The relationship of physiology and training to 10 km performance in female athletes

by

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Abstract

The relationship between endurance performance and physiology is well established. Most studies of this relationship do not examine the relationship of training to performance and physiology. In this study, 5 female subjects were recruited to provide training data in the four weeks immediately preceding a local 10k event (TC10k). Their training was quantified according to the TRIMP model (Banister *et al.*) in an attempt to examine the relationships between training, performance, and physiology. An additional 8 female subjects were recruited in order to confirm the relationships between performance and physiology. All subjects (n=13) raced in the TC10k, and underwent an evaluation of $\dot{V}O_{2max}$, LT and RE. The composite measures of $v\dot{V}O_{2max}$ and vLT were also calculated. TC10k performance ranged from 4.31 to 2.71 $m \cdot s^{-1}$. $\dot{V}O_{2max}$ (54.0 ± 6.9 $mL \cdot min^{-1} \cdot kg^{-1}$), $v\dot{V}O_{2max}$ (4.00 ± 0.45 $m \cdot s^{-1}$), LT (42.9 ± 5.1 $mL \cdot min^{-1} \cdot kg^{-1}$) and vLT ($3.13 \pm 0.36$ $m \cdot s^{-1}$) were all significantly correlated to race performance ($r^2=0.76-0.82$, $p<0.05$). Due to the small training ‘n’, a statistical analysis of the relationships of training to performance and physiology was not indicated. This study employed a number of changes to the TRIMP calculation of training, which bear further examination.

Supervisor: Dr. C.A. Gaul

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Appendix 1 – Review of Literature

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Dedication

To all of you who inspire me to run. My dad, who remains my running hero. My mom, who showed up at races in the most unusual places. Bruce, who is so much more than "my first coach". Kristin, who keeps with me, fast or slow, even when I feel like I'm going nowhere. All the runners out there, who, to me, demonstrate the determination of the human spirit. Even the bullies of my childhood - the real reason I learned how to run. Thank you all.

1. Introduction

In endurance runners, the relationships between training, performance (running speed over a given distance) and physiology have been examined over a range of performance levels and over a variety of distances (Helgerud, 1994; Helgerud, Ingjer & Strømme, 1990; Kenney & Hodgson, 1985; Morgan, Baldini, Martin & Kohrt, 1989; Paavolainen, Häkkinen, Hämäläinen, Nummela & Rusko, 1999; Padilla, Bourdin, Barthélémy & Lacour, 1992; Pate, Sparling, Wilson, Cureton & Miller, 1987; Pollock, 1977a, 1977b; Ramsbottom, Nute & Williams, 1987; Sjödin & Svedenhag, 1985; Yoshida, Udo, Iwai & Yamaguchi, 1993). Training improves running performance and this relationship appears to be mediated through improvements in a variety of physiological variables (Figure 1), most notably maximal aerobic power ($\dot{V}O_{2max}$), lactate threshold (LT) and running economy (RE) (Daniels, Yarbrough & Foster, 1978; Paavolainen *et al.*, 1999; Robinson, Robinson, Hume & Hopkins, 1991). Performance level may in turn influence the amount of training a runner can undertake, either as a result of their physiological profile or directly through some as of yet unexplored relationship.

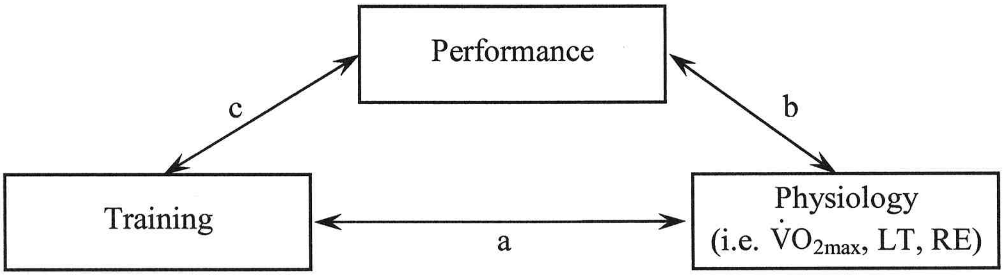


Figure 1. The potential interactions between training, physiology and performance. The strongest interactions are likely between training and performance through the intermediary of physiology (a + b), or through some other factor(s) (c). Performance level may also influence an athlete's ability to train. This too may be mediated through physiology (b + a) or some other factor(s) (c).

In elite distance runners, researchers have explored the relationship between physiology ($\dot{V}O_{2max}$, LT and/or RE) and performance in order to describe the physiological characteristics of elite athletes (Pate *et al.*, 1987; Pollock, 1977a, 1977b; Sparling, Wilson & Pate, 1987). Some of this research has provided anecdotal information about the training behaviours of elite runners. However the relationship between training and performance has been difficult to identify, due to the complexity of training variables, including intensity, duration, frequency and type of training. Studies of training, physiology and performance may well help explain the inter-relationships between these three factors in the elite athletic population. It is possible that at lower levels of performance, that training, physiology and performance interact differently than in the elite population. This may be due in part to a wider physiological range of $\dot{V}O_{2max}$, LT and/or RE associated with sub-elite performances. In order to fully understand the distance running population it is necessary to evaluate differences in physiology between the different performance levels and to evaluate the veracity of generalizing data from elite runners to the general running population.

1.1 Performance and Physiology

Three measures appear most useful in describing the physiology of endurance running performance: maximal aerobic power ($\dot{V}O_{2max}$), lactate threshold (LT) and running economy (RE). $\dot{V}O_{2max}$ represents the upper limit of aerobic power; LT reflects the sustainable portion of aerobic power of an athlete; and RE, defined as the metabolic cost of running, or Cr (di Prampero, Capelli, Pagliaro, Antonutto, Girardis, Zamparo &

Soule, 1993), reflects the efficiency of the athlete in utilizing their aerobic capacity while running at intensities below their LT.

$\dot{V}O_{2max}$ correlates strongly with distance running performance across a wide range of performance levels (r^2= 0.64 to 0.85) (Conley & Krahenbuhl, 1980; Costill, Thomason & Roberts, 1973; Fay, Londeree, LaFontaine & Volek, 1989; Ramsbottom *et al.*, 1987), but not in a homogenous group of highly trained runners (r^2= 0.01) (Conley & Krahenbuhl, 1980). As seen in the elite runners of Conley and Krahenbuhl (1980), sub-maximal physiological descriptors such as lactate threshold (LT) or running economy (RE) appear to be more effective in predicting the subtle performance differences in a homogenous group of runners than $\dot{V}O_{2max}$.

$\dot{V}O_{2max}$, LT and RE have been combined to produce composite measures of physiology. Common physiological composites include the representation of LT relative to $\dot{V}O_{2max}$ (i.e. as a percentage of $\dot{V}O_{2max}$) rather than as an absolute value. Other measures include $v\dot{V}O_{2max}$ ($m \cdot s^{-1}$), a linear approximation of running speed at $\dot{V}O_{2max}$ derived from the relationship between running speed and oxygen uptake evaluated when testing for RE. Similarly, RE and LT can be combined to represent LT as a running speed: vLT ($m \cdot s^{-1}$). These composite physiological measures have been reported to correlate well with performance over a narrow performance range (31-35 minutes for 10km) (Morgan *et al.*, 1989) and also over a wider range of performance (28-42 minutes for 10km) (Noakes, Myburgh & Schall, 1990).

Using a composite of reported measures of $\dot{V}O_{2max}$, LT and RE from various sources in the literature, Joyner (1991) produced a model to predict the potential upper limit to marathon performance:

$$\begin{aligned}\text{Predicted Running Speed } (\text{m}\cdot\text{min}^{-1}) &= \dot{V}O_{2max} \cdot \text{LT } (\%\dot{V}O_{2max}) \cdot \text{RE}\\ &= \text{mL } O_2\cdot\text{min}^{-1}\cdot\text{kg}^{-1} \cdot \% \cdot \frac{\text{m}\cdot\text{min}^{-1}}{\dot{V}O_2}\\ &= \text{m}\cdot\text{min}^{-1}\end{aligned}$$

where LT is represented as a percentage of $\dot{V}O_{2max}$ and RE as the slope of running speed ($\text{m}\cdot\text{min}^{-1}$) vs. oxygen consumption ($\dot{V}O_2$; in mL $O_2\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$). Joyner's equation predicts a potential upper limit for running speed at LT, and is based on his observation that elite marathon runners maintain a pace very close to their LT for the duration of the 42.2km event. Based on his calculations, Joyner (1991) predicted the best marathon performance at 1:57:48, nearly nine minutes faster than the world best marathon at the time (Joyner, 1991), and still faster than the new marathon record of 2:04:55, recently set at the Berlin Marathon (September 28, 2003).

One cause of this over-estimation of running speed for the marathon distance may have been Joyner's expectation that a marathon is run at LT. This assumption may be overly optimistic regarding the abilities of long distance runners to maintain such a running pace. A second explanation for the over-prediction may have been an overestimation of the average RE during a marathon from the short (less than 30 minute) lab test typically used to measure RE; running economy may deteriorate significantly over the marathon distance due to fatigue. Changes in environmental factors on a marathon course (i.e. temperature, humidity, terrain) that may also have a detrimental effect on RE are not accounted for in the laboratory. Joyner's model may be more appropriate to running events ranging from 3-10 km, as the running pace that elicits LT, and RE, may be better maintained over the shorter distances than it is over the marathon distance. While the application of Joyner's model to other events has yet to be examined, the model, and the work of others (Abe, Sakaguchi, Tsuchimochi, Endo, Miyake, Miyahiro, Kanamaru & Niihata, 1999; Billat, Beillot, Jan, Rochcongar & Carre, 1996; Billat, Bernard, Pinoteau, Petit & Koralsztein, 1994a; Billat, Lepretre, Heugas, Laurence, Salim & Koralsztein, 2003; Billat, Renoux, Pinoteau, Petit & Koralsztein, 1994b; Coen, Urhausen & Kindermann, 2001; Farrell, Wilmore, Coyle, Billing & Costill, 1979; Grant, Craig, Wilson & Aitchison, 1997; Hagan, Upton, Duncan & Gettman, 1987; Houmard, Craib, O'Brien, Smith, Israel & Wheeler, 1991; LaFontaine, Londeree & Spath, 1981; Nicholson & Sleivert, 2001; Tanaka & Matsuura, 1984; Weltman, Snead, Seip, Schurrer, Levine, Rutt, Reilly, Weltman & Rogol, 1987) recognizes the strength of the relationship of vLT to performance.

The description of physiological and training characteristics of different performance levels is the first step towards a comparison of different performance groups. Previous comparisons have examined elite runners in relation to non-elite runners (Morgan, Bransford, Costill, Daniels, Howley & Krahenbuhl, 1995; Pollock, 1977b; Sparling *et al.*, 1987) and have also compared male and female runners (Billat *et al.*, 1996; Helgerud, 1994; Helgerud *et al.*, 1990; Padilla *et al.*, 1992; Ramsbottom *et al.*, 1987; Sparling & Cureton, 1983). Most studies examining performance differences have been conducted with male subjects exclusively or have included a limited number of females. In addition, none of these studies has included an adequate description of training differences to allow for an examination of the relationships between training and physiology in the various performance groups. For an in-depth review of performance, physiology and training, see Appendix One.

1.2 Training and Physiology

Although many studies (Billat *et al.*, 1996; Helgerud, 1994; Helgerud *et al.*, 1990; Morgan *et al.*, 1995; Padilla *et al.*, 1992; Pollock, 1977b; Ramsbottom *et al.*, 1987; Sparling & Cureton, 1983; Sparling *et al.*, 1987) have examined the relationship between performance and physiology, there has been little evaluation of the relationships between training and performance, or training and physiology. One reason for this exclusion is the complexity of training as a dependent variable which can be manipulated by altering duration, intensity, frequency and/or modality (Daniels *et al.*, 1978; Paavolainen *et al.*, 1999; Sjödin & Svedenhag, 1985). Because of the multivariate nature of training, it is difficult to quantify training or to relate training to performance level or physiological profile.

One solution to this difficulty may be found in the quantitative systems model for training model (Training Impulse [TRIMP]) developed by Banister and colleagues (Banister & Fitz-Clarke, 1993; Banister, Morton & Fitz-Clarke, 1996; Morton, Fitz-Clarke & Banister, 1990). This model quantifies a training session as a (TRIMP) based on an athlete's training, resting and maximal heart rates ($HR_{exercise}$, HR_{rest}, and HR_{max}, respectively) and the duration (in minutes) of a training session (T):

$$\begin{aligned} &\mathrm{TRIMP} = T \cdot \Delta HR \cdot Y \\ &\text{where} \quad \Delta HR = (HR_{exercise} - HR_{rest}) \cdot (HR_{max} - HR_{rest})^{-1} \\ &\text{and} \quad Y = e^{1.67 \cdot \Delta HR} \end{aligned}$$

The metabolic arousal factor (Y) is based on the rise in blood lactate accompanying an increase in HR during exercise, and is an attempt to scale training so that high intensity (assumed to be high quality training) is weighted more heavily than low intensity (assumed to be lower quality training) (Banister & Fitz-Clarke, 1993; Banister *et al.*, 1996; Morton *et al.*, 1990). The general shape of the curve for Y with increasing HR is shown in Figure 2.

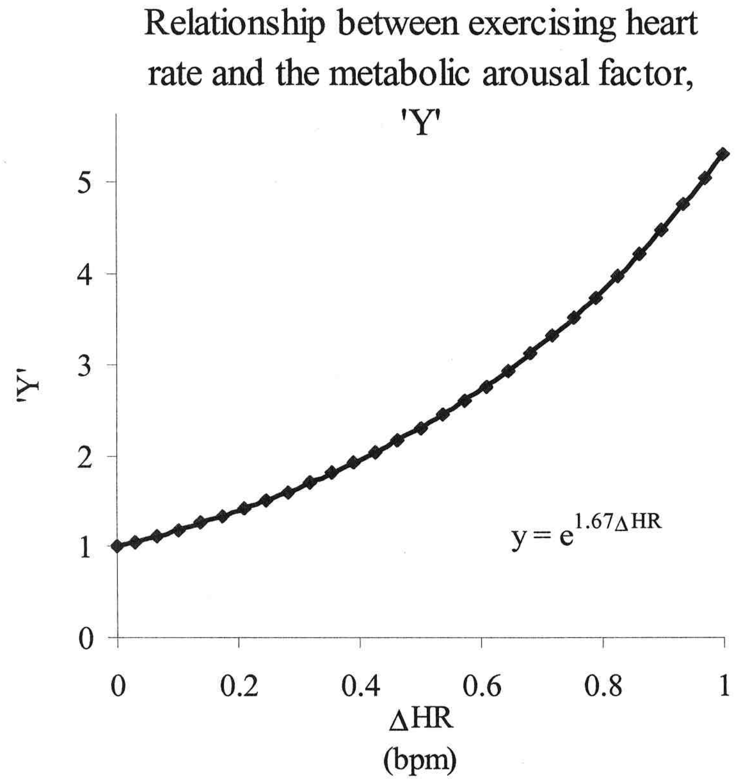


Figure 2. The relationship between heart rate, represented using the ΔHR ratio, and the metabolic arousal factor, 'Y', used in the quantification of training in TRIMPs. Adapted from Banister, Calvert, Savage & Bach (1975).

A high proportion of high intensity training in elite athletes, compared to the less intense training of sub-elite athletes, could help account for differences in the relationships between training, physiology and performance that may exist between these two groups. Alternately, the proportions of high and low intensity training may be quite similar across all athletes, with elite athletes simply completing a greater volume of training. In previous studies that have reported the training and training intensities of various groups of runners, this second scenario does not appear to hold true. Rather, the research thus far suggests that there are many training differences – in quality and quantity – between elite and sub-elite athletes (Daniels *et al.*, 1978; Emerick, Teed, Rusk & Fernhall, 1997; Hagan *et al.*, 1987; Scrimgeour, Noakes, Adams & Myburgh, 1986; Sparling *et al.*, 1987).

2. Purpose

As the majority of previous research in this area has studied male runners, this research proposed to examine the relationships between physiology, training and performance in female athletes capable of completing the 10 km distance in 35:00 to 55:00 minutes. Specifically, the purpose of this study was to investigate any differences in training that accompany the different performance levels and to subsequently correlate training with physiology and performance. A secondary purpose of this study was to test the efficacy of the TRIMP model (Banister & Calvert, 1980; Banister *et al.*, 1975; Banister & Fitz-Clarke, 1993; Banister *et al.*, 1996; Fitz-Clarke, Morton & Banister, 1991; Morton *et al.*, 1990) in examining relationships between training and performance.

2.1 Hypotheses

a) There is a significant relationship between the physiological measures of $\dot{V}O_{2max}$, LT and RE, and performance across a wide range of 10 km running performance.
b) There is a significant relationship between training, as represented by TRIMPs, and performance across a wide range of 10km running performance.
c) There is a significant relationship between training and physiological measures across a wide range of 10 km running performance.

2.2 Operational Definitions

Performance:	Race pace ($m \cdot s^{-1}$) over a given distance, in this instance 10km.
TRIMPs:	TRaining IMPulses. A quantity of training as calculated from training heart rate and duration. Higher intensity (high HR) training is weighted more than lower intensity (low HR) training in the TRIMP calculation.
$\dot{V}O_{2max}$:	Maximal aerobic power, in $mL \cdot min^{-1} \cdot kg^{-1}$. Determined as the single highest $\dot{V}O_2$ reading during a maximal running test.
Lactate Threshold:	(LT) The breakpoint in the lactate vs. $\dot{V}O_2$ curve determined mathematically from the intersection of the initial rise in [La] with the second, rapid, rise in [La].
Running Economy:	(RE) The oxygen cost of running per meter of ground covered, in $mL \cdot kg^{-1} \cdot m^{-1}$. RE is calculated by averaging the oxygen cost of running over a range of running speeds.

3. Methods

3.1 Subjects

Female athletes were recruited by posters and advertisements at local running stores, at the University of Victoria campus, and at local running events (see Appendix 2 for sample posting). Subjects were informed of the purpose of the study and signed their informed consent as required by the Human Subjects Ethics Committee of the University of Victoria (Appendix 3). In the original proposal for this research, subjects were to be recruited more than six weeks before the Times Columnist Garden City 10k (TC 10k, April 29th, 2002), in order to provide six weeks of training data. Due to a variety of confounding factors, the training timeline of the study was reduced to four weeks.

Runners who were recruited more than four weeks before the TC 10k were provided with a training log (see Appendix 4 for a training log sample page) and a heart rate monitor (HRM) (Polar Vantage XL or S610) so that training could be monitored consistently during the four weeks preceding the 10k performance. The timeline of this study is provided in Figure 3.

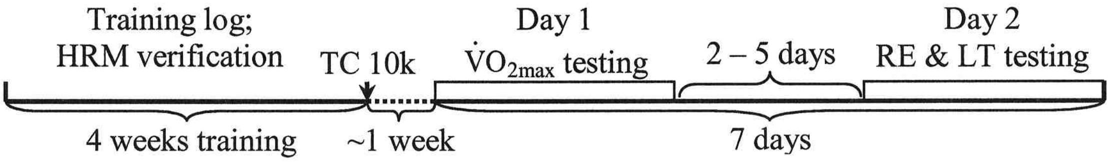


Figure 3. Timeline of the study. A subset of 5 subjects provided four weeks of training data before the Times Colonist 10k (April 29, 2002). Approximately one week after the race, all subjects reported to the lab for Day 1 of testing to determine $\dot{V}O_{2max}$. At least 48 hours separated Day 1 from Day 2 of testing to evaluate LT and RE.

A total of 20 women were recruited for this study. Inclusion criteria for the study were:

1) having competed in more than three 10k running events in the previous year;
2) having competed in running events for more than 3 years;
3) intending to race in the 2002 TC 10k.

These restrictions were included as an attempt to control for training and competitive experience. While it was originally intended that all runners would be recruited from local running clubs, with running being their primary competitive choice, the local community is heavily populated with triathletes. As a result, a number of subjects who volunteered for this study were triathletes, and performed a significant amount of non-specific (cross-training) training during the weeks leading up to the 10k race. The crossover effects of cycling or swimming in triathletes (for example) pose significant challenges to quantifying the training impulse (TRIMP).

Due to subject attrition, only 13 subjects completed all testing. Most attrition was due to voluntarily withdrawal, for a variety of personal reasons. One subject completed the 10k event, but was admitted to hospital for an unrelated surgical emergency before completing the physiological testing. Other subjects dropped out for equally valid, though less extreme, reasons. Only two subjects were removed from the subject pool after completing all testing. In one case, the subject had not run the whole 10k, but had walked with a friend for the majority of the race. The other subject had performed her training, and completed the race, while injured, but only admitted to the injury after the second day of testing. It was assumed that her training and performance were both sub-optimal due to her injury, so her data were removed from the study. Descriptive characteristics (mean ± sd) of the 13 subjects who completed testing are listed in Table 1.

Table 1. Summary characteristics of all runners (n=13).

	Age *years*	Height *cm*	Weight *kg*	S5SF *mm*	10 k race pace $m \cdot s^{-1}$	$\dot{V}O_{2max}$ $mL \cdot kg^{-1} \cdot min^{-1}$	LT $\%\dot{V}O_{2max}$	RE $mL\ O_2 \cdot kg^{-1} \cdot m^{-1}$
n = 13	30 ± 5	166 ± 7	60.3 ± 6.3	60 ± 20	3.37 ± 0.42	54.0 ± 6.9	79.3 ± 4.9	0.23 ± 0.02

Note: Values are given as mean ± sd.
S5SF = Sum of 5 Skinfolds (CSEP, 1995)

3.2 Training Data

Eight subjects were recruited four weeks before the TC 10k, and these subjects provided a daily log of training during these four weeks (See Appendix 4 for a sample page of the training log). Of these eight subjects, only five are included in the final data set. Two subjects dropped out without explanation, while the data from the third subject was taken out of the data pool when it was revealed that she had trained, raced, and been tested while nursing an injury. It was felt that the injury was serious enough to confound the relationship between performance and physiology. Her injury also did not allow her to complete all the training that she had anticipated leading up to the TC10k, and so the training information was also excluded.

Subjects were asked to summarize their training each day (average heart rate and total time), and include such other information as resting heart rate, how many hours they had slept the previous night, comments on their training habits and any other comments that they thought might be appropriate. The subjects that provided training information (TD subjects) were also loaned a Heart Rate Monitor (HRM; Polar S610 or Vantage XL) to wear while training. TD subjects were instructed in the use of the HRM. Training information recorded in the training logs included the duration, intensity (approximate HR) and type of training (ex. hills, intervals, long runs). At the end of each week, TD subjects met with the study investigator to communicate training data and to download the HR data files to Polar Training Software (Polar Precision Performance Software v3.02.007). HRM data files provided a profile of each training session at a sampling frequency of 0.067 Hz (every 15s). The information from the training logs and the HRM was cross-referenced to ensure accuracy of reporting in the logs, and in the case of the Vantage XL, to determine the respective dates of the data files.

3.2.1 Training Quantification

Training data was quantified according to the previously described methods of Banister and colleagues (Banister & Fitz-Clarke, 1993; Banister *et al.*, 1996; Morton *et al.*, 1990), with two modifications. First, in contrast to Banister's calculation of TRIMPs based on average HR and total training time (Banister & Fitz-Clarke, 1993; Banister *et al.*, 1996; Morton *et al.*, 1990), TRIMPs in the present study were calculated on the 15-second data interval provided by the HRM, and summed over the total exercise period to provide a total TRIMP score for each training session. The serial 15-s measures of HR reflect training HR more accurately than does averaging HR over the entire training session. The second modification was the exclusion of very low intensity training from the TRIMP calculation. Any information returned from the HRM was considered as very low intensity training if the HR was lower than the average HR observed during that subject's recovery at the end of the training session. This modification was an attempt to distinguish between 'training' and 'recovery' in an exercise session, and to exclude any recovery from the calculation of TRIMPs. An example of the calculation of TRIMPs from a single training session is included as Appendix 5.

Once physiological testing was complete and LT was determined (see Day 2 of Physiological Testing, below), TRIMPs from high intensity (>LT) training were also determined in order to examine the relationship between the volume of high intensity training and performance and physiology. Training volume was calculated as weekly training volume (TRIMPs·wk^{-1}) and also as average training volume per training day (Daily TRIMPs).

3.3 TC10k Performance

In addition to the eight TD subjects recruited more than 4 weeks before the TC10k, an additional 12 subjects (PP subjects) were recruited before or shortly after the TC 10k in order to carry out a comparison between performance and physiology. All subjects ran the TC 10k. The TD subjects all wore their HRM during the race in order to time their 10k race. Results from the official race website (www.timescolonist10k.com) were used for all the PP subjects. The TC 10k uses an electronic timing chip as their timing system. This timing system is used commonly in local, provincial, national and international calibre events.

3.4 Physiological Testing

Two testing days occurred within the two weeks following the TC 10k, and were separated by at least 48 hours. Before each testing session, subjects were informed of the testing procedures and again provided their informed consent. Day 1 involved the determination of maximal aerobic power ($\dot{V}O_{2max}$). Day 2 included measurement of the submaximal performance variables of running economy (RE) and lactate threshold (LT). Subjects were tested at approximately the same time of day to minimize any circadian effects.

3.4.1 Testing Day 1

Subjects reported to the UVic Sport and Fitness Center (SFC) after 24 hours of minimal activity. They were asked to refrain from consuming alcohol and caffeine for at least 24 hrs prior to the testing period. On entering the SFC, height, weight and skinfolds from five sites (S5SF: subscapular, biceps, triceps, suprailiac and mid-calf) (CSEP, 1996) were recorded. Subjects were instrumented with a Polar Heart Rate Monitor and were allowed a 10 minute warm-up at an easy, self-selected running pace on the treadmill (Quinton USA), at 1% grade. At the end of the warm up, subjects were given the option to stretch for up to 10 minutes. During this time, the flow sensor (SensorMedics USA) was calibrated using a 3 litre syringe and a flow rate of 3 $L \cdot s^{-1}$, and the metabolic cart (Vmax 990, SensorMedics USA) was calibrated against two primary standards (26% O_2, balance N_2 and 16% O_2, 4% CO_2, balance N_2). Following the 10-minute stretching break, the subject returned to the treadmill and donned the mouthpiece and headgear used to monitor pulmonary measures ($\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}E$ and RQ). Pulmonary data were recorded every 20 seconds using a mixing chamber procedure.

The maximal test was a continuous graded running test, beginning at the subject's self-selected warm-up pace, again starting at 1% grade. Treadmill speed was increased by 0.45 $m \cdot s^{-1}$ every 2 minutes, until RQ-values were consistently above 1.0. Once this point was reached, treadmill speed was held constant and the treadmill grade was increased by 1% each minute until the subject could no longer continue. Criteria for the determination of $\dot{V}O_{2max}$ included a plateau in $\dot{V}O_2$ (an increase in workload with less than a 2 $mL \cdot min^{-1} \cdot kg^{-1}$ increase in $\dot{V}O_2$); an RQ-value ≥ 1.15; attainment of the subject's age-predicted maximum heart rate (220-age); and volitional exhaustion of the runner.

Achievement of two or more of these criteria was considered sufficient evidence of the attainment of $\dot{V}O_{2max}$, and $\dot{V}O_{2max}$ was taken as being as the highest single reading from the maximal test.

3.4.2 Testing Day 2

Submaximal physiological variables of Running Economy (RE) and Lactate Threshold (LT) were measured in a second testing session conducted 2 to 5 days after the $\dot{V}O_{2max}$ test. Bourdon (2000) asserts that the short-step (2 minute) work durations of the $\dot{V}O_{2max}$ test sessions are insufficient for an accurate evaluation of LT. Rather, tests stages need to be at least 4 minutes, with longer stages producing a more accurate assessment of LT. Following similar rest and warm-up procedures as Day 1, subjects performed a discontinuous series of five minute runs, starting at their warm-up running speed, again at 1% grade. At the end of each run stage there was a short 1 minute rest, during which the runner remained on the treadmill and a finger-prick blood sample was taken for capillary blood lactate concentration (Accusport Lactate Pro). At the end of the rest minute the speed of the treadmill was increased by 0.22 $m \cdot s^{-1}$ (0.5 mph) and subjects immediately began running again. Test stages were continued until the athlete was no longer capable of completing the full five minute interval at the prescribed treadmill speed.

LT was determined by a 2-part linear plot of [La] vs. $\dot{V}O_2$. LT was determined as the mathematical intersection of the equation of the initial change in [La] with $\dot{V}O_2$ with the equation of the later rapid increase in [La] with increasing $\dot{V}O_2$. A representative example of the [La] vs. $\dot{V}O_2$ relationship with the two-part linear plot is provided in Figure 4.

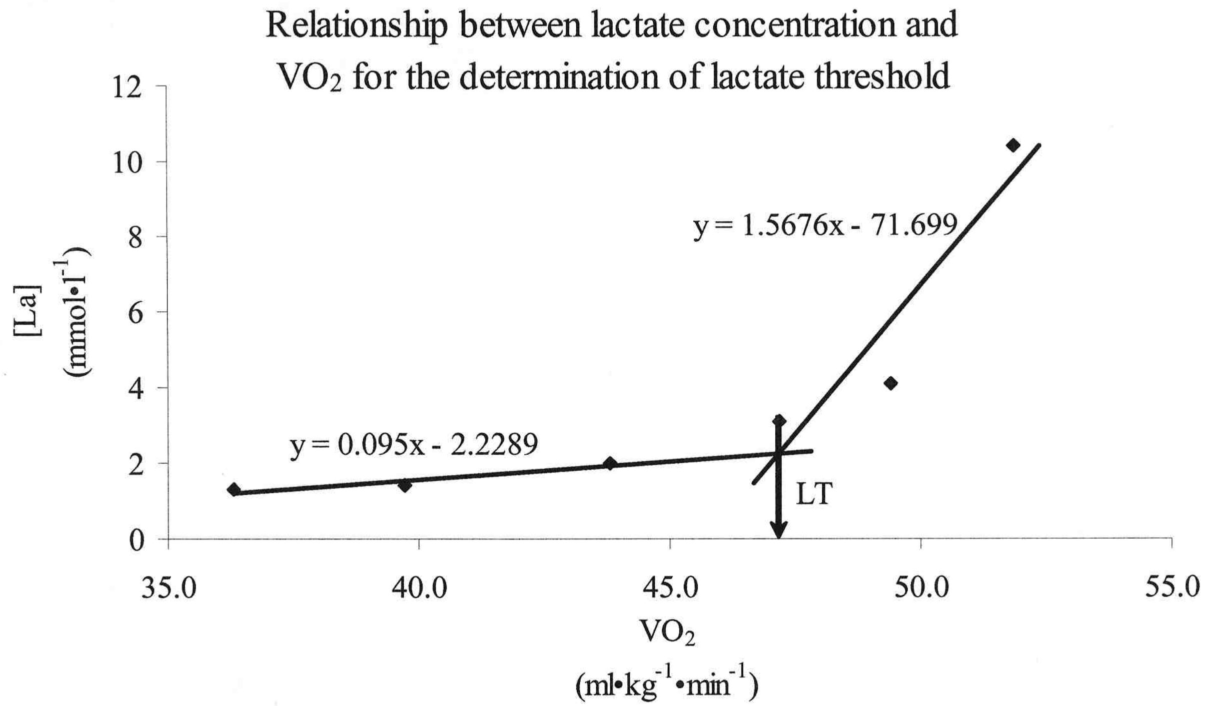


Figure 4. Relationship between blood [Lactate] and $\dot{V}O_2$ for the determination of lactate threshold. The threshold was calculated by equating the equations for the two lines and solving for 'x' to determine their intersection point on the x-axis.

Data for the determination of RE were taken from the steady-state portion of each stage of the submaximal test. This corresponded to the last three minutes of each stage. HR data over this period were averaged to determine the steady-state HR for each test stage. $\dot{V}O_2$ data over the final three minutes were also averaged to produce the steady-state $\dot{V}O_2$ for that stage of the test. RE was then calculated as the oxygen cost ($\dot{V}O_2$) divided by running speed (in metres per minute):

$$\text{Running Economy (RE)} = \frac{\dot{V}O_2}{\text{Running Speed}} = \frac{\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}}{\text{m}\cdot\text{min}^{-1}} = \text{mL}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$$

The relationship between $\dot{V}O_2$ and running speed at sub-threshold running speeds has been reported to be constant and linear (Daniels & Daniels, 1992; Daniels, 1985; Margaria, Cerretelli, Aghemo & Sassi, 1963; Ramsbottom *et al.*, 1987), indicating that

RE is independent of running speed. As a result, RE was reported as the average RE across all test stages.

Composite measures of physiology are those which combine two or more physiological variables. LT represented as a running speed (vLT) is a combination of a subject's LT and their running economy. Joyner's model of performance (Joyner, 1991) is a composite method of predicting running speed at LT from the highest values of $\dot{V}O_{2max}$, LT (as a percentage of $\dot{V}O_{2max}$), and RE for male endurance runners reported in the literature. Predicted running speed at $\dot{V}O_{2max}$ ($v\dot{V}O_{2max}$) combines an individual's running economy and $\dot{V}O_{2max}$ from the linear relationship observed between $\dot{V}O_2$ and running speed, following the methods of Morgan *et al.* (1989). These researchers have previously found $v\dot{V}O_{2max}$ to be a good predictor of 10 km race performance in men. An example of the determination of $v\dot{V}O_{2max}$ is shown in Figure 5.

4. Analysis of Results

Data for performance (TC 10k time), physiology ($\dot{V}O_{2max}$, LT and RE) and training (TRIMPS and proportion of TRIMPS from high intensity training) are reported as the mean ± sd for all subjects. Composite variables such as vLT and $v\dot{V}O_{2max}$ are also reported as mean ± sd. Linear regression analyses (SPSS for Windows, version 10.0.1) were used to describe and evaluate the significance of the relationships between performance and each individual physiological variable, as well as between performance and each of the composite variables. Significance for all tests was set at $\alpha=0.05$.

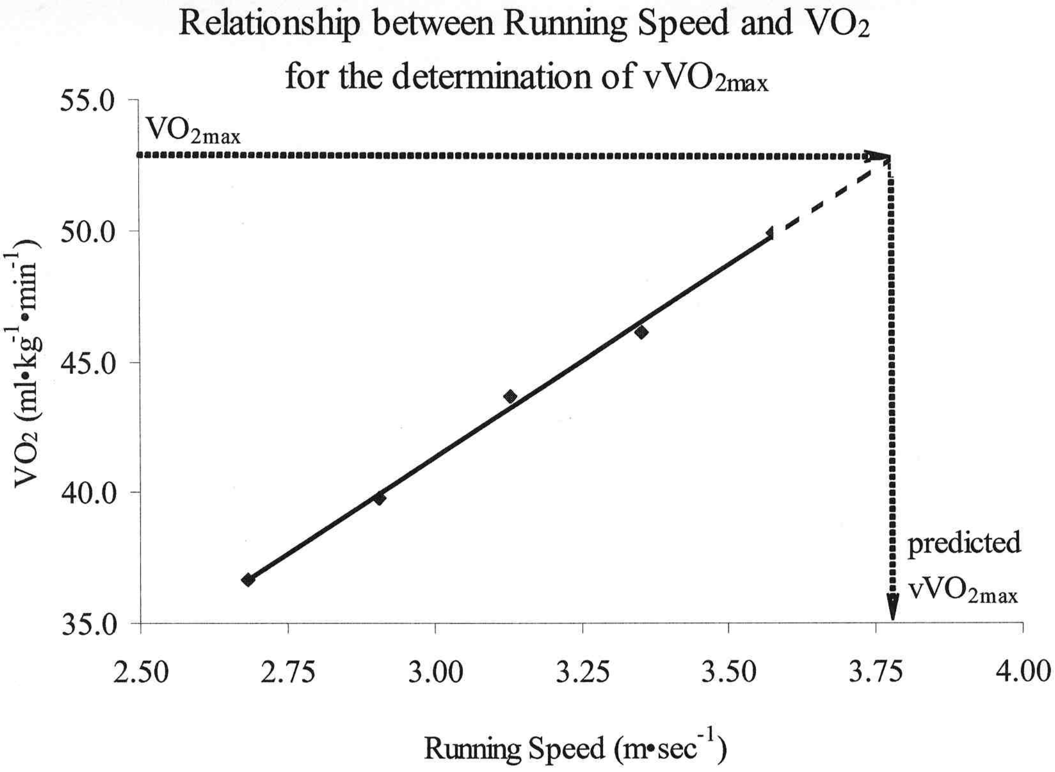


Figure 5. Relationship between running speed and $\dot{V}O_2$ for the prediction of v$\dot{V}O_{2max}$. From the linear relationship between sub-threshold (below LT) $\dot{V}O_2$ and running speed, an estimate of running velocity at $\dot{V}O_{2max}$ can be made. Adapted from Morgan *et al.* (1989).

5. Limitations and Assumptions

There are two major assumptions made from the outset of this study, which are consistent with previous scholarship in this area. The first assumption is that $\dot{V}O_{2max}$, LT and RE are accurate descriptors of physiology in endurance athletes, and that one or more of these variables are useful in both characterizing the physiology of endurance athletes, and correlating their physiology to their performance. Significant correlations between $\dot{V}O_{2max}$, LT, and v$\dot{V}O_{2max}$ and vLT in the literature support this assumption.

A second assumption that motivates this study was that there is an identifiable relationship between endurance training and performance. This assumption has a long history in the literature (Banister *et al.*, 1975; Busso, Carasso & Lacour, 1991; Foster, Hector, Welsh, Schrager, Green & Snyder, 1995; Haskell, 1985; Millet *et al.*, 2002a; Paavolainen *et al.*, 1999; Saltin *et al.*, 1968; Saltin & Rowell, 1980). However the assumption that four weeks of training can be correlated to endurance performance, may not be upheld in the present study due to the small 'n' of the TD subjects. The small 'n' is due in part to the timeline between the project proposal, obtaining ethical approval, recruiting subjects, and the target performance tests.

One limitation of this research relates to the issue of a male researcher recruiting female subjects. This obstacle may hinder subject recruitment, which subsequently delays timelines. In combination with the researchers' greater integration into the triathlon population than the running population, these factors are some of the challenges that were faced in the initial stages of this research. Once the subjects had been informed of the project goals and procedures, the difficulties appear to have been overcome, as most subjects remained in the study for the duration of testing.

Finally, although 20 subjects were recruited for this study, there was a 35% (7 of 20) drop-out rate. This high rate of attrition could be cause for concern, as it may introduce bias into the results. However the subjects that withdrew from the study did so for a variety of reasons, including problems both related to training (i.e. injury due to overtraining) and unrelated surgical concerns (p.11). As the attrition was distributed throughout the subject pool, and not concentrated in any particular way, the likelihood of the subject drop-out being a result of some factor intrinsic to the study, or that the attrition may bias the results in some way, is likely very small.

6. Results

6.1 Performance and Physiology

TC10k results were obtained from the race website, and confirmed through the self-reported race times of each participant. In the cases of the TD subjects, the race time from the HRM data file was also used to verify their 10k performance. There was a wide performance range in this subject group (38:39 to 61:25 mm:ss). The mean 10k time was 50:10 ± 6:00. $\dot{V}O_{2max}$ ranged from 38.3 $mL·kg^{-1}·min^{-1}$ to 64.1 $mL·kg^{-1}·min^{-1}$ (54.0 ± 6.9 $mL·kg^{-1}·min^{-1}$). LT ranged from 70.7 to 85.6% of $\dot{V}O_{2max}$ (79.3 ± 4.9%). The range of RE was 0.20 to 0.26 $mL·kg^{-1}·m^{-1}$ (0.23 ± 0.02 $mL·kg^{-1}·m^{-1}$). Performance and physiological results are summarized in Table 2.

6.1.1 Composite measures of Physiology

Data for the range and averages of the composite measures of physiology and 10K race pace are provided in Table 3. Each subject's $v\dot{V}O_{2max}$ was significantly faster than their actual 10k performance (paired t-test; $p<0.05$), while their vLT was slower than their race pace (paired t-test; $p<0.05$).

Table 2. Performance and Physiological data for all subjects (n=13).

Subject *	Race Result		$\dot{V}O_{2max}$	LT		RE
#	time	$m \cdot s^{-1}$	$mL \cdot kg^{-1} \cdot min^{-1}$	$mL \cdot kg^{-1} \cdot min^{-1}$	$\% \dot{V}O_{2max}$	$mL \cdot kg^{-1} \cdot m^{-1}$
1 (r)	38:39	4.31	64.0	53.5	83.5%	0.23
2 (r)	42:37	3.91	64.1	48.9	76.2%	0.22
3 (t;TD)	47:03	3.54	58.3	47.2	80.9%	0.23
4 (r)	47:13	3.53	53.5	40.9	76.5%	0.23
5 (t;TD)	48:01	3.47	59.6	42.4	71.2%	0.24
6 (t)	48:29	3.44	56.1	42.6	76.0%	0.23
7 (r;TD)	50:31	3.30	49.9	42.5	85.3%	0.22
8 (t)	50:56	3.27	52.7	44.4	84.2%	0.23
9 (r;TD)	51:26	3.24	55.2	43.1	78.1%	0.24
10(r;TD)	53:25	3.12	50.7	40.7	80.3%	0.26
11(t)	54:39	3.05	50.8	38.8	76.5%	0.21
12(t)	57:41	2.89	48.5	40.8	84.0%	0.25
13(r)	61:25	2.71	38.3	32.4	84.0%	0.20
mean	50:10	3.37	54.0	42.9	79.7%	0.23
sd	06:00	0.42	6.9	5.1	4.3%	0.02

*Note: Triathletes (t); Runners (r); Subjects who provided training information (TD).

Table 3. Range and average performance and composite physiological variables.

n=13	Race pace	$v\dot{V}O_{2max}$	vLT
maximum	4.31	4.86	3.87
minimum	2.71	3.28	2.68
mean	3.37 [a, b]	4.00	3.13
sd	0.42	0.45	0.36

a: significantly different ($p<0.05$) from $v\dot{V}O_{2max}$

b: significantly different ($p<0.05$) from vLT.

All data are in $m \cdot s^{-1}$.

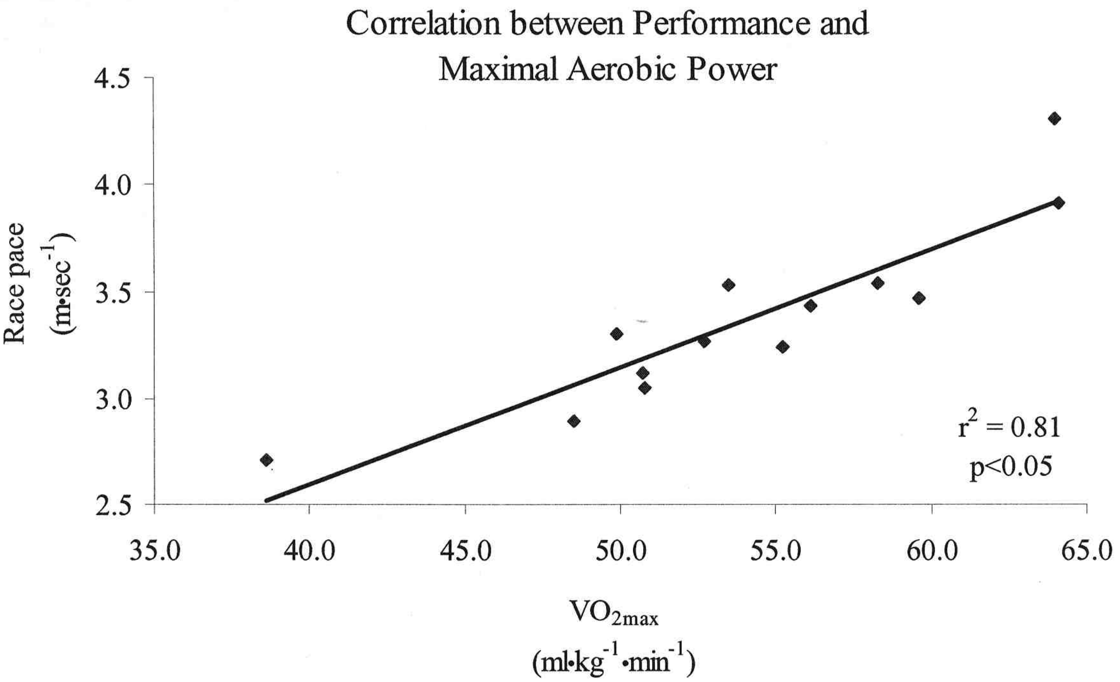
Table 4. Correlation matrix for performance and physiology, including single and composite measures of physiology. (n=13)

(r^2)	Race Pace	$\dot{V}O_{2max}$	LT	RE	$v\dot{V}O_{2max}$	vLT
Race Pace	1.00	*0.81	*0.82	0.01	*0.76	*0.82
$\dot{V}O_{2max}$		1.00	*0.81	0.08	*0.81	*0.60
LT			1.00	0.09	*0.62	*0.75
RE				1.00	0.01	0.03
$v\dot{V}O_{2max}$					1.00	*0.70
vLT						1.00

* $p<0.05$

6.1.2 Correlations between Performance and Physiology

$\dot{V}O_{2max}$, LT and RE were all examined individually for their relationship to 10k performance, as were $v\dot{V}O_{2max}$ and vLT. A correlation matrix of all physiological variables to performance is provided in Table 4. Race performance correlated well with $\dot{V}O_{2max}$ (r^2= 0.81, $p<0.01$) and LT (r^2= 0.82, $p<0.01$) (Figure 6), but not with RE (r^2= 0.01, p=0.38). However when RE was combined with each of $\dot{V}O_{2max}$ and LT, to form $v\dot{V}O_{2max}$ and vLT, respectively, the correlations between race performance and these composite measures of physiology were significant (r^2= 0.76, $p<0.01$ for $v\dot{V}O_{2max}$ and r^2= 0.82, $p<0.01$ for vLT) (Figure 7).



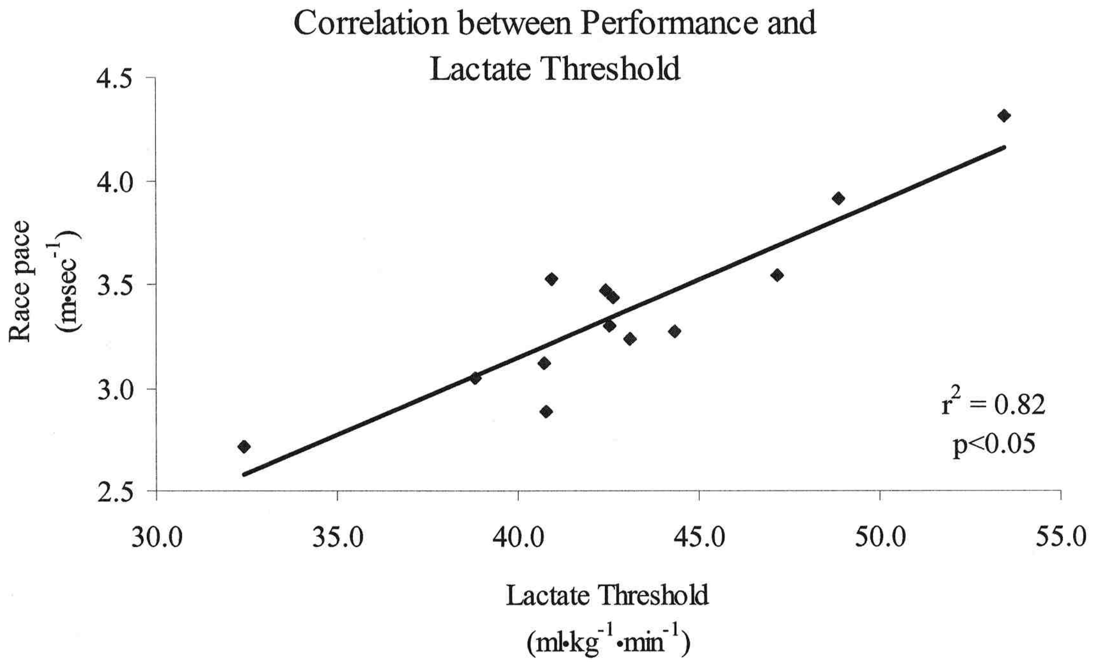


Figure 6. The relationship between performance expressed as race pace and physiology, represented by $\dot{V}O_{2max}$ (top) and LT (bottom), over the wide range of 10km race performance demonstrated in this study.

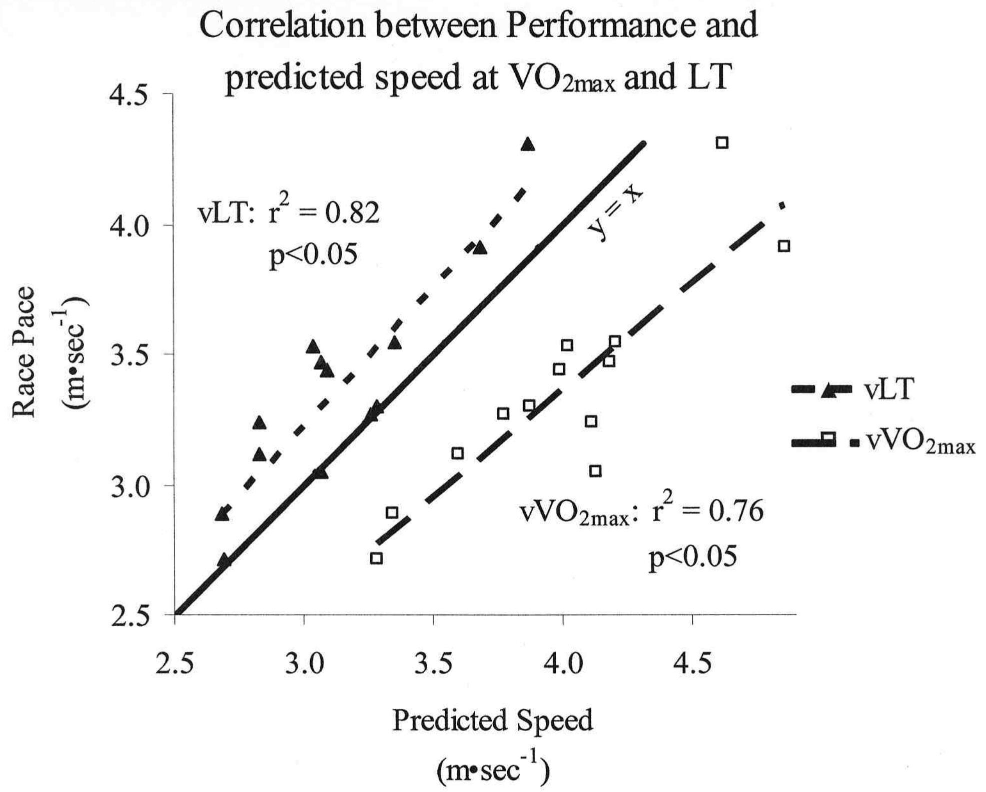


Figure 7. The relationship between performance (expressed as race pace) and predicted running speed at both $\dot{V}O_{2max}$ ($v\dot{V}O_{2max}$) and at lactate threshold (vLT). The solid line is the line of unity: $y=x$.

6.2 Training

As previously discussed, only 5 of the initial 8 TD subjects provided complete training data for the 4 weeks leading up to the 10k performance. The subjects who did not provide training information (PP; n=8), were not significantly different from those who did provide training information, in terms of performance or physiology ($p>0.05$). The TD subjects trained between two and five days·wk^{-1} in the four weeks leading up to the 10k, with a mean daily training volume of 132 ± 14 TRIMPs. Weekly training volumes ranged from 327 to 710 TRIMPs·wk^{-1}, with 24 ± 9% of TRIMPs coming from training above LT. A detailed description of the training information is provided in Table

5. Of the five TD subjects, three performed run-only training. The other two participants were triathletes, and as such performed a large portion of their training as swimming or bicycling. Furthermore, in the PP group, five of eight subjects also participated in triathlon. As both groups consisted of runners and triathletes, the TD group might still be considered a representative sub-set of the whole subject group.

Table 5. Performance and training data for the TD subjects (n=5).

Subject *	Race Result		TRIMPS			training freq.	Recovery[a] HR
#	time	$m \cdot s^{-1}$	Weekly	Daily	%>LT	$days \cdot wk^{-1}$	bpm
3(t)	47:03	3.54	710	136	9%	5	129
5(t)	48:01	3.47	536	117	31%	4	120
7(r)	50:31	3.30	538	144	24%	4	120
9(r)	51:26	3.24	423	145	24%	4	126
10(r)	53:25	3.12	327	117	31%	2	126
mean	50:05	3.33	507	132	24%	4	124
sd	2:35	0.17	102	14	9%	1	4

*Note: t = Triathletes; r = Runners

[a] Recovery HR is the average HR from recovery data included in some HRM data files

7. Discussion

7.1 *Performance*

The performance range of the female athletes that volunteered for this study was somewhat greater than was defined in the original inclusion criteria, and included runners both faster and slower than outlined in the original proposal. At the higher end of the performance range, it is most likely that subjects gave their best effort in the TC10k. At the lower end of the performance range, the inclusion criteria may not have been sufficient to ensure that the subjects were used to producing maximal exertion.

Nonetheless, a linear relationship between performance and physiology (i.e. $\dot{V}O_{2max}$) was observed. This suggests that the relationship between performance and physiology was consistent across the range of performance, whether subjects produced a maximal effort or not.

The range of running performance demonstrates that the study group was not homogenous. This is a departure from the subject profiles of many recent studies, which appear to focus specifically on a narrow, and generally high, performance level (Billat, Demarle, Paiva & Koralsztein, 2002; Billat *et al.*, 2003; Billat, Demarle, Slawinski, Paiva & Koralsztein, 2001; Millet, Dreano & Bentley, 2003; Mujika, Goya, Ruiz, Grijalba, Santisteban & Padilla, 2002; Paavolainen, Häkkinen, Hämäläinen, Nummela & Rusko, 2003; Smith & Jones, 2001).

The ranges of performance and physiology reported in the present study are comparable to two previous studies of female athletes, and 10k runners (Evans, Davy, Stevenson & Seals, 1995; Fay *et al.*, 1989). Evans *et al.* (1995) studied 'highly trained' female athletes and their performance in 10k running, along with differences in physiology with age. Their subject group had a range of 10k performance from approximately $3.25 m \cdot s^{-1}$ to $4.60 m \cdot s^{-1}$, a range that is slightly faster than the performance range observed in the present study. Fay *et al.* (1989) studied a group of females that were comparable in performance to the top half of the women studied here. Their group reported 10k performances ranging from $3.48\ m \cdot s^{-1}$ to $4.73\ m \cdot s^{-1}$. These performances can be compared to the 2003 BC women's 10,000m standard of 36:40.00 or $4.54 m \cdot s^{-1}$ (http://www.bcathletics.org/selcrit03wcsg.htm) required in order to compete at the Western Canada Summer Games.

7.2 Physiology

7.2.1 Maximal Aerobic Power ($\dot{V}O_{2max}$)

Reflecting the wide range in performance, the range of maximal aerobic power exhibited in the athletes of the present study was also quite broad. The highest $\dot{V}O_{2max}$ in this group of women was 64.1 $mL \cdot kg^{-1} \cdot min^{-1}$, and corresponded to the second best 10k performance of 42:37. The lowest $\dot{V}O_{2max}$ from the subject group, 38.3 $mL \cdot kg^{-1} \cdot min^{-1}$, was returned by the slowest runner, who had a 10km race time of 61:25. The physiological ranges of the present study are also similar to the results of Evans *et al.* (1995) and Fay *et al.* (1989), who reported $\dot{V}O_{2max}$ values of 38 to 62 $mL \cdot kg^{-1} \cdot min^{-1}$ and 51.7 to 68.4 $mL \cdot kg^{-1} \cdot min^{-1}$, respectively.

$\dot{V}O_{2max}$ has long been held as the single best correlate with aerobic performance across a wide performance range. In practical terms, with limited resources, monitoring $\dot{V}O_{2max}$ may be a good way of monitoring the physiological profile of individual athletes. This may be particularly appropriate when athletes are at a sub-elite performance level, and will likely experiences improvements in $\dot{V}O_{2max}$ in parallel with their improvements in performance. Both the relationship between $\dot{V}O_{2max}$ and performance (Billat *et al.*, 1994a; Butts, Henry & McLean, 1991; Deason, Powers, Lawler, Ayers & Stuart, 1991; di Prampero, Atchou, Bruckner & Moia, 1986; di Prampero *et al.*, 1993; Evans *et al.*, 1995; Grant *et al.*, 1997; Helgerud, 1994; Morgan *et al.*, 1989; Noakes *et al.*, 1990; Paavolainen, Nummela & Rusko, 2000; Sjödin & Svedenhag, 1985; Tanaka & Matsuura, 1984; Wiswell, Jaque, Marcell, Hawkins, Tarpenning, Constantino & Hyslop, 2000) and between *improvements* in $\dot{V}O_{2max}$ and performance (Daniels *et al.*, 1978; Davies &

Knibbs, 1971; Dolgener, Kolkhorst & Whitsett, 1994; Gollnick, Armstrong, Saltin, Saubert, Sembrowich & Shepherd, 1973; Saltin, Blomqvist, Mitchell, Johnson, Wildenthal & Chapman, 1968) have been well documented. However other examinations of these relationships suggest that at very high performance levels, $\dot{V}O_{2max}$ may not improve with training, although there may be significant performance gains (Acevedo & Goldfarb, 1989; Paavolainen *et al.*, 1999). This may be one reason why at the elite level the relationship between $\dot{V}O_{2max}$ and performance breaks down. Nevertheless, the relative ease of testing $\dot{V}O_{2max}$ and the long history of it being tested in athletes suggests that even at the elite level, it will remain a descriptive characteristic, if not a central theme, to further study of performance.

7.2.2 Lactate Threshold

While $\dot{V}O_{2max}$ represents the upper limit of aerobic power, LT is indicative of the portion of $\dot{V}O_{2max}$ that can be sustained over endurance running distances without the fatiguing effects of lactic acid. Over the time and distance associated with the marathon, runners avoid fatigue, induced in part by the anaerobic production of lactic acid, by racing at running speeds below LT (Joyner, 1991). As race times and distances decrease, running speeds increase towards intensities reflective of LT, suggesting that over these time frames, athletes can withstand some level of lactic acid accumulation. In the present study, subjects raced at speeds slightly, but significantly ($p<0.05$) higher than the running speed associated with LT (vLT).

In addition to a specific determination of the lactate threshold, the balance between aerobic and anaerobic energy contributions to race performance can be represented in a variety of ways. Broadly speaking, the anaerobic threshold (AT) represents the point during progressive exercise where anaerobic metabolism begins to contribute heavily to energy production (Wasserman, Hansen, Sue, & Whipp, 1987; Whipp, Ward, & Wasserman, 1984), although AT is usually used specifically to indicate a ventilatory threshold (Wasserman, Whipp, & Davis, 1981; Wasserman, Whipp, Koyl, & Beaver, 1973). AT and LT are both measures of the same phenomenon; the transition from primarily aerobic exercise to an exercise intensity that relies heavily on anaerobic metabolism. It is not surprising, then, that while the two measures are determined differently, there is a robust relationship between them (Anderson & Rhodes, 1989; Cheng, Kuipers, Snyder, Keizer, Jeukendrup, & Hesselink, 1992; Davis, Bassett, Hughes, & Gass, 1983). In addition to determining the aerobic-anaerobic transition from blood lactic acid or ventilatory measures, other researchers have attempted to identify this point by other deflections, including a deflection in HR, used in the Conconi method (Conconi, Ferrari, Ziglio, Droghetti, & Codeca, 1982; Conconi, Grazzi, Casoni, Guglielmini, Borsetto, Ballarin, Mazzoni, Patracchini, & Manfredini, 1996). The relationship between the HR threshold and LT is less reliable than the relationship between VT and LT (Jones & Doust, 1997).

There may be more methodological approaches to the determination of LT than for any other variable associated with endurance performance (Bourdon, 2000; MacDougall & Wenger, 1990). In addition to the many LT test protocols, there are almost as many methods of analysis to determine LT from the test results. A discussion of some of the issues surrounding the determination of LT is included in the review of literature, Appendix 1.

As with $\dot{V}O_{2max}$, the LT values reported in the present study are similar to the work of Evans *et al.* (1995) and Fay *et al.* (1989), in terms of running speed at LT as well as in terms of $\dot{V}O_2$ and $\%\dot{V}O_{2max}$ at LT. The correlations of LT to performance are also similar to those reported by Evans *et al.* (1995).

In addition to the prevalence of LT, or some other representation of the aerobic-anaerobic transition threshold in the research literature, this variable is also common in the realm of coaching. This popularity may be in part due to the many field tests for various measures related to the aerobic-anaerobic transition, including the Conconi test (Conconi *et al.*, 1982; Conconi *et al.*, 1996). The utility of thresholds in setting various zones of intensity for training, along with the present finding that LT correlated as well with performance as $\dot{V}O_{2max}$ suggests that LT may be the most relevant physiological measure to examine when monitoring athletes. The non-invasive evaluation of the Conconi threshold, and the minimal invasiveness of the newer, small hand-held lactate analysers, will likely result in the continued use, and application, of various threshold evaluations by coaches and athletes.

7.2.3 Running Economy

A numbers of studies have examined the utility of using running economy as a predictor of performance for athletes in the high performance range (Conley & Krahenbuhl, 1980; Daniels & Daniels, 1992; Millet *et al.*, 2003). In cases where all athletes have maximised both their aerobic capacity and lactate threshold (i.e. elite athletes), RE appears to provide the additional resolution necessary to correlate the physiological profiles of elite athletes to their performance. However, the relationship between RE and performance over a wide performance range, or in the sub-elite performance range, has not previously been examined.

Over the wide range of performances observed in the present group of athletes (n=13), running economy did not correlate significantly with 10km running performance (r^2=0.01, p=0.38). In addition to suggesting that RE was not an important factor in determining performance across this range of athletes, these results also indicate that over the wide performance range, $\dot{V}O_{2max}$ and LT were the dominant physiological determinants of performance.

Further study of the relationship between RE and performance might include a study of a subject group with a narrower performance range than the present study, but still within the sub-elite range of performance. In contrast to previous studies of RE in elite athletes (Conley & Krahenbuhl, 1980; Daniels & Daniels, 1992; Millet *et al.*, 2003), such a group would likely not have maximized their $\dot{V}O_{2max}$ and LT, and the potential range of all three physiological variables would likely be quite wide.

7.2.4 Composite measures of physiology

Composite measures of physiology such as vLT or v$\dot{V}O_{2max}$ are being studied more and more often in the research literature. These measures have two main advantages over the direct measures of physiology: first, they represent two or more physiological measures, and so represent more information in a single variable and; second, both vLT or v$\dot{V}O_{2max}$ are represented as running speeds. Running speeds are well understood by coaches and athletes alike, and thus appeal to a greater audience than the strict physiological measures of $\dot{V}O_{2max}$, LT or RE.

Running economy on its own did not correlate well with running performance in the present group of female athletes. However, when combined with $\dot{V}O_{2max}$ or LT to form v$\dot{V}O_{2max}$ or vLT respectively, the correlation of both of these composite measures with performance was significant, though in the case of v$\dot{V}O_{2max}$, slightly lower than the relationship of $\dot{V}O_{2max}$ to performance (0.81 vs. 0.76, respectively). Differences in the relationship of v$\dot{V}O_{2max}$ to performance and $\dot{V}O_{2max}$ to performance were not evaluated. With the small n (13 subjects) in this study, it is incorrect to assume that there is any real difference in the relationships of v$\dot{V}O_{2max}$ or $\dot{V}O_{2max}$ to performance. However as both athletes and coaches use running speeds in their everyday language, representing LT or $\dot{V}O_{2max}$ in terms of running speed may encourage their cooperation in the physiological monitoring of athletes Further, 10k race pace appears to be closer to vLT than v$\dot{V}O_{2max}$ (Figure 7, p.20), suggesting that it may be a very accurate representation of an athlete's potential performance. The similarity of vLT to race pace can also be used as evidence that subjects provided their best effort in the TC 10k performance measure.

7.3 Training

Unfortunately, too few TD subjects (n=5) provided sufficient training data for effective, appropriate statistical analysis of the trilateral relationships between training, physiology and performance. There did appear to be a trend in weekly training volume (TRIMPs·wk^{-1}), and also training frequency, with increasing performance level (Table 5).

There are a number of confounding factors that may obscure the relationship between training and performance or physiology. The relationship between total training and performance or physiology in runners as compared to triathletes is an issue that was not addressed in this study. Of the TD subjects in this research, two performed a substantial amount of cross training in the form of swimming and cycling, and are better classified as triathletes than as runners. The remaining three TD athletes performed run-only training. Within an individual, the inclusion of various training modalities poses significant challenges to the TRIMP method of quantifying training. These challenges also extend to the comparison of training between individuals. In comparing different athletes' training using the TRIMP quantification method, and comparing training to performance or physiology, it appears that athletes should be drawn from the same training population in order to minimize the difficulties of quantifying training based on the TRIMP method. A further refinement to standardizing the training population might be to ensure a consistent training history (i.e. training age) in the subject group. For example, athletes with a long training history may maintain their performance potential in spite of any de-training effects. As a result, they may not have to conduct as much training in the future to produce the same performance level (or improvement in performance) that a novice athlete, starting at the same initial performance level, might require.

In the course of this research a number of concerns with the original TRIMP calculation were also identified. The TRIMP calculation (Banister & Fitz-Clarke, 1993; Banister *et al.*, 1996; Morton *et al.*, 1990) is based on an athlete's training, resting and maximal heart rates ($HR_{exercise}$, HR_{rest}, and HR_{max}, respectively) and the duration of training. Since HR_{max} in the present study was determined through treadmill testing, and HR_{max} for each of swimming and cycling are not the same as HR_{max} for running (Basset & Boulay, 2000; Roecker, Striegel & Dickhuth, 2003), the calculation of TRIMPs from swim or bike training using the running HR_{max} is not precise. Further, the TRIMP calculation does not accurately reflect the quantity of training undertaken through weight training, as such training may be performed without a substantial increase in heart rate. These examples of specificity highlight one concern that is not addressed in the current TRIMP quantification method.

Performance improvements gained from any form of aerobic training may be classified as either a central or peripheral, sport-specific effects. Central (cardiovascular) adaptations can be considered as general adaptations to any form of aerobic training. The peripheral (muscular) training effect is specific to the particular mode of training that is undertaken. Of the three training modalities performed by triathletes, swim training has the least direct benefit on run performance or physiological improvements examined using run tests (Millet, Candau, Barbier, Busso, Rouillon & Chatard, 2002a). The sport specific effect of swim training is predominantly an upper body adaptation – the major propulsion through the water comes from the arms, and the major active musculature in swimming includes the muscles of the upper torso and the arms; there is minimal training stimulus to the muscles used for running. Further, the central adaptation to swim training may be smaller, as the increase in training heart rate is attenuated due to the lower volume of active musculature, and the lower O_2 demand (Millet *et al.*, 2002a). With less of a training stimulus on the heart and other parts of the circulatory system, there may be less central drive, and therefore central adaptation.

Cycling has a greater cross-over training effect to run performance than does swim training (Millet *et al.*, 2002a), but still does not provide the same run-related training effect as run training. The peripheral adaptations associated with cycling are likely similar to that of run training; the major muscles of the legs are used in cycling, as in running, although the recruitment and movement patterns are different. Central adaptations to cycle training are also likely analogous to those of run training, as there is similar active musculature, demand for O_2, and exercising heart rates.

The result of this variation in training modalities, as seen with the triathletes, is a decrease in the precision of the TRIMP quantification and a potential weakening of the correlations between training, and performance, and physiology. It may be that a correction factor could be developed to scale non-specific training to reflect the degree to which it may be beneficial to a particular sport. For example, one could hypothesize that cycle training could have a scaling factor of 1.00 for bicycle specific performance and physiology, but a factor of 0.75 for running specific performance and physiology. Swim training would have a lower factor, such as 0.45, for cross-over effects to running, reflecting the commonality of the central (cardiovascular) drive, but also acknowledging the differences in the peripheral influence (upper vs. lower body). The higher scaling factor of bike training to run performance reflects the commonality of both central and peripheral training influence in the two training modes. There is as yet no research into the cross-over effect of training in other training modalities (quantified as TRIMPs) to running performance. A larger sample size and additional training data would be necessary to fully explore this effect.

Other aspects of the training data that merit further discussion include the modified calculation of TRIMPs from endurance training (see Appendix 5 for a sample calculation of TRIMPs). Banister's original TRIMP calculation uses average HR and total training duration to calculate the Training Impulse. Over the course of the four weeks of training information collected in this study, a single training session could be considered an

"Impulse" (Banister *et al.*, 1975; Fitz-Clarke *et al.*, 1991). However averaging HR across a training session is a poor representation of the variation in HR over the training session. This is most notable during interval training, where average HR is not an accurate reflection of the actual training HR. 'Blocking' HR into intervals within a training session is one option employed in this study to reduce the simplification of averaging HR across the entire training session. Nevertheless, the error in averaging or 'blocking' HR still translates into error in the TRIMP calculation. The data files from the HRM used in this study provided serial HR recordings every 15 s. Such HR data offer the opportunity to optimize TRIMP scores. Using the serial HR data, TRIMPs were calculated for each data point in a data file and summed across the complete data file to provide a total TRIMP value for the training session. As this TRIMP calculation is performed on each 15s HR data point, the calculation reflects the fidelity of the HR data itself.

A second modification to TRIMP calculation was the determination of a minimum HR requirement for HR data to be considered 'training'. While all subjects began recording data at the beginning of each workout, in some cases, TD subjects did not stop the HRM until after they had finished exercising. In addition to providing an excellent profile of HR recovery after training, this data provided an indication of the subjects' recovery HR. Recovery HR for each subject was estimated by averaging the recovery HR, defined as any HR information recorded after both the cessation of running and the rapid phase of the heart rate recovery, from the data files that included this information. This recovery HR, or HRthreshold was used to filter recovery and other very low intensity activity from the TRIMP data set. TRIMPs calculated from serial HR points that were greater than this recovery HR average were included as training, while TRIMPs from HR points below the recovery HR average were filtered from the training data. Recovery HR averaged 124 ± 4bpm, approximately 64% of HR_{max}. Scaling training HR between recovery and maximal HR is a marked departure from Banister's use of ΔHR to scale training HR between HR_{rest} and HR_{max}, and could be explored further in examining the relationship between training and performance. Figures 8 and 9 portray the HR profiles of a continuous and interval running workout, respectively, as well as the TRIMP calculations based on the actual, 'blocked', and average HR of the training session.

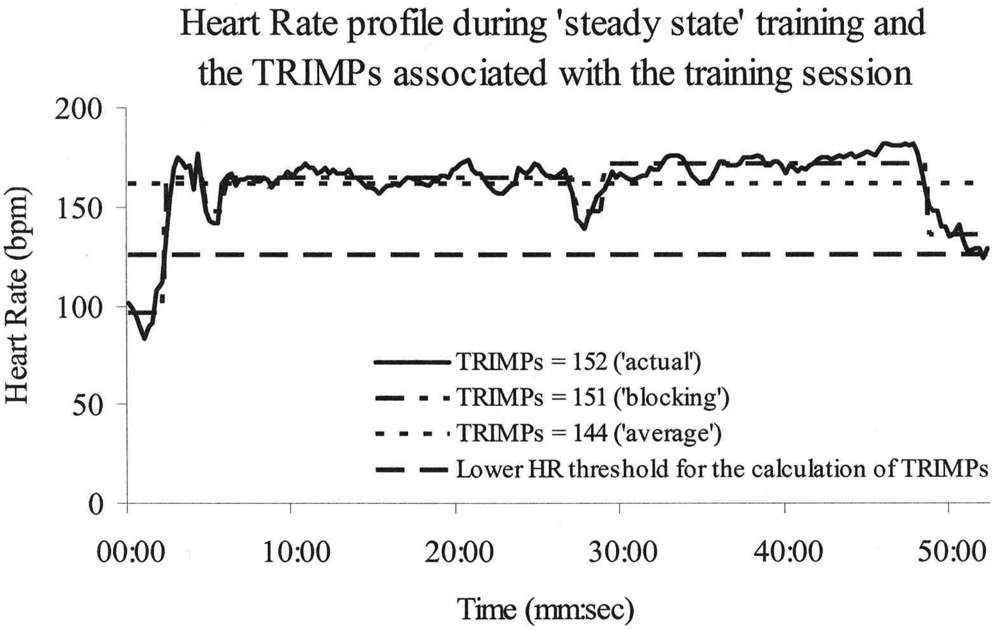


Figure 8. The HR profile over a 52-minute running workout. The actual HR profile of the session returns a TRIMP quantity 8 points higher than the average HR of the training session.

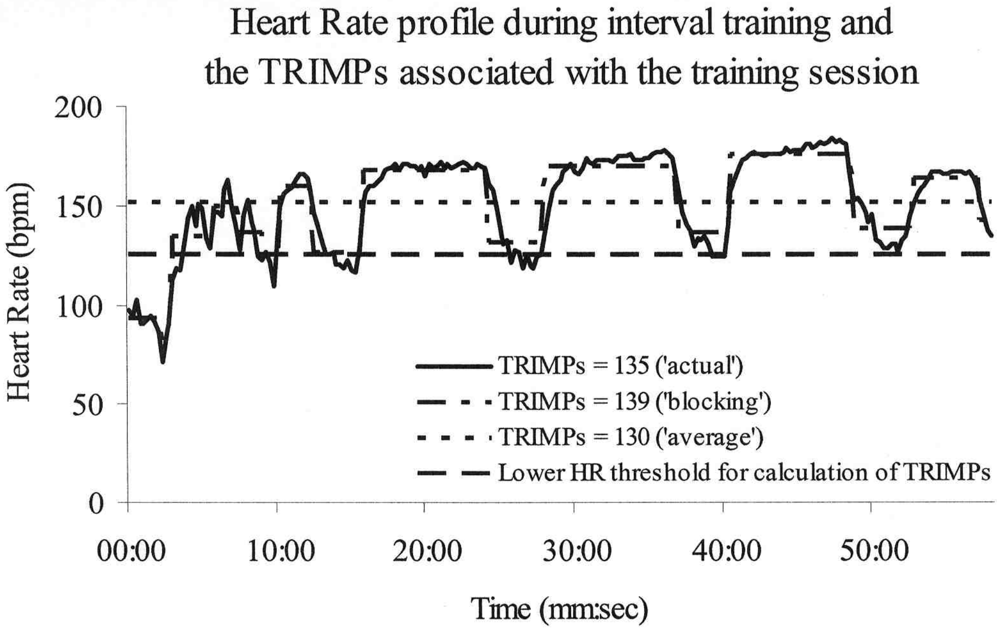


Figure 9. The HR profile over a 58-minute interval session, involving a warm-up, 3x1-mile intervals with rest between each interval, and a brief cool down. The actual HR of the session returns a TRIMP quantity 5 points higher than the average HR of the training session, and is actually lower than the 'blocking' of HR by portions of exercise.

8. Conclusions

This study provides further support to previously established relationships between physiology and performance, and also modifies the TRIMP method of quantifying training (Banister, 1990; Banister *et al.*, 1975; Banister & Fitz-Clarke, 1993; Banister, Good, Holman & Hamilton, 1986; Banister *et al.*, 1996; Calvert, Banister, Savage & Bach, 1976; Fitz-Clarke *et al.*, 1991; Morton *et al.*, 1990). The small 'n' recruited in time to provide training data before the TC 10k prohibited an effective trilateral analysis of the relationships between training, performance and physiology.

9. Future Directions

This thesis was a first step in the examination of the relationships between training, performance and physiology. Given that it was not possible to examine the relationship between training and either performance or physiology, an obvious extension of this work is to attempt to recruit more subjects and collect a longer period of their training data in order to complete such analyses. In addition to examining the general relationship between training and both performance and physiology across a wide range of performance, future research might also explore any differences in these relationships due to such factors as previous training history (i.e. training age). A second step in clarifying the trilateral relationships between training, performance and physiology would be a comparison of these relationships between men and women.

This project has put forward improvements in the quantification of training using the TRIMP model. While it appears likely that matching the precision of the original HR measurements from an HRM would improve the precision of the TRIMP calculation, these improvements are as yet untested against the original calculations.

Few studies into the relationships between performance and physiology have included an indication of the training status of their runners. This omission obscures the distinction between gender-based differences in performance and physiology, and training-based differences in performance and physiology. The few studies that have examined the physiology of performance-matched men and women have found no significant differences in the physiological descriptors of men and women. Examining performance-matched men and women for differences in training would be a useful next step in distinguishing between gender and training effects on performance and physiology.

Finally, there have been a number of recent training studies that have demonstrated improvements in running performance, and related these enhancements to changes in RE (Millet, Jaouen, Borrani & Candau, 2002b; Paavolainen *et al.*, 1999; Turner, Owings & Schwane, 2003). Identifying the biomechanical and physical factors that influence running economy, and the trainability of these factors, is another potential direction for future research.

10. References

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Appendix 1 – Review of Literature

A1.1 INTRODUCTION

The relationships between training and performance, and physiology have been explored in a number of circumstances. Extensive research relating performance to physiology has been conducted on elite (Cavanaugh, 1989; Kenney & Hodgson, 1985; Pollock, 1977a, 1977b), recreational and untrained individuals (Butts, Henry & McLean, 1991; Ramsbottom, Williams, Boobis & Freeman, 1989; Williams & Nute, 1983), men (Craib, Mitchell, Fields, Cooper, Hopewell & Morgan, 1996; Pimentel, Gentile, Tanaka, Seals & Gates, 2003; Robinson, Robinson, Hume & Hopkins, 1991) and women (Allor, Pivarnik, Sam & Perkins, 2000; Banister & Hamilton, 1985; Pate, Sparling, Wilson, Cureton & Miller, 1987; Sparling, Wilson & Pate, 1987). This review will deal specifically with endurance running performance, though the relationship is similar for other endurance sports, including bicycling (Coyle, 1995; Coyle, Coggan, Hopper & Walters, 1988; Urhausen, Gabriel, Weiler & Kindermann, 1998; Veicsteinas, Samaja, Gussoni & Cerretelli, 1984), rowing (Bangsbo, Michalsik & Petersen, 1993; Coen, Urhausen & Kindermann, 2003; Haykowsky, Chan, Bhambhani, Syrotuik, Quinney & Bell, 1998; Messonnier, Freund, Bourdin, Belli & Lacour, 1997), swimming (Brigham, Beard, Krimmel & Kenney, 1993; Cellini, Vitiello, Nagliati, Ziglio, Martinelli, Ballarin & Conconi, 1986; Costill, Flynn, Kirwan, Houmard, Mitchell, Thomas & Park, 1988; Tanaka & Seals, 1997) and triathlon (Banister, Carter & Zarkadas, 1999; Millet, Candau, Barbier, Busso, Rouillon & Chatard, 2002; Sleivert & Rowlands, 1996).

In distance runners, the relationships between training, performance (time to complete a given race distance) and physiology have been examined over a range of performance levels and over a variety of distances (Deason, Powers, Lawler, Ayers & Stuart, 1991; Evans, Davy, Stevenson & Seals, 1995; Grant, Craig, Wilson & Aitchison, 1997; Maffulli, Capasso & Lancia, 1991; Scrimgeour, Noakes, Adams & Myburgh, 1986; Sparling & Cureton, 1983). Training has been found to improve running performance and this relationship appears to be mediated through improvements in a variety of physiological variables, most notably maximal aerobic power ($\dot{V}O_{2max}$), lactate threshold (LT) and running economy (RE) (Daniels, Yarbrough & Foster, 1978; Paavolainen, Häkkinen, Hämäläinen, Nummela & Rusko, 1999; Robinson *et al.*, 1991) (Figure A1.1). Training-induced improvements in performance and physiology may in turn enhance quality of training.

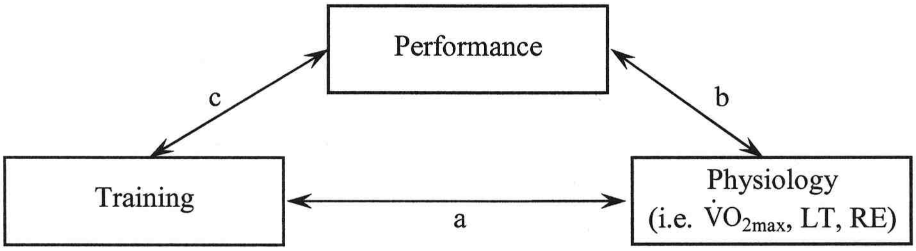

Figure A1.1. The potential interactions between training, physiology and performance. The strongest interactions are likely between training and performance, either through physiology (a + b) or through some other mechanism (c). Conversely, performance may also influence an athlete's ability to undertake a high training load. This too may be mediated by physiology (b + a) or some other mechanism (c).

In elite runners, researchers have explored the relationship between physiology ($\dot{V}O_{2max}$, LT and/or RE) and performance in order to describe the physiological characteristics of these athletes (Pate *et al.*, 1987; Pollock, 1977a, 1977b; Sparling *et al.*, 1987). In this context, however, data relating to athletes training has largely been absent.

While some research has provided some anecdotal information about the training behaviours of elite runners, the complexity of training variables – including broad ranges of intensity, duration and frequency, and modes of training – has complicated attempts to identify the relationship between training and performance at the elite level. Another confounding factor is the possibility that at lower performance levels, performance, physiology and training interact in different ways. This difference in interactions may be due in part to the larger physiological range of $\dot{V}O_{2max}$, LT and RE that can be identified at the lower performance level. In order to fully describe the running population it is necessary to evaluate differences in physiology between the different performance levels and to evaluate the accuracy of generalising data from elite runners to the general running population.

The general purposes of this review are:

1. Provide an overview of the literature on performance, training and physiology in distance running;
2. Highlight research on female runners and differences between genders;
3. Identify areas that may merit further study, or that have not been previously examined.

A1.2 PERFORMANCE

In order to study the relationships between performance, physiology and training, performance must first be defined. While the most commonly studied performance group, elite performance is poorly defined in the literature. Exceptions include Pollock (Pollock, 1977a, 1977b), Pate (Pate *et al.*, 1987; Sparling *et al.*, 1987) and Padilla

(Padilla, Bourdin, Barthélémy & Lacour, 1992) who all provide specific criteria for their selection of athletes as "elite". Pollock (Pollock, 1977a, 1977b) described the physiological characteristics of the best male US distance runners in 1972. These athletes were "members of either a Pan American or Olympic team, and/or who had earned a National Collegiate Athletic Association (NCAA) or American Amateur Athletic Union (AAU) title" (p279). It took fifteen years before Pate and colleagues (Pate *et al.*, 1987; Sparling *et al.*, 1987) reproduced the work led by Pollock using a similarly qualified group of female runners who had "either won a national championship (TAC or NCAA) or had previously been ranked in the top 10 in her event during the previous three years" (p73). These studies (Pate *et al.*, 1987; Pollock, 1977a, 1977b; Sparling *et al.*, 1987) represent the most comprehensive descriptions of elite distance runners of their eras, including performance variables to represent performance (race times), physiology (i.e. $\dot{V}O_{2max}$) and in some cases also training (miles·wk^{-1}) (Table A1.1).

Table A1.1. Data on the performance, physiology and training status of male and female runners. Male data taken from (Pollock, 1977a, 1977b). Female data taken from (Pate *et al.*, 1987; Sparling *et al.*, 1987).

		Men			Women		
		Elite	Good	Active	Elite	Good	Active
n		11	8	8	16	14	8
$\dot{V}O_{2max}$	mL·min^{-1}·kg^{-1}	76.9	69.2	60	67.1	58.6	52.9
RE	mL·min^{-1}·m^{-1}	0.200	0.206	0.196	0.195	0.207	0.194
Performance	10 km time	28:12	33:15	-	32:56	38:37	-
	5 km time	13:13	-	18:39	16:02	-	21:48
Training	miles·wk^{-1}	86.2	60	60-80	64.5	39.1	60-80

More recently, Padilla (Padilla *et al.*, 1992) examined physiological correlates with running performance in a group of male and female French runners. The criteria for inclusion were very specific: performances better than 88 and 90% of the year's best performances for French females and males, respectively, over the athlete's best distance (either 1500m or 3000m). The above studies included performance data for the athletes as well as physiological measures. By contrast, Daniels and Daniels (Daniels & Daniels, 1992) conducted a physiological comparison between elite male and female runners in 1992, without defining the athletes performance levels. While all of the Daniels' subjects were NIKE sponsored athletes (most of whom competed at the 1984 US Olympic trials), implying a high level of performance, the performance level of these athletes was not defined.

The performance range in the literature that is categorized the performance of 'good' runners is much broader than that of elite runners. 'Good' runners include those who are only slightly slower than their elite counterparts, for example 10 km finishing times of 38:37±1:15 for good female runners, compared to 32:56±0:41 for elite women (Sparling *et al.*, 1987). The range of 'good' runners also includes most recreational athletes, with average 10 km times of 44:00 and 52:30 for men and women, respectively.

A1.2.1 Gender and Performance

In 1992, Whipp and Ward (Whipp & Ward, 1992) predicted an intersection of men and women's marathon race times in 1998 at 2:01:59. While both men and women set new records over the marathon distance in 1998 at 2:06:05 and 2:20:47, respectively, neither men or women achieved this predicted time, nor did the women's performance level catch up to the men's (www.iaaf.org/statistics/records).

There are many pitfalls of which to be wary when comparing the progress of the men and women's world records. One of the errors made by Whipp and Ward (Whipp &

Ward, 1992) was the assumption of linear progression in world record performance. In examining the progression of the men's mile world record from 1910 to the present (Figure A1.2), it is readily apparent that the trend is neither linear nor continuous. Rather it contains areas of exponential growth to a limit and areas where the limit changes. This change releases performance from the previous limit and allows further improvement towards a new limit. The shift in limit may be caused by a number of factors including changing approaches to physical training, improved technologies for track surfaces and running equipment, and the entrance of different groups into athletic competition (Joyner, 1993; Noakes, 1991). All of these factors increase the complexity of interpreting the progression of world record performances.

Another factor that may have misled Whipp and Ward (Whipp & Ward, 1992) is the early improvement in marathon times. When women were finally allowed to enter into competitive athletics, the initial progression of their performance reflected a phase of accelerated improvement, as women reaped the combined benefits of an increased opportunity to compete with simultaneous changes in training methods (Joyner, 1993; Noakes, 1991). Once this period of accelerated improvement to performance was complete, the progression of women's world records became similar to that of men. Since the late 1970's the progression of the women’s world record for the mile has paralleled that of men (Sparling, O'Donnell & Snow, 1998) (Figure A1.3). The current world record times for the mile are 3:43.13 for men, and 4:12.56 for women, a difference of 11 percent.

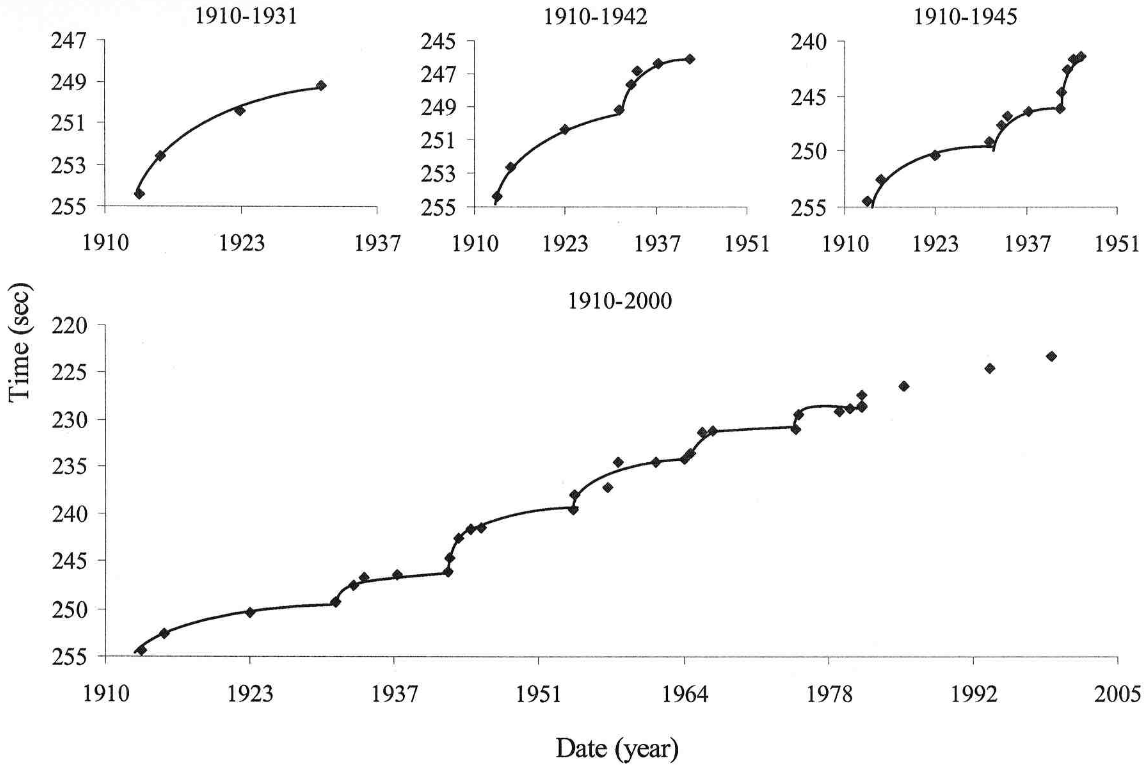

Figure A1.2. The world record (WR) progression in the men's mile, demonstrating the non-linear and discontinuous nature of WR progressions.

In addition to comparing the progression of world record times for a single distance (i.e. the mile), one can also compare world records across different distances. The difference in world record times for men and women is consistently 7-12 % over running distances from the mile to the marathon (Table A1.2). Over all given distances, the improvement in world record times for men and women has equalized over the last ten years (Sparling *et al.*, 1998). The average separation of almost 11% across the range of distances is curiously similar to the difference in haemoglobin between men and women (Cureton, Bishop, Hutchinson, Newland, Vickery & Zwiren, 1986; Sparling, 1980). When all other factors (training, body mass and adiposity) are accounted for, haematocrit may be the only remaining difference between men and women.

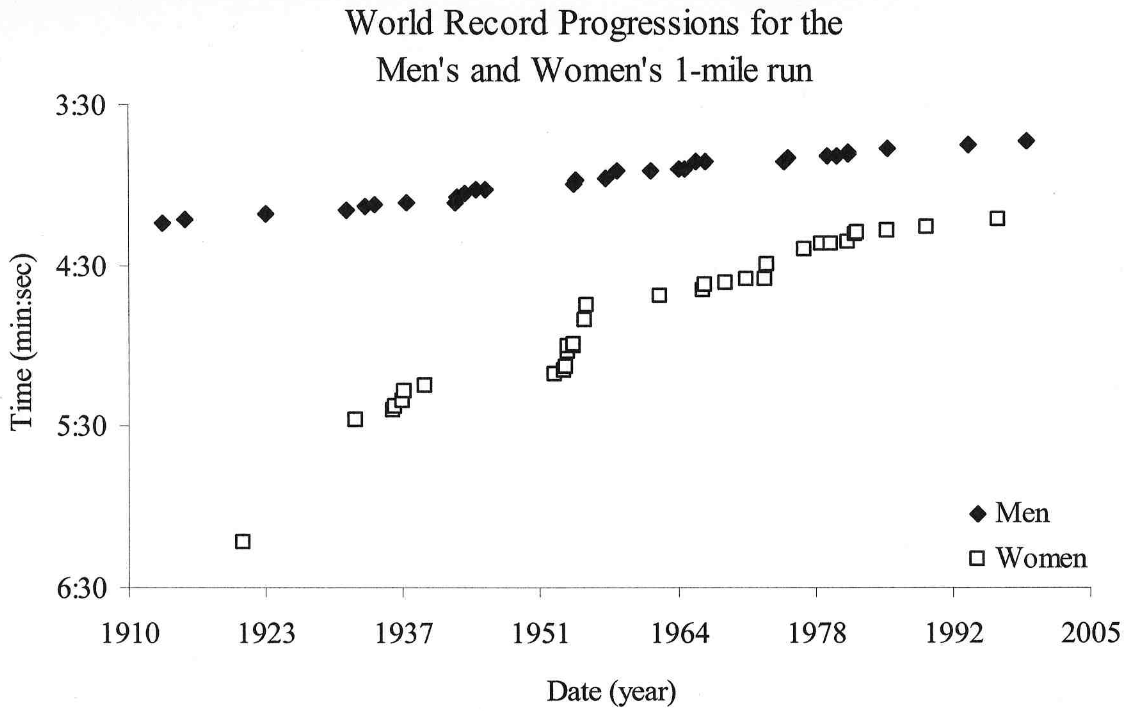

Figure A1.3. The WR progression for men and women in the mile. Over the past 10 years the separation of 1-mile WR times has been a consistent 11% (Sparling *et al.*, 1998). The current WRs for men and women are 3:43 and 4:12, respectively (www.iaaf.org/statistics/records).

Table A1.2. A comparison of World Records for men and women from the mile to the marathon. WR times are current as of September 29, 2003.

Distance	Men's WR	Women's WR	Difference (%)
1 mile (1,609m)	3:43.13	4:12.56	11.65%
5,000m	12:39.36	14:28.09	12.53%
10,000m	26:22.75	29:31.78	10.67%
21.1km (half marathon)	59:17	1:06:44	11.16%
42.2km (marathon)	2:04:55	2:15:25	7.22%

The gender difference in world record performance also extends through all levels of performance (Joyner, 1993). In comparing the finish times of men and women in both a 10km and half marathon event (Figure A1.4), the distribution curve for women is displaced relative to the men. For a local 10km event in 2002, the difference in the mean finishing times for men and women is 10:10 minutes (17.8%), while for a local half marathon the difference between means is 14:12 minutes (11.4%).

Obviously there are real performance differences between men and women, both at the elite level, and also in comparing the male and female populations. There also appear to be definite physical and physiological differences between men and women. However, explaining the performance differences of men and women based on differences in physiology may be a more difficult task than it appears.

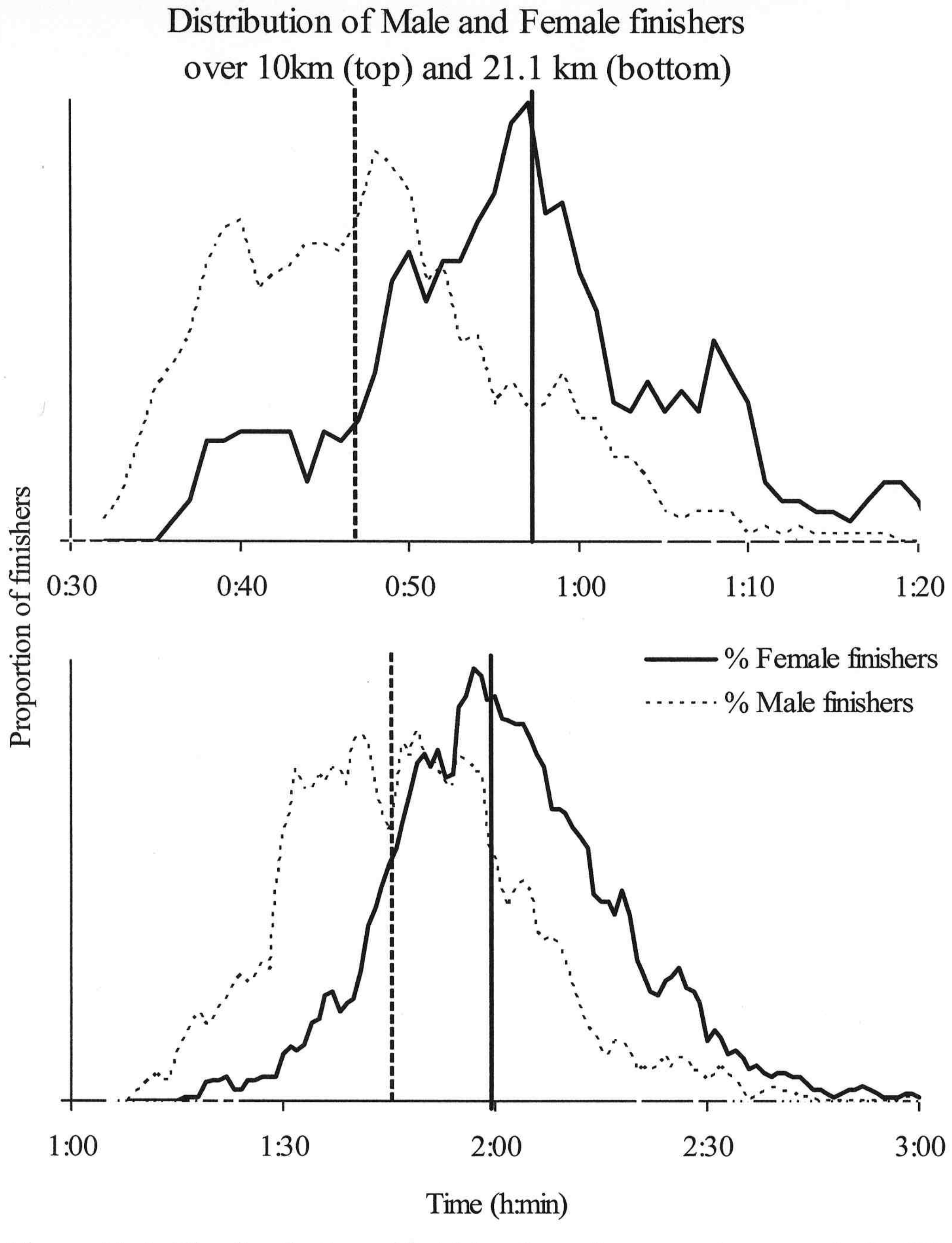

Figure A1.4. The distribution of finishing times for men and women in the "Richmond Flatlands 10k" (top) and the "First Half" half marathon (bottom). The performance difference that has been observed in elite men and women (Joyner, 1993; Sparling *et al.*, 1998) is apparent when examining the distributions of all male and female finishers, so that the curve for men is displaced to the left (faster finishing times) with respect to women.

A1.3 PHYSIOLOGY

Maximal aerobic power ($\dot{V}O_{2max}$), lactate threshold (LT), and running economy (RE) are the three physiological variables that appear to exert the greatest influence on aerobic performance (Fay, Londeree, LaFontaine & Volek, 1989; Joyner, 1993; Kenney & Hodgson, 1985; Noakes, 1991; Ramsbottom, Nute & Williams, 1987). The relationships between performance and physiology may be different for different levels or types of athletes, for example in a comparison of elite and recreational runners, or between male and female runners. This section will explore some of the relationships between performance level and physiology, and how these relationships may be different at different levels of performance, or for men as compared to women. While ranges of performance and physiology are continuous, it is helpful to distinguish between good and elite performance to illuminate the differences in physiology that are associated with heightened performance. Similarly, there is an observed difference in world record performance between men and women and this difference is reflected in differences in physiology.

A1.3.1 Maximal Aerobic Power ($\dot{V}O_{2max}$)

In running events of 800m (approximately two minutes) and farther, aerobic metabolism is the primary source of energy. The larger the volume of oxygen one can take in, the greater amount of O_2 will be available to the working muscles for the production of energy. The relationship between O_2 uptake ($\dot{V}O_2$) and running performance may be traced back to the early work of A. V. Hill (Hill, 1925). Hill assumed an absolute upper limit to $\dot{V}O_2$ ($\dot{V}O_{2max}$) of 4 $l \cdot min^{-1}$ based on the limited data that he collected in the early 1920's (Hill, 1925). We now know that $\dot{V}O_{2max}$ varies across individuals, based on elements that contribute to the functional demand for oxygen such as body mass, lean and fat mass proportions, and the mass of the active musculature (Richardson, 1998). A wide variety of other factors, including cardiac output, haematocrit, blood gas dissociation, acid-base balance and ventilation also influence $\dot{V}O_{2max}$ as important determinants of effective oxygen uptake at the lung and delivery to the cell (Poole & Richardson, 1997). Whether oxygen demand or delivery limit aerobic performance and $\dot{V}O_{2max}$ is a subject still under debate (Bassett & Howley, 1997; Noakes, 1997, 1998).

Traditionally, $\dot{V}O_{2max}$ was thought to be restricted by the cardiopulmonary system due to limitations at the lung and vasculature to take up and deliver oxygen to working muscle (Poole & Richardson, 1997; Richardson, 1998; Sutton, 1992). Controversy over whether central (cardiovascular) or peripheral (muscular-metabolic) factors ultimately limit $\dot{V}O_{2max}$ developed when Noakes and supporters (Bassett & Howley, 1997; Noakes, 1988, 1997, 1998) postulated that intrinsic muscular metabolic activity may limit the rate of O_2 extraction from the blood and thereby limit $\dot{V}O_{2max}$. Evidence that supports their claim is the effects of altitude on aerobic metabolism that highlight the accommodating change in anaerobic demand due to decreased access to aerobic pathways (Noakes, 1997). The unexpectedly small rise in anaerobic activity at altitude may imply that intrinsic muscular factors are the primary determinants of metabolic processes, irrespective of the oxygen supply – either atmospheric or delivered to the muscle (Noakes, 1988, 1997). While the underlying factors that limit $\dot{V}O_{2max}$ are still unresolved, an athlete's $\dot{V}O_{2max}$ remains an important contributor to their aerobic performance (Coyle, 1995; Sjödin & Svedenhag, 1985; Sutton, 1992; Wasserman, Hansen, Sue & Whipp, 1987).

$\dot{V}O_{2max}$ correlates well with endurance running performance and training in a group of runners who have a wide performance range and also a wide range in $\dot{V}O_{2max}$ values. Pollock and collaborators (Pollock, 1977a, 1977b) produced a comprehensive study of $\dot{V}O_{2max}$ in a group of elite runners. They found average $\dot{V}O_{2max}$ values of 76.0 $mL \cdot min^{-1} \cdot kg^{-1}$ for the elite runners, and also reported previous data for good runners and untrained men, $\dot{V}O_{2max}$ values of 69.2 and 54.0 $mL \cdot min^{-1} \cdot kg^{-1}$, respectively. In combination, good and elite runners exhibit a wide range of performance, and a good correlation between their performance and $\dot{V}O_{2max}$ ($r \geq 0.80$) (Christensen & Ruhling, 1983; Costill, Thomason & Roberts, 1973; Fay *et al.*, 1989; Grant *et al.*, 1997). When examining a narrower range of endurance running performance and physiology, for example in only elite runners, there is a much poorer correlation ($r \leq 0.15$) between $\dot{V}O_{2max}$ and performance (Conley & Krahenbuhl, 1980; Daniels & Daniels, 1992; Kenney & Hodgson, 1985). The requirement of additional factors (i.e. LT and RE) to discriminate between performances in this narrower range of endurance running performance also indicates that these other factors play a role in determining running performance.

A1.3.2 Lactate Threshold

While $\dot{V}O_{2max}$ is by definition a measure of maximal aerobic metabolism, some component of the energy utilised when exercising at an intensity that elicits $\dot{V}O_{2max}$ is derived from anaerobic sources, the end product of which is lactic acid (La). As energy demand increases with increasing work-rate, there comes a point where aerobic processes are no longer able to meet the rate of energy demand for the activity and the anaerobic contribution to energy production begins to increase. As anaerobic contributions rise with further increases in work rate, whole body La production exceeds La clearance, and La begins to accumulate. The concept of lactate threshold (LT) represents the portion of $\dot{V}O_{2max}$ that can be sustained during endurance distance events while minimising the accumulation of La.

Other names used to refer to the lactate threshold include aerobic threshold, anaerobic threshold (LT), onset of blood lactic acid (OBLA) and ventilatory threshold (VT) (Bunc, Hofmann, Leitner & Gaisl, 1995; Farrell, Wilmore, Coyle, Billing & Costill, 1979; Helgerud, 1994; Hollmann, 1985; Hurley, Hagberg, Allen, Seals, Young, Cuddihee & Holloszy, 1984; Wasserman *et al.*, 1987). While there are slight variations in the specific definitions, all refer to the same phenomenon - the work rate at which aerobic metabolism alone cannot meet the demands of physical activity. LT has been arbitrarily defined as the work rate that elevates blood [La] 1mM above rest, produces a [La] of 4mM in the blood, or the point at which the increase in [La] with increasing work rate ceases to appear linear, and begins to rise exponentially (Coyle *et al.*, 1988; Farrell *et al.*, 1979; Hurley *et al.*, 1984; Saltin, 1969; Wasserman *et al.*, 1987). Alternative measures used to reflect LT, including heart rate or ventilatory threshold, are strongly correlated with direct measures of blood [La]. Using these measures, the threshold is defined as the point at which the slope of the threshold parameter changes from linear to exponential with increasing workload (Coyle *et al.*, 1988; Farrell *et al.*, 1979; Hurley *et al.*, 1984; Saltin, 1969; Wasserman *et al.*, 1987).

At exercise intensities above LT, and approaching $\dot{V}O_{2max}$, the concentration of lactic acid in muscle and/or blood increases above the resting value as the whole body rate of La production exceeds the rate of La clearance. One view of $\dot{V}O_{2max}$ and LT suggests that this increase in blood [La] and an associated continual decrease in blood pH are the ultimate cause of muscular fatigue (Hurley *et al.*, 1984). Since blood [La] may be a major contributing factor to a feeling of fatigue, and may also inhibit muscle metabolic activity, performing at an intensity that leads to an overly large [La] may reduce an individual's ability to continue at that level of endurance activity. For athletes who are participating in endurance events, this necessitates running at an intensity below that which produces an overabundance of blood [La]. In events taking longer than 15 minutes, the $\dot{V}O_2$ at which the lactate threshold (LT) is reached may be the single most important factor limiting performance (Farrell *et al.*, 1979; Hurley *et al.*, 1984).

A1.3.3 Running Economy

An individual with a high $\dot{V}O_{2max}$ has a large metabolic resource that may be called upon during exercise. A well-trained individual with a high LT has a high proportion of their $\dot{V}O_{2max}$ available to them for the production of energy without the fatiguing effects of an excessive increase in [La]. A third factor that may limit running performance is running economy (RE). This variable can be thought of as the oxygen demand ($\dot{V}O_2$) required for a given running speed, or the efficiency of producing forward motion using aerobic energy sources (Bunc & Heller, 1989; Daniels & Daniels, 1992; Joyner, 1993; Morgan, Craib, Krahenbuhl, Woodall, Jordan, Filarski, Burleson & Williams, 1994; Morgan, Martin & Krahenbuhl, 1989b). The lower the oxygen requirement, the greater the running economy. RE can be represented as the slope of $\dot{V}O_2$/running speed (Bunc & Heller, 1989; Daniels & Daniels, 1992; Joyner, 1991), or simply as the $\dot{V}O_2$ at one running speed (Cureton & Sparling, 1980). The relationship between $\dot{V}O_2$/running speed appears to be constant over sub-maximal running speeds, indicating that the oxygen cost of running is in direct relation to the change in running speed (Bunc & Heller, 1989; Daniels & Daniels, 1992).

Running economy may account for the difference in running speed between individuals who have a similar $\dot{V}O_{2max}$ and LT, since the more economical runner will cover more ground for a given level of oxygen consumption. RE may also account for similar performances from individuals with a significant difference in their $\dot{V}O_{2max}$. This possibility is explored in the three hypothetical runners outlined in Table A1.3. The first athlete (Athlete 1) has a high $\dot{V}O_{2max}$, and LT, but has an intermediate RE. Athlete 2 is similar to Athlete 1 in both $\dot{V}O_{2max}$ and LT, but has a substantially lower RE, so has a lower performance level than Athlete 1. In contrast, Athlete 3 has a low $\dot{V}O_{2max}$, but high LT and RE. As a result, Athlete 3 has a similar performance level to Athlete 1, even though Athlete 1 has a substantially higher $\dot{V}O_{2max}$.

Table A1.3. The combined effects of hypothetical values for $\dot{V}O_{2max}$, lactate threshold (LT) and running economy (RE) on running speed. Athlete 1 is for reference. Athlete 2 demonstrates that a poor RE will inhibit performance, whereas Athlete 3 demonstrates that excellent running economy may make up for poor $\dot{V}O_{2max}$.

Athlete	$\dot{V}O_{2max}$ $mL \cdot min^{-1} \cdot kg^{-1}$	LT $\%\dot{V}O_{2max}$	RE $mL \cdot m^{-1} \cdot kg^{-1}$	Race Speed $m \cdot min^{-1}$	10km time min:ss
1	75	90	0.200	337.1	29:40
2	75	90	0.237	284.4	35:10
3	65	90	0.174	337.1	29:40

A1.3.4 Composite Measures of Physiology

Individually, $\dot{V}O_{2max}$, LT and RE correlate with performance to varying degrees, based on factors such as the performance level of the athlete, event distance and gender (Joyner, 1993). $\dot{V}O_{2max}$, LT and RE can also be variously combined to produce composite measures of physiology, and these composite measures correlate well with performance (Morgan, Baldini, Martin & Kohrt, 1989a; Noakes, Myburgh & Schall, 1990). Common physiological composites include the representation of LT relative to $\dot{V}O_{2max}$ (i.e. as a percentage of $\dot{V}O_{2max}$) instead of as an absolute value. Similarly, $\dot{V}O_{2max}$ and RE have been combined to predict running speed at $\dot{V}O_{2max}$, or v$\dot{V}O_{2max}$. This combination represents a linear approximation of running speed at $\dot{V}O_{2max}$, derived from the relationship between running speed and oxygen uptake evaluated when testing for RE.

In one effort to combine $\dot{V}O_{2max}$, LT and RE to produce a model predictive of running performance, Joyner's (1991) model describes the general relationship between these three physiological variables and performance:

$$\begin{aligned} \text{Predicted Running Speed (m/min)} &= \dot{V}O_{2max} \cdot \text{LT}\ (\%\dot{V}O_{2max}) \cdot \text{RE} \\ &= \text{mL } O_2 \cdot \text{min}^{-1} \cdot \text{kg}^{-1} \cdot \% \cdot \frac{\text{m} \cdot \text{min}^{-1}}{\dot{V}O_2} \\ &= \text{m} \cdot \text{min}^{-1} \end{aligned}$$

where LT is represented as a percentage of $\dot{V}O_{2max}$ and RE as the slope of running speed vs. oxygen consumption ($\dot{V}O_2$; in mL $O_2 \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$). This is a mathematical solution to the estimation of running speed at LT.

Joyner used the highest values for $\dot{V}O_{2max}$, LT and RE reported in the literature to compute a predicted marathon performance, then reduced this estimated running speed by 10% to account for 1) the differences in RE on the treadmill as compared to overland running, and 2) the upward drift in $\dot{V}O_2$ that is seen during long-duration running (Joyner, 1991). The resulting prediction was nearly nine minutes faster than the world best marathon performance at the time. This over-estimation of running speed for the marathon distance can be attributed to many factors, including the assumption that a marathon is run at LT. This assumption may be overly optimistic of the abilities of long distance runners to maintain a running pace equivalent to LT. A second explanation for the over-prediction may have been an overestimation of the average RE during a marathon from the short (less than 30 minute) lab test typically used to measure RE; running economy may deteriorate significantly over the marathon distance due to fatigue. Changes in environmental factors on a marathon course (i.e. temperature, humidity, terrain) which may have a detrimental effect on RE are also not accounted for in the laboratory. Joyner addresses a number of other potential explanations for the disparity between the modeled and the actual marathon world best, and acknowledges that there are many other factors that contribute to running performance that were not incorporated into the model. He also posits that exceptional values in one of $\dot{V}O_{2max}$, LT and RE may preclude high values in another (Joyner, 1991, 1993). Finally, Joyner's model may be more appropriate to other running events, if it is assumed that LT reflects the sustainable level of aerobic performance for the event distance, and further that RE may be better maintained over the shorter distances than it is over the marathon distance (Tanaka &

Matsuura, 1984; Yoshida, Chida, Ichioka & Suda, 1987). The application of Joyner's model to other events has not yet been examined.

Researchers have identified relationships between physiology and performance across a large range of performance levels (Bunc & Heller, 1989; Christensen & Ruhling, 1983; Conley & Krahenbuhl, 1980; Daniels & Daniels, 1992; Helgerud, 1994; Kenney & Hodgson, 1985; Yoshida, Udo, Iwai & Yamaguchi, 1993). To perform at an elite level, athletes must maximize their physiology in order to maximize performance. This maximization is reflected in the observation that elite athletes have very high $\dot{V}O_{2max}$ levels (75-80 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$). However $\dot{V}O_{2max}$ alone is not a strong enough predictor of performance within the narrow performance range of these athletes (Conley & Krahenbuhl, 1980; Kenney & Hodgson, 1985; Morgan *et al.*, 1989a; Noakes *et al.*, 1990). Elite runners are also able to utilize a high proportion of their $\dot{V}O_{2max}$ without generating excessive lactate loads, reflected in generally high LT values, both as a percent of their $\dot{V}O_{2max}$ and in absolute terms. In correlating performance with physiology, a combination of two or more of the physiological variables produces a better prediction of performance. The combined variables of $v\dot{V}O_{2max}$ and vLT are both better predictors of performance across a narrower range of performance.

When making comparisons between populations, for example elite and good runners, or male and female runners, it is imperative to keep in mind all of the differences - in performance, physiology and training - between the populations, to ensure an accurate analysis of their differences, and their relationships. Many examinations of gender difference have looked at elite men and women without acknowledging their inherent performance differences (Billat, Lepretre, Heugas, Laurence, Salim & Koralsztein, 2003;

Daniels & Daniels, 1992). Not surprisingly, these studies have identified a number of physiological differences between these two groups.

However a large proportion of these studies have failed to acknowledge the performance discrepancy between elite men and women, and have used their findings to re-enforce the quickly disintegrating arguments of gender differences, when the findings may more accurately reflect the performance differences between elite men and women. The next section will examine the relationship between performance and physiology in the context of male and female runners, in an attempt to identify any gender differences in physiology that may remain, when performance level is taken into consideration.

A1.4 PHYSIOLOGY and GENDER

The majority of research about the relationships between physiology and performance has focused on male athletes. Historically, women were considered less physically capable than men, not able to run as fast, jump as high, or last as long in endurance competition as their male counterparts. However the logic underlying these assumptions has been thoroughly debunked (Bam, Noakes, Juritz & Dennis, 1997; Bunc & Heller, 1989; Dowling, 2001; Helgerud, 1994; Helgerud, Ingjer & Strømme, 1990; Joyner, 1993; Sparling, 1980; Sparling *et al.*, 1998; Sparling *et al.*, 1987; Whipp & Ward, 1992). Many differences (training, physiology and performance) are apparent in comparisons of male and female athletes. However the relationships *between* all of these variables are similar for male and female athletes. When examining runners of differing performance levels, regardless of gender, there are associated differences in physiology (Padilla *et al.*, 1992), and likely also differences in training. When examining runners of similar performance levels, again regardless of gender, the differences in physiology become insignificant (Helgerud *et al.*, 1990) (Table A1.4).

Table A1.4. Differences in performance are reflected in differences in physiology, in this instance in $\dot{V}O_{2max}$ (Padilla *et al.*, 1992). When the performance difference is removed, men and women exhibit the same physiological profile (Helgerud *et al.*, 1990).

(Padilla *et al.*, 1992)	men	women	significance
3000m run speed $(m \cdot s^{-1})$	6.13	5.38	$p<0.05$
$\dot{V}O_{2max}$ $(mL\ O_2 \cdot min^{-1} \cdot kg^{-1})$	71.9	65.3	$p<0.05$
AT $(\%\dot{V}O_{2max})$	87.9	86.4	ns
RE $(mL \cdot kg^{-1} \cdot m^{-1})$	0.18	0.18	ns
(Helgerud *et al.*, 1990)			
Marathon run speed $(m \cdot s^{-1})$	3.53	3.48	ns
$\dot{V}O_{2max}$ $(mL\ O_2 \cdot min^{-1} \cdot kg^{-1})$	61.5	60.0	ns
AT $(\%\dot{V}O_{2max})$	84.6	84.5	ns
RE $(mL \cdot kg^{-1} \cdot m^{-1})$	0.19	0.20	ns

There are many physical characteristics such as body mass or adiposity that influence $\dot{V}O_{2max}$, LT and RE. These traits vary within and across gender and much of the gender difference in $\dot{V}O_{2max}$, LT and RE between men and women can be explained by physical variation. Even though there may be absolute differences in physiology between men and women, the physiological variables that correlate well with performance in males also correlate well with performance in female athletes (Fay *et al.*, 1989; Helgerud, 1994; Helgerud *et al.*, 1990; Joyner, 1993; Pate *et al.*, 1987; Pollock, 1977a, 1977b; Sparling *et al.*, 1987). As a result, gender related differences in $\dot{V}O_{2max}$, LT and RE have been used to explain the differences in performance level between elite male and female runners (Fay *et al.*, 1989; Helgerud, 1994; Helgerud *et al.*, 1990; Joyner, 1993; Lewis, Kamon & Hodgson, 1986; Sparling & Cureton, 1983).

A1.4.1 Maximal Aerobic Power

Similar to the work of Pollock *et al.* (1977a; 1977b), Sparling organized a comprehensive study of elite female athletes (Pate *et al.*, 1987; Sparling *et al.*, 1987) to describe the physiology of these runners, who had a range of training and performance levels. The relationship between $\dot{V}O_{2max}$ and performance across a wide range of performance first observed in men was also seen in women (Pate *et al.*, 1987; Sparling *et al.*, 1987). Elite women exhibited mean $\dot{V}O_{2max}$ values of 67.1 mL·min^{-1}·kg^{-1}. In contrast, good female athletes produced $\dot{V}O_{2max}$ values of 58.6 mL·min^{-1}·kg^{-1}.

The difference in $\dot{V}O_{2max}$ between men and women depends on the expression used to represent $\dot{V}O_{2max}$. These expressions can be used to identify the gender-based factors that affect $\dot{V}O_{2max}$. Sparling's (1980) meta-analysis identifies a number of aspects of gender difference in $\dot{V}O_{2max}$. In absolute terms (L·min^{-1}), there is a difference of up to 60% [((m-f)/f)x100] in $\dot{V}O_{2max}$ between men and women. Ranges for men as compared to women are 2.76-4.80 L·min^{-1} and 1.92-3.30 L·min^{-1}, respectively (Sparling, 1980). The major contributor to this large difference is a difference in body size. Men are generally much larger than their female counterparts, and the absolute difference in $\dot{V}O_{2max}$ reflects this difference in mass. When $\dot{V}O_{2max}$ is represented per unit mass (mL·min^{-1}·kg^{-1}), the difference between men and women is reduced by half, to 28% (45.2-71.0 mL·min^{-1}·kg^{-1} vs. 35.7-55.0 mL·min^{-1}·kg^{-1}) (Sparling, 1980). Since Sparling's meta-analysis, higher $\dot{V}O_{2max}$ values have been reported for both elite male runners (84.4 mL·min^{-1}·kg^{-1}) (Pollock, 1977b) and elite female runners (73.0 mL·min^{-1}·kg^{-1}) (Pate *et al.*, 1987), a difference of only 15%.

The majority of the remaining difference in $\dot{V}O_{2max}$ expressed per unit body mass is due to differences in body fatness specific to gender. While body fat adds to the load that an individual carries, it is essentially dead weight: it increases the energy required for movement without contributing to the immediate production of that energy (Cureton & Sparling, 1980; Sparling, 1980). $\dot{V}O_{2max}$ can be expressed per unit lean body mass ($mL \cdot min^{-1} \cdot kgFFM^{-1}$) to account for the difference in body fat. When Sparling used this method of representation, the difference in $\dot{V}O_{2max}$ between men and women from the studies that he examined was reduced again by almost half, to 15% (52.9-80.7 $mL \cdot min^{-1} \cdot kgFFM^{-1}$ for men vs. 46.0-67.8 $mL \cdot min^{-1} \cdot kgFFM^{-1}$ for women) (Sparling, 1980). In a different sample of runners, Cureton and Sparling (1980) added excess weight to a group of men to adjust the amount of lean body mass (as a percentage of total weight) to similar values in a group of women who were similar in training habits and competitive experience. Equating the proportion lean body mass between men and women reduced the difference in $\dot{V}O_{2max}$ ($mL \cdot min^{-1} \cdot kg^{-1}$total mass) to non-significant levels in their study.

After accounting for the impact of sex-specific differences in adiposity, Sparling proposed that factors including training habits and haemoglobin concentration [Hb] account for the remaining 15% difference in $\dot{V}O_{2max}$ (in $mL \cdot min^{-1} \cdot kgFFM^{-1}$) between men and women (Sparling, 1980). On average, women have a [Hb] that is 10-15% lower than men, similar to the remaining percent difference in $\dot{V}O_{2max}$ from Sparling's meta-analysis (Sparling, 1980). The [Hb] difference may limit the $(a-\bar{v}O_2)$difference in women if they do not possess any mechanisms to assist in loading or offloading O_2 from haemoglobin (Joyner, 1993). Cureton *et al.* (1986) equated the [Hb] between men and women of similar endurance training backgrounds. This was accomplished by the withdrawal of 650-1000mL of blood, followed by two days to allow the restoration of plasma volume. They concluded that the sex difference in [Hb] does account for a small portion of the sex difference in $\dot{V}O_{2max}$, but that many other factors play larger roles in determining $\dot{V}O_{2max}$ (Cureton *et al.*, 1986).

A1.4.2 Lactate Threshold

The primary physiological difference between men and women related to endurance performance is $\dot{V}O_{2max}$. The absolute difference in lactate threshold between men and women is a reflection of this gap. When LT is expressed as a percentage of the $\dot{V}O_{2max}$, this gender variance is accounted for and there is no observed difference between men and women of similar training or fitness level, regardless of the method used to determine LT (Helgerud, 1994; Helgerud *et al.*, 1990; Ramsbottom, Williams, Kerwin & Nute, 1992).

A1.4.3 Running Economy

Running economy (mL $O_2 \cdot kg^{-1} \cdot m^{-1}$) is also no different between similarly trained men and women (Daniels & Daniels, 1992). When performance or level or training is not controlled, conflicting reports on the economy of running appear (Bourdin, Pastene, Germain & Lacour, 1993). This discrepancy points to the importance of making controlled comparisons between men and women at similar levels of training or performance.

Davies *et al.* (1997) used three methods of body mass adjustment to compare the RE of men and women who were moderately skilled runners with a diverse range of running ability. Even with this diverse group, adjustments for body mass were sufficient to equalize the cost of running between men and women. Davies concluded that only body mass need be accounted for to demonstrate that the aerobic demand of running is similar between men and women (Davies *et al.*, 1997). If performance or training levels are also controlled, it is possible that women could be more economical runners than men.

$\dot{V}O_{2max}$ correlates strongly with distance running performance across a wide range of performance (r^2= 0.64 to 0.85) (Costill *et al.*, 1973; Fay *et al.*, 1989; Ramsbottom *et al.*, 1987), but not in a homogenous group of highly trained runners (r^2= 0.01) (Conley & Krahenbuhl, 1980). Over a narrower range of performance, as seen in the elite runners of Conley and Krahenbuhl (1980), sub-maximal physiological descriptors such as lactate threshold (LT) or running economy (RE) appear to be more effective in predicting the subtle performance differences in a homogenous group of runners than $\dot{V}O_{2max}$.

The description of physiological and training characteristics of different performance levels is the first step towards a comparison of different performance groups. Previous comparisons have examined elite runners in relation to non-elite runners (Morgan, Bransford, Costill, Daniels, Howley & Krahenbuhl, 1995; Pollock, 1977b; Sparling *et al.*, 1987) and also compared male and female runners (Billat, Beillot, Jan, Rochcongar & Carre, 1996; Helgerud, 1994; Helgerud *et al.*, 1990; Padilla *et al.*, 1992; Sparling & Cureton, 1983). Most studies examining performance differences have been conducted with male subjects or have had a limited inclusion of females. In addition, none of these studies has included an adequate description of training differences to allow for an examination of the relationships between performance and training across a wide range of performance groups.

A1.5 TRAINING

The physiological differences between elite, good and untrained runners are also reflected in an examination of their varying performance levels. Indeed, differences in physiology and performance can be attributed in large part to different levels of training corresponding to the different abilities of the respective groups. However, within any single group (i.e. within a group of elite runners) the correlations between physiology and performance and between training and physiology are much more difficult to identify. This difficulty is due in large part to (1) inconsistent reporting or representation of training data in the literature, and (2) the complexity of training, including the variety of variables that can be manipulated (i.e. duration, frequency and intensity). While it is widely accepted that training improves performance in a dose-response manner, the specific relationships between the training stimulus (dose) and physiology and/or performance (response) have not yet been elucidated.

A1.5.1 Training and Performance

Notwithstanding the complexity of the training stimulus, there is an identifiable relationship between physical training and performance, as exemplified by the parallel differences in performance and training for elite and good runners (Pate *et al.*, 1987; Pollock, 1977a, 1977b; Sparling *et al.*, 1987). There is also an observed limit to this relationship, in that there is a diminishing performance return from increased training (Daniels *et al.*, 1978; Hurley *et al.*, 1984; Saltin, 1969). This limit to performance may be set by physiological and metabolic limitations. Indeed, the highest values for $\dot{V}O_{2max}$, LT, and RE in athletes from many different sports have remained largely unchanged during the past 20 years, despite any improvements in training techniques (Joyner, 1993). This consistency in physiological measures suggests that elite athletes may have reached the physiological limit to performance, although additional improvement could be achieved through technological advances in equipment, the use of performance enhancing substances, and the increasing diversity of individuals now competing in elite class competition (Joyner, 1993). It may also be possible that the physiological variables that are the focus of today's scientific inquiries are less important than has been historically assumed, and that other factors, physiological or otherwise, may have significant impacts on athletic performance (Joyner, 1993; Noakes, 1991).

While the trilateral relationships between training, performance, and physiology are identifiable when examining a broad range of performance (or training) groups, it is more difficult to identify these relationships when examining a narrower range of performance (i.e. elite males). The difficulty in relating physiology to performance has been discussed in a previous section of this review. Similar difficulties are encountered when attempting to relate training to performance or physiology over the narrower range of training, performance and physiology. Similar to the complexities of physiology, there are many factors that contribute to the training stimulus. These many factors generally are not accurately reported in the literature. The time-sensitive nature of the training stimulus further complicates the task of accurately reporting training.

A1.5.2 Training and Gender

The challenge to reporting training within a group (i.e. elite men) is also apparent when making comparisons between groups (i.e. men vs. women). A major deficiency in much of the previous work in the literature relating the physiological or performance differences between men and women is that it has not accounted for the disparity in training status between these two groups. An examination of the disparity between men and women in terms of training, performance and physiology in the current literature is made difficult by the inadequate methods of comparison. Studies that do not account for dissimilar training levels between men and women reveal differences in their physiology and performance, in part due to gender differences. However, these differences may also be due to the disparate training profiles of the two groups. As such, much of the gender difference in physiology and hence performance may easily be accounted for by a discrepancy in training volume, training intensity, history of training, or any number of other training variables that have yet to be accounted for.

Once the effects of disparate training have been accounted for, differences in physiology and performance between men and women that are the result of gender or biology can be identified. Similar patterns in the multiple relationships between performance, physiology and training are seen within one gender as well as when comparing between genders. Training impacts female physiology in much the same manner as it does male physiology: improvements in performance reflect improvements in physiology (Billat *et al.*, 2003; Billat, Demarle, Slawinski, Paiva & Koralsztein, 2001; Dowling, 2001). The decreased return on increased training for high performance athletes observed for men is also seen in women, and the potential for further training-induced improvements in performance decreases as the male or female athlete approaches their own limitations to performance. Historically, is has been assumed that the relative degree to which training affects performance in females is markedly different from their male counterparts. However because of the shape of the improvement curve, it is very difficult to make a direct comparison between men and for women.

There is some debate over how one selects appropriate groups of men and women to make a direct comparison of training effects. Two possibilities exist, both with their own benefits and drawbacks. First, as has been frequently studied in the past, elite men and women could be examined, providing a comparison of the highest levels of male and female physiology and performance, while at the same time providing an enlightening report of the differences in training between elite male and female runners. The primary limitation in studying elite runners is that further training will result in little, if any, significant improvement in performance. While a fraction of a second may be sufficient to set a new world record, there is little if any statistical significance in such a small improvement, limiting the interpretation of the training impact on physiology and performance.

A second approach is to examine men and women who have similar performance levels, and possibly similar training habits. This approach may allow an exploration of gender differences, as well as any differences in the effects of similar training between men and women. Although these men and women are of the same absolute performance level, they do represent different levels of ability within their own gender. Men running a 40 minute 10,000m race are 13:37 off the male world record pace, while women at the same time are only 10:28 away from the female world record. This position in their respective cohorts may lead to different potentials for improvement between men and women of similar absolute performance level, a variation that may come to light during the course of a training study. Alternately, similarly performing men and women may still show the same improvements if the performance difference is more strongly tied to differences in training than to a gender difference that has been manufactured to explain differences in training between elite male and female athletes.

A1.5.3 Quantification of Training

Although many studies (Billat *et al.*, 1996; Helgerud, 1994; Helgerud *et al.*, 1990; Morgan *et al.*, 1995; Padilla *et al.*, 1992; Pollock, 1977b; Ramsbottom *et al.*, 1987; Sparling & Cureton, 1983; Sparling *et al.*, 1987) have examined the relationship between performance and physiology, they have not evaluated the relationship between training and performance, or training and physiology. One reason for this exclusion is the complexity of the training variable which may be manipulated by altering frequency, intensity, duration or type of training (Daniels *et al.*, 1978; Paavolainen *et al.*, 1999; Shephard, 1968, 1974; Sjödin & Svedenhag, 1985).

Perhaps in part because of the complexity of the training stimulus, training is represented largely subjectively in the literature (Daniels *et al.*, 1978; Davies & Knibbs, 1971; Franch, Madsen, Djurhuus & Pedersen, 1998; Gibbons, Jessup, Wells & Werthmann, 1983; Paavolainen *et al.*, 1999; Pate, Macera, Bailey, Bartoli & Powell, 1992; Robinson *et al.*, 1991; Scrimgeour *et al.*, 1986; Shephard, 1968) and a comparison of the effect of a defined quantity of training has rarely been carried out (Banister & Fitz-Clarke, 1993). Only by applying a standard quantity and profile of training may any difference in physiology between men and women with the same performance level be isolated.

The lack of application of a consistent training model may be resolved by using a systems model to quantify training and to model its effect on performance (Banister &

Calvert, 1980; Banister, Calvert, Savage & Bach, 1975; Banister & Fitz-Clarke, 1993; Banister, Morton & Fitz-Clarke, 1996; Busso, Carasso & Lacour, 1991; Calvert, Banister, Savage & Bach, 1976; Fitz-Clarke, Morton & Banister, 1991; Morton, Fitz-Clarke & Banister, 1990). Studying the effects of training on physiology or performance is usually accomplished by comparing a training stimulus with its training effect. It is a relatively simple task to measure the change in physiological parameters and running performance. It is more difficult to quantify the training stimulus. As previously mentioned, the majority of studies to date that have examined the effect of training on human physiology and performance have only assessed the training load in a qualitative manner (Daniels *et al.*, 1978; Davies & Knibbs, 1971; Hurley *et al.*, 1984). This makes it impossible to analyse the effects of different training stimuli on performance in the previous literature.

The quantitative systems model developed by Banister and colleagues (Banister & Calvert, 1980; Banister *et al.*, 1975; Banister & Fitz-Clarke, 1993; Banister *et al.*, 1996; Calvert *et al.*, 1976; Fitz-Clarke *et al.*, 1991; Morton *et al.*, 1990) can be used to quantify a training stimulus on an individual basis. A training session can be quantified as a training impulse (TRIMP) by measuring the average increase in heart rate (ΔHR) during training, and the duration of training (T):

$$\begin{aligned} &\text{TRIMP} = T \cdot \Delta HR \cdot Y \\ &\quad \text{where} \quad \Delta HR = (HR_{exercise} - HR_{rest}) \cdot (HR_{max} - HR_{rest})^{-1} \\ &\quad \text{and} \quad Y = e^{1.67 \cdot \Delta HR} \end{aligned}$$

A metabolic arousal factor (Y), based on the rise in blood lactate accompanying an increase in HR, is used to weight the intensity of training from the elevation of heart rate during training, so that high intensity (assumed to be high quality) training is weighted more heavily than low intensity (and presumably lower quality) training (Banister & Fitz-Clarke, 1993; Banister *et al.*, 1996; Morton *et al.*, 1990) (Figure A1.5).

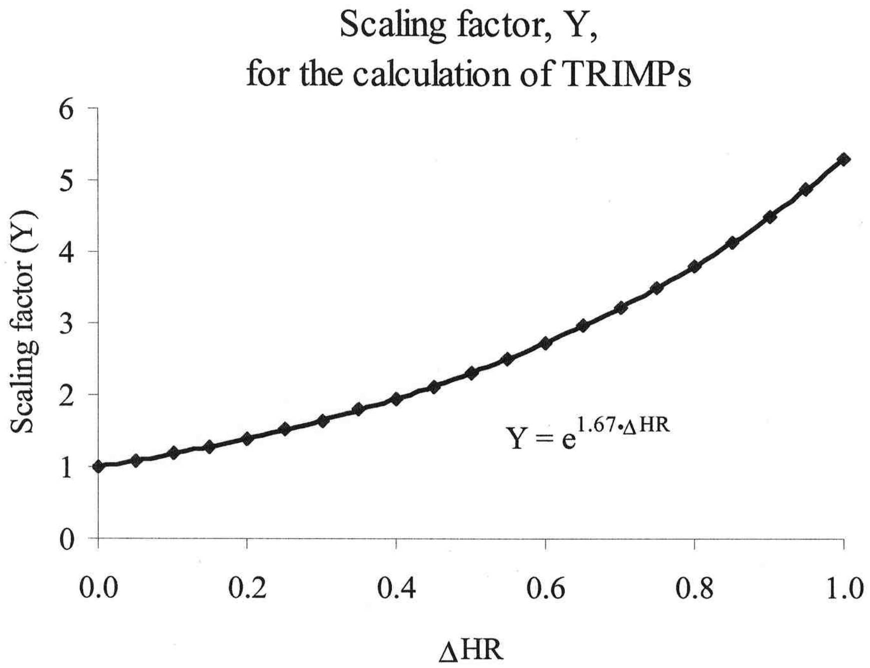

Figure A1.5. Calculation of the metabolic arousal factor, 'Y', from ΔHR, based on the increase in blood lactate with increasing exercise intensity. Y is a scaling factor intended to weight high intensity exercise over lower intensity, long duration exercise (Banister & Fitz-Clarke, 1993; Banister *et al.*, 1996; Morton *et al.*, 1990).

In addition to providing a method of quantifying training, Banister and collegues (Banister & Calvert, 1980; Banister *et al.*, 1975; Banister & Fitz-Clarke, 1993; Banister *et al.*, 1996; Calvert *et al.*, 1976; Fitz-Clarke *et al.*, 1991; Morton *et al.*, 1990) address the time-sensitive nature of the training stimulus, and attempt to model the effects of training on performance. This model applies two components in order to represent the influence of a training stimulus on performance; a benefit (fitness) and a detriment (fatigue). Training produces an increase in both fitness and fatigue, with the increase in fitness and fatigue depending on training intensity. In general the immediate effect of training is fatigue, while the longer term effect of training is fitness (Fitz-Clarke *et al.*, 1991; Morton *et al.*, 1990). On the cessation of training, fitness and fatigue begin to decay exponentially, with the rate constant of fatigue being larger than that of fitness, so that fatigue diminishes faster than fitness (Banister & Calvert, 1980; Banister *et al.*, 1975; Banister & Fitz-Clarke, 1993; Banister *et al.*, 1996; Calvert *et al.*, 1976) (Figure A1.6). Subsequent training builds on the residual fitness and fatigue from a previous session of training, so that the effect of additional training is cumulative. During periods of intense training, the increase in fatigue predominates over accumulating fitness, and the athlete may experience a decrease in performance level. In preparation for competition, a taper period allows some relief from the high volume of training, so that fatigue is largely eliminated, while as much as possible preserving accumulated fitness. The athlete's performance level rises and, in theory they enter competition when there is the greatest difference between fitness and fatigue.

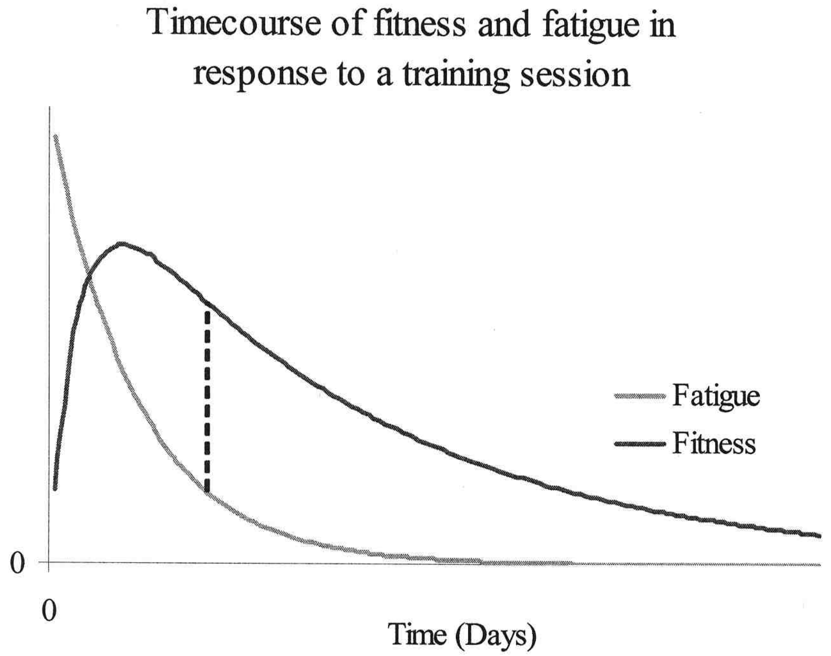

Figure A1.6. The influence of a single training session, at time zero, on the two components of performance, labelled Fitness and Fatigue (Banister & Calvert, 1980; Banister et al., 1975; Banister & Fitz-Clarke, 1993; Calvert et al., 1976).

In Banister's model, predicted performance is compared to the actual level of performance using a running criterion performance (CP). A series of CPs may be performed during a training period, and the prediction of performance from training can be manipulated so that the progression of modelled performance mirrors the variation in CPs. This is accomplished through adjusting a series of constants for both the accumulation and decay of fitness and fatigue (Banister & Calvert, 1980; Banister *et al.*, 1975; Banister & Fitz-Clarke, 1993; Banister *et al.*, 1996).

A1.6 CONCLUSIONS

The general relationships between training, physiology and performance are readily apparent when examining the running population as a whole. Comparing sub-populations of runners highlights specific differences between, for example, elite and recreational runners in training, physiology and performance. While many different sub-populations have been examined, comparisons of these groups have not adequately accounted for implicit differences in physiology that may exist (i.e. between elite and recreational runners). Similarly, the training undertaken by different groups has not been well integrated into the research on performance. Because of the complexity of the inter-relationships between training, physiology and performance, there are many outstanding questions despite the large volume of research into these three variables.

Determining the dose-response relationship between training and performance, or training and physiology, is one potential application of the TRIMP model. However, due to the individuality of an athlete's response to training, as well as the complex nature of training itself, it may be more realistic to use this model at the level of the individual, in order to better understand the athlete's unique relationships between training and performance, and physiology. Similar to the intentions of physiological testing, monitoring an athlete's training, and their physical and physiological responses to training, should not be used to compare athletes to each other, nor as a 'predictive' test for the selection of future gold medalists (MacDougall & Wenger, 1990). Rather, monitoring training and physiology are both methods of providing feedback to the athlete and coach, in order to optimize the athlete's individual training.

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Appendix 2 – Recruitment Poster

Runners Wanted!!!

A study at UVic is recruiting women runners to explore the relationships between training, 10km running performance and physiology.

If you are

- Female
- Aged 20-35
- Run a 10km faster than 50 minutes
- Have been running for more than 3 years
- Competed in three running events last year

and consider running your primary form of training and competition, we want you!!!

Participants will track their training during the weeks leading up to the Garden City Times Columnist 10k (April 28, 2002).

In the week after the TC 10k, we will test your VO_2max, lactate threshold and running economy at the Sport and Fitness Centre at UVic.

Interested runners please contact
Tim Hartley for more information
Ph: 995-1216 e: thartley@uvic.ca

Appendix 3 – Informed Consent

University of Victoria
Office of the Vice-President, Research
Human Research Ethics Committee

Participant Informed Consent Form

Training, physiology and performance in female 10 km runners

You are being invited to participate in a study entitled "Training, physiology and performance in female 10 km runners" that is being conducted by Tim Hartley. I am a graduate student in the School of Physical Education at the University of Victoria and you may contact me if you have any questions by email (thartley@uvic.ca) or telephone (995-1216). If you have any questions or concerns about this study, please bring them to my attention.

As a graduate student, I am required to conduct research as part of the requirements for a degree in Exercise Physiology. It is being conducted under the supervision of Kathy Gaul. You may contact my supervisor by email (kgaul@uvic.ca) or by phone (721-8380).

The purpose of this research project is to examine the relationships between physiology, training and performance in a group of female runners who are capable of running the 10 km distance in under 50 minutes to determine any differences in training that accompany differences in performance and also to correlate training with physiology and performance.

Research of this type is important because it builds on the existing literature in comparing physiology within and across performance levels and relates physiology and performance to the training that subjects have undertaken to achieve these levels.

You are being asked to participate in this study because you meet the following criteria:

- Your age is between 20 and 35 years
- You have a 10 km running time of under 50 minutes.
- You have completed more than three (3) running events in the previous year and have participated in running events for more than three (3) years
- You consider running as your primary mode of exercise/training and as your primary competitive choice

If you agree to voluntarily participate in this research, your participation will include:

- Providing training information in weekly meetings (approx ½ hr. each) with me from now (March 29, 2002) until the Times Columnist 10k (April 28, 2002).
- You will be given a training log to document your daily training, and this will be verified by the use of a heart rate monitor during training. If you do not have a HRM that is sufficient for this task, I will provide you one for use during the study. I have a limited number of HRMs, so you may not be able to use it for the entire duration of the study.
- Provide performance data. This will be your finishing time at the Garden City Times Columnist 10 km run, April 28, 2002.
- Complete the physiological testing procedures at the Sport and Fitness Centre at UVic. There will be two testing sessions on two separate days: a Maximal Aerobic Power (VO2max) test and a sub-maximal test for Running Economy (RE) and Anaerobic Threshold (AT). Additional information on the testing sessions is attached.

The total study duration is estimated at 6 weeks.

There are some potential risks to you in participating in this research, which include possible physical discomfort and potential for injury. The potential risk associated with this study is no greater than the risk associated with your regular training. As experienced runners, you are familiar with these risks. They include but are not limited to muscular aches and pains, overuse (i.e. shin splints) or acute (i.e. sprained ankle) injuries due to training, shortness of breath, etc. To prevent or to deal with these risks you no doubt have your own network of health and medical support services. However should you wish a recommendation to some other professional (Sports Medicine Physician, Registered Massage Therapist, Physiotherapist, etc.) I can provide you with a listing of practitioners out of the BC Sports Medicine Council's listings.

The potential benefits of your participation in this research include benefits to yourself and to the scientific community:

For you, knowledge of training, performance and physiological information is excellent information that can be used to plan future training programs for running. The opportunity to monitor training, performance and physiology will assist you in better understanding your responses to training

In the broader community, the relationships between training, physiology and performance are not completely understood. This study hopes to contribute to that state of knowledge by further describing the relationship between physiology and performance and by extending that relationship to include the training undertaken in the six (6) weeks prior to a running event

Your participation in this research must be completely voluntary. If you do decide to participate, you may withdraw at any time without any consequences or any explanation. If you do withdraw from the study your data will not be used in the study.

To make sure that you continue to consent to participate in this research, I will be meeting with you throughout the study. If you wish to withdraw at any time, you can let me know at any of our meetings or by contacting me by phone at 995-1216 or by email at thartley@uvic.ca.

In terms of protecting your anonymity, while the race results of the Times Columnist 10 k are reported by name, you will be assigned a subject data code for the collection of all other data. Coding will be unique to each subject and will be used in place of naming for identification purposes. No personal information will be released. As principal investigator, I will be the only individual with access to the coding key.

Your confidentiality and the security of the data will be protected by password protecting (on computer) and storing data in a locked filing cabinet (computer disk back-up and hard copy data). Data will be disposed of after five (5) years. Any information that could potentially identify you as a participant of this study will be altered or destroyed (deleted files, shredded hard copies, removal of identifying information) at the conclusion of data collection for the study. All data will be destroyed (deleted files, shredded hard copies) at the end of five (5) years

As this research is being conducted in partial requirement of a Masters of Science in Physical Education, the results of the research will be written as the thesis of this degree. Additionally, the results of this study may be presented at a conference of exercise physiologists and published in a journal of exercise physiology.

As a participant in this study you are entitled to free access to your own data at any time, and you will be given a summary of your results at the end of the study. I will discuss the implications of the information that is being collected with you at any time before, during and after the conclusion of the study. If you have any questions, please don't hesitate to ask. If you are interested in hearing about the results, let me know and I will contact you when I have a finished product to share.

In addition to being able to contact the researcher and his supervisor at the above phone numbers, you may verify the ethical approval of this study, or raise any concerns you might have, by contacting the Associate Vice-President, Research at the University of Victoria (250-472-4362).

Your signature below indicates that you understand the above conditions of participation in this study and that you have had the opportunity to have your questions answered by the researchers.

Name of Participant	*Signature*	*Date*

A copy of this consent will be left with you, and a copy will be taken by the researcher.

University of Victoria
Office of the Vice-President, Research
Human Research Ethics Committee

Testing Session Informed Consent Form

Training, physiology and performance in female 10 km runners

You are being invited to participate in a study entitled "Training, physiology and performance in female 10 km runners" which I am undertaking as part of my M.Sc. at UVic.

This information sheet is intended to fully describe the testing procedures for the physiological testing sessions that will conclude your participation in this study. If at any time you have any questions about these tests or the study itself, please ask me. You may contact me by email (thartley@uvic.ca) or telephone (995-1216). You can also contact my supervisor, Kathy Gaul by email (kgaul@uvic.ca) or by phone (721-8380). Your participation in this research must be completely voluntary. If you do decide to participate, you may withdraw at any time without any consequences or any explanation. If you do withdraw from the study your data will not be used in the study.

Testing Procedures:

Two testing days will occur approximately one week after the TC 10k. Day 1 will evaluate maximal aerobic power (VO_2max). Day 2 will evaluate the submaximal performance variables of running economy (RE) and anaerobic threshold (AT). The two testing sessions will be separated by approximately 48 hours.

Day 1: Please report to the UVic Sport and Fitness Center (SFC) after 24 hours of inactivity. During these 24 hours please also refrain from consuming alcohol or caffeine. Fifteen minutes after your arrival at the SFC, resting HR, height, weight and skinfolds from five sites (subscapular, biceps, triceps, suprailiac and mid-calf) will be measured. Once these measurements are finished, you will be allowed a 10 minute self-paced warm-up on the treadmill. At the end of the warm up, you may stretch for up to 10 minutes. You will then be instrumented for the monitoring of your exercising HR and pulmonary measures (VO_2, VCO_2, VE and RQ). The maximal test will be a continuous graded running test, beginning at 5 mph ($134.1 m \cdot min^{-1}$). Treadmill speed will be increased by 0.5mph ($13.4 m \cdot min^{-1}$) every 2 min, up to 2 mph ($53.6 m \cdot min^{-1}$) past your 10 km pace, calculated from your 10 km race pace during the Times Columnist 10k. Once you reach this running speed, the treadmill grade will be increased by 1% each minute until you can no longer continue.

Day 2: Submaximal physiological variables will be measured in a separate testing session at least 48 hours after the VO_2max test. Following the same rest and warm-up procedures as Day 1, you will perform a discontinuous series of runs for 5 minutes each for the determination of anaerobic threshold and running economy. At the end of each increment there will be a short 1 minute rest, during which you will remain standing on the treadmill and a finger-prick blood sample for capillary blood lactate concentration will be taken. This blood sampling will be done using sterile techniques and the collection of a small droplet of blood. At the end of the minute, you will immediately begin running again. The speed of the treadmill will be increased by 0.5mph ($13.4 m \cdot min^{-1}$) at the beginning of each increment, until you are no longer capable of completing the five minute interval at the specified treadmill speed.

In addition to being able to contact me or my supervisor (as above), you may verify the ethical approval of this study, or raise any concerns you might have, by contacting the Associate Vice-President, Research at the University of Victoria (250-472-4362).

Your signature below indicates that you understand the above conditions of participation in this study and that you have had the opportunity to have your questions answered by the researchers.

Name of Participant	*Signature*	*Date*

A copy of this consent will be left with you, and a copy will be taken by the researcher.

Appendix 4 – Training Log sample page

Training Log
Participant:_________
____

Training, Performance and Physiology
University of Victoria
School of Physical Education

Date:_____________

Hours Sleep:_______
Resting HR:_______

Training
Duration:__________

Training HR:_______

Type of training: (i.e. hills, intervals, tempo, recovery, etc.)
Description:____

____

____

____

____

____

____

____

____

____

Comments (include information like weather, diet, mood and other activities such as work, etc.)

____

____

____

____

____

Questions? Comments?

Please contact Tim Hartley

Ph: 995-1216

e: thartley@uvic.ca

Appendix 5: Calculation of TRIMPs

The HR profile of the training session portrayed in Figure9 (p. 39) is used in this example calculation of TRIMPs. The total time of the workout was 58 minutes. The average HR for the workout was 152 bpm. The subject's HR_{rest} (measured laying supine, first thing in the morning) and HR_{max} (measured directly in lab $\dot{V}O_{2max}$ test) are 56 bpm and 194 bpm, respectively (Table A5.1).

Table A5.1. Heart rate and training variables for the calculation of TRIMPs

Variable	Value
Training Time (T)	58 min
Average training HR ($HR_{exercise}$)	152 bpm
Resing HR (HR_{rest})	56 bpm
Max HR (HR_{max})	194 bpm
HR Threshold	126 bpm

1. The original TRIMP calculation:

$$\text{TRIMPs} = T \cdot \Delta HR \cdot Y$$

where
$$\Delta HR = (HR_{exercise} - HR_{rest}) \cdot (HR_{max} - HR_{rest})^{-1}$$
$$\Delta HR = (152 - 56) \cdot (194 - 56)^{-1}$$
$$\Delta HR = 0.68$$

and
$$Y = e^{1.67 \cdot \Delta HR}$$
$$Y = 3.14$$

Therefore number of TRIMPs $= 58 \cdot 0.7 \cdot 3.2$
$= 130$

2. The modified TRIMP calculation:

Using the modified calculation for TRIMPs outlined in the Methods (p.13), separate TRIMPs were calculated for each 15-s (0.25min) of the training using the serial 15-s HR data provided by the HRM throughout the full training session and subsequent recovery period. Based on the recovery HR data from the subjects HRM data files, a threshold HR was set to exclude HR data that was not 'training' *per se*, but rather HR data that was included after running training had ceased. Any serial HR data point that was less than the HR threshold was not included in the calculation of the total TRIMPs for that training session. All of the individual TRIMPs from the included (above HR threshold) serial 15-s HR data were summed to produce total TRIMPs from the workout. In this particular example, T would always be 0.25min (15-s period), ΔHR would be calculated for each 15-s HR data point from the HRM, and Y would also be calculated from the individual ΔHR for that data point. Adding all of the TRIMPs from each accepted 15-s period produces the total TRIMPs for the workout. An example of this calculation is provided below:

Table A5.2. An example of the calculation of TRIMPs on each 15s HR data set from the HRM.

	Time	HRex	HRrest	HRmax	TRIMPs	HRthreshold
	00:00	97	56	194	[a] 0.00	126
	00:15	94			0.00	
	00:30	103			0.00	
	00:45	90			0.00	
	01:00	90			0.00	
	01:15	92			0.00	
	01:30	94			0.00	
	01:45	91			0.00	
	02:00	86			0.00	
	.	.			.	
	.	.			.	
	.	.			.	
	56:00	167			[b] 0.77	
	56:15	166			0.75	
	56:30	167			0.77	
	56:45	164			0.72	
	57:00	159			0.65	
	57:15	153			0.57	
	57:30	146			0.48	
	57:45	138			0.40	
	58:00	135			0.37	
TOTAL TRIMPs					135	

a – since HRex<HRthresh, TRIMPs = 0

b – since HRex>HRthresh, TRIMPs are calculated for this 15-s interval and are applied to the summation of total TRIMPs for the workout.

This modification in the calculation of TRIMPs may be limited to training durations where the sampling rate of the HRM (i.e. 15-s) is much shorter than the duration of training, or an interval within the training session. For example, this calculation may not be effective in very short, intense intervals, as the HR information from the HRM will not accurately reflect the HRex.