

ABSTRACT

ARNETT, M. S. The physiological effects of drafting in runners. MS in Adult Fitness/Cardiac Rehabilitation, December 2002, 35 pp. (C. Foster)

The drafting effect has not been thoroughly studied in running. The purpose of this study was to compare VO_2 , HR, BLA, and RPE during 6-minute running bouts with variations of wind velocities and with drafting. Six collegiate runners (3 male, 3 female) performed a maximal GXT and six, 6-minute running trials against a wind velocity of $0 \text{ m}\cdot\text{s}^{-1}$, $3.64 \text{ m}\cdot\text{s}^{-1}$, and $4.7 \text{ m}\cdot\text{s}^{-1}$. Three of these trials were done when drafting off a second runner, one at each wind velocity and three trials without. Comparisons were made using repeated measures ANOVA. Volume of oxygen consumed (VO_2) was significantly lower ($p = 0.02$) when drafting at a wind velocity of $4.7 \text{ m}\cdot\text{s}^{-1}$ (53.9 ± 6.42 vs. 52.4 ± 7.32) which equates a 2.9% reduction in VO_2 . RPE was significantly lower ($p = 0.029$) when drafting at a wind velocity of $4.7 \text{ m}\cdot\text{s}^{-1}$ (5.5 ± 1.23 vs. 3.8 ± 0.75). There was no significant difference in HR or BLA at any wind velocity. The results are in partial agreement with similar research. The drafting effect in running may help coaches and runners to train for performances and to develop time and energy saving racing strategies.

THE PHYSIOLOGICAL EFFECTS OF DRAFTING IN RUNNERS

A MANUSCRIPT STYLE THESIS PRESENTED

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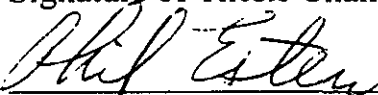
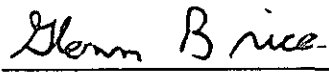
THESIS FINAL ORAL DEFENSE FORM

Candidate Mary S. Arnett



We recommend acceptance of this thesis in partial fulfillment of this candidate's requirements for the degree:

Master of Science in Adult Fitness/Cardiac Rehabilitation

The candidate has successfully completed the thesis final oral defense.

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INTRODUCTION

The physiological effects of drafting have been studied in cycling, speed skating, and swimming (3,6,7,10,19,20,22,24,25). The air resistance associated with high velocities in cycling, speed skating, and water resistance in swimming makes drafting an important part of training regimes and competitive strategies in these sports. One area in which drafting has been inadequately studied is during running. Given the lower velocities of running, drafting might be comparatively less important than in cycling. However, even slight changes in physiological requirements can affect performance enough to influence a competitive result. Comparisons of performance differences between medallists and non-medallists at high-level competition often reveal less than 1% difference in average velocity (8). Additionally, this area of research is important for both racing strategy and training. Drafting behind a runner in practice might influence the physiological provocation provided by a given training session.

Pugh, in the 1970's, was among the first to study wind resistance and its effects on running. He found that "the energy cost of overcoming air resistance in track running may be 7.5% of the total energy cost at middle distance speed and 13% at sprint speed." Further, "running one meter behind another runner virtually eliminated air resistance and reduced [oxygen uptake] by 6.5% at middle distance speed" (23). In another study of VO_2 in running with observations on the effect of air resistance, Pugh found that "the energy cost of overcoming air resistance in track running is about 8% of total energy cost at 21.5 km/hr (5000 m race pace) and 16% for sprinting (100 m in 10.0 sec)"(22).

More recently, a study of nine highly trained runners by Corvalán-Grössling (unpublished thesis), “runners who drafted in a second and third position when compared to the lead runner significantly reduced VO_2 (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) ($p < 0.05$).” Corvalán-Grössling also looked at RPE during these drafting trials. There was a significant reduction in RPE for the runner in the third drafting position. These studies and others (14,2) provide the rationale that supports the positive effects of drafting in running and suggests its practical importance to the field of competitive running, and the need for further study.

Therefore, we hypothesized that the drafting effect during running would significantly effect the physiological responses in runners. Further, we hypothesized that the responses would proportionally differ in relation to wind velocity. Accordingly, the purpose of this study was to compare oxygen uptake (VO_2), heart rate (HR), blood lactate (BLa), and rate of perceived exertion (RPE), during six-minute running bouts with variations of wind velocities and the use of a drafting device.

METHODS

Subjects. Six healthy competitive runners (3 male, 3 female) from the University of Wisconsin-La Crosse (UWL) volunteered to participate. The subjects were cross country team members who had been training for more than three months with an average of 76.6 ± 31.2 km/week. The average age of the participants was 20.1 ± 1.5 years. Descriptive data are listed in Table 1. Informed consent (Appendix B) was

Table 1. Characteristics of Subjects (mean \pm SD)

Characteristic	Male	Female
Age (yr)	19 \pm 1	21 \pm 1
Height (cm)	176 \pm 1.5	168 \pm 6.7
Weight (kg)	72 \pm 5.6	54 \pm 5.5
VO _{2peak} (ml*min ⁻¹ *kg ⁻¹)*	62.3 \pm 2.26	53.4 \pm 3.28
HR _{peak} (beat*min ⁻¹)*	190 \pm 10.6	192 \pm 13.0
% VO _{2peak} at VT*	87 \pm 3	84 \pm 4

* Treadmill max test

obtained prior to testing. The University Institutional Review Board for the protection of human subjects approved the protocol before data collection.

A questionnaire (Appendix A) was used to document the length of the current training period, total hours spent running per week, total kilometers run per week, best five kilometer race time, personal best mile split time in a five kilometer run, and average pace for a comfortable run. These results were used to help determine a correct running speed for each subject. The results are displayed in Table 2.

Table 2. Running Performance Statistics (mean \pm SD)

Criteria	Male	Female
Length of current training period (months)	17.6 \pm 19.05	29.0 \pm 19.00
Total hours spent running per week (hrs)	7.8 \pm 1.15	5.7 \pm 0.58
Total km run per week (km)	100.6 \pm 25.12	52.3 \pm 6.97
Best 5.0 km race time (min:sec)	15:56.00 \pm 00:21.93	19:18.33 \pm 01:34.52
Personal best mile split time in 5.0 km run (min:sec)	04:53.00 \pm 00:04.36	05:50.00 \pm 0:00.20
Average pace per mile for a comfortable run (min:sec)	06:40.00 \pm 00:08.66	08:00.00 \pm 00:00.00

Protocol. Each subject was studied in the laboratory seven times. Each subject's height and weight were measured before their first test. Gas exchange was measured using open circuit spirometry (Quinton, QMC, Seattle, WA). Heart rate was monitored using radiotelemetry (Polar Vantage XL, Polar Instruments, Port Washington, NY).

Blood for lactate measurements was taken from a fingertip and analyzed using an enzyme electrode system (YSI, Yellow Springs, Ohio). Following each trial and each stage, the subjects were asked to rate their perceived exertion (RPE) using the category ratio Borg scale (0-10).

Graded Exercise Test Procedure. The first test was a maximal incremental exercise test (GXT) on a treadmill. Subjects warmed up on the treadmill for approximately five minutes at a comfortable pace. At the start of the test, the grade was set at a constant 2.5% and the speed was set at the average velocity for easy training runs (Table 2) for the subject. The first stage was three minutes in duration and the following stages were each one minute in duration. The speed increased by $0.2 \text{ m}\cdot\text{s}^{-1}$ (0.5 mph) per stage until volitional fatigue. Respiratory exchange was measured throughout the test, as was heart rate. A blood sample for lactate analysis was obtained from a fingertip two minutes post exercise.

Drafting Procedure. A fan was used to create artificial wind for the subject running on a motor driven treadmill. The fan was placed 2.98 - 3.28 and 2.50 – 2.80 meters in front of the runner for low and high wind velocity, respectively. Wind velocity was measured using a wind gauge (Kestrel[®] 1000 Pocket Wind[™] Meter, Nielsen Kellerman, Chester, PA). During the drafting trials, a person stood 0.9 m in front of the subject to simulate drafting in an actual run. Two trials were done each with a wind velocity of $0 \text{ m}\cdot\text{s}^{-1}$ (0 mph), $3.64 \text{ m}\cdot\text{s}^{-1}$ (8 mph), and $4.7 \text{ m}\cdot\text{s}^{-1}$ (10.5 mph). Within each wind velocity trial, one was done without and the other with the person providing the draft. Therefore, a total of six trials were completed, the non-drafting trials first and then

the drafting trials, with wind velocity applied in random order. Blood samples for lactate determination were taken immediately following each trial.

Subjects warmed up for five to ten minutes prior to the first test and then completed three trials in one session with six minutes of walking between each one. Drafting was done in a linear fashion. Subjects ran for six minutes in each trial at a pace approximately $0.4 \text{ m}\cdot\text{s}^{-1}$ (1 mph) slower than their maximal speed from their max GXT. This pace was kept constant throughout all trials. Data was recorded at each minute and values were used from the last continuous minute.

Statistical Treatment. Group means and standard deviations were calculated for all physical characteristics (age, body weight, height). Physiological variables (VO_2 , HR, BLa, and RPE) measured in the six drafting and non-drafting trials were reported as mean and standard deviation for the last continuous minute of exercise (15). Means were compared using repeated measures analysis of variance to test the hypothesis that drafting would progressively reduce the physiological responses (VO_2 , HR, BLa, and RPE) during submaximal running. Specifically, we hypothesized that VO_2 , HR, BLa, and RPE at each wind speed would be reduced during drafting. A Tukey's post hoc test was done on significant data. Differences were considered significant if $p < 0.05$.

RESULTS

For VO_2 , the interaction effect between wind velocity and drafting revealed a significant difference, $p = 0.02$. A Tukey's post hoc test revealed a significant difference in VO_2 at the wind velocity of $4.7 \text{ m}\cdot\text{s}^{-1}$. Therefore, drafting 0.9 m behind a runner at wind speed of $4.7 \text{ m}\cdot\text{s}^{-1}$ reduced wind resistance enough to significantly decrease VO_2 . This is shown in Table 3 and Figure 1.

Similar results were found with RPE. The interaction effect between drafting and wind velocity was significantly different, $p = 0.029$. A post hoc test revealed a significant difference at the wind velocity of $4.7 \text{ m}\cdot\text{s}^{-1}$. Therefore, drafting .9 m behind a runner at a wind speed of $4.7 \text{ m}\cdot\text{s}^{-1}$ was perceived as significantly easier than running against the same wind without drafting. This is shown in Table 4 and Figure 2.

There was no significant difference in HR, but the trend (shown in Table 5 and Figure 3) was similar to that of VO_2 and RPE. Blood lactate values were not significantly different at any level (Table 6 and Figure 4).

Table 3. VO_2 ($\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$) Values in Non-drafting and Drafting Trials (mean \pm SD)

Wind Velocity	Non-drafting Trial	Drafting Trial
$0 \text{ m} \cdot \text{s}^{-1}$	52.5 ± 6.82	52.8 ± 6.98
$3.64 \text{ m} \cdot \text{s}^{-1}$	53.7 ± 6.38	53.7 ± 6.52
$4.7 \text{ m} \cdot \text{s}^{-1}$	53.9 ± 6.42	$52.4 \pm 7.32^*$

* = significant difference

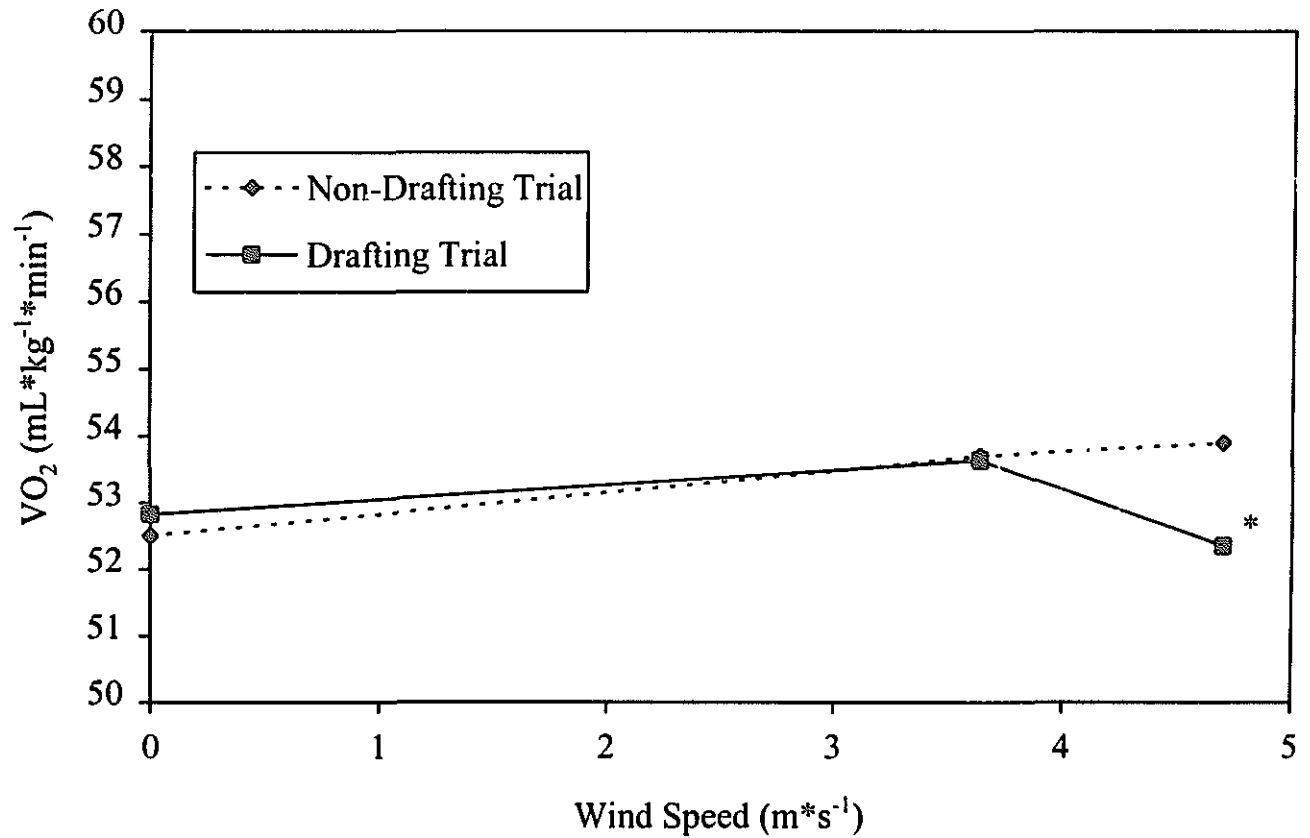


Figure 1. Wind speed versus VO_2 . (* = significant difference)

Table 4. RPE Values in Non-drafting and Drafting Trials (mean \pm SD)

Wind Velocity	Non-drafting Trial	Drafting Trial
0 m*s ⁻¹	4.3 \pm 0.82	4.2 \pm 1.33
3.64 m*s ⁻¹	4.3 \pm 1.03	4.0 \pm 1.10
4.7 m*s ⁻¹	5.5 \pm 1.23	3.8 \pm 0.75*

* = significant difference

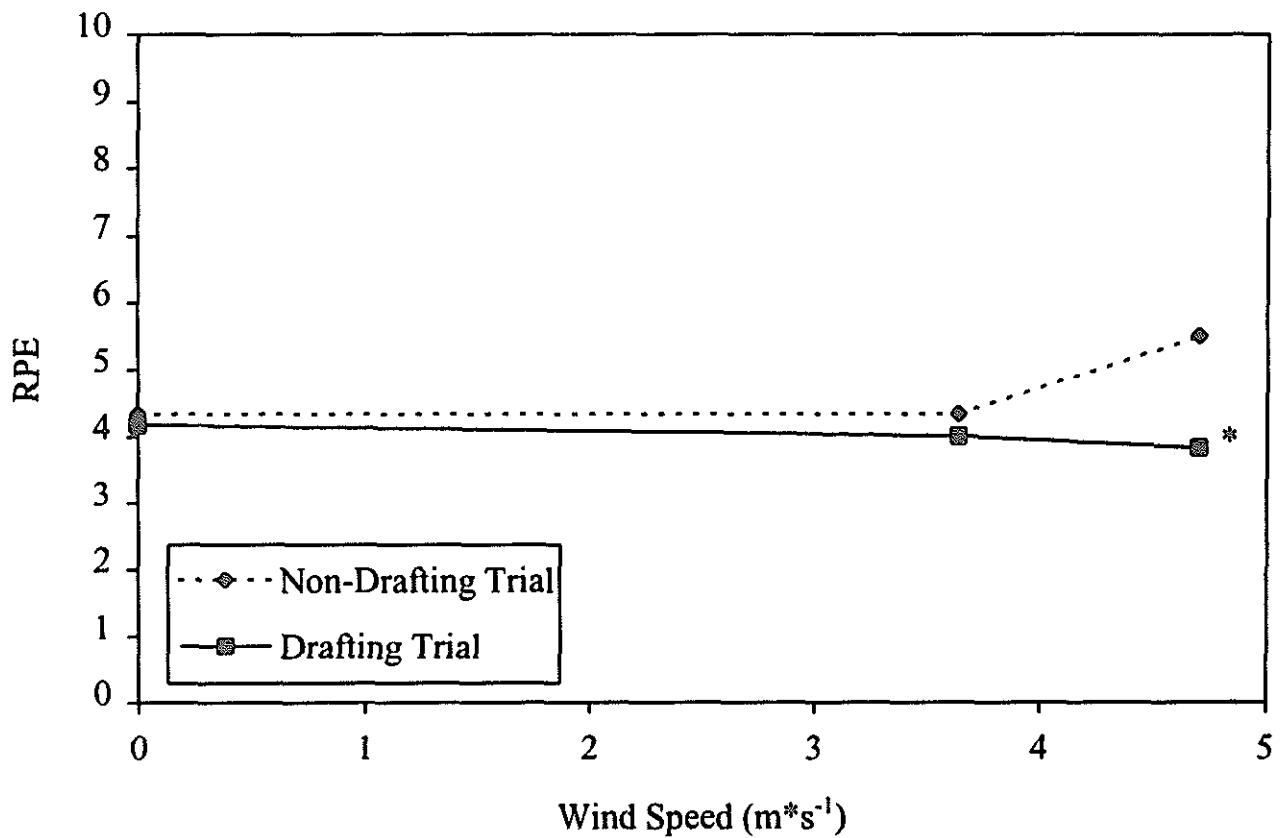


Figure 2. Wind speed versus RPE. (* = significant difference)

Table 5. HR ($\text{beat} \cdot \text{min}^{-1}$) Values in Non-drafting and Drafting Trials (mean \pm SD)

Wind Velocity	Non-drafting Trial	Drafting Trial
$0 \text{ m} \cdot \text{s}^{-1}$	179.8 ± 13.57	179.0 ± 14.63
$3.64 \text{ m} \cdot \text{s}^{-1}$	180.0 ± 14.07	178.5 ± 13.31
$4.7 \text{ m} \cdot \text{s}^{-1}$	181.8 ± 14.18	177.7 ± 12.57

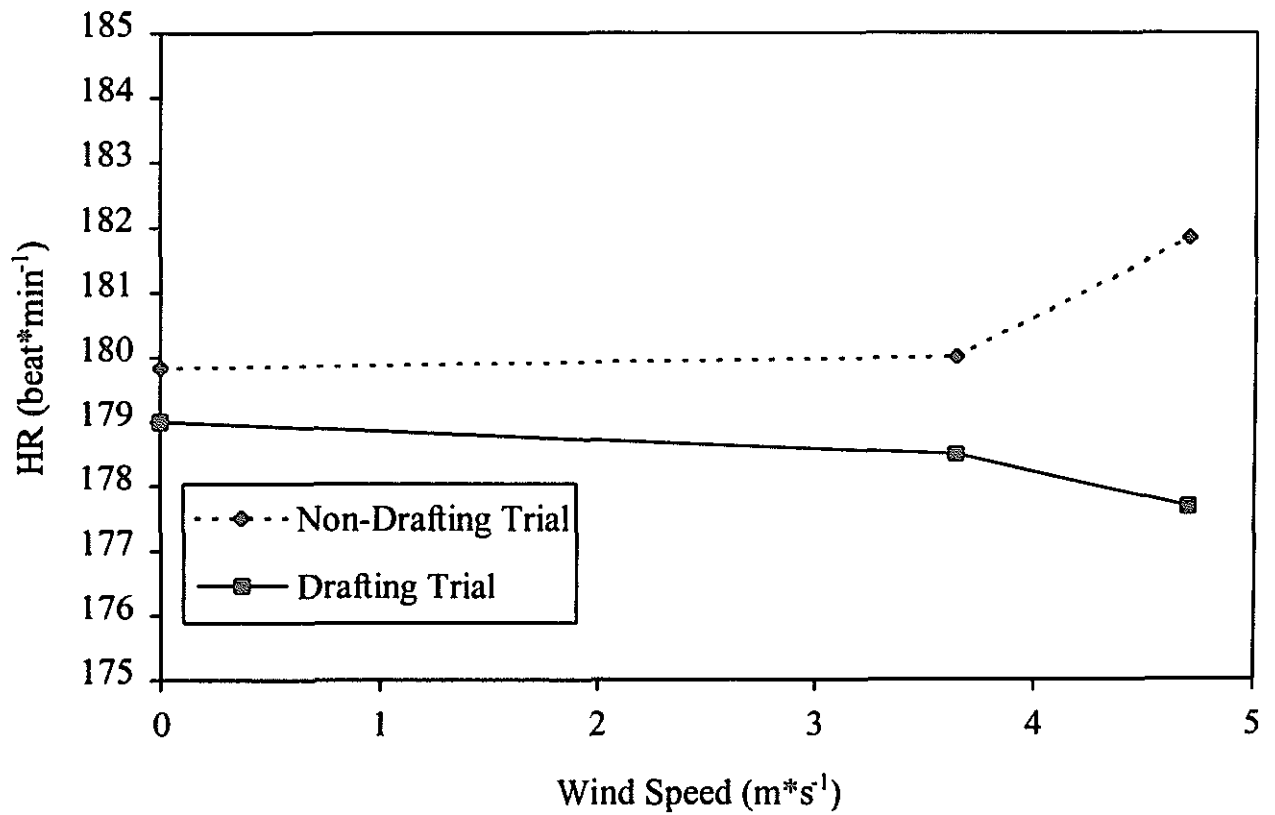


Figure 3. Wind speed versus HR.

Table 6. BLa ($\text{mmol}\cdot\text{L}^{-1}$) Values in Non-drafting and Drafting Trials (mean \pm SD)

Wind Velocity	Non-drafting Trial	Drafting Trial
$0 \text{ m}\cdot\text{s}^{-1}$	3.2 ± 0.88	2.9 ± 1.15
$3.64 \text{ m}\cdot\text{s}^{-1}$	3.0 ± 0.75	2.4 ± 0.55
$4.7 \text{ m}\cdot\text{s}^{-1}$	3.2 ± 0.81	2.9 ± 0.90

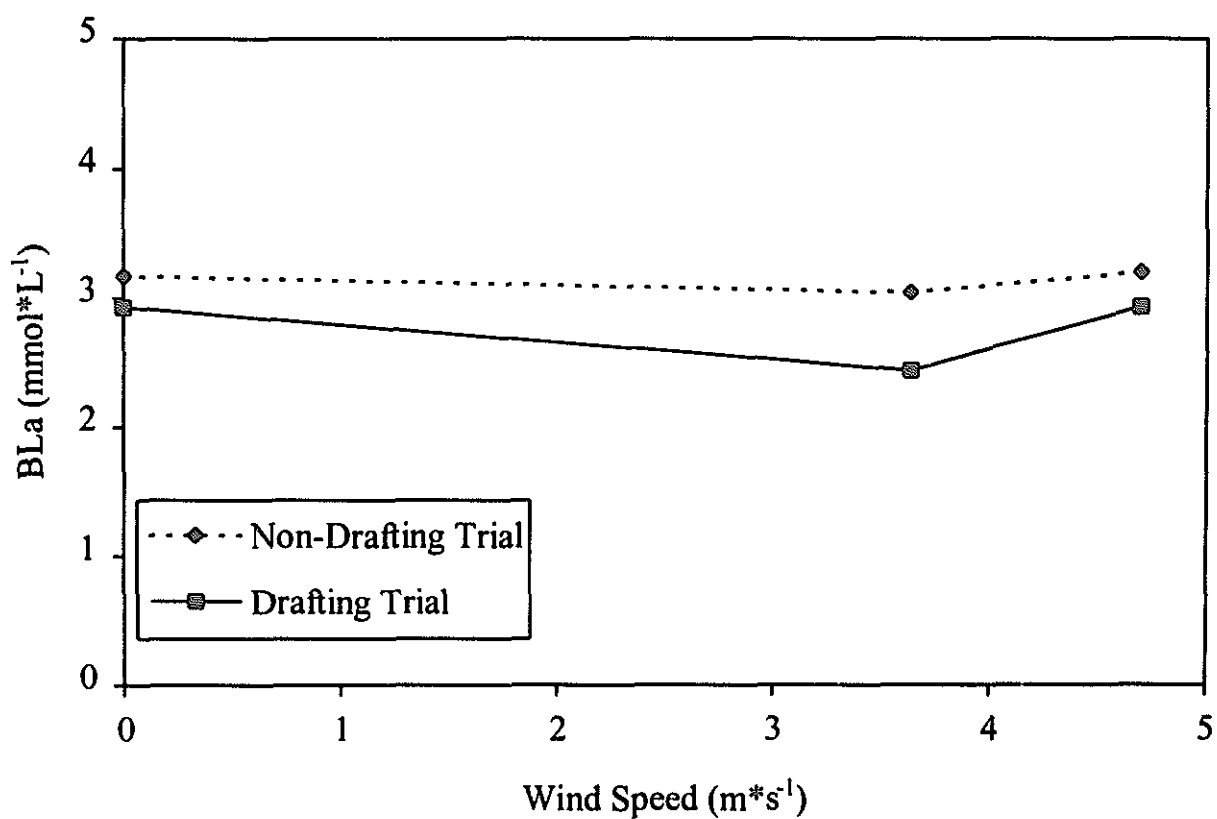


Figure 4. Wind speed versus BLa.

DISCUSSION

These results are consistent with research by Pugh (22) and Corvalán-Grössling (unpublished thesis) regarding a significant decrease in VO_2 of a runner who employs drafting techniques. The current study found a 2.9% reduction in VO_2 when running against a $4.7 \text{ m}\cdot\text{s}^{-1}$ wind. However, Pugh's subjects had a 6.5% reduction in VO_2 at an average running velocity of $6 \text{ m}\cdot\text{s}^{-1}$ and Corvalán-Grössling's subjects had a 5.2% reduction in VO_2 at an average running velocity of $4.47 \text{ m}\cdot\text{s}^{-1}$. To compare data among these studies, it was calculated that there was a 2.2% reduction in VO_2 at an average running velocity $4.45 \text{ m}\cdot\text{s}^{-1}$ in the current study. Therefore, even though the current study found a significant reduction in submaximal VO_2 , the reduction is not as great as compared to other studies (Figure 5).

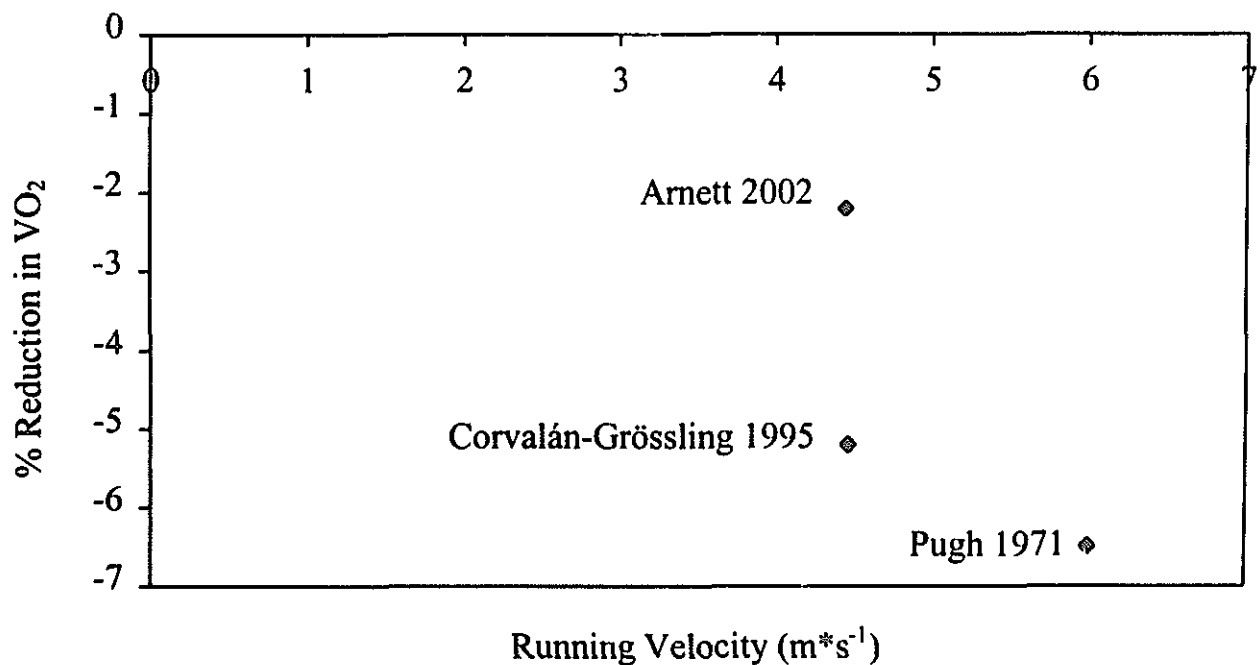


Figure 5. % Reduction in VO_2 with drafting.

The main difference between our protocol and those of Pugh (22) and Corvalán-Grössling (unpublished thesis) is that both of these studies employed overground running whereas we used treadmill running with imposed air movement. However, in one study directly comparing overground versus treadmill running, Bassett (1) found no differences that could account for the differences in our results and those of Pugh and Corvalán-Grössling. Accordingly, we are at a loss to explain the observed differences.

In addition to VO_2 , Kyle (14) found a significant improvement in performance time attributable to the drafting effect. The current study did not evaluate performance, but a reduction in submaximal VO_2 should allow an overall improvement in performance. It would be projected that the decrease in submaximal VO_2 throughout a competition would allow the runner to have more energy at the end of the race and therefore perform better.

Daniels (5) took a different approach to studying the wind resistance to a runner. He had runners complete six-minute trials at sea level and then at altitude (i.e. reduced air density thus decreased air resistance at 2,300 m). In both studies, runners ran in the field and on a treadmill. Using Daniels' data points, a trend line was applied to predict VO_2 values for different running speeds. In the field, it is predicted that running at $6.0 \text{ m}\cdot\text{s}^{-1}$ (as Pugh's subjects did), there would be a 6.8% reduction in VO_2 at altitude as compared to at sea level. In our study, subject ran at an average pace of $4.5 \text{ m}\cdot\text{s}^{-1}$. This should result in a 5.4% reduction in VO_2 at altitude as compared to sea level using Daniels' data (Figure 6).

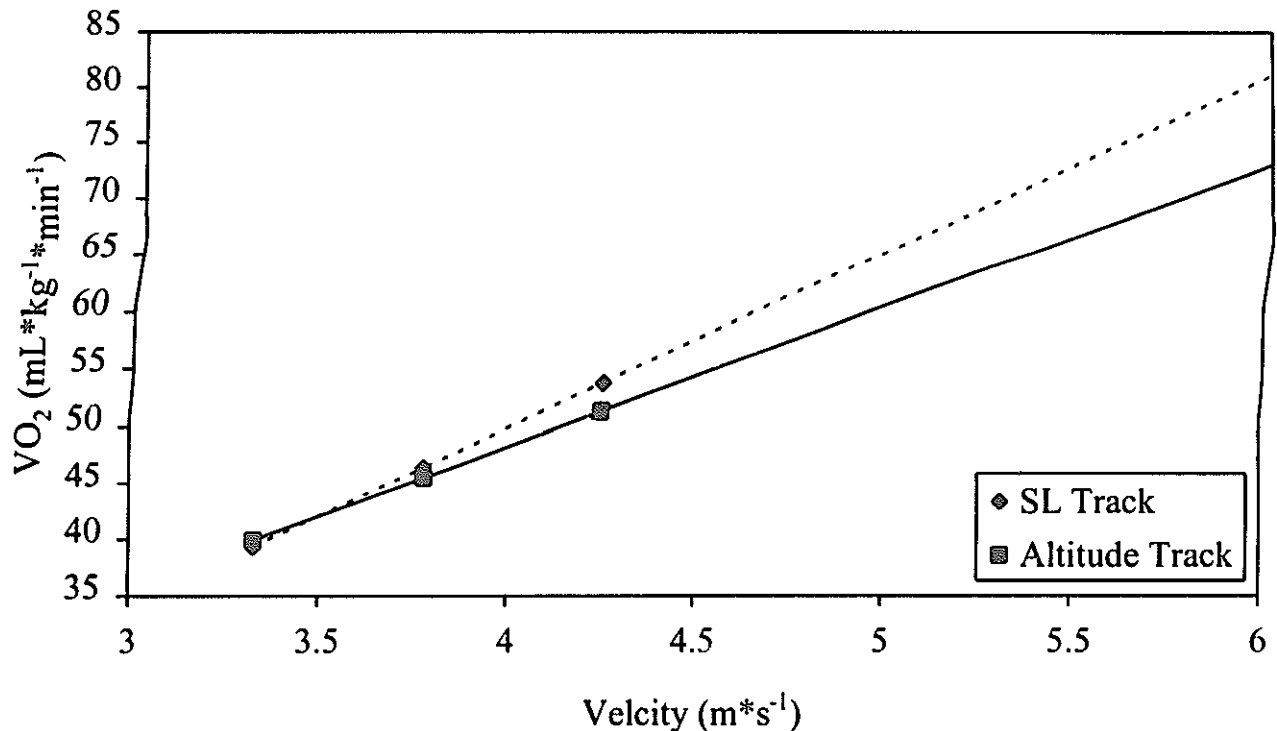


Figure 6. Sea level versus altitude running cost in the field (track).

On the treadmill, it is predicted that running at 6 m*s^{-1} would result in a 5.7% reduction in VO_2 at altitude as compared to sea level. Again, at a running velocity of 4.5 m*s^{-1} , as our subject did, we would expect to see a 3.8% reduction in VO_2 at altitude (Figure 7).

Comparing Daniels' data from the treadmill to running in the field with consideration of wind resistance by the level of altitude one would predict a difference of 1.1% ($6.8\% - 5.7\%$) when running at 6 m*s^{-1} . This study provides the rationale for future studies done on drafting and air resistance to be completed in the field.

Rating of perceived exertion was significantly lower for runners during drafting, which is in agreement with an unpublished thesis by Corvalán-Grössling.

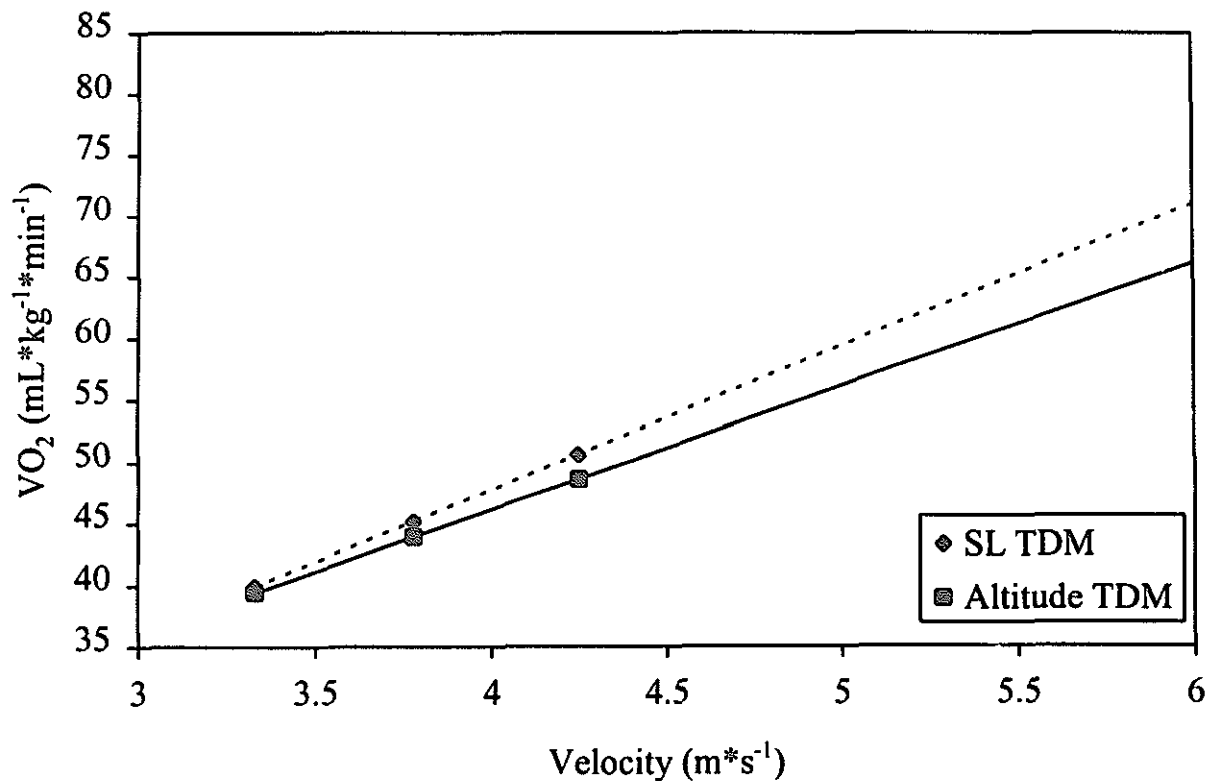


Figure 7. Sea level versus altitude running cost on a treadmill.

The current study found a 30% reduction in RPE for runners drafting against a wind velocity of $4.7 \text{ m}\cdot\text{s}^{-1}$ (5.5 ± 1.2 (hard) vs. 3.8 ± 0.8 (somewhat hard)). The importance of a reduction in RPE to a runner who is drafting can be advantageous in practice sessions and competition to motivate the runner. Rating of perceived exertion is a subjective rating; therefore there can be a lot of variation among runners. This study along with Corvalán-Grössling's study provides the rationale for other research to be conducted in the psychological area of sport performance.

The drafting effect in running may help coaches and runners to train for performances and to develop time and energy saving racing strategies. Drafting should not be limited to racing performance only, but also should be applied during practice

sessions. A runner who continually runs in the middle of a pack might not reach full potential or gain the most benefit out of a practice session. Drills that focus on every runner leading the group at some point or a decrease in focus on group running drills can help the runner to maximize their potential. Educating runners about these techniques that can be used in competition can also be beneficial.

Future research should focus on field studies that are more comparable to actual running competition and practices. Although the difference between exercise on a treadmill and field exercise is still debated (1,4,8,9,11,12,16,17,18,22) a study done in the field would simulate a drafting situation more accurately. Clothing type worn by runners should be closely matched to that worn in competition (2). Other factors such as hair trimmings should be similar in both runners (13), eliminating any unwanted error. Body types or shapes should also be closely matched for the previously mentioned reasons.

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APPENDIX A
SUBJECT QUESTIONNAIRE

SUBJECT QUESTIONNAIRE

Please fill out the questionnaire to the best of your knowledge.

1. Estimate total miles run per week: _____
2. Estimate of total hours spent running per week: _____
3. Estimate the length of time that you have been running the amount of miles per week as listed in question 1: _____
4. Please list your personal best 5 km/5000m (3 mile) race time: _____
5. Please list your personal best **mile split time** for a 5 km/5000m (3 mile) run: _____
6. Please list your mile split time for a comfortable run: _____

APPENDIX B
INFORMED CONSENT FORM

INFORMED CONSENT FORM

The Physiological Effects of Drafting In Runners

I _____ give my informed consent to participate in this study that will examine the physiological effects of drafting on runners. I consent to presentation and publication or other dissemination of study results so long as the information is confidential so that no individual identification can be made. I have been informed that participation in this study will involve a maximum graded exercise test on a treadmill and six, six-minute trials on a treadmill. This will require a maximum of three laboratory visits of 1 to 1.5 hours that will take place between October 15, 2001 and January 31, 2002.

I have been informed that some equipment and procedures may cause minimal discomfort. I understand blood samples will be taken from a finger prick and that universal precautions will be observed. Precautions will be taken to minimize all risks.

I have been informed that the results of my graded exercise test will be reported to me along with the overall results of the study. This will allow me to know my aerobic capacity and any benefits of drafting.

I have been informed that my information will be kept confidential and I will be assigned a number when my data is recorded.

I have been informed that participation is voluntary and that I may at any time, for any reason, discontinue or refuse to participate and this will involve no penalty or loss of benefits to which I am otherwise entitled.

I have been informed that concerns about any aspects of this study may be referred to Mary Arnett (796-1514) and the faculty supervisor, Dr. Carl Foster, Mitchell Hall, (785-8687).

Questions regarding the protection of human subjects may be addressed to Dr. Dan Duquette, the Chair of the UW-La Crosse Institutional Review Board for the Protection of Human Subjects, (608) 785-8124.

Subject

Researcher

Date

Date

APPENDIX C
REVIEW OF LITERATURE

REVIEW OF LITERATURE

Air Resistance During Forward Movement

Pugh was a pioneer in the subject matter of air resistance and its effect on forward movement, specifically walking and running. Pugh (23) had subjects complete trials on a treadmill and also in the field to study the effect of wind resistance on performance. He developed an equation to calculate VO_2 based on wind velocity. He states, "if wind velocity and running velocity are equal, as in running on a track in calm air, ΔVO_2 will increase as the cube of velocity" (23, p. 823).

Through further research, Pugh (22) found that in running and walking against wind, O_2 intake increased as the square of wind velocity. His extensive research has been the basis for many other studies that have been done on this subject matter.

Morgan and Craib (20) examined the physiological aspects of running economy including air and wind resistance. They concluded that wind resistance is great enough to effect performance and energy expenditure. In their opinion, the degree to which air resistance effects performance is still uncertain, as there is little experimental data on the degree to which wind resistance affects performance.

Ward-Smith (25,26,27,28,29,30) has thoroughly studied running performance and has developed mathematical models in attempt to quantify performance. His first mathematical models for still conditions were developed based on the law of thermodynamics (26).

Ward-Smith (27) then examined the effects of air resistance and assistance. In one particular study done in 1985, Ward-Smith studied the influence of adverse and favorable winds on sprinting performance. While it is known that wind assistance can decrease performance time, Ward-Smith developed a mathematical equation to quantify this amount. He concluded that in races over 100 m, the advantage provided by wind assistance increases with wind velocity. The amount of wind assistance was quantified to show that $2 \text{ m}\cdot\text{s}^{-1}$ of wind assistance provides a benefit of about 0.18 seconds on running time for a 100 m sprint.

In 1999, Ward-Smith (29) continued his research in wind assistance and resistance. He examined body lean while sprinting against a head wind and concluded that it has a small effect on performance. When a runner leans forward while running to compensate for wind resistance, the runner can develop a more propulsive force to compensate for the wind resistance. Again, Ward-Smith was able to mathematically quantify this amount. His research and development of mathematical equations to quantify wind assistance and resistance are important to this subject matter.

Linthorne (17) and Mero et al. (19) also studied the effect of wind on 100 m sprint times. Linthorne (17) used data from international official competitions. He found that the race times gradually increased with increasing wind velocity. Therefore, the disadvantage of a head wind was greater than the benefit of a tail wind of the same magnitude. "The advantage of a $2 \text{ m}\cdot\text{s}^{-1}$ following wind was $0.10 \pm 0.01 \text{ s}$ for the male sprinters and $0.12 \pm 0.02 \text{ s}$ for the female sprinters" (17, p. 110).

Davies (6) studied the effects of wind assistance and resistance on the forward motion of a runner. His subjects consisted of three male runners who ran with and against varying wind speeds in a wind tunnel. Davies compared this data to downhill and uphill gradient running on a treadmill. He concluded, “the energy cost of overcoming air resistance on a calm day outdoor was calculated to be 7.8% for sprinting ($10 \text{ m}\cdot\text{s}^{-1}$), 4% for middle distance ($6 \text{ m}\cdot\text{s}^{-1}$), and 2% for marathon ($5 \text{ m}\cdot\text{s}^{-1}$) running” (6, p. 702).

Kyle and Mastropaolo (14) set out to measure the effect of wind resistance in middle and long distance running. They studied cyclist and then mathematically applied this information to runners. They concluded that in running, overcoming wind resistance accounts for 15–25% of energy expenditure. They introduced the idea that applications to running might require development of special skills, tactics, and training methods, such as drafting.

Di Prampero et al. (7) studied endurance running energetics in marathon and half marathon runners. He compared maximal oxygen consumption and energy cost of running between marathon and half marathon runners and tried to correlate those values with running velocity. Air resistance was taken into account when he did these calculations, emphasizing the important role air resistance has in performance and energy expenditure.

Behncke (2) examined wind resistance in track running. He used an equation to quantify wind resistance. It contained two components; one in the direction of the run and the other is a perpendicular component. Behncke introduced the idea that runners typically face wind resistance from many direction as a run is completed around a track.

His work was done on the 100 and 200 m sprint, but he estimated wind resistance or assistance in longer distance runs. Further, Behncke pointed out that different parts of a runner's body move at different velocities during the course of a run. This effect is called dynamic resistance and can further contribute to drag.

Not only does wind resistance of the physical body affect energy expenditure and drag when walking and running, but also clothing, attire, or hair can significantly affect energy expenditure. Kyle and Caiozzo (13) studied these effects on running performance. Their results show that it is possible to lower the wind resistance significantly by improving clothing or by trimming or covering the hair, and that a small aerodynamic drag reduction can result in a significant performance increase. This is especially important in competition when performances differ by a second or less.

Brownlie et al. (3) compared the drafting effect of three different commercially available running outfits to newly developed bodysuits made of water vapor permeable fabric. These suits were put on manikins in a wind tunnel to measure their effectiveness. The newly developed body suits provided a lesser wind drag than the commercially available running apparel. In fact one newly developed body suit allowed drag reductions between 17.5% and 7.4%.

Shanebrook and Jaszczak (24) developed an equation to quantify aerodynamic drag in sprinters and then apply that to all running speeds. The Shanebrook-Jaszczak model of the human body consists of shapes (circular cylinders and a sphere for the head) to simulate an actual runner. Once the speed of the runner and the dimensions of the human

body were known, the total aerodynamic drag force acting on the runner could be determined.

Treadmill versus Field Exercise

Incremental treadmill exercise has been questioned on its validity in maximal physiological testing. Often, obtaining metabolic data is challenging in the field, and therefore a treadmill is used to simulate running in the field. However, treadmill running does not allow for variations in running velocity, as would be present in actual competition. Morgan et al. (21) in their review of literature on factors effecting running economy recognizes the debate over treadmill and field running, as do the following studies.

Daniels (5) took a different approach to studying the wind resistance to a runner in the field and on the treadmill. He had runners complete six-minute trials at sea level and then at altitude (2,300 m). In both studies, runners ran in the field and on a treadmill. He found that track running is more demanding than treadmill running at an equal speed, and this becomes more obvious at running velocities greater than $3.75 \text{ m}\cdot\text{s}^{-1}$.

In 1970, Pugh (23) concluded that the relationship between O_2 intake and speed for athletes on the track was not comparable to the incremental treadmill running. He attributed these differences to wind resistance in the field.

Crouter et al. (4) compared free range running and incremental treadmill exercise. He tested fifteen competitive collegiate runners in both field and treadmill settings. No significant difference was found in the peak physiological variables volume of oxygen

consumed, ventilation, heart rate, and oxygen pulse between the two groups. However, a significant difference was found in blood lactate values, similar to cycling data.

Similarly, McMiken and Daniels (18) also found no significant difference in maximal and submaximal VO_2 , maximal and submaximal respiratory exchange ratio, and running speed between treadmill and field running. However, they did find a correlation between VO_2 max and body weight.

Basset et al (1) studied the aerobic requirements of overground versus treadmill running. They questioned the validity of the American College of Sports Medicine (ACSM) VO_2 prediction formulas for running at speeds under $260 \text{ m} \cdot \text{min}^{-1}$ ($4.3 \text{ m} \cdot \text{s}^{-1}$) for both treadmill and field running at grades ranging from 0% to 5.7%. After conducting their study, they found no significant difference in the values they measured relative to those calculated using the ACSM equations, thus supporting the equations.

Léger and Mercier (16) studied the gross energy cost of horizontal treadmill and track running. They argued that previous studies done on this topic were based on a small amount of runners and that values were highly subjective because they were based on runner's individual characteristics. They used 130 subjects from 10 different studies in their review. Results showed wide variations in the energy cost of running from one study to another and also in between individuals. They suggest that specific standardized equations to estimate energy cost should be developed for specific population groups such as male, female, athletes, and previously sedentary individuals.

Foster et al. (8,9) have studied pacing and how it affects performance. One study (8) focused on the differences in physiological values in non-athletic and patient

populations. Using a cycle ergometer, subjects were found to reach a significantly greater VO_2 max when they could cycle at their own pace, as in free-range (FR) exercise, as compared to a graded exercise test (GXT). However, there was no significant difference in the mean peak power output between GXT and FR. Pacing is not allowed on continuous work output ergometers such as motor driven treadmills or bicycles. Therefore, Foster et al. argue that maximal physiological values cannot be obtained on this equipment.

Léger and Ferguson (15) studied the effect of pacing on oxygen uptake and peak lactate for a mile run. They compared the regimen of fast-medium-very slow pace to slow-medium-very slow pace on a treadmill. No significant difference was found in oxygen consumption or post exercise peak lactate values. Although several world-class milers have used a fast-medium-slow-fast pace, this study could not explain why this might be the best strategy to employ.

The argument as to whether treadmill running can accurately assess maximal physiological values as compared to field running consists of many components; one previously mentioned is the idea of pacing. Another difference is to what degree does the lack of air or wind resistance affect performance or energy expenditure on a treadmill as compared to field running.

Jones and Doust (11) found that running at a grade of 1% on a treadmill most accurately reflects the energy cost of outdoor running. The lack of wind resistance during treadmill running causes a decrease in energy expenditure that is unequal to that of running outdoors at the same workload.

Hill (10) argues, “the experience in the University of North Texas laboratory is that athletes are not able to perform close to their personal best times on the treadmill, despite the lack of wind resistance”(10, p. 478). He contributes this to the lack of motivation in laboratory running compared to actual competition. Also, as previously mentioned, runners cannot adjust their pace on the treadmill, as they can in actual field running.

The current literature is inconclusive regarding treadmill running versus field running, despite the contradicting research done on topics such as pacing that predicts that there should be a significant difference.

Drafting and Running

While extensive research has been done on the effects of wind assistance and resistance to the forward motion of a runner, many studies have not looked at the effect of drafting on running performance or energy expenditure. Once again, Pugh’s (22) research has set the standard for the field. He found that the energy cost of overcoming air resistance in track running may be 7.5% of the total energy cost at middle distance speed and 13% at sprint speed. Further, running 1 m behind another runner virtually eliminated air resistance and reduced VO_2 by 6.5% at middle distance speed. He reported that at a typical middle distance speed of $6 \text{ m}\cdot\text{s}^{-1}$, a runner traveling 1 m behind another would consume 6% less total energy. This resulted from an 80% decrease in the metabolic effect of wind resistance (which is about 7.5% of the total energy consumption at this speed).

Brownlie et al. (3) found similar results when they studied sixteen male runners and the drafting effect. They concluded that running one meter behind another runner is the optimal distance to follow behind the lead runner. At a forward velocity of $7.1 \text{ m}\cdot\text{s}^{-1}$, drafting provided a 62.7% reduction in drag.

Corvalán-Grössling (unpublished thesis) also studied the drafting effect. She 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. The drafting style she used consisted of three runners in a triangle configuration. Results showed that runners in the second and third positions had a significantly lower VO_2 as compared to the leader.

Kyle et al. (12,14) studied the reduced wind drag of cyclists and runners traveling in groups. Kyle, using Pugh's research in 1971, examined and developed an equation to predict the amount of time that could be taken off of a race such as a mile. For example, 40% shielding in a mile run at $7 \text{ m}\cdot\text{s}^{-1}$ (close to world record pace) could result in a time advantage of about 1.66 s per lap. This suggests that if a team rotated leading runners and shielded the ultimate leading individual, this individual should be able to take several seconds off of his/her best time. Kyle's systematic approach could improve racing times even more.

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