Oxygen Demand, Uptake, and Deficits in Elite Cross-Country Skiers during a 15-km Race

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[1]Department of Physics, University of Oslo, Oslo, NORWAY; [2]Department of Physical Performance, Norwegian School of Sport Sciences, Oslo, NORWAY; [3]Norwegian Ski Federation, Alpine Skiing, Department of Sport Science, Oslo, NORWAY; and [4]Center for Computing in Science Education, Department of Physics, University of Oslo, Oslo, NORWAY

ABSTRACT

GLØERSEN, Ø., M. GILGIEN, D. K. DYSTHE, A. MALTHE-SØRENSSEN, and T. LOSNEGARD. Oxygen Demand, Uptake, and Deficits in Elite Cross-Country Skiers during a 15-km Race. *Med. Sci. Sports Exerc.*, Vol. 52, No. 4, pp. 983–992, 2020. **Purpose:** This study aimed to quantify the repeated oxygen deficits attained during intermittent endurance exercise by measuring oxygen consumption ($\dot{V}O_2$) and oxygen demand ($\dot{V}O_2^{dem}$) throughout a simulated roller ski race. **Methods:** Eight male elite cross-country skiers ($\dot{V}O_{2peak}$, 77.4 ± 4.4 mL·kg^{-1}·min^{-1}) raced a 13.5-km roller ski time trial on a World Cup course. On two additional days, athletes completed (i) six submaximal loads (~5 min) and ~4-min maximal trial to establish athlete-specific estimates of skiing economy, $\dot{V}O_{2peak}$, and maximal ΣO_2^{def} (MAOD); and (ii) a simulation of the time trial on a roller skiing treadmill. During the simulation, external work rate (P_{prop}) and skiing speed (v) were adjusted to match the P_{prop} and v measured during the time trial, and pulmonary $\dot{V}O_2$ was measured breath by breath. $\dot{V}O_2^{dem}$ and ΣO_2^{def} were calculated using an athlete-specific model for skiing economy throughout the treadmill simulation. **Results:** During the treadmill simulation, $\dot{V}O_2$ was on average 0.77 $\dot{V}O_{2peak}$, and active $\dot{V}O_2^{dem}$ (i.e., excluding the time in simulated downhill) was on average 1.01 $\dot{V}O_{2peak}$. The athletes repeatedly attained substantial oxygen deficits in individual uphill sections of the treadmill simulation, but the deficits were typically small compared with their MAOD (average 14%, range ~0%–50%). However, the ΣO_2^{def} summed over all periods of active propulsion was on average 3.8 MAOD. **Conclusion:** Athletes repeatedly attain substantial oxygen deficits in the uphill segments of a distance cross-country ski race. Furthermore, the total accumulated oxygen deficit of all these segments is several times higher than the athletes' MAOD. This suggests that the rapid recovery of the energy stores represented by the oxygen deficit is necessary during downhill sections, and that this might be an important determinant of distance skiing performance. **Key Words:** METABOLIC RATE, OXYGEN CONSUMPTION, ANAEROBIC CAPACITY, OXYGEN DEFICIT, CROSS-COUNTRY SKIING, PROPULSIVE POWER, INTERMITTENT EXERCISE

O ne of the most important demands of endurance sports is the ability to sustain a high metabolic rate for prolonged periods of time (1). Because energy released through aerobic oxidation is the only metabolic pathway that is sustainable over prolonged periods of time, the average rate of aerobic energy release throughout the duration of a competition is a key determinant of endurance performance (1). Energy from anaerobic pathways may also provide a substantial contribution; however, the average rate of anaerobic energy release typically decreases inversely with competition duration. Therefore, the contributions from the different energy pathways can, to a good approximation, be predicted from the competition duration for endurance sports with relatively constant exercise intensity, such as track running, swimming, and speed skating (2). The contributions of the different energy pathways are less clear for endurance sports held on courses with altering course inclination. Cycling and cross-country skiing are examples of sports where the undulating terrain dictates an uneven propulsive power distribution and metabolic energy expenditure, and where downhill sections present opportunities for partial metabolic recovery during periods of reduced propulsive demand. A key point that must be established is the conditions required for the recovery of anaerobic energy sources. Experiments from ergometer cycling or treadmill running indicate that the recovery of anaerobic work capacity is possible whenever the propulsive power output

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falls below the participant's critical power (P_c) output (3). P_c also coincides with the highest power output where steady-state metabolic conditions are achieved (4) and is therefore interpreted as the maximal sustainable aerobic rate (4–6). During exercise where mechanical efficiency cannot be considered constant, it is more appropriate to view this rate limitation as a critical rate of oxygen consumption, $\dot{V}O_{2crit}$ (4–6). In well-trained endurance athletes, this threshold typically lies between 80% and 90% of $\dot{V}O_{2max}$ (4). Therefore, in endurance sports where the anaerobic energy stores are negligible compared with the total energy requirement (i.e., duration 30 min or more), one should expect that athletes maintain an average metabolic rate close to their $\dot{V}O_{2crit}$. In addition, in sports with an uneven metabolic power distribution, the athletes choose work rates in excess of $\dot{V}O_{2crit}$—and most likely also $\dot{V}O_{2peak}$—in certain segments of the competition, thus repeatedly attaining oxygen deficits. To date, the magnitude of these oxygen deficits and the recovery of the anaerobic energy stores represented by them during less strenuous segments of the race have received relatively little attention in the literature.

Cross-country skiing is an interesting model with which to study this phenomenon because the variations in metabolic power output are very pronounced and greatly exceed the responsiveness of the cardiovascular system (7). Specifically, the metabolic power in uphill sections has been shown to be up to 110%–160% of athletes' $\dot{V}O_{2peak}$ (8,9) during distance skiing (~15 km), which is very high given the relatively long race duration (>30 min) (2). This suggests that the contribution from anaerobic energy sources during certain segments of the race is substantial. However, anaerobic capacity is traditionally not seen as a limiting factor for distance skiing performance (10), which suggests that although cross-country skiers make a substantial use of anaerobic energy pathways in a distance ski race (7–9), they probably do not come close to exhausting their anaerobic capacity in individual uphill sections. Therefore, we hypothesize that during a distance ski race, athletes will repeatedly attain substantial oxygen deficits, but that the magnitude of these deficits is small relative to the athletes' maximal oxygen deficits.

The purpose of the current study was to test this hypothesis by measuring oxygen demand and oxygen uptake in a racelike situation. This was achieved by combining a recently developed method to calculate propulsive power using global navigation satellite systems (8), laboratory measurements of skiing economy (8), and a treadmill simulation of a roller skiing time trial. These allowed us to continuously assess both oxygen demand and consumption using laboratory-grade gas analyzers during the treadmill simulation.

METHODS

Overview of experimental procedures. The participants completed three different protocols on separate days. Each test day was separated by at least 4 d, and all three tests were completed within 14–53 d. On day 1, athletes conducted a 13.5-km roller skiing field time trial on a race course similar to World Cup courses to mimic a typical 15-km cross-country skiing competition. Skiing speed and propulsive power were calculated using a combination of GNSS and inertial measurements as described in (7). On day 2, each athlete's skiing economy was assessed during six submaximal loads on a roller skiing treadmill. These measurements were used as input in a model to predict oxygen demand as a function of skiing speed and propulsive power. Day 2 also included a maximal effort 1000-m performance test to determine $\dot{V}O_{2peak}$ and maximal accumulated oxygen deficit (MAOD) (11). On day 3, the athletes completed a treadmill simulation based on their performance in the field time trial (day 1). Oxygen consumption was measured continuously during the treadmill simulation. Blood lactate concentration was measured three times during the simulation and directly after the simulation.

Participants. Eight skiers (seven cross-country skiers and one biathlete, $\dot{V}O_{2peak}$ 77.4 ± 4.4 mL·kg^{-1}·min^{-1}, mean ± SD, FIS point range of 13–117) volunteered for the study and gave their written consent to participate. The study was approved by the ethics committee at the Norwegian School of Sport Sciences, found advisable by the Norwegian Centre for Research Data, and conducted according to the Declaration of Helsinki.

Day 1: time trial. The time trial was carried out on the roller skiing course in Holmenkollen, Oslo, Norway, where the topography of the course (Fig. 1A) is similar to race courses used in competitive cross-country skiing on snow (height difference 51 m, maximum climb 32 m, and total climb 166 m). The procedure has been described in detail in a previous study (7) but is summarized here for clarity. We asked the athletes to complete a time trial consisting of three laps of 4.5 km in the shortest time possible using ski skating techniques. As part of their warm-up procedure, the athletes were instructed to complete one lap at an easy pace, which was later used to familiarize them to skiing a simulated course on the roller skiing treadmill during days 2 and 3, but were otherwise free to warm up as they would do before a regular competition. All athletes used the same model of roller skis and were equipped with position tracking devices consisting of a 10-Hz standalone GNSS module and a nine-axis inertial measurement unit (accelerometer, gyroscope, and magnetic field measurements). The weight of each athlete plus their equipment (including ski boots, roller skis, ski poles, clothing, and helmet) was measured before the warm-up procedure. A mean skiing trajectory through the course was measured using a high-end differential GNSS. Propulsive power generated for each athlete was calculated based on the combination of the measurements from the standalone GNSS receivers and inertial measurements units carried by the athletes and the highly accurate differential GNSS measurements of the course (7).

Day 2: skiing economy, $\dot{V}O_{2peak}$, and MAOD. The athletes first completed a warm-up procedure on a roller skiing treadmill simulating the warm-up lap (duration ~15 min) they completed before the field time trial. After the warm-up, they completed six different loads (~5 min with 2.5-min breaks) with varying treadmill speeds and inclinations. Exercise
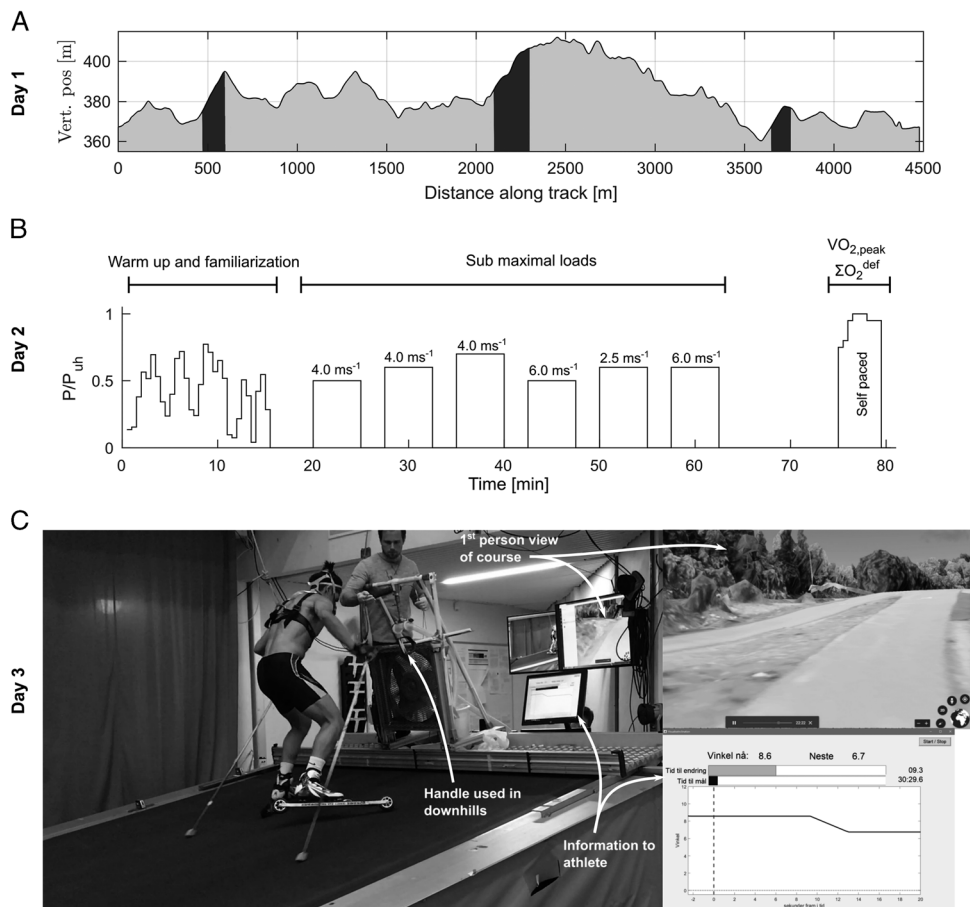
FIGURE 1—A, Height profile of the race track used during day 1. The time trial consisted of three consecutive laps. Propulsive power during the three longest uphill sections (marked in black) was used to create individually adjusted submaximal loads for day 2. B, Test protocol for day 2: the athletes completed six submaximal workloads and a self-paced 1000-m performance test. C, Picture from the treadmill simulation (day 3). The treadmill changed configuration every 20 s to match the average propulsive power and the skiing speed during day 1. In downhill terrain, the treadmill was set to level, and the athletes were instructed (visually and verbally) to hold on to the handle at the front of the treadmill.

intensity during these loads was adjusted individually for each athlete based on their performance in the field time trial and ranged from 50% to 70% of the mean propulsive power output in the three longest uphill segments during the time trial (Fig. 1A). The submaximal loads were individualized to cover moderate-to-heavy exercise intensities, where a steady-state $\dot{V}O_2$ is attainable. The choice of 50%–70% of mean uphill propulsive power was based on pilot testing, with expected oxygen demands ranging from 60% to 85% of $\dot{V}O_{2peak}$. Speed varied from 2.5 to 6.0 m·s^{-1} as shown in Figure 1B. Treadmill inclination was calculated from the speed and propulsive power using a second-order Taylor approximation and ranged from 0.8° to 6.5°. After an active rest period of approximately 10 min following the last submaximal load, the athletes completed a self-paced 1000-m maximal effort test at a 6° incline to calculate $\dot{V}O_{2peak}$ and MAOD (11). $\dot{V}O_2$ was measured during all submaximal loads and the 1000-m test; blood lactate concentration [La$^-$] and rating of perceived exertion (RPE, scale 6–20) were assessed immediately after the completion of each load. $\dot{V}O_2$ from 3 to 5 min was considered to reflect the $\dot{V}O_2^{dem}$ for the given speed and inclination during the submaximal loads.

Day 3: treadmill simulation of the field time trial.
The treadmill was programmed to simulate each athlete's performance during the field time trial described in day 1. Specifically, the treadmill was set to match the skiing speed during the field time trial, after segmentation into 20-s intervals. Inclination was calculated (using a second-order Taylor approximation) so that the average propulsive power in each segment was equal to the propulsive power generated during the field time trial. Calculated inclinations less than 0.5° were defined as downhill terrain. In this case, the treadmill's inclination was set at 0.0°, treadmill speed was set to 7 m·s^{-1}, and the athlete was instructed to assume a semisquatting position while holding a handle close to the front edge of the treadmill (Fig. 1C). For safety reasons, the treadmill's speed was restricted to ≤7.0 m·s^{-1} in all segments. Because all athletes competed at the limit of their physiological capacity during day 1, they could adjust the skiing speed during the simulation if they felt unable to complete the test. The adjustments were made in increments of 2.5% of the previously set speed and were communicated orally to the test leader. Because the simulation was segmented into 20-s intervals, adjusting the speed had no effect on the finishing

time, but it reduced (or increased) propulsive power by 2.5% from the previously set protocol. During the simulation, the athlete could see his position on the course in a first-person view using Google Earth (Googleplex, Mountain View, CA). This was achieved by creating a Keyhole Markup Language file for each athlete that contained the GNSS position measurements from the field time trial on day 1, along with their time stamps. The rate of oxygen consumption was measured during the entire simulation. Blood lactate concentration was measured once every lap during the long downhill section from about 2700 to 3600 m from the start (Fig. 1A) and directly after the simulation.

Instruments and materials. All tests were performed on Swenor Skate Long roller skis using wheel type 2 (coefficient of rolling resistance; $C_{rr} = 0.0225 \pm 0.0009$), except the 1000-m performance test on day 2. This test was completed using the same roller skis with wheel type 1, as this is a standardized test in our laboratory. The athletes used their personal ski boots and ski poles during the outdoor test. During the treadmill tests, the athletes all used the same pair of roller skis and Swix Triac 1.0 ski poles (Swix Sport, Lillehammer, Norway) with customized treadmill ferrules and of equal lengths to the poles used during day 1.

The standalone GNSS receivers (Catapult Optimeye S5, mass 67 g, firmware version 7.18) carried by the athletes have recently been validated during cross-country skiing (12) and were capable of measuring instantaneous horizontal plane speed with an accuracy of <0.1 m·s^{-1} in ideal conditions. The differential GNSS receiver (Alpha-G3T, antenna: GrAnt-G3T, Javad, San Jose, CA) used to measure the reference trajectory had an expected accuracy of <5 cm (13) when double difference ambiguities were fixed. The expected accuracy of the estimates of P_{prop} ranged from 0.1 W·kg^{-1} at the lowest skiing speeds to 0.6 W·kg^{-1} at the highest skiing speed where active propulsion was generated (7).

The rate of oxygen consumption was measured breath by breath using an automatic ergospirometry system (Oxycon Pro; Jaeger GmbH, Höchberg, Germany). Blood lactate concentration was measured using blood from capillary fingertip samples (Biosen C-line, EKF diagnostic GmbH, Magdeburg, Germany). Both the lactate analyzer and the ergospirometry system were calibrated according to the manufacturers' specifications. Directly after the simulation on day 3, the flow turbine was calibrated again to check whether sputum had congested the turbine. The calibration factor did not change significantly during the simulation (99.8% ± 0.6% of pretest value). Body mass and mass including equipment were measured before the field time trial and the treadmill tests.

Data analysis and statistics. P_{prop} was defined as the time derivative of the sum of work done on the environment (W_{env}) and the change in mechanical energy (E_{mech}) of a point mass (m) representing the athlete and equipment, in accordance with the definition used in several previous cross-country skiing studies (for an overview, see, e.g., Gløersen et al. [7]). Work done on the environment was the sum of work due to air drag ($\mathbf{F}_d$) and work due to rolling resistance ($\mathbf{F}_f$). Therefore, propulsive power was estimated using the following relation (7):

$$P_{prop} = \mathbf{v} \cdot (m(\dot{\mathbf{v}} - \mathbf{g}) - \mathbf{F}_d - \mathbf{F}_f),$$

where $\mathbf{g} = 9.81$ m·s^{-1} is the acceleration due to gravity, and $\dot{\mathbf{v}}$ is the point mass acceleration. The reader is referred to (7) for details on how $\mathbf{F}_d$ and $\mathbf{F}_f$ were calculated. For the special case of treadmill roller skiing, the acceleration ($\dot{\mathbf{v}}$) and the air drag ($\mathbf{F}_d$) terms in the equation above become negligible, and the expression reduces to $P_{prop} = mgv(\sin\theta + C_{rr}\cos\theta)$, where θ is the treadmill's inclination.

Breath-by-breath measurements of $\dot{V}O_2$ are susceptible to measurement errors because of the requirement to synchronize the gas flow measurements at the mouth with the time the expired gas sample reaches the analyzers. Therefore, we did a validation study comparing breath-by-breath measurements of $\dot{V}O_2$ with measurements obtained using the mixing chamber method, which has been validated against the Douglas bag method and shown to be accurate (14). The validation study is described in a separate document (see Appendix, Supplemental Digital Content 1, Validation study of the oxygen consumption measurements, http://links.lww.com/MSS/B831), and the results showed that the breath-by-breath measurements systematically underestimated $\dot{V}O_2$ by 10% compared with mixing chamber measurements. Therefore, $\dot{V}O_2$ measurements were corrected using the calibration equation $\dot{V}O_2 = 1.10 \dot{V}O_2^{b \times b} - 0.14$ [L·min^{-1}], which resulted in a typical error of the estimate (15) of 0.11 mL·min^{-1}. Because we present the data normalized to each athlete's $\dot{V}O_{2peak}$, these corrections do not affect the overall conclusions of the study, but the absolute measurements of $\dot{V}O_{2peak}$ and ΣO_2^{def} should provide a higher validity.

$\dot{V}O_{2peak}$ was defined as the highest rate of oxygen consumption averaged over 60 s during the 1000-m test on day 2 (11). Oxygen demand ($\dot{V}O_2^{dem}$) was predicted assuming a linear relationship between the cost of transport (C) and the propulsive force (F_{prop}). This relationship has previously been observed during classic skiing (16) and is supported by the experiments presented in Supplemental Digital Content 2 (see Appendix, Supplemental Digital Content 2, Experiments that underpin the model used to predict oxygen demand, http://links.lww.com/MSS/B832). This formulation implies that $\dot{V}O_2^{dem}$ increases linearly with P_{prop} at constant v, and that $\dot{V}O_2^{dem}$ increases linearly with v at constant P_{prop}. Therefore, we used a model of the form $\dot{V}O_2^{dem} - \dot{V}O_2^{rest} = \beta_1 P_{prop} + \beta_2 v$. However, because P_{prop} is linearly correlated to v (because $P_{prop} = F_{prop}v$), the relation was expressed through C by dividing $\dot{V}O_2^{dem} - \dot{V}O_2^{rest}$ by v to avoid multicollinearity in the regressors: $(\dot{V}O_2^{dem} - \dot{V}O_2^{rest})v^{-1} = \beta_1 F_{prop} + \beta_2$. Baseline metabolic rate ($\dot{V}O_2^{rest}$) was set equal to 5.1 mL·kg^{-1}·min^{-1}, following the results of Medbø et al. (17). Because we aimed to predict $\dot{V}O_2^{dem}$ rather than C, a weighted least squares regression with v as weight was used. This ensured that the model's residuals

	Speed (m·s^{-1})	Incline (°)	$\dot{V}O_2$ (mL·kg^{-1}·min^{-1})[a]	[La] (mmol·L^{-1})	RPE[b]	MAOD (mL·kg^{-1})
Submaximal loads	4.0 ± 0.0	2.3 ± 0.4	50.1 ± 2.7	1.2 ± 0.5	11.0 ± 1.3	
	4.0 ± 0.0	3.1 ± 0.4	57.8 ± 3.3	1.7 ± 0.6	12.9 ± 0.8	
	4.0 ± 0.0	3.8 ± 0.5	64.8 ± 3.2	2.9 ± 0.8	14.4 ± 0.7	
	6.0 ± 0.0	1.1 ± 0.2	54.1 ± 2.7	1.4 ± 0.5	10.9 ± 1.2	
	2.5 ± 0.0	5.7 ± 0.7	55.8 ± 3.5	1.7 ± 0.5	12.3 ± 0.5	
	6.0 ± 0.0	1.6 ± 0.3	62.6 ± 3.2	2.4 ± 1.0	13.1 ± 0.6	
1000 m	3.9 ± 0.3	6.0 ± 0.0	77.4 ± 4.4	12.2 ± 2.7		83 ± 18

Treadmill speed was the same for all athletes during the submaximal loads, but the incline was set individually based on time trial performance, as described in the text. All values are presented as mean ± SD.
[a]Average over the last 2 min for submaximal loads, highest 1 min average for 1000-m test.
[b]On a scale from 6 to 20.

were in units of volume of oxygen per time rather than volume of oxygen per distance.

Accumulated oxygen deficit (ΣO_2^{def}) was calculated as the difference between accumulated oxygen demand and accumulated oxygen consumption over a specified time interval. The ΣO_2^{def} during the 1000-m test was defined as MAOD. During the treadmill simulation, ΣO_2^{def} was evaluated throughout all course segments where the athlete was generating active propulsion (i.e., not holding the handle).

Statistics. The relationship between kinematic variables and $\dot{V}O_2^{dem}$ during the time trial (day 1) was assessed by a multiple linear regression with $\dot{V}O_2^{dem}$ as the dependent variable and skiing speed and acceleration as predictors. Further, $\dot{V}O_2^{dem}$ was averaged over different time windows of varying length τ to assess the relationship between the duration of a course segment and the average $\dot{V}O_2^{dem}$ in that segment. The length of the time windows ranged from 5 to 480 s. The first time window started at $t = 0$, and succeeding time windows were moved in increments of $\Delta t = 1$ s until $t = t_{finish} - \tau$. This resulted in $n = (t_{finish} - \tau)\Delta t^{-1}$ data points per athlete per window length. The average oxygen demands, $\dot{V}O_2^{dem}(\tau)$, were plotted versus the length of the time windows. Because the number of measurements was very large, $\dot{V}O_2^{dem}(\tau)$ was downsampled at random to 1000 data points per time window before plotting.

Missing data. Because of a treadmill malfunction, the treadmill simulation was aborted for one athlete, when 3.5 min of the simulation session remained and 89% of the simulation had been completed. The measurements taken before the malfunction are included in the analyses. Blood lactate measurements were missing for one athlete during the last lap of the treadmill simulation and for two of the athletes after the 1000-m performance test.

RESULTS

Results from the submaximal loads and 1000 m performance test during day 2, which were used as input to the model for $\dot{V}O_2^{dem}$, are summarized in Table 1. C was linearly related to F_{prop} during the submaximal loads, having a coefficient of determination $R^2 = 0.997 \pm 0.002$ when the model was applied to each athlete individually (Fig. 2). The SE of the estimate for the model for $\dot{V}O_2^{dem}$ was 1.1 ± 0.3 mL·kg^{-1}·min^{-1},

and the regression coefficients (averaged over all athletes) were $\beta_1 = 0.25 \pm 0.01$ mL·J^{-1} and $\beta_2 = 2.6 \pm 0.7$ mL·m^{-1}.

Day 1: field time trial. The athletes completed the field time trial in 31:48 ± 1:47 [mm:ss]. The athletes were in the tucked position (not generating propulsion) for 19% ± 6% of the race time. The average $\dot{V}O_2^{dem}$ excluding the time in the tucked position, termed active $\dot{V}O_2^{dem}$, was 101% ± 7% of $\dot{V}O_{2, peak}$. The athletes' instantaneous $\dot{V}O_2^{dem}$ plotted as a function of their position on the race course is shown in Figure 3A. From this figure, it is clear that $\dot{V}O_2^{dem}$ varied considerably throughout the time trial. Specifically, the SD of the instantaneous $\dot{V}O_2^{dem}$ throughout the time trial was 23.5 ± 2.7 mL·kg^{-1}·min^{-1}. The variation was approximately symmetrically distributed around the mean value, as seen in the histogram in Figure 4A.

Part of this variation can be explained by skiing speed and acceleration, as apparent in Figure 3B. Specifically, $\dot{V}O_2^{dem}$ decreased approximately linearly with skiing speed ($P < 0.001$). Furthermore, $\dot{V}O_2^{dem}$ was negatively correlated with acceleration in the skiing direction ($P < 0.001$). The coefficient of determination for this multiple linear regression was $R^2 = 0.31$, showing that a substantial part of the variation in $\dot{V}O_2^{dem}$ could not be explained by skiing speed and acceleration alone.
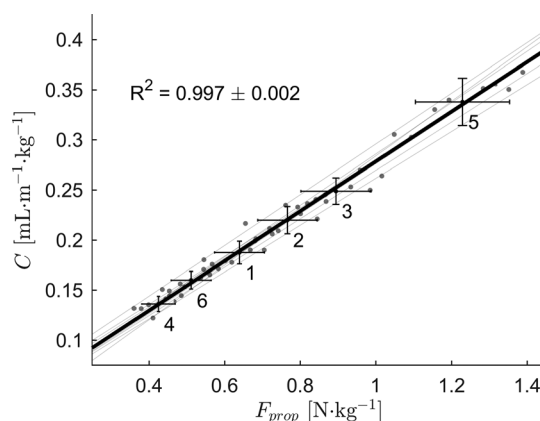

FIGURE 2—Model used to predict cost of transport (C) from propulsive force (F_{prop}) during the submaximal loads. This relationship was used to predict $\dot{V}O_2^{dem}$, as described in the text. Gray dots are the individual measurement points for all athletes. Enumerated error bars show the mean and the SD of each load in the order shown in Figure 1B. Thin gray lines are the athlete-specific regression models ($R^2 = 0.997 \pm 0.002$). The thick black line is the average of all athletes.
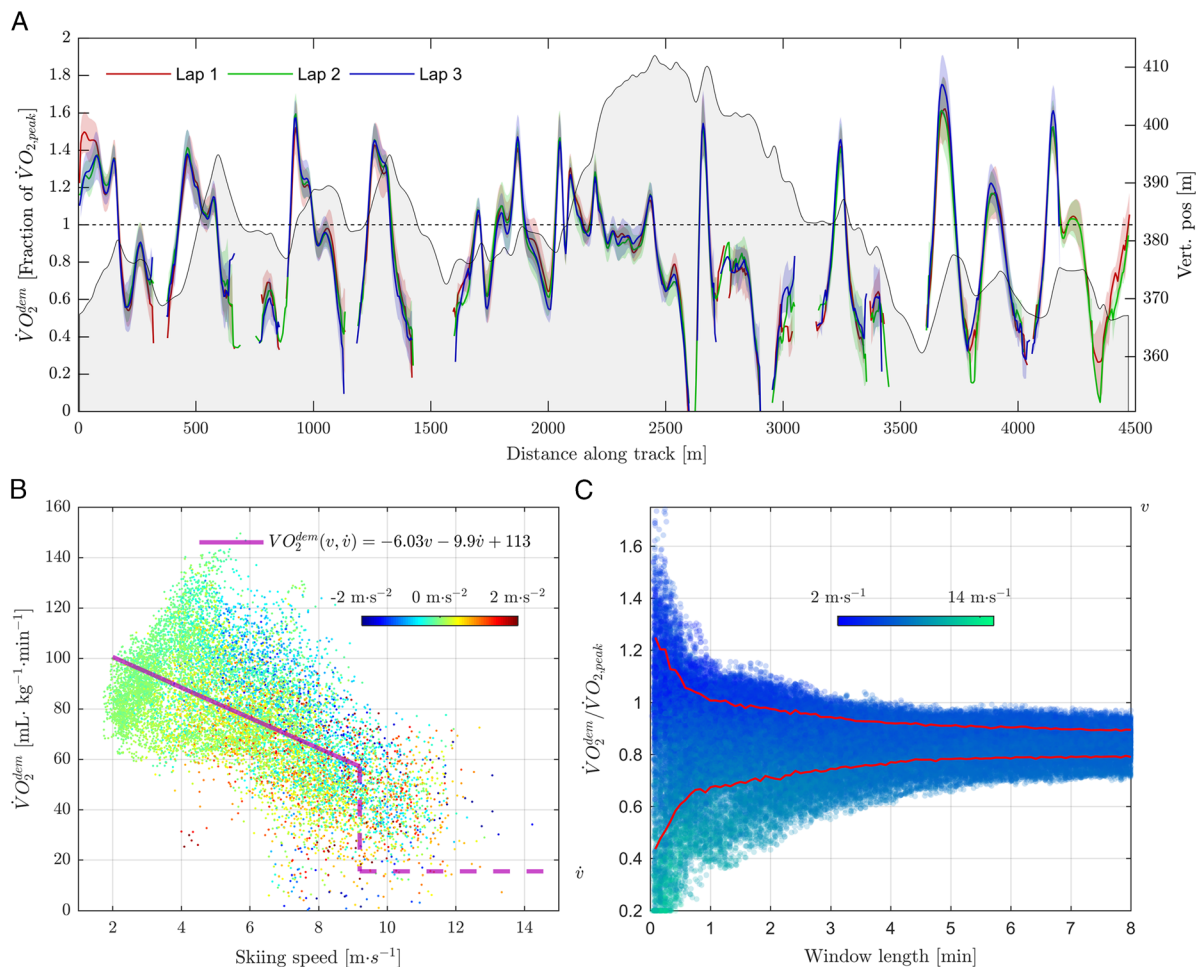
FIGURE 3—A, $\dot{V}O_2^{dem}$ plotted over distance for the three laps during the time trial (day 1). $\dot{V}O_2^{dem}$ varied considerably throughout the test, attaining values $\geq 150\%$ of $\dot{V}O_{2peak}$ in some of the uphill sections. The gaps in the estimates of $\dot{V}O_2^{dem}$ correspond to segments where the athletes were in the tucked position, where our model for $\dot{V}O_2^{dem}$ was not valid. B, $\dot{V}O_2^{dem}$ plotted against skiing speed (v) color coded with acceleration ($\dot{v}$). $\dot{V}O_2^{dem}$ decreased approximately linearly with skiing speed for speeds less than ~ 9 m·s^{-1}, which was the speed where the athletes transitioned to the tucked position. Furthermore, $\dot{V}O_2^{dem}$ was negatively correlated with acceleration, which indicates that $\dot{V}O_2^{dem}$ was higher at the beginning of uphill sections than at the end of uphill sections. This agrees with visual observations in panel A. The magenta-colored line shows the least squares fit to the data points, excluding measurements when the athletes were in the tucked position. A value of 0.2 $\dot{V}O_{2peak}$ was assumed for $v > 9$ m·s^{-1} and is displayed as a dashed line. C, Oxygen demand averaged over time windows ranging from 5 to 480 s during the time trial, color coded with average skiing speed during the time window. The red lines show mean ± SD of the $\dot{V}O_2^{dem}$ for each time window. Oxygen demand in the tucked position was set to 0.2 $\dot{V}O_{2peak}$ similar to panel B.

Some of this variation in $\dot{V}O_2^{dem}$ may be attributable to the different durations of uphill and downhill sections. This is illustrated in Figure 3C, which shows average $\dot{V}O_2^{dem}$ as a function of time window length. It is clear that the upper extreme values of $\dot{V}O_2^{dem}$ ($>150\%$ of $\dot{V}O_{2peak}$) were only sustained over short periods (<30 s). The longest uphill segment (2000–2400 m from the start; Fig. 3A) had a typical duration of ~ 2 min. From Figure 3C, it is clear that over this time window, the highest oxygen demands had reduced to $\sim 110\%$ of $\dot{V}O_{2peak}$.

Day 3: treadmill simulation. Two athletes managed to complete the simulation at the preset speed, five athletes requested one or more reductions in speed, and one athlete requested an increase in speed. Overall, the average speed was 97.7% ± 2.4% of the preset speed used from the field time trial. The average active $\dot{V}O_2^{dem}$ was similar to the field time trial (99.3% ± 5% of $\dot{V}O_{2peak}$), and the variation in $\dot{V}O_2^{dem}$ was smaller compared with the field time trial (mean ± SD,

14.8 ± 1.3 mL·kg^{-1}·min^{-1}; Fig. 4B). This was most likely due to the segmentation into 20-s intervals. The average $\dot{V}O_2$ throughout the simulation was 77% ± 4% of $\dot{V}O_{2peak}$, and the distribution was bimodal (Fig. 4C), with a major peak between 85% and 95% of $\dot{V}O_{2peak}$ and a minor peak at $\sim 35\%$ of $\dot{V}O_{2peak}$. The ΣO_2^{def} in each period between simulated downhill ranged from 0% to 50% of MAOD, and the average ΣO_2^{def} for each bout was 14.0% of MAOD (Fig. 4D). The ΣO_2^{def} throughout all periods with active propulsion generated was 299 ± 46 mL·kg^{-1}, or 383% ± 94% of MAOD. Blood lactate concentration was 8.3 ± 2.5, 8.5 ± 1.6, 9.7 ± 2.6, and 9.2 ± 2.8 mmol·L^{-1} at laps 1, 2, 3, and at the end of the simulation, respectively.

DISCUSSION

This study is the first to calculate the oxygen deficits attained during bouts of active propulsion by continuously
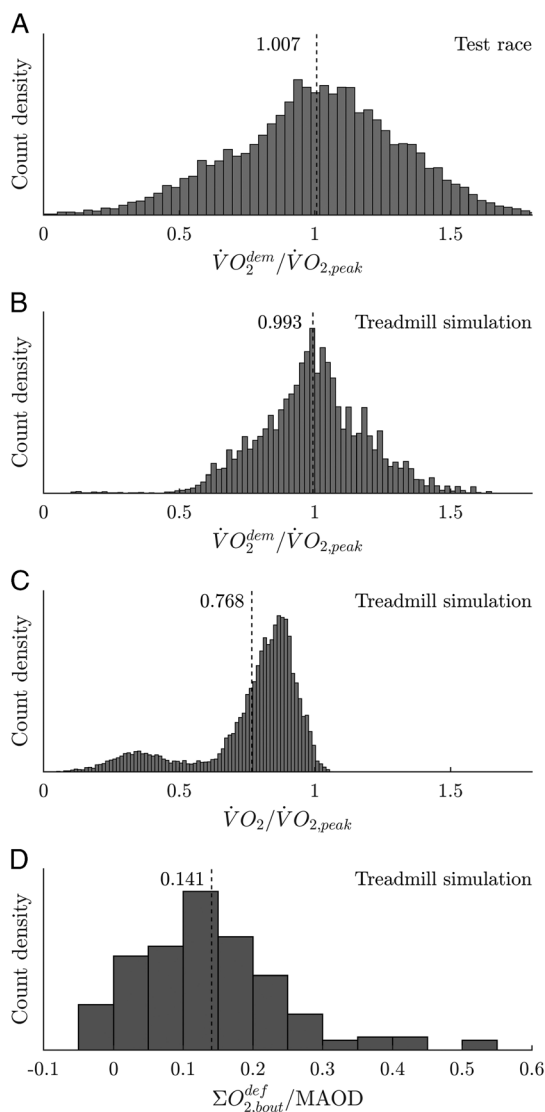
FIGURE 4—A, Distribution of oxygen demand during the time trial (day 1) when active propulsion was generated. Average oxygen demand during the time when active propulsion was generated was 101% of $\dot{V}O_{2peak}$. B, Same as panel A, but from the treadmill simulation (day 3) of the time trial. Average oxygen demand was slightly lower (99% of $\dot{V}O_{2peak}$) than during the time trial. C, Distribution of oxygen uptake throughout the treadmill simulation (day 3). D, Distribution of oxygen deficits attained during each bout of active propulsion of the treadmill simulation, relative to each athlete's individual MAOD. The deficits attained were typically small compared with MAOD (i.e., the oxygen deficit attained during the 1000-m performance test).

assessing the oxygen demand and consumption during a simulated cross-country skiing competition. Our findings show that athletes repeatedly attain substantial oxygen deficits throughout a distance skiing competition simulation, but that the oxygen deficits are small (approximately 50% or less) compared with athletes' individual MAOD. However, the oxygen deficit accumulated over all bouts of active propulsion exceeded MAOD by a factor of 3.8, indicating that a substantial recovery of the anaerobic energy stores represented by the MAOD occurs in downhill sections. The contributions from

these repeated partial depletions of the MAOD must ultimately be limited by the maximal rate of oxygen consumption.

Oxygen demand and consumption during cross-country skiing. To our knowledge, three studies (8,9,18) have analyzed oxygen demand and two studies (19,20) have analyzed oxygen consumption in a ski racelike situation, whereas no studies have combined measurements of oxygen consumption and demand. Our measurements of oxygen demand during the field time trial agree well with the findings of Karlsson et al. (8), who used a similar methodology and the same roller skiing course. However, the method used by Karlsson et al. (8) only allowed assessment of $\dot{V}O_2^{dem}$ in certain segments of the course because it required a constant skiing speed and either steep inclines (~8°) or flat terrain (~0°). Because of the rapid changes in inclination, constant skiing speed is rarely attained during cross-country ski races, which limits the use of the method described by Karlsson et al. (8). The $\dot{V}O_2^{dem}$ from the field time trial is also in fair agreement with the estimations presented by Norman and Komi (9) and Norman et al. (18) approximately 30 yr ago, although their methodology differed substantially from the method used by Karlsson et al. (8) and in the current study. Our measurements of oxygen consumption are largely in agreement with those of Welde et al. (20), who measured $\dot{V}O_2$ throughout a 6-km test race for elite female junior skiers. They reported an average $\dot{V}O_2$ of 84% of $\dot{V}O_{2peak}$, but this average excluded the first minute of the race as well as the periods during the race used for blood sampling. Trimming our $\dot{V}O_2$ measurements in the same manner provided similar results to Welde et al. (20). Furthermore, our findings partially agree with the suggestion that pulmonary $\dot{V}O_2$ does not reach $\dot{V}O_{2max}$ during cross-country skiing competitions (19,20). In our study, $\dot{V}O_2$ was lower than 95% of $\dot{V}O_{2peak}$ for 93% of the time.

The finding that $\dot{V}O_{2max}$ is not (or is only rarely) attained during a cross-country skiing competition has two likely explanations: (i) $\dot{V}O_{2max}$ can only be elicited if a sufficiently high exercise intensity is maintained for more than ~2 min (21), which is longer than most continuous uphill sections in a cross-country skiing course; and (ii) the close link between attainment of $\dot{V}O_{2peak}$, the $\dot{V}O_2$ slow component and fatigue (22,23), which could impair an athlete's ability to recover sufficiently during the short bouts of relative rest in downhill segments. These mechanisms seem to cause the athletes to reduce their effort in long uphill sections to ensure sufficient recovery during downhill or flat sections, with the consequence that $\dot{V}O_{2peak}$ is not attained. This interpretation is supported by the observation that oxygen demand in the longest uphill segments seems to decline from an initial value substantially greater than $\dot{V}O_{2peak}$ toward values close to, or even below, $\dot{V}O_{2peak}$ at the end of the uphill segment (Fig. 3A; 400–600 m and 2000–2400 m from the start).

To summarize, the results of this study clearly show that cross-country skiers repeatedly attain supramaximal exercise intensities (assessed through instantaneous oxygen demand), but that the oxygen deficits associated with these supramaximal bouts are small relative to their MAOD.

Furthermore, a substantial recovery of the anaerobic energy stores represented by the MAOD must occur in downhill sections. The ability to recover these energy stores rapidly is therefore likely to be a key performance-determining factor for cross-country skiers as well as for athletes in other sports with similar demands on bioenergetic systems.

Bioenergetics of intermittent endurance exercise. The bioenergetics of intermittent exercise depends not only on the total work done over a given period but also on the durations of the work and recovery periods. Specifically, when the work and recovery periods are short (typically 30 s or less), muscles' energy release is shifted toward high-energy phosphate breakdown and oxidative phosphorylation, whereas longer work and recovery periods with the same average power output shift energy release toward anaerobic glycolysis (24). Because substantial anaerobic glycolysis is associated with fatigue, the pacing strategies of athletes during exercise modes such as cross-country skiing are likely to be shaped by this. Additional insight into the pacing strategies was obtained through the critical power framework, recently reviewed with respect to intermittent exercise (25). Briefly, the critical power framework states that anaerobic work capacity (or at least the W' parameter) can be recovered whenever $P < P_c$ and is depleted whenever $P > P_c$, resulting in an inverse relationship between average power output and exercise duration. In the current study, we followed Poole et al. (4), Keir et al. (5), and Vanhatalo et al. (6) and applied this to metabolic power (or $\dot{V}O_2^{dem}$) too, shown schematically in Figure 5A. Figure 5B shows the same data as Figure 3C—it is therefore in principle a power–duration plot like Figure 5A. Furthermore, eight data points (one for each athlete) corresponding to the 1000-m performance test (day 2) were added to the figure, as shown in black. The theoretical line of fatigue from Figure 5A is shown in black and indicates the maximal attainable power output for a given window length. This line assumes that $\dot{V}O_{2crit} = 85\%$ $\dot{V}O_{2peak}$ and that the athlete is in a fully recovered state at the start of the segment (i.e., the energy reserves represented by the MAOD are fully recovered). The latter assumption is obviously not true for any but the first data point, and it does not consider that the MAOD is dependent on inclination. Karlsson et al. (8) showed that the MAOD in flat terrain (1°) was reduced by approximately 25% compared with an 8° incline. MAOD in the current study was measured on a 6° incline, which suggests that the line of fatigue could be underestimated on steep inclines and overestimated in flat sections.

The results shown in Figure 5B add further support to the interpretation that downhill sections are used to recover the oxygen deficits attained in uphill sections (9,27). Furthermore, the oxygen demand is substantially below the predicted maximal attainable power output (black line) for time windows comparable with or smaller than the longest uphill sections (~120 s), which is in agreement with the finding that oxygen deficits attained in single uphill bouts during the treadmill simulation were small compared with the maximal oxygen deficits (Fig. 4D). For long time windows, the oxygen demand converges toward 85% of $\dot{V}O_{2peak}$, which is close to the
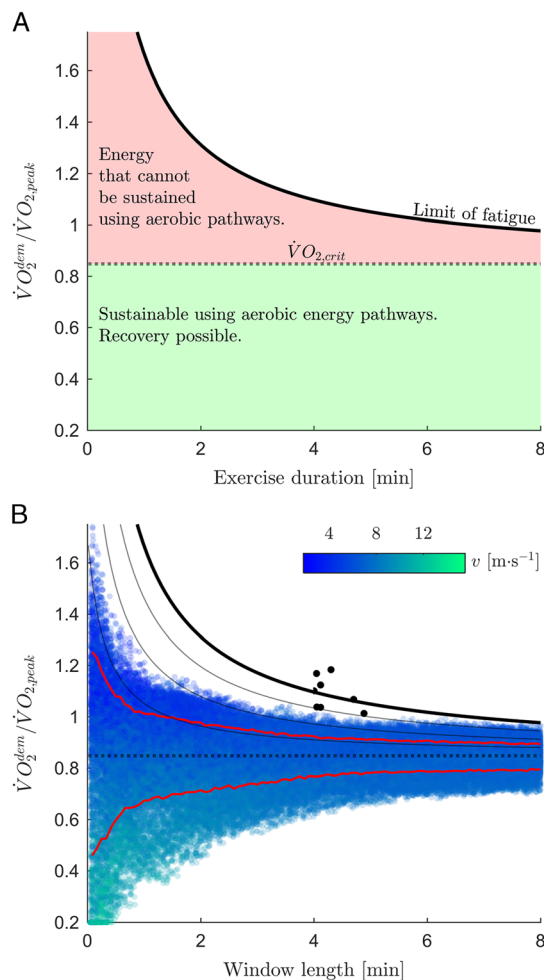

FIGURE 5—A, Illustration of the critical power theory expressed using oxygen demand instead of external power or speed. Briefly, athletes can maintain an exercise intensity $< \dot{V}O_{2crit}$ "indefinitely," but $\dot{V}O_2^{dem} > \dot{V}O_{2crit}$ depletes energy stores that cannot be sustained through cardiovascular oxygen supply. However, these energy stores can be recovered when the exercise intensity drops below $\dot{V}O_{2crit}$. See text for details. B, This panel shows the same data as Figure 3C and is therefore a "power–duration" plot similar to panel A. The solid black line indicates the maximal work rate sustainable over the given time window (assuming a fully recovered athlete). It was defined as $\dot{V}O_2^{dem}(\tau) = \dot{V}O_{2crit} + MAOD \cdot (\tau - k)^{-1}$, where τ is the window length, $k = 18.6$ s (following the findings in (26)), and $\dot{V}O_{2crit} = 0.85 \dot{V}O_{2peak}$, which is typical for well-trained endurance athletes (4). The thin black lines indicate 25%, 50%, and 75% of the MAOD. The eight black dots correspond to the finishing time and average $\dot{V}O_2^{dem}$ during the 1000-m performance test (day 2), and fall approximately along the line of fatigue, as expected.

expected $\dot{V}O_{2crit}$ for well-trained endurance athletes (4) and in line with the predictions of the critical power concept.

Both MAOD and W', although not equivalent measures (28), represent an energy reserve that can be used in excess of $\dot{V}O_{2crit}$. This energy reserve can mainly be attributed to three different sources: local oxygen stores (the aerobic contribution), high-energy phosphate stores (the alactic contribution), and anaerobic glycolysis or glycogenolysis (the lactic contribution). During exhaustive exercise, the relative contributions from these three energy sources are approximately 5%–10%, 20%–30%, and 60%–70%, respectively (29). The

rate of recovery of these energy sources is known to vary substantially. The recovery of local oxygen and high-energy phosphate stores is a relatively fast process, with a half time of about 20 s (30,31), whereas the recovery of the lactic part of MAOD (or W') seems to be a significantly slower process (32). Although the mechanisms behind recovery of the lactic energy source are poorly understood, there are indications that a substantial use of lactic energy pathways might delay the recovery of alactic energy sources (31) and reduce work economy (23,33).

Practical applications. In summary, the present findings suggest that MAOD *per se* is not an important determinant of distance cross-country skiing performance; rather, it is the ability to repeatedly use and recover the energy reserves represented by the oxygen deficits. As is apparent from Figure 5B, the oxygen demand can drop below 50% of $\dot{V}O_{2peak}$ for periods of up to ~2 min, which suggests that a relatively large fraction of the alactic and aerobic parts of the expended oxygen deficits can be recovered during downhill or flat sections. The fraction of MAOD typically used in supramaximal bouts in the current study is comparable in magnitude with the expected aerobic and alactic components of the MAOD. However, it is important to note that the use of the different energy systems is not strictly sequential (2), and therefore a substantial use of all energy pathways must be expected. This is underlined by the high blood lactate concentrations seen in both the present and previous studies (19,20).

From a training perspective, it is of interest to understand how the rate of recovery of MAOD can be improved. Recovery from supramaximal bouts of exercise is an aerobic process, and there is ample evidence that increased oxygen availability has a positive effect on performance during repeated sprint exercise (34). The main adaptation produced by endurance training is an increased oxygen delivery capability, which could suggest that endurance training has a positive effect on the rate of recovery from supramaximal exercise. However, a review of studies investigating the effect of endurance training on the rate of recovery during repeated sprint exercise concludes that evidence for such an effect is sparse and conflicting (34). Therefore, it is difficult to conclude decisively what type of training can improve the rate of recovery from supra-aerobic exercise.

Methodological considerations. The model used to predict oxygen demand in the current study assumes that there is a constant linear relationship between oxygen demand, skiing speed, and propulsive power. This assumption is challenged by the $\dot{V}O_2$ slow component, which becomes apparent during prolonged exercise at exercise intensities above the critical aerobic rate. Therefore, the model used in the current study may have underestimated the metabolic energy requirements, particularly toward the end of the race. In addition, the relationship between propulsive power and

metabolic power changes substantially in different terrain during cross-country skiing. This is an important point that is further discussed in Supplemental Digital Content 2, http://links.lww.com/MSS/B832.

Recently, an extension of the critical power model applicable to intermittent exercise has been developed (35,36). We did not include this model in our analysis, both because it would require further development for application to our data and because it has not yet been thoroughly validated. However, this would be an interesting approach that should be addressed in future studies.

In the current study, we used a treadmill simulation of a roller skiing time trial in field. This differs from previous field studies of distance cross-country skiing (19,20); however, treadmill simulations have been used to simulate sprint skiing (37,38). A limitation with the treadmill simulation used in the current study was that the treadmill could not perfectly mimic the race conditions. Most importantly, it required segmentation into 20-s intervals—reducing the variability in metabolic demand (Fig. 4A, B)—and a treadmill cannot simulate changes of direction. However, treadmill simulations give better control over the propulsive power compared with field measurements and allow the use of a laboratory-grade gas analyzer. A thorough discussion of the errors in the field measurement of P_{prop} is provided by Gløersen et al. (7).

CONCLUSION

The pacing strategies of elite cross-country skiers during a competition of duration ~30 min include repeated periods where oxygen demand exceeds $\dot{V}O_{2peak}$, but only a relatively small fraction of their MAOD is expended in each of these periods. The energy represented by this small fraction of MAOD corresponds roughly to the size of energy stores that can be rapidly recovered, which could partly explain this choice of pacing strategy. However, high blood lactate concentrations indicate that anaerobic glycolysis also provide a substantial contribution to the overall energy release. Consequently, the current study clearly indicates that different energy systems work in concert to satisfy rapid changes in metabolic power output during intermittent endurance sports.

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