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Effect of Intense Interval Workouts on Running
Economy Using Three Recovery Durations

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A Thesis Submitted to the Faculty of Graduate Studies and Research in Partial
Fulfilment of the requirements for the Degree of Master of Arts (M.A.)

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ABSTRACT

The purposes of this study were to determine if (1) RE is adversely affected by intense interval bouts of 10 x 400-m, and (2) if there is an interaction effect between RE and recovery duration during the workouts. Twelve highly trained male runners ($\text{VO}_{2\text{max}} = 72.5 \pm 4.3 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) performed 3 interval workouts of 10 x 400-m with a minimum of 4 days between runs. Recovery between repetitions was randomly assigned at 60, 120 or 180 s. The velocity for each 400-m run was determined from a treadmill $\text{VO}_{2\text{max}}$ test. The average running velocity was $357.9 \pm 9.0 \text{ m}\cdot\text{min}^{-1}$. Following the workout, rating of perceived exertion (RPE) increased significantly ($p<0.01$) as recovery duration decreased (14.4 at 180 s; 16.1 at 120 s; 17.7 at 60 s recovery). Prior to and following each workout, RE was measured at speeds of 200 and 268 $\text{m}\cdot\text{min}^{-1}$. Changes from pre to post RE tests in VO_2 , HR, and RER were similar for the three recovery conditions. Averaged across conditions, VO_2 increased significantly ($p<0.01$) pre to post tests (38.5 to 40.5 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ at 200 $\text{m}\cdot\text{min}^{-1}$ and from 53.1 to 54.5 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ at 268 $\text{m}\cdot\text{min}^{-1}$). HR increased (124 to 138; and 151 to 157 bpm) and RER decreased (0.90 to 0.78; and 0.93 to 0.89) at 200 and 268 $\text{m}\cdot\text{min}^{-1}$, respectively ($p<0.01$). This study showed that RE can be perturbed after a high-intensity interval workout and that changes in VO_2 , HR and RER were independent of the recovery duration between repetitions.

RÉSUMÉ

Le but de cet étude était de déterminer si (1) le coût énergétique de la course (CEC) était affecté par un entraînement intense d'intervalles de 10 x 400-m, et (2) s'il y a une interaction entre le temps de récupération entre les répétitions et le CEC pendant les entraînements. Douze coureurs masculin en bonne condition physique ($VO_{2max} = 72.5 \pm 4.3 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) ont fait 3 entraînements d'intervalles de 10 x 400-m, avec un minimum de 4 jours entre les courses. Le temps de récupération entre les répétitions était, donné au hasard, de 60, 120 ou 180 s. La vitesse pour chaque course de 400-m était déterminé du test de VO_{2max} du tapis roulant. La vitesse moyenne était $357.9 \pm 9.0 \text{ m}\cdot\text{min}^{-1}$. Après l'entraînement, l'évaluation de la perception de la fatigue a augmenté d'une façon significative ($p < 0.01$) pendant que le temps de récupération diminuait (14.4 à 180 s; 16.1 à 120 s; 17.7 à 60 s temps de récupération). Avant et après chaque entraînement, CEC était mesuré à des vitesses de 200 et 268 $\text{m}\cdot\text{min}^{-1}$. Aucune différence était trouvé dans les valeurs de CEC après l'entraînement chez les trois temps de récupération. En comparant avec les différents conditions, VO_2 avait augmenté d'une façon significative ($p < 0.01$) avant et après les tests (38.5 à 40.5 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ à 200 $\text{m}\cdot\text{min}^{-1}$ et de 53.1 à 54.5 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ à 268 $\text{m}\cdot\text{min}^{-1}$). La fréquence cardiaque (F_c) avait aussi augmenté (124 à 138; et 151 à 157 bpm) et le ratio d'échange respiratoire (RER) avait diminué (0.90 à 0.78; et 0.93 à 0.89) à 200 et 268 $\text{m}\cdot\text{min}^{-1}$ respectivement ($p < 0.01$). Cet étude démontre que le CEC peut être affecté après un entraînement d'intervalles à haute intensité, et que les changements dans le VO_2 , F_c et RER étaient indépendants du temps de récupération entre les répétitions.

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Introduction

Running economy (the VO_2 measured at a given submaximal velocity) is one of many physiological variables associated with successful running performance among a homogeneous group of runners (Conley and Krahenbuhl 1980; Conley et al. 1981, 1984; Morgan 1989a,b, 1992). These studies have shown that improved running economy (RE) results in heightened running performance. Variances in RE among and within cohorts of runners are influenced by many biomechanical, physiological and anthropometric factors (Morgan 1989b; Pate et al. 1992).

Fatigue induced by submaximal long duration exercise significantly increases the aerobic demand of running (Breuckner et al. 1995; Cavanagh et al. 1985; Guezennac et al. 1996; Xu and Montgomery 1995). Following prolonged activity, increases in VO_2 have been associated with increases in heart rate, core temperature, fat catabolism and blood catecholamines as well as decreases in biomechanical efficiency, muscle glycogen and liver glycogen content (Bailey and Pate 1991; Kalis et al. 1988; MacDougall et al. 1974; Morgan and Craib 1992; Williams and Cavanagh 1987). In contrast, some studies have shown that long duration runs at 74 to 90% of $\text{VO}_{2\text{max}}$ did not alter RE (Dressendorfer 1991; Martin et al. 1987; Morgan et al. 1990, 1996). Since the acute effects of intense interval workouts on RE have not been examined, the purposes of this study were to determine if RE is adversely affected following intense interval workouts and to determine if there is an interaction effect between RE and recovery duration during the workouts.

Methods

Subjects

Twelve highly trained male runners volunteered for this study. Subjects signed a consent form prior to participating in the investigation. Four subjects qualified for the 1996 Canadian Olympic Trials, and one subject was a Canadian record holder in the triathlon. Based on the Mercier Scoring Tables (Mercier 1994), personal best times were rated between 612 and 840 points (mean 727 ± 82 points).

Table 1 shows the physical and training characteristics. The subjects were lean with sum of 6 skinfolds equal to 44.8 ± 5.0 mm. Skinfold thickness was measured at six sites (chest, triceps, suprailiac, subscapular, thigh and abdomen) and converted to percent fat (Yuhasz 1974).

All subjects participated in 5 testing sessions which included: (1) treadmill accommodation runs; (2) a $\text{VO}_{2\text{max}}$ test; (3) and three interval training sessions with RE tests at 200 and 268 $\text{m}\cdot\text{min}^{-1}$.

Session 1: Treadmill accommodation runs

Since previous research has determined that treadmill accommodation runs of 30 to 60 minutes are required for subjects to settle into a consistent running pattern (Cavanagh and Williams 1982; Schieb 1986), all subjects performed an accommodation session on a calibrated, Quinton Q65 treadmill (Quinton instrument Co.). Subjects warmed-up at 200 $\text{m}\cdot\text{min}^{-1}$ for 5-min, and then ran three, 10-min bouts at 268 $\text{m}\cdot\text{min}^{-1}$ with a 5-min recovery between runs.

Session 2: Determination of $\text{VO}_{2\text{max}}$ and velocity for the three interval workouts

Approximately 4–5 days after the treadmill accommodation session, subjects performed a $\text{VO}_{2\text{max}}$ test. Measurements were averaged every 20 seconds using a SensorMedics 2900 metabolic cart (SensorMedics Corp., Yorba Linda, CA). After a standard 5-min warmup ($201 \text{ m}\cdot\text{min}^{-1}$), subjects ran at $215 \text{ m}\cdot\text{min}^{-1}$ for 1-min at 0% grade. Treadmill speed was increased $13.4 \text{ m}\cdot\text{min}^{-1}$ (0.5 mph) every minute while the grade remained at 0%. The test ended when subjects reached volitional exhaustion. HR was recorded every 5 seconds using a Polar Vantage XL heart rate monitor (Polar Electro Oy, Finland). Peak VO_2 was determined from the highest 60-s period and was designated as $\text{VO}_{2\text{max}}$. The $\text{VO}_{2\text{max}}$ averaged $72.5 \pm 4.3 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ($5.01 \pm 0.53 \text{ L}\cdot\text{min}^{-1}$). This value is consistent with $\text{VO}_{2\text{max}}$ data reported previously for well-trained and elite middle distance runners (Daniels et al. 1977; Morgan et al. 1996; Svendsen and Sjödén 1985). Maximum HR values ranged from 172 to 208 bpm. Time to exhaustion on the treadmill varied from 10.9 to 13.7 minutes (mean 12.3 ± 0.9 minutes). When running on a track compared to a level treadmill, Pugh (1970, 1971) suggested a reduction in speed by 4% to account for differences in oxygen cost associated with overcoming wind resistance during overground running at $360 \text{ m}\cdot\text{min}^{-1}$. Thus, we reduced the final treadmill velocity on the $\text{VO}_{2\text{max}}$ test by 4% in order to establish the speed for the 10 x 400-m interval workouts.

Sessions 3-5: RE tests - pre and post workouts

In order to minimize daily variation in running economy within individuals and

to avoid any circadian influences (Daniels et al. 1984; Morgan et al. 1994), subjects performed three interval workouts and RE tests at the same time each day and wearing the same shoes. Subjects refrained from eating for two hours prior to each session.

Two RE tests were performed prior to and after each interval workout. Temperature in the lab was controlled between 20 and 23°C. After a 5-min warmup at 201 m·min⁻¹ and stretching, subjects ran at 200 and 268 m·min⁻¹ (0% grade) for 6-min with a five minute passive recovery between each RE test. RE was calculated in ml·kg⁻¹·min⁻¹ and L·min⁻¹ by averaging the VO₂ during the last three minutes of each bout. Post test RE values were adjusted to account for changes in body mass due to the 10 x 400-m interval session.

The interval workouts were performed indoors on a 200-m banked track with a mondo-surface. Subjects ran 10 x 400-m with active recovery (60, 120, 180 s) randomly assigned. The RE tests were performed 10-min prior to and following each workout. Mean environmental conditions in the fieldhouse for temperature, barometric pressure, and relative humidity were: 23.4 ± 2.4°C, 756 ± 6.6 mm Hg, and 62 ± 7.2%. Subjects ran alone with verbal encouragement and 200-m split times provided by the investigators. A minimum of four days recovery was allowed between workouts.

Heart rate was continually recorded using a Polar Vantage XL monitor using 5 s recording intervals. Peak HR per repetition and minimum HR during each recovery were recorded.

Statistical analyses

The experimental designs were two repeated measures ANOVAs (one for each RE speed) with subjects (S) crossed with recovery (R) and time (T), and described as : $S_{12} \times R_3 \times T_2$. The dependent variables were VO_2 ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ and $\text{L}\cdot\text{min}^{-1}$), HR, V_E , and RER. Statistical significance was declared if $\alpha < 0.05$.

Results

From Table 2, the mean velocities were 357.4, 359.0 and 357.5 $\text{m}\cdot\text{min}^{-1}$ in the 60, 120 and 180 s recovery conditions, respectively. No differences ($p < 0.05$) were found among the recovery conditions. Mean weight loss ranged from 0.9 to 1.1 kg. The rating of perceived exertion (Borg 1982) indicated that the workout was "moderately difficult" with 180 s recovery between reps, "difficult" with 120 s recovery, and "very difficult" with only 60 s recovery. The RPE ratings were statistically significant from each other ($p < 0.01$).

During the workout, peak HR increased significantly ($p < 0.01$) from rep 1 to rep 10 with the highest values in the 60 s recovery condition (Figure 1). Minimum recovery HR increased ($p < 0.01$) as the recovery duration decreased with mean values of 116 ± 25 , 122 ± 22 , and 148 ± 15 bpm following repetition 9 for the 180, 120, and 60 s recovery conditions, respectively.

Table 3 compares the RE data prior to and following the interval training sessions. At 268 $\text{m}\cdot\text{min}^{-1}$, the mean VO_2 was $53.1 \pm 2.8 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ which is similar to that reported by Pollock (1977) for elite middle and long distance runners. At

200 $\text{m}\cdot\text{min}^{-1}$, the mean VO_2 was $38.5 \pm 2.6 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ which is similar to that reported by Morgan (1990). The RE values were 4 - 5 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ or 11.5% lower than predicted by the ACSM equation for the general population (ACSM 1995).

Pre to post test comparisons showed no changes in V_E . In contrast, VO_2 , HR, and RER changed significantly from pre to post test ($P < 0.01$) at both RE velocities independent of the recovery duration. HR increased by 14 bpm at 200 $\text{m}\cdot\text{min}^{-1}$ and by 6 bpm at 268 $\text{m}\cdot\text{min}^{-1}$. Averaged across recovery conditions, VO_2 increased ($p < 0.01$) by 2.0 and 1.4 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ at RE speeds of 200 and 268 $\text{m}\cdot\text{min}^{-1}$, respectively. RER decreased by 0.12 and 0.04 ($p < 0.01$) independent of the recovery duration.

Discussion

Following an intense interval workout at 100% $\text{VO}_{2\text{max}}$, we observed an increase in VO_2 of 2.6 and 5.0% during RE tests at 268 and 200 $\text{m}\cdot\text{min}^{-1}$ which were independent of the recovery duration. These data corroborate earlier findings where O_2 cost measured immediately after running bouts at 60 to 80% of $\text{VO}_{2\text{max}}$ increased 3.9 - 6.6% at RE speeds between 188 and 243 $\text{m}\cdot\text{min}^{-1}$ (Breuckner et al. 1991; Guezennec et al. 1996; Xu and Montgomery 1995). The VO_2 during a RE test may remain elevated for several days following high intensity exercise. Two athletes competing in the 10,000 m (mean time = 28 min) at the 1984 Olympic games, were tested 2 and 4 days post - exercise (Cavanagh et al. 1985). At 268 $\text{m}\cdot\text{min}^{-1}$, VO_2 increased by 4.5%.

In contrast, four studies report no change in RE after intense exercise (Dressendorfer 1991; Martin et al. 1987; Morgan et al. 1990, 1996). Of these studies,

only Dressendorfer (1991) tested RE immediately post-workout. Following a 21.1 km run at race pace ($239 \pm 33 \text{ m} \cdot \text{min}^{-1}$ which was equivalent to 74 - 80 % $\text{VO}_{2\text{max}}$), VO_2 increased insignificantly by 1.4%. Also, in the investigations by Martin et al. (1987), and Morgan et al. (1990, 1996), RE was unchanged following 30 min training runs at 90% of $\text{VO}_{2\text{max}}$.

For this study, high calibre runners were selected since the daily variation in RE within this population is only 1 - 2% (Morgan et al. 1994). RE was assessed at 200 and 268 $\text{m} \cdot \text{min}^{-1}$ for several reasons. First, these speeds permitted all subjects to complete both runs with an RER value below 1.00. Second, previous studies have traditionally used 268 $\text{m} \cdot \text{min}^{-1}$ as the most common speed to measure RE (Cavanagh et al. 1985; Conley et al. 1980, 1981, 1984; Daniels et al. 1977; Londeree 1986; Morgan and Daniels 1994; Pollock 1977), thus our results are comparable to these studies. Third, Daniels and Daniels (1992) suggested that RE should be measured at various speeds because efficiency may vary with velocity. Middle distance runners are more efficient at 800-m and 1500-m speeds than at marathon speeds, while long distance runners are more economical at slower than at faster velocities (Costill 1972; Londeree 1986; Pollock 1977).

Several mechanisms have been proposed to account for the rise in VO_2 (worsened RE) after prolonged activity. These mechanisms include an increase in heart rate to compensate for decreasing stroke volume, an increase in core temperature as a result of thermal stress, an increase in blood catecholamines, a change in substrate utilization with an increase in fat metabolism resulting from a decrease in muscle and liver glycogen, and

a decrease in biomechanical efficiency, (Bailey and Pate 1991; Kalis et al. 1988; MacDougall et al. 1974; Morgan and Craib 1992; Williams and Cavanagh 1987).

During the interval workouts, there was a gradual upward drift in peak HR of 10 bpm from repetition 1 to repetition 10 and a weight loss of 1 kg. Furthermore, a comparison of the post workout RE tests with the pre workout tests showed an increase in HR by 14 bpm at $200 \text{ m}\cdot\text{min}^{-1}$ and 6 bpm at $268 \text{ m}\cdot\text{min}^{-1}$. The upward drift in HR during exercise may be attributed to a fall in central blood volume causing decreased filling pressure resulting in decreased stroke volume (Nielsen et al. 1984). A decrease in blood volume from pre to post workout can be attributed to water loss from sweating and a compartmental shift of water from plasma to interstitial fluid. A compartmental shift of 250 ml of water occurs within 10 minutes from the onset of exercise (Nielsen et al. 1984). As well, a withdrawal of parasympathetic tone was probable (Kalis et al. 1988).

An increase in core temperature (T_c) affects RE (MacDougall et al. 1974; Saltin and Stenberg 1964). With the increase in T_c the metabolic rate rises due to the Q_{10} effect. This process elicited by exercise increases the energy cost (Brooks et al. 1995). During prolonged exercise there is an upward drift in VO_2 in hyperthermic conditions (MacDougall et al. 1974). In moderate environmental conditions, Saltin and Stenberg (1964) showed that VO_2 rose by 5% during three hours of steady state exercise. We also observed a 5.2% increase in VO_2 when RE was assessed at $200 \text{ m}\cdot\text{min}^{-1}$ and a 2.6% increase at $268 \text{ m}\cdot\text{min}^{-1}$ following interval workouts. An increase in T_c induces an increase in V_E with an accompanying oxygen cost for the respiratory muscles (Bailey and

Pate 1991; Hanson et al. 1982). In this study V_E was elevated by $4.1 \text{ L}\cdot\text{min}^{-1}$ at $268 \text{ m}\cdot\text{min}^{-1}$ from pre to post test.

An increase in blood catecholamines and a change in substrate utilization with an increased dependency on fat combustion are also partly responsible for the rise in VO_2 (Bailey and Pate 1991; Kalis et al. 1988). Carbohydrates are a more efficient fuel for energy production than fats, by about 7% (Brooks et al. 1995). Therefore, when carbohydrates are available and used as the substrate for energy production, a lower oxygen cost occurs (Bailey and Pate 1991). A decrease in RER indicates that relatively more fat is being used for the generation of ATP. Following the interval workouts, we observed decreases in RER of 0.12 ($200 \text{ m}\cdot\text{min}^{-1}$) and 0.04 ($268 \text{ m}\cdot\text{min}^{-1}$). Although muscle biopsy procedures were not employed in this study, it is reasonable to assume that an interval workout of 10 x 400-m at a mean velocity of $358 \text{ m}\cdot\text{min}^{-1}$ would substantially lower muscle glycogen. Green (1978) reported that 10 x 60 s reps of high intensity skating (120% of $\text{VO}_{2\text{max}}$) lowered muscle glycogen from 85.6 to $25.6 \text{ mmol}\cdot\text{kg}^{-1}$ wet weight in the vastus lateralis muscle. Also, reductions in muscle glycogen concentration, RE ($\Delta\text{RE} = 2.0 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) and RER ($\Delta\text{RER} = 0.06$) have been reported in trained subjects who performed 5 days of high-intensity running ($20 \text{ km}\cdot\text{day}^{-1}$ at $80\% \text{ VO}_{2\text{max}}$) while on a low carbohydrate diet (Kirwan et al. 1988).

During our RE test at $200 \text{ m}\cdot\text{min}^{-1}$, VO_2 increased by $100 \text{ ml}\cdot\text{min}^{-1}$ when comparing pre and post tests. Based on calculations using the thermal equivalence of oxygen for the non-protein respiratory quotient (McArdle et al. 1996), we estimate that increased dependency on fat combustion was the major factor accounting for the changes

in RE. Also, some CO_2 may have been retained to replenish bicarbonate stores that were used to buffer hydrogen ions from lactic acid accumulation during the interval repetitions.

Morgan et al. (1989) reviewed biomechanical variables that may influence running economy. They noted that limb morphology was potentially a significant influence on the energy cost of locomotion. Recently, Morgan et al. (1996) measured RE and 9 biomechanical variables, 1, 2, and 4 days following a 30 min running bout at 90% of $\text{VO}_{2\text{max}}$. Running style remained unaltered after the high intensity runs.

We speculated that changes in RE would be greater following the workout with 60 s of recovery between repetitions compared to the 180 s recovery condition. Our physiological (HR) and psychological (RPE) data support this view. It is also reasonable to assume that more lactate would accumulate in the 60 s condition since less time was available for removal of lactate and for re-synthesis of ATP and PCr. However, our results indicated that changes in RE were independent of recovery duration. We attribute these findings to the fact that regardless of the recovery duration, running time at 100% of $\text{VO}_{2\text{max}}$ was the same in each condition. The intensity of each repetition and not the duration of the recovery influenced RE in a similar manner.

To our knowledge, the present study is the first to compare the acute effects of an interval workout at 100% $\text{VO}_{2\text{max}}$ on RE and to examine the effects of recovery duration on RE. The practical application to the present findings is the knowledge that RE can be perturbed with 10 repetitions of 400-m. Since RE is worsened after repeated hard efforts, quantification of the time needed to re-establish base line economy values

athletes in optimizing training. For example, coaches/athletes could schedule the required interval workouts from a typical microcycle in a more scientific fashion by knowing the time it takes for RE to return to pre-workout levels.

Conclusion

This study showed that RE can be perturbed after an intense interval bout of 10 x 400-m. Also, changes in VO_2 , HR and RER during the RE tests were independent of the recovery duration between repetitions.

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Table 1 Physical and training characteristics (n = 12)

Variable	Mean	SD	Range
Age (years)	24.8	5.1	18 - 34
Mass (kg)	69.2	6.5	60.5 - 82.3
Height (cm)	180.3	7.3	168.9 - 191.5
Sum of six skinfolds (mm)	44.8	5.0	36.7 - 52.0
Fatness (%)	8.0	0.5	7.2 - 8.7
VO _{2max} (L·min ⁻¹)	5.01	0.53	4.45 - 6.00
VO _{2max} (ml·kg ⁻¹ ·min ⁻¹)	72.5	4.3	64.3 - 80.5
HR _{max} (bpm)	189	11	172 - 208
Training (years)	7.6	4.5	1.0 - 17.0
Training (km·week ⁻¹)	72.5	23.1	40.0 - 120.0
Personal Best (Mercier points)	727	82	612 - 840

Table 2 Weight loss, RPE, and velocity of the 10 x 400-m Workouts (mean $\pm$ SD)

Variables	Recovery Condition		
	60 s	120 s	180 s
Velocity (m·min ⁻¹)	357.4 $\pm$ 8.7	359.0 $\pm$ 8.6	357.5 $\pm$ 10.0
Velocity (s per 400-m)	67.2 $\pm$ 2.7	66.9 $\pm$ 2.7	67.2 $\pm$ 2.0
RPE	17.7 $\pm$ 0.9	16.1 $\pm$ 1.1**	14.4 $\pm$ 0.8**
Post workout weight loss (kg)	0.9 $\pm$ 0.3*	1.1 $\pm$ 0.4*	1.0 $\pm$ 0.4*

* significantly different compared with pre workout ($p < 0.01$)

** significantly different compared with 60 s recovery condition ($p < 0.01$)

Table 3 Physiological variables during the RE tests prior to and following the interval workouts (Mean $\pm$ SD).

Dependent variables	RE Test	Recovery Condition		
	($\text{ml} \cdot \text{min}^{-1}$)	60 s	120 s	180 s
VO_2 ($\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$)	Pre 200	38.5 ± 3.0	38.4 ± 2.8	38.5 ± 2.3
	Post 200	$40.5 \pm 2.4^*$ +2.0	$40.7 \pm 2.8^*$ +2.3	$40.4 \pm 3.0^*$ +1.9
	Pre 268	52.9 ± 2.8	52.8 ± 2.9	53.7 ± 2.9
	Post 268	$54.3 \pm 2.4^*$ +1.4	$54.3 \pm 2.1^*$ +1.5	$55.2 \pm 3.2^*$ +1.5
VO_2 ($\text{L} \cdot \text{min}^{-1}$)	Pre 200	2.67 ± 0.34	2.66 ± 0.30	2.67 ± 0.32
	Post 200	$2.77 \pm 0.30^*$ +0.10	$2.77 \pm 0.29^*$ +0.11	$2.76 \pm 0.36^*$ +0.09
	Pre 268	3.66 ± 0.41	3.66 ± 0.34	3.72 ± 0.41
	Post 268	$3.71 \pm 0.37^\Phi$ +0.05	$3.69 \pm 0.34^\Phi$ +0.03	$3.78 \pm 0.39^\Phi$ +0.06
HR (bpm)	Pre 200	125 ± 11	124 ± 11	124 ± 12
	Post 200	$139 \pm 14^*$ +14	$138 \pm 13^*$ +14	$136 \pm 14^*$ +12
	Pre 268	151 ± 11	150 ± 11	151 ± 13
	Post 268	$157 \pm 12^*$ +6	$157 \pm 11^*$ +7	$156 \pm 13^*$ +5
RER	Pre 200	0.89 ± 0.05	0.90 ± 0.04	0.90 ± 0.03
	Post 200	$0.77 \pm 0.04^*$ -0.12	$0.79 \pm 0.03^*$ -0.11	$0.79 \pm 0.04^*$ -0.11
	Pre 268	0.92 ± 0.04	0.94 ± 0.03	0.92 ± 0.03
	Post 268	$0.88 \pm 0.04^*$ -0.04	$0.89 \pm 0.04^*$ -0.05	$0.89 \pm 0.04^*$ -0.05
VE ($\text{L} \cdot \text{min}^{-1}$)	Pre 200	65.1 ± 9.8	64.6 ± 11.0	64.3 ± 11.2
	Post 200	65.8 ± 10.5 +0.7	66.6 ± 10.2 +2.0	66.9 ± 11.3 +2.6
	Pre 268	92.0 ± 10.9	92.8 ± 13.7	94.0 ± 13.7
	Post 268	95.6 ± 11.6 +3.6	95.9 ± 13.2 +3.8	98.1 ± 11.2 +4.1

* $p < 0.01$ compared with pretest values; Φ $p = 0.054$ compared with pretest values

Legend

Figure 1 Peak HR per repetition and minimum HR per recovery interval.

* significantly different from rep 1 ($p < 0.01$)

Φ significantly different from 120 and 180 s recovery condition ($p < 0.01$)

Figure 2 VO_2 , HR, and RER during the RE tests prior to and following the interval workouts.

* significantly different from pre RE test ($p < 0.01$)

Φ borderline significant from pre RE test ($p = 0.054$)

APPENDICES

APPENDIX A

REVIEW OF LITERATURE

INTRODUCTION

Successful running performance in middle and long distances is associated with many physiological variables, namely $\text{VO}_{2\text{max}}$ (Costill, 1967, 1973; Costill & Fox, 1969; Davies & Thompson, 1979; Evans et al., 1995; Farrell et al., 1979; Foster et al., 1978; Ramsbottom et al., 1987; Sjödin & Svendenhag, 1985; Williams & Cavanagh, 1987), fractional use of $\text{VO}_{2\text{max}}$ (Conley et al., 1984; Davies & Thompson, 1979; Léger & Mercier., 1986; Sjödin & Svendenhag, 1985), anaerobic threshold (Costill et al., 1973; Evans et al., 1995; Farrell et al., 1979, Ramsbottom et al., 1989; Rhodes & McKenzie, 1984), body composition (Pollock et al., 1977b, Wilmore et al., 1977), and muscle fiber type (Costill et al., 1976; Coyle et al., 1991, 1992; Fink et al. 1977; Williams & Cavanagh, 1987). Among a group of runners with similar $\text{VO}_{2\text{max}}$ values, running economy—the VO_2 measured during submaximal running—has also been shown to correlate highly with performance (Conley & Krahenbuhl, 1980; Conley et al., 1981, 1984; Daniels, 1985; Daniels & Daniels, 1992; Krahenbuhl et al., 1989; Morgan et al., 1989a,b, 1992; Ramsbottom et al., 1987,1989; Sjödin & Schéle, 1982).

Morgan et al. (1995) recently provided evidence suggesting that running economy (RE) can vary significantly between trained and untrained runners, and between elite and non-elite groups. They showed that elite Olympic calibre 10-km runners had greater $\text{VO}_{2\text{max}}$ and better RE than their less-talented counterparts, and that trained subjects exhibited better RE than untrained subjects.

RE and $\text{VO}_{2\text{max}}$ have also been shown to differ among runners who compete in varying distance events. For example, middle distance (MD), long distance (LD), and

marathon runners all have different RE and $\text{VO}_{2\text{max}}$ (Brandon, 1995; Daniels & Daniels, 1992; Pollock, 1977a; Svendsen & Sjödín, 1994). Average $\text{VO}_{2\text{max}}$ scores of elite MD runners range from 68 to 75 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (Boileau et al., 1982; Joyner, 1993) while elite LD runners vary between 75 and 85 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (Boileau et al., 1982; Åstrand & Rodahl, 1986).

Although average RE values (at 268 $\text{m}\cdot\text{min}^{-1}$) of elite MD and LD runners are found to be 52 - 55 and 46 - 53 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ respectively (Londeree, 1986; Pollock, 1977a), both economical and uneconomical MD and LD runners can be found among these elite athletes (Morgan et al., 1995). For instance, Steve Scott, a world class MD runner in the 1980's, had submaximal VO_2 values resembling those of a world class LD runner. In fact, over a training period of one year, Steve Scott's VO_2 at 268 $\text{m}\cdot\text{min}^{-1}$ varied from 49 to 46 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (Conley et al., 1984). Nevertheless, MD runners generally have inferior RE and $\text{VO}_{2\text{max}}$ values than elite LD runners (Svendsen & Sjödín, 1994). Not surprisingly, when running at faster speeds, MD runners were more economical than LD runners (Daniels & Daniels, 1992).

Though much is known about RE and performance, many questions remain to be answered. For instance, fatigue is one factor which has been shown to affect RE; however, the effect of fatigue on RE has not been extensively researched. Previous research has examined the effects of prolonged, submaximal exercise on RE, however the acute effects of intense intervals workouts on RE have not been studied. This question deserves further review.

The review of literature covers various issues pertinent to RE. This review

summarizes the following topics in relation to running economy: (1) measurement of RE; (2) $\text{VO}_{2\text{max}}$ and performance; (3) interval and continuous training; (4) fatigue; (5) temperature; (6) treadmill versus overground running; (7) intra-individual variability; (8) biomechanical considerations; and (9) other factors.

Measurement of Running Economy

Running economy can be obtained by measuring the steady-state VO_2 for a standardized running speed (Morgan et al., 1989b). At steady-state, VO_2 , HR, C.O., and La levels show no major fluctuations and remain stable (Åstrand & Rodahl, 1986). Aerobic (and not anaerobic) metabolism should be the main energy source when performing a RE test. By running at a steady-state submaximal speed, the total energy cost of exercise will not be underestimated from the measured VO_2 (Bransford & Howley, 1977). When determining RE, Morgan et al. (1992b) suggest three criteria. First, a steady-state VO_2 (represented by a balance between the energy requirements of the active muscles and the aerobic resynthesis of ATP); second, blood lactate accumulation less than $4 \text{ mmol}\cdot\text{L}^{-1}$; and third, a RER of less than 1.00 (Bransford & Howley, 1977; Conley & Krahenbuhl, 1980; Daniels & Daniels, 1992; Krahenbuhl & Pangrazi, 1983; Pierce et al., 1993; Powers et al., 1983).

The individual's fitness level must be considered when taking RE measurements. Blood lactic acid accumulation varies at different speeds according to the subject's fitness level, and the total energy expenditure seems to rise exponentially as a function of running velocity, at least beyond 80% $\text{VO}_{2\text{max}}$ (Daniels, 1985). Therefore, choosing

speeds which elicit 80% of $\text{VO}_{2\text{max}}$ or more may potentially underestimate the total VO_2 requirement since anaerobic metabolism contributes to the energy source. The anaerobic threshold (AT) is defined as "the exercise intensity that supposedly represents the limit at which aerobic processes predominate" (MacDougall, 1977), or, as "the speed below which the rate of muscle lactate production does not exceed lactate uptake or removal [by other tissues]" (Green, 1991). A RE measurement should not be taken at or above the subject's AT due to the absence of a steady-state. High performance endurance athletes frequently run at velocities above 80% of $\text{VO}_{2\text{max}}$ and more without reaching the AT. However, average, untrained people usually elicit the AT at 50-65% of $\text{VO}_{2\text{max}}$ (Fox, 1979; Wasserman et al., 1987).

Although various speeds are used to measure RE, the most common velocity used in the literature has been $268 \text{ m}\cdot\text{min}^{-1}$ (Cavanagh et al., 1985; Conley et al., 1980, 1981, 1984; Daniels et al., 1977; Londeree, 1986; Morgan & Daniels, 1994; Morgan et al., 1996; Pollock, 1977a) especially for elite MD and LD runners. RE tests have been conducted at speeds as low as $177 \text{ m}\cdot\text{min}^{-1}$ (Londeree, 1986), and as high as $350 \text{ m}\cdot\text{min}^{-1}$ for elite MD and LD runners (Daniels & Daniels, 1992). One reason why the velocity of $268 \text{ m}\cdot\text{min}^{-1}$ (10 mph; $4.47 \text{ m}\cdot\text{s}^{-1}$; 6:00-mile pace) is a typical submaximal test intensity is that a heterogeneous group of runners can attain this speed within each runner's aerobic capacity (Daniels & Daniels, 1992). Also, this speed has been shown to elicit a more constant metabolic response than at slower velocities (Morgan et al., 1994). However, Daniels & Daniels (1992) have also suggested that RE tests be given at speeds which elicit 95% of a runner's $\text{VO}_{2\text{max}}$ (for 10 km runners) or at speeds which

simulate racing conditions (for MD runners) so that an "aerobic profile" for each athlete can be made even though the anaerobic threshold is exceeded.

Single speed RE tests are not as effective as multiple speed RE tests if the purpose is to compare individual RE values (Daniels & Daniels, 1992; Morgan, 1989a). The rationale for multiple tests is that some runners are more efficient at a particular speed than at another speed. For example, MD runners are shown to be more efficient at 800-m and 1500-m speeds than at marathon paces, while LD runners are shown to be more economical at slower marathon-like speeds than at faster velocities (Daniels & Daniels, 1992). Other investigators have also demonstrated that LD runners are more economical when running at slower paces than MD runners (Costill, 1972; Londeree, 1986; Pollock, 1977a).

The duration of the RE test varies with times of five minutes (Cavanagh et al., 1985), six minutes (Daniels & Daniels, 1992; Morgan et al., 1995, 1996; Xu & Montgomery, 1995), and ten minutes (Dressendorfer, 1991; Morgan et al., 1990a, 1995). Whipp & Wasserman (1972) suggested that the time to reach steady-state is dependant on both the speed and fitness level of the subjects. Furthermore, at low to moderate work-rates, it is possible that a steady-state condition can be found within three minutes (Whipp & Wasserman, 1972). Nevertheless, Morgan et al. (1989b) advised that the length of a RE test should be between six to ten minutes (Morgan et al., 1989b). Any RE measurement longer than ten minutes increases VO_2 , HR, and body core temperature (Raven & Stevens, 1988; Saltin & Stenberg, 1986).

Researchers have determined an individual's RE value by averaging the last two

(Conley & Krahenbuhl, 1980; Daniels & Daniels, 1992; Dressendorfer, 1991; Morgan et al., 1995, 1996; Williams & Cavanagh, 1987), three (Conley et al., 1981; Krahenbuhl et al., 1983, 1989; Xu & Montgomery, 1995) and four minutes (Morgan et al., 1990a). During multiple speed RE tests, a three to fifteen minute rest between tests is recommended (to allow for adequate recovery) depending on the age and fitness level of the subjects (Conley et al., 1984; Conley & Krahenbuhl, 1980; Daniels & Daniels, 1992; Morgan et al., 1989a, 1990a).

With regard to the number of testing sessions required to obtain stable RE values, Williams et al. (1991) indicated that 90% of the intra-individual variation in economy could be accounted with two days of consecutive testing. Additionally, five days of consecutive testing explained 98% of the intra-individual variation in RE. These authors stated that the average of two economy values per subject yielded an acceptable measure of aerobic demand, and that the small improvement in precision gained with more testing is not practical.

Previous research has determined that treadmill accommodations between 30 and 60 minutes are required for runners to settle into a consistent biomechanical running pattern (Cavanagh & Williams, 1982; Schieb, 1986). Therefore, when measuring RE, treadmill accommodation runs should precede any RE test so that consistent VO_2 values are recorded.

Running Economy, VO_{2max} , and Performance

Although the relationships between RE, performance and VO_{2max} are interrelated with one another, I have disseminated these variables into pairs for better comprehension.

Running Economy and Performance

The association between RE and performance has been extensively measured. Among a homogenous group of runners [runners with similar VO_{2max} values], RE correlates highly with performance (Conley & Krahenbuhl, 1980; Conley et al., 1981, 1984; Daniels, 1985; Daniels & Daniels, 1992; Krahenbuhl et al., 1989; Morgan et al., 1989a,b, 1992; Ramsbottom et al., 1987; Sjödín & Schéle, 1982). RE is positively correlated ($r=0.82$ and $r=0.64$) with 10-km performance time among runners with similar VO_{2max} values and ability (Conley & Krahenbuhl, 1980; Morgan, 1989a). Sjödín & Schéle (1982) reported a strong positive correlation ($r=0.74$) between RE at $268 \text{ m} \cdot \text{min}^{-1}$ and performance over 3.2-km. Moreover, longitudinal studies documented that the performance improvement of a world class MD runner [Steve Scott] and another elite LD runner over a year was due to improved RE (Conley et al., 1981, 1984). As well, gradual improvement in running performance of young males over seven years was accompanied by better economy and not by a higher relative VO_{2max} [even though improvement in RE occurred in the absence of training] (Krahenbuhl et al., 1989).

It appears that when a heterogeneous group of trained runners were used, some studies did show modest correlations between RE and performance, while other studies did not. At speeds of $250 \text{ m} \cdot \text{min}^{-1}$ for the RE test, correlations of $r=0.59$ and $r=0.55$

have been reported with performance over 3.2-km (Costill et al., 1979) and 42.2-km (Sjödín & Svendsen, 1985) for male runners. Ramsbottom et al. (1987) used RE speed tests of $188 \text{ m} \cdot \text{min}^{-1}$ for males and females and found correlations of $r=0.39$ and $r=0.34$ with performance over 5-km.

In contrast, other studies showed no significant correlations between RE and distance running performance (Costill et al., 1973; Deason et al., 1991; Evans et al., 1995; Williams & Cavanagh, 1987), perhaps because these runners studied were not similar in performances and $\text{VO}_{2\text{max}}$ (i.e. 30:30 - 38:30 for 10-km, Williams & Cavanagh, 1987; $52.4 - 68.2 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ Deason et al., 1991).

Correlations between RE and performance are usually positive. A positive correlation between RE and performance indicates that a lower RE at a given speed is associated with a faster time in a given running distance. However, one study showed that a negative correlation ($r=-0.71$) existed between 5-km performance and RE at $215 \text{ m} \cdot \text{min}^{-1}$ (Ramsbottom et al., 1989). This research showed that a higher oxygen cost incurred from training resulted in better 5-km performance times (Ramsbottom et al., 1989). Nonetheless, when manipulating the data to express RE as a relative percentage of $\text{VO}_{2\text{max}}$, oxygen cost decreased with training, and thus RE and 5-km performance becomes positive, implying that better RE is associated with better performance.

Running Economy and $\text{VO}_{2\text{max}}$

The literature has shown a negative relationship (Morgan et al., 1995; Nevill et al., 1992; Pate et al., 1989; Pollock et al., 1977a; Svendsen & Sjödín, 1994), a positive relationship (Mayhew, 1977; Morgan & Daniels, 1994; Padilla et al., 1992; Pate

at al., 1992), and no relationship (Daniels et al., 1984; Sjödín & Shéle, 1982) between RE and $\text{VO}_{2\text{max}}$. A negative relationship between RE and $\text{VO}_{2\text{max}}$ means that runners with high maximal aerobic power consume less oxygen for a given running velocity than runners with low maximal aerobic power, while a positive relationship indicates that runners with high maximal aerobic power consumes more oxygen for a given running velocity than runners with low maximal aerobic power.

Pate et al. (1989) have described the relationship between $\text{VO}_{2\text{max}}$ and RE at $160 \text{ m} \cdot \text{min}^{-1}$ as negative. In a similar situation, a study has shown that RE and $\text{VO}_{2\text{max}}$ is significantly lower in elite marathon runners than in elite MD runners, indicating that a negative relationship between RE and $\text{VO}_{2\text{max}}$ exists but that MD runners have a higher oxygen cost (with higher $\text{VO}_{2\text{max}}$) than marathon runners (Pollock et al., 1977a). Pollock and colleagues suggested that [mechanical] efficiency may be a factor affecting oxygen uptake during running.

Svendenhag & Sjödín (1994) revealed that while $\text{VO}_{2\text{max}}$ was lower in elite MD runners as compared to elite LD runners, oxygen cost was higher in the MD group. Morgan et al. (1995) reported significantly diverse $\text{VO}_{2\text{max}}$ and RE values of four different categories of runners [(1) elite 10-km runners who qualified for the Olympic trials, (2) sub-elite 10-km runners, (3) good 10-km runners, (4) and non-trained physical education students]. Although both economical and uneconomical runners were found within each category, generally the lowest oxygen cost was found among the elite runners (runners with the highest $\text{VO}_{2\text{max}}$ values), and highest among the non-trained physical education students (runners with the lowest $\text{VO}_{2\text{max}}$ values). Nevill et al. (1992) also

demonstrated that runners with higher $\text{VO}_{2\text{max}}$ have better RE values than runners who had lower $\text{VO}_{2\text{max}}$, suggesting that differences in the relationship of VO_2 (or RE) with running speed exists between subjects' with different levels of $\text{VO}_{2\text{max}}$.

A few studies have also shown a positive relationship between RE and $\text{VO}_{2\text{max}}$ (Mayhew, 1977; Morgan & Daniels, 1994; Padilla et al., 1992; Pate et al., 1992). The majority of these reports show that runners with higher maximal aerobic power had greater oxygen uptake for a given running velocity compared to runners with low maximal aerobic power. Among homogeneous elite 10-km runners, Morgan & Daniels (1994) found a significant correlation of 0.59 between RE and $\text{VO}_{2\text{max}}$ among runners displaying comparative levels of aerobic fitness. Padilla et al. (1992) found similar results with a homogeneous group of elite MD runners ($r=0.75$). Pate et al. (1992) confirms that the VO_2 tends to be higher in subjects with higher maximal aerobic power, and lower in subjects who have lower maximal aerobic power. These researchers found a significant positive correlation ($r=0.26$) between RE (at $161 \text{ m}\cdot\text{min}^{-1}$) and $\text{VO}_{2\text{max}}$.

Sometimes, LD runners have similar performance times but different profiles for RE and $\text{VO}_{2\text{max}}$. For example, a runner with a low $\text{VO}_{2\text{max}}$ may compensate with superior RE and compete with a runner with a high $\text{VO}_{2\text{max}}$ and poor RE.

Three reasons which may explain a positive association between RE and $\text{VO}_{2\text{max}}$ are mentioned by Pate et al. (1992). First, there is an indication that body weight to the first power is not the appropriate variable to use when normalizing for body size (Pate et al., 1992). However, the reason that $\text{VO}_{2\text{max}}$ and RE were significantly correlated in these studies may be that most of the energy cost of running is associated with

movements of limbs which constitute only a fraction of body weight. Weight distribution between the trunk and limbs varies across subjects and is not appropriately controlled by dividing VO_2 by body weight (Pate et al., 1992). As such, persons who have a greater fraction of body weight in the limbs may tend to have a greater $\text{VO}_{2\text{max}}$ because of the greater muscle mass. During submaximal running, these same people tend to show higher VO_2 because of the increased energy cost of moving the heavier limbs (Pate et al., 1992). In fact, Padilla et al. (1992) found that the energy cost of running was significantly correlated with body mass ($r=-0.55$ for women, and $r=-0.43$ for men), and that differences in RE among various ages and sex are related to body mass (Bourdin et al., 1993). As such, these correlations indicate that the heavier subjects display better RE. However, when normalizing submaximal VO_2 relative to a power function of $\text{kg}^{0.75}$, the RE differences between the sexes as well as intra-individual variations of RE which occur during adolescence are mostly nullified (Svendsen, 1995). Bergh et al. (1991) also suggested that VO_2 during running is better related to $\text{kg}^{0.75}$ than to $\text{kg}^{1.00}$. As such, re-analyzing the data on the association between RE and $\text{VO}_{2\text{max}}$ might yield different results with expressing VO_2 in terms of $\text{ml}\cdot\text{kg}^{-0.75}\cdot\text{min}^{-1}$ instead of $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$.

The second reason which may explain the positive association between $\text{VO}_{2\text{max}}$ and RE is related to substrate utilization during submaximal exercise. It is known that the percentage of energy expenditure due to fat oxidation during submaximal exercise is inversely related to $\text{VO}_{2\text{max}}$ (Pate et al., 1992). Since the amount of oxygen needed to produce a given amount of ATP is greater when fat is a fuel source (as compared to carbohydrate or protein), oxygen cost would increase for individuals better able to utilize

fat to produce energy. Thus, runners with higher $\text{VO}_{2\text{max}}$ probably required higher VO_2 during submaximal running partly because of greater reliance on fat oxidation (Bailey & Pate, 1991).

The third reason as to why $\text{VO}_{2\text{max}}$ and RE are positively associated is the speed at which economy was measured ($161 \text{ m}\cdot\text{min}^{-1}$; 10 min per mile) which represents relative exercise intensities ranging from 46% to 91% $\text{VO}_{2\text{max}}$ that were often atypical of a normal training pace. It is possible that runners with higher $\text{VO}_{2\text{max}}$ values were less comfortable with running at this pace and therefore were less economical due to mechanical and/or neuromuscular factors (Pate et al., 1992).

Other data show no correlation between RE and $\text{VO}_{2\text{max}}$ (Daniels et al., 1984; Sjödin & Shéle, 1982). Usually, heterogeneous groups produce higher correlations since variability of scores on both variables are large, and therefore not restricted.

$\text{VO}_{2\text{max}}$ and Performance

Historically, $\text{VO}_{2\text{max}}$ has been the best choice for assessing running endurance (Åstrand & Rodahl, 1986; Boileau et al., 1982; Londeree, 1986). When assessing the relationship between $\text{VO}_{2\text{max}}$ and distance running performance among a heterogeneous group of runners [runners with varying performances and $\text{VO}_{2\text{max}}$ values], strong negative correlations ($r=-0.76$ to -0.91) are found (Costill, 1967; Costill & Fox, 1969; Davies & Thompson, 1979; Evans et al., 1995; Farrell et al., 1979; Foster et al., 1978; Ramsbottom et al., 1987; Sjödin & Svendsen, 1985; Williams & Cavanagh, 1987). Therefore, this would indicate that the use of a heterogeneous sample in a study allows for a stronger correlation in the relationship between RE and $\text{VO}_{2\text{max}}$.

Conversely, when a homogeneous group of runners is studied, $\text{VO}_{2\text{max}}$ becomes poorly correlated with performance (Daniels & Daniels, 1992). Conley & Krahenbuhl (1980) and Morgan & Daniels (1994) found the relationship between $\text{VO}_{2\text{max}}$ and 10-km performance was insignificant ($r=-0.12$ and $r=-0.21$) due to the homogeneity of the subjects.

Deason et al., (1991) suggests that the insignificant negative correlation ($r=-0.49$) between $\text{VO}_{2\text{max}}$ and 800-m running time indicates that $\text{VO}_{2\text{max}}$ alone is not a good predictor of performance, even though the use of a heterogeneous sample might indicate otherwise. $\text{VO}_{2\text{max}}$ might not be as important in 800-m as compared to longer distances because approximately 60% of the ATP comes from anaerobic metabolism. Furthermore, a summary of studies located in Brandon's (1995) review shows that $\text{VO}_{2\text{max}}$ and 800-m performance exhibit moderate negative correlations (-0.49 to -0.66), while strong negative correlations (-0.79 to -0.87) are found between $\text{VO}_{2\text{max}}$ and 3000-m times.

In Sjödin & Svendsen's review (1985), high negative correlations (-0.63 to -0.91) are found between $\text{VO}_{2\text{max}}$ and marathon time. However, Davies & Thompson (1979) showed that with increasing distance, the association of $\text{VO}_{2\text{max}}$ between male athletic performance diminishes, but nevertheless remains significant ($r = -0.85$, 5-km; $r = -0.82$, marathon; $r = -0.72$, 84.64-km) while the relationship between the fractional use of VO_2 ($\%\text{VO}_{2\text{max}}$) and time simultaneously increases. This suggests that success at both marathon and ultramarathon distances is possibly solely dependent on the development and utilization of a large percentage of $\text{VO}_{2\text{max}}$, and also may explain why individual performances for a specific event are hazardous to predict (Davies &

Thompson, 1979).

Nonetheless, the preponderance of data clearly shows that $\text{VO}_{2\text{max}}$ is more important for distances around 5000-m than for ultramarathon or 800-m running, since LD running is associated closer to submaximal efforts near the anaerobic threshold (60 to 90% of $\text{VO}_{2\text{max}}$) [Coetzer et al., 1993]. On the other hand, MD runners compete at intensities as high as 135% $\text{VO}_{2\text{max}}$; thus greater anaerobic capacity is required for distances ranging from 800 to 3000-m. Still, to compete at a world-class level, a high $\text{VO}_{2\text{max}}$ is an important component for elite performance in events ranging from 800-m to the marathon.

Velocity at $\text{VO}_{2\text{max}}$ and Performance

Velocity at $\text{VO}_{2\text{max}}$ ($v\text{VO}_{2\text{max}}$) appears to be a better predictor of running success than $\text{VO}_{2\text{max}}$ or running economy alone (Morgan et al., 1989b). $v\text{VO}_{2\text{max}}$ is a good predictor of performance because it gives insight as to how fast an individual can run when operating at his/her maximal aerobic power or any fraction of $\text{VO}_{2\text{max}}$ (Daniels & Daniels, 1992). These authors showed that $\text{VO}_{2\text{max}}$ and RE explained only part of the performance difference between males and females, and having equal RE or $\text{VO}_{2\text{max}}$ values did not guarantee equal performance. However, different combinations of $\text{VO}_{2\text{max}}$ and RE can produce similar 10-km run times and $v\text{VO}_{2\text{max}}$ (Morgan et al., 1989a). For example, $v\text{VO}_{2\text{max}}$ correlated higher with 10-km performance times ($r=-0.87$) than either RE ($r=0.64$) or $\text{VO}_{2\text{max}}$ [$r=-0.45$] (Morgan et al., 1989a). Furthermore, high correlations found between $v\text{VO}_{2\text{max}}$ and 5 - 10-km race times were similar to that explained by treadmill velocities which elicited a 4 mmol·L⁻¹ blood lactate concentration

($OBLA_{vel}$) in runners (-0.81 to -0.89; Sjödín & Jacobs, 1981; Evans et al., 1995; Ramsbottom et al., 1989).

Interval and Continuous Training

It is common knowledge that endurance training improves running performance and alters many physiological and metabolic variables. Some of these changes which occur from endurance training are: increases in VO_{2max} (Bailey & Messier, 1994; Burke et al., 1994; Conley et al., 1981, 1984; Overend et al., 1992; Poole & Gaesser, 1985; Ramsbottom et al., 1989), increases in $OBLA_{vel}$ (Burke et al., 1994; Dotan et al., 1989; Ramsbottom et al., 1989; Sjödín et al., 1982) increases VT_{vel} [Burke et al., 1994; Olson et al., 1988; Overend et al., 1992; Poole & Gaesser., 1985], increases in fat catabolism while running (as shown by a decrease in RER) [Gorostiaga et al., 1991; Ramsbottom et al., 1989], decreases in heart rate at submaximal velocities (Bailey & Messier, 1991; Gorostiaga et al., 1991; Ramsbottom et al., 1989), and increases in various oxidative (mitochondrial) enzymes (Sjödín et al., 1982; Gorostiaga et al., 1991). Over the last twenty years, longitudinal research has provided evidence that oxygen demand decreases with both regular interval (Conley et al., 1981, 1984; Svendenhag & Sjödín, 1985) and continuous (Bailey & Messier, 1991; Brisswalter & Legros, 1995; Daniels et al., 1978a; Patton & Vogel, 1977; Sjödín et al., 1982) types of training regardless of whether subjects are previously trained or not.

Conversely, attempts to improve RE in trained and untrained subjects with interval and continuous training have been unsuccessful (Brisswalter et al., 1994b;

Daniels et al., 1978b; Dotan et al., 1989; Petray & Krahenbuhl, 1985; Wilcox & Bulbulian, 1984) or have documented higher oxygen cost with training (Lake & Cavanagh, 1990; Ramsbottom et al., 1989). However, closer scrutiny of the data from Ramsbottom et al. (1989) showed that when RE was expressed as a relative percentage of $\text{VO}_{2\text{max}}$, RE did not worsen with training, but improved. In a similar situation, RE among high performing male college MD and LD runners did not change over a period of five months in which these runners ran cross-country, indoor and outdoor track; but when VO_2 was expressed as a relative percentage of $\text{VO}_{2\text{max}}$, a 1.5% reduction in oxygen cost was observed over three seasons at RE speeds of 200 and 268 $\text{m}\cdot\text{min}^{-1}$ (Brisswalter & Legros, 1994b). Although this improvement in RE may be attributed to increases in $\text{VO}_{2\text{max}}$ by the end of the training period, it is not known whether interval or continuous training was responsible in this case since both were used extensively.

Overtraining and detraining have been shown to effect RE. Overtraining (defined as an imbalance between exercise and recovery, resulting in prolonged and severe fatigue) is speculated to increase VO_2 due to the added recruitment or stimulation of motor units (Kuipers & Keizer, 1988). Even though one study confirmed that overtraining increases oxygen cost (Pizza et al., 1995), most findings have shown that RE remains unaltered after periods of increased training (Dotan et al., 1989; Houmard et al., 1989; Pizza et al., 1995), or improved after periods of very heavy training (Legros et al., 1992; Brisswalter & Legros, 1995). In Brisswalter's & Legros's (1995) study, homogeneous elite MD runners increased the amount of continuous training done at 80% $\text{VO}_{2\text{max}}$ by 300%. After two weeks, RE improved by 9%, but this occurred only

at the training pace which elicited 80% $\text{VO}_{2\text{max}}$. This implies that improvement in RE may be indicative of one's training pace. In another study, an increase in work volume from 120-km to 240-km per week resulted in an improvement in RE (Legros et al., 1992). Furthermore, 11 trained runners doubled their training load by either cross-training (cycling and running) or by just running (Pizza et al., 1995). By doubling run training only, RE did not change; but by increasing training load with cycling (cross-training), oxygen cost increased. Cross-training may not be a useful way of improving performance since the combination of cycling and running increases oxygen demand.

There are studies involving detraining in which athletes reduced running volume by 60% in one week (Dotan et al., 1989), 60% in 10 days (Houmard et al., 1989), or a two week, 100% complete cessation of training (Houmard et al., 1992). In these studies, RE did not significantly change, suggesting that RE is not symptomatic of a decrement in cardio-respiratory fitness (Houmard et al., 1992). However, when expressed as a relative percentage of $\text{VO}_{2\text{max}}$, oxygen demand increased—albeit probably insignificantly—with complete cessation of training for two weeks (Houmard et al., 1992). In two studies, RE even improved after three weeks of reduced training (associated with elevated carbohydrate utilization) and similarly with one week of tapering to 15% of original weekly mileage (Houmard et al., 1990, 1994).

Little consensus exists regarding the effects of training on running economy. Studies have been criticized for the different training protocols used (Gorostiaga et al., 1991) and for limitations in experimental design. Such limitations are small sample sizes; lack of multiple economy measures to account for normal intra-individual

variation; and failure to control factors which may potentially influence RE such as training status, fatigue and circadian variation (Morgan et al., 1989b).

A retrospective cross-sectional analysis ($n = 89$) has found that RE differs among subject groups varying in calibre and training status (Morgan et al, 1995). As well, Morgan et al. (1995) has shown that although economical and uneconomical runners can be found in all calibre of athletes, trained subjects exhibit superior RE than untrained, and elite runners have higher VO_{2max} and better RE values than their less talented counterparts such that elite runners > sub-elite runners > good runners > untrained runners. However, the least economical "elite" athlete displayed an aerobic demand that was greater than the mean VO_2 values for the other two running groups (sub-elite and good runners). This indicates that "the variability in RE viewed within a particular sample [$\approx 20\% \pm 2\%$] is independent of performance ability, training status, or familiarity with running...and when viewed collectively, these data provide support for the dual notions that better or worse economy is not necessarily a function of performance or training status and that anatomical and physiological characteristics may influence an individual's economy profile" (Morgan et al., 1995).

Definitions and Purposes of Interval & Continuous Training

Both interval training (IT) and continuous training (CT) are necessary to maximize potential for competition (MacDougall & Sale, 1981). Interval training is a type of training which alternates periods of rest and recovery (Daniels & Scardina, 1984). It involves repeated bouts of work, each lasting anywhere from 30 seconds to 5 minutes, usually at the same intensity (95 to 100% VO_{2max}) and with a recovery period following

each work bout which is equal to, or shorter in duration than the work bout which it follows (Daniels & Scardina, 1984). Interval training has a major advantage over continuous training as it allows one to perform more work at high intensity with less lactic acid accumulation. The general purpose of IT is "to stress the aerobic capacity of an individual while he or she is performing a specific endurance-type exercise" (Daniels & Scardina, 1984). Since the intensity and duration of exercise will determine the production and accumulation of lactate (Olson et al., 1988), altering the work:rest ratio (WR) changes the contribution of anaerobic and aerobic metabolism, and the total energy needs may be manipulated (Fox et al., 1969). In interval training (like other forms of physiological conditioning), the intensity of exercise should be geared to the particular energy systems to be trained (McArdle et al., 1996). Skeletal muscle adapts to aerobic interval training (1:1 WR) to stress the long-term energy system so that the capacity for aerobic metabolism increases and lactate production decreases (Jansson et al., 1990). Moreover, high intensity IT exerts its greatest effect on the structural and biochemical properties of the muscle (MacDougall & Sale, 1981). But as the intensity of the interval work (1:1 WR) approaches and exceeds 100% $\text{VO}_{2\text{max}}$, the anaerobically generated acidosis becomes a major factor in contributing to muscle fatigue (MacDougall & Sale, 1981); thus, the predominant energy system emphasized is glycolysis (McArdle et al., 1996). Therefore, two types of IT are established: (1) low power output interval training (LPO-IT), which is characterized by exercise and pause periods of at least 2 minutes; and (2), high power output interval training (HPO-IT), which is characterized by exercise and pause periods of less than 1 minute (Fox et al., 1977) so that the succeeding exercise

interval begins before the recovery is complete (McArdle et al., 1996).

CT is different from IT in that CT does not involve repeated bouts of work with alternated periods of rest and recovery. CT involves continuous "non-stop" exercise at a constant submaximal intensity (Poole & Gaesser, 1985) somewhere around 70 to 90% of maximum HR (McArdle et al., 1996). While IT is done at approximately 95-100% $\text{VO}_{2\text{max}}$ for short periods of time, CT is done at intensities between 50 and 80% $\text{VO}_{2\text{max}}$ for much longer periods (longer than 20 minutes). Low intensity CT involves steady-state running, while higher intensity CT (at around 80% $\text{VO}_{2\text{max}}$) involves running at or just above the anaerobic threshold. The purpose of low and high intensity CT is to exert its greatest effect on the oxygen transport system of the body (MacDougall & Sale, 1981), by augmenting the oxidative capacity of type I (ST) fibers (Henriksson & Reitman, 1976). In addition, CT around the anaerobic threshold theoretically increases OBLA_{vel} , thereby increasing distance running performance by allowing an individual to run at a faster pace while still maintaining a steady-state. Past research supports the notion that OBLA_{vel} and VT_{vel} increases with CT at approximately 80% $\text{VO}_{2\text{max}}$ (Brisswalter & Legros, 1995; Dotan et al., 1989; Hollmann et al., 1981; Overend et al., 1992; Sjödín et al., 1982). Additionally, Gorostiaga et al., (1989) concluded that even low intensity CT for eight weeks (3x per week, 30 min·day⁻¹) at 50% of $\text{VO}_{2\text{max}}$ increased the OBLA_{vel} of previously non-trained subjects.

Although both IT and CT regimens are used to improve fitness, there is more conflicting evidence as to which is more effective in improving aerobic parameters (Fox, 1975; Hollmann et al., 1981; Gorostiaga et al., 1991; Overend et al., 1992; Poole &

Gaesser, 1985). While some studies show that CT has little effect on $\text{VO}_{2\text{max}}$ (Conley et al., 1981) and that IT increases $\text{VO}_{2\text{max}}$ more so than CT (Gorostiaga et al., 1991; Overend et al., 1992), other studies have shown that CT is equally effective as IT in elevating maximal aerobic power (Fox, 1975; Poole & Gaesser, 1985). Furthermore, while CT appears to be better than IT at increasing both VT_{vel} and OBLA_{vel} (Gorostiaga et al., 1991; Hollmann et al., 1981; Poole & Gaesser, 1985), another study has shown that CT is equally effective as IT in increasing these parameters (Overend et al., 1992). Since training studies used different exercise durations, frequencies, program lengths, and varying initial fitness levels of subjects, these factors may explain the variety of conclusions. However, studies have shown that interval training between 85-100% $\text{VO}_{2\text{max}}$ increases one or both of these parameters as well (Burke et al., 1994; Olson et al., 1988). Debate continues whether CT or IT is more beneficial in elevating aerobic capacity, OBLA_{vel} and VT_{vel} . There is no doubt that IT and CT results in performance success and both should be used to vary training and perhaps achieve a more psychologically pleasing training program (McArdle et al., 1996).

Fatigue

The onset of fatigue can potentially increase oxygen cost by increasing the demand for either internal energy (HR, ventilation, temperature) or external energy [segmental mass distribution, stride length, biomechanical variables] (Bailey & Pate, 1991). As glycogen depletes from working muscles, the reduction in RER due to increased fat catabolism increases oxygen cost (Bailey & Pate, 1991; Ramsbottom et al.,

1989).

The direct and/or indirect effects of fatigue on running economy have been examined in nine studies. All studies examined the effects of prolonged exercise on RE. Four studies showed no change in RE after a prolonged exercise bout (Dressendorfer, 1991; Martin et al., 1987; Morgan et al., 1990a, 1996), while five reported changes in RE (Brueckner et al., 1991; Guezennec et al., 1996; Cavanagh et al., 1985; Wilcox et al., 1990; Xu & Montgomery, 1995).

Dressendorfer (1991) had nine average male marathon runners perform a half-marathon (21.1 km) road run at their best previous marathon race pace ($\approx 90\%$ of $\text{VO}_{2\text{max}}$). Average finishing time was 89 minutes (S.D. ± 16.5 minutes). Within 30-min after the race, RE was measured. The steady-state VO_2 increased insignificantly from 44.4 to 45 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ while RER decreased ($\Delta = 0.03$). A 1.4% increase in oxygen translates into a one minute addition in marathon performance time (Morgan et al., 1995). The small sample size ($n = 9$) may have attributed to the insignificant absolute changes in RE.

Martin et al. (1987) and Morgan et al. (1990a, 1996) had LD male runners exercise for approximately 30 minutes at 89% of $\text{VO}_{2\text{max}}$. RE and RER were unchanged after one, two, and four days of hard training runs. However, in the Martin et al. (1987) investigation, RE did not change despite a decrease in RER and elevated blood fatty acid concentrations. In Morgan et al.'s (1990a) study, RER values were significantly lower one and two days after the exhaustive run ($\Delta = 0.02$), yet no changes in RE were observed. They speculated that the increase in estimated percentage of kilocalories

derived from fat was only 6.6% and therefore not sufficient enough to produce a significant rise in VO_2 .

Xu & Montgomery (1995) confirmed that within 10 minutes after a 90 minute run on a track at 60 and 80% of $\text{VO}_{2\text{max}}$, oxygen demand increased (3.9% to 8% depending on the speed of the RE test). They stated that the decrease in RER ($\Delta = 0.05 - 0.10$) post-test partly explained the increase in aerobic demand. Also, Cavanagh et al. (1985) showed that oxygen cost increased after an all-out Olympic 10,000-m race. Specifically, Cavanagh et al. (1990) showed that RE improved 4.5% when re-tested four days after the 10,000-m heats, as compared with the RE measured 2 days after the Olympic heats. This suggests that oxygen demand increased after the intense, exercise bout, and then decreased as time allowed for recuperation from fatigue. However, no pre-RE test was given to these Olympic athletes prior to the 10,000-m race, thus, it is not known whether RE returned to original values after four days, or if fatigue was still a factor 4 days post-test. Moreover, the small sample size ($n = 2$) in this study may limit the universality of their findings. Furthermore, Wilcox et al. (1987) showed that VO_2 increased 2.9% one day after a 5-km downhill run (-10% grade), and maintained the increase in VO_2 two and three days post-run. Since all subjects ran at an easy pace ($\approx 48\%$ of $\text{VO}_{2\text{max}}$), the nature of fatigue is unclear. Two credible reasons may account for why VO_2 increased after the 5-km downhill run: (1) minute muscle tears in the quadriceps femoris muscles resulting from the eccentric contractions of downhill running; and (2) the training status of the subjects. Untrained subjects may be fatigued with minimal downhill runs. Guezennec et al. (1996) wanted to verify that the energy cost of running increased at the

end of a triathlon. Compared with a control 10-km run, VO_2 increased ($p < 0.05$) from 47.8 to 51.2 $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ during the 10-km running portion of a triathlon. They suggested that the increase was partly due to the 12 $\text{L} \cdot \text{min}^{-1}$ increase in ventilation and the 14.4% decrease in plasma volume. Brueckner et al. (1991) measured the energy cost of 10 amateur runners after completing 15, 32, or 42-km at constant speed on an indoor track. These authors demonstrated that there was an insignificant rise in VO_2 after 15-km, but after 32 and 42-km, a 4.3 and 6.6% increase ($p < 0.05$) occurred. They suggested that the stable RE values which remained up to 15-km are a result of unaltered neuromuscular coordination. Table 1 and 2 summarizes the results of the literature on fatigue and RE.

Table 1: Studies showing no change in RE following fatigue

Authors	Subjects	Duration & Intensity	RE Test Relative to Exercise (days)	Speed (m · min ⁻¹)	VO ₂
Dressendorfer, 1991	9 ♂ LD	21.1 km (≈89min) @ 74-80% of max	immediately after	239 ± 33	NS
Martin et al., 1987	8 ♂ LD	hard training run	1 day	NM	NS
Morgan et al., 1990a	16 ♂ LD	30 min ≈89% of max	1, 2, 4 days after	200	NS
Morgan et al., 1996	10 ♂ LD	30 min @ 90% of max	1, 2, 4, days after	241 - 295	NS

LD long distance runners

NM not mentioned

NS not significant

Table 2: Studies showing that fatigue affected RE

Author	Subjects	Duration & Intensity	RE Test Relative to exercise (days)	Speed ($\text{m} \cdot \text{min}^{-1}$)	VO ₂
Breuckner et al., 1991	10 amateur ♂ LD	each ran 15, 32, or 42 km twice @ 65% of max	immediately after each bout	231	NS after the 15 km bout, but ↑ 4.3 & 6.6% after the 32 & 42 km bout
Guezennec et al., 1996	11 ♂ triathletes	1.5 km swim, 40 km cycle, 10 km run. ($\approx 77\% \text{ VO}_{2\text{max}}$)	immediately after the triathlon	243 (10-km pace)	6.6% ↑ after the triathlon
Cavanagh et al., 1985	2 ♂ elite LD	10 km (28min) @ 90 of max	about 2 and 4 days after	268	↓ of 4.5% between 2 & 4 days after
Wilcox et al., 1990	7 ♂ and 4 ♀ subjects	5 km downhill (20 min) @ -10% grade & 48% of max	1, 2, 3, days after	♂ 188 & 215 ♀ 161 & 188	↑ of 2.8% after day 1 and maintained the 2.8% ↑ 2 & 3 days after
Xu & Montgomery, 1995	10 amateur & 4 elite ♂ LD runners or triathletes	two 90 min runs at 60 & 80% of max	immediately after	188 & 228	↑ 3.9% & 6% @ 228 $\text{m} \cdot \text{min}^{-1}$ ↑ 4.7% & 8% @ 188 $\text{m} \cdot \text{min}^{-1}$

LD long distance runners

Temperature

An increase in body core temperature (Q_{10} effect) affects RE (MacDougall et al., 1974; Saltin & Stenberg, 1964). Under normal environmental conditions, a 5% rise in VO_2 occurred during three hours of prolonged steady-state exercise (Saltin & Stenberg, 1964). Under hyperthermic conditions, MacDougall et al. (1964) also observed VO_2 drift occurring in subjects working at 70% of VO_{2max} . They suggested several reasons for this rise in VO_2 including hyperthermia (because of the increased energy requirement of peripheral circulation), increased sweat-gland activity, increased hyperventilation, and decreased efficiency of energy metabolism. An increase in catecholamines in circulating blood, and a change in substrate utilization (from carbohydrates to fat) are also partly responsible for the rise in VO_2 (Hamilton et al., 1991; Kalis et al., 1988).

In contrast, other studies have shown either no VO_2 drift or reduced oxygen consumption with an increase in body core temperature (Dill, 1965; Maron et al., 1976; Rome, 1982; Rowell et al., 1969). These authors believe that muscular efficiency improves as muscle temperature increases because the amount of oxygen needed to produce a given amount of ATP is reduced. In fact, both phenomena may occur. As muscle temperature increases, oxygen cost decreases initially, but then increases as the mechanisms involved in heat dissipation are activated (Bailey & Pate, 1991).

Furthermore, it is suggested that training-induced adaptations to heat increases plasma volume by 12% which assists in maintaining stroke volume in hyperthermic conditions thereby minimising myocardial work (Bailey & Pate, 1991). Plasma volume expansion contributes to increased sweating capacity and enables the body to tolerate

greater heat production (Bailey & Pate, 1991).

Treadmill versus Overground Running

To evaluate field situations, RE measurements is typically carried out indoors on treadmills, where air and wind resistance are minimal (Morgan et al., 1989b). Depending on the runner, the oxygen cost of running is 2% to 8% higher outdoors compared with treadmill running (Daniels et al., 1986; Davies, 1980a; Pugh, 1970, 1971). Davies (1980a) states that the oxygen cost of overcoming air resistance on a calm day outdoors is 8% for sprinting ($10 \text{ m}\cdot\text{s}^{-1}$; $600 \text{ m}\cdot\text{min}^{-1}$), 4% for MD running ($6 \text{ m}\cdot\text{s}^{-1}$; $360 \text{ m}\cdot\text{min}^{-1}$), and 2% ($5 \text{ m}\cdot\text{s}^{-1}$; $300 \text{ m}\cdot\text{min}^{-1}$) for marathon running.

In comparison, Pugh reported that the aerobic demand of overcoming air resistance was 8% in an 5000-m race with the VO_2 increasing as a function of the square of the opposing wind velocity (Pugh, 1970, 1971). Likewise, when wind and running velocity were the same as would occur during overground running in calm air, the added oxygen cost increased with the cube of the wind velocity. Pugh also hypothesized that athletes who run in a more aerodynamical position directly behind a competitor (drafting) could save about one second per 400-m. Specifically, drafting approximately 1-m behind a runner at $360 \text{ m}\cdot\text{min}^{-1}$ decreases the total energy expenditure by 7% (Pugh, 1970). Daniels et al. (1986) observed similar results to Pugh's with VO_2 7.8% higher when running in calm air (at 268 and $322 \text{ m}\cdot\text{min}^{-1}$) compared to treadmill running. Additionally, Daniels et al. (1986) observed two more phenomena: first, the energetic disadvantage of running into a headwind was relatively greater than the energetic

advantage gained by running with a tailwind; and second, when running velocity and tailwind velocity were equal, overground VO_2 was equivalent to treadmill running.

In disagreement are two studies that observed no difference in RE between track/overground running and treadmill running (McMiken & Daniels, 1976; Bassett et al., 1985). McMiken & Daniels (1976) compared track and treadmill running at 180, 210, and 260 $\text{m}\cdot\text{min}^{-1}$ on a level surface and up a grade. Bassett et al. (1985) used velocities between 136 and 286 $\text{m}\cdot\text{min}^{-1}$ and a grade of 5.7% for treadmill running, and overground running (Bassett et al., 1985).

Intra-individual Variability in Running Economy

Since attention is being focused on modifying economy with various research paradigms, it is essential to know about the daily stability of a person so that the efficacy of a particular intervention is established (Morgan et al., 1989b; Morgan & Craib, 1992). Learning about within-subject stability in RE is also important in determining the number of tests required to obtain a stable criterion measure prior to experimental manipulation (Brisswalter & Legros, 1994a; Morgan & Craib, 1992). Intra-individual variation in RE have been reported to vary between 0.2% and 11% (Brisswalter & Legros, 1994a; Daniels et al., 1984b; Morgan et al., 1987, 1989b). Instrumental error accounts for 3% of the total variation, while 97% is attributed to body weight variation (Morgan et al., 1990b). However, the preponderance of the literature indicates that if the testing environment is controlled (i.e. time of day, training activity, footwear, and treadmill accommodations between 30 - 60 minutes), the mean coefficient of variation in RE over

a wide range of speeds (170 to 268 m·min⁻¹) is only 1.0 to 4.7% in moderately and well-trained male and female runners over 2, 4, 20, and 28 days (Armstrong & Costill, 1985; Becque et al., 1993; Brisswalter & Legros, 1994a; Daniels et al., 1984; Morgan et al., 1990b, 1991, 1994; Williams et al., 1991). Morgan et al. (1994) also indicated that with trained male and female runners with high $\text{VO}_{2\text{max}}$ values (69 and 59 ml·kg⁻¹·min⁻¹) who raced frequently, RE only varied between 1 and 2%. The variability of VO_2 was smallest at the highest speed (268 m·min⁻¹) compared to lower speeds (241 and 214 m·min⁻¹), suggesting a more stable metabolic response with the faster pace.

With regard to the number of testing sessions required to obtain stable RE values, Williams et al. (1991) indicated that 90% of the intra-individual variation in economy explained with two days of consecutive testing. Additionally, five days of consecutive testing explained 98% of the intra-individual variation in RE. The average of two economy tests per subject yields an acceptable measure of aerobic demand, and the small improvement in precision gained with more testing is not practical (Morgan et al., 1994; Williams et al., 1991). Treadmill accommodations between 30 and 60 minutes are required for runners to settle into a consistent running pattern (Cavanagh & Williams, 1982; Schieb, 1986), and thus when treadmill accommodation is allowed before a RE measurement, stable RE values are obtained with 2 testing sessions.

Biomechanical Considerations Affecting Running Economy

Running Mechanics and Economy

There has been limited research on the various descriptors of mechanical and biomechanical factors which may affect RE. Williams & Cavanagh (1987) reported that more economical runners have significantly lower first peaks at heel strike and tend to have smaller anterior-posterior and vertical peak forces and more of a rear foot striking pattern. Lower oxygen cost is speculated from a rear-foot striking pattern because rear-foot strikers allow footwear and bone structures to take more load than fore-foot strikers who have to rely more so on the gastrocnemius and soleus muscles to assist in the cushioning. Additional evidence confirming the notion that footwear can influence RE comes from Frederick et al. (1986). These authors established that the oxygen cost of running can be reduced by 2.4% with a softer-soled shoe compared to a similar shoe with a firmer cushioning system, even though the pair of softer-soled shoes may be 31 grams heavier.

Williams & Cavanagh (1987) found that economical runners ($37 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ at $214 \text{ m}\cdot\text{min}^{-1}$) had less vertical oscillation per stride (only 9.1 vs 9.6 cm), greater trunk angle (5.9° vs 2.4°), smaller wrist excursion (81 vs 86 cm), smaller knee velocity (99 vs $116 \text{ cm}\cdot\text{s}^{-1}$), greater knee flexion in the support phase (43° vs 39°), and greater plantar flexion angle (74° vs 67°) than less economical ($41.5 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ at $214 \text{ m}\cdot\text{min}^{-1}$) runners with a similar $\text{VO}_{2\text{max}}$. However, they also expressed that there is no single "template" that can be applied to all individuals in order to produce an economical running style, and, "the solution to the question of economy will always be a unique one

where many facets of the individual are considered."

Martin et al. (1993) speculated that more economical individuals would have lower relative mechanical power outputs at a particular running speed. They used three mechanical power calculations (mechanical power, energy transfer, and angular impulse expressions) for biomechanical analyses of running. Only 32% of the differences in power were explained by the inter-individual differences in VO_2 , suggesting that mechanical work (power) does not explain economy variations among individuals with varying body size.

Stride Length and Economy

Stride length and frequency have also been associated with RE (Cavanagh & Williams, 1982; Högberg, 1952; Kaneko et al. 1987; Powers et al., 1982). These studies tend to support the notion that the aerobic demand of running at given speeds tend to increase curvilinearly as stride length is either lengthened or shortened from that freely chosen by the runner. Högberg (1952) was the first to document that variation in stride length from that which was freely chosen by a runner resulted in increased oxygen cost. Running with a longer (13.3%) stride length than what was normally self-chosen resulted in a 11.9% increase in VO_2 , but an exact 13.3% decrease in stride length only increased VO_2 by 6% (Högberg, 1952).

Conversely, two studies claim that VO_2 (at given speeds) does not rise curvilinearly as stride length is lengthened or shortened (Williams & Cavanagh, 1982; Svendenhag & Sjödin, 1994). Svendenhag & Sjödin (1994) demonstrated that the aerobic demand of running increased linearly as stride is lengthened. This linear relationship

may result from the fact that VO_2 was measured in $\text{ml}\cdot\text{kg}^{-0.75}\cdot\text{min}^{-1}$, whereas other studies measured submaximal oxygen consumption in $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ or $\text{L}\cdot\text{min}^{-1}$. Moreover, Williams & Cavanagh (1982) revealed that equal increases and decreases in stride length from the self-selected condition increased VO_2 identically (Williams & Cavanagh, 1982). It appears that the rise in VO_2 with increasing stride rates or lengths may be associated with greater recruitment of fibers, predominantly FT fibers (Kaneko et al., 1987).

Nonetheless, in accordance with the literature, it appears that there is little need for a coach or trainer to dictate a particular stride length profile in runners since they do display almost optimum stride lengths. Experienced runners are likely to possess greater relative stride lengths than less experienced runners (Dillman, 1975), and elite LD runners possess shorter stride length/velocity slopes than elite MD runners. Furthermore, it is shown that MD runners maintain longer stride lengths than elite LD runners throughout all running speeds; especially during faster speeds (Svendsen & Sjödén, 1994).

Intra-individual mean daily variations in stride length among a cohort of runners varies between 1 to 11% (Craib et al., 1994; Brisswalter & Legros, 1994a, 1995; Morgan et al., 1987, 1991; Schieb, 1986). This suggests that the variability in stride lengths at different speeds may depend on treadmill accommodation and that trained runners exhibit minimal variability (mean coefficient of variation = 1 to 2%) compared to untrained runners (Brisswalter & Legros, 1994a, 1995).

Body Mass and Segmental Mass Distribution

Running economy is usually normalized to body mass such that the aerobic demand of oxygen is expressed in $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$. Therefore, RE should be independent of body mass. Davies & Thompson (1979) and Davies (1980b) showed that lightweight and heavier men are similar economically. Also, Skinner et al. (1973) reported similar VO_2 during walking for lean, obese, and weighted lean subjects.

However, other researchers have reported that body mass can influence economy. Negative relationships between body mass and VO_2 were found, meaning that heavier runners have lower aerobic demands than lighter individuals (Bourdin et al., 1993; Padilla et al., 1992; Pate et al., 1992; Williams et al., 1987). Specifically, Bourdin et al. (1993) reported a significant negative correlation ($r=-0.55$, female runners; $r=-0.59$, female basketball players) between body mass and the energy cost of running, and that differences in RE attributed to age and sex were related to body mass. These relationships have been hypothesized to result from individual differences in the distribution of mass among limb segments (Bailey & Pate, 1991). Davies (1980b) found that 11 to 13 year old children who were carrying 5% of their body weight on their trunk while running, displayed a lower aerobic demand at faster speeds ($233 - 267 \text{ m}\cdot\text{min}^{-1}$) compared to the un-weighted group condition. When a load is carried on the trunk, VO_2 increased by 1% per kg, whereas when the load is carried on the ankle VO_2 is increased by 10% per kg of load, indicating that oxygen cost is less as the load is positioned closer to the trunk (Martin, 1985; Myers & Steudel, 1985).

The units for measuring VO_2 have been controversial. Historically, RE has been

in expressed in $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (Svendsen & Sjodin, 1994). However, Bergh et al. (1991) suggested that both submaximal and maximal VO_2 during running are better related to $\text{kg}^{0.67}$ or $\text{kg}^{0.75}$ than to $\text{kg}^{1.0}$. The reason for suggesting that VO_2 should be proportional to the 0.75 power of body mass is based on limitations imposed by elastic components of biological material (Svendsen & Sjodin, 1994). Another reason why the aerobic demand of running is related to $\text{kg}^{0.75}$ relates to variation in weight distribution between the trunk and the limbs (Pate et al., 1992). Expressing aerobic power as $\text{ml}\cdot\text{kg}^{-0.75}\cdot\text{min}^{-1}$ and not $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ reduces inter-individual variation, and maintains steady RE values during adolescence (Sjodin & Svendsen, 1992; Svendsen, 1995). This scaling factor depicts the true VO_2 dependence on body mass during near level running and partially answers questions pertaining to differences in RE the sexes.

Bourdin et al. (1993) and Léger & Mercier (1984) reported differences in RE among various age/gender groups were related to $\text{kg}^{1.0}$. When their data were expressed in $\text{ml}\cdot\text{kg}^{-0.75}\cdot\text{min}^{-1}$, the differences among groups were reduced significantly (Sjodin & Svendsen, 1992; Svendsen, 1995).

Other Factors Affecting Running Economy

A few other factors affecting RE are velocity of movement, muscle fiber composition and diet. These are explained below.

Running Velocity and VO_2

The association between running velocity and VO_2 has been extensively examined

(Bransford & Howley, 1977; Conley & Krahenbuhl, 1980; Costill & Fox, 1969; Costill et al., 1971, 1973; Davies & Thompson, 1979; Dressendorfer et al., 1977; Hagen et al., 1980; Hopkins & Powers, 1982; Margaria et al., 1963; Mayhew, 1977; McMiken & Daniels, 1976; Pugh, 1970; Shepard, 1969; Williams & Nute, 1983; Svendsen & Sjödin, 1994). RE has generally been described as a linear relationship (Daniels, 1985; Nevill et al., 1992), although some authors have suggested that this relationship might be quadratic (Daniels, et al., 1977; Fellingham et al., 1978; Van der Walt & Wyndham, 1973).

Nevill et al., (1992) examined the studies which found a linear relationship between VO_2 and velocity and commented that statistical tests were not carried out to confirm the homogeneity of the slope and intercept parameters. When these group regression lines were compared, the slope and intercept parameters varied considerably. The regression lines of velocity vs VO_2 had steeper slopes and negative intercepts in the studies where subjects had high $\text{VO}_{2\text{max}}$ values (Bransford & Howley, 1977; Conley & Krahenbuhl, 1980; Costill & Fox, 1969; Costill et al., 1971, 1973; Davies & Thompson, 1979; Hopkins & Powers, 1982; Mayhew, 1977) while regression lines using subjects with lower $\text{VO}_{2\text{max}}$ values were flatter and had positive intercepts (Bransford & Howley, 1977; Dressendorfer et al., 1977; Hagen et al., 1980; Hopkins & Powers, 1982; McMiken & Daniels, 1976; Pugh, 1970; Shepherd, 1969; Williams & Nute, 1983).

Regression curves developed from running at relatively low speeds may be flatter than those developed at high speeds (Hopkins & Powers, 1982). However, when all subjects were tested using identical velocities, significant differences were found in the

relationship of VO_2 vs speed among the subjects dependant on their $\text{VO}_{2\text{max}}$ values (Nevill et al., 1992). Consequently, these researchers show that differences in RE, in part, are based on subjects $\text{VO}_{2\text{max}}$ and precludes the use of a single regression line to summarize the performance of the group as a whole. These findings were supported by Svendenhag & Sjödín (1994) and Daniels & Daniels (1992) and support the notion that elite LD runners are more economical than elite MD runners.

Muscle Fiber Type and VO_2

Two major categories of muscle fibers are typically found in muscle tissue: fast-twitch (FT), which are better at providing energy anaerobically; and slow-twitch (ST) fibers, which are relatively better able to provide energy aerobically (Thoden, 1991). The proportion of each fiber type may vary from one muscle to another within an individual. Between individuals, the proportion of each fiber type can also vary within the same muscle (Saltin & Gollnick, 1983).

Generally, it seems to be true that athletes with predominantly ST fibers tend to perform better in LD events, while athletes with smaller proportions of ST fibers do better in shorter events (Costill et al., 1976; Fink et al., 1977). For example, muscle biopsies of the gastrocnemius muscle showed that national and world class LD distance runners averaged 69% and 79% ST fibers while comparable MD runners had only 52% and 62% ST fibers (Costill et al., 1976; Fink et al., 1977). However, the percentage of ST fibers varied widely among MD and LD runners (41-79% MD runners and 64-74% LD runners, Costill et al., 1976; 41-70% MD runners and 50-92% LD runners, Fink et al., 1977). Significant negative correlations were observed ($r=-0.88$ and $r=-0.62$)

between %ST fibers in the gastrocnemius and 10-km time among heterogeneous group of runners (Williams & Cavanagh, 1987; Fink et al., 1977), although one study found a low correlation between %ST fibers and $\text{VO}_{2\text{max}}$ (Costill et al., 1976).

Few studies (only 3) have actually compared VO_2 and muscle fiber type. Williams & Cavanagh (1987) observed no difference in %ST fibers among runners who exhibited poor, medium, and good economy. Conversely, Coyle et al. (1991) advocated that muscle fiber type distribution and VO_2 were correlated. Using well-trained cyclists, these authors found that the oxygen cost varied as much as 15% during submaximal cycling and suggested that some of the variation in cycling economy was due to the muscle fiber type. Cyclists who exhibited greater economy possessed a greater number of ST fibers in their legs than those cyclists who exhibited poorer economy, possibly because ST fibers are more mechanically efficient than FT fiber types (Coyle et al., 1991, 1992). Bosco et al. (1987) also showed a significant relationship ($r=0.60$) between %FT fibers and net oxygen uptake per-unit-distance-travelled during submaximal running in 17 athletes. In explaining this relationship, these authors noted that ST fibers may be more mechanically efficient than FT fibers. They suggested that ST fibers may retain stored elastic energy longer without cross-bridge detachment, thus reducing reliance on energy from oxidative phosphorylation. Also, a significant association ($r=-0.66$) was found between the net aerobic demand of running and the ratio of muscular work performed during pre-stretched jumps compared with no pre-stretch jumps. From these observations, Bosco and colleagues alleged that the data obtained on elastic behaviour of muscles during jumping might somehow apply to running.

Diet and VO_2

Altering RE by modifying the type of fuel (carbohydrate or fat) used to produce ATP may be possible (Bailey & Pate, 1991). When carbohydrates (CHO) are used to produce energy, 5.05 kcal of energy are produced for every litre of oxygen consumed whereas when fats are used for energy production, 4.70 kcal of energy are produced (Brooks & Fahey, 1984). Therefore, when more CHO's are used at a given running speed, a lower oxygen cost should occur (Bailey & Pate, 1991). As such, increasing CHO intake or reducing fat intake should allow this to occur. An increase in RER indicates that more CHO is being used for the generation of ATP (Bailey & Pate, 1991; Ramsbottom et al., 1989). Although ingestion of CHO has been shown to improve endurance performance and increase RER, Davies et al. (1988) have shown that oxygen cost is not really affected with added CHO intake. In this study, either a 275-ml of 2.5% or 6% CHO beverage, or placebo were administered every 20 minutes over two hours of cycling. No differences in the aerobic demand were observed between treatments although RER was significantly greater in the group which ingested the 6% CHO beverage.

Contrary to Davies and colleagues, VO_2 increased by 4% and RER decreased by 7% (at 185 and 238 $m \cdot min^{-1}$) in highly trained MD runners after they reduced daily CHO intake by approximately 50% and increased training load by 1.5 times per day for five days (Kirwan et al., 1988). Although the control group also had marked decreases in the total glycogen content of the gastrocnemius muscle after five days of increased training, the group which ingested 50% less CHO (LO-CHO group) showed the most

decrease in glycogen content of the muscle (90 vs 65 mmol·kg⁻¹ wet weight of glycogen). Kirwan and colleagues stipulated that the increase in $\dot{V}O_2$ and concomitant 0.07 decrease in RER in the LO-CHO group were partly due to the increase in fat oxidation. The shift from glycogenolysis to lipolysis occurred to a greater extent in the LO-CHO group than in the control group when glycogen levels of ST fibers became depleted. After three days of complete rest, RE and RER returned to pre-training levels in both groups and muscle glycogen stores (particularly in ST fibers) returned to 85% of pre-training levels.

APPENDIX B

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REFERENCES

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APPENDIX C

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Table 1: Physical and training characteristics of the subjects

Subject	Age	Mass	Height	Fatness	Training	Training	Personal Best
	(yrs)	(kg)	(cm)	(%)	(yrs)	(km·week ⁻¹)	(Mercier pts)
JND	21	66.5	173.4	7.7	8	100	817
GZ	25	71.0	188.0	7.2	11	80	784
GN	34	74.0	183.0	8.3	17	120	790
MC	18	61.5	171.0	8.7	4	60	751
AH	20	65.0	184.2	7.7	5	65	840
DP	21	75.9	191.5	8.3	7	60	684
LM	25	74.8	184.2	7.5	1	60	622
TG	20	64.1	172.1	8.6	10	55	711
MO	26	66.5	179.1	7.6	3	40	612
LS	27	68.3	181.6	8.3	9	100	810
PC	27	82.3	186.4	8.3	4	70	648
PS	33	60.5	168.9	7.6	12	60	655
Mean	24.8	69.2	180.3	8.0	7.6	72.5	727
SD	5.1	6.5	7.3	0.5	4.5	23.1	81.7

Table 2: Results of the $\text{VO}_{2\text{max}}$ test

Subject	$\text{VO}_{2\text{max}}$ ($\text{L}\cdot\text{min}^{-1}$)	$\text{VO}_{2\text{max}}$ ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	VE_{max} ($\text{L}\cdot\text{min}^{-1}$)	HR_{max} (bpm)	RER_{max}	TTE (min)	SPEED (s per 400-m)
JND	5.10	74.8	199.0	182	1.21	12.67	66.5
GZ	4.53	64.3	178.6	195	1.23	12.53	66.5
GN	6.00	80.5	229.6	172	1.14	11.67	69.0
MC	4.45	72.4	163.4	208	1.11	13.00	66.5
AH	4.83	75.4	141.7	189	1.09	13.67	64.2
DP	5.43	72.4	191.6	202	1.13	12.58	66.5
LM	5.28	70.1	164.2	188	1.13	10.91	71.7
TG	4.87	76.7	187.8	189	1.11	11.67	69.0
MO	4.53	68.3	161.2	172	1.12	11.00	71.7
LS	4.73	69.6	169.9	194	1.21	13.00	66.5
PC	5.84	70.9	185.5	194	1.09	12.33	66.5
PS	4.57	75.0	162.5	176	1.09	13.00	66.5
Mean	5.01	72.5	178.1	189	1.14	12.32	67.6
SD	0.53	4.3	22.7	11	0.05	0.85	2.3

TTE = time to exhaustion on the $\text{VO}_{2\text{max}}$ test

Table 3: Conditions for the 10 x 400-m (60 s recovery) interval training session

Subject	Speed (m·min ⁻¹)	Speed (s per 400-m)	Temp. (°C)	P _B (mm Hg)	Humidity (%)
JND	365.2	65.7	29	759	62
GZ	358.7	66.9	25	757	75
GN	352.9	68.0	22	754	59
MC	360.9	66.5	22	760	52
AH	372.7	64.4	24	755	57
DP	358.7	66.9	22	755	57
LM	340.8	70.4	22	755	57
TG	353.4	67.9	22	755	57
MO	343.8	69.8	22	764	63
LS	359.0	66.8	22	759	62
PC	360.3	66.6	22	768	52
PS	362.0	66.3	22	757	60
Mean	357.4	67.2	23	758	59
SD	8.7	1.7	2	4	6

Table 4: Conditions for the 10 x 400-m (120 s recovery) interval training session

Subject	Speed (m·min ⁻¹)	Speed (s per 400-m)	Temp. (°C)	P _B (mm Hg)	Humidity (%)
JND	362.0	66.3	27	746	63
GZ	359.8	66.7	31	736	71
GN	354.5	67.7	22	759	64
MC	364.2	65.9	24	753	68
AH	372.7	64.1	22	764	63
DP	361.4	66.4	25	757	71
LM	344.3	69.7	22	765	63
TG	353.0	68.0	22	764	63
MO	344.3	69.7	22	754	57
LS	367.0	65.4	24	754	70
PC	363.0	66.1	22	752	52
PS	361.4	66.4	22	759	64
Mean	359.0	66.9	24	755	64
SD	8.6	1.7	3	8	6

Table 5: Conditions for the 10 x 400-m (180 s recovery) interval training session

Subject	Speed (m·min ⁻¹)	Speed (s per 400-m)	Temp. (°C)	P _B (mm Hg)	Humidity (%)
JND	362.5	66.3	28	751	89
GZ	361.4	66.4	27	740	64
GN	352.4	68.1	23	764	54
MC	362.5	66.2	22	755	67
AH	375.0	64.0	25	755	57
DP	363.1	66.1	23	757	62
LM	339.0	70.8	25	748	57
TG	348.8	68.8	22	755	57
MO	340.9	70.4	22	755	57
LS	359.0	66.8	22	759	62
PC	364.0	66.0	22	765	64
PS	361.4	66.4	21	758	57
Mean	357.5	67.2	23	755	62
SD	10.4	2.0	2	7	9

Table 6: Ratings of perceived exertion for each recovery condition

Subjects	Recovery Conditions		
	60 s	120 s	180 s
JND	16.0	15.0	14.0
GZ	18.0	16.0	15.0
GN	17.0	15.0	14.0
MC	18.0	18.0	15.0
AH	18.0	15.0	13.0
DP	18.0	18.0	15.0
LM	18.0	17.0	15.0
TG	16.0	15.0	13.0
MO	18.0	15.0	14.0
LS	18.0	17.0	14.0
PC	18.0	16.0	15.0
PS	19.0	16.5	15.5
Mean	17.7	16.1	14.4
SD	0.9	1.2	0.8

Table 7: Repeated measures ANOVA for VO_2 ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) at $200 \text{ m}\cdot\text{min}^{-1}$

SOURCE	SS	DF	MS	F	P
Test	81.50	1	81.50	71.55	0.000
ERROR	12.53	11	1.14		
Recovery	0.11	2	0.05	0.03	0.97
ERROR	45.40	22	2.06		
Test x Recovery	0.45	2	0.23	0.47	0.63
ERROR	10.61	22	0.48		

Table 8: Repeated measures ANOVA for VO_2 ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) at $268 \text{ m}\cdot\text{min}^{-1}$

SOURCE	SS	DF	MS	F	P
Test	36.84	1	36.84	16.65	0.002
ERROR	24.34	11	2.21		
Recovery	12.86	2	6.43	1.25	0.31
ERROR	113.48	22	5.16		
Test x Recovery	0.08	2	0.04	0.07	0.93
ERROR	11.48	22	0.52		

Table 9: Repeated measures ANOVA for VO_2 ($\text{L} \cdot \text{min}^{-1}$) at $200 \text{ m} \cdot \text{min}^{-1}$

SOURCE	SS	DF	MS	F	P
Test	0.18	1	0.18	38.62	0.000
ERROR	0.05	11	0.01		
Recovery	0.00	2	0.00	0.02	0.99
ERROR	0.20	22	0.01		
Test x Recovery	0.00	2	0.00	0.19	0.83
ERROR	0.05	22	0.00		

Table 10: Repeated measures ANOVA for VO_2 ($\text{L} \cdot \text{min}^{-1}$) at $268 \text{ m} \cdot \text{min}^{-1}$

SOURCE	SS	DF	MS	F	P
Test	0.04	1	0.04	4.67	0.054
ERROR	0.10	11	0.01		
Recovery	0.08	2	0.04	1.75	0.20
ERROR	0.50	22	0.02		
Test x Recovery	0.00	2	0.00	0.69	0.51
ERROR	0.05	22	0.00		

Table 11: Repeated measures ANOVA for RER at 200 m·min⁻¹

SOURCE	SS	DF	MS	F	P
Test	0.25	1	0.25	278.73	0.000
ERROR	0.10	11	0.00		
Recovery	0.00	2	0.00	0.78	0.47
ERROR	0.04	22	0.00		
Test x Recovery	0.00	2	0.00	1.42	0.26
ERROR	0.01	22	0.00		

Table 12: Repeated measures ANOVA for RER at 268 m·min⁻¹

SOURCE	SS	DF	MS	F	P
Test	0.03	1	0.03	32.18	0.000
ERROR	0.01	11	0.00		
Recovery	0.00	2	0.00	0.46	0.64
ERROR	0.04	22	0.00		
Test x Recovery	0.00	2	0.00	0.69	0.52
ERROR	0.01	22	0.00		

Table 13: Repeated measures ANOVA for HR at 200 m·min⁻¹

SOURCE	SS	DF	MS	F	P
Test	3334.72	1	3334.72	84.34	0.000
ERROR	434.94	11	39.54		
Recovery	54.25	2	27.13	2.46	0.11
ERROR	4243.08	22	11.05		
Test x Recovery	26.03	2	13.01	1.97	0.16
ERROR	145.31	22	6.61		

Table 14: Repeated measures ANOVA for HR at 268 m·min⁻¹

SOURCE	SS	DF	MS	F	P
Test	612.50	1	612.50	47.72	0.000
ERROR	141.17	11	12.83		
Recovery	11.08	2	5.54	0.37	0.69
ERROR	327.58	22	14.89		
Test x Recovery	6.83	2	3.04	0.91	0.42
ERROR	73.25	22	3.33		

Table 15: Repeated measures ANOVA for VE at 200 m·min⁻¹

SOURCE	SS	DF	MS	F	P
Test	35.98	1	35.98	1.96	0.189
ERROR	201.77	11	18.34		
Recovery	3.63	2	1.81	0.14	0.87
ERROR	283.33	22	12.88		
Test x Recovery	7.09	2	3.54	0.75	0.48
ERROR	103.77	22	4.72		

Table 16: Repeated measures ANOVA for VE at 268 m·min⁻¹

SOURCE	SS	DF	MS	F	P
Test	135.58	1	135.58	3.00	0.111
ERROR	497.71	11	45.25		
Recovery	107.11	2	53.56	1.35	0.28
ERROR	876.06	22	39.82		
Test x Recovery	29.15	2	14.57	0.83	0.43
ERROR	385.82	22	17.54		

Table 17: Summary of F values from the ANOVA tables

F Values						
Source	Speed (m·min ⁻¹)	VO ₂ (ml·kg ⁻¹ ·min ⁻¹)	VO ₂ (L·min ⁻¹)	RER	HR	VE
Test	200	0.00	0.00	0.00	0.00	0.19
Recovery	200	0.97	0.98	0.47	0.11	0.87
Test x Recovery	200	0.63	0.83	0.26	0.16	0.48
Test	268	0.00	0.05	0.00	0.00	0.11
Recovery	268	0.31	0.20	0.64	0.69	0.28
Test x Recovery	268	0.93	0.51	0.52	0.42	0.45

Table 18: Average VO_2 values for the last three minutes of each RE test ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)

SUBJECT	60 S RECOVERY				120 S RECOVERY				180 S RECOVERY			
	PRE		POST		PRE		POST		PRE		POST	
	200	268	200	268	200	268	200	268	200	268	200	268
JND	36.5	49.6	39.3	52.2	38.9	52.9	42.7	53.6	39.3	51.8	40.2	52.1
GZ	34.9	50.0	38.2	51.9	33.7	48.5	35.7	48.1	35.6	50.1	38.9	54.0
GN	46.4	59.4	46.0	60.0	44.4	56.0	45.7	57.7	44.9	61.6	47.9	63.3
MC	38.6	52.0	41.3	55.3	39.0	51.2	42.1	55.3	38.3	54.2	40.4	58.4
AH	40.7	55.2	44.0	56.5	40.5	55.8	43.7	59.3	39.6	53.4	42.7	55.3
DP	35.7	51.0	38.1	53.0	36.1	47.3	38.3	50.3	37.4	53.2	40.7	56.0
LM	38.9	55.5	41.0	56.1	39.8	55.1	41.2	56.7	38.5	52.7	38.5	54.4
TG	39.2	53.2	40.8	54.4	38.6	55.4	41.4	56.4	39.2	54.8	41.4	55.2
MO	36.9	52.1	38.6	54.0	36.6	51.8	38.0	53.0	37.0	51.7	38.4	52.8
LS	37.0	51.4	40.0	53.2	39.1	52.4	41.2	54.8	38.5	53.7	41.5	54.2
PC	38.4	51.4	39.7	52.2	36.0	51.3	38.2	50.5	37.2	51.8	39.3	51.4
PS	39.3	53.7	38.5	52.7	37.8	55.6	39.9	53.9	36.6	54.8	35.3	54.9
MEAN	38.5	52.9	40.5	54.3	38.4	52.8	40.7	54.1	38.5	53.7	40.4	55.2
SD	3.0	2.8	2.4	2.4	2.8	2.9	2.8	3.3	2.3	2.9	3.0	3.2
RANGE	11.5	9.8	7.9	8.1	10.0	8.7	10.0	11.2	9.3	11.5	12.6	11.9

Table 19: Average RER values for the last three minutes of each RE test

SUBJECT	60 S RECOVERY				120 S RECOVERY				180 S RECOVERY			
	PRE		POST		PRE		POST		PRE		POST	
	200	268	200	268	200	268	200	268	200	268	200	268
JND	0.96	0.98	0.81	0.94	0.94	0.95	0.80	0.89	0.93	0.98	0.83	0.95
GZ	0.92	0.93	0.78	0.92	0.97	0.97	0.80	0.96	0.93	0.96	0.81	0.94
GN	0.86	0.89	0.77	0.86	0.90	0.95	0.77	0.92	0.87	0.89	0.74	0.81
MC	0.81	0.82	0.72	0.81	0.92	0.96	0.79	0.89	0.86	0.88	0.76	0.85
AH	0.94	0.95	0.78	0.91	0.86	0.89	0.73	0.83	0.93	0.94	0.85	0.93
DP	0.90	0.93	0.77	0.88	0.95	0.95	0.78	0.89	0.87	0.88	0.74	0.86
LM	0.89	0.92	0.78	0.90	0.86	0.92	0.78	0.89	0.88	0.92	0.83	0.93
TG	0.95	0.98	0.83	0.92	0.87	0.90	0.77	0.87	0.89	0.92	0.81	0.91
MO	0.87	0.94	0.72	0.85	0.91	0.94	0.80	0.83	0.93	0.96	0.80	0.91
LS	0.87	0.93	0.75	0.86	0.86	0.93	0.87	0.91	0.87	0.91	0.74	0.85
PC	0.85	0.88	0.73	0.86	0.9	0.95	0.79	0.93	0.85	0.91	0.78	0.90
PS	0.91	0.93	0.74	0.88	0.89	0.91	0.76	0.87	0.89	0.9	0.75	0.86
MEAN	0.89	0.92	0.77	0.88	0.90	0.94	0.79	0.89	0.90	0.92	0.79	0.89
SD	0.05	0.04	0.04	0.04	0.04	0.03	0.03	0.04	0.03	0.03	0.04	0.04
RANGE	0.15	0.16	0.11	0.13	0.11	0.08	0.14	0.13	0.08	0.10	0.11	0.14

Table 20: Average heart rate values for the last three minutes of each RE test (bpm)

SUBJECT	60 S RECOVERY				120 S RECOVERY				180 S RECOVERY			
	PRE		POST		PRE		POST		PRE		POST	
	200	268	200	268	200	268	200	268	200	268	200	268
JND	125	148	148	159	122	145	144	154	130	153	139	153
GZ	127	155	145	165	130	156	147	165	131	157	144	166
GN	110	136	119	142	105	132	119	140	102	128	112	134
MC	142	167	151	171	142	172	157	174	142	173	155	177
AH	123	153	142	158	123	147	136	154	121	147	132	154
DP	133	161	160	174	130	161	153	172	137	165	156	174
LM	135	163	149	166	134	158	138	161	133	155	141	161
TG	133	158	139	158	128	155	133	156	127	156	133	156
MO	112	138	117	141	112	142	123	149	113	142	121	149
LS	129	155	145	162	129	154	149	161	122	151	144	156
PC	121	146	137	149	120	145	137	158	119	147	135	154
PS	107	134	117	138	107	137	121	139	109	132	117	134
MEAN	125	151	139	157	124	150	138	157	124	151	136	156
SD	11	11	14	12	11	11	13	11	12	13	14	13
RANGE	35	33	43	36	37	40	38	35	40	45	44	43

Table 21: Average ventilation values for the last three minutes of each RE test (L·min⁻¹)

SUBJECT	60 S RECOVERY				120 S RECOVERY				180 S RECOVERY			
	PRE		POST		PRE		POST		PRE		POST	
	200	268	200	268	200	268	200	268	200	268	200	268
JND	61.0	87.5	62.1	88.3	67.8	93.8	66.5	94.0	63.8	96.8	65.3	94.0
GZ	62.3	93.4	69.0	104.5	63.4	96.9	63.6	97.1	60.1	90.7	61.1	103.9
GN	88.6	117.7	88.5	116.8	94.9	131.3	91.2	130.0	95.4	131.1	95.9	120.6
MC	53.8	72.0	59.0	82.8	60.5	84.0	63.1	87.5	55.5	80.2	55.1	93.9
AH	73.3	101.0	72.6	97.5	61.4	86.2	64.4	88.6	68.1	88.9	66.0	89.0
DP	72.2	99.5	80.7	113.3	70.1	98.1	79.7	106.5	71.9	104.1	80.5	113.7
LM	61.9	95.6	63.4	96.9	63.7	96.2	63.0	98.2	61.1	91.5	63.7	99.1
TG	68.5	95.9	63.7	94.6	59.7	86.1	62.7	87.4	66.6	95.8	66.0	98.1
MO	63.3	96.7	58.1	96.5	60.4	89.4	61.2	97.9	64.1	95.2	65.0	98.6
LS	56.3	82.2	61.7	89.2	55.9	84.9	64.9	87.1	55.8	81.8	62.7	86.2
PC	65.9	91.0	61.2	89.6	66.7	90.1	68.5	98.5	60.4	91.4	66.7	99.6
PS	53.5	77.6	49.9	77.0	50.1	76.0	50.2	77.5	52.8	79.9	54.2	80.1
MEAN	65.1	92	65.8	95.6	64.6	92.8	66.6	95.9	64.3	94.0	66.9	98.1
SD	9.8	10.9	10.5	11.6	11.0	13.7	10.2	13.2	11.2	13.7	11.3	11.2
RANGE	35.1	39.7	38.6	39.8	44.8	55.3	41.0	52.5	42.6	51.2	41.7	40.5

Table 22: Average VO_2 values for the last three minutes of each RE test ($\text{L}\cdot\text{min}^{-1}$)

SUBJECT	60 S RECOVERY				120 S RECOVERY				180 S RECOVERY			
	PRE		POST		PRE		POST		PRE		POST	
	200	268	200	268	200	268	200	268	200	268	200	268
JND	2.47	3.36	2.61	3.47	2.63	3.58	2.82	3.54	2.64	3.49	2.65	3.46
GZ	2.44	3.50	2.63	3.58	2.36	3.40	2.46	3.31	2.49	3.51	2.66	3.70
GN	3.44	4.40	3.35	4.36	3.31	4.18	3.34	4.23	3.36	4.61	3.52	4.66
MC	2.40	3.23	2.54	3.40	2.42	3.17	2.57	3.38	2.37	3.35	2.46	3.55
AH	2.58	3.51	2.76	3.55	2.64	3.63	2.76	3.75	2.57	3.47	2.71	3.51
DP	2.70	3.85	2.85	3.95	2.75	3.61	2.87	3.77	2.77	3.95	2.98	4.11
LM	2.91	4.15	3.03	4.15	2.97	4.11	3.01	4.15	2.85	3.90	2.83	4.00
TG	2.48	3.36	2.56	3.41	2.45	3.51	2.59	3.52	2.49	3.48	2.60	3.64
MO	2.44	3.40	2.53	3.54	2.43	3.44	2.50	3.49	2.46	3.43	2.52	3.48
LS	2.53	3.51	2.71	3.60	2.64	3.54	2.74	3.65	2.61	3.64	2.76	3.61
PC	3.20	4.28	3.25	4.27	2.99	4.27	3.15	4.17	3.13	4.35	3.25	4.24
PS	2.45	3.35	2.39	3.27	2.33	3.43	2.42	3.27	2.27	3.41	2.18	3.38
MEAN	2.67	3.66	2.77	3.71	2.66	3.66	2.77	3.69	2.67	3.72	2.76	3.78
SD	0.34	0.41	0.3	0.37	0.30	0.34	0.29	0.39	0.32	0.41	0.36	0.39
RANGE	1.04	1.17	0.96	1.09	0.98	1.1	0.92	0.96	1.09	1.26	1.34	1.28

Table 23: Mean weight loss (kg) of subjects in each recovery condition

Subject	60 S Recovery			120 S Recovery			180 S Recovery		
	Pre	Post	Diff.	Pre	Post	Diff.	Pre.	Post	Diff.
JND	67.7	66.4	-1.3	67.6	66.0	-1.6	67.3	66.0	-1.3
GZ	70.0	68.9	-1.1	70.1	68.8	-1.3	70.0	68.6	-1.4
GN	74.0	72.7	-1.3	74.6	73.2	-1.4	74.8	73.6	-1.2
MC	62.1	61.5	-0.6	62.0	61.2	-0.8	61.8	60.8	-1.0
AH	63.5	62.8	-0.7	65.2	63.3	-1.9	65.0	63.5	-1.5
DP	75.6	74.6	-1.0	76.2	75.0	-1.2	74.1	73.4	-0.7
LM	74.8	73.9	-0.9	74.6	73.2	-1.4	74.0	73.5	-0.5
TG	63.2	62.8	-0.4	63.5	62.5	-1.0	63.50	62.7	-0.7
MO	66.2	65.6	-0.6	66.5	65.8	-0.7	66.4	65.8	-0.6
LS	68.4	67.8	-0.6	67.5	66.6	-0.9	67.8	66.6	-1.2
PC	83.3	81.9	-1.4	83.2	82.6	-0.6	84.0	82.6	-1.4
PS	62.5	62.0	-0.5	61.7	60.7	-1.0	62.2	61.7	-0.5
Mean	69.3	68.4	-0.9	69.4	68.3	-1.1	69.2	68.2	-1.0
SD	6.5	6.3	0.3	6.6	6.6	0.4	6.5	6.4	0.4

APPENDIX D

FIGURES

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>
1	Peak HR per repetition and minimum HR per recovery interval
2	VO ₂ (ml·kg ⁻¹ ·min ⁻¹) during the RE tests prior to and following the interval workout
3	VO ₂ (L·min ⁻¹) during the RE tests prior to and following the interval workout
4	RER during the RE tests prior to and following the interval workout
5	HR (bpm) during the RE tests prior to and following the interval workout

Legend

Figure 1

* significantly different from rep 1 ($p < 0.01$)

Φ significantly different from 120 and 180 s recovery condition

Figures 2 - 5

* significantly different from pre RE test ($p < 0.01$)

Φ borderline significant from pre RE test ($p = 0.054$)

APPENDIX E

McGILL UNIVERSITY ETHICS APPROVAL

APPENDIX F**CONSENT FORM**

CONSENT FOR EXERCISE TESTING

I, _____ (print name) authorize Dr. David Montgomery and Gerry Zavorsky to administer the exercise tests outlined below which will be used for research purposes. I understand that I may discontinue the testing if at any time I experience unusual discomfort. I understand that the staff conducting the tests will ask me to discontinue the tests if any indication of abnormal response to the tests becomes apparent. I understand that I will perform the tests as listed below and I have the opportunity to question and discuss the exact procedure to be followed.

TESTS TO BE PERFORMED

1) Treadmill accommodation: You will warm-up on the treadmill at $200 \text{ m}\cdot\text{min}^{-1}$ (7:28 min per mile) for 5 minutes. Then after some stretching, you will perform three, 10 min runs at $268 \text{ m}\cdot\text{min}^{-1}$ (6 min mile pace) with 5 minutes rest between.

1) Aerobic capacity ($\text{VO}_{2\text{max}}$): You will warm-up on the treadmill for 5 minutes at $200 \text{ m}\cdot\text{min}^{-1}$. Then after some stretching, you will start at $213 \text{ m}\cdot\text{min}^{-1}$ (8 mph) at 0% grade. Every minute, the speed will increase 0.5 mph keeping the elevation at 0%. You should run as long as possible so that a true value can be obtained.

2) Running economy test (12 tests total): You will run on the treadmill for 6 minutes at 7.5 mph, then rest 5 minutes, and then run on the treadmill for 6 minutes at 10 mph. This will be done before each interval workout of 10 x 400-m. Then after ≈ 10 minutes after each interval workout, the same two running economy tests will be performed again.

3) Interval workouts (3 total): You will run 10 x 400-m at the speed specified by the researcher(s), not faster, not slower. Active recovery (jogging between each interval) will be allowed and drinking water will also be allowed. 200-m split times will be given to everyone.

A video camera will be filming your biomechanical running gait during certain occasions

I acknowledge that I have read this form and I understand the test procedure to be performed and the inherent risk and I consent to participate. I understand that the data will be released only to the principal investigators unless I deem otherwise.

SIGNATURE OF SUBJECT: _____ DATE: _____

IMAGE EVALUATION TEST TARGET (QA-3)

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