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Running head: Physiology of world-class female skiers

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ABSTRACT

Purpose: To compare the physiological capacity and training characteristics of the world's six highest ranked female cross-country skiers (WC) with those of six competitors of national class (NC). **Methods:** Immediately before the start of the competition season, all skiers performed three 5-min submaximal stages of roller skiing on a treadmill for measurement of oxygen cost, as well as a 3-min self-paced performance test employing both the double poling (DP) and diagonal stride (DIA) techniques. During the 3-min performance tests, the total distance covered, peak oxygen uptake ($\text{VO}_{2\text{peak}}$) and accumulated oxygen deficit were determined. Each skier documented the intensity and mode of their training during the preceding 6 months in a diary. **Results:** There were no differences between the groups with respect to oxygen cost or gross efficiency at the submaximal speeds. The WC skiers covered 6-7% longer distances during the 3-min tests and exhibited average $\text{VO}_{2\text{peak}}$ values of ~ 70 and $\sim 65 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$ with DIA and DP, respectively, which were 10 and 7% higher than the NC skiers (all $P < 0.05$). However, the accumulated oxygen deficit did not differ between groups. From May to October, the WC skiers trained a total of 532 ± 73 hours (270 ± 26 sessions) versus 411 ± 62 hours (240 ± 27 sessions) for the NC skiers. In addition, the WC skiers performed 26% more low-intensity and almost twice as much moderate-intensity endurance and speed training (all $P < 0.05$). **Conclusions:** This study highlights the importance of a high oxygen uptake and the ability to utilize this while performing the different skiing techniques on varying terrain for female cross-country skiers to win international races. In addition, the training data documented here provide benchmark values for female endurance athletes aiming for medals. **Keywords:** aerobic capacity, anaerobic capacity, cross-country skiing, efficiency, endurance training, strength training.

INTRODUCTION

World-class cross-country skiers exhibit some of the highest maximal oxygen uptake (VO_2max) values ever reported, i.e., >80 and >70 $\text{mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$ for men and women, respectively (5, 6, 21, 32, 33). Clearly, the development of and ability to utilize high aerobic power while performing various skiing techniques on varying terrain are key determinants of performance in cross-country skiing, with maximal demands being placed on every aspect of oxygen transport (5, 23-25). In addition, the ability to efficiently convert energy into power and speed in connection with the various skiing techniques distinguishes cross-country skiers of different performance levels (23, 25, 26).

Since 5 of the 6 Olympic and World Championship competitions for each gender today involve mass-starts, the outcome is often decided by increases in speed during the race and/or in the final sprint. To attain such high speeds, the ability to generate long cycle lengths (1, 8, 25, 29, 30) and to produce high amounts of energy anaerobically (10, 26) is advantageous for male skiers. Furthermore, upper-body power represents a major difference between male and female skiers (4, 22). However, less is known about the sport-specific physiological demands faced by world-class female skiers and the factors that differentiate between competitors with different rankings.

Endurance training has always been the major component of the training performed by cross-country skiers. The endurance training of successful cross-country skiers involves large amounts of low-intensity training and low-to-moderate levels of high-intensity training (11, 20, 24, 26, 27, 33). Although the proportions of training at these different levels of intensity have not

changed during the past three decades, cross-country skiers now perform more endurance training on roller skis, which places greater focus on the upper-body, as well as more systematic strength and speed training (24). However, the training strategies of the female skiers currently ranked highest in the world and possible differences between their strategies and those of lower-ranked female skiers have yet to be examined.

Insight into the unique performances of gold medal-winning athletes requires integrative examination of their sport-specific physiological capacity and training characteristics. Accordingly, the primary purpose of the present study was to compare the physiological capacity and training characteristics of highly successful world-class (WC) female cross-country skiers to those of national-class (NC) skiers. Our major hypothesis was that the peak oxygen uptake and skiing efficiency of the WC skiers while roller skiing both on flat and uphill terrain are superior to those of NC skiers and that these differences coincide with more endurance training at a low- and moderate-intensity among WC skiers.

METHODS

Participants

Of the 12 female Norwegian cross-country skiers who participated, the 6 in the WC group were ranked 1 to 6 overall in the World Cup in 2015 and included a total of 4 Olympic Champions and 5 World Champions. The 6 NC skiers were all highly trained elite athletes who ranked among the top 15 in Norwegian FIS races, two of whom also finished among the top 15 in one World Cup race. The characteristics of these participants are presented in Table 1. Before providing their written consent to participate, all were fully informed about the nature of the

study, which was approved by the Regional Committee of Medical and Health Research Ethics in Central Norway.

Overall design of the study

Immediately prior to the competition season, all skiers performed three 5-min submaximal stages at constant speed (at low to moderate intensity) and a 3-min self-paced performance test of roller skiing on a treadmill, alternating between the double poling (DP) and diagonal stride (DIA) techniques (for the detailed protocol, see below). Cardiorespiratory variables and cycle characteristics were monitored continuously during every test. In addition, the blood lactate concentration and rating of perceived exertion (RPE) were assessed following every test, and during the 3-min tests, the total distance covered (as a measure of performance) and peak oxygen uptake ($\text{VO}_{2\text{peak}}$) were determined. Furthermore, the accumulated oxygen deficit ($\sum \text{O}_2$ deficit) was calculated from the 3-min test in DIA and gross efficiency as the work rate divided by the metabolic rate during the submaximal tests with both techniques. Custom-designed training diaries were employed to document the volume, frequency, intensity and mode of daily training during the preceding six months.

Instruments and materials

Respiratory variables were measured using open-circuit indirect calorimetry. Expired gas was passed through a mixing chamber and analyzed continuously (Oxycon Pro, Jaeger GmbH, Hoechberg, Germany). Before each test, the instruments were calibrated against the O_2 and CO_2 concentrations in ambient air and in a highly precise commercial gas mixture (14.90% and 6.05%, respectively). The flow transducer (Triple V, Erick Jaeger GmbH, Hoechberg, Germany)

was calibrated using a 3-L high-precision syringe (5530 series, Hans Rudolph Inc., Kansas City, Missouri, USA). Heart rate was recorded continuously with a Polar S610i monitor (Polar Electro Oy, Kempele, Finland) synchronized with the Oxycon Pro system. The lactate concentration in 5 μ L of blood taken from the fingertip was assayed using the Lactate Pro LT-1710t kit (ArkRay Inc, Kyoto, Japan), which has been validated by Medbø et al. (12). Rating of perceived exertion (RPE) was assessed utilizing the 6-20 point Borg Scale (2). The body mass of each participant was determined prior to starting the test protocol (Seca model nr: 877; Seca GmbH & Co, Hamburg, Germany).

Tests were performed on a 3-by-4.5-m motor-driven roller ski treadmill (Rodby, Södertälje, Sweden), of which the slope and speed were controlled before, during and after the study. The treadmill belt was covered with non-slip rubber that allowed the skiers to use their own poles (length: $83.3 \pm 0.6\%$ of body height), equipped with special carbide tips. For security, the skiers wore a safety harness connected to an automatic emergency brake during the tests. The speed during the self-paced 3-min tests was monitored employing two laser beams (BDL120, Black & Decker, Towson, Maryland, USA) separated by 60 cm.

All skiers wore their own classical cross-country skiing shoes, but used the same pair of Swenor roller skis (Swenor, Sarpsborg, Norway) with an NNN binding system (Rottefella, Klokke, Norway) and standard wheels. The rolling friction coefficient (μ) of these skis was tested before, at various times during, and after the study with the towing test described by Sandbakk and colleagues (25), providing an average μ value of 0.028 that was used for calculating work rate.

Cycle characteristics were determined on the basis of recordings by a 50-Hz video camera (Canon HF100, Canon Inc., Tokyo, Japan) fixed in the sagittal plane of the treadmill, using the Dartfish Pro 4.5 program (Dartfish Ltd., Fribourg, Switzerland). Treadmill and video data were synchronized by using frame-by-frame video and the first movement of the treadmill belt represented 0 s.

Test protocols and measurements

Submaximal tests

Following 10 min of low-intensity warm-up on the treadmill, each skier performed six 5-min stages of roller skiing at constant speed, alternating between the DP (at an incline of 3%) and DIA (12%) techniques (i.e., such that the six stages were performed in the order DP-DIA-DP-DIA-DP-DIA). A 2-min break was given between each stage. The speed of the first stage was chosen individually on the basis of earlier testing (i.e., the NC skiers started at a speed of 2.5 or 3.0 m·s⁻¹ for DP and 1.50 or 1.75 m·s⁻¹ for DIA, while the WC skiers started at a speed of 3.0 or 3.5 m·s⁻¹ for DP and at 1.75 or 2.00 m·s⁻¹ for DIA). Thereafter, the speed increased in each successive stage by 0.5 m·s⁻¹ in the case of DP and 0.25 m·s⁻¹ for DIA. All skiers performed one stage of DP at 3.5 m·s⁻¹ and one of DIA at 2.25 m·s⁻¹, which allowed for a direct comparison of the physiological responses between the two groups at these speeds. Cardiorespiratory variables were monitored continuously and the averages for the final two minutes provided the steady-state values utilized for further analyses. Blood lactate and RPE were assessed immediately after the submaximal tests. The time required to perform 10 cycles during the third minute at each stage was used to calculate cycle rate and cycle length.

Performance tests

In the case of the 3-min self-paced performance tests, each skier first carried out the DP test and, following a 20-min break, the DIA test. The speed was fixed the first 30 s to avoid over-pacing (5 and 3 m·s⁻¹ for the DP and DIA tests, respectively). Thereafter, the skiers controlled the speed by adjusting their position on the treadmill relative to the laser beams. Each contact of the front wheels with the front or the rear laser resulted in an increase or reduction in speed, respectively, by 0.25-0.5 m·s⁻¹ in the case of DP and 0.25 m·s⁻¹ for DIA. Each skier received continuous visual and verbal feedback concerning the time that had elapsed, but knew nothing about the performance of the other skiers. Changes in speed and the accumulated distance skied were registered automatically. Cardiorespiratory variables were monitored continuously and the highest average VO₂ during a continuous 30-s period defined as VO_{2peak}. The highest 5-s heart rate was considered to be peak heart rate (HR_{peak}). Blood samples were taken for determination of blood lactate concentration and RPE rated approximately 1.5 min after each test. Cycle rate and length were calculated for the final 8-12 cycles during the initial 30 s (i.e., at constant speed), as well as during each subsequent 30-s period (i.e., at varying individual speeds).

Work rate was calculated as the sum of power against gravity and friction, as follows:

$$P_g + P_f = m \cdot g \cdot v \cdot (\sin(\alpha) + \cos(\alpha) \cdot \mu)$$

where P_g is the work against gravity, P_f the work against friction, *m* the mass of the skier plus equipment, *g* the gravitational constant, *α* the incline of the treadmill, *μ* the frictional coefficient and *v* the speed of the treadmill. The metabolic rate at submaximal workloads was calculated as the product of VO₂ and the oxygen energetic equivalent utilizing the associated respiratory exchange ratio and standard conversion tables (16). Gross efficiency was then calculated as the

work rate divided by the metabolic rate and presented as a percentage. One cycle encompassed one right and one left pole push-off; cycle length was obtained by multiplying cycle time with the speed of the treadmill belt and cycle rate as the reciprocal of cycle time.

The accumulated oxygen demand (ΣO_2 demand) associated with the 3-min DIA test was calculated by extrapolating the individual linear regression lines for submaximal work rates versus steady-state oxygen cost (13). This was not done for DP, since the relationship between work rate and steady-state oxygen cost was non-linear for some of the skiers in this case. The ΣO_2 deficit was then obtained by subtracting the accumulated oxygen uptake from the ΣO_2 demand.

Individual training for the entire season was quantified on the basis of the skier's personal online training diary, and examined in detail from May to October. Endurance training was characterized by the session-goal HR procedure, which has previously been reported to provide a valid and accurate measurement of the duration and intensity of training by cross-country skiers (31). Training was categorized as low- (heart rate < 81% HRmax), moderate- (81-88% HRmax) or high-intensity (>88% HRmax). In addition, speed and strength training were quantified and categorized in a similar manner. Strength training involved general exercises in the gym (i.e., 10-30 repetitions designed primarily to improve the general strength and stability of the upper-body) or semi-specific exercises focusing on maximal strength and power (i.e., 1-6 repetitions using both free weights and machines). Speed training was mainly ski-specific, e.g., roller skiing, skiing on snow and jumping uphill with or without poles. The durations of the speed and strength sessions were defined as the period between the first and last sprint/set in the entire session

(normally including 1-3-min recovery periods between sprints/sets). However, in the case of sprints during a low- or moderate-intensity session, the number of sprints was multiplied by 1.5 min, since the first 1-1.5 min following each sprint was performed at very low-intensity (note that these 1-1.5 min were not included in the total low-intensity time). Training modes were categorized as roller skiing or skiing with the classical or skating techniques, running, or other (e.g., cycling, kayaking, games, etc.). The time spent stretching was not included. Additional information concerning their strategies for training and recovery was acquired from the diaries, as well as from qualitative interviews with the individual skiers and their coaches.

Statistical analyses

The distributions of all sets of data were examined using a Shapiro-Wilk test and appeared to be non-normally distributed. Therefore, a non-parametric Mann-Whitney U test was applied to identify differences between the two groups. Within-group differences in training hours during the six-month period were compared with a two-way analysis of variance with repeated measurements. In all cases, the values for the NC skiers were set to 100%. Pilot testing among these skiers indicated that repeated measurements of the physiological variables and cycle characteristics determined here have intra-class correlation coefficients of > 0.95 . Statistical significance was set at an alpha level of 0.05 and, in addition, alpha levels between 0.05 and 0.1 were considered to indicate trends. All statistical analyses were carried out in IBM SPSS Statistics for Windows, Version 21.0 (IBM Corp., Armonk, NY, USA).

RESULTS

At the submaximal speeds (i.e., $3.50 \text{ m}\cdot\text{s}^{-1}$ for DP and $2.25 \text{ m}\cdot\text{s}^{-1}$ for DIA), the WC skiers did not differ from the NC skiers with respect to the oxygen cost or gross efficiency, but the WC skiers did exhibit 6 and 4% lower % VO_2peak , 11 and 10% lower % HRpeak , as well as lower RPE and blood lactate concentrations when employing DP or DIA, respectively (Table 2; all $P < 0.10$). In addition, the WC skiers tended to have a lower cycle rate and longer cycle length with DIA than the NC skiers (Table 2; both $P < 0.10$).

The WC skiers covered 7% (range: 962-1010 vs 845-962 m) and 6% (range: 560-614 vs 531-577 m) longer distances in connection with DP and DIA than the NC skiers, respectively (Table 3; both $P < 0.05$). All skiers in the WC group covered longer accumulated distances for the two 3-min tests than the best NC skier (WC: $1575 \pm 25 \text{ m}$, range: 1538-1603 m vs NC: $1474 \pm 25 \text{ m}$, range: 1375-1511 m). For both techniques, the difference in speed between the WC and NC groups was significant from approximately 1 min, and this difference remained relatively constant at ~10% throughout the rest of the test (Figure 1A-B; $P < 0.05$). This speed difference was accompanied by higher cycle rates among the WC skiers during the final two minutes of DP ($P < 0.05$), while neither cycle rate nor length differed significantly in the case of DIA (Figure 1C-F). After normalization for body mass, the VO_2peak of the WC group was 10% (range: 60.5-70.8 vs 54.5-64.3 $\text{mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$) and 7% (range: 68.0-74.8 vs 61.4-71.8 $\text{mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$) higher during DP and DIA skiing, respectively, than that of the NC group (Table 3; both $P < 0.05$). There were no between-group differences in the total ΣO_2 deficit, either in absolute values or as a percentage of the ΣO_2 demand with DIA or in the peak respiratory exchange ratio or peak blood lactate concentration with either technique (Table 3).

The training characteristics of each group during the 6-month period examined in detail are illustrated in Figures 2 and 3. The WC and NC skiers trained for a total of 532 ± 73 and 411 ± 62 hours during 270 ± 26 and 240 ± 27 sessions, respectively ($P < 0.05$ for the differences between groups in both cases). On the average, the sessions of the WC skiers were 18% longer (~ 2.0 vs ~ 1.7 hours per session) than those of the NC skiers ($P < 0.05$). The WC skiers carried out 26% more low-intensity endurance training and almost twice as much moderate-intensity and speed training as the NC skiers (Figure 2A; all $P < 0.05$). In addition, the WC skiers tended to perform more strength training ($P = 0.09$) and less high-intensity endurance training ($P = 0.07$). The relative amounts of endurance training at low, moderate, and high intensity from May to October were 91%, 5% and 4% for the WC skiers and 90%, 4% and 6% for the NC group ($P > 0.05$ for the differences between groups in all cases). On average, the WC skiers trained for 80-95 hours each month from May to October, whereas the NC group tended to increase the amount of their training successively from May to August (Figure 3A, $P = 0.09$). The training volume of the WC skiers was higher during all months ($P < 0.05$) except July and September. There were no differences in the number of days spent training on snow (22 ± 3 vs 18 ± 4 days), whereas the WC group spent more days at >1500 m above sea level (42 ± 6 vs 25 ± 6 days; $P < 0.05$).

Running and roller-skiing were the main modes of exercise, accounting for $39 \pm 3\%$ and $44 \pm 4\%$, respectively, of the training by the WC skiers and $43 \pm 5\%$ and $42 \pm 3\%$ for the NC group ($P > 0.05$ for the differences between groups in both cases). WC skiers spent 33% more time running and 40% more time training the skating technique (skiing and roller skiing) than NC skiers (Figure 2B and 3B; both $P < 0.05$). For both groups, most of the running was of low intensity and on varied terrain on soft surfaces, whereas moderate- and high-intensity running

was mainly on steep uphill terrain. Representative training weeks at low altitude during the preparation period are described in the Appendix (see Table, Supplemental Digital Content 1, typical training week for the WC and six NC skiers at low altitude during the preparation period, <http://links.lww.com/MSS/A626>). For both groups, the number of training hours per week varied in general less than 20%, although following extensive training camps there were some less intense weeks, with 40% reductions in training volume. During all phases of training, the number of moderate- to high-intensity sessions remained relatively constant at 2 or 3 per week. Note that the volume of training at sea level and higher altitude did not differ, but that less high-intensity exercise was performed at higher altitude.

Compared to the period of preparation (May-October), the skiers trained less during the competition season (November-April) (i.e., 388 ± 56 and 298 ± 49 hours for WC and NC skiers) and the training by both groups was more polarized, involving 26% more hours as high-intensity exercise (including competitions) in the case of the WC group ($P < 0.05$) with no change for the NC group, as well as approximately 50% less strength and speed training for both groups ($P < 0.05$ in all cases). The relative amounts of endurance training at low-, moderate-, and high-intensity from November to April was 89%, 4% and 7% for the WC skiers and 89%, 3% and 8% for the NC group ($P > 0.05$ for the differences between groups in all cases). In addition, both groups routinely carried out 3-5 following competitions during the season of competition, which, at least from a physiological point of view, can be regarded as high-intensity blocks. This organization of training differed from that during the 6-month preparation period.

DISCUSSION

The present comparison of physiological capacity and training characteristics revealed that the world's highest ranked female cross-country skiers performed better and exhibited higher VO_2peak , both with the DP technique on nearly flat terrain and with DIA uphill, than Norwegian competitors of lower ranking. In the case of DP, the difference in speed was due primarily to the higher cycle rates of the WC skiers, while neither cycle rate nor length differed significantly between the groups during DIA. Nor did the two groups differ substantially with respect to submaximal oxygen cost, skiing efficiency or ΣO_2 deficit. During the 6 months preceding these tests, the WC skiers performed more low- and moderate-intensity endurance training, in combination with more speed training.

Physiological capacities

The WC skiers covered 6-7% longer distances on the treadmill than the NC skiers during the 3-min tests with both the DP and DIA techniques. In both cases, the speed during the initial 30 s was similar, after which (i.e., with self-pacing) the speed differences increased gradually and remained relatively constant at approximately 10% during the last half of the tests.

To attain these higher speeds during the 3-min DP test, the WC skiers employed more rapid cycles. In contrast to the skating technique, where differences in cycle length are the primary determinants of performance (1, 8, 25, 29, 30), more rapid cycles of DP are consistently correlated to higher speeds (8, 14, 29). The ability to combine rapid cycle rates with relatively long cycle lengths, demonstrated by our female WC skiers, is especially important for obtaining high speeds with DP (8). This impact of cycle rate may reflect the short poling times available

for the rapid generation of propulsive force, as well as the ability of the WC skiers to cope more effectively with fatigue to maintain their cycle rate. In the case of DIA, neither cycle rate nor length differed significantly between the two groups, indicating that our WC skiers combine these two factors more effectively than NC skiers to achieve higher speed.

During the 3-min tests the WC skiers attained 10 and 7% higher $\text{VO}_{2\text{peak}}$ in DP and DIA, respectively, indicating that the major portion of the performance differences between groups can be explained by variations in production of aerobic energy. For the WC group, the average $\text{VO}_{2\text{peak}}$ value for the group associated with DIA was somewhat higher than $70 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$, a value in agreement with previous reports on female world-class cross-country skiers (6, 21, 32, 33). However, our study is the first to report $\text{VO}_{2\text{peak}}$ values for WC female skiers performing DP, which averaged ~ 65 and $\sim 59 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$ for the WC and NC skiers, respectively. These values represent $\sim 91\%$ of the $\text{VO}_{2\text{peak}}$ values associated with DIA for both groups, thereby corresponding to previous findings on elite male skiers (5).

The highest individual oxygen uptakes observed here during DIA and DP were ~ 75 and $\sim 71 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$, respectively, which are the highest values yet reported for female skiers employing ski-specific techniques. Although certain individual skiers in the NC group exhibited performance and $\text{VO}_{2\text{peak}}$ values comparable to those of the WC skiers with one of these techniques, only the WC skiers scored high levels with both. Thus, to achieve world-class status, female skiers must perform well and demonstrate high peak oxygen uptake on both uphill and flat terrain.

The $\sum O_2$ deficit during the 3-min DIA test was the same for our two groups, indicating that technique-specific production of anaerobic energy does not distinguish successful female cross-country skiers from their counterparts of lower rank. This observation disagrees with previous reports that better male sprint skiers demonstrate a greater $\sum O_2$ deficit (10, 26), even greater than specialists in distance skiing (9). However, it should be noted that our WC and NC skiers were specialized in sprint and distance skiing to the same extent. Moreover, their $\sum O_2$ deficits (averaging close to $50 \text{ mL}\cdot\text{kg}^{-1}$ in both cases) were only slightly lower than those attained by elite male skiers ($\sim 60 \text{ mL}\cdot\text{kg}^{-1}$) (10), indicating that elite female skiers require relatively high anaerobic capacity.

It was recently shown that the upper-body power of elite male and female cross-country skiers differs considerably (4). However, the difference between the performance of our WC and NC female skiers was similar with DP and DIA, even though the former makes greater demands on upper-body power (22). Apparently, upper-body power did not seem to influence performance in the present context, although during the last decade strength and power have become more important in general for success as a competitive skier (24).

The submaximal stages with either technique were less demanding for our WC skiers, even though the oxygen cost and skiing efficiency did not differ and the group differences in submaximal cycle characteristics were minor. These findings are in contrast to previous observations on submaximal skiing, where the efficiency with which metabolic energy is transformed into work rate and speed, together with cycle length differ between skiers of different levels of performance (23, 25). Possibly, all of our elite skiers had optimized the

efficiency of their techniques during submaximal roller skiing with classical techniques to a similar extent. Whether this would also be the case at higher skiing speeds or on snow, which is regarded as more technically demanding, requires future attention.

Training characteristics

As might be expected from their superior performance and physiological characteristics, the WC skiers trained more hours caused by 13% more sessions and, on the average, 18% longer sessions than the NC skiers. In particular, their low- and moderate-intensity sessions were longer, with all of the WC skiers performing 2 or 3 low-intensity sessions lasting more than 2.5 hours each week. This was the case both during the half-year preparation period examined here, when the WC group trained 532 hours (averaging 89 hours, including nearly 80 hours of endurance training, per month) and over the entire year, although with less training during the competition season and some individual variation. This amount of training is larger than ever previously reported for cross-country skiers (11, 26, 33) and is reflected in the unique level of performance by this group.

To attain such high training volumes, our WC skiers exercised at high loads from May to October, a period during which the NC group progressively increased the extent of their training. This difference may simply reflect the part-time work or studies being carried out by the NC skiers during the first few months analyzed, allowing less time for recovery between training sessions. Differences in recovery strategies, such as nutritional optimization, sleeping patterns, mental recovery and other daily activities, may also have exerted an influence in this regards and should be examined further.

Our present observation that the amounts of low- and moderate-intensity endurance training by the two groups differed provides further support for the proposal that such training constitutes the preparatory foundation for competitions in cross-country skiing (28). Indeed, several other investigations have demonstrated that extensive training of this type probably contributes to the superior aerobic capacities and performance of elite endurance athletes (3, 24, 26, 27, 33). However, since all such studies have been based on retrospective analysis of training data and prospective experimental designs for tests of world-class athletes are almost entirely lacking, caution should be applied in connection with such conclusions.

The reported endurance training pattern among successful cross-country skiers is to combine such large amounts of low-intensity training with moderate amounts at high-intensity (20, 27, 33). Here, the WC skiers performed more low- and moderate-intensity training, while actually tending to do less high-intensity training than the NC group. This can be explained in part by the fact that the WC group spent more days at moderate altitude (i.e., sleeping at altitudes of ~1800-2000m and training between 1500-3000 m), where low- and moderate-intensity training were given highest priority. Although it can be argued that more days at moderate altitude might provide additional stimulus, a number of short-term interventions have led to the conclusion that high-intensity exercise induces the physiological adaptations most beneficial to performance (7). Our present observations do not bring the importance of high-intensity training into question, although it can be speculated that in such highly trained athletes as ours the quality of each session (i.e., optimization of physical, technical and mental aspects) is more significant than the total number. In addition, the period of preparation is followed by the competition season, during which polarized training, with more high-intensity sessions between competitions,

is more strongly emphasized by both groups. Whether the more progressive increase in the intensity of training over the year exhibited by our WC skiers is beneficial for the long-term development of elite endurance athletes requires further attention.

The WC group employed a relatively “flat” week-to-week periodization during the 6-month preparation period, with weekly training hours varying mainly between 20 and 25 hours per week, although there were some less arduous weeks with 15-18 hours of training immediately after extensive training camps. In addition, the number of moderate- to high-intensity sessions remained relatively constant at 2 or 3 per week during all phases of training, with the exception of training at higher altitude, which involved less high-intensity training. The periodization utilized by the NC group was the same, although generally with fewer training hours and less training at moderate altitudes. Several studies indicate that block periodization of high-intensity training may enhance the performance of both cyclists and cross-country skiers to a greater degree than an equal number of high-intensity sessions distributed more evenly (17-19). However, our subjects placed greater emphasis on high-intensity training and periodized such training in blocks to a greater extent during the competition period. Nonetheless, the manner in which each athlete optimizes periodization within each week by varying the type of (endurance, strength and speed) and mode of training (i.e., loading of the upper and/or lower body), the terrain, and intensity of endurance training daily requires further examination. These strategies differentiate cross-country skiing from most other endurance sports and their effects sorely need to be better understood.

Our WC skiers also performed a greater number of training sessions focused on developing speed and also tended to carry out more strength training. A similar difference in the amount of speed training performed by male WC and NC sprint skiers has been observed (26), probably reflecting the demands for speed made by today's races (24). The single investigation to date on the impact of speed training on the performance and physiological characteristics of cross-country skiers reported positive effects of 20-s intervals of DP on both DP sprint and endurance performance (15), clearly, the potential effects of combined speed and endurance training require further evaluation. Our present findings allow us to speculate that, for female athletes performing the amount of endurance training documented here, additional strength and speed training could help develop and maintain muscle mass and power, particularly in the upper body.

During the six months of dry-land training analysed here, both groups devoted 50-60% of their training time to sport-specific exercises (i.e., roller skiing and skiing) and most of the remainder to running. This pattern is similar to the annual training characteristics of gold medal-winning male and female skiers reported previously (33). This variation between sport-specific training and cross-training may help athletes to tolerate such large amounts of training during the preparation period, as well as lower the risk of injury. Our cross-country skiers varied their mode of low-intensity training considerably, while their moderate- and high-intensity training was more ski-specific. Altogether, our WC skiers spent more of their training time running and skating, whereas the NC skiers tended to use the classic technique relatively more. However, if and to what extent such variations in the utilization of training modes in general, as well as in the different training zones, influence physiological capacities remains to be determined.

Another factor that may facilitate tolerance of the high training loads observed here is extensive low-intensity running on soft surfaces in varied terrain. This is traditionally regarded as the most important mode of cross-training and our athletes did a great deal of running, particularly on heavy muskeg terrain (i.e., soft and wet surface common in the Arctic areas and comparable to marsh). This type of training activates large muscle groups and has been proposed to improve the tolerance for performing long training sessions and the ability to recover rapidly, thereby improving the general aerobic capacity of cross-country skiers (33).

The characteristics of a female champion

In the current study, we analyzed the physiological capacity and training characteristics of the most successful female competitor ever in the winter Olympics. With a body height of 166 cm and a mass of 65 kg, she demonstrated $\text{VO}_{2\text{peak}}$ values of 4.6 and 4.2 $\text{L}\cdot\text{min}^{-1}$ (~ 70 and ~ 65 $\text{mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$), combined with relatively high skiing efficiency when employing DIA and DP, respectively, as well as an ΣO_2 deficit of ~ 55 $\text{mL}\cdot\text{kg}^{-1}$ with DIA. Although her $\text{VO}_{2\text{peak}}$ values normalized to body mass were not outstanding, the combination of high absolute $\text{VO}_{2\text{peak}}$, skiing efficiency and ΣO_2 deficit values allowed her to be one of the best WC skiers during the 3-min test with either technique. Since this group consisted of the six highest ranked female skiers in the world, this unique combination of capacities may have been the key to her world-class performance in both sprint (~ 1.5 km) and distance races (10-30 km).

To achieve such capacities, she performed ~ 980 hours of training during the preceding year and ~ 575 hours during the 6-month preparation period (May-October) examined in detail here. During this half year her training included 80% low-, 4% moderate- and 3% high-intensity,

with 2% speed and 11% strength training, ~55% of the endurance training being technique-specific (i.e., skiing and roller skiing), and most of the remainder (45%) consisting of running in varied terrain. As for the other members of the WC group, she performed less low- and moderate-intensity training during the subsequent six months (November-April), with a major focus on ski-specific and more polarized endurance training in the form of more high-intensity sessions and 43 cross-country skiing competitions. This is similar to the training patterns described previously for successful cross-country skiers (33) although she trained somewhat more. Overall, the unique physiological capacities and training characteristics of this female champion may provide benchmark values for female endurance athletes aiming for gold medals.

Conclusions

Our present findings reveal that world-class female skiers attain higher average speeds and exhibit higher peak oxygen uptake, both on uphill and flat terrain, than national-class female competitors with a lower level of performance. This clearly highlights the importance of both high aerobic power and the ability to utilize this capacity while skiing on varying terrain. Although cross-country skiing, in general, demands efficient skiing, the gross efficiency of the WC and NC skiers examined here did not differ. During the 6-month preparation training period, the WC skiers executed more endurance training of low- and moderate-intensity, as well as more speed and strength training. It is likely that this pattern of training contributed to their success and, in that case, provides benchmark values for female endurance skiers striving for medals. However, experiments designed to provide data that might support this conclusion are almost entirely lacking and substantial variations within the WC group also highlight individual

approaches, demonstrating the importance of matching the training routine to the unique characteristics of each skier.

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FIGURE LEGENDS

FIGURE 1- Speed, cycle rate and cycle length for every 30-s period during the 3-min self-paced performance tests while roller skiing with the double poling (A-C) and diagonal stride (D-F) techniques for six world-class (filled circles) and six national-class (open circles) female cross-country skiers

* $P < 0.05$ in comparison to the corresponding value for the NC group

FIGURE 2- Total training volume categorized according to intensity (A) or mode (B) during the six months (May-October) prior to the competition season for six world-class (left) and six national-class (right) female cross-country skiers

LIT = low-intensity endurance training; MIT = moderate-intensity endurance training; HIT = high-intensity endurance training.

* $P < 0.05$, # $P < 0.1$ in comparison to the corresponding value for the NC group

FIGURE 3- Total training volume categorized according to intensity (A) and mode (B) for each of the six months prior to the competition season for six world-class (WC) and six national-class (NC) female cross-country skiers

LIT = low-intensity endurance training; MIT = moderate-intensity endurance training; HIT = high-intensity endurance training.

Supplemental Digital Content

Appendix.docx—typical training week for the WC and six NC skiers at low altitude during the preparation period

Figure 1

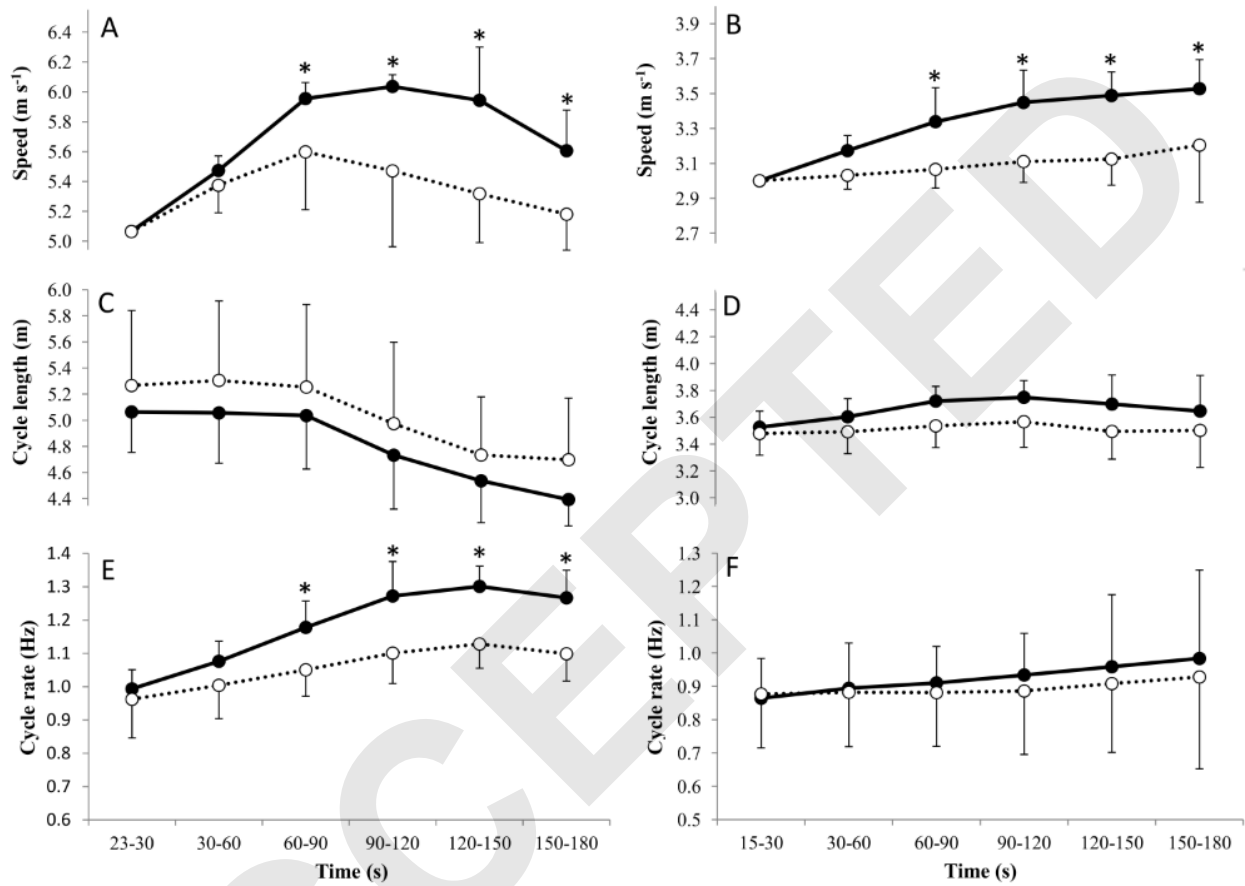
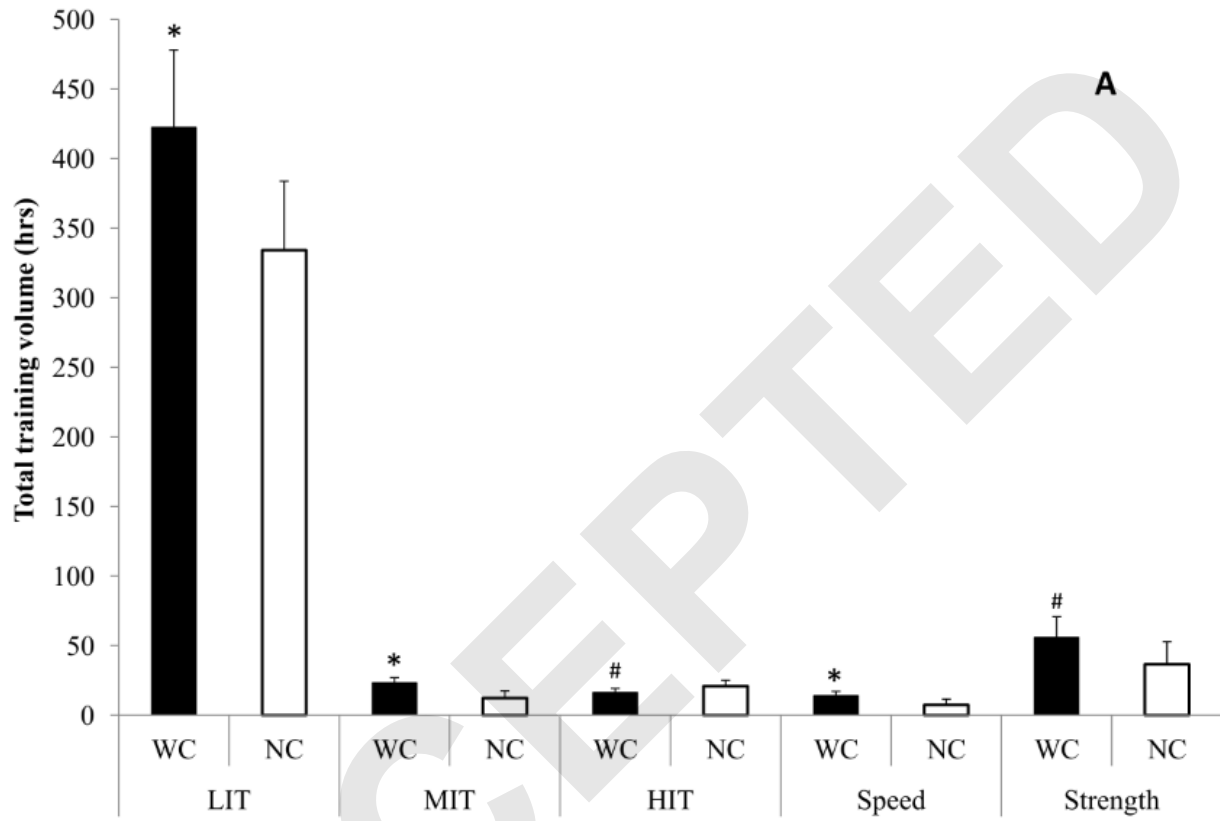


Figure 2



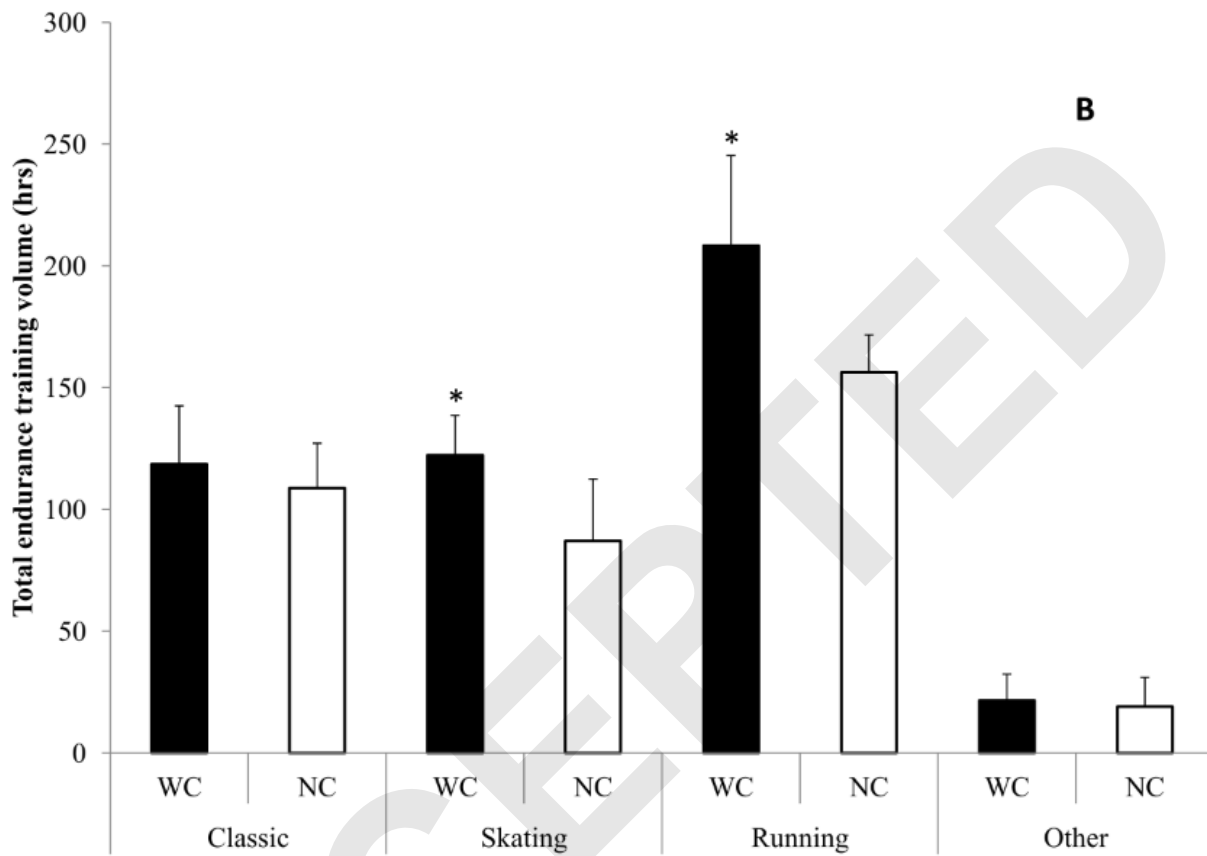
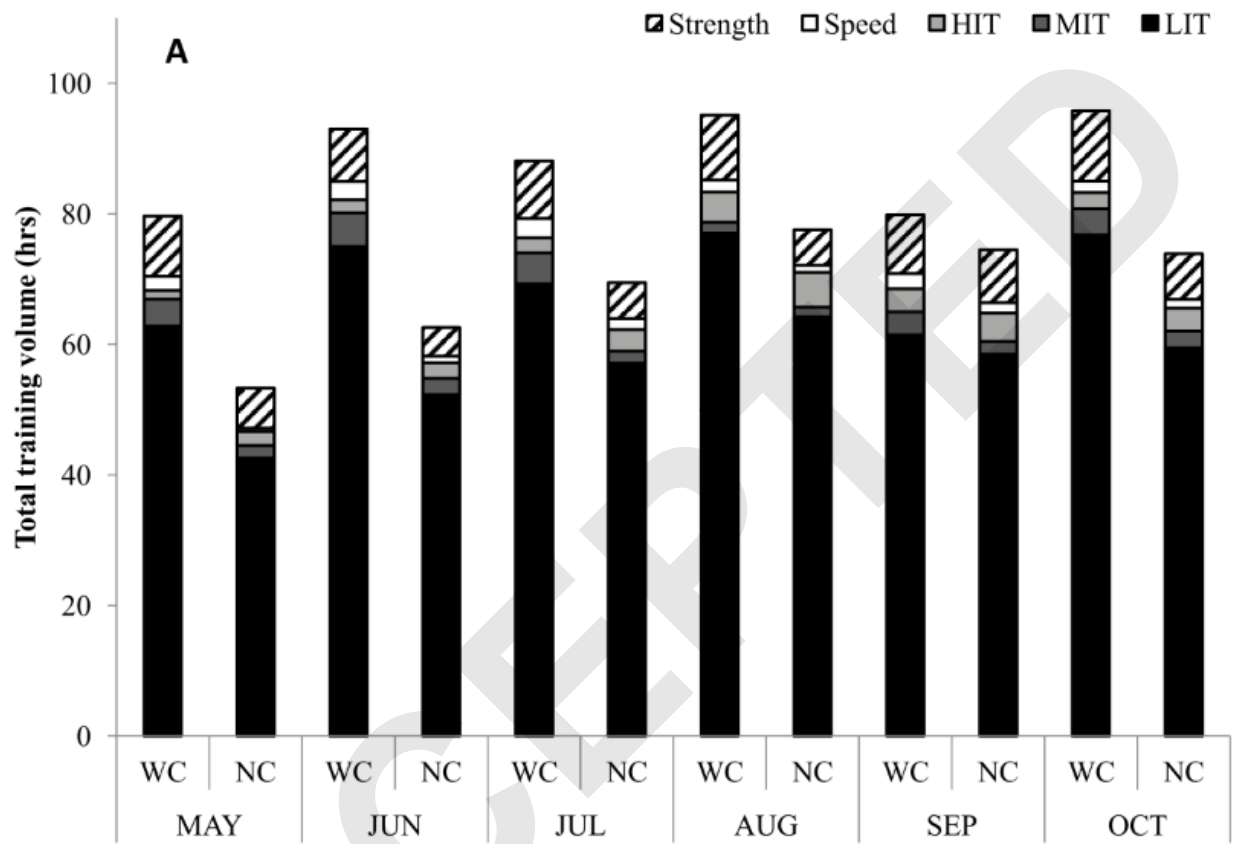


Figure 3



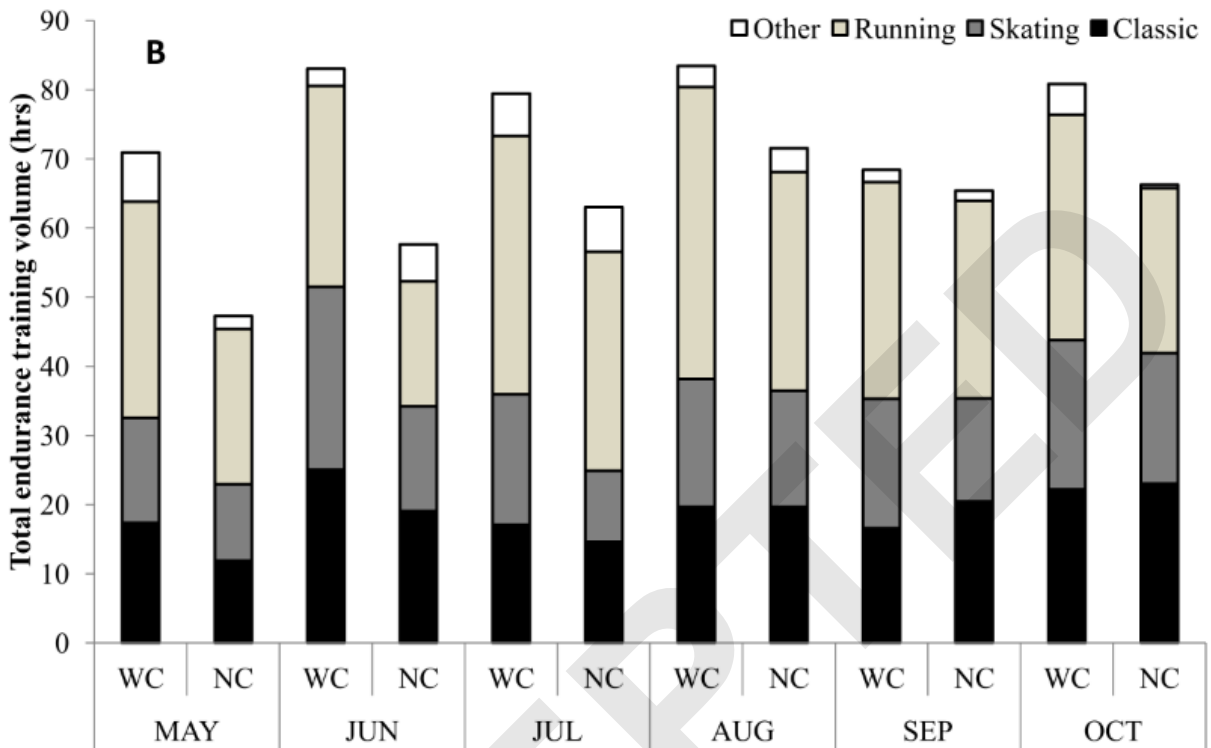


TABLE 1. Characteristics (means \pm SD) of the six world-class (WC) and six national-class (NC) female cross-country skiers who participated in this study

	WC	NC
Age (yrs)	26.0 \pm 4.3	24.4 \pm 4.2
Body height (cm)	165.0 \pm 3.9 [#]	169.5 \pm 2.6
Body mass (kg)	60.0 \pm 5.1	62.6 \pm 5.8
Body Mass Index (kg·m ⁻²)	22.0 \pm 1.1	21.7 \pm 1.5
Training hours per year	920 \pm 81*	709 \pm 75
FIS points	8 \pm 10*	72 \pm 22

* $P < 0.05$, [#] $P < 0.1$ in comparison to the corresponding value for the NC group

FIS = International Ski Federation

TABLE 2. Physiological responses and cycle characteristics (means \pm SD) during submaximal roller skiing employing the double poling (3% incline) and diagonal stride (12% incline) technique for six world-class (WC) and six national-class (NC) female cross-country skiers

	Double poling at 3.5 m·s ⁻¹		Diagonal stride at 2.25 m·s ⁻¹	
	WC	NC	WC	NC
VO ₂ (L·min ⁻¹)	2.30 \pm 0.24	2.39 \pm 0.30	3.24 \pm 0.24	3.26 \pm 0.27
VO ₂ (mL·min ⁻¹ ·kg ⁻¹)	38.3 \pm 2.3	38.2 \pm 2.6	54.0 \pm 1.5 [#]	52.2 \pm 1.4
% VO _{2peak} ^a	59 \pm 5*	65 \pm 7	76 \pm 2*	80 \pm 3
Ventilation (L·min ⁻¹)	72 \pm 7	68 \pm 13	91 \pm 11	89 \pm 15
Respiratory exchange ratio	0.89 \pm 0.04	0.91 \pm 0.04	0.86 \pm 0.02*	0.90 \pm 0.03
Heart rate (beats·min ⁻¹)	132 \pm 15*	160 \pm 18	153 \pm 13*	176 \pm 12
% of peak heart rate ^a	74 \pm 6*	85 \pm 8	84 \pm 5*	94 \pm 5
[Blood lactate] (mmol·L ⁻¹)	1.5 \pm 0.3*	2.3 \pm 0.7	1.5 \pm 0.6 [#]	3.0 \pm 1.5
RPE (Borg scale)	11 \pm 2*	13 \pm 1	13 \pm 2*	15 \pm 1
Work rate (W)	123 \pm 10	128 \pm 11	206 \pm 17	214 \pm 19
Metabolic rate (W)	787 \pm 79	822 \pm 107	1101 \pm 85	1122 \pm 89
Gross efficiency (%)	15.7 \pm 1.0	15.7 \pm 1.2	18.7 \pm 0.5	19.0 \pm 0.5
Cycle rate (Hz)	0.78 \pm 0.04	0.77 \pm 0.14	0.71 \pm 0.04*	0.77 \pm 0.04
Cycle length (m)	4.49 \pm 0.24	4.64 \pm 0.82	3.18 \pm 0.17 [#]	2.94 \pm 0.17

* $P < 0.05$, [#] $P < 0.1$ in comparison to the corresponding value for the NC group

^a percentage of the peak value while roller skiing with the same technique

TABLE 3. Performance and physiological responses (means \pm SD) during a 3-min self-paced performance test while roller skiing employing the double poling (3% incline) and diagonal stride (12% incline) technique for six world-class (WC) and six national-class (NC) female cross-country skiers

	Double poling		Diagonal stride	
	WC	NC	WC	NC
Distance (m)	990 \pm 31*	926 \pm 42	585 \pm 21*	548 \pm 17
Average speed (m·s ⁻¹)	19.8 \pm 0.4*	18.5 \pm 0.8	11.7 \pm 0.4*	11.0 \pm 0.4
VO ₂ peak (L·min ⁻¹)	3.88 \pm 0.20 [#]	3.70 \pm 0.34	4.24 \pm 0.24 [#]	4.06 \pm 0.38
VO ₂ peak (mL·min ⁻¹ ·kg ⁻¹)	65.0 \pm 3.3*	58.8 \pm 3.5	70.9 \pm 2.7*	65.0 \pm 3.6
Peak ventilation (L·min ⁻¹)	152 \pm 12	142 \pm 13	158 \pm 12*	142 \pm 13
Peak respiratory exchange ratio	1.10 \pm 0.06	1.13 \pm 0.02	1.10 \pm 0.04	1.10 \pm 0.06
Peak heart rate	177 \pm 10	186 \pm 8	181 \pm 9	186 \pm 5
Σ O ₂ demand (mL·kg ⁻¹)	n.d.	n.d.	223 \pm 47 [#]	206 \pm 14
Σ O ₂ deficit (mL·kg ⁻¹)	n.d.	n.d.	47 \pm 8	48 \pm 11
Σ O ₂ deficit (%)	n.d.	n.d.	21.8 \pm 2.4	22.8 \pm 3.6
Peak [blood lactate] (mmol·L ⁻¹)	9.4 \pm 1.5	9.4 \pm 1.5	11.4 \pm 1.9	10.4 \pm 1.9

* $P < 0.05$, [#] $P < 0.1$ in comparison to the corresponding value for the NC group

n.d. = not determined

APPENDIX. A typical training week for our six world-class (WC) and six national-class (NC) female cross-country skiers at low altitude during the preparation period.

Day	WC	NC
Monday	AM: 5 x 5-min HIT*, uphill running/walking with poles PM: 1.5 hrs LIT, roller ski skating in varying terrain	AM: 6 x 4-min HIT*, uphill running with poles PM: 0.5 hrs LIT, running
Tuesday	AM: 1.5 hrs LIT/MIT, classic roller skiing with double poling PM: 2 hrs LIT, running	AM: 2 hrs LIT, classic roller skiing in varying terrain PM: Rest
Wednesday	AM: 1.5 hrs, LIT roller ski skating, incl. 10 x 12-s sprints PM: Strength training [#]	AM: 1.5 hrs LIT, roller ski skating PM: Warm-up + 30 min strength training
Thursday	AM: 2.5 hrs LIT, running on soft surfaces PM: Rest	AM: 2 hrs LIT, running on soft surfaces PM: Rest
Friday	AM: 7 x 8-min MIT*, roller ski skating PM: 1.5 hrs LIT, classic roller skiing	AM: 5 x 6-min MIT/HIT*, roller ski skating PM: 1 hrs LIT, classic roller skiing, incl. 8 x 10-15-s sprints
Saturday	AM: 10 x 10 maximal jumps + strength training [#] PM: 1.5 hrs LIT, classic roller skiing, incl. 8 x 10-15-s sprints	AM: Strength training [#] PM: 1.5 hrs LIT, classic roller skiing
Sunday	AM: 3.5 hrs LIT, running on soft surfaces PM: Rest	AM: 2.5 hrs LIT, running on soft surfaces PM: Rest

LIT = low-intensity training: blood lactate concentration < 2.5 mmol/L, heart rate < 81% max.

MIT = moderate-intensity training: blood lactate concentration 2.5-4.0 mmol/L, heart rate 81-87% max.

HIT = high-intensity training: blood lactate concentration 4.0-10.0 mmol/L, heart rate > 87% max.

* MIT and HIT sessions routinely included approximately 40-60 min of LIT, as warm-up and cool-down.

Strength sessions typically consisted of 30 minutes low-intensity warm-up (running/cycling) followed by 15-30 min maximal upper-body strength training and 30-45 min core/stabilization exercises