THE INTERINDIVIDUAL VARIATION, COMPARISON OF THE STATE OF TRAINING, AND THE EFFECTS OF PROLONGED WORK ON RUNNING ECONOMY

by

JONATHAN E. BULA

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The University of British Columbia
Vancouver, BC Canada

ABSTRACT

The purpose of this study was to examine the differences in running economy between a group of well-trained runners and a group of non-runners. A secondary objective was to ascertain the effects of a prolonged run, near the ventilatory threshold, on the subjects' running economy. Two groups of ten males (X ± SD: age 25.6 ± 4.8, $\dot{V}O_{2max}$ 4.8 ± 0.7 $L \cdot min^{-1}$ for the runners; X ± SD: age 20.6 ± 2.3, $\dot{V}O_{2max}$ 3.9 ± 0.5 $L \cdot min^{-1}$ for the non-runners) performed two running economy tests on three separate occasions. They also performed a prolonged-run, of a maximum of 60 minutes, at an intensity near the subject's individual ventilatory threshold. The prolonged run was followed by two more running economy tests. Despite the statistically significant difference in $\dot{V}O_{2max}$ ($p<0.01$), the groups did not differ significantly in their running economy. Also, no statistically significant differences were found when running economy was measured as a function of distance ($ml \cdot kg^{-1} \cdot km^{-1}$), and when body mass was scaled to an exponent of 0.75 ($ml \cdot kg^{-0.75} \cdot min^{-1}$, $ml \cdot kg^{-0.75} \cdot km^{-1}$). The prolonged run had no statistically significant effects on the running economy of either group. The results from this study indicate, that despite a marked difference in training status between the groups, there were no running economy differences elucidated. Also the effects of a prolonged run near the ventilatory threshold were of insufficient duration and/or intensity to significantly affect the running economy of either group.

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CHAPTER 1: INTRODUCTION

1.1 Introduction

Running economy (RE), defined as the steady-state oxygen consumption ($\dot{V}O_2$) for a given running velocity, has received considerable attention in the literature, however a paucity of information still exists. There are numerous factors that affect RE, some are the following: intraindividual variability, gender, age, treadmill versus overground running, fatigue, training status, as well as a number of biomechanical considerations (Morgan et al. 1989). Running economy is typically quantified by measuring the steady-state $\dot{V}O_2$, expressed with respect to body mass and time, for a standardized, submaximal running speed (Morgan et al. 1989). As such a measure is obtained that represents the aerobic demand of running at that particular speed. Running economy has been shown to account for a large proportion of the variability in distance running performance among runners similar in $\dot{V}O_{2max}$ (Conley and Krahenbuhl, 1980). They were able to show, that within an elite group of distance runners homogeneous in $\dot{V}O_{2max}$, 65.4% of the variation observed in race performance on the 10 km race could be explained by variation in RE. Because of the variability in RE between individuals (Morgan et al., 1995), the results are still inconclusive as to whether trained individuals are always more economical than their untrained counterparts. As RE seems to account for a large proportion of the variation in distance running performance, understanding the differences in RE between individuals is important. This would help understand the degree in which it can be altered, as well as guiding future studies attempting to improve RE.

It has been shown that fatigue, induced by long duration exercise, can adversely influence RE (Morgan et al, 1989; Brueckner et al. 1991; Cavanagh et al. 1985). In contrast, some studies have shown that long duration submaximal runs does not alter RE (Dressendorfer 1991; Martin et al. 1987; Morgan et al. 1990, and 1996). How fatigue affects individuals of different training status has yet to be determined.

1.2 Statement of the Problem

RE appears to be multifactorial, in that there seems to be many possible determinants including skill or biomechanics, training velocity, muscle fiber type, $\dot{V}O_{2max}$, substrate utilization, muscle power and flexibility (Berg 2003). RE has been shown to account for a large proportion of the variation in distance running performance among runners similar in $\dot{V}O_{2max}$ (Conley and Krahenbuhl 1980). This has been shown for both well trained elite runners, as well as runners who are relatively untrained but have similar fitness levels (Conley and Krahenbuhl 1980). RE has a high interindividual variability even among trained runners. Svendenhag and Sjodin (1994) found that RE varied by as much as 30% in trained runners. Due in part to the variability in RE between individuals, the results are still inconclusive as to whether trained individuals are always more economical than their untrained counterparts. Despite the variability found in RE, it is a measure that has been found to be highly correlated to distance running performance with correlation coefficients as high as $r = 0.83$ (Conley and Krahenbuhl 1980; Morgan and Daniels 1994). A better RE enables a runner to maintain a higher velocity for a given amount of oxygen consumption which is of obvious benefit to distance running performance. Because of the strong relationship between RE and distance running performance, especially among runners similar in $\dot{V}O_{2max}$, it is important to understanding the differences in RE between individuals. In order for coaches and runners to be able to optimize performance it is important to understand the degree in which RE can be altered through training. Understanding the differences in RE between individuals as well as how much improvement in RE can be expected is essential in guiding future studies attempting to improve RE through different training modalities.

1.3 Definitions

1. Running Economy - steady-state $\dot{V}O_2$ for a given running velocity, typically expressed in $ml \cdot kg^{-1} \cdot min^{-1}$.

2. Respiratory Exchange Ratio (RER) – the ratio of the pulmonary exchange of carbon dioxide produced to oxygen consumed.

3. Ventilatory Threshold (Tvent) - the point where the aerobic energy response is of insufficient magnitude to supply the tissues energy requirement and there is an increased reliance on anaerobic processes with an accompanying abrupt increase in excess CO_2.

4. Steady state - defined, as an exercise intensity that is below Tvent and the RER is less than 1.00. Work at this level is considered to be almost entirely aerobic and may be performed theoretically for an indefinite duration.

1.4 Delimitations

This study will be delimited by:

1. A sample of subjects from UBC students and a few others from the Vancouver area.
2. A respiratory gas-sampling rate set at 15-second intervals.
3. The methodology used to determine running economy, Tvent, and $\dot{V}O_{2max}$.

1.5 Limitations

This study will be limited by:

1. The gas analysis capabilities of the Sensor Medics metabolic cart.
2. The individual's metabolic response to testing protocols.
3. The individual effort during testing procedures.

1.6 General Hypotheses

Trained runners will be more economical (lower sumaximal $\dot{V}O_2$) at all running speeds and will be more economical following the prolonged run when compared to non-runners.

1.6.1 Secondary Hypotheses

1. The trained group will have a significantly higher T_{vent}, relative (measured as a % of $\dot{V}O_{2max}$) as well as absolute (expressed in $ml \cdot kg^{-1} \cdot km^{-1}$).
2. The untrained group will have a decreased RE following the prolonged run.

1.7 Significance of the Study

Morgan et al. (1995) stated that a 1% reduction in the aerobic demand of running would potentially translate into a 1-min improvement in elite-marathon race performance. Since the margin of victory in endurance running events is so small a more thorough understanding of the variation in RE would be beneficial in order to understand the degree in which RE can be altered, as well as guiding future studies that attempt to enhance RE through training interventions. It has been shown that fatigue can have an effect on an individual's RE (Kyrolainen et al. 200; Sproule 1998). How fatigue affects the RE of individuals of different training status is yet to be determined definitively. Results of this study would be beneficial to athletes, coaches and researchers by improving our understanding of the differences in economy between trained and untrained individuals. This would aid knowing what improvements in RE are possible through training.

CHAPTER 2: Review of Related Literature

2.1 Introduction

Running economy, defined as the steady-state $\dot{V}O_2$ for a given running velocity, has received considerable attention in the literature, but a paucity of information still exists. The terms running efficiency and running economy are related, but should not be used interchangeably. Daniels in 1985 stated the following:

> "Efficient" refers to the relationship between work done and energy expended, and minimizing or eliminating unwanted or counter-productive muscular movement is a desirable goal for any distance runner. The terms "efficient" and "efficiency" should not be used to relate the energy demands of running to velocity of running because running velocity represents only part of the work being performed by the body while it is transported from one point to another. For this reason, running "economy" is more applicable to the description of this relationship between running velocity and energy expenditure.

Efficient utilization of energy, intuitively, should produce optimum performance in any type of endurance event. Having the ability to provide the exercising muscles with the energy that they need is extremely important, and being able to maintain a fast pace (high intensity) without negatively affecting the rate of utilization of total energy sources is also critical (Daniels 1985). An 'efficient' runner will get more work from the energy expended, and an economic runner is able to run at greater velocities while using less oxygen.

There are numerous factors that affect running economy, some of which are: intraindividual variability, gender, age, treadmill versus overground running, fatigue, training status, as well as a number of biomechanical considerations (Morgan et al, 1989). Running economy is typically quantified by measuring the steady-state $\dot{V}O_2$, expressed with respect to body mass and time, for a standardized, submaximal running speed

(Morgan et al, 1989). This measure will represent the aerobic demand of running at that particular speed and must therefore be measured at a speed at which a steady state is attainable. Running economy has been shown to account for a large proportion of the variation in distance running performance among runners similar in $\dot{V}O_{2max}$ (Conley and Krahenbuhl, 1980). This has been shown for both well trained elite runners, as well as runners who are relatively untrained but have similar fitness levels. What is still equivocal in the research however, is the question of the differences in running economy between individuals. Because of the variability in running economy between individuals, the results are still inconclusive as to whether trained individuals are always more economical than their untrained counterparts. Understanding the differences in running economy between individuals is essential in order to understand the degree in which running economy can be altered. This information could guide future studies attempting to improve running economy.

It has been suggested that fatigue induced by long duration exercise, may adversely influence RE (Morgan et al, 1989). Others have also found decreases in RE economy following prolonged activity (Brueckner et al. 1991; Cavanagh et al. 1985). In contrast, some studies have shown that long duration submaximal runs did not alter RE (Dressendorfer 1991; Martin et al. 1987; Morgan et al. 1990,1996). How fatigue affects individuals of different training status is yet to be determined definitively.

This review will focus on the physiology behind running economy, its measurement, associated factors, environmental and physiological influences, as well as differences within and between individuals.

2.2 Measuring Running Economy

Unlike the inherent problems in quantifying the energy cost of maximal or near-maximal running, RE can be determined through the use of indirect calorimetry. This method will accurately reflect metabolic rates during exercise, but is based on two assumptions (Morgan et al. 1989). The first assumption that is made is that the ATP requirement of the active musculature is derived wholly from cellular respiration, and not from any anaerobic pathway (Brooks and Fahey 1984). At non-steady-state exercise rates the contribution of anaerobic metabolism constitutes a portion of the total energy expenditure of the active muscle. Therefore, the aerobic demand of running at near-maximal speeds may underestimate the true energy cost (Bransford and Howley 1977). The second assumption of using indirect calorimetry is that the contribution of protein and amino acid degradation to the active energy requirement is insignificant (Brooks and Fahey 1984). Given the short duration (6 to 10 minutes) and submaximal nature of running economy tests, the validity of this assumption is probably not in question (Morgan et al. 1989). The key element to obtaining a valid measure of RE is collecting the metabolic data after the subject has reached a steady state. Attainment of a steady-state $\dot{V}O_2$ condition is dependent upon $\dot{V}O_2$ kinetics (Morgan et al. 1989). The two ways that have been used to verify if a steady state has been reached are inspection of the subject's anaerobic threshold and respiratory exchange ratio (RER) (Bransford and Howley 1977; Conley and Krahenbuhl 1981). The subject must be performing at or below the anaerobic threshold and with an RER of less than 1.00, both these situations support the presence of a steady state. This makes the selection of what velocities to use when measuring RE an important issue for the researcher, and must be given adequate consideration.

2.3 Running Economy and its Relationship to VO_{2max} *and Performance*

In the past three decades researchers have paid greater attention to the predictive and diagnostic value of RE. Considered to be of little importance in the past, RE has been shown to relate to distance running success among athletes possessing similar $\dot{V}O_{2max}$ profiles (Conley and Krahenbuhl 1980; Morgan et al. 1989; Morgan and Craib 1992). In 1980, Conley and Krahenbuhl published the results of a study in which the intent was to determine the relationship between RE and distance-running performance in highly trained and experienced distance runners of comparable ability. They found the relationships between steady-state $\dot{V}O_2$ at 241, 268, and 295 $m \cdot min^{-1}$ and 10 km run time were $r = 0.83$, 0.82, and 0.79 ($p<0.01$), respectively. The authors concluded that among highly trained and experienced runners homogeneous in competitive ability and $\dot{V}O_{2max}$, RE accounts for a large and significant amount of the variation observed in performance on a 10 km race. The importance of RE to performance can be viewed from another way, the relationship between RE and $\dot{V}O_{2max}$. A better economy enables a runner to maintain a more rapid velocity during a race (Daniels 1985; Morgan et al. 1989). Daniels 1985 concluded that this interplay between $\dot{V}O_{2max}$ and RE could be expressed by calculating the predicted running velocity at $\dot{V}O_{2max}$ ($v\dot{V}O_{2max}$). $v\dot{V}O_{2max}$ is determined by expressing economy in $ml \cdot kg^{-1} \cdot km^{-1}$ and dividing that value by $\dot{V}O_{2max}$ in $ml \cdot kg^{-1} \cdot min^{-1}$.

For example:

$\dot{V}O_{2max} = 75\ ml \cdot kg^{-1} \cdot min^{-1}$; $RE = 185\ ml \cdot kg^{-1} \cdot km^{-1}$

$\dot{V}O_{2max}$ / RE * 60min/hour = 24.3 km/hr = $v\dot{V}O_{2max}$

Jones and Carter (2000) stressed the importance of the requirement for both valid measures of $\dot{V}O_{2max}$ and for exercise economy to be measured at several moderate intensities below the lactate threshold in order for an accurate determination of $v\dot{V}O_{2max}$. A study by Morgan and Daniels in 1994 attempted to assess the relationship between $\dot{V}O_{2max}$ and RE in elite distance runners. The authors stated that the primary finding of their study suggested that among a group of elite distance runners, a positive relationship existed between $\dot{V}O_{2max}$ and RE. Their data supported the notion that the interplay between $\dot{V}O_{2max}$ and RE can be predictive of distance-running performance ($r = -0.57$; $p = 0.006$ was found between $v\dot{V}O_{2max}$ and $\dot{V}O_{2submax}$). Currently it is felt by most that a high $\dot{V}O_{2max}$ helps an individual gain membership to the elite performance cluster, but it does not discriminate between success among these individuals. The runner's economy, and perhaps more accurately the $v\dot{V}O_{2max}$ are better determinants of performance among distance runners of comparable abilities (Douglas and Krahenbuhl 1980; Morgan et al. 1989; Morgan and Daniels 1994; Brandon 1995).

2.4 Physiological and Environmental Factors Affecting Running Economy

2.4.1 Intraindividual Variation in Running Economy

Because of the frequent use of RE to predict endurance performance, the study of the within-subject variability is both a relevant and necessary consideration. Daniels 1985 stated that the following factors appear to influence RE within an individual: (1) age; (2) air or wind resistance; (3) body temperature; (4) stride length; (5) weight added to or taken from the body, with shoe weight being a greater factor than weight added to the trunk; (6) training. Despite the number of potential influencing factors, RE when measured properly seems to be a fairly stable measure. Morgan et al. 1991 looked at 17 trained male runners. The subjects performed two level treadmill runs at 3.33m/s; these runs were preceded by 30-60 minutes of treadmill accommodation. They found that RE demonstrated high day-to-day reliability (r = 0.95), and the mean coefficient of variation in RE was 1.32% (range = 0.30 – 4.40%). Pereira and Freedson, 1997 suggested that the results from Morgan and co-workers might not have realistically reflected variability in RE over several weeks or months (the duration of a competitive season or a training study). They stated that extrinsic and intrinsic factors may play a larger role in affecting the degree of biological variation. Pereira and Freedson, 1997 conducted a study with the purpose of assessing the intraindividual variation in RE among highly trained and moderately trained males during steady rate treadmill running below the lactate breakpoint. The mean coefficient of variations of the two groups were not statistically different from each other (highly trained = 1.77%, moderately trained = 2.00%). They stated that after accounting for technological error, biological variation was found to comprise approximately 94% of the intraindividual variation in RE. The findings of

Morgan et al. and Pereira and Freedson are consistent with other values found in the literature. From these findings and others (Morgan et al. 1991; Williams et al. 1991), it is possible to conclude that group measures of RE remain relatively stable across treadmill running sessions. This is true if subjects receive ample time for treadmill accommodation, are tested at the same time of day, in the same footwear, and are nonfatigued when testing occurs. Williams et al. 1991 stated that RE appears to be a stable physiological measure in moderately trained male runners and that a criterion value based on the average of two measures per subject is recommended to obtain an acceptably stable RE value. Pereira and Freedson (1997) stated that in training interventions and other types of treatment studies where physiological responses are outcomes, it seems unlikely that baseline differences in fitness across groups of trained runners will confound or mask treatment effects.

2.4.2 Gender

The gender differences in RE have been investigated, but with mixed findings. Some investigators have reported no difference in running economy, based on gender (Daniels et al. 1977; Daniels 1985; Davies and Thompson 1979); others have found males to be more economical (Bhambani and Singh 1985; Bransford and Howley 1979). A good example showing males being more economical than females was the study by Bransford and Howley in 1979. They found that trained and untrained male subjects exhibited significantly lower aerobic demands, relative to body mass, when compared to trained and untrained females, respectively. In contrast, a study by Daniels and Daniels in 1992 showed that when compared in RE, men used less oxygen ($ml \cdot kg^{-1} \cdot min^{-1}$) at common absolute velocities. $\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot km^{-1}$) was not different between men and women at equal relative intensities (%$\dot{V}O_{2max}$). When they compared men and women of equal $\dot{V}O_{2max}$ values, they found the men were significantly more economical. In complete contrast to the previously cited papers, research by Geertje et al. 1997 found a sex difference in economy. What was different, however, was the finding that over the whole age range (this was a longitudinal study) from 13 to 27 years females showed a significantly higher RE in comparison with males. The authors did state a reason for this finding that is contrary to the other sex-related differences in RE reported in the literature. The reason is as follows: at all ages and all workloads the females were running at a significantly higher percentage of their $\dot{V}O_{2max}$ than the males. The authors hypothesized that the females may have been deriving more of their energy cost through anaerobic metabolism. Other hypotheses have been advanced in order to explain why some studies have found males to be more economical. Some include the following: (1) differences in vertical displacement of the body and training experience and intensity (Bransford and Howley 1977), and (2) higher stride frequency and greater oxygen dept exhibited by females may contribute to the higher overall energy cost of running (Bhambani and Singh 1985). These mixed findings clearly illustrate the importance of future studies that will attempt to find and explain gender differences (if any) in RE.

2.4.3 Age

In a comprehensive study by Astrand, 1952 involving males and females of various ages, it was quite clearly shown that younger children are less economical in running than older children. The older children are in turn less economical than adults. Others have substantiated these findings (Krahenbuhl and Williams 1992; Krahenbuhl et al. 1989; Geertje et al. 1997). Geertje et al. 1997 published some of the findings of the Amsterdam Growth and Health Study. They were looking at the longitudinal development of RE in males and females from teenage to young adult age (13 to 27 years of age). They found a significant decrease in $\dot{V}O_2$ at given submaximal speeds for both males and females with increasing age, implying a significant increase in RE for both sexes. The exact reasons for these differences are not completely clear, but various suggestions have been put forth. Bailey and Pate 1991 suggested that adults have lower ventilation and a lower cardiac frequency than children. Adults need less energy for ventilation and for work of the heart because they seem to breathe more efficiently, and adults have a more efficient combination of cardiac frequency and stroke volume. Morgan et al. 1995 suggested that the age-related increase in RE might be differences in running style. They stated that children have a more immature running style owing to a poorer economy of motion. Krahenbuhl and Williams 1992 suggested that perhaps the difference in basal metabolic rates between adults and children could partially explain the differences in economy. They went on to state, however, that even the cumulative impact of the above three items does not fully explain the differences observed in RE between children and adults. It is clear that more research in this area would be beneficial in understanding the age-related development in running economy.

2.4.4 Temperature

There is evidence in the literature supporting both an increase and a decrease in RE in hyperthermic conditions. MacDougall et al. 1974 observed that $\dot{V}O_2$ was significantly higher in subjects who exercised at 70% under hyperthermic conditions compared to normal or hypothermic conditions. They suggested some reasons for this increase, which include the following: an increased energy requirement for peripheral circulation, increased sweat gland activity, hyperventilation, and a decreased efficiency of energy metabolism. Conversely, Maron et al. 1976 reported a reduction in $\dot{V}O_2$ during the latter portion of a prolonged run, implying the possibility of increased muscular efficiency with elevated muscle temperature. It would seem that the true effect of temperature on RE remains to be elucidated.

2.4.5 Fatigue

The relationship between RE and fatigue is a contentious issue. Early investigations were unable to produce a consensus, and led to the adoption of divergent strategies (a conservative start, a fast start, a steady pace) to achieve minimal oxygen costs during short term, maximal runs (Morgan et al. 1989). More recently Morgan et al. 1990 conducted a study that looked at the effects of a prolonged maximal run of 30 minutes on RE. They measured RE at two different speeds before and at one, two, and four days after the 30-minute run. They found no significant difference in RE following the prolonged maximal run. Somewhat in contrast to Morgan and co-workers, Kyrolainen et al. 2000 showed that RE following a marathon race was significantly decreased. There was an increase in oxygen consumption, ventilation, and heart rate, with a simultaneous decrease in the oxygen difference (%) between inspired and expired air, and respiratory exchange ratio. It was suggested that weakened RE occurred because of the increased physiological loading due to the following: (1) increased utilization of fat as an energy substrate, (2) increased demands of body temperature regulation, and (3) possible muscle damage. Sproule 1998 looked at RE following 60 minutes of exercise at 80% VO_{2max}. He found that RE became worse during prolonged runs and the magnitude of the deterioration in economy increased with both increasing exercise intensity and time. Zavorsky et al. 1998 had12 highly trained male athletes complete through 3 interval workouts with varying recovery durations between the repetitions. They found that RE deteriorated significantly following the interval workout independent of the recovery duration between the repetitions. There have been mechanisms put forth as to the reasons for the worsened economy observed by the above researchers. These include the following: (1) an increase in heart rate to compensate for a decreased stroke volume, (2) an increase in core temperature, (3) an increase in blood catecholamine levels, (4) a change in substrate utilization with an increase in fat metabolism resulting from a decrease in muscle and liver glycogen, and (5) a decrease in biomechanical efficiency. It is noted that the other three studies cited looked at RE immediately following intense exercise. In the study by Morgan and co-workers the second economy measure was at least 24 hours after the exercise bout. These findings could have practical implications to the training athlete in planning the training schedule.

2.5 Effects of Training on Economy

When Morgan and Craib (1992) looked at the physiological aspects of RE, they concluded that little consensus exists regarding the effects of training on RE. Morgan et al. 1989 suggested that this disparity is partly due to a lack of longitudinal studies and limitations in experimental design. Some of the problems are as follows: (1) the use of small sample sizes; (2) the lack of multiple economy measures to account for normal intraindividual variation; and (3) failure to control factors which may potentially influence economy (e.g. fatigue level, state of training, circadian variation, training accommodation, footwear mass and design). The following Tables (1 and 2) summarize the findings of various research exploring the effects of training interventions on RE. Table 1 examines studies that revealed no change or a slight increase in the aerobic demand of running following relatively short training periods (6-11 weeks). Table 2 examines studies that have reported a wide range of improvements in running economy by employing different combinations of distance, interval, and uphill training performed over longer time spans (14 wk-5 yr).

TABLE 1. Summary of studies reporting no change in or worsened economy with training (adapted from Morgan and Craib 1992).

Reference	**Subjects**	**Regimen**	**VO_2 change**
Daniels et al. 1978b	15 rec tr M	8 wk; LD & I	0%
Lake et al. 1990	15 rec act M	6 wk; LD	+3%
Petray and Krahenbuhl 1985	50 M children	11 wk; LD & Rinstr	0%
Wilcox and Bulbulian 1984	7 tr F	8 wk; LD & I	0%

rec = recreational; tr = trained; M = male; F = female; act = active; LD = long-distance training; I = interval training; Rinstr = instruction on running techninque.

TABLE 2. Summary of studies reporting improvements in running economy with training.

Reference	**Subjects**	**Regiment**	**VO_2 change**
Conley et al. 1981	1 elite M	18 wk; LD & I	-13%
Conley et al. 1984	1 elite M	9 mo; LD & I	-5%
Daniels et al. 1978a	11 adol M	2-5 yrs; MD & LD	-18%
Patton and Vogel 1977	60 unt & tr M	6 mo; LD	-10%
Sjodin et al. 1982	8 tr M	14 wk; normal trng + 1 LTR$\cdot$wk^{-1}	-3%
Svendenhag and Sjodin 1985	16 elite M	22 mo; LD, I, & UPH	-1% to –4%$\cdot$yr^{-1}
Franch et al. 1998	36 rec M	6 wk; group 1 LD, group 2 LIT, group 3 SIT	-3.1% group 1 -3.0% group 2 -0.9% group 3 (not significant)

M = male; adol = adolescent; unt = untrained; tr = trained; rec = recreational; trng = training; LD = long-distance training; I = interval training; LIT = long-interval training; SIT = short-interval training; MD = middle-distance training; LTR = lactate-threshold run; UPH = uphill-run training.

Improvements in RE, with endurance training, may result from the following: (1) improved muscle oxidative capacity, (2) associated changes in motor unit recruitment patterns (Coyle et al. 1992), (3) reductions in exercise ventilation and heart rate for the same exercise intensity (Franch et al. 1998), and (4) improved technique (Williams and Cavanagh 1987). These improvements may be partly offset by an increased utilization of fat as an exercise substrate following training. There is a greater amount of oxygen required for fat metabolism when compared to carbohydrate metabolism (Jones and Carter 2000). There is a possibility that running economy is related to muscle elasticity. It has been speculated that RE might be related to 'fluency' of movement and that it might therefore be improved by flexibility training (Cavanagh and Kram 1985; Godges et al. 1989). In contrast to this theory are the findings of Craib et al. in 1996. They stated that results from the analysis of 19 well-trained runners suggested that inflexibility in certain areas of the musculoskeletal system may enhance RE. This may be due to the increased storage and return of elastic energy and the minimization of the need for muscle-stabilizing activity. An interesting study, conducted by Paavolainen et al. in 1999, demonstrated that 'explosive strength training' (involving sprinting and jumping exercises and weight training using high to maximal movement speeds and low loads (0 to 40% of 1 RM)) can improve both RE and 5km race performance. They suggested that the improved neuromuscular control, resulting from the training, could have improved RE by allowing a tighter regulation of muscle stiffness and better utilization of muscle elasticity. It is clear that more research, exploring the effects of different types of training on RE is needed.

2.6 Interindividual Variation

Traditionally it has been accepted that the aerobic demand for a given submaximal exercise task is not different between the trained and untrained individual (Gollnick 1988; Hollosky and Coyle 1984). Recent evidence, however, suggests that RE may vary as a function of training (Morgan et al. 1995). Results from limited cross-sectional research are equivocal. Some studies reveal no difference in economy between trained and untrained subjects (Daniels and Yarbrough 1978; Dolgener 1982; Wilcox and Bulbulian 1984) and others reporting better economy in trained subjects and elite (vs. sub-elite) runners (Bransford and Howley 1977; Conley et al. 1981 and 1984; Pate et al. 1987; Pollock et al. 1980; Sjodin et al. 1982; Svendenhag and Sjodin 1985). Lake and Cavanagh 1990 actually demonstrated increased oxygen cost in the trained group. Morgan et al. 1995, in an attempt to resolve the ambiguity of the previous findings, conducted a retrospective analysis on data obtained from a large contingent of subjects (N = 89) exhibiting varying performance and training backgrounds. The authors stated, from their analysis, that trained distance runners are more economical when compared with untrained subjects. Running economy differences, between trained and untrained subjects, may be a function of repeated exposure to moderate training loads. They also noted that the similarity, in the range of RE values observed across their four subject categories, implies that performance capability, training status, and practice are not necessarily associated with a particular individual economy profile. The narrow span in $VO_{2submax}$ reported by the authors lends support to the hypothesis that RE cannot be perturbed beyond some moderate limit. Of noteworthy importance, however, is the fact that a mere 1% reduction in the aerobic demand of running would potentially translate into a 1-min improvement in elite-marathon race performance (Morgan et al. 1995). It is clear that a more thorough understanding of the interindividual variation in RE is needed in order to understand the degree in which RE can be altered. This would help to guide future studies that attempt to enhance RE through training interventions.

CHAPTER 3: Methodology

3.1 Subjects

Two groups of 10 subjects were selected for this experiment. Group one, consisting of 10 trained male runners, was termed the Vm70 group (Vm70 representing the groups mean $\dot{V}O_2$ of roughly 70 $ml \cdot kg^{-1} \cdot min^{-1}$), and group 2 consisting of non-runners was termed the Vm50. The sample size was determined based on the previous research conducted by Williams and colleagues in 1991 that examined the issue of how many subjects should be tested to detect statistically significant differences in RE. The authors reported that the smaller the effect size, the greater the number of subjects required to detect statistical significance ($P = 0.05$). Based on standard deviation values from their study, sample size estimations required to detect an effect size of 1.25 $ml \cdot kg^{-1} \cdot min^{-1}$ at the running speeds of 2.68, 3.13, and 3.58 m/s are 10, 11, and 11 respectively. Vm50 consisted of relatively untrained, non-running males whose $\dot{V}O_{2max}$ values were less than 55 $ml \cdot kg^{-1} \cdot min^{-1}$. Vm70 consisted of well-trained males whose $\dot{V}O_{2max}$ values were greater than 65 $ml \cdot kg^{-1} \cdot min^{-1}$. An effort was made to ensure that the groups were as homogeneous as possible in age (college age), height, weight, and %body fat. This was done to reduce the confounding effect these variables might have had on running economy measures. All subjects were non-smoking healthy individuals.

3.2 Testing Procedures

All testing was performed in the J.M. Buchanan Exercise Science Lab at the University of British Columbia. All testing sessions were separated by at least 48 hours. Subjects were asked to be at least 2 hours post absorptive, use the same footwear for every test, and to schedule testing at the same time of day for all tests. During all the running tests heart rates were monitored using an Accurex Plus Polar heart rate monitor, and expired gas samples were collected and analyzed with a Sensor Medics V-Max Metabolic Cart. All running tests were conducted on a Quinton treadmill. All equipment was calibrated prior to each use.

This experiment consisted of two separate parts (a part 'A' and 'B').

3.2.1 Part A: Session One

During the first session subjects signed a consent form detailing the testing procedures, potential hazards, and benefits of being involved in the study. They verbally completed a questionnaire designed to determine their current activity level and help in the initial subject screening process. If the subject met the inclusion criteria for the study, they proceeded with initial anthropometric measures of height, weight, and relative fatness determined by the sum of 5 skinfold sites (bicep, triceps, subscapular, iliac crest and medial calf). The subjects then performed a graded maximal exercise test (GXT) to determine their respective $\dot{V}O_{2max}$ values. This test was used as the final screening of the subjects. The protocol for the GXT was as follows: a five minute warm-up, followed by the GXT which began at a speed of 5 mph for the untrained group and 6 mph for the trained, increased 0.5 mph every minute until 10 mph was reached, after which a grade increase of 2% occurred every minute. Expired gas samples were analyzed using a Sensor Medics V-Max Metabolic Cart. The test was terminated when the subject reaches volitional fatigue and was unable to continue. A $\dot{V}O_{2max}$ test was considered acceptable if the subject met 3 of the following criteria: a plateau (defined as an increase of no greater than 2 $ml \cdot kg^{-1} \cdot min^{-1}$ during the final stage of the GXT) or slight decrease in $\dot{V}O_2$, an RER greater than 1.1, a heart rate of within10% of the age predicted maximum, a blood lactate concentration exceeding 8 mM/L. If the subject faied to reach these criteria a supramaximal test was to be performed at one stage higher in intensity than the subject reached in order to insure a true maximal value for oxygen consumption was reached.

3.2.2 Part A: Sessions Two, Three, and Four

During these testing days measures of RE were taken. Subjects performed a five-minute warm-up run followed by two ten-minute RE tests. The velocities for the RE tests were as follows:

- Velocity one; an absolute measure of 2.68 m/s
- Velocity 2; a relative measure corresponding to the subject's group mean velocity at T_{vent} minus 0.5 mph (0.22 m/s).

The order of the tests was randomized to reduce any order effect, and 10 minutes of rest was allocated between each running economy test. Expired gases were analyzed during the final 4 minutes of each running economy test using the same metabolic cart as with the $\dot{V}O_{2max}$ test. RE was calculated by averaging the values obtained in the final 4 minutes of the test, a method previously used by Morgan et al. in 1990. T_{vent} was calculated from the data obtained during the $\dot{V}O_{2max}$ test. The excess carbon dioxide method ($ExCO_2$) was used to calculate T_{vent}. Gaskill et al. 2001 stated that the $ExCO_2$ method of determining T_{vent} would be the best method to use if only one method were available.

3.2.3 Part B

Part B began with the subjects performing a 60-minute run on the treadmill at the velocity that corresponded to their respective ventilatory thresholds minus 0.5 mph. Subjects were weighed before and after the 60-minute run to determine any weight loss. A blood lactate sample was measured at 3 minutes post. Two 6-minute RE tests were performed no later than 10 minutes following the 60-minute run. The order of the RE tests was randomized. RE was calculated by averaging the $\dot{V}O_2$ during the last three minutes of each bout. Heart rate was monitored throughout the testing session.

3.3 Data Analysis

The dependent variables that were measured in this study are as follows: HR, Ventilatory Threshold (Tvent), $\dot{V}O_2$, RE, VE, RER, and Lactate concentration in mM/L. An analysis of variance was used to compare the two groups on the above dependent variables. A statistical significance level of 0.05 was set a priori. A 2x2 repeated measures ANOVA was performed to examine the effects of a 60-minute run near Tvent on these same variables.

CHAPTER 4: Results

4.1 Descriptive Measures

Selected physical and metabolic characteristics for the subjects are shown in Table 1. The groups were similar in height and weight. Analysis of variance revealed that the subjects in the Vm70 group were older, and had a smaller sum of five skinfolds than subjects in the Vm50 group. Subjects in the Vm70 group possessed significantly higher $\dot{V}O_{2max}$ values and higher minute ventilation values than the subjects in the Vm50 group. The groups were found to have similar maximum heart rates.

Table 1. Physical and metabolic characteristics for subjects.

Variable	**Vm70 (N=10)**	**Vm50 (n=10)**
Age	25.6 (4.8)*	20.6 (2.3)*
Height (cm)	175.1 (6.3)	178.5 (7.3)
Weight (kg)	68.1 (6.6)	75.7 (10.8)
SO5SF (mm)	30.5 (5.6)*	43.5 (16)*
VO_{2max} (ml · kg^{-1} · min^{-1})	70.9 (6.3)*	51.6 (1.9)*
VO_2 (L · min^{-1})	4.8 (0.7)*	3.9 (0.5)*
VE_{max} (L · min^{-1})	131.7 (15.1)*	111.7 (14.5)*
HR_{max} (beats · min^{-1})	186.5 (10.3)	191.8 (8.4)

Values are mean (standard deviation)
* = significantly different ($P < 0.05$)

4.2 RE Comparisons

A comparison of running economy values ($\dot{V}O_{2submax}$) at 2.68 m · s^{-1} between the groups is shown in Table 2. At this work load the Vm50 group had a significantly higher RER, minute ventilation, and heart rate. These subjects were also working at a significantly higher percentage of their $\dot{V}O_{2max}$ values. Despite the fact that the Vm50 group was working harder at this workload, the groups did not differ in their oxygen consumption. This was shown for both absolute (L · min^{-1}) and relative (ml · kg^{-1} · min^{-1}) measures of $\dot{V}O_{2submax}$. Since the groups were significantly different in body composition, in order to remove the effect of mass the running economy of the groups were compared using allometric scaling measured in $ml \cdot kg^{-0.75} \cdot min^{-1}$, $ml \cdot kg^{-0.75} \cdot km^{-1}$ (Bergh et al. 1991). There were no significant differences found.

A comparison of running economy values at a workload that would elicit the subject's individual ventilatory threshold (T_{vent}) are displayed in table 3. The Vm50 group ended up working at a significantly higher relative workload than the Vm70 group, as displayed by the significantly higher $\%\dot{V}O_{2max}$. The Vm50 group had a higher RER, and heart rate, but the speed at which the group ran at was significantly slower. The Vm70 group was working at a higher $\dot{V}O_{2submax}$ than the Vm50 group, but when the cost of running (measured in $ml \cdot kg^{-1} \cdot km^{-1}$) was compared there were no significant differences found between the groups. This was also true when the groups were compared using allometric scaling.

Table 2. Running economy ($\dot{V}O_{2submax}$) values, and other selected physiological measures at $2.68\ m \cdot s^{-1}$ for both subject groups.

Variable	**Vm70 (N = 10)**	**Vm50 (N = 10)**
RER	0.88 (0.05)*	0.96 (0.04)*
$VO_{2submax}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	37.5 (2.5)	38.1 (2.1)
$VO_{2submax}$ ($ml \cdot kg^{-0.75} \cdot min^{-1}$)	107.8 (6.6)	112.1 (7.1)
$VO_{2submax}$ ($L \cdot min^{-1}$)	2.57 (0.25)	2.88 (0.44)
$VO_{2submax}$ ($ml \cdot kg^{-1} \cdot km^{-1}$)	232.8 (15.3)	236.7 (13.3)
$VO_{2submax}$ ($ml \cdot kg^{-0.75} \cdot km^{-1}$)	669.5 (41.2)	696.2 (44.3)
$\%VO_{2max}$	54 (7)*	74 (6)*
VE ($L \cdot min^{-1}$)	47 (7)*	63 (12)*
HR (bpm)	126 (13)*	160 (14)*
%HRmax	64 (11)*	83 (6)*

Values are mean (standard deviation) * = significantly different ($P < 0.05$)

Table 3. Running economy ($\dot{V}O_{2submax}$) values, and other selected physiological measures at near T_{vent} velocity for both subject groups.

Variable	**Vm70 (N = 10)**	**Vm50 (N = 10)**
RER	0.93 (0.05)*	1.00 (0.03)*
$VO_{2submax}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	53.7 (4.4)*	43.4 (2.3)*
$VO_{2submax}$ ($ml \cdot kg^{-0.75} \cdot min^{-1}$)	154.0 (12.5)*	127.3 (5.6)*
$VO_{2submax}$ ($L \cdot min^{-1}$)	3.68 (0.45)*	3.26 (0.39)*
$VO_{2submax}$ ($ml \cdot kg^{-1} \cdot km^{-1}$)	232.9 (14.2)	232.8 (12.2)
$VO_{2submax}$ ($ml \cdot kg^{-0.75} \cdot km^{-1}$)	667.4 (38.6)	683.3 (34.5)
$\%VO_{2max}$	76 (6)*	84 (5)*
VE ($L \cdot min^{-1}$)	75.6 (16.0)	76.1 (11.3)
HR (bpm)	159.7 (12.4)*	173.6 (12.9)*
%HRmax	86 (4)*	90 (5)*
Speed ($m \cdot s^{-1}$)	3.85 (0.23)*	3.11 (0.12)*

Values are mean (standard deviation)
* = significantly different ($P < 0.05$)

4.3 Variation in RE

Variation in $\dot{V}O_{2submax}$ values within and across subject groups is displayed in figures 1 and 2. Both groups displayed a wide range of economy values. Expressed relative to the least economical subject, variation in running economy between minimum and maximum $\dot{V}O_2$values ($ml \cdot kg^{-1} \cdot km^{-1}$) for the Vm50 group was 16% at 2.68 $m \cdot s^{-1}$ and 16% at the second higher workload. The same values for the Vm70 group were 18% at 2.68 $m \cdot s^{-1}$ and 17% at the second higher workload.

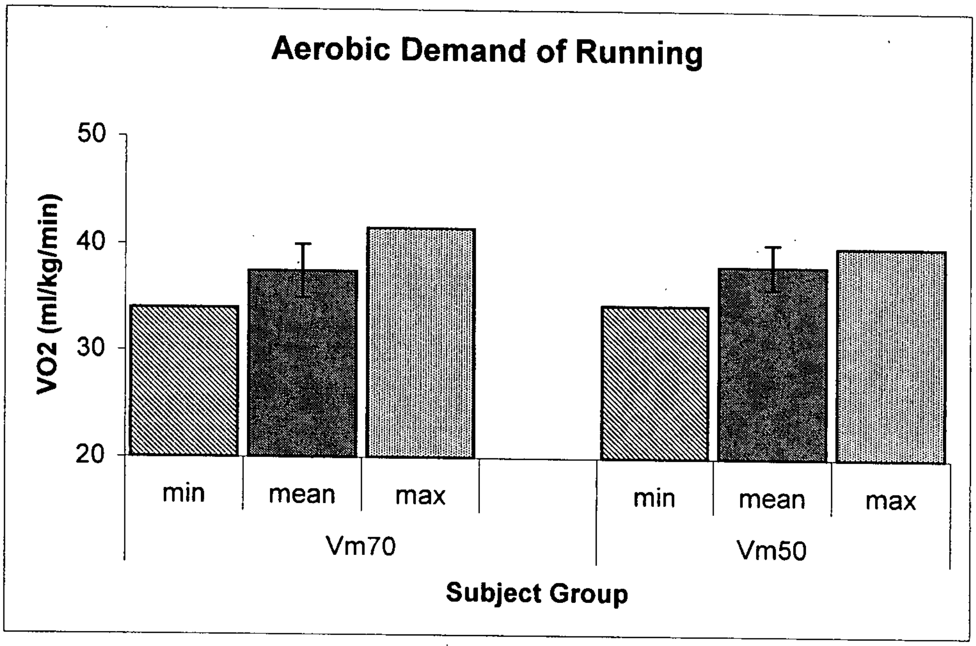

Figure 1 – Minimum, mean, and maximum running economy values at 2.68 $m \cdot s^{-1}$ for both subject groups.

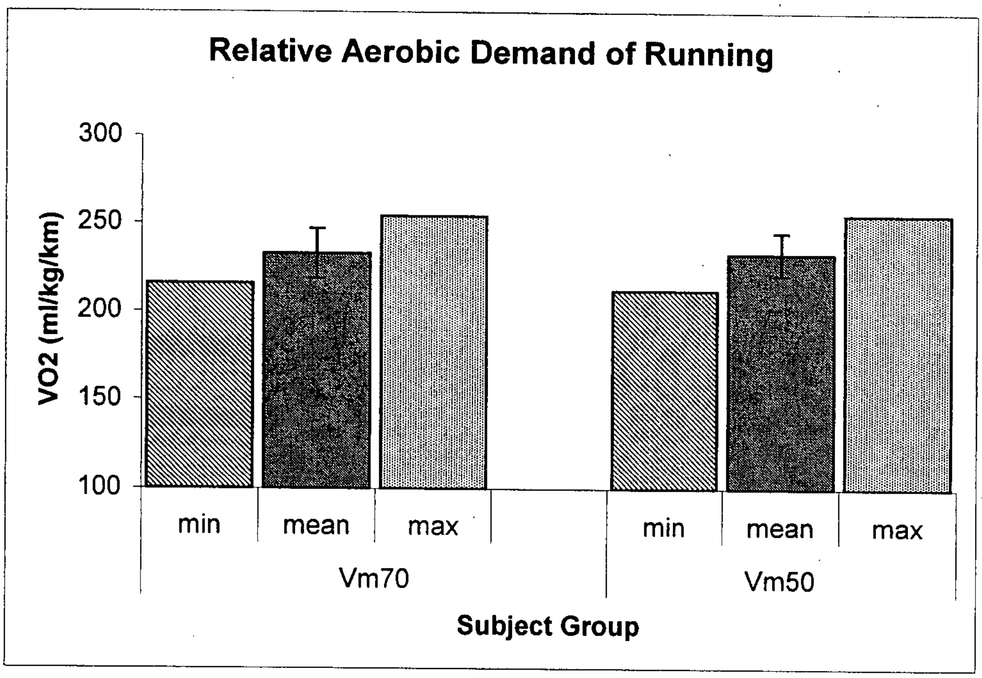

Figure 2 – Minimum, mean, maximum running economy values for both subject groups expressed as per kilometer. Values at subject's T_{vent} used.

4.4 Effects of Prolonged Running

The effects of a prolonged run at a velocity designed to elicit T_{vent} on running economy and other selected physiological variables are displayed in tables 4 and 5. The prolonged run did not seem to affect the running economy of either group. The only variable that was significantly different statistically from the RE tests before to the ones following was the prolonged run was the RER at 2.68 m · s^{-1}. It was lower following the prolonged run for both groups. The HR during the post RE test was elevated from the pre RE tests, but the difference was not significant. This was true for both groups.

The subjects in the Vm70 group lost an average of 1.1 ± 0.5 kg of body mass during the prolonged run. The weight loss ranged from a low of 0.2 kg to a high of 1.8 kg. The subjects in the Vm50 group lost an average of 0.6 ± 0.5 kg during the prolonged run. The weight loss for this group ranged from a low of 0.1 kg to a high of 1.3 kg.

Table 4. The effects of a prolonged run on running economy at 2.68 m · s^{-1}.

Variable	**Vm70 Pre (N = 10)**	**Vm70 Post (N = 10)**	**Vm50 Pre (N = 9)**	**Vm50 Post (N = 9)**
RER	0.88 (0.05)*	0.78 (0.04)*	0.96 (0.04)*	0.89 (0.06)*
$VO_{2submax}$ (ml · kg^{-1} · min^{-1})	37.5 (2.5)	37.6 (2.2)	38.0 (2.3)	38.4 (3.4)
$VO_{2submax}$ (ml · $kg^{-0.75}$ · min^{-1})	107.8 (6.6)	107.7 (5.9)	112.1 (7.1)	113.2 (3.1)
$VO_{2submax}$ (L · min^{-1})	2.57 (0.25)	2.52 (0.25)	2.92 (0.45)	2.91 (0.39)
$\%VO_{2max}$	53.7 (6.5)	52.3 (4.6)	73.9 (6.2)	74.0 (7.3)
VE (L · min^{-1})	47.4 (7.2)	48.1 (7.7)	64.3 (11.6)	67.3 (11.5)
HR (bpm)	126.3 (12.8)	139.8 (16.7)	161.4 (14.3)	166.4 (14.8)
%HRmax	64.0 (10.6)*	74.9 (6.7)*	84.1 (5.1)	86.8 (6.0)

Values are mean (standard deviation) * = significantly different ($P < 0.05$)

Table 5. The effects of a prolonged run on running economy. 'Pre' values are the mean from previous RE measures; 'Post' values were recorded immediately following the prolonged run at T_{vent}.

Variable	Vm70 Pre (N = 9)	Vm70 Post (N = 9)	Vm50 Pre (N = 9)	Vm50 Post (N = 9)
RER	0.93 (0.05)	0.86 (0.04)	1.00 (0.03)	0.97 (0.06)
$VO_{2submax}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	53.7 (4.4)	53.6 (4.7)	43.2 (2.4)	42.9 (2.9)
$VO_{2submax}$ ($ml \cdot kg^{-0.75} \cdot min^{-1}$)	154.0 (12.5)	152.7 (14.7)	127.3 (5.6)	126.5 (7.0)
$VO_{2submax}$ ($L \cdot min^{-1}$)	3.67 (0.45)	3.58 (0.52)	3.30 (0.39)	3.25 (0.37)
$VO_{2submax}$ ($ml \cdot kg^{-1} \cdot km^{-1}$)	232.9 (14.2)	233.6 (13.3)	231.9 (12.6)	230.4 (16.7)
$VO_{2submax}$ ($ml \cdot kg^{-0.75} \cdot km^{-1}$)	667.4 (38.6)	664.7 (37.7)	683.3 (34.5)	680.0 (47.0)
$\%VO_{2max}$	76.3 (6.0)	74.3 (3.4)	83.6 (4.8)	82.6 (5.5)
VE ($L \cdot min^{-1}$)	75.6 (16.0)	72.0 (12.4)	77.9 (10.9)	82.4 (11.7)
HR (bpm)	159.7 (12.4)	164.9 (14.5)	175.3 (12.5)	174.4 (12.8)
%HRmax	85.6 (3.7)	88.4 (5.2)	91.4 (3.5)	91.1 (5.2)

Values are mean (standard deviation) * = significantly different ($P< 0.05$)

CHPTER 5: Discussion

5.1 Descriptive Measures

The age range for all subjects in the present study (19 – 32 yr) is consistent with that of many other studies examining running economy (Dolgener 1982; Morgan et al. 1991 and 1995; Sproule 1998). All the subjects in the Vm50 group were students at the University of British Columbia. Four of the members of the Vm70 group were also from the University, while the remaining members of the Vm70 group tended to be older and consisted of runners from local running clubs. In contrast to the age difference, the other statistically significant group characteristic differences were typical and expected for groups differing substantially in level of training. The sum of skinfolds for the Vm70 group was typical for competitive distance runners (Berg et al. 1991) and lower than what is expected from a group of young adult males.

5.2 $\dot{V}O_{2max}$ Comparisons

The $\dot{V}O_{2max}$ protocol used in this study appeared to be valid as all test results satisfied the criteria for the achievement of a $\dot{V}O_{2max}$ (Brooks and Fahey 1984). The Vm70 group was significantly higher in both absolute ($L \cdot min^{-1}$) and relative ($ml \cdot kg^{-1} \cdot min^{-1}$) measures of $\dot{V}O_{2max}$. The values for the Vm70 group were consistent with other studies describing the group as highly trained (Daniels and Daniels 1992; Morgan et al. 1991 and 1995), and the Vm50 group values were consistent with other studies describing the subjects as untrained (Morgan et al. 1995) or recreational runners (Farrell et al. 1979).

5.3 RE Comparisons

There were no statistical differences between the two groups in running economy at 2.68 m · s^{-1}. While this finding is in accordance with some studies demonstrating that running economy is equivalent in the trained vs. untrained state (Dolgener 1982; Wilcox and Bulbulian 1984), it is in conflict with the results of others (Bransford and Howley 1977; Conley et al. 1981 and 1984; Morgan et al. 1995; Paavolainen et al. 1999). It is evident from the significant differences observed in other metabolic measures such as $\%HR_{max}$, $\%\dot{V}O_{2max}$, minute ventilation, and RER that the Vm50 group was working at a higher relative intensity.

The main reason, for this lack of difference, may be due to the interindividual variability in running economy. In a recent review, Berg (2003) stated that running economy appears to be multifactorial, with possible determinants including skill or biomechanics, training velocity, muscle fiber type, $\dot{V}O_{2max}$, substrate utilization, muscle power, and flexibility. Perhaps this complexity is the reason for the observed variability in running economy observed even in highly trained runners (Conley and Krahenbuhl, 1980). Svedenhag and Sjodin (1985) found that economy varied by as much as 30% in trained runners. In the present study, the Vm70 group varied in economy at 2.68 m · s^{-1} by as much as 17%, and the Vm50 group varied up to 16%.

Measuring running economy in ml · kg^{-1} · min^{-1} may not be entirely acceptable. Both actual mechanical work performed and substrate utilization are not accounted for in a ml · kg^{-1} · min^{-1} measure. Some runners could be producing more horizontal force while running at a given submaximal $\dot{V}O_2$. It is possible that the more fit runners in the Vm70 group were able to utilize more fat metabolism. The Vm70 group had a significantly lower RER. It has been suggested that a higher, rather than lower submaximal $\dot{V}O_2$ may be beneficial in long duration events such as the marathon. This may be associated with a greater utilization of fat as a substrate, and would promote the sparing of glycogen stores (Berg 2003).

A study by Daniels and Daniels (1992) looked at the economy of elite male and female runners of varying distances. They found that at marathon pace, the marathon runners were more economical than the middle distance runners. However the opposite was also true; at middle-distance pace the 800m and 1500m specialists were more economical. Running economy may not be independent of speed as has been earlier suggested (Cavagna et al. 1964). Daniels and Daniels (1992) found that out of 65 elite male and female runners there were 16 who showed equal aerobic demands over all speeds tested and six runners had lower $\dot{V}O_2$ data at higher speeds than at slower paces. They went on to explain that the runners in the latter category were 800 or 1500m specialists. They spend a great deal of time training at higher velocities relative to what is spent at slow running speeds. It is possible that the Vm70 and the Vm50 group did not differ in economy at 2.68 $m \cdot s^{-1}$ because this velocity is much too slow to be a training speed. The trained runners, some of whom were middle distance runners, habitually train at much higher velocities.

In the present study, economy was also measured at a velocity that would elicit an effort near the subject's individual ventilatory threshold. This was attempted in order to examine relative economy measures closer to the velocities more commonly used by the trained runners. No significant group differences were elucidated when economy was expressed in ml · kg^{-1} · km^{-1}. The fact that no group differences were demonstrated could be due in part to the testing velocity utilized. It may have still not been close enough to the trained runners' actual race pace. The average intensity for the Vm70 group during this economy test was only 76% of $\dot{V}O_{2max}$. Most elite marathoners and especially middle distance runners race at higher relative intensities (Daniels and Daniels 1992).

Data from a study by Bergh et al. (1991) explored the relationship between body mass and oxygen uptake. This study clearly indicated that linear scaling did not adequately adjust for body mass. They observed that the oxygen demand of running did not increase proportionally to body mass. This would effectively lead to lighter people requiring a seemingly higher oxygen uptake per kg of body mass than heavier people when expressed as ml · kg^{-1} · min^{-1}. It would seem valuable to express the submaximal oxygen uptake during running as ml · $kg^{-0.75}$ · min^{-1} in order to rule out the effects of unequal body mass. Bergh et al. 1991 found that instead of an exponent of 1.0, exponents may actually vary between about 0.67 and 0.75. When the RE data in this study were adjusted so the mass was scaled to an exponent of 0.75, there were still no statistically significant group differences found in ml · $kg^{-0.75}$ · min^{-1} or in ml · $kg^{-0.75}$ · km^{-1}. Scaling mass to an exponent of 0.67 was also attempted with no significant differences found between groups.

5.4 Effects of Prolonged Running

A few studies have examined the acute affects of prolonged exercise on running economy(Xu and Montgomery 1995; Sproule 1998; Kyrolainen et al. 2000). Data from the current investigation suggest that prolonged running near the ventilatory threshold [(average run time of 44 min for Vm50, and 60 min for Vm70) (average run intensity:

Vm50 = 84% $\dot{V}O_{2max}$, Vm70 = 76% $\dot{V}O_{2max}$)] did not have an effect on the RE of either group. A study by Sproule (1998) also attempted to discover the effects of prolonged running on RE. Sproule used three different run intensities: 40 min at 80% $\dot{V}O_{2max}$, 60 min at 70% $\dot{V}O_{2max}$, and 60 min at 80 % VO_{2max}. The subjects in Sproule's study were similar in age, and $\dot{V}O_{2max}$ (Age 23 (2) yrs; $\dot{V}O_{2max}$ 56.5 (4.6) ml · kg^{-1} · min^{-1}) to those in the Vm50 group of this study. They found that RE decreased significantly immediately following both 60 min runs. However they found no statistically significant difference in RE following the 40 min run at 80% $\dot{V}O_{2max}$. It was concluded that these results supported the notion that RE deteriorates during prolonged running, and that the magnitude of the deterioration in RE increases with both increasing exercise intensity and duration. Sproule's results agree somewhat with those found in this investigation. The results from the 40 min run at 80% $\dot{V}O_{2max}$ were similar to the Vm50 group. They ran for an average of 44 min at 84% $\dot{V}O_{2max}$, with both showing no effect on RE. In contrast to Sproule's results, the Vm70 group in this study (who ran for 60 minutes at 76% $\dot{V}O_{2max}$) showed no statistically significant decreases in RE after a prolonged run. Also, in contrast to the present work, are the results from the following two studies. Xu and Montgomery in 1994 investigated the effects of a 90-minute run at two different speeds on RE. They found that both a 90-min run at 65% and 80% $\dot{V}O_{2max}$ decreased RE. They found that the magnitude of the increase in submaximal oxygen consumption following the prolonged run was greater for the 80% $\dot{V}O_{2max}$ intensity. Kyrolainen et al. 2000 studied the effects of marathon running on RE. They found that after the marathon, a standardized 5-min submaximal running test, resulted in a significant increase in oxygen consumption, ventilation, and heart rate. In support of the observations made in this investigation are the findings from a study by Dressendorfer (1991). RE was tested following a 21.1 km run (mean race time 89.5 min) at race pace [3.98 (0.55) $m \cdot s^{-1}$, equivalent to 74-80% $\dot{V}O_{2max}$], and no significant increase in $\dot{V}O_2$ was evident.

The current investigation looked at RE economy immediately following the prolonged run. Another study by Morgan et al. (1990), investigated RE 1 to 4 days post run, and had similar findings. These authors attempted to document the effects of a 30 min maximal run (89% $\dot{V}O_{2max}$) on running economy. They found no significant difference in RE up to four days following the prolonged maximal run. Zavorsky et al. (1998) examined the effects of intense interval workouts on RE and found that RE decreased after the high-intensity workout. Changes in $\dot{V}O_2$, HR and RER were observed and were found to be independent of the recovery duration between the repetitions.

In the present study there was a statistically significant decrease in RER during the RE test at 2.68 $m \cdot s^{-1}$ following the prolonged run for both groups. Most studies have reported a decrease in RER following prolonged running. It has been attributed to an increased reliance on fat as an energy source (Morgan et al. 1990; Dressendorfer 1991; Xu and Montgomery 1994). Since carbohydrates are a more efficient fuel for energy production (Brooks et al. 2000), it has been suggested that an increased dependency on fat combustion could be partly responsible for a rise in submaximal $\dot{V}O_2$ following prolonged work (Bailey and Pate 1991). In this investigation, since a lower RER was found after the prolonged run, it would seem reasonable to assume that fewer carbohydrates were available to be used as a source of energy. However, it would seem that this increased reliance on fat and subsequent decrease in RER was insufficient to significantly affect the oxygen consumption of the subjects in this investigation.

It has been suggested that the increase in oxygen cost during prolonged exercise may be attributed to several mechanisms. These include the following: (1) an increase in HR to compensate for a decrease in stroke volume, (2) an increase in core temperature as a results of thermal stress, (3) an increase in blood catecholamine levels, (4) a shift in substrate utilization to an increase in fat metabolism resulting from decreases in muscle and liver glycogen stores, (5) a decrease in biomechanical efficiency (Bailey and Pate 1991; Kalis et al. 1988; MacDougall et al. 1974; Morgan and Craib 1992; William and Cavanagh 1987).

For the study reported here HR values increased during the prolonged run from a mean of 150 to 170 bpm in the Vm70 group, and from 165 to 180 bpm in the Vm50 group. The gradual increase in HR, observed during a constant velocity prolonged run, is evidence of a circulatory change. It may be attributed in part to a fall in central blood volume which causes a decreased filling pressure, and results in a decreased stroke volume (Nielsen et al. 1984). Another more recent explanation for stroke volume decline during exercise has been offered by Fritzsche et al. (1999). They found, that in a thermoneutral environment, a stroke volume decline during prolonged exercise relates to increased exercise heart rate and not increased cutaneous blood flow. They stated that more than likely the progressive increase in heart rate with cardiovascular drift during exercise decreases end-diastolic volume, subsequently decreasing stroke volume. The decreased stroke volume, coupled with a possible withdrawal of parasympathetic tone (Kalis et al. 1988), should describe the increases in HR observed during the prolonged run. Despite the observed increase in HR during the prolonged run, there was no significant difference in HR values between pre and post RE tests for either group. During the prolonged runs subjects were encouraged to ingest water. The weight loss observed as a result of the prolonged run was 1.6% of body weight for the Vm70 group and 0.7% for the Vm50 group. Even small amounts of dehydration (1% - 4.2% reduction in body weight) can lead to an increase in core body temperature (Montain and Coyle, 1992), and negatively influence endurance performance (Davies and Thompson, 1986). An increase in core temperature directly affects metabolic rate through the Q_{10} effect (MacDougall et al. 1974). An increase in core temperature can also induce an increase in VE, and this in turn should increase the metabolic cost for the respiratory muscles and thus increase VO_2 (Bailey and Pate 1991). In the present study, there were no observed increases in VE and coupled with the relatively low weight loss, the possibly increased core temperature seemed to have had no significant effects on RE.

Despite the observed decrease in RER and the reduction of body weight no statistically significant difference in RE was found immediately following the prolonged run. This author can only speculate that perhaps the prolonged run for the Vm50 group was of insufficient duration (44 min average), and that of the Vm70 group was of insufficient intensity to cause an increase in their respective economy values. It would seem that RE is a stable measure not easily perturbed by prolonged work of less than 60 minutes at intensities less than 80% of $\dot{V}O_{2max.}$ This study seems to demonstrate that for both trained and untrained individuals there may be a critical workload that must be maintained in order to cause decreases in a runner's economy.

5.5 Summary

The present study explored the differences in running economy between a group of highly trained males and a group of moderately to untrained males, as well the effects of prolonged running on economy. As was expected, the groups were statistically significantly different in $\dot{V}O_{2max}$ as well as a few other anthropometric variables. What was interesting to note is that there were no differences between groups in RE. This was true for both relative and absolute measures of economy. Even when the RE was expressed as $ml \cdot kg^{-0.75} \cdot min^{-1}$ in order to rule out the effects of the significantly different mean body mass of the two groups, there were still no significant differences found. This study showed that improved RE may only occur at the velocities at which an athlete trains. At unfamiliar running velocities RE appears to vary significantly between individuals, this is true for both highly trained and untrained individuals. This variation in RE appears to mask the differences, if any, found between groups differing significantly in training status.

The data in this investigation showed that following a prolonged run for up to 60 minutes at an intensity near the subject's individual ventilatory threshold, RE was not perturbed from previously recorded values. This was true for both groups. This study demonstrated that RE is a fairly stable value that is not easily disturbed by exercise at intensities near the ventilatory threshold for 60 minutes or less, regardless of training status.

5.6 Recommendations for Future Research

1. Examine the differences in RE between groups with differing fitness levels using $\%\dot{V}O_{2max}$ as the criteria for the intensity of the RE tests. Measure treadmill velocity when a steady state as near as possible to the desired intensity has been reached. Test a variety of intensities (60, 70, and 80%).
2. Test runners at a self-selected pace that most closely matches their most frequent training velocity.
3. Obtain a detailed history of run-trained subjects; group in terms of performance times, middle-distance versus long-distance, years of training. Look for correlates to RE among these variables.
4. Examine the relationship between $\dot{V}O_{2max}$ and RE in a group of runners homogeneous in performance times. Obtained detailed training history and attempt to find any correlations between RE and type of training.

After having completed this study and having studied the related literature it is this author's opinion that RE remains to be an interesting and worth while area for future investigation. There are still many questions that surround this topic remaining to be answered. Examining the effects of different training methods on RE, as well attempting to determine the amount that RE can be improved are both valuable and challenging areas that require much more investigation. Due to the observed variability between individuals observed in RE the comparison of individuals differing in training status becomes difficult. When attempting to examine these differences fuel utilization is an important thing to take into consideration. Results from this study show that groups can be similar in submaximal$\dot{V}O_2$, but may be significantly different in RER. This could possibly lead to erroneous conclusions about groups differences in RE. Careful control of the factors affecting RE is of utmost importance when attempting to make comparisons within and between individuals. This author feels that RE should be tested at velocities that are comfortable for the subjects. Use testing velocities that most closely match the runner's most frequent training velocity, and ensure that non-runners become familiar with the treadmill and run at velocities below their ventilatory threshold. It is questionable whether comparing two groups differing in running abilities at a common velocity (i.e. 6mph) is acceptable. If the better runners never run at these speeds are we really examining the effects of training on RE.

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APPENDIX A

Table 6. Non-runners (Vm50) during the prolonged run

Subject	Prolonged Run Time (min)	Lactate at end of run (mmol)	Prolonged Run Velocity (mph)
1	37.7	11.3	7.0
2	60.0	6.4	7.0
3	37.0	11.3	6.5
4	45.0	5.4	7.0
5	26.0	5.2	7.0
6	40.0		6.5
7	45.0	5.3	7.0
8	42.3		7.0
9	60.0	4.1	7.5
10	injured		
Mean	**43.7**	**7.0**	**6.9**

Table 7. Comparison of VO_2 at Tvent velocity during VO_{2max} test to the VO_2 at Tvent velocity during RE tests for Vm50 group.

		A		B			
Subject	VO_{2max}	Tvent from VO_{2max}		During RE test		A -B	Velocity@ Tvent
		ml/kg/min	$\%VO_{2max}$	ml/kg/min	$\%VO_{2max}$		
1	50.8	42.3	83.3	43.2	85.1	0.9	7.0
2	52.6	430	81.7	42.2	80.2	-0.8	7.0
3	48.2	36.9	76.7	41.1	85.4	4.2	6.5
4	52.0	36.7	70.7	40.1	77.2	3.4	7.0
5	53.3	39.9	74.8	43.5	81.5	3.6	7.0
6	49.7	38.0	76.6	41.4	83.4	3.4	6.5
7	50.3	42.0	83.5	45.6	90.7	3.6	7.0
8	52.6	41.7	79.2	47.8	90.8	6.1	7.0
9	52	40.1	77.2	43.7	84.1	3.6	7.5
10	54.6	40.6	74.4	45.3	82.9	4.6	7.0
Mean	**51.6**	**40.1**	**77.8**	**43.4**	**84.1**	**3.3**	**7.0**
SD	**1.9**	**2.2**	**4.1**	**2.3**	**4.2**	**1.9**	**0.3**

Table 8. Comparison of VO_2 at Tvent velocity during VO_{2max} test to the VO_2 at Tvent velocity during RE tests for Vm70 group.

Subject	VO_{2max}	A: Tvent from VO_{2max}		B: During RE test		A -B	Velocity@ Tvent
		ml/kg/min	$\%VO_{2max}$	ml/kg/min	$\%VO_{2max}$		
1	75.0	55.2	73.6	56.4	75.3	1.2	9.0
2	66.4	44.2	66.5	45.4	68.4	1.2	8.0
3	75.8	54.7	72.1	57.5	75.8	2.8	9.0
4	77.6	57.5	74.1	59.6	76.8	2.1	9.0
5	63.4	42.4	66.9	51.1	80.7	8.7	8.0
6	64.8	47.7	73.6	58.3	90.0	10.6	8.5
7	65.5	47.0	71.8	52.7	80.4	5.6	8.5
8	82.2	53.6	65.2	54.9	66.9	1.3	9.5
9	68.4	46.3	67.7	49.5	72.5	3.2	8.5
10	69.8	49.3	70.7	51.6	74.0	2.3	8.0
Mean	**70.9**	**49.8**	**70.2**	**53.7**	**76.1**	**3.9**	**8.6**
SD	**6.3**	**5.1**	**3.3**	**4.4**	**6.6**	**3.3**	**0.5**