹ stage and because the speed of 160 m·min⁻¹ was well below the training speeds of both groups, only data at 215 m·min⁻¹ were compared between groups. Validity of ratio standards was investigated before any analyses of relative VO₂submax at 215 m·min⁻¹. Tanner (1949) reported that ratio standards were valid if the correlation between the newly formed variable (i.e., relative VO₂submax) and the dependent variable (i.e., body mass) equaled zero. Correlations between relative VO₂submax and body mass were not significantly different from zero (\( r_{\text{males}} = 0.04; r_{\text{females}} = -0.16, p > 0.05 \), for both), thus validating the use of ratio standards.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Men (n = 12)</th>
<th>Women (n = 11)</th>
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<tbody>
<tr>
<td>Height (cm)</td>
<td>179.3 ± 8.0</td>
<td>165.5 ± 5.8*</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>70.2 ± 6.6</td>
<td>55.2 ± 3.4*</td>
</tr>
<tr>
<td>Experience (years)</td>
<td>7.2 ± 4.1</td>
<td>5.8 ± 3.8</td>
</tr>
<tr>
<td>Age (years)</td>
<td>25.9 ± 5.3</td>
<td>24.7 ± 2.5</td>
</tr>
<tr>
<td>Distance-run (km)</td>
<td>57.2 ± 20.9</td>
<td>42.5 ± 15.6</td>
</tr>
<tr>
<td>Pace-mi-1 (min:s)</td>
<td>6.41 ± 0.32</td>
<td>7.52 ± 0.23*</td>
</tr>
<tr>
<td>Peak oxygen uptake (L·min⁻¹)</td>
<td>4.53 ± 0.74</td>
<td>2.95 ± 0.22*</td>
</tr>
<tr>
<td>(ml·kg⁻¹·min⁻¹)</td>
<td>63.8 ± 6.9</td>
<td>53.6 ± 4.7*</td>
</tr>
<tr>
<td>HRmax (b·min⁻¹)</td>
<td>190 ± 8</td>
<td>192 ± 5</td>
</tr>
<tr>
<td>REUmax</td>
<td>1.23 ± 0.16</td>
<td>1.20 ± 0.16</td>
</tr>
<tr>
<td>RPEmax</td>
<td>9 ± 1</td>
<td>9 ± 1</td>
</tr>
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Note: HRmax = maximal heart rate; REUmax = maximal respiratory exchange ratio; RPEmax = maximal ratings of perceived exertion.
* p ≤ .01.
A technique of Vanderburgh, Mahar, and Chou (1995) was used to determine that allometric scaling exponents for men (1.07) and women (0.86) did not differ significantly between genders. Next, data for men and women were pooled, and that exponent (1.01) was not significantly different from the ratio standard exponent of 1, using 95% confidence intervals (see Table 2). As a result of nearly identical exponents of ratio standards and allometric scaling, a scaling exponent of 1 was used to represent both methods (ratio standards and allometric scaling). Relative VO₂submax at 215 m-min⁻¹ and selected submaximal data are reported in Table 3.

For ANCOVA, a homogeneity of regression test revealed that absolute VO₂submax-body mass slopes were not significantly different between genders (p > .05). Assumptions of homogeneity of variance (p > 0.05) and linearity between absolute VO₂submax and body mass (r_s = 0.73; r_females = 0.69, p < 0.05, for both) were confirmed. Adjusted absolute VO₂submax at 215 m-min⁻¹ was not significantly different between genders, with body mass as a covariate (see Table 4).

**Discussion**

In the present study, three statistical adjustment methods (ratio standard, allometric scaling, and ANCOVA) were compared and no differences in running economy at 215 m-min⁻¹ were observed between genders, regardless of adjustment methods. No gender differences in running economy have been reported throughout the literature (Cunningham, 1990a; Daniels et al., 1977; Maksud et al., 1976; Pate et al., 1985; Wells et al., 1981). Researchers have utilized various statistical methods (i.e., t tests and regression analyses) to examine only ratio standards of relative VO₂submax between genders. Prior studies included participants of varying training levels within genders and had sample sizes ranging from 8 per group to 12 per group, with 1 study testing only 4 women and 7 men (Wells et al., 1981).

Differences in percentage of VO₂peak are explained by the greater VO₂peak for men. In the present study, running at the same speed required the same physiological work in terms of relative oxygen uptake for both genders. Because men had a greater VO₂peak, they would require less percentage of their VO₂peak running at 215 m-min⁻¹ than women. In terms of heart rate, running at 215 m-min⁻¹ was also less taxing on the cardiovascular systems of the men than the women.

Ratio standards (i.e., ml·kg⁻¹·min⁻¹) assume that differences in body mass are controlled for by simply dividing absolute VO₂ by body mass. This is often erroneous, because a negative relationship might still exist between relative VO₂submax and body mass (Bergh et al., 1991). Significant negative relationships have been reported for elite male runners (r = -0.39; Williams & Cavanagh, 1986) and elite female runners (r = -0.52; Williams, Cavanagh, & Ziff, 1987). These findings suggested that lighter runners might have a higher absolute mass-specific aerobic demand than heavier runners. Because women were generally lighter than men, differences in body mass might account for men having better running economy (Bransford & Howley, 1977; Daniels et al., 1992). Consequently, studies reporting gender differences in running economy may not have adequately controlled for body mass, which possibly contributed to misleading results. In the present study, validity of ratio standards was confirmed before any analysis was conducted.

Validity of ratio standards has been challenged in exercise science. VO₂submax and VO₂max have

<table>
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<th>Variables</th>
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<tr>
<td>VO₂ (ml·kg⁻¹·min⁻¹)</td>
<td>42.4 ± 3.9</td>
<td>44.7 ± 2.4</td>
</tr>
<tr>
<td>Percentage of VO₂max</td>
<td>66.8 ± 5.0</td>
<td>83.9 ± 7.6*</td>
</tr>
<tr>
<td>HR (b·min⁻¹)</td>
<td>152 ± 12</td>
<td>177 ± 11*</td>
</tr>
<tr>
<td>HRmax (%)</td>
<td>79.7 ± 4.8</td>
<td>92.2 ± 4.2*</td>
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</tbody>
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*Note. VO₂ = oxygen uptake; VO₂max = maximal oxygen uptake; HR = heart rate; HRmax = maximal heart rate. *p ≤ .01.

<table>
<thead>
<tr>
<th>Absolute VO₂submax (L·min⁻¹)</th>
<th>Men (n = 12)</th>
<th>Women (n = 11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original means</td>
<td>2.98 (0.39)</td>
<td>2.47 (0.18)*</td>
</tr>
<tr>
<td>Adjusted means</td>
<td>2.67</td>
<td>2.78</td>
</tr>
</tbody>
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*Note. VO₂submax = submaximal oxygen uptake. *p ≤ .01.
been found to increase disproportionately to changes in body mass (Bergh et al., 1991; Nevill et al., 1992). Researchers have calculated a body mass exponent of 0.75, which scaled VO$_2_{\text{submax}}$ without the confounding effects of body mass (Bergh et al., 1991; Morgan et al., 1995; Rogers, Olson, & Wilmore, 1995). Recently, Rogers et al. (1995) reported that adult men and women did not differ in relative or scaled (ml·kg$^{-0.75}$·min$^{-1}$) VO$_2_{\text{submax}}$ at 3 and 5 mph. However, Nevill (1994) argued that a body mass exponent of 0.75 was spurious and influenced by the greater proportion of muscle mass (m$^{-1}$) in the proximal leg muscles, which shifted up the theoretical exponent of 0.67 to 0.75. In the present study, the allometric scaling exponent was not significantly different from the ratio standard exponent of 1.0. Therefore, results of no gender differences were identical for both methods.

According to Winter (1992), the use of ANCOVA provides more control on the adjustment variable than the use of ratio standards. ANCOVA is similar to allometric scaling, because it completely removes the influence of body mass on the criterion variable but with a regression-based approach. However with ANCOVA, assumptions of homogeneity of regression and variance as well as linearity between the criterion variable and body mass must be confirmed (Pedhazur, 1982). If these assumptions are not satisfied, robustness of this technique will be compromised. With these assumptions satisfied, ANCOVA confirmed the results of ratio standards and allometric scaling in the present study.

This study attempted to control for the effects of body mass on absolute VO$_2_{\text{submax}}$ at 215 m·min$^{-1}$ in male and female runners with various statistical adjustment methods. All three methods were shown to be valid, and each revealed no gender differences in running economy. This suggests that competitive male and female runners have a similar aerobic demand of running at 215 m·min$^{-1}$.

References


Authors’ Notes

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