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Walking and Running Economy: Inverse Association with Peak Oxygen Uptake

Brandon J. Sawyer¹, Jason R. Blessinger², Brian A. Irving³, Arthur Weltman², James T. Patrie⁴, and Glenn A. Gaesser⁵

¹Department of Kinesiology, Point Loma Nazarene University, San Diego, CA

²Department of Human Services, University of Virginia, Charlottesville, VA

³Endocrine Research Unit, Mayo Clinic College of Medicine, Rochester, MN

⁴Department of Public Health Sciences, University of Virginia, Charlottesville, VA

⁵Healthy Lifestyles Research Center, Arizona State University, Mesa, AZ

Abstract

Purpose—To test the hypothesis that $\dot{V}O_{2peak}$ is positively correlated with the regression coefficients of the curve-linear relationship between $\dot{V}O_2$ and speed during a protocol consisting of submaximal walking and running.

Methods—19 healthy males (age 26.4 ± 6.4 yr.; height 179.9 ± 7.2 cm; weight 77.7 ± 8.7 kg; % fat 16.3 ± 7.3) and 21 healthy females (age 25.6 ± 4.9 yr.; height 167.2 ± 5.4 cm; weight 61.6 ± 7.7 kg; % fat 24.0 ± 6.8) underwent an incremental treadmill test to determine $\dot{V}O_{2peak}$, and on two separate days performed an exercise protocol consisting of treadmill walking on a level grade at 2.0 mph (54 m.min⁻¹), 3.0 mph (80 m.min⁻¹), and 4.0 mph (107 m.min⁻¹), and running at 6.0 mph (161 m.min⁻¹). Subjects exercised for 5 min at each velocity, with 3 min rest in between each exercise bout. Pulmonary ventilation ($\dot{V}_E$) and gas exchange were measured breath-by-breath each min. The average of $\dot{V}O_2$ values obtained during the last two min of exercise for both exercise sessions was used in polynomial random coefficient regression (PRCR) analysis.

Results—In the PRCR analysis for walking speeds only, both linear ($r = 0.31$; $p = 0.053$) and quadratic ($r = 0.35$; $p = 0.029$) were modestly correlated with $\dot{V}O_{2peak}$. Steady-state $\dot{V}O_2$ during walking at 3.0 and 4.0 mph, and running at 6.0 mph, was also modestly correlated with $\dot{V}O_{2peak}$ ($r = 0.30 - 0.48$).

Conclusion—The results confirm our hypothesis and suggest that, as walking speed increases, the increase in $\dot{V}O_2$ is positively correlated with the $\dot{V}O_{2peak}$. Our findings are consistent with the notion that cardiorespiratory fitness and exercise economy are inversely related.

Keywords

efficiency; exercise; aerobic capacity; quadratic; fitness

Corresponding author: Brandon Sawyer, MEd, ATC, Point Loma Nazarene University, 3900 Lomaland Drive, San Diego, CA 92106, Ph: 619-849-2779; Fax: 619-849-3215, brandonsawyer@pointloma.edu.

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Introduction

Both exercise economy and maximum oxygen uptake (VO_2) influence endurance performance (5,21). Somewhat counterintuitively, an inverse relationship between $\text{VO}_{2\text{max}}$ and exercise economy has been demonstrated for cycling (7,14,16,22) and running (19,23). In studies of running, steady-state VO_2 at a single speed typically has been used as a measure of economy (5,9,19,23). In contrast, for cycling the linear relationship between VO_2 and power output has been used to assess exercise efficiency (i.e., $\Delta\text{VO}_2/\Delta\text{work rate}$, with the inverse of this relationship used to define cycling efficiency) (4,7,10,14,16,18,20). A positive correlation between $\Delta\text{VO}_2/\Delta\text{work rate}$ and $\text{VO}_{2\text{max}}$ has been reported (7,14,16). The reason for the inverse relationship between $\Delta\text{VO}_2/\Delta\text{work rate}$ and $\text{VO}_{2\text{max}}$ in cycling remains unclear, although muscle fiber type and mitochondrial factors may play a role (3,4,12,18). Noakes (22) proposed that among competitive endurance athletes with similar performance characteristics, the relationship between $\text{VO}_{2\text{max}}$ and running/cycling economy will always be inverse, i.e., competitors with low $\text{VO}_{2\text{max}}$ compensating with higher movement economy in order to achieve the same performance (19,22). Thus it is the peak work rate (or running speed) reached during a maximal exercise stress test that is the best predictor of endurance performance, with the $\text{VO}_{2\text{max}}$ achieved on the test being dependent upon both peak work rate (or running speed) achieved and the exercise economy of the performer (21,22). However, an inverse relationship between $\text{VO}_{2\text{max}}$ and $\Delta\text{VO}_2/\Delta\text{work rate}$ in cycling also has been reported for untrained persons (7,16).

For walking, Hunter et al. (12) reported an inverse relationship between $\text{VO}_{2\text{max}}$ and walking economy in sedentary women. In that study walking economy was assessed at one speed, 3.0 miles per hour (mph). We are unaware of any published data that examines whether the slope of the VO_2 –walking/running relationship is related to $\text{VO}_{2\text{max}}$. Figures from previously published work indicate that the slope of the VO_2 –walking/running relationship may vary considerably among individuals (5,8,17,21). However, in these studies the relationships between VO_2 -treadmill speed slope and $\text{VO}_{2\text{max}}$ were not reported.

Therefore, we examined the relationship between $\text{VO}_{2\text{peak}}$ and submaximal exercise VO_2 elicited during a walking/running protocol in men and women heterogeneous for cardiorespiratory fitness. Because the slope of the VO_2 -walking speed relationship is nonlinear (8,17,24), we analyzed data with a polynomial random coefficient regression model. We hypothesized that $\text{VO}_{2\text{peak}}$ would correlate positively with both linear and quadratic coefficients of the model.

Methods

Subjects

Fifty-two subjects (29 females; 23 males) between the ages of 19 and 40 enrolled in the study. Subjects were generally physically active, and none of the subjects was a competitive runner or race-walker. Written informed consent was obtained from each subject, and the University of Virginia's Institutional Review Board approved the study. A pre-participation medical history and exam was completed on each subject to ensure good health. Due to exclusions on the basis of exercise test data (see below), 21 females and 19 males were used for data analysis (Table 1).

Experimental design

Each subject reported to the exercise physiology laboratory on three occasions, each separated by at least 48 hours. On one occasion body fat percentage was determined by air displacement plethysmography (6) and incremental walking protocol was administered to assess VO_2 peak.

On each of the two other occasions subjects performed a routine involving walking and running (2). These two protocols were identical in nature and for a given subject were performed at the same time of day on each occasion. Subjects were instructed to come to the laboratory at least two hours post-absorptive, to not perform any exercise prior to the session on the day of the test, and to not engage in strenuous exercise on the day before the test.

Incremental treadmill walking protocol

A modified Balke protocol was performed on a motorized treadmill for determination of $\text{VO}_{2\text{peak}}$. Subjects began walking at 3.3 mph ($88 \text{ m}\cdot\text{min}^{-1}$), 0% grade for the first min. The grade was increased to 2% for one min, and then increased by 1% every min thereafter. If a 25% grade was reached, treadmill speed was increased by 0.5 mph ($13.4 \text{ m}\cdot\text{min}^{-1}$) every min. The test was terminated at the point of volitional exhaustion. During the test verbal encouragement was given to all subjects. Subjects were not permitted to hold on to handrail supports at any time during the test. Pulmonary ventilation and gas exchange were measured breath-by-breath with the VmaxST portable metabolic measurement system (VIASYS, Yorba Linda, CA, USA). We previously reported that this system provides reliable measurements of VO_2 during walking and running (2). Time to exhaustion averaged 24.5 ± 4.1 min. $\text{VO}_{2\text{peak}}$ was taken as the highest 30-s average during the test. To be included in the data analysis subjects had to have either a peak respiratory exchange ratio (R) ≥ 1.10 or a peak heart rate $\geq 90\%$ of age-predicted maximum. Three subjects were excluded by these criteria. At exhaustion heart rate averaged 187 ± 11 beats per min (97.4 ± 6.1 percent of age-predicted maximum) and R averaged 1.14 ± 0.09 .

Walk/Run Protocol

Upon arrival to the laboratory subjects were fitted with the VmaxST system. After a 5-min period of seated rest, subjects then walked on a motor-driven treadmill at 2.0 mph ($53.6 \text{ m}\cdot\text{min}^{-1}$), 3.0 mph ($80.5 \text{ m}\cdot\text{min}^{-1}$), and 4.0 mph ($107.3 \text{ m}\cdot\text{min}^{-1}$), and ran at 6.0 mph ($160.9 \text{ m}\cdot\text{min}^{-1}$). Subjects exercised for 5 min at each speed, with 3 min of rest (standing) between each exercise period. Ventilation and gas exchange were measured breath-by-breath during each min of each exercise bout, and VO_2 was averaged over the last 2 min of exercise. This walk/run protocol was repeated for each subject (for purposes of assessing reliability of the VmaxST system, published previously (2)), and the average of the two trials was used in the statistical analysis. Nine subjects were excluded from the data analysis due to failure to achieve a steady-state VO_2 during the run at 6.0 mph (steady-state defined as a $< 100 \text{ ml/min}$ increase in VO_2 during the last 2 min of the test).

Statistical Analyses

The relationship between VO_2 and walking/running speed was examined by way of polynomial random coefficient regression (PRCR). The VO_2 (ml/kg/min) measurements at walking speeds of 2.0, 3.0 and 4.0 mph and at the running speed of 6.0 mph represented the response measurements in the PRCR analysis. Separate analyses were performed using all speeds in the same regression model (i.e., walking and running bouts combined) and for walking speeds only. Walking and running speed represented the predictor of VO_2 in the PRCR analysis with a second order curve-linear polynomial model specification that included linear and quadratic terms. We also performed the same analyses with time to exhaustion included in the model as a predictor of VO_2 . Marginal PRCR coefficient estimates (i.e., average) and *subject-specific* intercepts and linear and quadratic coefficient *best linear unbiased predictions* (BLUPS) were derived by way of restricted maximum-likelihood. Statistical inferences with respect to the marginal regression PRCR coefficients were based on Type III F-tests. A $p < 0.05$ decision rule was utilized as the criterion for rejecting the null hypothesis that the PRCR marginal coefficient was equal to 0.

The correlations between $\text{VO}_{2\text{peak}}$ and the PRCR *subject-specific* linear and quadratic coefficient BLUPS were assessed by way of the univariate Pearson correlation coefficients. A $p < 0.05$ decision rule was utilized as the criterion for rejecting the null hypothesis of zero correlation.

The SAS PROC MIXED and PROC CORR procedures of SAS version 9.1.3 (SAS Institute Inc. Cary NC) were used to conduct the PRCR analysis and the Pearson univariate analyses, respectively.

Results

As expected, the relationship between VO_2 and walking speed was curve-linear (Figure 1), with a significant quadratic coefficient ($p < 0.0001$) and a marginally significant linear coefficient ($p = 0.0549$) (Table 2). Both linear and ($r = 0.036$; $p = 0.023$) and quadratic ($r = 0.54$; $p < 0.001$) coefficients were significantly correlated with $\text{VO}_{2\text{peak}}$ (Figure 2). Including treadmill time to exhaustion to the random coefficient regression model did not improve predictions ($p = 0.763$).

When the PRCR analysis was restricted to only the walking speeds, both linear and quadratic coefficients were significant (Table 2), and both linear ($r = 0.31$; $p = 0.053$) and quadratic ($r = 0.35$; $p = 0.029$) coefficients were correlated with $\text{VO}_{2\text{peak}}$ (Figure 3). There were no differences between men and women with regard to PRCR coefficients.

Steady-state VO_2 at each speed was also positively correlated with $\text{VO}_{2\text{peak}}$, with the strongest correlation at the running speed of 6 mph (Figure 4).

Discussion

Our finding of a positive relationship between $\text{VO}_{2\text{peak}}$ and the regression coefficients of the VO_2 -walking speed relationship confirms our hypothesis and suggests that what has been reported for cycling (4,7,10,14,16,18,20) also applies to walking. The higher the $\text{VO}_{2\text{peak}}$ of the subject, the greater is the increase in VO_2 when speed is increased throughout a range of walking speeds from slow (2.0 mph) to brisk (4.0 mph). Because we obtained data on only one running speed, additional experiments are necessary to confirm that our findings extend to running.

The reason for including only one running speed was due to the fact that the original design of this study was to evaluate the reliability of a portable metabolic measurement system, and we focused primarily on walking speeds that would ensure steady-state VO_2 (2). Nevertheless, the results for the two PRCR analyses (i.e., with and without the running speed in the analysis) yielded similar results (Table 2), and the correlations between $\text{VO}_{2\text{peak}}$ and the linear and quadratic regression coefficients from the models with and without the one running speed included in the analysis were qualitatively similar (Figures 2 and 3).

The results of our regression analyses are consistent with the findings of others who reported positive relationships between $\text{VO}_{2\text{max}}$ and steady-state VO_2 in walking (12) and running (19,23). Hunter et al. (12) reported a correlation of 0.28 between VO_2 walking at 3.0 mph and $\text{VO}_{2\text{max}}$ in sedentary women, which is very close to the correlation of 0.30 that we found for our subjects (Figure 4). For running, Pate et al. (23) reported a correlation of 0.26 between $\text{VO}_{2\text{max}}$ and VO_2 while running at 6.0 mph in a 188 men and women distance runners. This is lower than the correlation of 0.48 that we observed for our subjects (Figure 4). Compared to our subjects, Pate et al.'s subjects had higher $\text{VO}_{2\text{max}}$ values (50.3 ml/kg/min vs. 40-45 ml/kg/min), and slightly higher VO_2 values for running at 6.0 mph (33.9 ml/kg/min vs. ~32.8 ml/kg/min (Table 1)). The ~3% higher VO_2 at 6.0 mph in the subjects studied by Pate et al. is

consistent with the notion that higher $\text{VO}_{2\text{max}}$ values are associated with lower economy (22).

Why increases in walking speed (or cycling power output) elicit greater increases in VO_2 in subjects with higher $\text{VO}_{2\text{peak}}$ is not well understood. Muscular factors may be involved in cycling efficiency and exercise economy (3,4,12,18). Buemann et al. (3) reported that cycling efficiency was reduced in subjects with a specific polymorphism of the uncoupling protein (UCP) 2 gene. Similarly, Mogensen et al. (18) reported that cycling efficiency was inversely correlated with muscle UCP 3 and positively correlated with type I fiber percentage. This latter observation is similar to that of Coyle et al. (4), who reported that cycling efficiency in experienced cyclists was correlated with type I muscle fiber percentage. In contrast, Mallory et al. (16) found that cycling efficiency was unrelated to type I muscle fiber percentage ($r = 0.11$) and to citrate synthase activity ($r = 0.21$) but was significantly inversely correlated with $\text{VO}_{2\text{peak}}$ ($r = -0.51$).

With respect to treadmill exercise, Hunter et al. (12) found that VO_2 walking at 3.0 mph was positively correlated with type IIa muscle fiber percentage in gastrocnemius muscle of sedentary women, and that both of these variables were positively correlated with $\text{VO}_{2\text{max}}$. Hunter et al. suggested that individuals with a high proportion of energetically inefficient type IIa muscle fibers will tend to be both less economical and have a greater oxidative capacity, with the greater “capacity” being a consequence of the higher O_2 demand of the inefficient type IIa fibers (12). If true, and if recruitment of type II fibers is influenced by both the percentage of muscle comprised of type II fibers and the exercise intensity, it could help explain why the correlations between $\text{VO}_{2\text{peak}}$ and the linear and quadratic regression coefficients were higher when the running speed of 6.0 mph was included in the analysis (Figures 2 and 3). It also may help explain why the correlation between $\text{VO}_{2\text{peak}}$ and steady-state VO_2 was highest for the running speed (Figure 4).

In contrast to the discussion above, Layec et al. (13) recently reported that the energy cost of muscle contraction was not different in trained and untrained subjects differing markedly in $\text{VO}_{2\text{max}}$ (67.1 ml/kg/min vs. 42.3 ml/kg/min). Muscle fiber characteristics of subjects were not obtained. Nevertheless, this study, in combination with some of the inconsistent findings described above, suggest that there may be factors other than skeletal muscle morphology and oxidative capacity that influence the slope of the relationship between VO_2 and increases in work rate.

A number of anthropometric variables have been hypothesized to contribute to economy during walking and/or running, including leg length, stride characteristics and other biomechanical characteristics, body mass and weight distribution between the trunk and limbs (1,12,15,23). We have no data to contribute to discussion of this issue. Selected exercise intensity (walking/running speed) could also affect assessment of economy. In the study Pate et al. (23), the running speed used to assess economy (6.0 mph; 10 min.mile⁻¹ pace) was much slower than typical training pace (~8.4 min.mile⁻¹) of their subjects, and this may have influenced their results. However, Morgan and Daniels (19) reported a significant correlation of 0.59 between $\text{VO}_{2\text{max}}$ and submaximal VO_2 in elite distance runners running at speeds typically encountered in daily training.

For walking and running studies, determination of economy typically involves measurement of steady-state VO_2 at one or more selected speeds, without analysis of the characteristics of the VO_2 -speed relationship (1,5,12,15,17,19,23). However, it is apparent that considerable between-individual variation in the slope of the VO_2 -speed relationship exists (5,19,21). Our results demonstrate that, similar to a number of reports on cycling (7,14,16), the regression

coefficients describing the curve-linear relationship between VO_2 and walking speed are positively correlated with $\text{VO}_{2\text{peak}}$.

A limitation of our study is that we only had three walking speeds. Our speeds, however, did encompass a range that is typically used for studies of energy expenditure during walking (1, 8, 12, 15). Speeds slower than 2.0 mph are below freely chosen walking speeds for young healthy adults (17), and speeds above 4.0 mph typically approach a transition speed in which subjects “walk-jog,” thus affecting gait. It is unlikely that inclusion of more speeds between 2.0 and 4.0 mph would have materially affected the PRCR analyses. Our subjects were asked to not eat or drink calorie- or caffeine-containing beverages for two hours prior to the exercise sessions. Two hours post-absorptive does not reflect a true fasted state and, therefore, metabolism may have been slightly affected by the subjects' previous meal. In order to control for this we tested the subjects at the same time of day and asked them to eat and drink the same before each session. We also did not control for stage in the menstrual cycle for the female subjects.

On the other hand, a major strength of the study is that VO_2 values used in the PRCR analyses represented the average of two identical trials of treadmill walking/running for each subject. As previously reported, the VmaxST system used in the present study produces reliable measurements of VO_2 , with coefficients of variation of 5.5-7.5%, intraclass correlation coefficients of 0.77-0.90, and R^2 of 0.88-0.95 (2). Furthermore, we excluded subjects who appeared not to have achieved a $\text{VO}_{2\text{peak}}$ and who also appeared to have a significant slow component of VO_2 at 6.0 mph (11).

In summary, we observed significant positive correlations between $\text{VO}_{2\text{peak}}$ and both linear and quadratic coefficients of the curve-linear relationship between VO_2 and walking speed. These findings are similar those reported for cycling (7, 14, 16), and are consistent with the inverse relationship between $\text{VO}_{2\text{peak}}$ and economy demonstrated for submaximal steady-state walking (12) and running (19, 23). Because so much of the variance in the relationship is unexplained (Figures 2 and 3), understanding the causal factors will be challenging.

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Figure 1.

VO₂ – treadmill speed relationship. Lines for each subject were generated using polynomial random coefficient regression (PRCR: see text for details) that included linear and quadratic coefficients. Solid dark line depicts the mean response.

Figure 2.

Relationship between $\text{VO}_{2\text{peak}}$ and the linear (Panel A) and quadratic (Panel B) regression coefficients of the PRCR analysis depicted in Figure 1. $n = 40$.

Figure 3.

Relationship between VO₂peak and the linear (Panel A) and quadratic (Panel B) regression coefficients of the PRCR analysis depicted in Figure 1, using only the three walking speeds (2-4 mph) in = 40.

Figure 4.

Relationship between VO_{2peak} and steady-state VO_2 at walking speeds of 2.0, 3.0, and 4.0 mph, and at the running speed of 6.0 mph. The correlations become increasingly stronger as treadmill speed increases. $n = 40$.

Table 1Subject characteristics and oxygen uptake during treadmill exercise (Mean $\pm$ SD)

	Males	Females
Age (yr)	26.4 $\pm$ 6.4	25.6 $\pm$ 4.9
Height (cm)	179.9 $\pm$ 7.2	167.2 $\pm$ 5.4
Weight (kg)	77.7 $\pm$ 8.7	61.6 $\pm$ 7.7
Body fat (%)	16.3 $\pm$ 7.3	24.0 $\pm$ 6.8
Fat-free mass (kg)	65.9 $\pm$ 8.8	47.6 $\pm$ 5.3
VO ₂ peak (ml/kg/min)	45.0 $\pm$ 6.2	40.0 $\pm$ 6.1
Time to Exhaustion (min)	26.5 $\pm$ 3.5	24.2 $\pm$ 3.4
VO ₂ at 2.0 mph (ml/kg/min)	10.6 $\pm$ 1.1	10.9 $\pm$ 1.3
VO ₂ at 3.0 mph (ml/kg/min)	13.3 $\pm$ 1.4	13.9 $\pm$ 1.9
VO ₂ at 4.0 mph (ml/kg/min)	19.5 $\pm$ 2.2	20.0 $\pm$ 2.0
VO ₂ at 6.0 mph (ml/kg/min)	33.2 $\pm$ 3.1	32.5 $\pm$ 3.4

Table 2

Polynomial random coefficient regression model summary for the population (marginal) parameter estimates for the regression of VO₂ on speed.

Effect	Estimated β	Standard Error	T-statistic	Probability
Model includes walking and running				
Intercept	6.70	0.64	10.5	<0.0001
Linear	0.68	0.35	1.9	0.0549
Quadratic	0.62	0.04	14.4	<0.0001
Model Restricted to walking speeds only				
Intercept	14.94	0.99	15.1	<0.0001
Linear	-5.37	0.70	-7.7	<0.000
Quadratic	1.64	0.11	14.2	<0.0001