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ABSTRACT

Purpose: To investigate the effects of aerodynamic drag and drafting on propulsive force (F_{PROP}), drag area (C_DA), oxygen cost ($\dot{V}O_2$), 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:** 10 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; 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; men, 3 to 7 $m \cdot s^{-1}$; women 3 to 6 $m \cdot s^{-1}$. **Results:** Drafting resulted in significantly ($P<0.05$) lower F_{PROP}, C_DA, $\dot{V}O_2$ and $\dot{E}$, compared to leading, for both genders at racing speed but not at lower speeds, while HR was only affected for the male skiers at racing speed. The test without wind resulted in significantly lower F_{PROP}, $\dot{V}O_2$ and $\dot{E}$ at all tested speeds compared to the tests with wind present, while 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, $\dot{V}O_2$, $\dot{E}$ 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

INTRODUCTION

Cross-country skiing (xc-skiing) includes elements of classical and freestyle skiing, each with several sub-techniques, 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 depends 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, e.g., 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. While body mass stays constant, the frontal area, length, and height, both in line and perpendicular to the flow, and shape varies when the body segments move in relation to each other at different frequencies and range of motion, depending on sub-technique, travelling 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-minute rest, each pair of skiers repeated the same skiing style and course but changed positions. This resulted in a 7 and 9 $b \cdot min^{-1}$ 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_DA), 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 semi-squatting 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, while 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_DA, 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 2D camera placed in front of the skier. The results showed large differences in C_DA, 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 3D camera. The results generally showed slightly lower values for A compared to 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 sub-techniques currently is double poling (DP). Sometimes DP is the sole sub-technique 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 heart rate during roller skiing on a treadmill in a wind tunnel using the double poling technique. Since 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 25.4 ± 5.1 yr., body height and weight 1.84 ± 0.05 m and 80.5 ± 5.0 kg, $\dot{V}O_2$ max 5.8 ± 0.6 L · min^{-1}, HR max 192.7 ± 7.3 b · min^{-1}; Women: n = 10, age 26.3 ± 4.2 yr., body height and weight 1.66 ± 0.06 m and 63.0 ± 6.6 kg, $\dot{V}O_2$ max 3.9 ± 0.5 L · min^{-1}, HR max 191.9 ± 9.4 b · min^{-1}), 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 double poling 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, i.e., 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 while the speed was increased from 3 to 7 $m \cdot s^{-1}$ (women 3 to 6 $m \cdot s^{-1}$) in 1 $m \cdot s^{-1}$ increments every 4^{th} minute without a break between the different speeds. Due to 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 $m \cdot s^{-1}$, n = 8). The order of the three test situations was evenly distributed between the skiers. A 10-minute warm-up period was conducted at the upcoming initial testing speed. The skiers had a 30- to 40-minute break between the testing situations while their pulmonary ventilation and gas concentrations were measured using Douglas Bags, allowing them to recover from muscle fatigue and excess post-exercise 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 Eq. 1.

$$F_{PROP} = F_{RES} \qquad (1)$$

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

$$F_{PROP} = F_R \cos \alpha \qquad (2)$$

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, while F_{RES} for the test condition without wind only included $F\mu_R$. Therefore, the F_D for the wind conditions, F_D leading and F_D drafting, were calculated as shown in equations 3 and 4, respectively.

$$F_D\ leading = F_{PROP}\ leading - F_{PROP}\ no\ wind \qquad (3)$$

$$F_D\ drafting = F_{PROP}\ drafting - F_{PROP}\ no\ wind \qquad (4)$$

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

$$C_D A = \frac{2F_D}{\rho v^2} \qquad (5)$$

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 ($kg \cdot m^{3-1}$) is the air density and v ($m \cdot s^{-1}$) is the resulting headwind due to the skiers travelling speed.

The rolling resistance is expressed as

$$F_\mu = \mu_R\ F_N = \mu_R\ mg \cos\alpha \qquad (6)$$

where Fμ (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, and 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 ($m \cdot s^{2-1}$) and α is the inclination of the substrate. In this study, the inclination of the treadmill was 0 degrees.

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 ± 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 heart rate monitor (Polar Electro OY, Esbo, Finland) and Douglas Bag system with an extended hose length as described in an earlier paper (16). The content of the bags' expired gas fractions were measured using O_2 and CO_2 gas analyzers (AEI Technologies Inc, Pittsburg, USA), while 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 ± 0.2 °C, 41 ± 10%, and 1.17 ± 0.01 kg $\cdot$ m$^{3-1}$ during the measurements. The skiers' ventilation and oxygen uptake ($\dot{V}O_2$) were then calculated according to STPD 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 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, P_{INT} (W) 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 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 as for the other roller skis. The influence of different F_N (200 to 500 N in 100 N increments) and speeds (3 to 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 non-extreme weather and snow conditions (20, 21). The $F\mu$ 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 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 paper (22).

The F_{PROP} of the poles were measured (400 Hz) with a custom-made, lightweight (70 g each) pole force system (University of Salzburg, Austria). Uniaxial strain gauge load cells (ME-systems, 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 ± 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., China). The videos were recorded at 120 fps average frame rate in variable frame rate mode and with a 1920 x 1080 pixel resolution. The videos were re-encoded 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.

Due to 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, Illinois, USA). 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 $F\mu$, while 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, Fμ, RQ, and GE at any speed for men or women.

Men. F_{PROP}, C_DA, $\dot{V}O_2$ and HR where significantly lower in drafting at 5 m · s^{-1}, 6 m · s^{-1} and 7 m · s^{-1} (P<0.05) and there was a non-significant (NS) difference at lower speeds (3 m · s^{-1} and 4 m · s^{-1}, NS), see Figures 1-4. $\dot{E}$ was lower in drafting at 6 m · s^{-1} and 7 m · s^{-1} (P<0.001) and there was no difference at lower speeds (NS), see Table 1.

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

With versus without wind

There were significant differences ($P<0.05$) observed between the test condition without wind vs. the two test conditions with wind. Differences were found in F_{PROP}, $\dot{V}O_2$ and $\dot{E}$ at all testing speeds for both genders, while HR and RQ were different at high speeds ($p<0.05$) but not at low speeds (NS), see Figures 1, 3 and 4 and Table 1. Some significant differences were also present for F_N, Fμ, and GE, but only to a small extent (Table 1). The results below are only reported for the tests conducted without wind versus the leading position with wind. Generally, the differences observed between the no-wind condition versus 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 ($P=0.98$).

Men. F_{PROP}, $\dot{V}O_2$ and $\dot{E}$ was lower without wind compared to with wind at all speeds: 3 $m \cdot s^{-1}$, 4 $m \cdot s^{-1}$, 5 $m \cdot s^{-1}$, 6 $m \cdot s^{-1}$ and 7 $m \cdot s^{-1}$ ($P<0.05$), see Figure 1, 3 and Table 1. HR was lower without wind at 5 $m \cdot s^{-1}$, 6 $m \cdot s^{-1}$, and 7 $m \cdot s^{-1}$ ($P<0.01$), while the difference was non-significant at lower speeds (NS); see Figure 4. RQ was lower without wind at 6 $m \cdot s^{-1}$ and 7 $m \cdot s^{-1}$ ($P<0.01$), while no differences were observed at lower speeds (NS), see Table 1. F_N and Fμ were higher without wind at 6 $m \cdot s^{-1}$ ($P<0.01$), while no differences were found at the other speeds (NS). Finally, GE did not change with or without wind at any speed (NS); see Table 1.

Women. F_{PROP}, $\dot{V}O_2$, $\dot{E}$ and HR was lower without wind compared to with wind at all tested speeds: 3 $m \cdot s^{-1}$, 4 $m \cdot s^{-1}$, 5 $m \cdot s^{-1}$, and 6 $m \cdot s^{-1}$ ($P<0.05$), see Figure 1, 3 and 4 and Table 1. RQ was lower and F_N and $F\mu$ higher without wind at 6 m · s^{-1} (P<0.05), while no differences were observed at lower speeds (NS), see Table 1. Finally, GE was lower without wind at 4 m · s^{-1} (P<0.05), while no differences were found at other speeds (NS); see 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 heart rate at high speeds, but not at lower speeds, and 2) the comparison between wind versus no-wind test conditions (as in normal testing indoors on treadmill) resulted in greater differences in propulsive force, oxygen uptake, metabolic rate and heart rate, with definitive lower values without wind recorded even at lower speeds.

Leading vs. 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 m^2 (~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 b · min^{-1} (7-3%) lower HR in the drafting position (P<0.05). As regards HR, this is a similar result as was observed by Bilodeau (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 m^2 (~26%) lower C_DA, at the two highest speeds (5 and 6 m · s^{-1}), while $\dot{V}O_2$ and $\dot{E}$ was 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 ($P<0.10$) towards 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 double poling 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 who 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 minutes, which in distance corresponds to 2.8 km. For women, the effect 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, due to 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 minutes, 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). Since 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 non-windy conditions, where the aerodynamic drag only consists of the headwind that arises from the skiers' travelling 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, e.g., 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 advantage from drafting, an increase in $\dot{V}O_2$ saving from 5 to 10%, compared to 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 gross efficiency 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 towards 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 (30).

In Ainegren (13), the average C_DA (0.44 m^2) was measured on a force plate using a skier standing in different static positions, representing the range of motion (ROM) of the double poling 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 m^2 for both men and women in the leading position and significantly lower at racing speed for the drafting position (0.3-0.4 m^2). In Spring et al. (3), the C_DA was 0.65 m^2 in the upright position and 0.27 m^2 in the semi squatted position. The ROM in double poling 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 vs. no-wind conditions shows 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 heart rate 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. Since 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 vs. 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 double poling 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 cross-country skiing when using double poling have been the main focus of this study. At higher speeds, the positive effects of drafting behind a skier during double poling were obvious and resulted in a significantly lower propulsive force, aerodynamic drag, drag coefficient, oxygen uptake, metabolic rate and heart rate. 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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Conflict of Interest

The authors declare no conflict of interest. The results of the present study do not constitute endorsement by ACSM. We declare that the results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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FIGURE LEGENDS

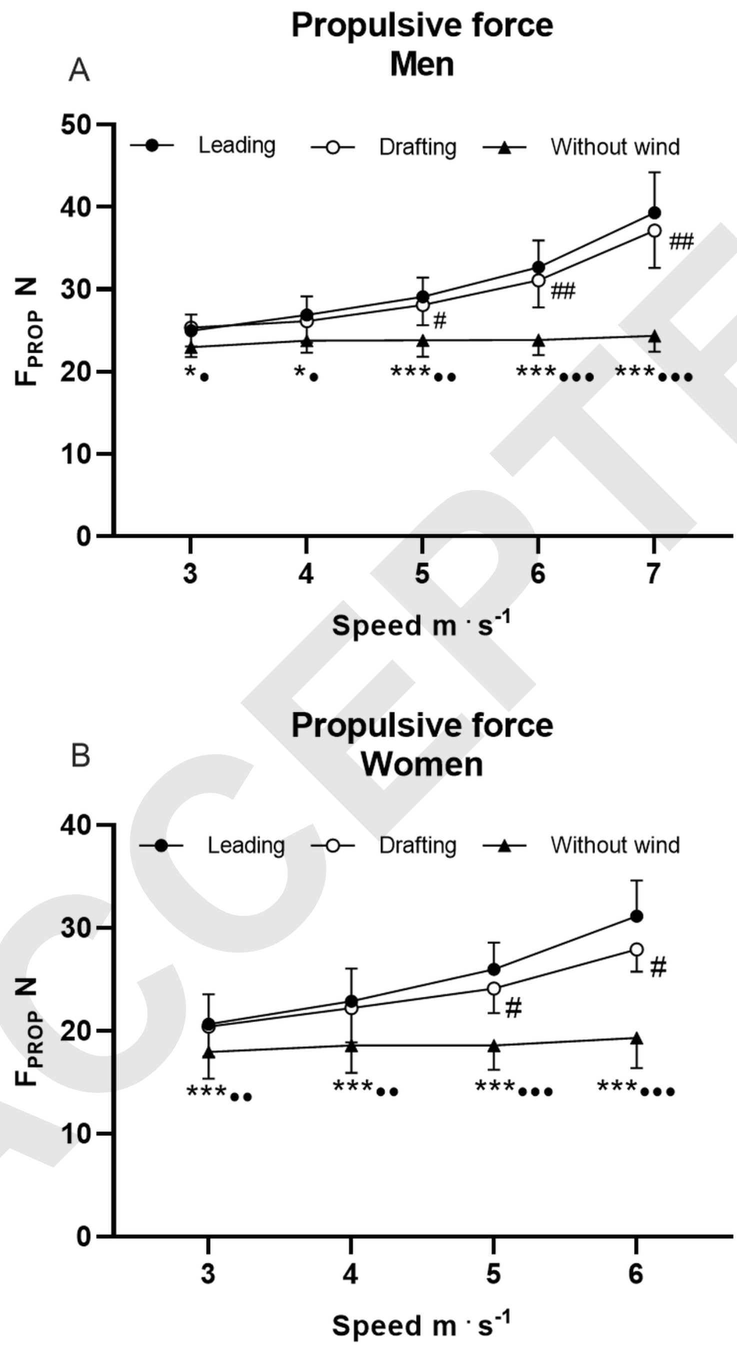
FIGURE 1. Results of propulsive force for the three test conditions: leading, drafting, and without wind. Mean and SD for the male (A) and female (B) skiers. Leading vs. drafting, #$p<0.05$, ##$p<0.01$; without wind vs. leading, *$p<0.05$, ***$p<0.001$; without wind vs. drafting, •$p<0.05$, ••$p<0.01$,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

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. #$p<0.05$, ##$p<0.01$.

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, ••$p<0.01$, •••$p<0.001$.

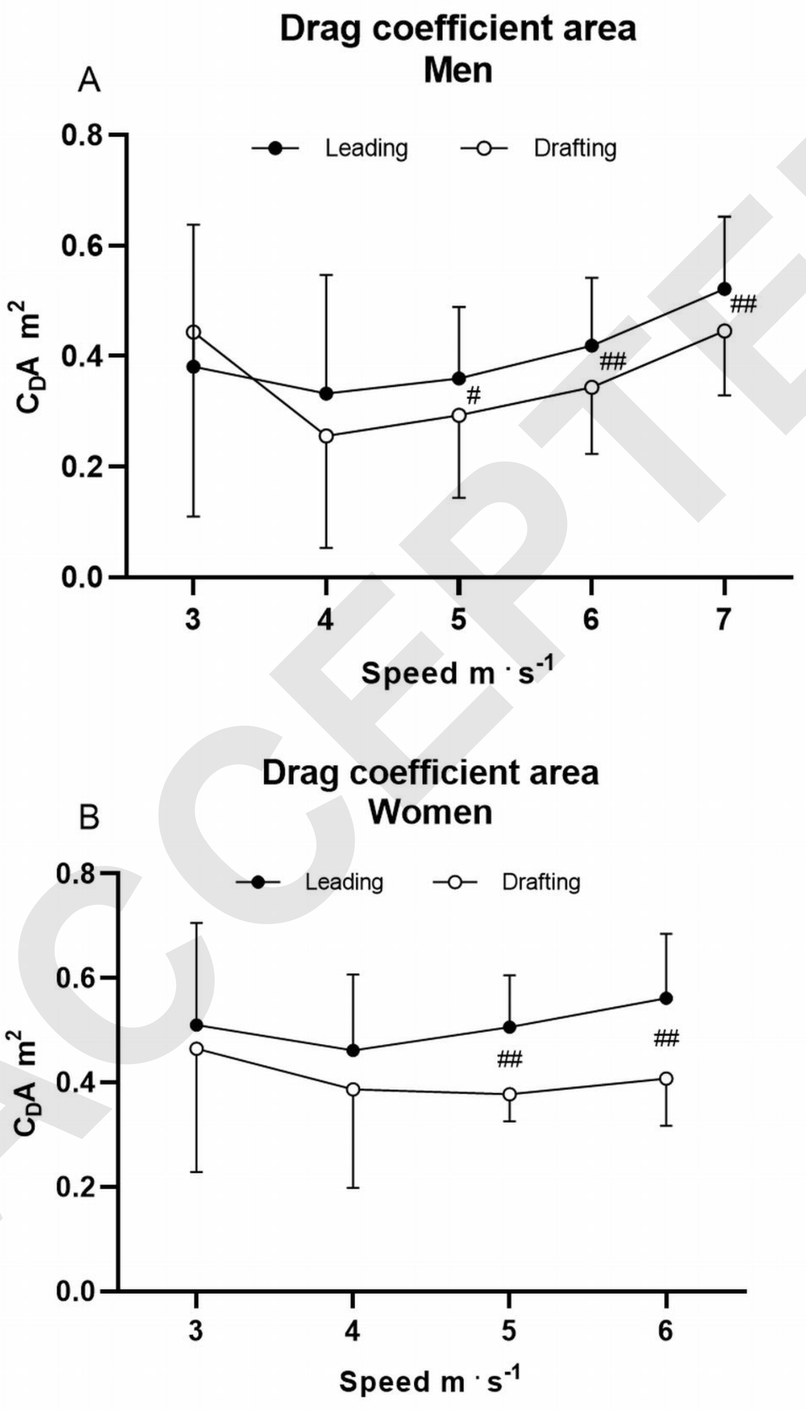
FIGURE 4. Results of heart rate for the three test conditions: leading, drafting, and without wind. Mean and SD for the male (A) and female (B) skiers. Leading vs. drafting, #$p<0.05$, ##$p<0.01$, ###$p<0.001$; without wind vs. leading, *$p<0.05$, **$p<0.01$, ***$p<0.001$; without wind vs. drafting,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

Figure 1



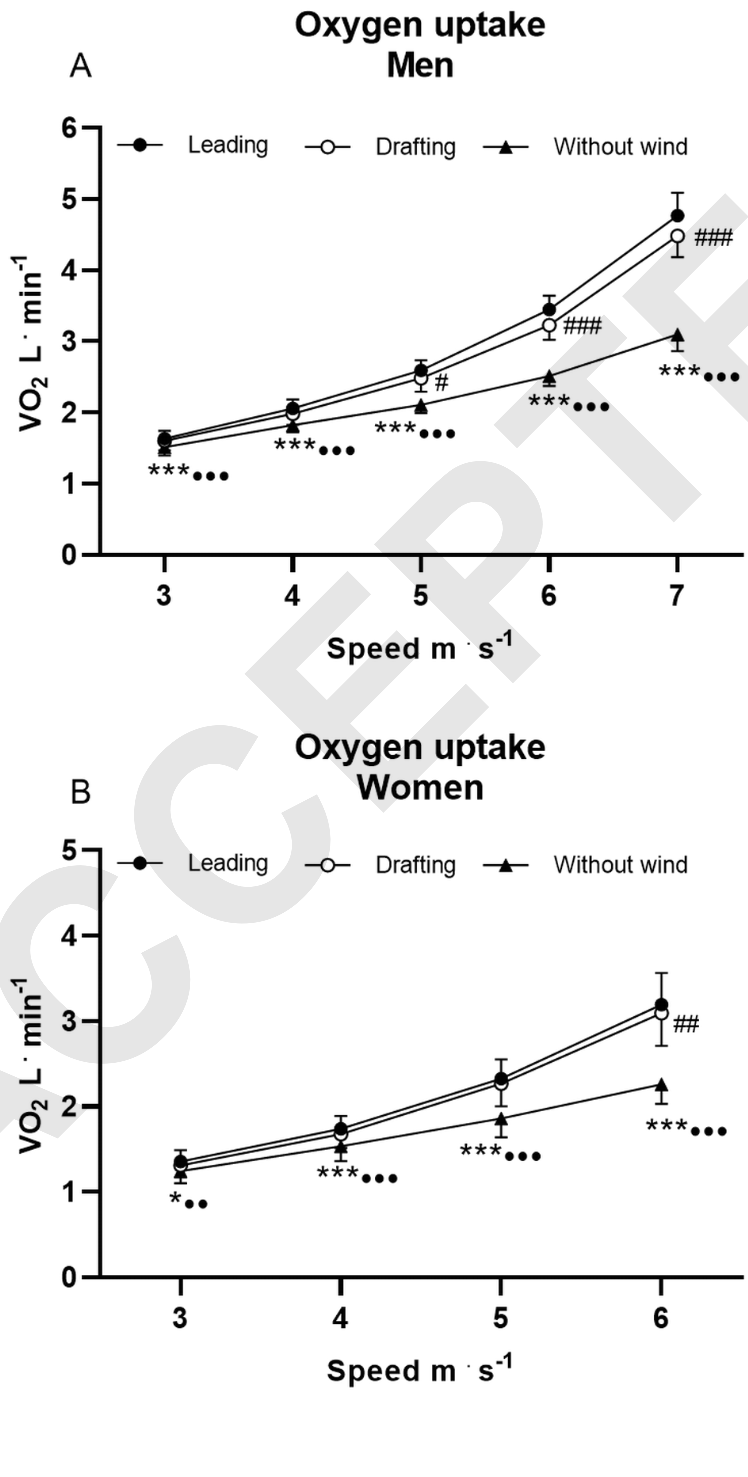
A
Propulsive force
Men
Leading
Drafting
Without wind
F_{PROP} N
Speed m · s^{-1}
B
Propulsive force
Women
Leading
Drafting
Without wind
F_{PROP} N
Speed m · s^{-1}

Figure 2



Drag coefficient area
Men
A
Leading
Drafting
0.8
0.6
0.4
0.2
0.0
C_DA m^2
#
##
##
3
4
5
6
7
Speed m · s^-1
Drag coefficient area
Women
B
Leading
Drafting
0.8
0.6
0.4
0.2
0.0
C_DA m^2
##
##
3
4
5
6
Speed m · s^-1

Figure 3



Oxygen uptake
Men
A
Leading
Drafting
Without wind
VO2 L · min-1
Speed m · s-1
Oxygen uptake
Women
B

Figure 4

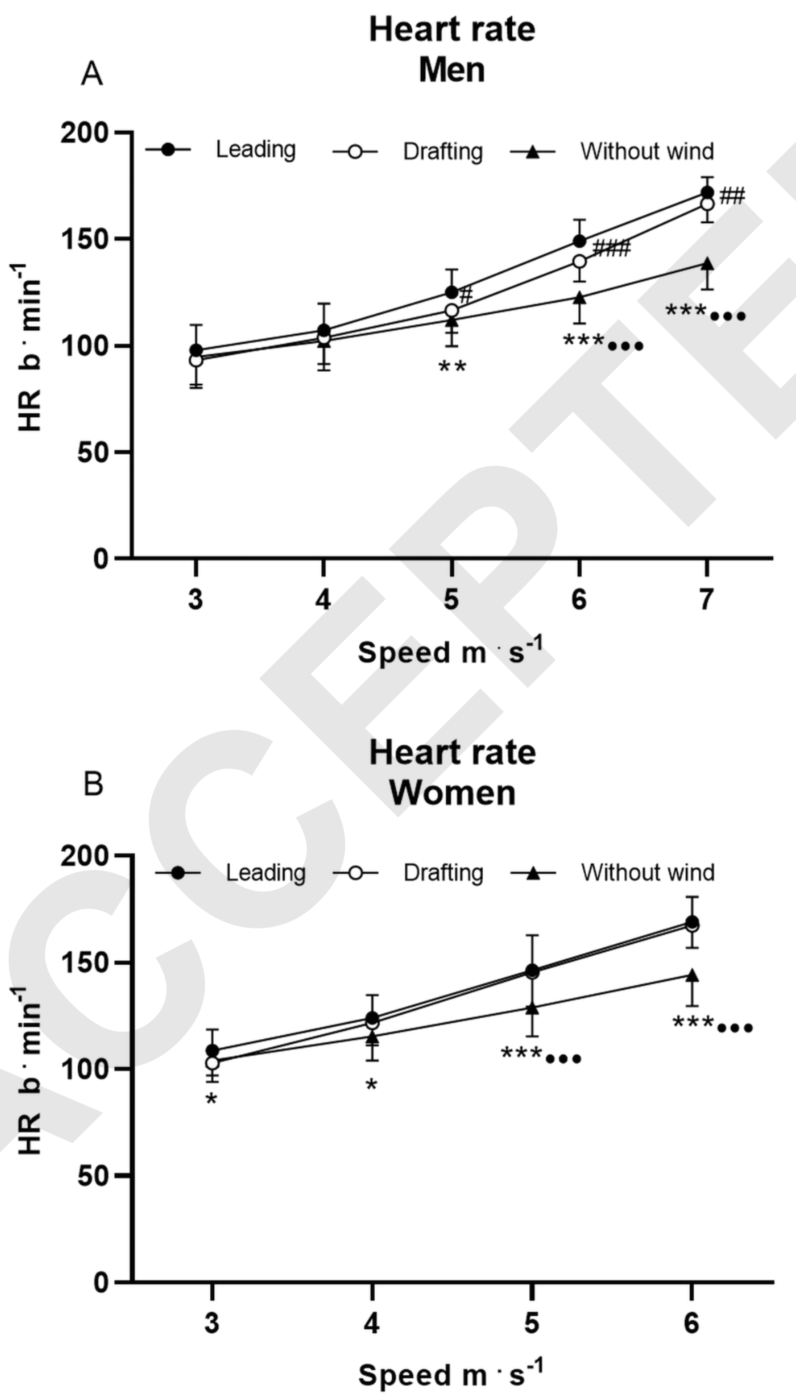

Heart rate
Men
A
Leading
Drafting
Without wind
HR b · min-1
Speed m · s-1
##
###
#
**
***•••
***•••
Heart rate
Women
B
*
*
***•••
***•••

TABLE 1. Results of the skiers' normal force (F_N), rolling resistance ($F\mu$), respiratory quotient (RQ), metabolic rate ($\dot{E}$) and gross efficiency (GE), for the different speeds and test conditions. Mean ± SD.

		Speed	Men			Women		
Variable	Unit	m/s	Leading	Drafting	Without wind	Leading	Drafting	Without wind
F_N	N	3	762 ± 89	773 ± 71	772 ± 87	637 ± 76	637 ± 72	654 ± 67
		4	765 ± 91	773 ± 73	770 ± 93	639 ± 75	635 ± 74	644 ± 63
		5	762 ± 95	772 ± 71	774 ± 88	635 ± 72	635 ± 76	649 ± 68
		6	758 ± 86	768 ± 69	777 ± 79**	626 ± 71	632 ± 78	639 ± 75**
		7	765 ± 46	761 ± 68	775 ± 76			
F_μ	N	3	19.0 ± 2.2	19.3 ± 1.8	19.3 ± 2.2	15. 6 ± 1.9	15.8 ± 1.7	16.4 ± 1.7
		4	19.1 ± 2.3	19.3 ± 1.8	19.3 ± 2.3	16.1 ± 1.7	15.4 ± 1.5	15.9 ± 1.5
		5	19.1 ± 2.4	19.3 ± 1.8	19.4 ± 2.2	16.0 ± 1.6	15.9 ± 2.0	16.0 ± 1.7
		6	18.9 ± 2.2	19.2 ± 1.7	19.4 ± 2.0**	15.6 ± 1.8	15.8 ± 1.9	16.0 ± 1.9**
		7	19.1 ± 1.1	19.0 ± 1.7	19.4 ± 1.9			
RQ		3	0.82 ± 0.04	0.82 ± 0.05	0.82 ± 0.06	0.82 ± 0.04	0.82 ± 0.05	0.82 ± 0.04
		4	0.83 ± 0.03	0.84 ± 0.04	0.83 ± 0.04	0.83 ± 0.06	0.86 ± 0.04	0.83 ± 0.04
		5	0.86 ± 0.03	0.88 ± 0.03	0.85 ± 0.04•	0.89 ± 0.06	0.91 ± 0.07	0.85 ± 0.07
		6	0.92 ± 0.04	0.91 ± 0.03	0.86 ± 0.04**•••	0.97 ± 0.07	0.94 ± 0.05	0.87 ± 0.05*••
		7	0.99 ± 0.04	0.98 ± 0.03	0.88 ± 0.04***•••			
$\dot{E}$	kCal · min^{-1}	3	7.87 ± 0.51	7.73 ± 0.05	7.31 ± 0.57***•••	6.54 ± 0.64	6.32 ± 0.65	6.00 ± 0.67**••
		4	9.96 ± 0.60	9.64 ± 0.75	8.83 ± 0.50***••	8.40 ± 0.68	8.16 ± 0.73	7.41 ± 0.81***•••
		5	12.63 ± 0.70	12.15 ± 0.94	10.25 ± 0.57***•••	11.41 ± 1.08	11.17 ± 1.23	9.03 ± 1.03***•••
		6	17.02 ± 0.91	15.92 ± 1.01###	12.27 ± 0.69***•••	16.02 ± 1.83	15.37 ± 1.77#	11.04 ± 1.03***•••
		7	23.98 ± 1.56	22.53 ± 1.53###	15.16 ± 1.20***•••			
GE	%	3	13.6 ± 1.3	14.2 ± 1.5	13.6 ± 1.1	13.6 ± 1.4	14.0 ± 1.2	13.1 ± 1.5•
		4	15.6 ± 1.7	15.7 ± 2.0	15.5 ± 1.2	15.8 ± 1.4	15.9 ± 1.7	14.6 ± 1.3*•
		5	16.8 ± 1.7	16.8 ± 2.0	16.9 ± 1.5	16.6 ± 1.2	16.0 ± 1.0	15.1 ± 1.6
		6	16.9 ± 1.8	17.1 ± 2.1	17.0 ± 1.0	16.8 ± 1.2	15.8 ± 1.0	15.1 ± 1.7
		7	16.9 ± 2.1	17.0 ± 2.3	16.5 ± 1.3			

Note: 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, #$p<0.05$, ###$p<0.001$.