

**THE PHYSIOLOGICAL AND PERCEIVED EFFECTS OF
DRAFTING ON A GROUP OF HIGHLY TRAINED
DISTANCE RUNNERS.**

By

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**We accept this thesis as conforming
to the required standard**

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ABSTRACT

This investigation examined and compared submaximal oxygen consumption, carbon dioxide production, minute ventilation, and heart rate responses during indoor track running in three running configurations in a group of highly trained distance runners. Maximal oxygen consumption performance testing was conducted to determine at what percentage of their maximal aerobic capacity the subjects were performing at during the test trials. Oxygen consumption, carbon dioxide production, minute ventilation, and heart rate values were measured every 20 seconds during all test trials using a portable calorimeter. Following each trial, runners were asked to rate their perceived exertion using the Borg scale. Subjects were randomly assigned configurations and order of testing. A recovery period of 15 minutes was required between all trials.

Nine subjects were tested at 4.47 m/s in three positions, L, D1 and D2. During the 4.47 m/s trials, drafting (D1 + D2) significantly reduced oxygen consumption (4.02 ± 0.18 l/min leading versus 3.81 ± 0.13 l/min drafting), and carbon dioxide production (3.74 ± 0.23 l/min leading versus 3.32 ± 0.13 l/min drafting) ($p < 0.05$). There was no significant difference in the reduction of oxygen consumption or carbon dioxide production between running directly behind a single runner, position D1, and running behind on the inside of a triangle, position D2. Minute ventilation and heart rate were not significantly reduced during the drafting (D1 + D2) trials. There was a significant reduction in the rating of perceived exertion for running behind on the inside of a triangle, position D2.

A sub-group of five subjects was also tested at 5.36 m/s in two positions, L and D1. During the 5.36 m/s trials, drafting in position D1 had the same effect as it did at the 4.47 m/s with the exception that the reductions were slightly larger than those observed for the slower pace. Drafting in position D1 substantially reduced oxygen consumption (4.76 ± 0.20 l/min leading versus 4.35 ± 0.20 l/min D1), and carbon dioxide production (4.44 ± 0.28 l/min leading versus 4.16 ± 0.26 l/min D1). Minute ventilation, heart rate, and rating of perceived exertion were not reduced during the drafting (D1) trials.

These results demonstrate that running within the aerodynamic shadow of another runner is very advantageous for distance runners. Both drafting positions tested were found to be equally effective in conserving energy. Drafting on the inside of a triangle was the position of choice. Coaches should expose athletes to drafting situations in training so that athletes can successfully employ this energy-saving strategy. One must also be aware that athletes who consistently run within a pack or drafting are not obtaining the full benefits of their training regimen.

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DEDICATION

To Dr. Jack Taunton

CHAPTER ONE

INTRODUCTION

Distance Runners

The contributions of metabolic, physical, and mechanical variables to running performance are a function of distance and intensity. Maximal aerobic capacity (VO_{2max}), submaximal oxygen consumption (VO_2), and lactate threshold are metabolic variables that increase in importance as distance increases. In any endurance running event, optimum performance is generally achieved by efficiently utilizing the available energy. The longer the distance of the run, the more important the conservation of energy becomes. Having a high capacity for providing the exercising muscles with energy is critical, as is being able to maintain a high running speed without negatively affecting the rate of utilization of total energy sources. Figure 1 shows the relative demands placed on the athlete's anaerobic and aerobic energy system in relation to race distance.

Long distance runners (5 km or greater) have been characterized as having higher maximal aerobic capacities, using oxygen more efficiently, and having significantly lower lactate accumulations than middle distance runners (Butts 1985). At the elite level these athletes have optimized most aspects of their running mechanics. Their general movement sequences are similar, and they tend to use running strides that are near their optimum, the most relaxing stride which does not reduce momentum (Grabiner 1993). Long distance runners generally run at a constant pace throughout most of a race. Race velocities range from 4.5 to 6.5 m/s (Adrian et al. 1989, Foster et al. 1994).

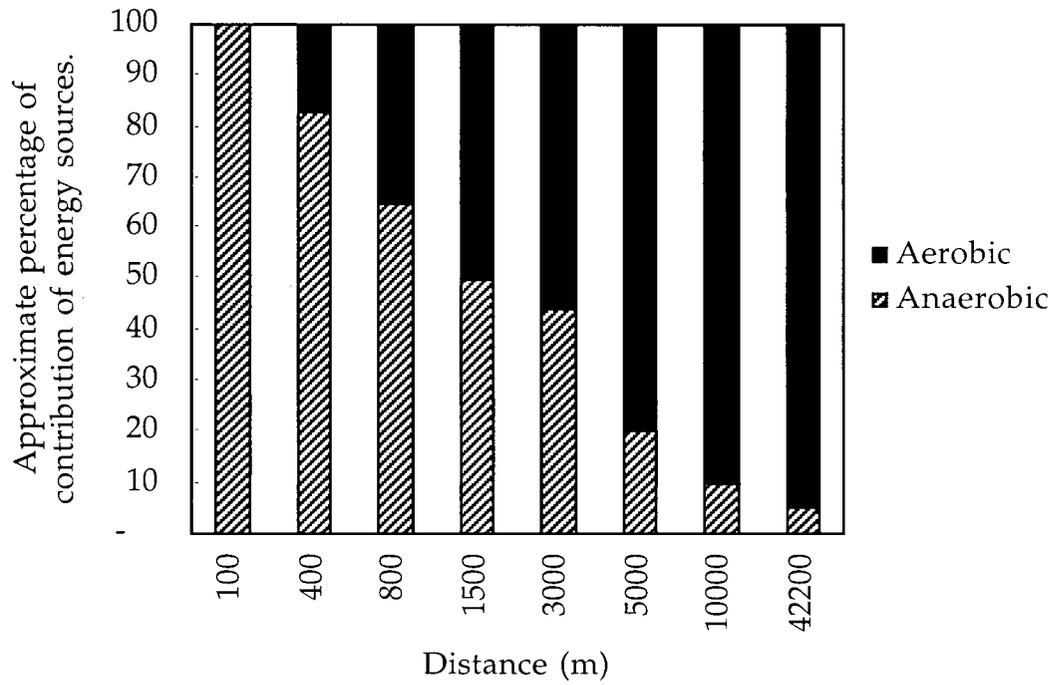


FIGURE 1: The energy demands of distance running. (modified from Fox et al. 1993)

Running Economy and Performance

In track and field how specific biomechanical, physiological, psychological, or environmental variations relate to the performance ability of runners are continually being assessed. There is a constant quest in athletics to find an aspect of running that can improve performance times. However, using running performance as a criterion for the effects of a particular factor can be confounded by the many factors affecting performance including running mechanics, physiological state, psychological factors, and race strategy. An alternative is to look at running economy. Running economy is defined as submaximal metabolic energy expenditure and generally refers to the aerobic demand of a particular running speed (Morgan et al. 1990). The changes in aerobic demand at a particular running speed can be used to investigate the differences in metabolism which may exist under different conditions or in different people.

Maximal aerobic capacity and running performance have been shown to be strongly related when examining a large population of distance runners with a variety of performance levels. However, the correlation between maximal aerobic capacity and performance among highly trained and experienced distance runners is much lower. This is not surprising considering they comprise a very homogeneous group of comparable ability and similar maximal aerobic capacities (Conley et al. 1980). There is a clear indication in the literature that running economy can be an important factor in performance especially at the elite level (Costill et al. 1973). Running economy varies considerably among highly trained runners, and has been found to account for a large amount of the variation observed in performance of this subgroup (Cavanagh 1990, Conley et al. 1980, Daniels 1985). Other factors which account for the variation in performance to a lesser extent include muscle fiber composition, anaerobic

threshold, peak muscle and blood lactate tolerance, biomechanics, and psychological factors.

Reducing oxygen consumption by optimizing running mechanics or changing racing strategies can improve performance by increasing the maximum sustainable speed. The advantages of working at a lower oxygen consumption rate are that the demands on the oxygen transport system are decreased and that the depletion of energy sources such as glycogen are reduced, delaying the onset of fatigue. This gives athletes the ability to increase their maximum sustainable speed and improve their performance times (see Figure 2). Even reductions in oxygen consumption as small as a percent or two could lead to meaningful improvements in performance times (Cavanagh 1990, Grabinger 1993, Williams 1985). Cavanagh (1990) suggests that a 2 % improvement translates into a 2.5 minute improvement in elite marathon race performance. Running economy has been shown to be limited by several intrinsic factors such as an athlete's age, weight, biomechanics, state of fitness and fatigue, as well as extrinsic environmental factors such as altitude, temperature, running surface, and aerodynamic drag (Daniels 1985).

Aerodynamics and Running

Air resistance is a major source of energy expenditure in many sports, particularly downhill skiing, ski jumping, the luge, bobsledding, speed skating, and cycling, where high velocities are reached (Halliday et al. 1988, Hill 1928, Kyle et al. 1984, di Prampero et al. 1976). Thus, efforts to reduce aerodynamic drag result in decreased energy cost. Air resistance is estimated to cost distance runners between 2-8% of their total energy (Davies 1980, Hill 1928, Pugh 1970,

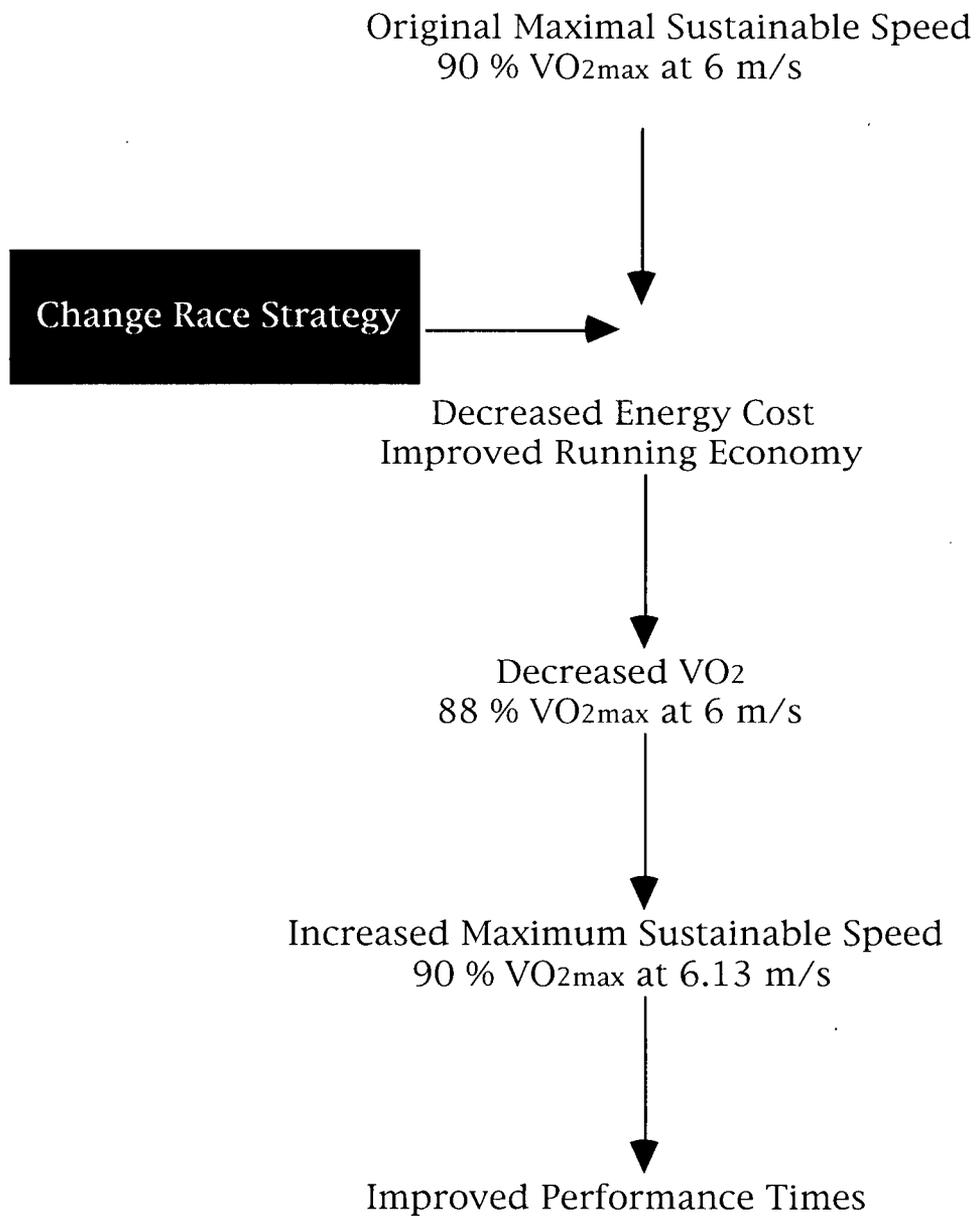
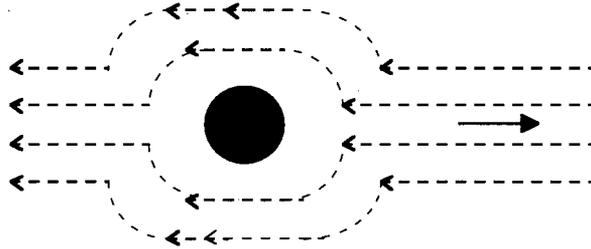


FIGURE 2: A proposed mechanism for improved performance times based on alterations in running strategies and their effects on running economy.

Pugh 1971). The energy cost of running at a constant velocity increases as wind resistance increases (Costill 1979).

Aerodynamic drag occurs for two reasons. One, the pressure that results from air molecules striking a surface and bouncing off, undergoing momentum changes and exerting normal forces on the surface. The other type of force, air friction, arises from the sliding motion of air molecules along the surface as they collide with rough surfaces. Fluid flow can be either laminar or turbulent, depending on many factors such as speed, surface roughness, and the type of surface material (Halliday et al. 1988, Olsen et al. 1987, Whitt 1982). At slow speeds the flow of air molecules will be laminar, this results in quite low drag forces. As the relative speed of the air and the surface increase, the laminar flow becomes unstable and layers of air begin to separate. The flow then becomes turbulent, characterized by whirling eddies of air (see Figure 3). Turbulent boundary layers have much higher drag than laminar layers. However, the highest drag is caused by instability at air velocities in the transition region between laminar and turbulent flow (Birkhoff 1960, Halliday 1988). The aerodynamic drag can be five times greater in the transition speed ranges than the aerodynamic drag for the purely turbulent flow. Therefore, it follows that to achieve low drag forces this transition region must be avoided. The transition region has been estimated to occur at speeds of about 4 m/s to 6 m/s for a cyclist (Tipler 1990). Considering the similarities in geometry and drag coefficients between cyclists and runners (Pugh 1976), the transition region would theoretically occur at the same speed range of 4-6 m/s for runners. This coincides with long distance racing paces.

Laminar Flow



Turbulent Flow

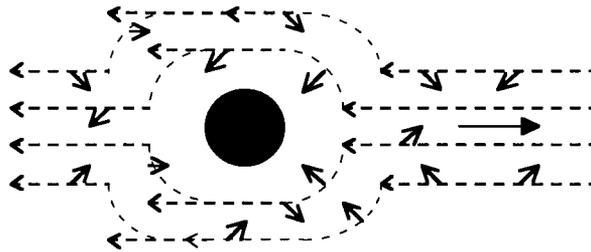


FIGURE 3: Laminar and turbulent air flow around a runner. The runner, moving right is simulated here by a filled circle.

The relative velocity of the air on the track or road is rarely zero. When running in a tail wind, the aerodynamic drag will provide a forward force. A head wind, on the other hand, provides a retarding force as it increases the aerodynamic drag. It has been estimated by Dapena et al. (1987) that a 2 m/s tail wind can give a 100 m sprinter a 0.07 second advantage; while, a 2 m/s head wind can result in a 0.085 second disadvantage. It appears that the hindrance produced by a head wind is larger than the time aid produced by a tail wind of the same intensity. Quantitatively, drag forces retarding forward motion are characterized by the equation: $F_D = 0.5C_D d A v^2$. Where F_D is the drag force, C_D is the drag coefficient, d is the air density, A is the projected frontal area of the runner, and v is the relative velocity of the air and the surface over which the air is flowing. This equation includes both air friction and pressure effects. However, it is only an estimate. The drag coefficient cannot be calculated for most real objects and is usually inferred from experimental data obtained from measurements made in wind tunnels.

Aerodynamic drag can be affected by changing any of the above variables. For example, air density which is relatively constant at a given location, changes with altitude. At 1.6 km above sea level air density is reduced by 10 %, thus reducing aerodynamic drag by 10 %. At first glance it seems possible that performance would improve at altitude due to the decrease in air resistance, however, this is not the case in endurance events. Any reduction in energy cost is cancelled and surpassed largely as a result of increased ventilatory cost in response to acute hypoxia (Daniels et al. 1970, Hagerman et al. 1975). Altitude is not the only environmental factor that influences air density; higher temperature and, to a lesser extent, humidity can also affect air density. Air density at 20 °C is 1.205 kg/m³ and at 40 °C drops to 1.128 kg/m³. A 5 °C increase in air temperature

produces a 1.5 % reduction in aerodynamic drag. Selecting a location with a higher temperature may not be an appropriate strategy to decrease the energy costs of overcoming aerodynamic drag forces, other physiological responses to higher temperatures must also be considered. Although an increase in body temperature improves muscle efficiency, it simultaneously increases the cost of circulation, ventilation, and sweating thus increasing oxygen consumption. The effects of humidity on air density are not as large as for altitude or temperature. Dry air at 30 °C and 1 atm has a density of 1.165 kg/m³; at the same temperature and pressure air completely saturated in water vapor has a density of 1.146 kg/m³. Selecting a high altitude location with high humidity theoretically could have an appreciable effect on performance but only in sports such as sprinting and speed cycling where there is insufficient time for the physiological responses to these environmental conditions to adversely affect performance.

Reducing frontal area and thus exposure to aerodynamic drag is easily accomplished by athletes in other sports. Cyclists lean forward until their backs are horizontal and their arms are tucked tightly against their bodies. Skiers can crouch down over their skis into the "egg" position until they are practically sitting on their ankles. Speed-skaters bend their upper bodies 90 degrees so they are parallel to the ground. Runners are limited in their postural adjustments but can decrease their frontal area by using tight fitting clothing and by trimming or covering their hair. Typical strategies employed by runners to reduce their aerodynamic drag are to reduce their coefficient of drag by using smooth spandex cloth, modified shoes, and head gear. Wind tunnel tests of clothing, hair, and shoes show that it is possible to reduce the aerodynamic drag of a runner by 0.5 % to over 6 % (Adrian et al. 1989, Kyle et al. 1986). Another means of reducing aerodynamic drag is by decreasing the drag coefficient. Streamlining

is a common technique employed in bicycle design. Race bicycles are being designed so that the laminar air flow is preserved during the ride (Halliday et al. 1988, Kyle et al. 1984).

A strategy that could reduce the aerodynamic drag forces on runners is drafting (see Figure 4). This technique is commonly applied in cycling, skiing, and other high drag sports. Many investigators and runners have recommended the tactic of running in the aerodynamic shadow of another runner, primarily based on anecdotal information and the results obtained from investigations on the effects of drafting in other sports (Higdon 1978, Hill 1928, Kyle 1979, Kyle 1979a). Only two studies have investigated this topic, but only one has been conducted on a runner (Pugh 1971). To date, the effects of drafting and running have only been cursorily examined. Further research is needed to quantitate the benefits of drafting in distance running.

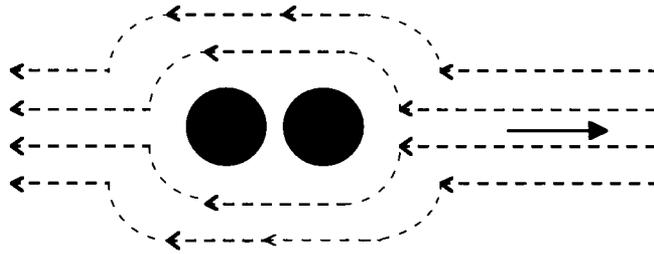


FIGURE 4: Air flow around a runner drafting behind another runner. The runners, moving right, are simulated here by filled circles.

STATEMENT OF THE PROBLEM

General Purpose Statement

To investigate how drafting, in various positions, affects specific physiological and perceptual variables of a group of highly trained elite level distance runners in a track environment. This study will investigate the following questions: a) Does drafting reduce the physiological variables: oxygen consumption, carbon dioxide production, minute ventilation and heart rate? b) Does drafting reduce the rate of perceived exertion? c) Do the effects of drafting, if any, affect the physiological variables differently at different speeds in the range of 4-6 m/s? d) Do the effects of drafting, if any, affect the rate of perceived exertion differently at different speeds in the range of 4-6 m/s? e) Do different drafting positions, running behind a single runner or a group of runners, affect the physiological variables differently? f) Do different drafting positions, running behind a single runner or a group of runners, affect the rate of perceived exertion differently? g) Which running position do elite distance runners, as represented in this group of subjects, find the most beneficial i.e. energy saving, less constricting, more comfortable, and applicable as race strategy?

SIGNIFICANCE OF THE STUDY

This study will provide the first values on oxygen consumption, carbon dioxide production, minute ventilation, heart rate, and rate of perceived exertion while drafting in the track environment. The practical implications are numerous: If findings are positive, athletes will be justified in using drafting as a means to conserve energy and then increase the maximal sustainable speed at the end of a race. Moreover, training methods will have to be reevaluated, since the front runners in a pack would be getting different benefits than drafters during each training session. By determining which positions result in the greatest reduction of air resistance, distance runners will be able to integrate this knowledge into their racing strategies. The findings of this study may shift the way races are run. For example, a team of runners could run at a record pace and maintain it by rotating the runners at the front, while shielding the ultimate winning individual, and the winning runner could easily be able to improve on his best time. An individual runner could run in the aerodynamic shadow of another runner, not only saving energy, but also putting psychological pressure on his competitor. At a strategic point in the race, the drafting runner could break away at a higher sustainable speed.

DELIMITATIONS

The study was delimited by:

1. The subject sample size,
2. The sample type (highly trained to elite level male distance runners),
3. The range of running speeds being tested (4.47 m/s and 5.36 m/s),
4. The number of positions being tested (3),
5. The testing period (three weeks),
6. The duration of each testing session (1-4 hours),
7. The recovery time between each trial (15 minutes),
8. The testing site (an indoor 200 m flat unbanked wooden oval track).

LIMITATIONS

The results of this study were limited by:

1. The data collection capabilities and accuracy of the AeroSport Teem 100 and CPX-D gas analyzers,
2. The experimental conditions and the inability to control temperature and humidity for the comfort of the subjects during testing,
3. The subjects' ability and motivation to perform maximally to exhaustion during the treadmill VO_{2max} test,
4. The subjects' metabolic and psychological responses to the protocols of the study,
5. The speeds selected to test subjects, which may differ from their typical race paces,
6. The effects of training and competitions during the testing period,
7. The effects repetitive exposure to the testing protocol,
8. The choice of dependent variables.

ASSUMPTIONS

1. The subjects' measured $\text{VO}_{2\text{max}}$ values were a true reflection of their maximal aerobic capacity.
2. The subjects were capable of running for a maximum of 10 minutes at a steady-state of exercise at the experimental speeds.
3. The training sessions aimed to familiarize subjects with the equipment, environmental test conditions, and drafting configurations were adequate.
4. A runner who was economical at a given speed of running would also be economical at other speeds.
5. Subjects had optimized most aspects of their running mechanics prior to participating in the study.
6. Subjects were capable of running at a speed higher than the one they were tested at for a minimum of 10 minutes.
7. A reduction in energy costs, decrease in oxygen consumption and carbon dioxide production, throughout a range of submaximal speeds of running would result in an improved performance time.
8. A prolonged maximal run (a race) would not produce an increase in aerobic demand of running or disrupt the gait pattern in subsequent short-term, submaximal runs (experimental trials).
9. Measures of oxygen consumption, carbon dioxide production, minute ventilation, and heart rate in highly trained male runners remained stable across the two testing sessions.
10. The runners were in a relatively steady-state condition, and that anaerobic sources contributed only minimally to the total energy expenditure and that minimal variations in substrate utilization occurred during the tests.

CHAPTER TWO

LITERATURE REVIEW

A.V. Hill (1928) was one of the first to investigate the question of air resistance on runners. He measured the pressure exerted on an 8-inch model of a running man at various air velocities in a 3-foot wind-channel. Hill produced an equation for the force exerted on a runner in terms of air density, the projected area of the runner, and the velocity. From his results he estimated that in still air 3-5% of the total energy requirement of a runner would be utilized to overcome air resistance. Pugh (1970) estimated the fraction of the total energy cost of track running required to overcome air resistance on the track to be about 13 % when running at a sprint velocity of 10 m/s, and 8% when running at a middle distance velocity of 6 m/s. Similarly, Davies (1980) estimated that the total energy cost of overcoming air resistance on a calm day would be 7.8 % at 10 m/s, 4 % at 6 m/s, and 2 % at 5.0 m/s. As a result of these findings, the focus of research has shifted to determining at which velocities air resistance begins to affect performance and to reducing the aerodynamic drag forces exerted on runners.

Maksud et al. (1971) found that at running speeds of 4.47 m/s and 5.36 m/s oxygen uptake was significantly higher during track runs when compared to treadmill runs, but that there were no significant differences between the two at the running speed of 3.13 m/s. Additional evidence indicating that the effect of air resistance on running economy progressively becomes greater as running speed increases has been provided by McMiken et al. (1976) and Daniels et al. (1985). McMiken et al. (1976) found no significant differences in running

economy until the running speeds of 4.33 m/s were reached. Daniels et al. (1985) reported that track running did result in higher aerobic demands at speeds above 4.47 m/s. From these three studies, it is clear that the drag forces play a significant role at speeds greater than 4.47 m/s. The regression equations derived from these studies are often used now to equate treadmill results to the track experience.

Considering that at the critical velocity range between 4-6 m/s, the estimated transition region between laminar and turbulent air flow and speeds at which elite distance runners compete in, it is possible that the energy expenditure and therefore running economy are markedly altered by the aerodynamic drag forces which an athlete encounters. It is surprising that there has been very little work on drafting and drafting configurations for distance runners. Pugh (1971) examined what would happen to the running economy when a runner drafted behind another runner. In this single case study, Pugh measured the oxygen consumption of an international middle and long-distance athlete while running on a treadmill at 4.46 m/s against varying wind velocities. He found that drafting, running about 1 m behind another runner, in calm air reduced this athlete's oxygen consumption by 0.15 L/min (4.8 %); while, drafting virtually eliminated air resistance and reduced this athlete's oxygen consumption by 0.25 l/min (6.5 %), when running against a 6 m/s wind. This is approximately an 80% reduction in the energy cost of overcoming air resistance. Pugh then measured the dynamic air pressure around the runner with a Pitostatic tube.

The pressure was negative 0.6 m behind the runner and still relatively low 1 m behind the runner. At the positions slightly to the side-behind the runner, the pressures were almost the same as the pressure 2 m in front of the runner. Pugh's pressure measurements are shown in Figure 5. The fact that running economy improved in this case study suggests that drafting could be a useful technique to evade aerodynamic drag. Moreover, the pressure results are useful for determining which drafting positions may be most effective. They suggest that drafting directly behind a runner may be more effective than drafting behind a competitors shoulder.

The only additional evidence available in the running literature that indicates that drafting can reduce a runner's aerodynamic drag is found in a study conducted on cyclists by Kyle (1979). Based on his results on cyclists coasting in a 200 m hallway, Margaria's data (1963) for the rate of energy consumed during running in still air, and the assumption that drag coefficient for the upright position in cycling was equivalent to that of runners, Kyle predicted that drafting would improve running economy by 4 % when drafting 1 m behind another runner at 6 m/s. Although this value has meaningful practical implications, it is slightly lower than that obtained by Pugh (1971). Methodological and computational differences could account for the discrepancy. However, another reason for the difference may result from the assumption made on the value of the coefficient of drag. The values estimated by other investigators differ considerably from those used by Kyle (Pugh 1976, Shanebrook et al. 1976).

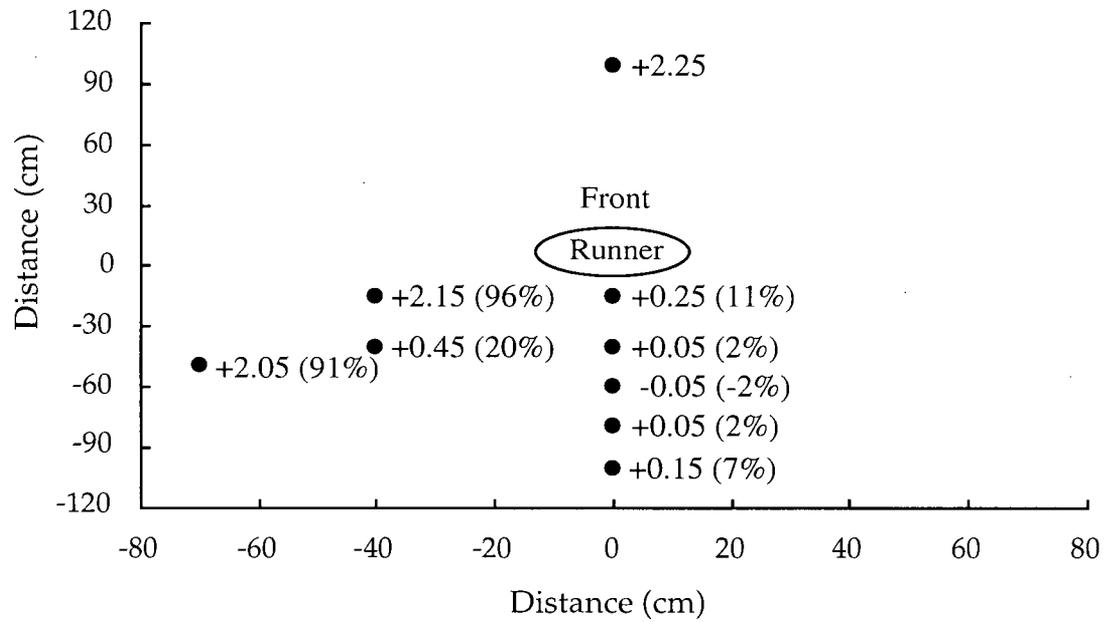


FIGURE 5: Dynamic air pressure in kgf/m² at various distances from a runner. Observations at a height of 126 cm and wind speed 6 m/s. Percentage reduction of air pressure is shown in parenthesis (from Pugh 1976).

The majority of the research on drafting's effects on aerodynamic drag, energy expenditure, and performance has been conducted on cyclists, but it yields useful information. In Kyle's (1979) investigation on the effects of drafting on cycling power output and wind resistance in a variety of positions, he found that drafting directly behind another rider reduced the air resistance by 44 % irrespective of the number of riders in the pace line. When a rider drafted in the center of a tightly packed cluster of riders the air resistance was surprisingly only reduced by 24 %; however, this effect was investigated in a single test. Kyle also reported that air resistance was only reduced by 23 % when the rider drafted in a position slightly to the side-behind instead of directly behind another rider. As would be expected from Pugh (1971) and Shanebrook et al. (1976) pressure data, he found the reduction in air resistance increased the closer a rider drafted behind another rider. McCole et al. (1990) conducted a similar study to Kyle's. They measured energy expenditure, oxygen consumption, of competitive cyclists on a flat stretch of straight road while drafting. They reported an 18 % reduction in oxygen consumption at 8.89 m/s and a 27 % reduction in oxygen consumption at 10.28 -11.11 m/s for subjects drafting behind one rider. Drafting 1, 2, 3, or 4 riders in a line resulted in the same reduction of oxygen consumption, while drafting a group of 8 riders at 11.11 m/s reduced oxygen consumption by 39 %. The latter results on the effect of drafting behind a pack of riders conflicts with Kyle's (1979) observation, demonstrating the need to have multiple subjects and trials in these investigations.

The relevance of these studies on cyclists lies in the configuration portion (Kyle 1979, McCole et al. 1990). They indicate that drafting behind a single runner may significantly increase running economy, and that the drafting behind a pack on a straight track may improve running economy even more. Drafting behind a

pack may turn out to improve running economy even more than running behind a single runner, but this position poses other strategic problems for runners. This position may conserve energy and be beneficial physiologically, but strategically a runner is at a disadvantage when boxed in.

The effects of drafting has been studied extensively in other sports where high drag forces must be overcome. In swimming, drafting has been found to reduce post-exercise oxygen consumption by 11%, blood lactate by 31%, and rating of perceived exertion by 21% (Basset et al. 1991). In cross-country skiing, Bilodeau et al. (1994) found that drafting significantly reduced heart rate by 5.6%, from 163 to 154 beats/min. While in kayaking, a similar technique of wash riding has been found to produce an 11% reduction in the energy cost of paddling (Gray 1992). In track & field, little has been done to quantify drafting's effects, mostly because of the difficulty in measuring oxygen consumption while running outdoors and in drafting configurations. These measurements are now possible with the development of two portable gas analyzers the Cosmed K2 (Rome, Italy) which has been found to be a reliable and valid instrument for measuring oxygen consumption, minute ventilation, and heart rate (Bishop et al. 1995, Crandall et al. 1994, Lucia et al. 1993), and the AeroSport Teem 100 (Ann Arbor, Michigan, U.S.A.) which has been found to be a reliable and valid instrument for measuring oxygen consumption, minute ventilation, heart rate, as well as, carbon dioxide production (Novitsky et al. 1995, Segal et al. 1994, Segal et al. 1995).

Two preliminary investigations have been conducted by Corvalán-Grössling et al. . In the first, a case study, the metabolic responses of an elite level distance runner to drafting outdoors in calm air were examined using the Cosmed K2. Corvalán-Grössling et al. (1994) found that drafting at the running speed of 4.47 m/s substantially reduced this athlete's oxygen consumption 0.72 l/min (29.0 %) and minute ventilation 20.6 l/min (18.7 %). Heart rate was only reduced 8 beats/min (5 %), while the subject rating of perceived exertion remained the same. The reductions in oxygen consumption and minute ventilation were observed to continue for at least the first two minutes of recovery as shown in Figures 6 and 7. The constraints imposed by the Cosmed K2 may have influenced these results. The face mask could possibly have altered this subject's breathing pattern as suggested by Loring et al. work (1990).

In the subsequent pilot study conducted by Corvalán-Grössling et al. (1995), testing was conducted indoors on a oval concrete corridor to have greater control over the environmental conditions. Less constricting test apparatus was also used to minimize the confounding effects which the equipment could produce on subjects respiration and heart rate. In this study, the metabolic responses to drafting at the running speed of 4.47 m/s was studied in eight highly trained male distance runners. Drafting was found to significantly reduce one minute post-exercise oxygen consumption 0.24 l/min (15 %), carbon dioxide production 0.31 l/min (22 %), and minute ventilation 8.6 l/min (17 %). The rating of perceived exertion went down by one point, while heart rate was not significantly reduced. One minute post-exercise measurements have been made in previous studies to gauge the effects of drafting and maximal oxygen

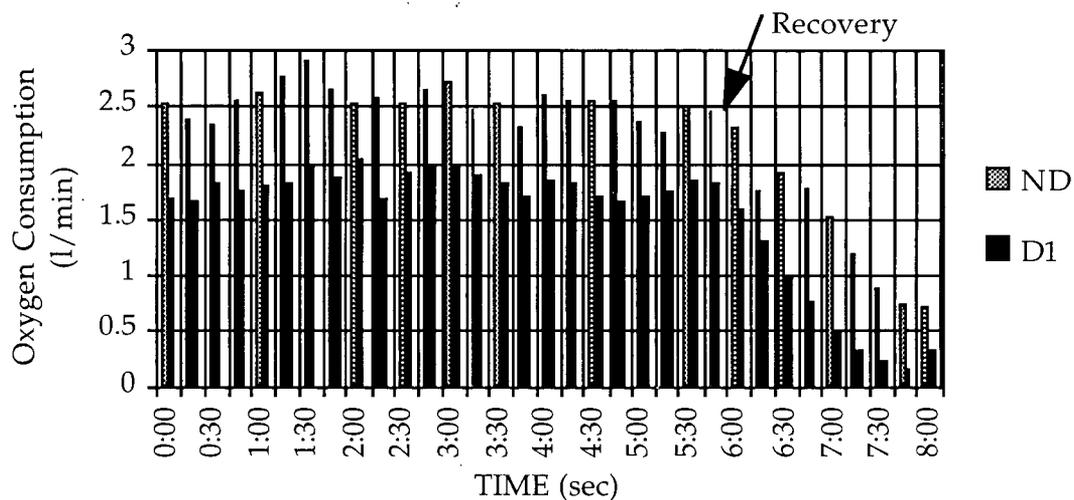


FIGURE 6: Oxygen consumption response to leading and drafting running positions. (from Corvalán-Grössling et al. 1994)

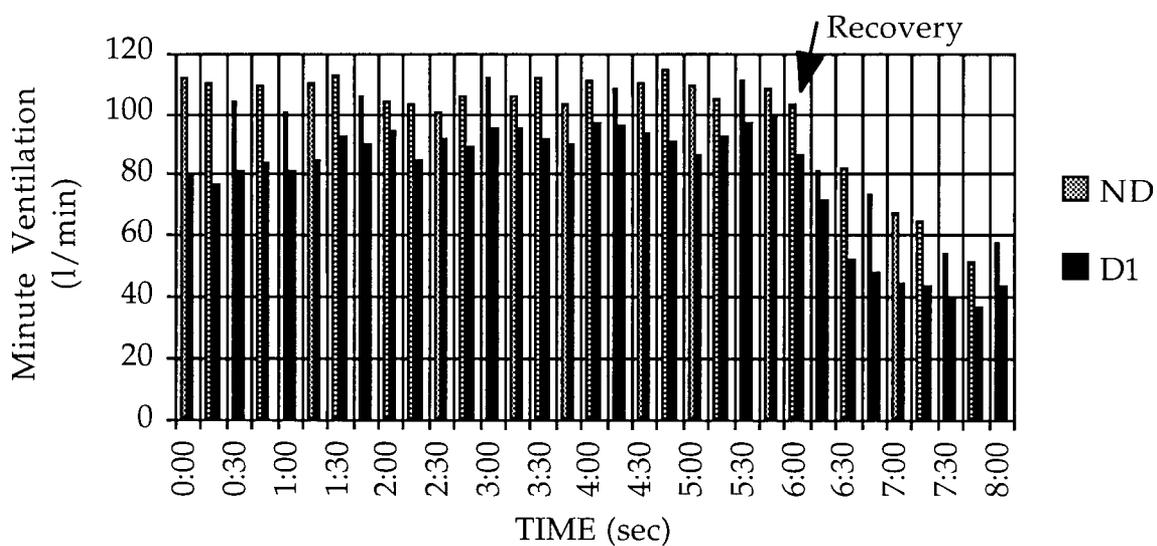


FIGURE 7: Minute ventilation response to leading and drafting running positions. (from Corvalán-Grössling et al. 1994)

consumption in swimmers and speed skaters (Basset et al. 1991, Brehm et al. 1986, Costill et al. 1985, Costill et al. 1991, Lavoie et al. 1983, Montpetit et al. 1981, di Prampero et al. 1976). However, measurements made during an activity are the most precise means of evaluating the physiological state of an athlete during that activity. Research is needed to determine which configurations improve running economy and are the most practical for distance runners to implement in competition; moreover, the question of how much drafting improves running economy in distance running still remains unclear.

HYPOTHESES

1. Submaximal oxygen consumption will be lower while running on a treadmill than while running on a windless flat unbanked wooden oval track ($p < 0.05$).
2. The physiological variables: submaximal oxygen consumption, carbon dioxide production, minute ventilation and heart rate, will be reduced during the drafting trials ($p < 0.05$).
3. The different drafting positions will affect the physiological variables differently ($p < 0.05$). Drafting behind a group of shield runners will reduce the physiological variables more than drafting directly behind a single shield runner.
4. The rating of perceived exertion will be reduced during the drafting trials ($p < 0.05$).
5. Both drafting behind a single shield and drafting behind a group of shield runners will reduce the rating of perceived exertion ($p < 0.05$).

CHAPTER THREE

METHODS

OBJECTIVES

The purpose of this study was to investigate how drafting, running in the aerodynamic shadow of another runner, affected specific physiological variables which are highly correlated to performance (Bunc et al. 1988, Costill et al. 1973, Daniels 1985, Schoeller et al. 1990, Steed et al. 1994). These variables included: submaximal oxygen consumption, carbon dioxide production, minute ventilation, and heart rate. Optimizing running economy can improve performance by increasing the maximum sustainable speed; thus, if drafting reduces oxygen consumption, minute ventilation, and heart rate, it is more than likely to improve performance.

In order to determine the optimal position for runners during a race, one leading position and two drafting positions were tested. Runners were also questioned as to which positions they found to be the most beneficial. Runners' perceived exertion was also measured in order to examine if drafting reduced the rate of perceived exertion. The study was composed of two experimental tests, and one maximal aerobic power test. The protocols followed for both portions of the study are described below.

SUBJECTS

A total of twelve highly trained and experienced male distance runners volunteered to participate in this investigation. Ten of the twelve athletes were internationally competitive senior members of local running clubs. Three of these athletes were also internationally competitive triathletes. One athlete was a

former competitive distance runner, while another athlete was a former competitive swimmer /now marathoner. By self-report, all subjects were competing in distance events ranging from 5 km to marathon distances, were actively training in excess of 40 km of distance running a week for at least one year, had completed a mile run in a time of 5 minutes or less within 2 months of their participation in the study, and were apparently healthy with no musculoskeletal complaints or documented history of cardiorespiratory disease. At the time of testing, all subjects were free of musculoskeletal complaints. All subjects were fully informed of the risks and potential discomfort associated with the testing procedures before giving their signed informed consent as required by the Behavioral Sciences Screening Committee for Research Involving Human Subjects at The University of British Columbia. All subjects provided health background information and underwent a medical screening and clearance by their coaches, as well as, a physician acquainted with the process and with the specific protocol that was employed.

Nine athletes completed all portions of phase I. A subgroup of five athletes participated in phase II. Due to the limited availability of test site, equipment and most importantly subjects and shield runners, it was impossible to test all the athletes at the two paces in the three different positions[†] Optimal sample size of nine was determined by using a computer program for statistical power, comparable cycling studies, and a preliminary pilot study. The minimum number of subjects necessary was estimated to be seven for phase I and ten for phase II (Schutz et al. 1987). The total group had similar characteristics to those

[†] Although subjects were in their prime condition, their availability for testing was limited by professional and personal commitments, as well as, the fact that testing coincided with the middle of the competitive season. Most athletes had races on weekends and two training sessions during the week. One athlete developed a running injury between the two phases of the study and thus did not participate in phase I.

reported for elite distance runners in Daniels et al. (1992). Subject characteristics for each phase are shown in Tables 1 and 2.

Using a large and diverse group of distance runners as subjects would make the results of this investigation more generally applicable: however, in this study the response of a specialized subgroup, elite distance runners, was examined to diminish the effects of confounding variables. The running speeds tested are submaximal and slightly below the current long distance race pace. It is expected that highly trained athletes who are competing at the elite level have optimized most aspects of their running mechanics and are capable of running comfortably at the running speeds being investigated. Another reason for testing this subgroup was that they are the ones who will benefit the most if the hypotheses are proven correct.

Since individuals in this study were competitive distance runners, there existed the possibility that the prolonged maximal performance required in competition could affect an individual's running economy and running mechanics (Cavanagh 1990); however, recent evidence suggests that a training run or 10 km race does not produce a significant increase in the aerobic demand of running or the gait pattern in subsequent short-term, submaximal runs (Morgan et al. 1990).

TESTING PROCEDURES

Treadmill maximal oxygen consumption test .

Maximal oxygen consumption (VO_{2max}) was assessed using a modified continuous treadmill running protocol. The purpose of this test was three fold: a) to measure the maximal aerobic capacity of each subject while running; b) to assess at what percentage of maximal aerobic power subjects were utilizing

TABLE 1
Phase I: Subject Characteristics

Subject	Age	Mass (kg)	Height (cm)	VO ₂ max (ml/min/kg)
1	26	73.9	185.4	73.4
2	27	76.5	185.9	62.4
3	32	78.0	175.0	71.9
4	32	68.0	175.3	60.4
5	19	71.2	184.2	61.9
6	34	69.9	170.2	68.4
7	24	70.3	175.3	66.7
8	20	75.0	183.1	68.2
9	28	62.6	170.2	56.5
Mean	26.8	71.7	178.3	65.5
Std. Dev.	5.3	4.7	6.4	5.6

TABLE 2
Phase II: Subject Characteristics

Subject	Age	Mass (kg)	Height (cm)	VO ₂ max (ml/min/kg)
1	26	73.9	185.4	73.4
5	19	71.2	184.2	61.9
8	20	75.0	183.1	68.2
11	26	73.9	175.3	74.3
12	20	74.8	188.0	66.3
Mean	22	73.8	183.2	68.8
Std. Dev.	3	1.5	4.8	5.1

during the track testing; and c) to assess and compare the metabolic response of subjects to running on a treadmill versus a windless, flat, unbanked wooden oval track.

The purpose and procedure of the test were clearly explained to the subjects prior to the test, as were the test objectives and the criteria for terminating the test. Subjects were instructed to report to the laboratory in a three hour post-prandial state and to refrain from strenuous physical activity on the day of the test. On arrival to the laboratory, subjects had their height and weight taken. Body weight included that of clothing since it will contribute to the workload. Height was measured with shoes removed. Subjects who had never run on a Quinton treadmill were required to participate in a practice run. This was optional for subjects with previous treadmill experience. All subjects were required to stretch and warm-up according to personal preference. The aim of the practice run was to accustom the subject to running on a motorized treadmill. After allowing these subjects to warm-up and stretch, they ran on the treadmill for at least 15 minutes at 2.24 m/s at 0 % grade.

At the start of the test, the subject was equipped with a belt ECG and pneumotach. The subject warmed-up for a period of 5 minutes on the treadmill at 2.24 m/s and 0 % grade. Treadmill speed was then increased to 3.13 m/s after 1 minute with 0.22 m/s increases every 1 minute. When the speeds of 4.47 m/s and 5.36 m/s were reached, the subject was required to run for 2 minutes instead of 1 minute before the speed was increased by 0.22 m/s. The test was terminated when the subject met at least two of the following criteria for attaining VO_{2max} : a) the point at which the subject voluntarily indicated fatigue (by grasping the

treadmill's handrails or becoming unable to maintain their position on the treadmill), b) a plateau in VO_2 , c) a respiratory exchange ratio ≥ 1.10 .

Expired gases were sampled with either the CPX-D analyzers and recorded by the Medical Graphics computer system, or the AeroSport Teem 100. The peak VO_2 values obtained from eight subjects who were tested with both systems were compared. Paired t-tests of the $\text{VO}_{2\text{max}}$ values obtained indicated no significant differences between the two systems. V. Katch (1995) and J.T. Kearney (1995) and several other investigators have reported similar observations when comparing the AeroSport Teem 100 to traditional large calorimeter systems (Novitsky et al. 1995, Segal et al. 1994, Segal et al. 1995). Heart rate was collected with a portable Polar HR unit. An additional group of five subjects ran for 5 minutes on the treadmill at 4.47 m/s to confirm that steady-state was being reached during $\text{VO}_{2\text{max}}$ testing. The CPX-D / Medical Graphics system was utilized for these runs.

Experimental test.

All trials of the experiment were conducted at the same time of the day (late evening) to minimize circadian rhythm effects. Testing was conducted in a large flat wooden floored showroom, the ShowMart, at the P.N.E. in Vancouver, B.C.. A 200 m track was marked with traffic cones. Athletes were randomly assigned the order of testing on the day of the test. Subjects which had not participated in previous related investigations were required to do a practice to ensure that the subjects were familiar with the experimental procedure and minimize learning effects. Subjects were also asked to practice forming the different drafting configurations.

Prior to testing, the subject warmed-up and stretched according to personal preference. The subject was instructed on his running position and running pace. The subject was then equipped with the belt ECG and pneumotach. A rollerblader carried the portable AeroSport Teem 100 in a chest carrier behind the subject. The subject reached the experimental speed in the first lap and continued running at the set pace for the next five laps. At the end of the sixth lap, the subject stopped running at the finish/start point, was relieved of the test equipment, and was asked to rate his perceived exertion using the Borg scale. The subject was then required to recover passively for 15 minutes. During this time, the subject was seated in the recovery room and connected to a portable pulse oximeter and a portable respiratory/carbon dioxide analyzer to ensure that the subject's heart rate and respiratory rate returned to pretrial values prior to the start of the subsequent trial. This procedure also ensured the same recovery conditions for all subjects.

All testing and data collections were conducted at the same site with the subject always running in the same counter-clockwise direction. Room temperature and humidity were recorded on each test session. To ensure that the warm-up and test paces were reached and maintained throughout each trial, a pace cyclist/investigator equipped with a CatEye Mity2 cycle computer rode closely behind the test group, and indicated verbally to the runners if they should adjust their pace or position. In addition, each lap was timed with a stop watch by a spotter who verbally indicated if and by how much the time was off the set lap time for the given pace. Three highly skilled rollerbladers carried the portable indirect calorimeter during the experiment. They bladed approximately 1.5 m behind the subject at the 4.47 m/s pace and 2.5 m behind the subject at the 5.36 m/s pace.

Experimental conditions.

In phase I, nine subjects were tested in three positions at 4.47 m/s. The first position, leading (L) was the control. Each subject performed the above protocol while running solo. The second position, drafting-1 (D1) was an experimental condition. In this position, the subject ran 1 m directly behind a shield runner. The third position, drafting-2 (D2), was the other experimental condition. In this position, the subject ran on the inside 1 m behind the left shoulder of the leading shield runner with another shield runner beside him on the outside and 1 m behind the right shoulder of the leading shield runner forming a triangle (see Figure 8). These positions were maintained throughout each trial. All three positions were tested on the same day with a minimum of 15 minutes recovery time between trials. In phase II, a subgroup of five subjects was tested in two positions, L and D1, at 4.47 m/s and at 5.36 m/s. Both these positions were tested on the same day with a minimum of 15 minutes recovery time between trials. At the end of experiment, subjects were questioned on the different configurations.

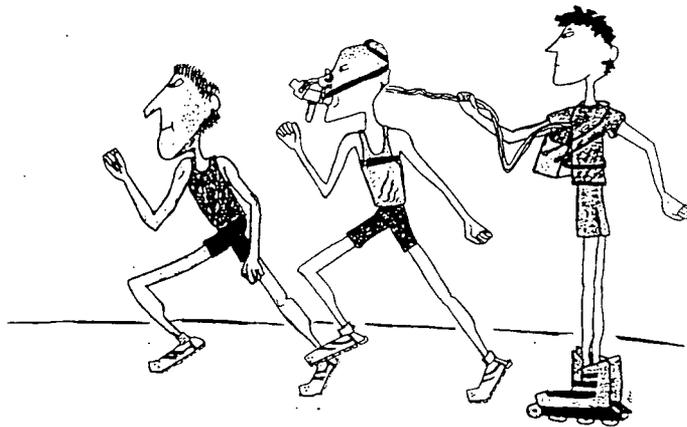
Data collection apparatus.

Manufacturer recommendations regarding operation and calibration of all test equipment was accurately followed. The AeroSport Teem 100 (Ann Arbor, Michigan, U.S.A.) was 25.4 by 25.4 by 8.9 cm and weighed approximately 3.3 kg, and had a fully integrated 12 V rechargeable battery. This system measured ventilation volume with a flat-plate orifice pneumotach, oxygen with a galvanic fuel cell, and carbon dioxide by the principle of non-dispersive infrared analysis. Ambient air was used to zero the carbon dioxide sensor output. Prior to the start of each test day the system was warmed up for 5 minutes, and autocalibrated at

Leading



Drafting-D1



Drafting-D2



FIGURE 9: Drafting Configurations.

the start of every trial to ensure accuracy. Continuous 20 second samples of VO_2 , VCO_2 , VE, and HR were recorded during each test. The values obtained for all twelve subjects indicated that they reached steady-state within the second minute of each trial. Steady-state values (minute 3 - second to last reading) were used for analysis. After each test, data was printed out and manually entered into a computer for further analysis.

Experimental design.

The independent variable in phase I was Position (factor 1 with 3 levels). The different levels of factor 1 were three different running positions, leading-L, drafting-1, and drafting-2. The independent variables in phase II were Position (factor 1 with 2 levels), and Speed (factor 2 with 2 levels). The two levels in factor 1 were running positions leading-L and drafting-1. The two levels in factor 2 were the running speeds of 4.47 m/s and 5.36 m/s. The dependent variables for this study were VO_2 , VCO_2 , VE, HR, and RPE.

Statistical analysis.

The statistical analysis used to investigate the effects of drafting on VO_2 , VCO_2 , and VE in phase I was a one-way multivariate analysis of variance (MANOVA) with repeated measures followed by univariate analyses of variance with repeated measures (RM ANOVA) for each dependent variable. The statistical analysis used to investigate the effect of drafting on HR and RPE were two one-way repeated measures analysis of variance (RM ANOVA). The level of significance was $p < 0.05$. The mean value of VO_2 , VCO_2 , VE, and HR were computed for each experimental condition. Preplanned orthogonal contrasts were used to compare means of VO_2 , VCO_2 , VE, HR, and RPE. The following contrasts were made for VO_2 , VCO_2 , VE, and HR between drafting and leading

conditions $((D1+D2)/2$ vs. L), and between drafting conditions (D1 vs. D2). The following contrasts were made for RPE between leading and drafting directly behind (L vs. D1) and between leading and drafting in the triangle configuration (L vs. D2). A paired t-test was used to compare leading and treadmill VO_2 means at the test speeds ($p < 0.05$). Due to the small sample size ($n=5$) in phase II, no statistical analyses were conducted on these results.

CHAPTER FOUR

RESULTS

Descriptive Statistics.

Table 3 contains the means of the four physiological variables and rating of perceived exertion for the nine subjects in the three running positions, as well as, the combined drafting effect, the average of both drafting positions. The percent reduction in oxygen consumption was 5.2 % for both drafting positions. During the leading trials, subjects were running on average at 85.6 % of their maximal aerobic capacity. During the drafting trials, subjects were running on average at 81.1 % of their maximal aerobic capacity. Carbon dioxide production was reduced approximately the same for both drafting positions, 12.3 % in position D1 and 10.4 % in position D2. Minute ventilation was only reduced 1.7 % in position D1 and 1.0 % in position D2. Heart rate increased slightly in position D1, 1.9 %, and remained the same in position D2. The rating of perceived exertion dropped by one point in position D2 (see Figure 9).

Table 4 contains the means and standard deviations of the four physiological variables and rating of perceived exertion for the subgroup of five subjects in the two running positions at the two running speeds. The percent reduction in oxygen consumption for this subgroup was 7.3 % at 4.47 m/s and 8.6 % at 5.36 m/s. During the 4.47 m/s trials, subjects on average ran at 83.5 % of their aerobic capacity while leading, and at 77.4 % while drafting in position D1. During the 5.36 m/s trials, subjects on average ran at 93.7 % of their aerobic capacity while leading, and at 85.6 % while drafting in position D1. Carbon dioxide production

TABLE 3
Phase I : Physiological responses to different running positions.

Position	VO ₂ (l/min)	VCO ₂ (l/min)	VE (l/min)	HR (beats/min)	RPE
Leading	4.02 ± 0.18	3.74 ± 0.23	82.6 ± 4.3	150 ± 6	12.4 ± 0.4
Drafting	3.81 ± 0.13 *	3.32 ± 0.13 *	83.4 ± 2.8	151 ± 4	11.4 ± 0.6 *
D1	3.82 ± 0.12	3.28 ± 0.16	83.1 ± 2.5	152 ± 4	11.8 ± 0.6
D2	3.80 ± 0.15	3.35 ± 0.12	83.6 ± 3.4	150 ± 5	11.1 ± 0.6 *

Values are mean ± sem. (n=9)

* Significantly different from leading.

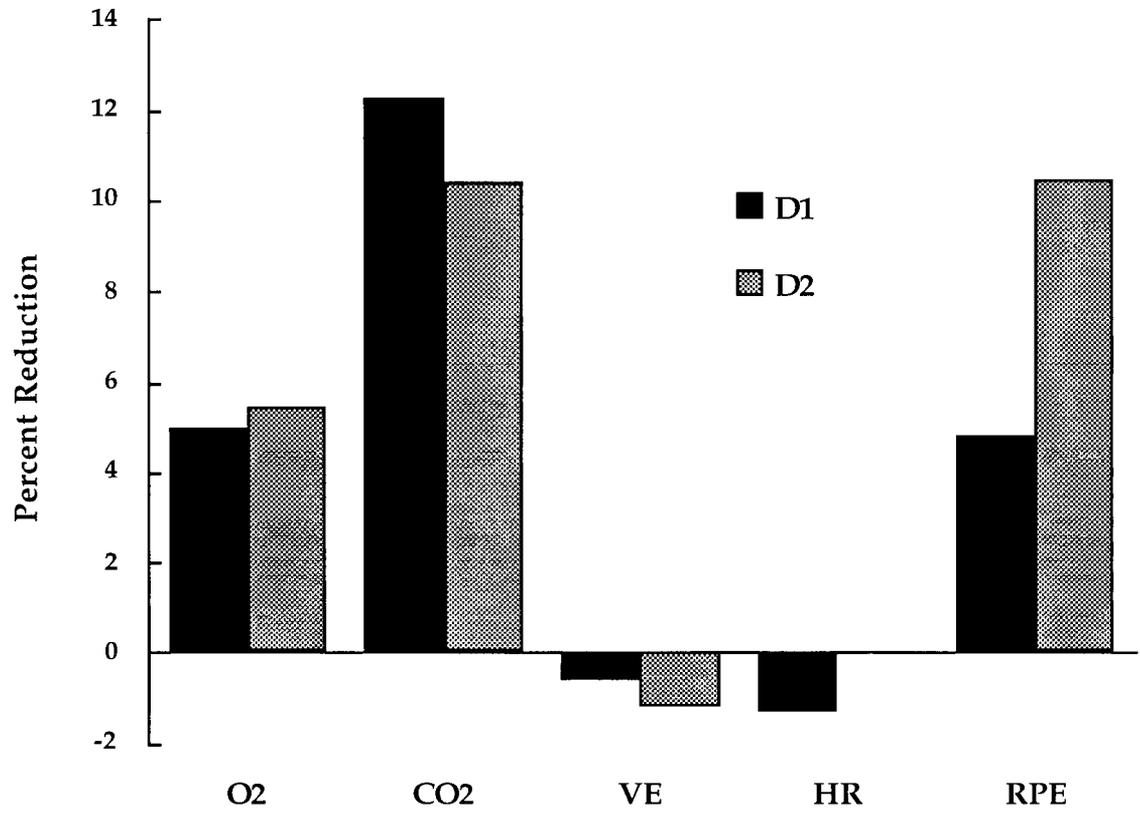


FIGURE 9: Percent reduction in oxygen consumption, carbon dioxide production, minute ventilation, heart rate, and RPE as a result of drafting in positions D1 and D2.

was reduced 8.2 % at 4.47 m/s and 6.3 % at 5.36 m/s. Minute ventilation was reduced by 5.0 % at 4.47 m/s but remained the same at 5.36 m/s. Heart rate was reduced slightly at 4.47 m/s, 2.3 %, and increased by 8.4 % at 5.36 m/s (see Figure 10).

Comparisons among means.

The steady state values for oxygen consumption during the treadmill maximal oxygen consumption test when the subjects were running at 4.47 m/s were compared using paired t-tests to track test results for the leading trials. Oxygen consumption was found to be significantly lower by 0.78 ± 0.12 l/min, 19.1 %, on the treadmill at 4.47 m/s ($n=12$, $p < 0.05$).

Multivariate analysis of variance (Table 5) revealed a significant VO_2 - VCO_2 - VE difference in the position in which subjects ran, F_m (Pillais) = 3.16, $p < 0.016$. Follow-up univariate ANOVAs indicated that this significant metabolic effect was due to differences in oxygen consumption and carbon dioxide production between the trials (where leading trials had higher values than drafting trials for both variables). Preplanned orthogonal contrasts indicated that there were significant reductions in oxygen consumption and carbon dioxide production during drafting trials in general ($p < 0.048$, $p < 0.004$); however, there were no significant differences between the two drafting positions.

Analysis of variance revealed that there was not a significant position main effect on heart rate, F (Huynh-Feldt) = 0.18, $p < 0.78$. Preplanned orthogonal contrasts indicated that there were no significant reductions heart rate during drafting trials in general ($p < 0.72$), nor between the two drafting positions ($p < 0.61$).

TABLE 4
Phase II : Physiological responses to different running positions
while running at 4.47 and 5.36 m/s.

Position	VO ₂ (l/min)	VCO ₂ (l/min)	VE (l/min)	HR (beats/min)	RPE
Speed = 4.47 m/s					
Leading	4.24 ± 0.16	3.67 ± 0.16	89.2 ± 8.0	149 ± 5	11.3 ± 1.0
D1	3.93 ± 0.19	3.37 ± 0.19	84.7 ± 5.8	145 ± 6	11.4 ± 0.5
Speed = 5.36 m/s					
Leading	4.76 ± 0.20	4.44 ± 0.28	110.2 ± 6.4	154 ± 10	13.8 ± 0.6
D1	4.35 ± 0.20	4.16 ± 0.26	109.8 ± 4.0	167 ± 5	13.3 ± 0.7

Values are mean ± sem. (n=5)

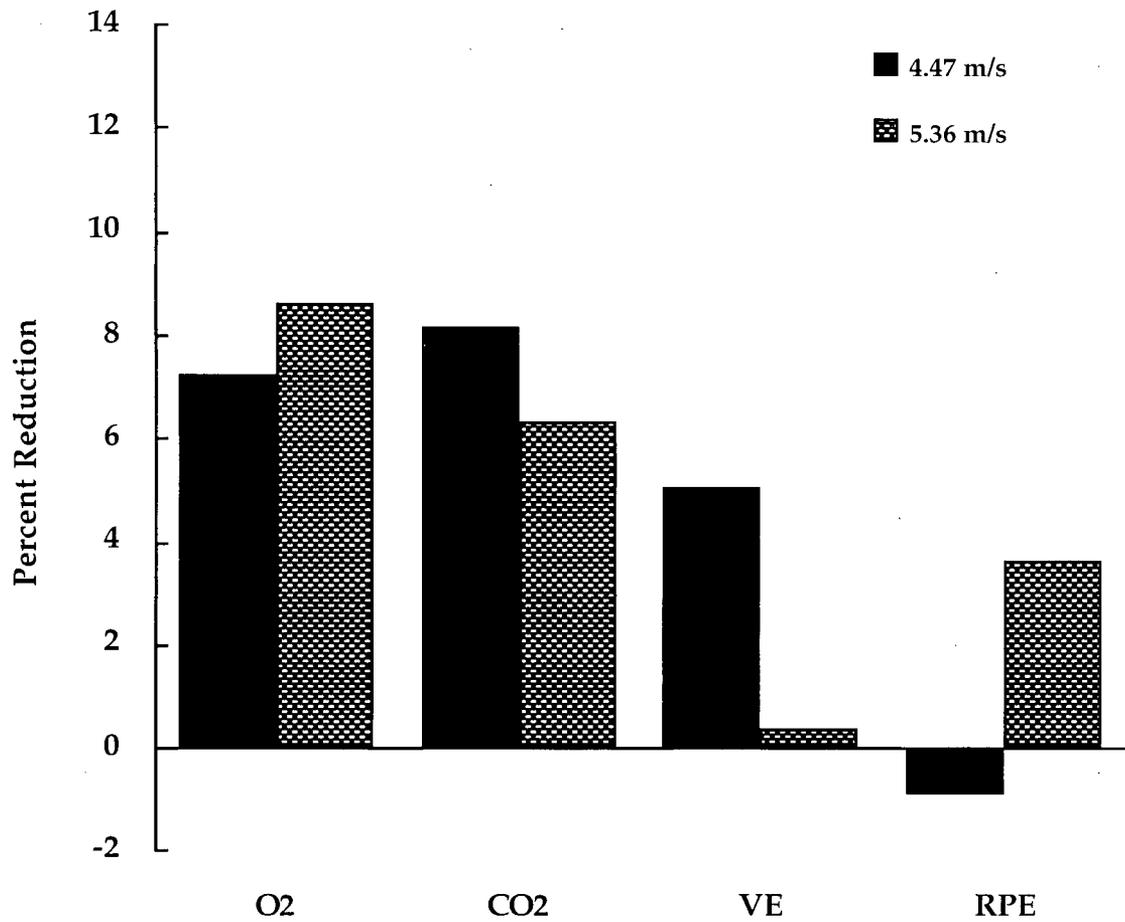


FIGURE 10: Percent reduction in oxygen consumption, carbon dioxide production, minute ventilation and RPE as a result of drafting in position D1 while running at 4.47 and 5.36 m/s.

TABLE 5
MANOVA Summary

Effect	Multivariate F (Pillais) (p)	Univariate (dependent var.'s sig at < 0.05)		
		VO ₂	VCO ₂	VE
Position	3.16 (0.016)	Sig. (0.048)	Sig. (0.004)	n.s.

Analysis of variance revealed that there was a significant position main effect on the rating of perceived exertion, F (Huynh-Feldt) = 5.75, $p < 0.016$. Preplanned orthogonal contrasts indicated that this position effect was due to a significant reduction in perceived exertion for the drafting position D2 when compared to leading ($p < 0.011$). No significant reduction was found between leading and drafting in position D1 ($p < 0.09$).

Survey Data.

Runners' opinions on drafting and the positions tested are shown in Table. 6.

TABLE 6
Survey Results

Numbers indicate the number of subjects who responded out of a total of twelve subjects who participated in the study.

Most energy consuming position	Leading: 0	Drafting: 12	
Most energy efficient position	Leading: 0	D1: 0	D2: 11
Felt constricted while drafting		Yes: 5	No: 7
Least constricting drafting position		D1: 2	D2: 4
Feel comfortable leading		Yes: 9	No: 3
Feel comfortable drafting		Yes: 12	No: 0
Most comfortable position	Leading: 1	D1: 0	D2: 11
Second most comfortable position	Leading: 1	D1: 11	D2: 0
Third most comfortable position	Leading: 10	D1: 1	D2: 1
Most applicable position for competition	Leading: 0	D1: 0	D2: 12
Second most applicable position	Leading: 4	D1: 8	D2: 0
Third most applicable position	Leading: 8	D1: 4	D2: 0

Results of Hypotheses.

VO_2 Leading Track > VO_2 Leading Treadmill	Accept
VO_2 Leading \neq VO_2 Drafting - D1 \neq VO_2 Drafting - D2	Accept
VO_2 Leading > VO_2 Drafting (D1 + D2)	Accept
VO_2 Drafting - D1 > VO_2 Drafting - D2	Reject
VCO_2 Leading \neq VCO_2 Drafting - D1 \neq VCO_2 Drafting - D2	Accept
VCO_2 Leading > VCO_2 Drafting (D1 + D2)	Accept
VCO_2 Drafting - D1 > VCO_2 Drafting - D2	Reject
VE Leading \neq VE Drafting - D1 \neq VE Drafting - D2	Reject
VE Leading > VE Drafting (D1 + D2)	Reject
VE Drafting - D1 > VE Drafting - D2	Reject
HR Leading \neq HR Drafting - D1 \neq HR Drafting - D2	Reject
HR Leading > HR Drafting (D1 + D2)	Reject
HR Drafting - D1 > HR Drafting - D2	Reject
RPE Leading \neq RPE Drafting - D1 \neq RPE Drafting - D2	Accept
RPE Leading > RPE Drafting - D1	Reject
RPE Leading > RPE Drafting - D2	Accept

CHAPTER FIVE

DISCUSSION

Air Resistance.

Air resistance results from the normal forces exerted by air molecules hitting the body and from the air friction caused by air molecules sliding along the bodies surface. During treadmill running, the ground moves backwards relative to the runner. Air molecules move only around the moving body segments. While during track running, both the ground and the air molecules move backwards relative to the runner. There is general agreement in the literature that at low to moderate running speeds, 2.27 - 4.33 m/s, the aerobic requirements of track running and treadmill running are equivalent (Davies 1980, McMiken et al. 1976, Morgan et al. 1992, Maksud et al. 1971). At more strenuous running speeds, 4.47 - 6.0 m/s, several investigators have found significant differences between the aerobic demands of the two running environments. Maksud et al. (1971) found that oxygen consumption on the track increased approximately 8 %, 0.3 l/min, while running at 4.47 m/s, and 10 %, 0.4 l/min, while running at 5.36 m/s. Daniels et al. (1985) found that at this same speed range oxygen consumption was increased by 7.1 % during level ground running in calm air when compared to level treadmill running. Similarly when Pugh (1970) compared track and treadmill running at 6 m/s on two athletes, he found that oxygen consumption on the track increased 8.4 %, 0.39 l/min. From the above work, it appears that the aerobic demands of running on the track in calm air would be 8 - 10 % higher than that of running on a treadmill.

All these studies were conducted on different types of tracks. Daniels et al. and Pugh conducted their tests on cinder or all weather tracks. Possible sources of

error on the outdoor tracks could arise from the presence of slight winds undetectable with the wind gages of the time. One of the advantages of conducting tests in indoor tracks is the added control over the environmental conditions. Maksud et al. (1971) conducted their track tests on a 128 m banked indoor track, and in the present study a 200 m wooden, flat, unbanked indoor track was used.

Another factor which could have influenced the results of these early investigations on the effects of air resistance is that expired air was collected from the runner by the Douglas bag method. Maksud et al. (1971) had the runner carry a Douglas bag on his back while running. Pugh (1970) used a vehicle to carry the collection equipment and drove next to the runner with a wind-screen. Needless to say, the face mask and collection apparatus may have been slightly cumbersome for the runners and could have affected them both psychologically and physiologically resulting in smaller increases in running economy during treadmill tests (Montpetit et al. 1981). In the present study, the mouth-piece and pneumotach hose worn by subjects was much less obtrusive and weighed less than 100 g.

Oxygen consumption was increased 0.78 l/min or 19.1 % at 4.47 m/s when running on a wooden, flat, unbanked indoor track. The difference between treadmill running and track running was approximately double to that of previous studies. Subjects were running at 86.0 % of their maximal aerobic capacity on the track and at 69.6 % of their maximal aerobic capacity on the treadmill. The differences in equipment and track environment from previous studies are likely the main reasons for the different findings. The consistency of the oxygen cost of treadmill running results and their agreement with previous

published work (Conley et al. 1980, Costill et al. 1973, Davies 1980, Maksud et al. 1971, Pollock 1977) provide evidence of the accuracy of the oxygen consumption measurements.

Intuitively, air resistance is the main difference between our two sites. It could be that the methodological procedures used to measure respiratory gases in previous studies masked the extent to which air resistance affected running economy. Another reason for the observed decrease in running economy could have arisen if the athletes biomechanics differed on the two sites. The surface of the wooden running track was smoother than that of the treadmill's rubberized running platform. Biomechanical changes may have been caused by differences in surface and ground compliance, as well as, increased slippage. On springy tracks the time spent rebounding from the surface is increased, so that a runner is slowed down and must work harder to maintain a set pace (McMahon et al. 1978). However, the degree to which this actually could have affected running economy is likely to be quite small in comparison to the 19.1 % decrease. Stride length, the most important biomechanical variable at the test speeds, when adjusted has been reported to affect oxygen consumption by 3.8-2.1 % (Heinert et al. 1980). Moreover, in a study comparing several track surfaces, only a 2.91 - 0.26 % difference in performance time was reported (McMahon et al. 1978). The increase in aerobic cost found in this study is probably a more accurate reflection of the extent to which both air resistance and motorized treadmill running surfaces affect running economy.

Shielding runners from air resistance.

Although running in the aerodynamic shadow of another runner is widely recommended in popular running magazines and the sports science literature,

there are athletes and scientists who feel that air resistance only costs a small percentage of their total energy and that the effects on running economy are negligible until you reach the higher sprint velocities (Schmidt-Nielsen 1972, Strnad 1985). From the huge differences observed between treadmill and track running, it is obvious that air resistance costs long distance runners a considerable percentage of their total energy. Any tactic which can reduce this cost would be very advantageous.

Oxygen Consumption.

In the present investigation, the employment of drafting positions during indoor track runs at 4.47 m/s resulted in an average drop in oxygen consumption of 0.21 l/min. This is a 5.2 % improvement in running economy. Pugh (1971) observed a 0.25 l/min reduction in oxygen consumption when his subject was running on a treadmill at 4.5 m/s against a 6.0 m/s head wind. In the pilot study conducted by Corvalán-Grössling et al. (1994), a 0.22 l/min reduction in one minute post-exercise oxygen consumption was observed for subjects running at 4.47 m/s in an oval corridor. Both Pugh's observations for a single subject, as well as, the pilot data show a remarkable degree of agreement with the present results. It appears that drafting reduces oxygen consumption by 0.19- 0.25 l/min when running at 4.47 m/s in calm air.

The largest reduction in oxygen consumption produced by drafting was 0.72 l/min for subject no. 8. This reduction is the same as the one first observed in a preliminary case study by Corvalán-Grössling (1994) on another runner who did not participate in this investigation. There were two subjects out of the total twelve for whom drafting did not result in a reduction in oxygen consumption. For one, subject no. 2, oxygen consumption remained relatively constant

throughout the experiment; while, for the other, subject no. 9, drafting in both positions increased his oxygen consumption by approximately 0.32 l/min. Drafting was found to be an effective tactic for reducing oxygen consumption for the majority of subjects.

The main premises of this study have been that a significant amount of energy is utilized by runners to overcome air resistance at the long distance running paces, and that air resistance and the net energy expenditure of a runner can be reduced by drafting behind another runner. There are several secondary mechanisms by which drafting could have improved running economy. One means could have been the synchronization of gait patterns between the shield and the drafting runners. The drafting runner, especially when in position D1, could also have adjusted his biomechanics to avoid being kicked by or bumping the shield runner. Biomechanical modifications, subconsciously, could have resulted from the reduction in aerodynamic drag forces. Synchronization, as well as, these other sources of biomechanical modifications could have improved some of the subjects' biomechanical efficiency. However, as mentioned earlier, relatively small changes in oxygen consumption have been found to accompany considerable changes in stride length and frequency, indicating that biomechanical changes could only have accounted for a portion of the observed effect (Brandon et al. 1992, Cavanagh et al. 1982).

One possible means of distinguishing how much aerodynamic drag and biomechanics contributed to the effects of drafting could be to reproduce the study on a different type of athlete such as cyclists. The test pace of 4.47 m/s would be easily maintained by cyclists. Consequently, there would be very little variation in their pedal frequency or kinematics. Changes in the drafting trials

would theoretically be solely due to reductions in aerodynamic drag. It would be assumed that both groups, cyclists and distance runners, expend the same amount of energy to overcome air resistance and that if there is a psychological factor involved, it would be the same for both groups. Thus, if the cyclists oxygen consumption was decreased by the same amount as the long distance runners in this study, it would indicate that the effect of drafting on oxygen consumption was due to the reduction in air resistance and factors other than biomechanical modifications.

Another secondary mechanism by which drafting may have influenced running economy could involve psychological factors. For example, mental concentration levels may have shifted during the test trials. Low levels of concentration during running tests have been associated with higher rates of oxygen consumption (Morgan et al. 1977). Subject's mood state may also have differed during the test trials. Positive mood states and low tension levels are strongly associated with lower rates of oxygen consumption in elite distance runners. Some subjects, when questioned at the end of the experimental session, stated that drafting permitted them to tune-out for a few moments during the test intervals. Subjects' rating of perceived exertion was reduced by one full unit during drafting-2 trials. Evidence has been found by Morgan (1992) that relaxation-based cognitive activity reduces oxygen consumption during submaximal exercise. It is possible that drafting permits athletes to reduce their arousal and stress levels. Taking as their own a competitor's pace may allow distance runners to relax during portions of a race.

Carbon Dioxide Production.

In the absence of portable carbon dioxide analyzers, carbon dioxide was seldom evaluated in air resistance and drafting studies. Oxygen consumption, which was and still is of primary interest due to its close relationship to running performance, was always measured and a respiratory ratio of RER=1 was usually assumed. Oxygen consumption and carbon dioxide production are very closely associated especially at submaximal levels of exercise where there is minimal production of lactic acid and the bicarbonate buffer system is less taxed. It was of great interest to observe how one of the waste products of muscle metabolism reacted to an energy saving strategy and if it mirrored that of oxygen consumption. The employment of drafting positions during indoor track runs at 4.47 m/s resulted in an average drop in carbon dioxide production of 0.42 l/min. This 11.1 % reduction is approximately double the reduction observed for oxygen consumption. In the pilot study, a similar reduction of 0.31 l/min was observed in the one minute post-exercise carbon dioxide production rate during test trials in position D1. A similar but less pronounced difference between the reductions in carbon dioxide production and oxygen consumption.

In the present investigation, the largest reduction in carbon dioxide production due to drafting of 1.40 l/min was for subject no. 3. The reduction in carbon dioxide production for this subject was much larger than for most; however, similar results were observed for this subject in pilot trial, and the same reduction was observed for both drafting positions (D1 and D2). Two subjects, no. 6 and no. 11, had very small reductions in carbon dioxide production, just 0.08 l/min. But, drafting reduced carbon dioxide production in all twelve subjects. From the significant reduction in oxygen consumption and the even larger reduction in carbon dioxide production, drafting appears to improve

running economy and reduce the production of metabolic bi-products in highly trained distance runners.

Minute Ventilation.

Reductions in oxygen consumption sometimes occur as a result of decreases in minute ventilation resulting from reduced breathing frequency and an increased tidal volume. This was not the case in the present investigation. Minute ventilation was not affected by the employment of drafting positions at 4.47 m/s and remained at approximately 83 l/min. The relationship between minute ventilation and oxygen consumption can be affected by the coupling of respiratory and locomotor rhythms. Loring (1990) found that individuals who breathed in rhythm with stepping frequency while walking on a treadmill could have their metabolic rate increase substantially by increasing the percent grade, while walking at the same constant pace, without affecting breathing frequency. Maksud et al. (1971) similarly found that oxygen consumption was significantly different between the two running environments, treadmill and track, at the same test speeds of 4.47 m/s and 5.36 m/s, while minute ventilations, as well as, heart rates were not significantly different irrespective of the changes in air resistance.

The coupling of respiratory and locomotor rhythms, also referred to as respiratory entrainment and mammalian locomotor respiratory coupling, has been long suspected of occurring spontaneously during rhythmic exercise. In sports such as cycling, rowing, and swimming, this coupling is developed intentionally in order to improve performance (Bramble 1983, Garlando 1985, Mahler 1991). In running, the coupling of respiratory and locomotor rhythms is most likely a spontaneous unconscious event. Bramble (1983) reported that there

is a clear tendency in highly trained runners to synchronize respiration and body motion during sustained running and that in the majority this phase locking can occur as quickly as the first five strides of a run.

It is interesting that although carbon dioxide production, in the present study, was significantly reduced during the drafting trials, minute ventilation remained the same. At rest, even small elevations in carbon dioxide partial pressure in arterial plasma will stimulate a large increase in minute ventilation. During exercise, however, a combination of simultaneous input from several chemical and neural stimuli control minute ventilation. In this case, neural stimuli from the motor cortex and peripheral mechanoreceptors seem to have had a predominant role in regulating respiration and possibly synchronizing it to limb movement. This change in the importance between respiratory regulators would also explain the difference in results between Maksud et al. (1971), the present study, and the pilot study. In the pilot study, respiratory gas samples were collected using the Douglas bag method one minute post-exercise while subjects were completely stationary. In this situation, it would be quite reasonable to infer that the chemical stimuli, carbon dioxide partial pressure and blood pH, would have been the predominant respiratory regulators.

Heart Rate.

The relationship between heart rate and oxygen consumption appears to be quite simple and predictable. As the energy demands of exercise increase with increasing exercise intensity, the heart is required to pump blood faster and a greater amount of oxygen is consumed by the body. It is a well documented relationship which tends to be linear throughout a large segment of the aerobic work range (Bunc et al. 1988, Haskel 1993, McArdle et al. 1991, McGinnes 1995,

Pate et al. 1989, Pate et al. 1992, Schoeller 1990). Currently, equations are being developed and modified to equate heart rate to oxygen consumption so that only heart rate measurements are required for determining the energy cost of a training session or a specific activity (Dishman 1994, Haskell 1993). It is also well known that the relationship between heart rate and oxygen consumption can be influenced by other variables, including environmental conditions, food intake, body posture, the muscle groups utilized during an activity, continuous versus discontinuous exercise, isometric versus rhythmic exercises, as well as, athletes psychological status (Haskell 1993, McArdle et al 1991, Schoeller 1990). In the present investigation, environmental conditions remained constant. Theoretically, limb movement was the same during all test trials at the set running paces. The only factor which could not be controlled was the subjects psychological status. The employment of drafting positions while running at 4.47 m/s did not affect heart rate. Similar heart rate results were observed in the pilot study for one minute post-exercise and exercise measurements. Maksud et al (1971) also found the same effect during treadmill versus track experiments. Both limb movement and psychological stress could have been involved in the heart rate responses. However, considering that oxygen consumption was reduced during the drafting trials while heart rate remained the same and that the correlation between psychological tension and oxygen consumption is as high as $r=0.81$ (Crews 1992), it would be reasonable to infer that the fact that heart rate did not go down was not due to increased stress but due to locomotor and cardiac rhythm coupling. Niizeki et al (1993) has reported such synchronization during treadmill exercise between heart rate and limb movements in untrained individuals. Athletes, especially at the elite level, would tend to have a larger degree of entrainment and it is therefore possible that a very strong interrelationship between cardiac, locomotor, and respiratory

rhythms may be present. Nevertheless, it is also possible that the psychological stress of having to draft behind a competitor may have limited the reduction in oxygen consumption observed. This could explain why carbon dioxide production was reduced twice as much as oxygen consumption and why heart rate was not significantly reduced.

Drafting Positions and Subject's Perceptions.

In this investigation, subjects perceived a difference between the two drafting positions. The rating for perceived exertion in position D2 was one full unit lower than that for leading; while, the rating for position D1 was essentially the same as that for leading. All subjects stated that position D2 felt the most efficient and applicable as a racing tactic. Eleven of the twelve felt that position D2 was the most comfortable of the three positions, and four out of six runners stated that it was the least constricting drafting position.

However, contrary to what subjects perceived, both drafting positions, D1 and D2, resulted in the same physiological responses. Oxygen consumption and carbon dioxide production were reduced by the same proportion in both positions when compared to leading trials; while, minute ventilation and heart rate remained relatively constant. There are two possible reasons as to why nearly identical physiological responses were found. One explanation is that both drafting positions provided runners with the same degree of shielding from aerodynamic drag forces and therefore resulted in similar physiological responses which were independent of psychological or perceived differences between the two positions. This explanation does not seem plausible if one considers 1) the strong association which exists between perceived exertion and

oxygen consumption (McGinnes et al. 1995, Skinner et al. 1973, Steed et al. 1994, Williams et al. 1990), and 2) that although position D2 has never been studied, evidence provided by Pugh's pressure measurements (1970) and the results from work conducted on cyclists riding in position D1, as well as, a position behind to the side, suggests that position D1 would protect athletes from aerodynamic drag forces to a greater extent than position D2 (Kyle 1979, McCole et al. 1990). The alternate explanation is that these two drafting positions did not provide runners with the same degree of shielding from aerodynamic drag forces, but that the combination of several different factors, physical, psychological and possibly biomechanical, produced the same physiological effects for both positions.

Running Speed and Drafting.

Through the cycling studies conducted by Kyle (1979) and McCole et al. (1990), it has been demonstrated that the reduction in energy expenditure which results from drafting directly behind another rider increases at faster riding velocities. In the present investigation, a similar trend was observed. The reduction in oxygen consumption increased 0.10 l/min at the faster pace (see Table 6). Subjects ran at 83.5 % of their maximal aerobic capacity at 4.47 m/s and 93.7 % of their maximal aerobic capacity at 5.36 m/s when leading. When subjects drafted in position D1, they ran at 77.4 % of their total aerobic capacity at 4.47 m/s and at 85.6 % of their total aerobic capacity at 5.36 m/s. Therefore, drafting directly behind another runner in position D1 at 5.36 m/s was approximately equivalent to leading at 4.47 m/s in terms of aerobic energy expenditure.

In this subgroup of five runners, the reduction in carbon dioxide production due to drafting in position D1 were essentially the same. At the 4.47 m/s pace, both

oxygen consumption and carbon dioxide production were reduced by equal amounts, while, average minute ventilation and heart rate remained the same. This strongly supports the theory that respiratory, cardiac and locomotor coupling occurred. At the 5.36 m/s pace, the reduction in oxygen consumption exceeded that of carbon dioxide production. This was most likely due to increasing levels of lactic acid. Minute ventilation again remained constant, while, heart rate fluctuated slightly. The rating of perceived exertion did not change in either of the two paces confirming the observations made for position D1 at 4.47 m/s for the nine runners.

CONCLUSIONS AND RECOMMENDATIONS

Each athlete will react differently to drafting tactics. In ten out of twelve of the runners tested, drafting as close as possible, approximately 1 m, behind runners produced significant reductions in oxygen consumption in the range of 5.2 %, and all twelve experienced significant reductions in carbon dioxide production in the range of 11.1 %. All subjects who participated in this study felt that they consumed more energy while leading than while drafting. Considering that a difference as small as 1 % can exist between the Gold-Medalist and nonmedalists at World Championship competitions, the degree to which drafting can physiologically benefit distance runners has definite implications on performance times. Moreover, if one considers the pacing behavior of distance runners in competition which is to accelerate during the terminal stages, drafting will enable runners to conserve energy for this critical stage while still running a fast race (Foster et al. 1994). In calm air the aerobic energy cost of overcoming air resistance was found to be 19.3 %, drafting reduced the aerobic energy cost of overcoming this force by 25 %. In outdoor races where runners can find themselves running against strong head winds, drafting will likely reduce this even more.

On the basis of the experimental results, running directly behind another runner (position D1) and running in a triangle on the inside of a lead runner's shoulder and with another runner next to you (position D2) produce the same reductions in energy expenditure. However, position D2 received a lower rating for perceived exertion, was found to be the most comfortable, and strategically applicable to races by the majority of runners. Position D2 is more strategically sound than position D1 because it reduces a runners risk of getting boxed in. It is

important to distinguish position D2 from just running on a lead runner's shoulder. The latter position would not be as advantageous as drafting directly behind a runner in position D1. The next best racing position was determined to be drafting directly behind another runner. Especially considering that drafting in this position at 5.36 m/s required approximately the same amount of energy as leading at 4.47 m/s.

All this being said there are certain circumstances where drafting would not be recommended. For instance, it would be detrimental for a runner to draft behind a competitor who has an uneven pace or an unpredictable stride. This situation would likely force the drafting runner to become less biomechanically efficient and the uneven pace may affect him psychologically. Any advantage which could have been gained by being protected from aerodynamic drag forces would probably be lost. This is, however, a very good strategy for runners to use to prevent or deter other competitors from drafting behind them (Higdon 1978). Another situation in which athletes should not draft each other is during training sessions unless the purpose of the exercise is to train athletes to draft. Coaches should be aware that athletes who consistently run within a pack or draft other runners are not obtaining the full benefits of their training.

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APPENDIX 1

DEFINITION OF TERMS

Aerodynamics	The systematic study of forces exerted by air or other gases (Halliday et al. 1988).
Air Resistance	The pressure exerted on solid objects by still air (Pugh 1971).
Beneficial	Producing the following benefits: energy savings, least discomfort or constriction of movement, and applicable as a race strategy.
Entrainment	The interaction between two periodic events in which one oscillator captures the frequency of another, resulting in phase locking of the two rhythms at an identical or at an integer ratio of frequencies.
Efficiency	The relationship between work done and energy expended.
Drafting	Following closely behind in the aerodynamic shadow of another athlete.
Drag	Term used in aerodynamics which refers to the force exerted by air on a solid moving object (Pugh 1971).
Laminar Flow	Fluid particles moving in smooth paths with one layer gliding smoothly over an adjacent layer (Olsen et al. 1987).
Maximal Aerobic Capacity (VO ₂ max)	The point during progressive exercise at which oxygen consumption ceases to rise and reaches a plateau or begins to fall even though the work rate continues to increase (MacDugal et al. 1991).
Road Race Environment	Running on a flat, straight road.
Running Economy	The steady-state oxygen consumption for a standardized running speed (Morgan et al. 1990).

Steady State Exercise	The intensity of exercise that can be performed for a prolonged period of time without appreciable elevations in VO_2 , HR, VE, or RER.
Turbulent Flow	Fluid particles moving with an irregular tumbling motion (Olsen et al. 1989).
Wind Resistance	The pressure exerted on solid objects by wind of a given velocity (Pugh 1971).

APPENDIX 2
CASE STUDY

The physiological effects of drafting on an elite level distance
runner.

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ABSTRACT

The metabolic responses of an elite level distance runner while running in two positions, leading and drafting-1, at 4.47 m/s were investigated. Testing was conducted outdoors on a level, gravel road. Oxygen consumption, minute ventilation, and heart rate were measured every 15 seconds during the six minute run and for the first two minutes of the recovery phase using a Cosmed K2 portable telemetry system. Following both trials, the runner was asked to rate his perceived exertion (RPE) using the Borg scale. Running directly behind another runner substantially reduced this subject's oxygen consumption (2.48 ± 0.04 l/min leading versus 1.76 ± 0.08 drafting), and minute ventilation (110.0 ± 2.0 l/min leading versus 89.4 ± 14.6 drafting). Heart rate was only slightly reduced (169 ± 11 beats/min leading versus 161 ± 10 beats/min drafting) while RPE was the same for both trials (RPE = 11). The reductions in oxygen consumption and minute ventilation were also evident during the first two minutes of recovery.

OBJECTIVE

The purpose of this case study was: 1) to examine the metabolic effects of running directly behind another runner, 2) to obtain an estimate of the magnitude and short-term duration of the effects of drafting on selected variables, and 3) to evaluate the testing protocol and testing apparatus.

METHODS

The Subject

A highly trained and experienced male runner volunteered to participate in this investigation. This athlete was a senior member of a university track team. By self-report, he trained in excess of 40 km/week, competed in distance events ranging from 5 km to 10 km, had been competitive for more than two years at the senior level, had completed a mile run in a time of 5 minutes or less several times within the last two months of his participation, and was apparently healthy with no musculoskeletal complaints or documented history of cardiorespiratory disease. The subject was fully informed of the risks and potential discomfort associated with the testing procedures before giving his signed informed consent as required by the Behavioral Sciences Screening Committee for Research Involving Human Subjects at the University of British Columbia. The subject had the following characteristics: age, 27, height, 162.0 cm, weight, 59.0 kg.

Testing Procedures

The test site was a flat, straight 3 km gravel road. Both trials were conducted in the late evening to minimize wind, temperature, and circadian rhythm effects. Both trials were conducted on the same section of the course with the subject running in the same direction. Prior to the start of the trials, ambient air temperature, barometric pressure, wind speed and direction were obtained from

Environment Canada weather station next to the test site. Testing was not conducted in the presence of a wind (wind speed > 2.7 m/s) or precipitation. The subject was given a practice session at the test site to enable him to become accustomed to the testing apparatus. After allowing the subject to warm-up and stretch according to his personal preference, a practice run at 4.47 m/s was performed. The subject was then tested leading. Two days after the first session the subject was retested drafting directly behind another runner of larger physical build. The testing sessions began after the warm-up and practice session. The subject was equipped with the portable Cosmed K2 telemetry unit as shown in Figure A1. The subject was then taken to the start and instructed when to begin running. With the aid of a pace cyclist, the subject reached the experimental speed of 4.47 m/s in the first 0.25 mile and continued running at this pace for 1 mile, running a total distance of 1.25 miles. At the end of the trial, the subject was instructed to rest passively for 6 minutes. The subject was then relieved of the portable Cosmed K2 unit. The subject then rated his perceived exertion using the Borg scale. The pace cyclist equipped with a CatEye Mity2 cycle computer rode closely behind the runner (s), recording time, distance, and average speed. To ensure that the subject maintained the 4.47 m/s pace and drafting configuration throughout the test, the pace cyclist continually verbally indicated to the subject any necessary adjustments and the travelling speed.

Test Apparatus

The portable Cosmed K2 telemetry unit (Rome, Italy) consisted of a transmitter, a battery, a face-mask/turbine flow meter assembly and a belt ECG monitor. The Cosmed K2 portable telemetry system measured oxygen consumption, minute ventilation, and heart rate every 15 seconds during the six minute trial and for the first two minutes of the recovery phase.

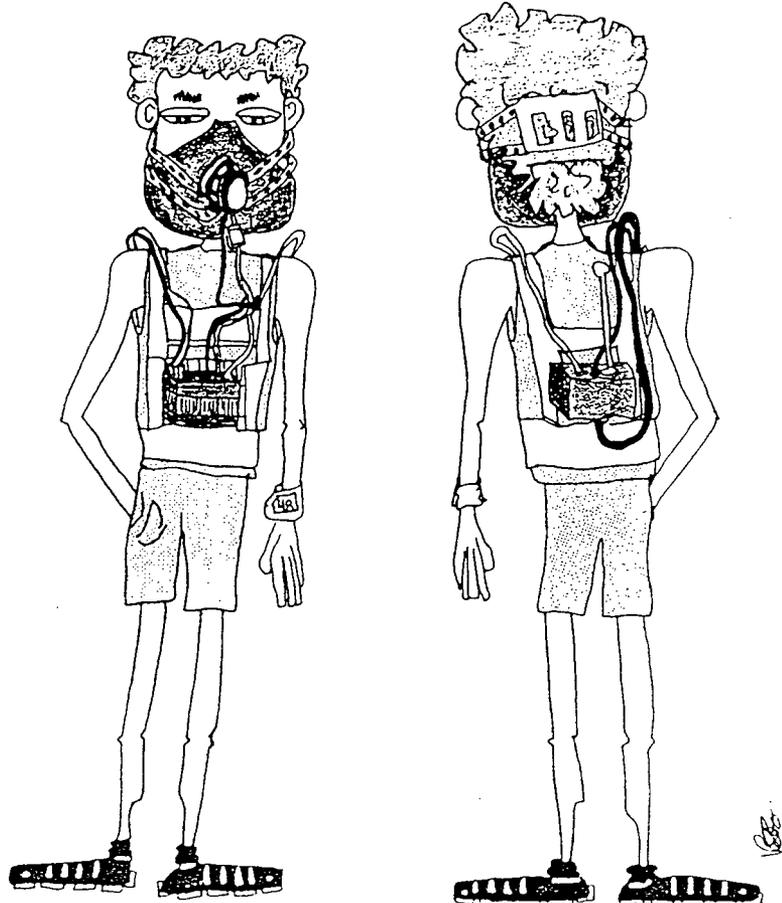


FIGURE A1: Diagram of Cosmed K2 telemetry unit used to measure oxygen consumption, minute ventilation, and heart rate.

RESULTS & DISCUSSION

Running directly behind another runner substantially reduced this subject's oxygen consumption (2.48 ± 0.04 l/min leading versus 1.76 ± 0.08 drafting), and minute ventilation (110.0 ± 2.0 l/min leading versus 89.4 ± 14.6 drafting). Heart rate was only slightly reduced (169 ± 11 beats/min leading versus 161 ± 10 beats/min drafting) while RPE was the same for both trials (RPE = 11). The reductions in oxygen consumption and minute ventilation carried over for at least the first two minutes of recovery (see Figures A2, A3, and A4).

There are several factors which may have affected the results observed. External environmental factors included light winds (< 2.7 m/s), humidity, the gravel surface, and decreasing daylight. The decreasing daylight and poor visibility due to the face mask could have increased the anxiety level and thus affected the subject's heart rate during one, or both of the trials. The gravel surface may have affected the subject's biomechanics thus affecting the physiological variables. This subject by self-report preferred leading during races and did not normally use drafting as a training or racing strategy. His unfamiliarity with the drafting-D1 position could possibly explain why no changes in heart rate were observed as anticipated. Additional factors which may have influenced results include the constraints imposed by the testing apparatus. It is possible that the face mask leaked environmental air during both or one of the trials, although the data does not suggest that this occurred and the face mask was fitted very securely to the subject. The weight of the equipment could have affected the subject's biomechanics. The subject did report that the equipment felt very constricting and difficult to breathe with. This could also have affected the subject's physiology especially heart rate and respiration. Mouth pieces and face masks are known to influence breathing pattern (Loring et. al. 1990) although running style is

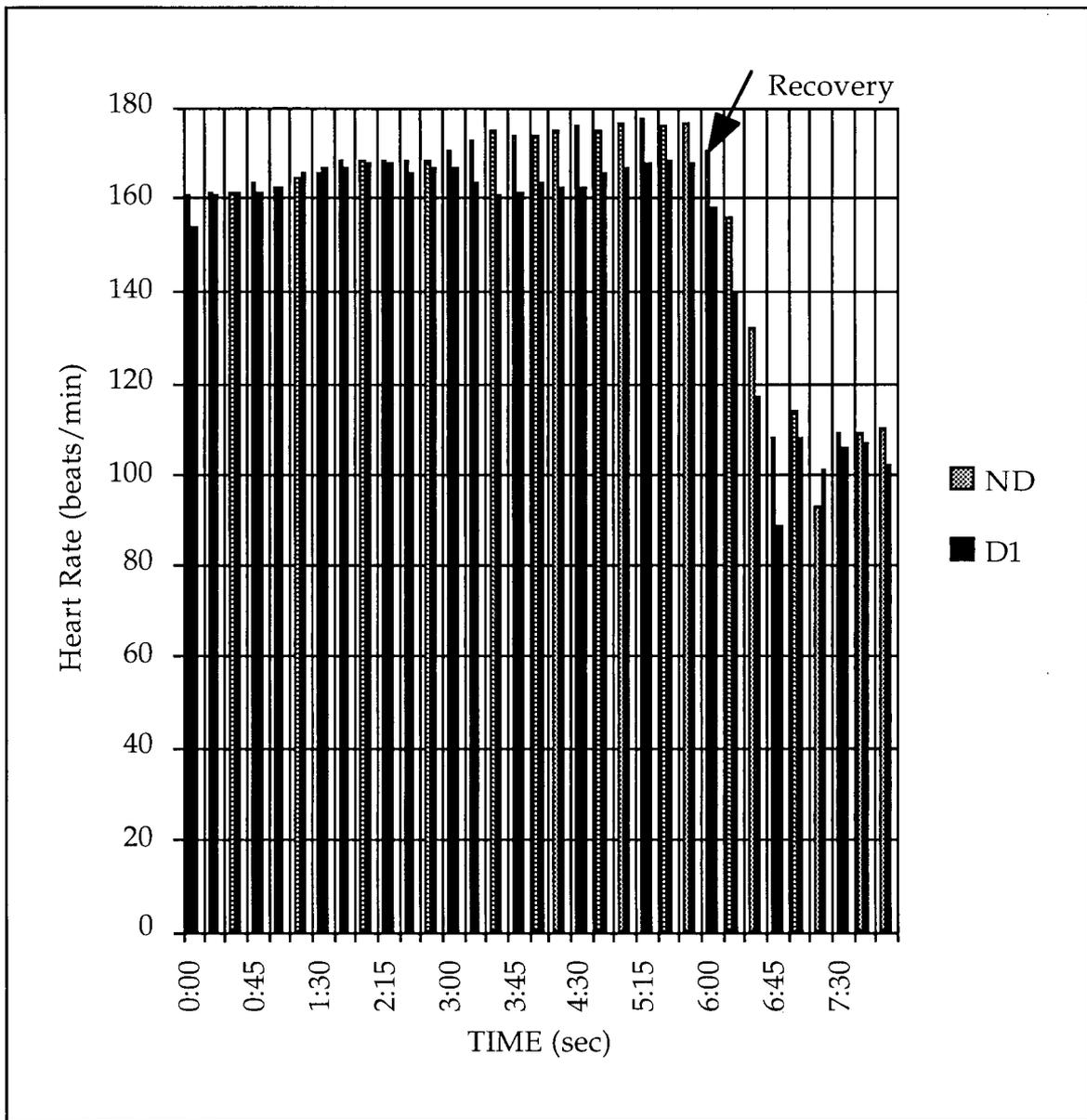


FIGURE A2: Heart rate response to running in leading and drafting positions.

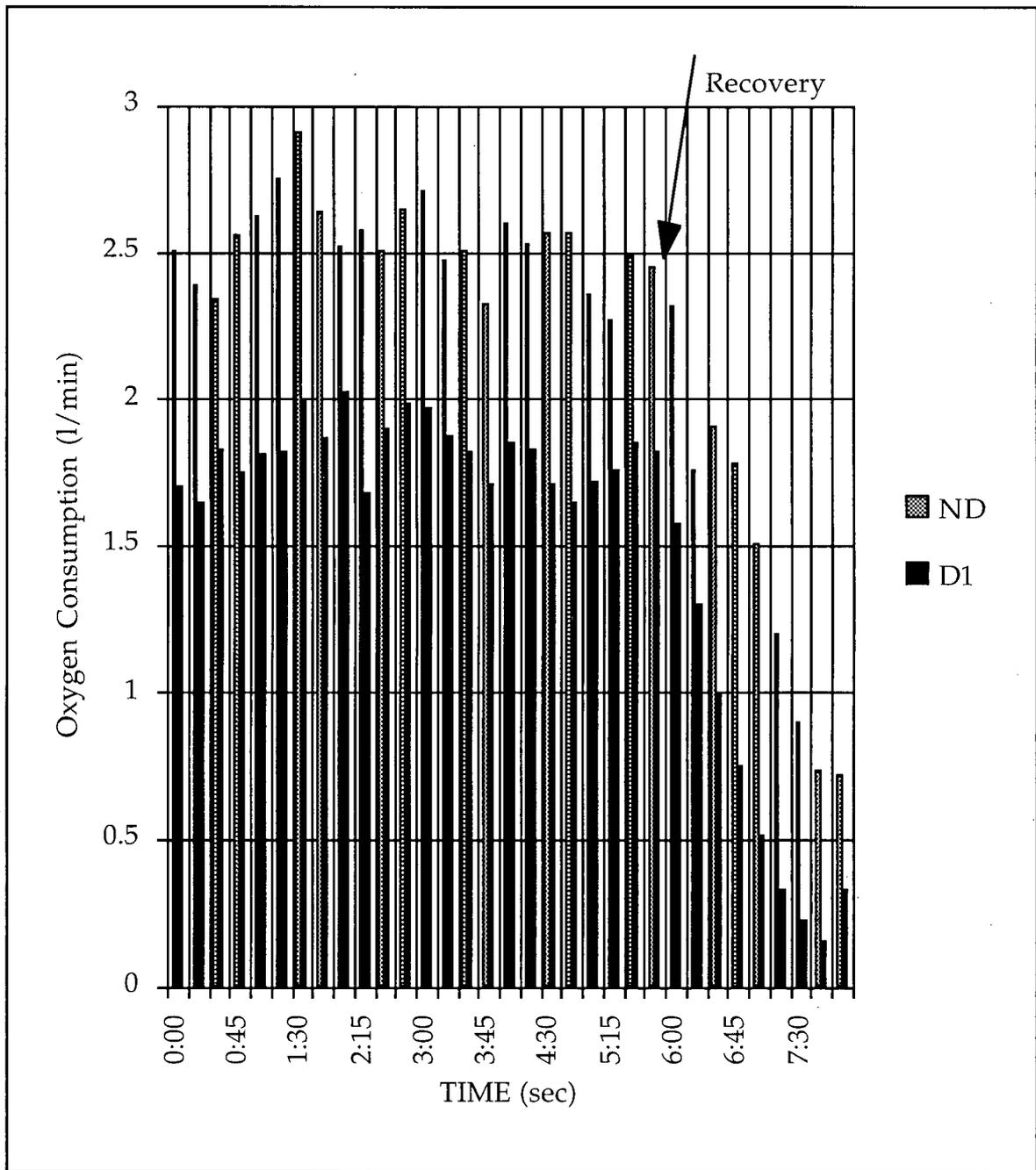


FIGURE A.3: Oxygen consumption response to running in leading and drafting positions.

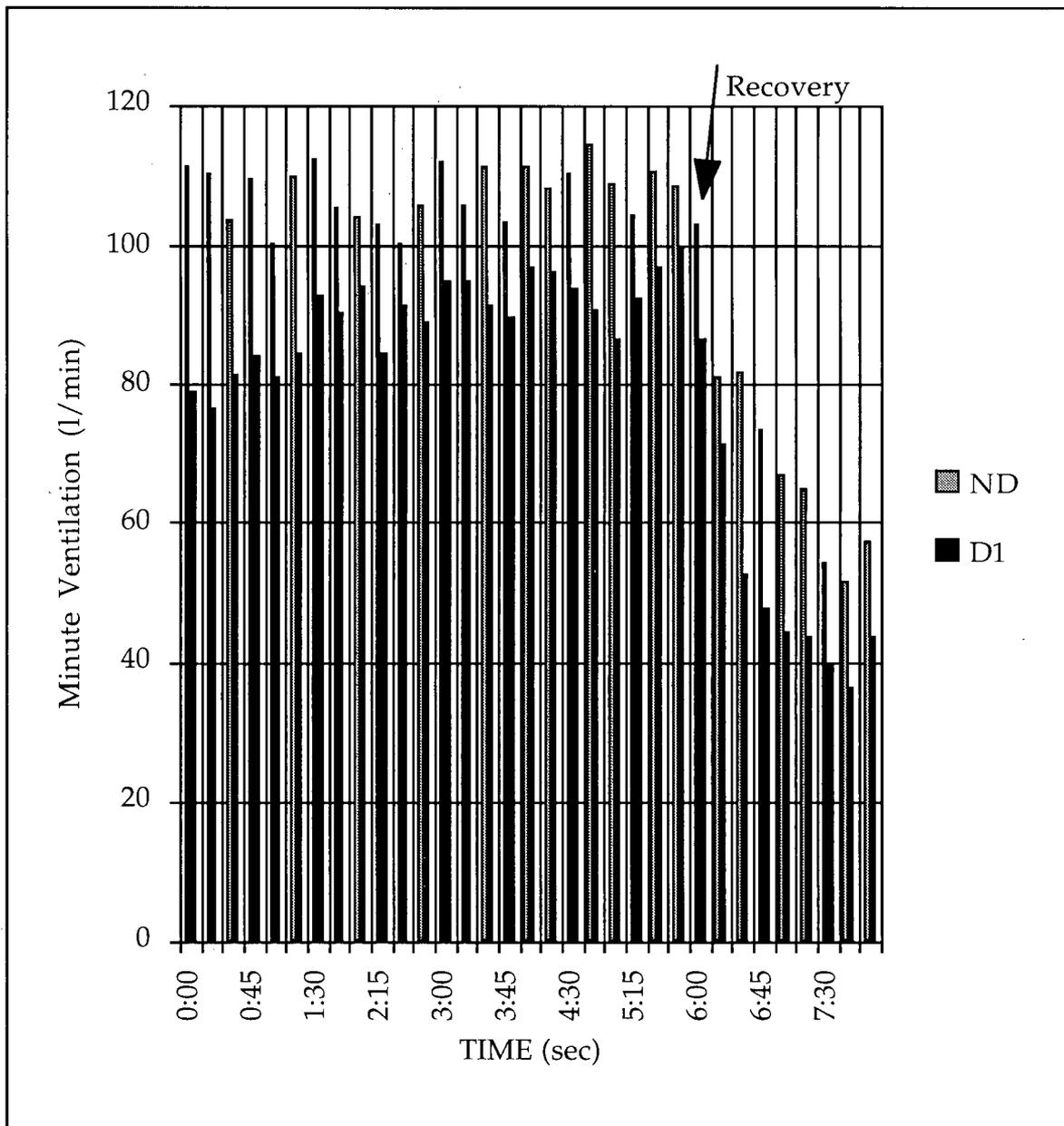


FIGURE A4: Minute ventilation response to running in leading and drafting positions.

generally unaffected at submaximal running speeds (Siler et. al. 1993). The main difficulty presented by the Cosmed K2 face mask is that it could have altered the subjects breathing pattern and may have affected his performance during the trials as a consequence. For this subject at least, the face mask could have hindered performance making it more difficult to evaluate the effects of drafting on the subject while running without the testing apparatus.

From this study, it was determined that using portable equipment outdoors had some definite disadvantages. It did however permit the first glimpse at the effects of drafting in a outdoor road race environment. A 29.0 % reduction in oxygen consumption, and 18.7% reduction in minute ventilation was found when a elite level distance runner drafted directly behind another runner. This case study suggests that drafting, running in the aerodynamic shadow of another runner, can reduce oxygen consumption and minute ventilation, and thus energy expenditure while running outdoors. Future studies using less constricting equipment are recommended to further evaluate the effects of drafting on distance runners.

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APPENDIX 3
PILOT STUDY

The effects of drafting on highly trained distance runners.

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ABSTRACT

The metabolic responses to running at 4.47 m/s directly behind another runner (drafting) were studied in eight trained male distance runners. Oxygen consumption (VO_2), carbon dioxide production (VCO_2), and minute ventilation (VE) were estimated from a 1 minute sample of expired air collected immediately after a 1.2 mile run. Heart rates were monitored every 15 seconds during all performances. Perceived exertion was measured using the Borg scale at the end of the expired air collection. Subjects were randomly assigned configurations. A recovery period of 15 minutes was allowed between all performances. Drafting significantly reduced post-exercise 1-minute VO_2 15% (1.33 ± 0.25 vs. 1.57 ± 0.34 L/min), VCO_2 22% (1.10 ± 0.30 vs. 1.41 ± 0.49 L/min), VE 17% (41.3 ± 8.5 vs. 49.9 ± 13.8), and rating of perceived exertion 11% (10 ± 0.4 vs. 11 ± 0.4) ($p < 0.01$). Heart rates were not significantly different between the two trials. These results showed that running in the aerodynamic shadow of another runner could be very advantageous for distance runners and that coaches should expose athletes to drafting situations in training so that athletes can practice this energy-saving strategy. Coaches

must also be aware that athletes who consistently run within a pack or drafting are not obtaining the full benefits of their training.

INTRODUCTION

In any endurance running event, optimum performance is generally achieved by efficiently utilizing the available energy. The longer the distance of a race, the more important the conservation of energy becomes. This concept implies that having a high capacity for providing the exercising muscles with energy is extremely important and that being able to maintain a high running speed without negatively affecting the rate of utilization of total energy sources is also critical.

Aerodynamic drag is a major source of energy expenditure in many sports, particularly downhill skiing, ski jumping, the luge, bobsledding, speed skating, and cycling, where high velocities are reached (Halliday et al. 1988, Kyle et al. 1984). Efforts to reduce aerodynamic drag result in decreased energy cost and improved performance. Aerodynamic drag is estimated to cost distance runners between 2-13% of their total energy (Davies 1980, Hill 1928, Pugh 1970, Pugh 1971). The energy cost of running at a constant velocity increases as aerodynamic drag increases (Costill 1979).

Aerodynamic drag occurs for two reasons. One, the pressure that results from air molecules striking a surface and bouncing off, undergoing momentum changes and exerting normal forces on the surface. The other type of force, air friction, arises from the sliding motion of air molecules along the surface as they collide with rough surfaces. Air flow can be either laminar or turbulent, depending on many factors such as relative speed, surface roughness, and the type of surface material (Halliday et al. 1988, Olsen et al. 1987). At slow speeds the flow of air molecules will be laminar, this results in quite low drag forces. As the relative speed of the air and the surface increase, the laminar flow becomes unstable and

layers of air begin to separate. The flow then becomes turbulent, characterized by whirling eddies of air. Turbulent boundary layers have much higher drag than laminar layers. However, the highest aerodynamic drag is caused by instability at air velocities in the transition region between laminar and turbulent flow (Birkhoff 1960, Halliday 1988). The aerodynamic drag can be five times greater in the transition speed ranges than the aerodynamic drag for the purely turbulent flow. Therefore, it follows that to achieve low drag forces this transition region must be avoided. The transition region has been estimated to occur at speeds of about 4-6 m/s for an upright cyclist (Tipler 1990). Considering the similarities in geometry and drag coefficients between cyclists and runners (Pugh 1976), the transition region would theoretically occur at the same speed range of 4-6 m/s for runners.

The relative velocity of the air on the track or road is rarely zero. When running in a tail wind, the aerodynamic drag will provide a forward force. A head wind, on the other hand, will provide a retarding force as it increases the aerodynamic drag. It has been estimated by Dapena et al. (1987) that a 2 m/s tail wind can give a 100 m sprinter a 0.07 second advantage; while, a 2 m/s head wind can result in a 0.085 second disadvantage. It appears that the hindrance produced by a head wind is larger than the time aid produced by a tail wind of the same intensity. Another factor which is relevant to distance runners, a group of athletes which tend to have similar physique - tall, light, and lean - is that the times of tall light athletes are more sensitive to changes in wind conditions, aerodynamic drag, than those of short and heavy athletes (Dapena et al. 1987). Distance runners, moreover, race in the 4.5-6 m/s speed range which is theoretically associated with the highest drag forces. Aerodynamic drag should be a concern for elite level distance runners.

Typical strategies employed by runners to reduce their aerodynamic drag are to reduce their coefficient of drag by using smooth spandex cloth, modified shoes, and head gear. Wind tunnel tests of clothing, hair, and shoes show that it is possible to reduce the aerodynamic drag of a runner by 0.5 % to over 6 % (Adrian et al. 1989, Kyle et al. 1986). Reducing frontal area and thus exposure to aerodynamic drag is easily accomplished by athletes in other sports. Cyclists lean forward until their backs are horizontal and their arms are tucked tightly against their bodies. Skiers can crouch down over their skis into the "egg" position until they are practically sitting on their ankles. Speed-skaters bend their upper bodies 90 degrees so they are parallel to the ground. Runners are limited in their postural adjustments but can decrease their frontal area by using tight fitting clothing and by trimming or covering their hair.

A strategy that could reduce the aerodynamic drag forces on runners is drafting. This technique is commonly applied in cycling, skiing, and other high drag sports. Many investigators and runners have recommended the tactic of running in the aerodynamic shadow of another runner, primarily based on anecdotal information and the results obtained from investigations on the effects of drafting in other sports (Hill 1928, Kyle 1979, Kyle 1979a). Only two studies have investigated this topic, but only one has been conducted on a runner (Pugh 1971). To date, the effects of drafting and running have only been cursorily examined.

The purpose of this study was to investigate how drafting, running in the aerodynamic shadow of another runner, affected specific physiological variables and perceived exertion. These physiological variables were: oxygen consumption, carbon dioxide production, minute ventilation, and heart rate.

These physiological variables have been found to be highly correlated to performance (Cavanagh 1990, Conley et al. 1980, Daniels 1985); thus, if drafting reduces oxygen consumption, carbon dioxide production, minute ventilation, and heart rate, it is more than likely to improve performance by permitting an athlete to increase his/her maximum sustainable speed.

Two different running positions were tested, drafting and leading. Runners' perceived exertion was measured in order to examine if drafting reduced the rate of perceived exertion and if it corresponded with changes, if any, in the physiological variables. The study was composed of one experimental test, and one maximal aerobic power test. The protocols followed for both portions of the study are described below.

METHODS

Subjects

Eight highly trained, male runners volunteered to participate in this investigation. Seven were intercollegiate long distance runners, and one was a former competitive swimmer/now marathoner. By self-report, each subject was competing in distance events ranging from 5000 m to marathon distances, was actively training in excess of 40 km of distance running a week for at least one year, had completed a mile run in a time of 5 minutes or less within 2 months of his participation in the study, and was apparently healthy with no musculoskeletal complaints or documented history of cardiorespiratory disease. All subjects were fully informed of the risks and potential discomfort associated with the testing procedures before giving their signed, informed consent, as required by the Behavioral Sciences Screening Committee for Research Involving Human Subjects at the University of British Columbia. The subjects had the

following characteristics: age, 25 ± 6 yr. (mean \pm SD); height, 169.8 ± 8.9 cm; mass, 64.9 ± 7.5 kg (see Table A1). Using a large and diverse group of distance runners as subjects would have made the results of this investigation more generally applicable. In this study, the response of a specialized subgroup, elite distance runners, was examined to diminish the effects of confounding variables such as training effects and changing biomechanics.

Since individuals in this study were competitive distance runners, there existed the possibility that the prolonged maximal performance required in competition may have affected their running economy and running mechanics during testing (Cavanagh 1990); however, recent evidence suggests that a training run or 10 km race does not produce a significant increase in the aerobic demand of running or the gait pattern in subsequent short-term, submaximal runs (Morgan 1990). To minimize these effects, subjects were tested at least three days after competing in a racing or strenuous training session.

Procedures in the laboratory

Maximal oxygen consumption (VO_{2max}) was assessed using a modified continuous treadmill running protocol. Prior to testing the purpose and procedure of the test were clearly explained to the subjects prior to the test, as was the test objectives and the criteria at which the test was terminated. Subjects were required to report to the laboratory in a three hour post-prandial state and have refrained from strenuous physical activity during the day of the test. The subjects had their height and weight taken. Body weight included that of clothing since it would contribute to the workload. Height was measured with shoes removed.

TABLE A1
Subject Characteristics

Subject	Age	Mass (kg)	Height ^a (cm)	VO ₂ max (ml/min/kg)
93	27	59.0	162.0	*
94	24	72.0	173.0	69.0
95	34	59.4	166.2	88.0
96	24	65.8	178.0	64.8
99	24	67.9	179.8	53.7
100	18	59.0	160.0	56.3
101	19	59.0	160.0	*
102	32	78.0	175.0	59.5
Mean	25	65.0	169.3	64.5
Std.Dev.	6	7.2	8.2	13.8

* Subjects were unavailable at the time of testing.

Practice Session: Subjects who had never run on a treadmill or undergone a VO_{2max} Test underwent a practice session. The purpose of the practice session was to accustom the subject to running on a motorized treadmill. After allowing the subject to warm-up on the treadmill and stretch according to personal preference, subjects performed a practice run of at least 15 minutes duration at a speed of 2.24 m/s and on 0% grade. In addition, five of the six subjects tested returned for a second test 3 weeks after the first session.

Testing Session: Expired gases were sampled with the CPX-D analyzers and recorded by the Medical Graphics computer system. Heart rate was collected with a portable Polar HR unit. The test was conducted on a Quinton treadmill. The subject was first equipped with the belt ECG and pneumotach. The subject warmed-up for a period of 5 minutes on the treadmill at 2.24 m/s and 0 % grade. Treadmill speed was then increased to 3.13 m/s after 1 minute with 0.22 m/s increases in velocity every 1 minute until physiological or volitional fatigue. At the 4.47 m/s and 5.36 m/s speeds, the subject ran for 2 minutes instead of 1 minute before the speed was increased by 0.22 m/s. The test was terminated when the subject met at least two of the following criteria: a) the point at which the subject voluntarily indicated fatigue (by grasping the treadmill's handrails or beginning to decrease cadence), b) a plateau in VO_2 , c) a respiratory exchange ratio > 1.10 .

Procedures in the field

Both trials of the experiment were conducted for each subject at the same time of the day to minimize circadian rhythm effects. The test site was a flat (0 % grade), oval, 0.4 mile concrete indoor corridor under constant environmental conditions. Athletes were randomly assigned the order of testing on the test day.

Practice Session: The purpose of the practice session was to accustom the subject to running on the test site course and testing procedures. After allowing the subject to warm-up and stretch according to personal preference, a practice run at a speed less than 3.57 m/s for at least 15 minute duration was performed. Subjects were asked to practice forming the different configurations during the run. Subjects were either tested at the end of this session or on the next day at the same time. All athletes were required to take at least 15 minutes rest between test trials and the practice session until HR was at resting levels.

Testing Session: After warming-up for at least 5 minutes and running 1 lap at 3.57 m/s, the subject was instructed on the configuration which was to be used for that trial. The subject was then be equipped with a portable Polar HR unit, Vantage XL. In the first lap (0.40 mile), the subject reached the experimental speed of 4.47 m/s and continued running at this 6 minute mile pace for the next two laps (0.8 mile). At the end of the third lap, the subject stopped running and was quickly equipped with a face mask connected to a meteorological balloon. A 1 minute air sample was collected. Following the air collection, the subject was asked to rate his perceived exertion using the Borg scale. After a fifteen minute recovery period the procedure described above was repeated for the second configuration. Both configurations were tested on the same day. One subject was tested twice on consecutive days with identical results.

All trials were conducted on the same section of the course with the subject running in the same direction. A pace cyclist equipped with a CatEye Mity2 cycle computer rode closely behind the runners, recording time, distance, speed, and indicating verbally to the test group if they should adjust their pace or position throughout the experiment to ensure that warm-up and trial paces and positions were reached and maintained. Air samples were analyzed a maximum of 5 hours post collection. Oxygen and carbon dioxide fractions were determined using Beckman oxygen and carbon dioxide analyzers (Fullerton, USA) calibrated with gases of known concentrations. Sample volumes were measured in a Tissot spirometer.

Running configurations tested

Leading-ND was the control configuration. Drafting-1 was the experimental position. In position D1 the subject ran directly behind another runner. All eight subjects were tested in these two positions, ND and D1, at the six minute mile pace (4.47 m/s). Another two of the eight subjects (100, 101) were tested in two additional positions, D2 and B2; while a third subject (102) was tested in the diamond configuration, D3. D2 had the subject drafting on the inside of a triangle with one runner in front and another runner beside him on the outside in position B2. D3 had the subject drafting behind a group of three runners as shown in Figure A5. In the drafting trials, the subject was 1 meter or less behind the leading runner. These conditions were maintained throughout the entire trial.

Experimental design and statistical analysis of data.

The independent variable in this study was Position (factor 1 with 2 levels: leading-ND and drafting-D1). The dependent variables for this study were VO_2 ,

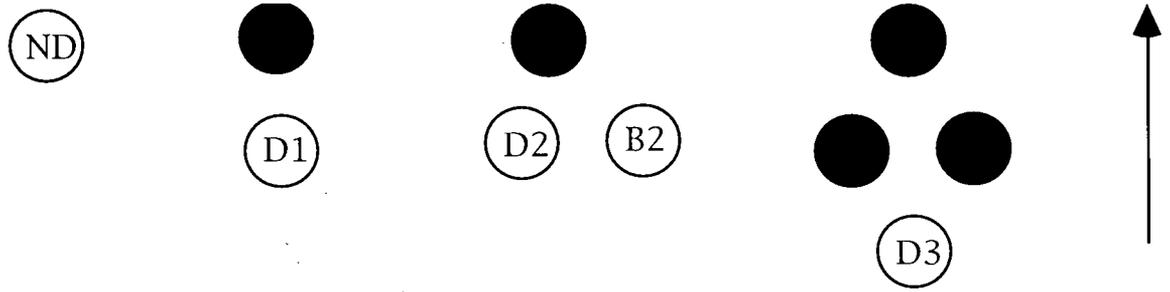


FIGURE A5: Running Configurations.

ND = Leading

D = Drafting

VCO₂, VE, HR, and RPE. The statistical analysis used to investigate the effect of drafting on VO₂, VCO₂, VE, HR, and RPE were 5 paired t-tests. The level of significance was $p < 0.05$.

RESULTS

The percent reduction in post-exercise_{1-minute} VO₂, VCO₂, VE, and RPE resulting from drafting behind a single runner at 4.47 m/s were 15%, 22%, 17%, and 11% respectively (see Figure A6). Post-exercise_{1-minute} VO₂, VCO₂, VE, as well as, RPE were significantly reduced after drafting behind a single runner ($p < 0.01$). Post-exercise_{1-minute} heart rate was reduced only slightly, 1.5%, when subjects drafted behind a single runner in the D1 position. Mean values are shown in Table A2.

The post-exercise_{1-minute} VO₂ for subjects 100 and 101 was reduced from 1.63 L/min and 1.56 L/min when they lead to 1.48 L/min and 1.26 L/min respectively when they drafted in the B2 position and to 1.38 L/min and 1.19 L/min when they drafted in the D2 position. Their drafting-D1 values were 1.45 L/min and 1.17 L/min. Similar trends were observed for post-exercise_{1-minute} VCO₂ and VE. RPE values were the same for leading-ND and B2, while drafting-D1 and D2 RPE values were the same but lower for both subjects (see Table A3). Drafting in positions B2 and D2 produced very similar physiological results to the values for drafting behind a single runner, D1. Position D2 seems to be slightly more favorable for these two subjects than B2 (see Table A3). Post-exercise_{1-minute} VO₂ for subject 102 was reduced from 2.16 L/min leading to

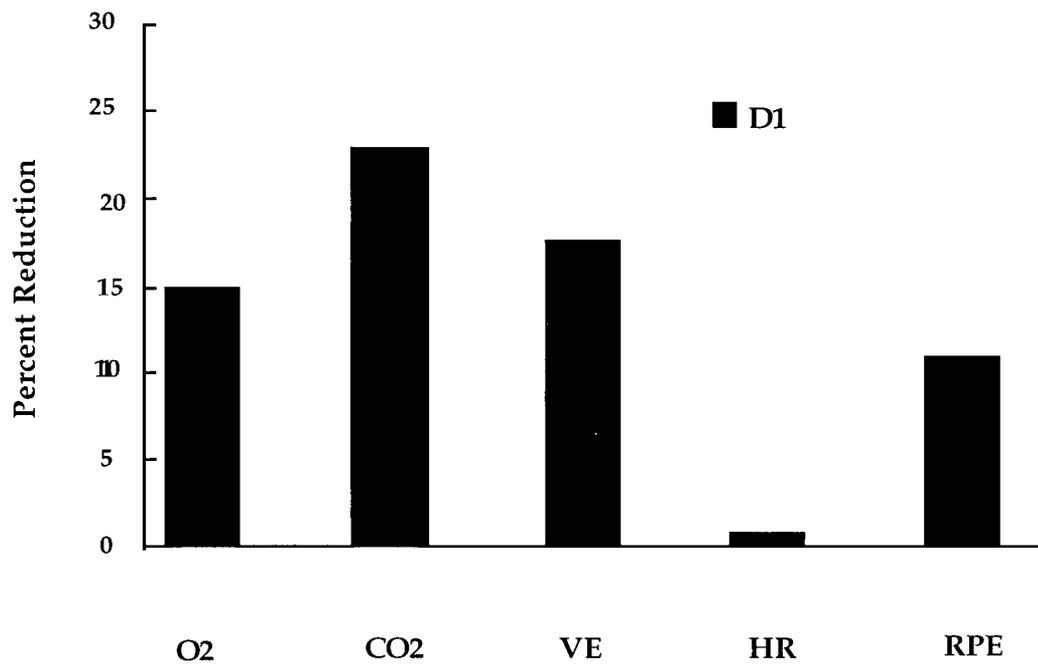


FIGURE A6: Reduction in oxygen consumption, carbon dioxide production, minute ventilation, heart rate, and RPE resulting from drafting directly behind another runner. * Significantly different from that while leading ($p < 0.05$).

TABLE A2

One minute post-exercise oxygen consumption, carbon dioxide production, minute ventilation, and heart rate values in leading and drafting positions.

Position	VO ₂ (l/min)	VCO ₂ (l/min)	VE (l/min)	HR (beats/min)	RPE
Leading	1.57 ± 0.12	1.41 ± 0.17	49.9 ± 4.9	115 ± 4	11.0 ± 0.4
Drafting	1.33 ± 0.09 *	1.10 ± 0.11 *	41.3 ± 3.0 *	111 ± 6	10.0 ± 0.4 *

All values are mean ± std. dev.

* Significantly different from leading trial.

TABLE A3

One minute post-exercise oxygen consumption, carbon dioxide production, minute ventilation, and heart rate values for subjects who were tested in additional drafting positions.

Subject. No.	Position	VO ₂ (l/min)	VCO ₂ (l/min)	VE (l/min)	RPE
100	ND	1.63	1.57	4.70	13
	D1	1.45	1.04	4.42	12
	D2	1.38	1.16	3.16	12
	B2	1.48	1.29	3.46	13
101	ND	1.56	1.60	5.83	13
	D1	1.17	1.08	3.82	10
	D2	1.19	1.09	3.34	10
	B2	1.26	1.11	3.64	13
102	ND	2.16	2.23	6.22	12
	D1	1.64	1.58	4.25	11
	D3	1.86	1.75	4.94	10

1.64 L/min in position D1 and to 1.86 L/min in position D3 (see Table A3). Similar trends were also observed for post-exercise_{1-minute} $\dot{V}CO_2$ and $\dot{V}E$. RPE was the lowest for D3 with a value of 10, second lowest for D1 with a value of 11, and 12 for ND.

DISCUSSION

Considering that at the critical velocity range between 4-6 m/s, the estimated transition region between laminar and turbulent air flow, and speeds at which elite distance runners compete in, it is possible that the energy expenditure and therefore running economy are markedly altered by the aerodynamic drag forces which an athlete encounters. Pugh (1971) examined what would happen to the running economy when a runner drafted behind another runner. He found from the result of a single case study that drafting, running about 1 m behind another runner, virtually eliminated air resistance and reduced oxygen consumption by 6.5 % when running at 4.5 m/s with a wind velocity of 6 m/s. This is approximately an 80 % reduction in the energy cost of overcoming air resistance. Pugh then measured the dynamic air pressure around the runner with a Pitostatic tube. The pressure was negative 0.6 m behind the runner and still relatively low 1 m behind the runner. At the positions slightly to the side-behind the runner, the pressures were almost the same as the pressure 2 m in front of the runner. Pugh's pressure results are useful for determining which drafting positions may be most effective. They suggest that drafting directly behind a runner may be more effective than to be in the position slightly to the side-behind a runner. The results of our investigation clearly found that drafting as close as possible, approximately 1 m, behind another runner of the same or larger physical build reduced post-exercise_{1-minute} oxygen consumption, carbon dioxide production, minute ventilation, as well as, perceived exertion. It is

interesting that in the data collected from two of our runners in additional positions, drafting in positions slightly to the side-behind the leading runner with another runner at the subject's side produced similar reductions in the post-exercise 1-minute physiological parameters as those observed during drafting trials where the subjects were directly behind a shield runner.

The only additional evidence available in the running literature that indicates that drafting can reduce a runner's aerodynamic drag was found in a study conducted on cyclists by Kyle (1979). Based on his results on upright cyclists coasting in a 200 m hallway, Margaria's data (1963) for the rate of energy consumed during running in still air, and the assumption that drag coefficient for the upright position in cycling was equivalent to that of runners, Kyle predicted that drafting would improve running economy by 4 % when drafting 1 m behind another runner at 6 m/s. Although this value has meaningful practical implications, it is lower than that obtained by Pugh (1971) and much lower than our results for post-exercise 1-minute oxygen consumption when drafting directly behind another runner at 4.47 m/s. Methodological and computational differences could account for the discrepancy. However, another reason for the difference may result from the assumption made on the value of the coefficient of drag. The values estimated by other investigators vary considerably from those used by Kyle (Pugh 1976, Shanebrook et al. 1976). In general, estimations of the coefficient of drag for runners have several inherent problems. One, the coefficient of drag has been calculated for a runner in a passive state and in Kyle's study a passive cyclist in an upright position. The assumption that the coefficient would be the same for a moving runner ignores the possible effects that the motion of body segments relative to each other may have on the net aerodynamic drag. Moreover, an upright cyclist may not have the same body

position to a moving runner. Another problem, which may also affect the estimations for aerodynamic drag energy cost, is that even in still air both the ground and the air molecules move backwards relative to the runner. This may affect the airflow and consequently the aerodynamic drag.

The majority of the research on drafting's effects on aerodynamic drag, energy expenditure, and performance has been conducted on cyclists. In Kyle's (1979) investigation on the effects of drafting on cycling power output and wind resistance in a variety of positions, he found that drafting directly behind another rider reduced the air resistance by 44 % irrespective of the number of riders in the pace line. When a rider drafted in the center of a tightly packed cluster of riders the air resistance was surprisingly only reduced by 24 %; however, this effect was investigated in a single test. Kyle also reported that air resistance was only reduced by 23 % when the rider drafted in a position slightly to the side-behind instead of directly behind another rider. As would be expected from Pugh (1971) and Shanebrook et al. (1976) pressure data, he found the reduction in air resistance increased the closer a rider drafted behind another rider. McCole et al. (1990) conducted a similar study to Kyle's. They measured energy expenditure, oxygen consumption of competitive cyclists on a flat stretch of straight road while drafting. They reported an 18 % reduction in oxygen consumption at 8.89 m/s and a 27 % reduction in oxygen consumption at 10.28 - 11.11 m/s for subjects drafting behind one rider. Drafting 1, 2, 3, or 4 riders in a line resulted in the same reduction of oxygen consumption, while drafting within a group of 8 riders at 11.11 m/s reduced oxygen consumption by 39 %. The latter results on the effect of drafting behind a pack of riders conflicts with Kyle's (1979) observation and our own results for position D3. Drafting in the diamond configuration, D3, reduced the subjects post-exercise 1-minute oxygen

consumption by 14%. While drafting in directly behind a shield runner reduced his post-exercise 1-minute oxygen consumption by 24%. Similar trends were found when comparing the other physiological parameters. Perceived exertion did not follow this trend.

Drafting behind a pack may turn out to improve running economy even more than running behind a single runner, but this position poses other strategic problems for runners. This position may conserve energy and be beneficial physiologically, strategically a runner is at a disadvantage when boxed in. Chances of winning are reduced. If the intent is to improve performance time, running with a stronger group would be recommended. During training sessions drafting and pack running should be discouraged unless the purpose is to train runners to draft.

In swimming, drafting has been found to reduce post exercise oxygen consumption by 11 %, blood lactate by 31 %, and rate of perceived exertion by 21 % (Basset et al. 1991). In cross-country skiing, Bilodeau et al. (1994) found that drafting significantly reduced heart rate by 5.6%, from 163 to 154 beats/min. Heart rates were not significantly different between the two trials in this study. There exists the possibility that due to the majority of the subjects inexperience with drafting, heart rates may have remained elevated due to the anxiety and stress related to running directly behind a runner and trying to avoid being kicked or kicking the leading runner. It is also possible that some synchronization between locomotion centers and cardiovascular centers may have occurred. Breathing frequency and heart rate synchronization with leg frequency during rhythmic exercise has been documented in laboratory animals

and reported to occur in cyclists and runners (Caretto et al. 1992, Niizeki et al. 1993).

From our results it is evident that drafting directly behind another runner reduces energy consumption during the initial stages of recovery. Post-exercise 1-minute measurements have been used in previous studies to gauge the effects of drafting during a swimming trial (Basset et al. 1991); however, measurements made during an activity will always be the best method to assess and truly evaluate the effects that a particular strategy has on an athlete during that activity. Future studies are being developed to investigate the physiological effects of drafting during trial runs in various positions with the aid of a portable indirect calorimeter. The aim of these studies will be to quantify the effect of drafting during trial runs and to clarifying the question of which position is the most economical for runners and which one do they perceive as being the most economical. We predict that the effects of drafting during distance running at the relative velocity of 4-6 m/s will produce reductions in metabolic energy expenditure much larger than previously estimated.

In summary, we found that drafting in distance running at a relative speed of 4.47 m/s resulted in a significant reduction in post exercise oxygen consumption, carbon dioxide production, and minute ventilation in the first minute of recovery, as well as, a significant reduction in perceived exertion. The fact that these changes occurred strongly suggests that drafting is a useful technique for distance runners to evade aerodynamic drag. By utilizing this technique, an athlete could conserve energy and thus improve his or her performance toward the end of a competition. In training sessions, however, drafting and pack runs should be avoided to maximize the training benefits, unless the objective is to

train athletes to draft. We found that only one of our subjects regularly drafted during races.

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