

Effects of Aerodynamic Drag and Drafting on Propulsive Force and Oxygen Consumption in Double Poling Cross-Country Skiing

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ABSTRACT

AINEGREN, M., V. LINNAMO, and S. LINDINGER. Effects of Aerodynamic Drag and Drafting on Propulsive Force and Oxygen Consumption in Double Poling Cross-Country Skiing. *Med. Sci. Sports Exerc.*, Vol. 54, No. 7, pp. 1058–1065, 2022. **Purpose:** This study aimed to investigate the effects of aerodynamic drag and drafting on propulsive force (F_{PROP}), drag area (C_{DA}), oxygen cost ($\dot{V}\text{O}_2$), metabolic rate (\dot{E}), and heart rate (HR) during roller skiing on a treadmill in a wind tunnel using the double poling technique. A secondary aim was to investigate the effects of wind versus no-wind test conditions on the same physiological parameters. **Methods:** Ten subjects of each gender participated in the experiments. One pair of skiers of the same gender roller skied simultaneously in line with the air flow; the distance between the skiers was ~2.05 m. Each pair was tested as follows: I) with wind, leading; II) with wind, drafting; and III) without wind. The treadmill inclination was 0° throughout the tests. For the wind conditions, the air velocity was similar to the treadmill belt speed: 3 to 7 m·s⁻¹ for men and 3 to 6 m·s⁻¹ for women. **Results:** Drafting resulted in significantly ($P < 0.05$) lower F_{PROP} , C_{DA} , $\dot{V}\text{O}_2$, and \dot{E} , compared with leading, for both genders at racing speed but not at lower speeds, whereas HR was only affected for the male skiers at racing speed. The test without wind resulted in significantly lower F_{PROP} , $\dot{V}\text{O}_2$, and \dot{E} at all tested speeds compared with the tests with wind present, whereas HR was lower only at higher speeds. **Conclusions:** At racing speed, but not at lower speeds, the positive effects of drafting behind a skier during double poling were obvious and resulted in a lower F_{PROP} , C_{DA} , $\dot{V}\text{O}_2$, \dot{E} , and HR. Tests without wind present put even lower demands on the skiers' physiology, which was also evident at lower speeds. **Key Words:** NORDIC SKIING, AIR RESISTANCE, KINETICS, PHYSIOLOGICAL RESPONSE

Cross-country skiing (xc-skiing) includes elements of classical and freestyle skiing, each with several subtechniques, using combined arm and leg movements.

A cross-country skier (xc-skier) must overcome aerodynamic drag and frictional force on all types of terrain, as well as gravitational force on uphill terrain (1–3).

The aerodynamic drag (F_{D}) is the force that arises from pressure and friction caused by the viscous flow to the surface of the body. A layered flow can separate from the surface of an object and continue as turbulent flow in the direction of flow, creating a volume of low pressure behind it (wake) (4). The extent of laminar/turbulent flow, size of the wake, and effects on F_{D} depend on the flow velocity and the shape and size of the object. In sports like cycling, running, and xc-skiing, athletes like to use the wake that arises behind another competitor to reduce the F_{D} (drafting). In sports with no or minimal changes to an object's size, frontal area, shape, and movements, for example, in bobsleigh and skeleton, laminar/turbulent flow transitions can be studied, geometries optimized, and effects on F_{D} investigated at relevant speeds and Reynolds numbers using force plate (5–8). However, a xc-skier is far from being a solid body without variance in size, frontal area, shape, and movements, except in tucked position used in downhill sliding. Although body mass stays constant, the frontal area, length, and height, both in line and perpendicular to the flow, and shape vary when the body segments move in relation to each other at different frequencies and range of motion (ROM), depending

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on subtechnique, traveling speed, and individual variations. It is thus difficult to optimize xc-skiers geometry and skiing technique with the same type of experimental setup. However, measurements of F_D including effects of drafting could be made under controlled conditions during roller skiing in a wind tunnel specially designed for physiological sports experimentation on a moving substrate (9).

Although extensive research has been conducted on xc-skiers, not many studies have been published in the field of aerodynamic drag on actual skiing conditions. Bilodeau et al. (10,11) investigated the difference in heart rate (HR) between leading and drafting positions during classical and freestyle skiing on a 2-km course on snow. After a 30-min rest, each pair of skiers repeated the same skiing style and course but changed positions. This resulted in a 7- and 9-bpm reduction in HR (4%–6%) in the drafting position for classical and freestyle skiing, respectively. Spring et al. (3) studied the influence of different clothing and postures used in downhill skiing on the drag area ($C_D A$), a product of the drag coefficient (C_D) and the frontal area (A), when rolling on roller skis on an asphalt surface. The study also investigated the effect of shielding with a skier in a semisquatting posture pacing up with a skier ahead and found a 25% decrease in drag.

Leirdal et al. (12) measured the effects of high, moderate, and deep postures in freestyle xc-skiing technique gear 5 on aerodynamic and metabolic variables using a slide board mounted on force plates in a wind tunnel. The results showed a 30% reduction in F_D from high to deep posture, whereas there was no difference in average HR and oxygen uptake ($\dot{V}O_2$) between the three different postures during a 3-min maximal test. Ainegren and Jonsson (13) measured $C_D A$, A , and C_D of different classical and freestyle techniques with a male skier standing on a force plate in a wind tunnel. A was determined from digital images taken with a two-dimensional (2D) camera placed in front of the skier. The results showed large differences in $C_D A$, A , and C_D between the different skiing techniques, with lower values found for techniques with deeper postures. Fruhwirth and Ainegren (14) repeated the area measurements on the same skier roller skiing on a treadmill with the use of a three-dimensional camera. The results generally showed slightly lower values for A compared with the 2D camera.

It is evident from both the research literature available and practical experience that drafting behind another skier provides an advantage, but how great the advantage is from a biomechanical and physiological point of view is currently unclear. In mass start races particularly, and most likely at higher speeds, the tactical aspects of skiing behind other skiers and taking advantage of a lower F_D probably play a decisive role in final placement in competitions.

In classical xc-skiing, one of the most used subtechniques currently is double poling (DP). Sometimes DP is the sole subtechnique used throughout, even over very hilly terrain and longer distance races, for example, in Visma Ski Classic races. In fact, given sufficient upper body capacity, DP can be more effective than the diagonal technique on uphill terrain (15).

Thus, the aim of this study was to investigate the effects of aerodynamic drag and drafting on propulsive force, drag area,

oxygen cost, metabolic rate, and HR during roller skiing on a treadmill in a wind tunnel using the DP technique. Because most studies conducted on xc-skiers are carried out using roller skis on a treadmill, where aerodynamic drag is normally absent, it was also of interest to investigate the effects of wind versus no-wind test conditions on the same physiological parameters.

METHODS

Subjects and protocol. A total of 20 xc-skiers (men: $n = 10$, age of 25.4 ± 5.1 yr, body height and weight of 1.84 ± 0.05 m and 80.5 ± 5.0 kg, $\dot{V}O_2$ max of 5.8 ± 0.6 L·min⁻¹, HR max of 192.7 ± 7.3 bpm; women: $n = 10$, age of 26.3 ± 4.2 yr, body height and weight of 1.66 ± 0.06 m and 63.0 ± 6.6 kg, $\dot{V}O_2$ max of 3.9 ± 0.5 L·min⁻¹, HR max of 191.9 ± 9.4 bpm), who at the time of conducting the study competed at an international level in Visma Ski Classic or World Cup races, participated in the experiments. Before the experiments started, the skiers gave their written consent to participate in the study, which was approved by the Regional Ethical Review Board in Umeå, Sweden (reg. no. 2016/282-31).

The experiments were carried out with the skiers roller skiing on a treadmill in a climatic wind tunnel (9) using the classical style DP technique. A validation of the working section flow field showed very good air flow conditions (9). A pair of skiers roller skied at the same time in line with the air flow with a distance of ~2.05 m between them, similar to the length of a classical style ski for on-snow skiing. The skiers were paired by gender and similar heights. The rear skier was instructed to maintain the same poling frequency and position as the front skier, that is, upright or tucked. During the experiments, the skiers wore 2017-model Swedish national racing suits (Craft Sportswear, Sweden, 82% polyester, 18% elastane) and regular racing boots.

Each pair of skiers was tested in the following three situations: I) with wind, leading position; II) with wind, drafting position; and III) without wind, where half of the skiers were tested at each position. For the wind conditions, the air flow was obtained by the wind tunnel fan, and the air velocity was similar to the treadmill belt speed. Thus, the wind conditions mimicked outdoor conditions when it is windless and the aerodynamic drag depends on the speed at which the skier travels. The situation without wind represented the condition that normally prevails in indoor experiments when roller skiing on a treadmill belt. The treadmill inclination was 0° throughout the tests, whereas the speed was increased from 3 to 7 m·s⁻¹ (women, 3–6 m·s⁻¹) in 1 m·s⁻¹ increments every fourth minute without a break between the different speeds. Because of a recent injury to the upper arm of one of the participants, one pair of female skiers did not perform the test at the final speed (6 m·s⁻¹, $n = 8$). The order of the three test situations was evenly distributed between the skiers. A 10-min warm-up period was conducted at the upcoming initial testing speed. The skiers had a 30- to 40-min break between the testing situations, whereas their pulmonary ventilation and gas concentrations were measured using Douglas Bags, allowing them to recover from muscle fatigue and excess postexercise oxygen consumption.

Forces. When a subject's position is maintained over time on a treadmill rolling belt, the propulsive force (F_{PROP}) is equal to the sum of the resisting forces (F_{RES}), see equation 1.

$$F_{PROP} = F_{RES} \quad [1]$$

In the present study, the skiers F_{PROP} was achieved through ground reaction forces from the ski poles. The F_{PROP} (N) was calculated as

$$F_{PROP} = F_R \cos \alpha \quad [2]$$

where F_R (N) is the resultant force measured in the direction of the poles and α is the angle between the poles and the moving substrate.

The F_{RES} (N) for the wind conditions consisted of the roller skis rolling resistance ($F\mu_R$) and F_D , whereas F_{RES} for the test condition without wind only included $F\mu_R$. Therefore, the F_D values for the wind conditions, F_D leading and F_D drafting, were calculated as shown in equations 3 and 4, respectively.

$$F_{D \text{ leading}} = F_{PROP \text{ leading}} - F_{PROP \text{ no wind}} \quad [3]$$

$$F_{D \text{ drafting}} = F_{PROP \text{ drafting}} - F_{PROP \text{ no wind}} \quad [4]$$

The skiers drag area (m^2) was calculated as

$$C_{DA} = \frac{2F_D}{\rho v^2} \quad [5]$$

where C_D is a drag coefficient that consists of a pressure and friction component, A (m^2) is the skiers projected frontal area, F_D (N) is the aerodynamic drag in the athlete's direction of travel, ρ ($kg \cdot m^{-3}$) is the air density, and v ($m \cdot s^{-1}$) is the resulting headwind due to the skiers traveling speed.

The rolling resistance is expressed as

$$F_\mu = \mu_R F_N = \mu_R mg \cos \alpha \quad [6]$$

where F_μ (N) is the roller skis rolling resistance; μ_R is a rolling resistance coefficient, which mainly results from the elastic deformation of the wheels and substrate and the resistance of the roller bearings; F_N (N) is the normal force perpendicular to the surface; m (kg) is the mass of the athlete with clothing and equipment; g is acceleration due to gravity ($m \cdot s^{-2}$); and α is the inclination of the substrate. In this study, the inclination of the treadmill was 0° .

Data collection and analyses. Both the front and the rear skier were measured simultaneously for pulmonary gas flow, HR, F_N on the roller skis, and the resultant force registered in the ski poles. The results, presented as mean \pm SD, were based on measurements taken during the last minute at each speed. The skiers' HR and pulmonary gas flow were collected using a Polar HR monitor (Polar Electro OY, Esbo, Finland) and Douglas Bag system with an extended hose length as described in an earlier article (16). The content of the bags' expired gas fractions was measured using O_2 and CO_2 gas analyzers (AEI Technologies Inc., Pittsburg, PA), whereas the gas volume, temperature, pressure, and relative humidity were measured in a water-sealed spirometer (custom made and enlarged copy of a Collins-Tissot) equipped with a combined pressure, humidity,

and temperature transmitter (PTU 300; Vaisala Oy, Helsinki, Finland). The ambient air pressure, temperature, relative humidity, and density were 966.7 ± 10 hPa, $15.0 \pm 0.2^\circ C$, $41\% \pm 10\%$, and 1.17 ± 0.01 $kg \cdot m^{-3}$ during the measurements. The skiers' ventilation and oxygen uptake ($\dot{V}O_2$) were then calculated according to standard temperature pressure and dry conditions (17).

The skiers' aerobic metabolic rate was calculated as

$$\dot{E} = \dot{V}O_2 (1.232 \cdot RQ + 3.815) \quad [7]$$

where \dot{E} ($kcal \cdot min^{-1}$) is the aerobic metabolic rate, $\dot{V}O_2$ ($L \cdot min^{-1}$) is the oxygen uptake, and RQ is the respiratory quotient of $\dot{V}CO_2/\dot{V}O_2$. Gross efficiency (GE) was calculated as

$$GE = \frac{P_{EXT}}{P_{INT}} = \frac{F_{PROP \cdot v}}{\dot{E}/0.01433} \times 100 \quad [8]$$

where GE (%) is the gross efficiency, P_{EXT} (W) is the propulsive power, v ($m \cdot s^{-1}$) is the treadmill belt speed, and P_{INT} (W) is the power from the skiers' aerobic metabolic rate where 0.01433 is a constant conversion from the unit $kcal \cdot min^{-1}$ to W (17).

The μ_R values of the two pairs of roller skis (Swix Classic Roadline C2, Lillehammer, Norway) used in the experiments were measured using equipment specific to this purpose (18). Several different wheels of the same type were initially mounted and tested on the roller skis to achieve a similar μ_R between them. For one of the roller skis, a rolling resistance regulating function (19) was used to increase the μ_R to a similar value to the other roller skis. The influence of different F_N (200–500 N in 100 N increments) and speeds ($3\text{--}7$ $m \cdot s^{-1}$ in 1 $m \cdot s^{-1}$ increments) on μ_R was also studied. Within the study, there was a $\mu_R = 0.025 \pm 0.002$ between the different roller skis and within the ranges of tested F_N and speeds, whereby it was accepted as a constant. The friction coefficient for skiing on snow varies, but the μ_R of the roller skis used in the study was relatively similar to the friction coefficient reported for on-snow skiing in nonextreme weather and snow conditions (20,21). The F_μ was thereby calculated using equation 6 with a $\mu_R = 0.025$, where F_N was the skiers' average normal force (obtained from the mass of the skier and the equipment) registered by the roller skis' force plates in the three different testing situations.

The F_N values of the left and right roller skis were measured at 400 Hz by a custom-made 2D force measurement binding system for xc-skiing (22). The system was calibrated using special calibration devices and procedures as described in an earlier article (22).

The F_{PROP} values of the poles were measured (400 Hz) with a custom-made, lightweight (70 g each) pole force system (University of Salzburg, Salzburg, Austria). Uniaxial strain gauge load cells (ME Systems, Hennigsdorf, Germany) were installed in a specially constructed light aluminum body fitted into the pole grips of selected racing poles adjusted to the preferred length of each skier ($84\% \pm 1\%$ of body height). Calibration of the pole force was processed with standard procedures in accordance with a previous study (23). The validity of the system was examined on an established force platform system. The mean absolute resultant pole force deviation over ground contact was 9 ± 4 N.

Force data were collected using the Coachtech online measurement and feedback system (24). Pole angles were recorded from the side using two Huawei Mate 9 mobile phone cameras (Huawei Technologies Co. Ltd., Shenzhen, China). The videos were recorded at 120 fps average frame rate in variable frame rate mode and with a 1920 × 1080 pixel resolution. The videos were reencoded from 120 fps variable frame rate mode to 120.0 fps constant frame rate with ffmpeg open-source software (<http://ffmpeg.org/legal.html>). To calculate pole angles from the videos, custom-made automatic angle recognition software (Datacenter CSC, Kajaani, Finland) was used. For the synchronization of force and motion data, an analogue trigger signal was simultaneously recorded by both data collection systems.

Because of technical problems, force data could not be compiled for one pair of skiers of each gender. Therefore, the results of F_{PROP} , F_{D} , and C_{DA} are based on eight skiers for each gender.

Statistical analyses. The statistical analyses were done in SPSS for Windows statistical software release 24.0 (SPSS Inc., Chicago, IL). Initially, an F -test of a two-way repeated-measures analysis of variance was used, which discovered significant effects of the test situation and speed on the dependent variables. Following this, an F -test of a one-way repeated-measures analysis of variance was used to discern significant differences between the different test situations at each speed. This was done for the dependent variables $\dot{V}O_2$, \dot{E} , HR, F_{PROP} , RQ, GE, F_{N} , and F_{μ} , whereas a paired t -test was used to evaluate significant differences in C_{DA} between the drafting and leading positions. The Bonferroni *post hoc* test was used to discern significant differences found in the F -tests and to correct α ($P < 0.05$).

RESULTS

Leading versus Drafting

Significant differences ($P < 0.05$) were found for both genders in F_{PROP} , C_{DA} , $\dot{V}O_2$, and \dot{E} , and in HR for men, between leading and drafting positions at high testing speeds with wind present. However, no significant differences ($P > 0.05$) were observed in these measures at lower speeds or in F_{N} , F_{μ} , RQ, and GE at any speed for men or women.

Men. F_{PROP} , C_{DA} , $\dot{V}O_2$, and HR were significantly lower in drafting at 5, 6, and 7 $\text{m}\cdot\text{s}^{-1}$ ($P < 0.05$), and there was a non-significant (NS) difference at lower speeds (3 and 4 $\text{m}\cdot\text{s}^{-1}$, NS; Figs. 1–4). \dot{E} was lower in drafting at 6 and 7 $\text{m}\cdot\text{s}^{-1}$ ($P < 0.001$), and there was no difference at lower speeds (NS; Table 1).

Women. F_{PROP} and C_{DA} were significantly lower in drafting at 5 and 6 $\text{m}\cdot\text{s}^{-1}$ ($P < 0.05$), but there was no difference at lower speeds (3 and 4 $\text{m}\cdot\text{s}^{-1}$ NS; Figs. 1, 2). $\dot{V}O_2$ and \dot{E} were lower in drafting only at 6 $\text{m}\cdot\text{s}^{-1}$ ($P < 0.05$) with no difference at lower speeds (NS; Fig. 3, Table 1). Finally, the difference in HR was non-significant between leading and drafting at all speeds (Fig. 4).

With versus Without Wind

There were significant differences ($P < 0.05$) observed between the test condition without wind versus the two test conditions with wind. Differences were found in F_{PROP} , $\dot{V}O_2$,

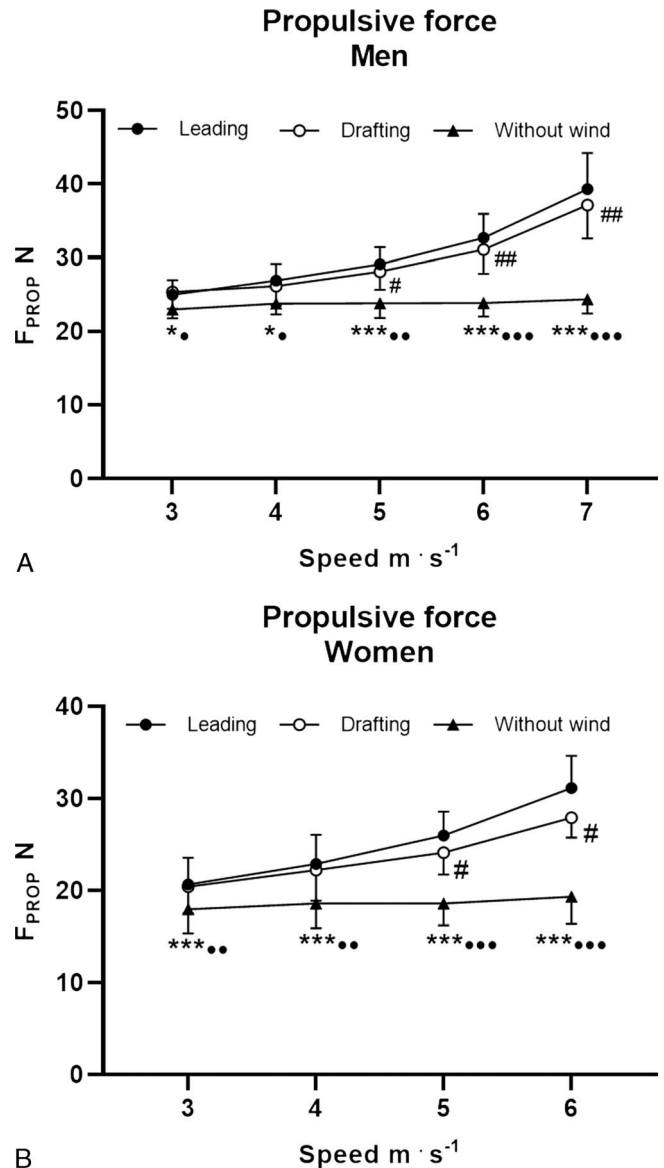


FIGURE 1—Results of propulsive force for the three test conditions: leading, drafting, and without wind. Mean and SD for the male (A) and female (B) skiers. Leading vs drafting: # $P < 0.05$, ## $P < 0.01$; without wind vs leading, * $P < 0.05$, *** $P < 0.001$; without wind vs drafting, • $P < 0.05$, •• $P < 0.01$, ••• $P < 0.001$.

and \dot{E} at all testing speeds for both genders, whereas HR and RQ were different at high speeds ($P < 0.05$) but not at low speeds (NS; Figs. 1, 3, 4; Table 1). Some significant differences were also present for F_{N} , F_{μ} , and GE, but only to a small extent (Table 1). The results hereinafter are only reported for the tests conducted without wind versus the leading position with wind. Generally, the differences observed between the no-wind condition and the drafting position with wind were smaller in absolute terms but very similar in terms of statistical significance, as can be seen in Figures 1, 3, and 4 and Table 1. A check was made for any interaction effect between front and rear positions versus the wind and no-wind conditions. The results showed no interaction effect on $\dot{V}O_2$ for either men ($P = 0.46$) or women ($P = 0.98$).

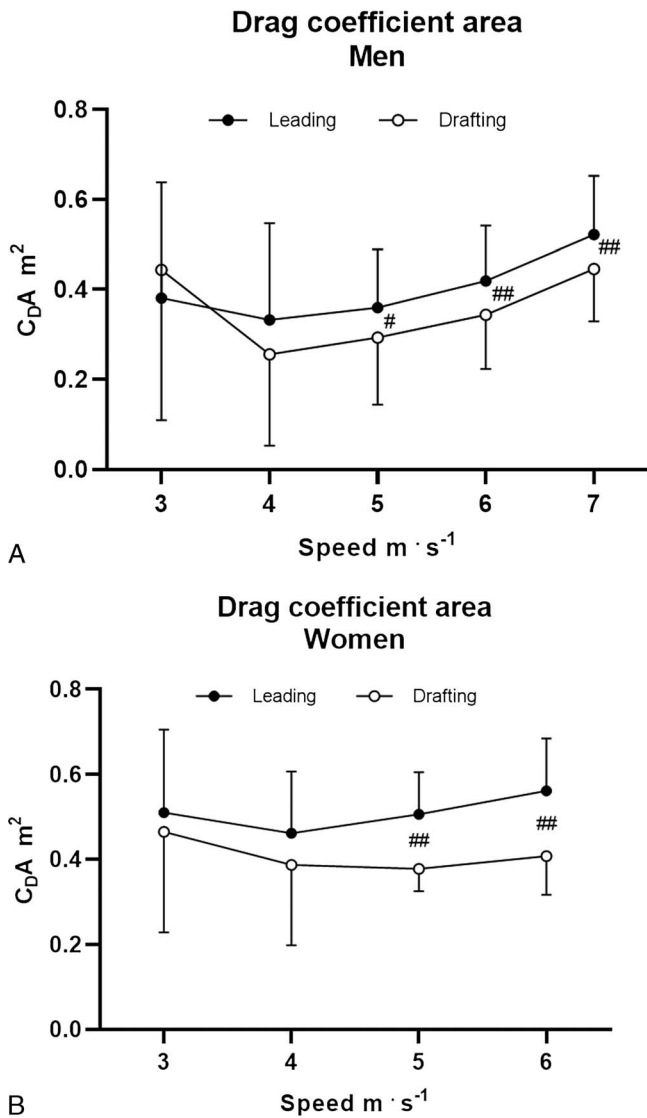


FIGURE 2—Results of drag coefficient area for the two test conditions of leading and drafting. Mean and SD for the male (A) and female (B) skiers. #*P* < 0.05, ##*P* < 0.01.

Men. F_{PROP} , $\dot{V}O_2$, and \dot{E} were lower without wind compared with wind at all speeds: 3, 4, 5, 6, and 7 m·s⁻¹ (*P* < 0.05; Figs. 1, 3; Table 1). HR was lower without wind at 5, 6, and 7 m·s⁻¹ (*P* < 0.01), whereas the difference was nonsignificant at lower speeds (NS; Fig. 4). RQ was lower without wind at 6 and 7 m·s⁻¹ (*P* < 0.01), whereas no differences were observed at lower speeds (NS; Table 1). F_N and $F\mu$ were higher without wind at 6 m·s⁻¹ (*P* < 0.01), whereas no differences were found at the other speeds (NS). Finally, GE did not change with or without wind at any speed (NS; Table 1).

Women. F_{PROP} , $\dot{V}O_2$, \dot{E} , and HR were lower without wind compared with wind at all tested speeds: 3, 4, 5, and 6 m·s⁻¹ (*P* < 0.05; Figs. 1, 3, 4; Table 1). RQ was lower and F_N and $F\mu$ were higher without wind at 6 m·s⁻¹ (*P* < 0.05), whereas no differences were observed at lower speeds (NS; Table 1). Finally, GE was lower without wind at 4 m·s⁻¹ (*P* < 0.05), whereas no differences were found at other speeds (NS; Table 1).

DISCUSSION

The aim of this study was to provide knowledge of aerodynamic drag and the advantages of drafting in xc-skiing based on measurements taken in a standardized, yet realistic, laboratory environment. The main findings were that 1) drafting behind another skier has a decisive positive effect on a skier's propulsive force, drag area, oxygen uptake, metabolic rate, and HR at high speeds, but not at lower speeds, and 2) the comparison between wind and no-wind test conditions (as in normal testing indoors on treadmill) resulted in greater differences in propulsive force, oxygen uptake, metabolic rate, and HR, with definitive lower values without wind recorded even at lower speeds.

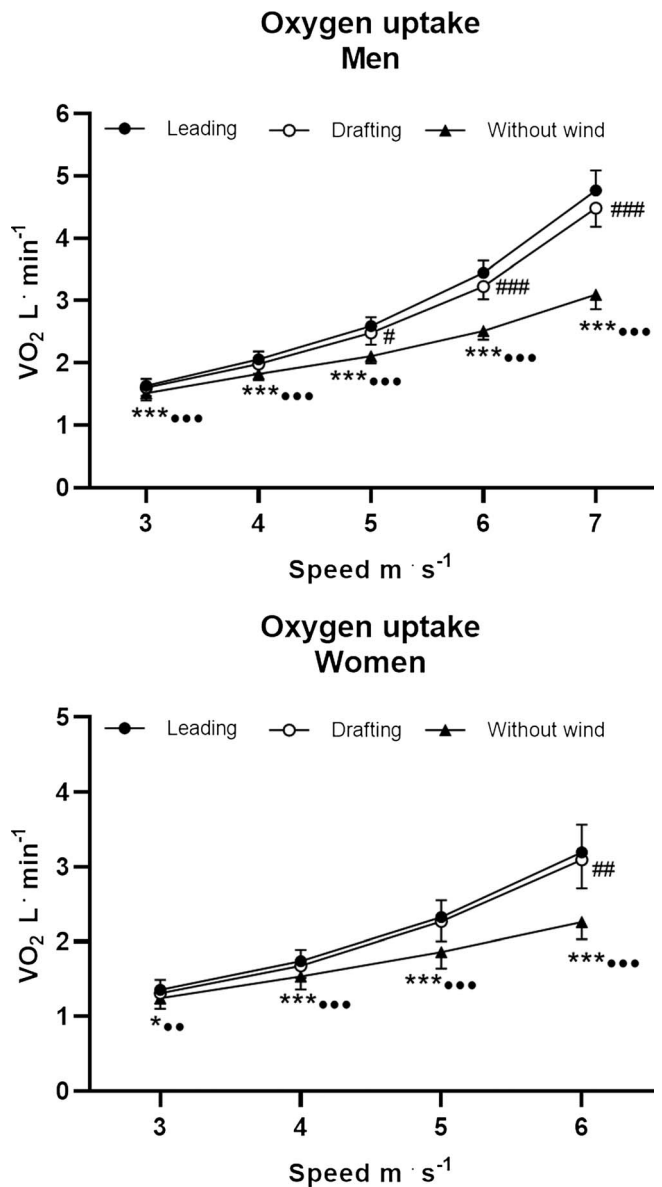


FIGURE 3—Results of oxygen uptake for the three test conditions: leading, drafting, and without wind. Mean and SD for the male (A) and female (B) skiers. Leading vs drafting: #*P* < 0.05, ##*P* < 0.01, ###*P* < 0.001; without wind vs leading: **P* < 0.05, ****P* < 0.001; without wind vs drafting: ***P* < 0.01, ****P* < 0.001.

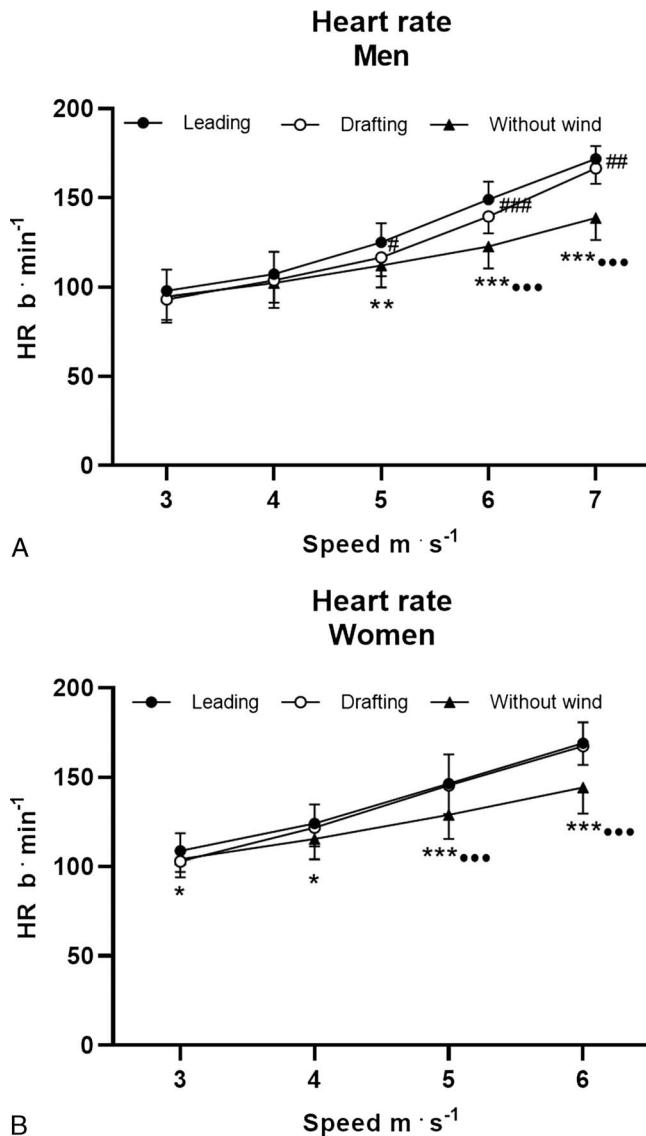


FIGURE 4—Results of HR for the three test conditions: leading, drafting, and without wind. Mean and SD for the male (A) and female (B) skiers. Leading vs drafting: # $P < 0.05$, ### $P < 0.01$, #### $P < 0.001$; without wind vs leading: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$; without wind vs drafting: *** $P < 0.001$.

Leading versus drafting. The results for leading and drafting positions showed that the three highest speeds for the male skiers (5, 6, and 7 m·s⁻¹) resulted in 1–2.2 N lower F_{PROP} (3%–6%), 0.07 m² (~17%) lower C_{DA} , 0.1–0.3 L·min⁻¹ (4%–6%) lower $\dot{V}O_2$, 0.5–1.5 (4%–6%) kcal·min⁻¹ lower \dot{E} , and 8–6 bpm (7%–3%) lower HR in the drafting position ($P < 0.05$). As regards HR, this is a similar result to that was observed by Bilodeau et al. (10,11) at similar speeds between leading and drafting skiers when skiing on snow. For the female skiers, drafting resulted in 1.9–3.2 N (7%–10%) lower F_{PROP} and 0.13–0.15 m² (~26%) lower C_{DA} , at the two highest speeds (5 and 6 m·s⁻¹), whereas $\dot{V}O_2$ and \dot{E} were only statistically different at 6 m·s⁻¹, with a 0.1 L·min⁻¹ (3%) lower $\dot{V}O_2$ and 0.7 kcal·min⁻¹ (4%) lower \dot{E} measured in the drafting position. Surprisingly, there was no difference in HR between drafting and leading at any speed for the female skiers.

There was no difference in RQ and GE at any speed for either gender. Also, there was no difference in F_N and $F_{\mu R}$ between leading and drafting, which shows that the effects of drafting were due to different F_D and not biased by different rolling resistance. A trend ($P < 0.10$) toward a lower \dot{E} in drafting could be seen at 4 m·s⁻¹ ($P = 0.058$) and 5 m·s⁻¹ ($P = 0.053$) in the men's part of the study.

The average racing speed in the classical style and longer races in the World Cup and Visma Ski Classics is similar to the two highest testing speeds for each gender in this study. For men, the effect of drafting behind another skier, when using the DP technique, is equal to a saving in $\dot{V}O_2$ and \dot{E} of 0.25 L·min⁻¹ and 1.3 kcal·min⁻¹ (6%), which corresponds to a difference in speed of 0.2 m·s⁻¹ (0.72 km·h⁻¹). For a male skier with a slightly lower racing speed than the top competitors, this means that through drafting, he can ski as fast as those without drafting travel at 0.2 m·s⁻¹ higher racing speed. For the longest ski race in the Visma Ski Classics (Vasaloppet, 90 km), this means a time saving of 7 min, which in distance corresponds to 2.8 km. For women, the effects of drafting on $\dot{V}O_2$ and \dot{E} are 0.1 L·min⁻¹ and 0.5 kcal·min⁻¹, which corresponds to a difference in racing speed of 0.1 m·s⁻¹ (0.36 km·h⁻¹). If the distance is the same as for men, the women's longer competition time, because of lower racing speed, compensates in part for the lower energy gain per unit of time. In Vasaloppet, the time saving will be slightly over 4 min, which in distance corresponds to 1.6 km.

For skiers with similar capacity and racing speed, the lower force and energy requirement during drafting means that a drafting skier can handle a sudden increase in speed better and has a greater chance of gaining an advantage from a speed increase than the leading skier. The drafting skier will also recover better after a temporary increase in speed through the continued lower force and energy requirement and thus lower central and peripheral (muscle) fatigue (25,26). Because the RQ was equivalent, it also means that a similar relative amount of glycogen can be saved to be used in the crucial stages of a long distance competition. Many races are decided by a sprint between skiers to the finish. Having a larger residual layer of glycogen and lower fatigue (27) than opponents can be crucial to winning a race under such circumstances, and this can be achieved through the lower aerodynamic drag and energy requirements of drafting.

It should be noted that the results from this study apply in nonwindy conditions, where the aerodynamic drag only consists of the headwind that arises from the skiers' traveling speed. In windy conditions, when the wind is in line with the headwind, the positive effects of drafting will be even greater. An additional wind of, for example, half the air velocity of that which hits the skier in no-wind conditions will likely double the positive effects of drafting at racing speeds. As can be seen in Figure 1, F_{PROP} increased exponentially for the two wind conditions. This is due to the squared velocity factor, confirming that equation 5 was valid in the experiments.

An extra test (results not shown here) was carried out in which one of the shortest female skiers (1.57 m) taking part in the study drafted behind one of the tallest male skiers (1.88 m). This test showed that the female skier doubled her

TABLE 1. Results of the skiers' F_N , F_M , RQ, \dot{E} , and GE for the different speeds and test conditions (mean \pm SD).

Variable	Unit	Speed, m·s ⁻¹	Men			Women		
			Leading	Drafting	Without Wind	Leading	Drafting	Without Wind
F_N	N	3	762 \pm 89	773 \pm 71	772 \pm 87	637 \pm 76	637 \pm 72	654 \pm 67
		4	765 \pm 91	773 \pm 73	770 \pm 93	639 \pm 75	635 \pm 74	644 \pm 63
		5	762 \pm 95	772 \pm 71	774 \pm 88	635 \pm 72	635 \pm 76	649 \pm 68
		6	758 \pm 86	768 \pm 69	777 \pm 79**	626 \pm 71	632 \pm 78	639 \pm 75**
		7	765 \pm 46	761 \pm 68	775 \pm 76			
F_M	N	3	19.0 \pm 2.2	19.3 \pm 1.8	19.3 \pm 2.2	15.6 \pm 1.9	15.8 \pm 1.7	16.4 \pm 1.7
		4	19.1 \pm 2.3	19.3 \pm 1.8	19.3 \pm 2.3	16.1 \pm 1.7	15.4 \pm 1.5	15.9 \pm 1.5
		5	19.1 \pm 2.4	19.3 \pm 1.8	19.4 \pm 2.2	16.0 \pm 1.6	15.9 \pm 2.0	16.0 \pm 1.7
		6	18.9 \pm 2.2	19.2 \pm 1.7	19.4 \pm 2.0**	15.6 \pm 1.8	15.8 \pm 1.9	16.0 \pm 1.9**
		7	19.1 \pm 1.1	19.0 \pm 1.7	19.4 \pm 1.9			
RQ		3	0.82 \pm 0.04	0.82 \pm 0.05	0.82 \pm 0.06	0.82 \pm 0.04	0.82 \pm 0.05	0.82 \pm 0.04
		4	0.83 \pm 0.03	0.84 \pm 0.04	0.83 \pm 0.04	0.83 \pm 0.06	0.86 \pm 0.04	0.83 \pm 0.04
		5	0.86 \pm 0.03	0.88 \pm 0.03	0.85 \pm 0.04*	0.89 \pm 0.06	0.91 \pm 0.07	0.85 \pm 0.07
		6	0.92 \pm 0.04	0.91 \pm 0.03	0.86 \pm 0.04****	0.97 \pm 0.07	0.94 \pm 0.05	0.87 \pm 0.05*,**
		7	0.99 \pm 0.04	0.98 \pm 0.03	0.88 \pm 0.04***,***			
\dot{E}	kcal·min ⁻¹	3	7.87 \pm 0.51	7.73 \pm 0.05	7.31 \pm 0.57***,***	6.54 \pm 0.64	6.32 \pm 0.65	6.00 \pm 0.67***,***
		4	9.96 \pm 0.60	9.64 \pm 0.75	8.83 \pm 0.50***,***	8.40 \pm 0.68	8.16 \pm 0.73	7.41 \pm 0.81***,***
		5	12.63 \pm 0.70	12.15 \pm 0.94	10.25 \pm 0.57***,***	11.41 \pm 1.08	11.17 \pm 1.23	9.03 \pm 1.03***,***
		6	17.02 \pm 0.91	15.92 \pm 1.01###	12.27 \pm 0.69***,***	16.02 \pm 1.83	15.37 \pm 1.77#	11.04 \pm 1.03***,***
		7	23.98 \pm 1.56	22.53 \pm 1.53###	15.16 \pm 1.20***,***			
GE	%	3	13.6 \pm 1.3	14.2 \pm 1.5	13.6 \pm 1.1	13.6 \pm 1.4	14.0 \pm 1.2	13.1 \pm 1.5*
		4	15.6 \pm 1.7	15.7 \pm 2.0	15.5 \pm 1.2	15.8 \pm 1.4	15.9 \pm 1.7	14.6 \pm 1.3**
		5	16.8 \pm 1.7	16.8 \pm 2.0	16.9 \pm 1.5	16.6 \pm 1.2	16.0 \pm 1.0	15.1 \pm 1.6
		6	16.9 \pm 1.8	17.1 \pm 2.1	17.0 \pm 1.0	16.8 \pm 1.2	15.8 \pm 1.0	15.1 \pm 1.7
		7	16.9 \pm 2.1	17.0 \pm 2.3	16.5 \pm 1.3			

Without wind vs leading: * P < 0.05, ** P < 0.01, *** P < 0.001; without wind vs drafting: * P < 0.05, ** P < 0.01, *** P < 0.001; drafting vs leading: # P < 0.05, ### P < 0.001.

advantage from drafting, an increase in $\dot{V}O_2$ saving from 5% to 10%, compared with when she was drafting behind one of the female skiers. In some national and international races, such as Vasaloppet, women and men can ski parts of the race together, and this result shows that the effects of a female skier drafting behind a larger male skier can double the effects of drafting. In comparison to skiing alone, skiing behind a female or male skier should make a huge difference in metabolic rate or racing speed. In fact, in Vasaloppet 2014, a male former top xc-skier was hired as a leader by one of the top female skiers who drafted behind him during the race (28,29).

In contrast to oxygen cost and metabolic rate, there was no difference in GE between drafting and leading situations or wind and no-wind conditions, except at low speeds for the female athletes in the study. The differences obtained in propulsive power were followed by corresponding relative changes in metabolic rate. The small trend toward an increased GE as a function of speed is not real. It is because the measured (gross) metabolic rate includes the skiers resting metabolic rate, which has different consequences for the calculations of GE at different power, which has also been pointed out by Ettema and Lorås (30).

In Ainegren and Jonsson (13), the average C_{DA} (0.44 m²) was measured on a force plate using a skier standing in different static positions, representing the ROM of the DP technique. Although static postures are assumed to cause lower F_D and C_{DA} than dynamic ROM during skiing (12), the C_{DA} in that study was similar to this one. The C_{DA} was ~0.4–0.5 m² for both men and women in the leading position and significantly lower at racing speed for the drafting position (0.3–0.4 m²). In Spring et al. (3), the C_{DA} was 0.65 m² in the upright position and 0.27 m² in the semisquatted position. The ROM in DP contains similar positions, and an average value in the mentioned study lands on the same C_{DA} as in this study.

With versus without headwind. The results between the wind and no-wind conditions show that aerodynamic drag, even at far below racing speeds, has a significant effect on skiers' oxygen uptake and metabolic rate. When simulating outdoor race conditions with a virtual environment, using the same speeds and track profile as outdoors, blood lactate and HR were higher during outdoor skiing, especially at high racing speeds (31). The greater technique changes and curves outdoors may explain some of the difference, but most likely, it was the absence of wind on the treadmill that was the major factor in making skiing easier on the treadmill. Because most studies conducted on xc-skiers are carried out using roller skis on a treadmill, where aerodynamic drag is normally absent, the difference between wind and no wind conditions can be used to add F_{RES} from increased rolling resistance and/or treadmill inclination to compensate for the lack of aerodynamic drag. A similar influence on the cardiovascular system can probably be achieved, but the influence on skiing technique from such a change is not known and needs further examination.

Perspectives and practical applications. The results of this study show that aerodynamic drag and drafting are important factors for performance in DP during xc-skiing. The advantage of drafting will change depending on prevailing wind and wind direction, friction between skis and snow, race distance and racing speed, and type of terrain. Skiers also have different body sizes and performance levels. Competitions differ between common start and interval start procedures, often carried out over several laps on a shorter course. In common starts, slower skiers have the opportunity to use drafting throughout the race. Also, skiers with the same capacity can alternate between leading and drafting, which means that they all ski at a consistently higher speed and benefits from drafting. In interval start races, faster skiers can catch up with slower skiers

who started before them, allowing the slower skiers to take up a drafting position and ski at a higher speed, and thus giving them the opportunity for a better final position in the race. All these factors should be considered when devising a skier's tactical plan for an upcoming competition.

CONCLUSIONS

The questions around aerodynamic drag and the advantages of drafting during xc-skiing when using DP have been the main focus of this study. At higher speeds, the positive effects of drafting behind a skier during DP were obvious and resulted in a significantly lower propulsive force, aerodynamic drag, drag coefficient, oxygen uptake, metabolic rate, and HR. At lower speeds,

those aspects did not play an important role. These results are relevant when considering the tactical aspects of cross-country ski racing, and knowledge of such effects may have a positive impact on a skier's race results in the future. It is notable that at all speeds, the wind versus no-wind condition showed that wind caused a pronounced increase in the dependent variables.

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