

# Gender differences in the physiological responses and kinematic behaviour of elite sprint cross-country skiers

Øyvind Sandbakk · Gertjan Ettema ·  
Stig Leirdal · Hans-Christer Holmberg

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**Abstract** Gender differences in performance by elite endurance athletes, including runners, track cyclists and speed skaters, have been shown to be approximately 12%. The present study was designed to examine gender differences in physiological responses and kinematics associated with sprint cross-country skiing. Eight male and eight female elite sprint cross-country skiers, matched for performance, carried out a submaximal test, a test of maximal aerobic capacity ( $VO_{2max}$ ) and a shorter test of maximal treadmill speed ( $V_{max}$ ) during treadmill roller skiing utilizing the G3 skating technique. The men attained 17% higher speeds during both the  $VO_{2max}$  and the  $V_{max}$  tests ( $P < 0.05$  in both cases), differences that were reduced to 9% upon normalization for fat-free body mass. Furthermore, the men exhibited 14 and 7% higher  $VO_{2max}$  relative to total and fat-free body mass, respectively ( $P < 0.05$  in both cases). The gross efficiency was similar for both gender groups. At the same absolute speed, men employed 11% longer cycles at lower rates, and at peak speed, 21% longer cycle lengths ( $P < 0.05$  in all cases). The current study documents approximately 5% larger gender differences in performance and  $VO_{2max}$  than those reported for comparable endurance sports. These differences reflect primarily the higher  $VO_{2max}$

and lower percentage of body fat in men, since no gender differences in the ability to convert metabolic rate into work rate and speed were observed. With regards to kinematics, the gender difference in performance was explained by cycle length, not by cycle rate.

**Keywords** Cross-country skiing · Efficiency · Maximal oxygen uptake · Men · Skating · Women

## Introduction

In recent decades, evaluation of successful athletes have been performed (Joyner and Coyle 2008; Saltin and Åstrand 1967), and gender differences in the performance of elite runners, track cyclists, swimmers and speed skaters of approximately 12% are revealed (Coast et al. 2004; Joyner 1993; Maldonado-Martin et al. 2004; Schumacher et al. 2001; Seiler et al. 2007). However, to our knowledge, possible gender differences in the performance of cross-country skiers have not yet been examined.

Elite cross-country skiing demands endurance in a variety of terrains and involves whole-body exercise, thereby requiring high maximal oxygen uptake ( $VO_{2max}$ ) and well-trained arms and legs (Holmberg 2009). Moreover, in the shorter sprint races, gross efficiency and peak/maximal speed influence performance significantly (Mikkola et al. 2010; Sandbakk et al. 2010a, b; Stöggl et al. 2007; Vesterinen et al. 2009). Accordingly, highly trained sprint skiers are appropriate subjects for the evaluation of gender differences with respect to both speed and endurance of whole-body exercise.

Gender differences in endurance performance are generally explained by a lower percentage of body fat and higher  $VO_{2max}$  in men (Calbet and Joyner 2010; Joyner

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Ø. Sandbakk (✉) · G. Ettema · S. Leirdal  
Department of Human Movement Science,  
Norwegian University of Science and Technology,  
7491 Trondheim, Norway  
e-mail: oyvind.sandbakk@svt.ntnu.no

H.-C. Holmberg  
Department of Health Sciences,  
Swedish Winter Sports Research Centre,  
Mid Sweden University, Östersund, Sweden

1993), amongst others. Thus, relative to fat-free body mass, the differences in  $\dot{V}O_{2\max}$  and endurance performance between men and women with comparable training are smaller, but still significant. This is likely due to the higher levels of hemoglobin in men (Astrand 1956; Calbet and Joyner 2010; Joyner 1993). On the other hand, no gender differences in strength and power are found in team handball players when normalised for fat-free body mass (van den Tillaar and Ettema 2004).

The present investigation was designed to examine gender differences in elite sprint cross-country skiers with regards to overall performance, physiological characteristics and kinematics. In addition, we analyzed the extent to which such gender differences can be explained by differences in body fat.

## Methods

### Subjects

Eight male and eight female Norwegian elite cross-country skiers, whose results in sprint competitions were among the top 30 in the World Cup, volunteered to participate in this study. These two gender groups were similar with regards to sprint performance on snow (FIS points), as calculated by the International Ski Federation (FIS 2009), and their background characteristics are shown in Table 1. This study was pre-approved by the Regional Ethics Committee, Trondheim, Norway, and all subjects were fully informed of its nature prior to providing their written consent to participate.

### Overall Design

All subjects were tested for performance, physiological response and kinematics in connection with three tests on a treadmill with roller skis employing the G3 skating

**Table 1** The anthropometric characteristics, annual training time and level of sprint performance (expressed as FIS points) in eight male and eight female elite sprint cross-country skiers

Subjects	Men	Women
Age (years)	25.8 ± 2.2	24.1 ± 2.4
Body height (cm)	183.8 ± 5.1*	168.0 ± 2.8
Body mass (kg)	83.3 ± 7.2*	60.1 ± 4.7
Body mass index ( $\text{kg m}^{-2}$ )	24.6 ± 0.6*	21.3 ± 1.4
Body fat (%)	8.5 ± 2.3*	14.5 ± 2.0
Fat-free body mass (kg)	76.1 ± 6.0*	51.3 ± 3.2
Training (h)	673 ± 96	686 ± 65
FIS points	49.9 ± 12.0	49.0 ± 14.3

All values presented are means ± SD

\*  $P < 0.001$  in comparison to the women

technique (Andersson et al. 2010) as follows: (1) a test consisting of three 5-min stages at increasing levels of submaximal performance; (2) one ~5 min-long test of maximal aerobic capacity ( $\dot{V}O_{2\max}$ ); and (3) one ~1 min-long test of maximal treadmill speed ( $V_{\max}$ ).

### Instruments and materials

Respiratory parameters were measured employing open-circuit, indirect calorimetry with an Oxycon Pro apparatus (Jaeger GmbH, Hoechberg, Germany). Prior to each measurement, the gas analyzers were calibrated using a mixture of gases of highly exact composition (i.e.,  $16.00 \pm 0.04\%$   $O_2$  and  $5.00 \pm 0.1\%$   $CO_2$ , Riessner-Gase GmbH & Co, Lichtenfels, Germany) and the expiratory flow meter calibrated with a 3-L syringe (Hans Rudolph Inc., Kansas City, MO). Heart rate (HR) was assessed with a monitor designed for this purpose (Polar RS800, Polar Electro OY, Kempele, Finland) and the 5  $\mu\text{L}$  of blood taken from the fingertip to determine blood lactate concentration (BLa) was assayed with the Lactate Pro LT-1710t (ArkRay Inc., Kyoto, Japan), as validated by Medbo et al. (2000) Body mass was determined on a Kistler force plate (Kistler 9286AA, Kistler Instrument Corp., Winterthur, Switzerland) and body height on a calibrated stadiometer (Holtain Ltd., Crosswell, UK). The percentage of body fat was estimated from skinfold measurements at four different sites (Holtain Skinfold caliper PE025, Holtain Ltd., Crosswell, UK), applying the calculations of Durnin and Womersley (Durnin and Womersley 1973) to the men and women.

All tests were performed on a  $6 \times 3$  m motor-driven treadmill (Bonte Technology, Zwolle, the Netherlands), the inclination and speed of which were calibrated using the Qualisys Pro Reflex system and the Qualisys Track Manager software (Qualisys AB, Gothenburg, Sweden). The non-slip rubber surface of the treadmill belt allowed the subjects to use their own ski poles (with a mean length of  $90 \pm 1\%$  of body height for both genders) after equipping these with special carbide tips. The subjects were secured to the treadmill with a safety harness during testing.

In order to minimize variations in resistance, all subjects used the same pair of skating roller skis with standard wheels (Swenor Roller skis, Troesken, Norway), which were pre-warmed before each test by 20 min of roller skiing on the treadmill, and tested for rolling friction force ( $F_f$ ) with the towing test previously described by Sandbakk et al. (2010a). The rolling friction coefficient ( $\mu$ ) was determined by dividing  $F_f$  by the normal force ( $F_n$ ) ( $\mu = F_f \cdot F_n^{-1}$ ) and the  $\mu$ -value thus obtained was employed to calculate work rate. Two synchronized 50-Hz Sony video cameras (Sony Handycam DCR-VX2000E, Sony Inc., Tokyo, Japan) fixed to the front and side of the treadmill recorded kinematics for

analysis by the Dartfish Pro 4.5 program (Dartfish Ltd., Fribourg, Switzerland).

## Test protocols and measurements

### *The submaximal test*

Physiological responses in connection with submaximal exertion were monitored during three 5-min sessions of treadmill skiing at 5% inclination, with a 1-min rest between sessions and a  $0.3 \text{ m s}^{-1}$  increase in speed for each successive stage. The initial speeds were  $3.9$  and  $3.6 \text{ m s}^{-1}$  for men and women, respectively. The gender groups were compared both at the same absolute speed ( $3.9 \text{ m s}^{-1}$ ) and at the speed at which blood lactate began to accumulate (OBLA) (defined as a concentration of  $4 \text{ mmol L}^{-1}$ , as calculated by a linearly interpolated point out of the three measurement points of BLA (Sjodin et al. 1982)).  $\text{VO}_2$ ,  $\text{VCO}_2$  and HR were monitored continuously and the average values for the final minute are presented. BLA was measured immediately after completion of each session.

Gross efficiency was calculated as the work rate divided by the metabolic rate under steady-state conditions. The work rate was calculated as the sum of power against gravity ( $P_g$ ) and friction ( $P_f$ ). The metabolic rate was determined from the values for  $\text{VO}_2$  and  $\text{VCO}_2$  utilizing the associated RER and standard conversion tables (Peronnet and Massicotte 1991). The current study used two methods to compare work economy at the same absolute speed: (a)  $\text{VO}_2$  and (b) metabolic rate, with both values normalized for total body mass.

### *Testing maximal aerobic capacity*

Maximal aerobic capacity was assessed with treadmill skiing at a 5% inclination at an initial speed of  $4.4$  and  $3.9 \text{ m s}^{-1}$  for men and women, respectively. The subsequent incremental increases in this speed were  $0.6 \text{ m s}^{-1}$  for minutes one and two and thereafter  $0.3 \text{ m s}^{-1}$  every minute until exhaustion, in accordance with earlier studies by Sandbakk et al. (2010a, b). A maximal level of effort was considered to have been attained if two of the following three criteria were met: (1) a plateau in  $\text{VO}_2$  despite increased exercise intensity, (2) a RER value  $> 1.10$ , and (3) a peak BLA  $> 8 \text{ mmol L}^{-1}$ .  $\text{VO}_2$  was monitored continuously, and the average of the three highest 10-s consecutive values was defined as  $\text{VO}_{2\text{max}}$ . The maximal HR obtained during the test was also recorded. BLA was assayed 1, 3, 6 and 10 min after completion of the test (with continuously skiing at  $2 \text{ m s}^{-1}$  between these measurements) and the highest of these four values designated as peak BLA. Clearance of blood lactate was examined according to a modification of McMaster et al. (1989) and calculated as the

peak concentration minus the level 10 min after completion of the test according to Sandbakk et al. (2010a).

### *Testing of maximal treadmill speed*

Maximal treadmill speed testing (at 8% inclination) was tested using a modified protocol introduced by Stöggl et al. (2006). This protocol was initiated by skiing for 30 s at medium intensity ( $3.9 \text{ m s}^{-1}$ ), before the speed was elevated to the initial level of  $4.4 \text{ m s}^{-1}$ , for both men and women. Thereafter, the treadmill was speeded up by  $0.3 \text{ m s}^{-1}$  every 10 s until exhaustion was reached, in accordance with earlier studies by Sandbakk et al. (2010a, b).

For the assessment of  $\text{VO}_{2\text{max}}$  and  $V_{\text{max}}$  exhaustion was defined as the time at which the subject was no longer able to maintain the front wheels of the roller skis' in front of a marker located 4 m behind the front edge of the treadmill. Peak speed for the  $\text{VO}_{2\text{max}}$  test and maximal treadmill speed in the  $V_{\text{max}}$  test as  $v = V_f + [(t \cdot T^{-1}) \cdot V_d]$ , where  $V_f$  was the speed associated with the final workload achieved,  $t$  the duration for which this final workload was maintained,  $T$  the duration of each individual workload and  $V_d$  the difference in the speeds associated with the last two workloads (Holmberg et al. 2005). Peak speed and maximal treadmill speed was used to assess peak and maximal work rates in the  $\text{VO}_{2\text{max}}$  and  $V_{\text{max}}$  test.

### *Kinematic analyses*

The cycle time was determined as the average time between two pole plants during six cycles of poling. This means that one cycle is defined from one pole plant to the next pole plant on the same push-off side in the G3 skating technique. The cycle length was calculated as the speed multiplied by the cycle time and the cycle rate as the reciprocal of cycle time. These kinematic parameters were assessed both during the final minute of skiing at the submaximal speed of  $3.9 \text{ m s}^{-1}$  and during the final 30-s workload in the  $\text{VO}_{2\text{max}}$  test (peak speed).

### *Scaling models*

To evaluate their effect on performance, work rate and oxygen uptake were normalized for total body mass. Moreover, these parameters were normalized for fat-free body mass to examine whether differences in fat mass could explain any gender differences observed. Fat-free body mass was calculated as the fat mass subtracted from the total body mass. In all cases considered in this study the best power fit was performed for variables of interest against body mass according to  $y = a + b (\text{mass})^s$ . In all cases considered in this study the mass exponent  $s$  was not significantly different from 1. Thus, a simpler linear

regression was used to compare regression lines between genders (see below).

### Statistical analysis

All data were found to be normally distributed utilizing a Shapiro-Wilks test and are presented as means  $\pm$  standard deviations (SD). The groups were compared employing the independent *t*-test procedure with alpha levels adjusted according to Bonferroni. Relationships between variables were analyzed by linear regression. When the values for both groups demonstrated significant linear regression constants, their slopes and intercepts were compared according to Crowder and Hand (1990). When this regression constant was significant for only one of the groups, we predicted the “hypothetical” individual values of the group with a non-significant regression, based on the significant regression line of the other group. Thereafter, we applied a dependent *t*-test to determine whether each individual’s actual values differed from the predicted ones. All statistical analyses were processed using the SPSS 11.0 Software for Windows (SPSS Inc., Chicago, IL), with an  $\alpha$  value of  $< 0.05$  being considered significant.

## Results

Physiological responses associated with submaximal and maximal exertion

### Comparison at the same absolute speed ( $3.9 \text{ m s}^{-1}$ )

As depicted in Table 2, at this speed men exhibited 36% higher absolute  $\text{VO}_2$  values and 39% higher work rates ( $P < 0.05$  in both cases). When normalized for total body mass there was no gender difference in  $\text{VO}_2$  or metabolic rate (i.e., work economy), while in relationship to fat-free body mass, the men exhibited 8% lower  $\text{VO}_2$  compared with the women ( $P < 0.05$ ). Furthermore, the percentages of  $\text{VO}_{2\text{max}}$  and peak HR at which the men worked were 12 and 9% lower, respectively, than for the women and the men also had lower BLa ( $P < 0.05$  in all cases). Graphing metabolic rate against work rate produced virtually identical regression lines for both groups, with no difference in slope or intercept (Fig. 1). Thus, the small, but non-significant gender difference with respect to gross efficiency was solely an effect of the higher male work rates.

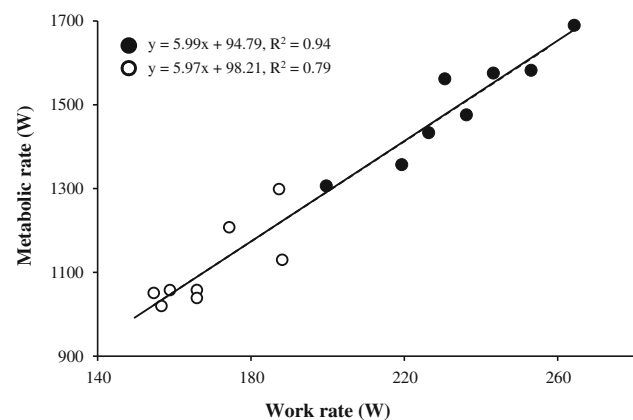
### Comparison at the same relative intensity of exertion (OBLA)

Although, the men demonstrated higher absolute speed ( $4.3 \pm 0.2$  vs.  $3.9 \pm 0.3 \text{ m s}^{-1}$ ,  $P < 0.05$ ), the percentages

**Table 2** Physiological responses and kinematics in eight male and eight female elite sprint cross-country skiers in connection with submaximal treadmill roller skiing

Parameter	Men	Women
Work rate (W)	$234 \pm 20^{**}$	$169 \pm 13$
$\text{VO}_2$ ( $\text{L min}^{-1}$ )	$4.32 \pm 0.38^{**}$	$3.18 \pm 0.27$
$\text{VO}_2$ ( $\text{mL min}^{-1} \text{ kg}^{-1}$ ) <sup>TBM</sup>	$52.0 \pm 1.7$	$52.9 \pm 2.9$
$\text{VO}_2$ ( $\text{mL min}^{-1} \text{ kg}^{-1}$ ) <sup>FFBM</sup>	$56.8 \pm 2.5^{**}$	$60.9 \pm 3.6$
$\text{VO}_2$ in % of $\text{VO}_{2\text{max}}$	$74.9 \pm 4.3^{**}$	$87.1 \pm 3.7$
HR (bpm)	$165 \pm 11^{**}$	$182 \pm 5$
HR in % of peak HR	$85.7 \pm 4.2^{**}$	$92.9 \pm 3.6$
BLa ( $\text{mmol L}^{-1}$ )	$3.2 \pm 0.5^{**}$	$4.2 \pm 1.1$
RER	$0.94 \pm 0.02$	$0.95 \pm 0.02$
Gross efficiency (%)	$15.4 \pm 0.4$	$15.2 \pm 0.9$
Cycle length (m)	$7.6 \pm 0.4^{**}$	$6.9 \pm 0.5$
Cycle rate (Hz)	$0.51 \pm 0.03^{**}$	$0.57 \pm 0.04$

5 min at  $3.9 \text{ m s}^{-1}$  with an incline of 5% employing the G3 technique  
 BLa blood lactate concentration, RER respiratory exchange ratio, HR heart rate, TBM normalized for total body mass, FFBM normalized for fat-free body mass. All values presented are means  $\pm$  SD.  
 $^{**} P < 0.01$  in comparison to the women



**Fig. 1** Submaximal metabolic rates in relationship to work rates for male and female elite sprint cross-country skiers while treadmill roller-ski skating at the same absolute speed ( $3.9 \text{ m s}^{-1}$ ). Individual values and significant trend lines (based on linear regression) are shown for both the men (filled circles and straight line) and women (open circles and dashed line)

of peak speed achieved by the men and women in connection with the  $\text{VO}_{2\text{max}}$  test did not differ ( $71.0 \pm 2.8\%$  vs.  $74.7 \pm 3.9\%$ ,  $P = 0.36$ ). In relationship to total body mass absolute  $\text{VO}_2$  was higher in the men ( $56.5 \pm 3.3$  vs.  $53.3 \pm 3.2 \text{ mL kg}^{-1} \text{ min}^{-1}$ ,  $P < 0.05$ ), but as a percentage of  $\text{VO}_{2\text{max}}$ , this value was higher in the women ( $87.6 \pm 2.6\%$  vs.  $81.3 \pm 3.9\%$ ,  $P < 0.05$ ). When normalized for fat-free body mass,  $\text{VO}_2$  and work rate at OBLA were similar in the men and women ( $61.7 \pm 3.5$  vs.

**Table 3** Physiological responses, performance and kinematics in eight male and eight female elite sprint cross-country skiers performing incremental treadmill roller skiing employing the G3 skating technique

Parameter	Men	Women
TTE (s) <sup>a</sup>	299 ± 71	232 ± 35
Peak speed (m s <sup>-1</sup> )	6.1 ± 0.3**	5.2 ± 0.2
Work rate (W)	368 ± 34**	227 ± 16
Work rate (W kg <sup>-1</sup> ) <sup>TBM</sup>	4.4 ± 0.2**	3.8 ± 0.1
Work rate (W kg <sup>-1</sup> ) <sup>FFBM</sup>	4.8 ± 0.2*	4.4 ± 0.2
VO <sub>2max</sub> (L min <sup>-1</sup> )	5.77 ± 0.49**	3.64 ± 0.43
VO <sub>2max</sub> (mL min <sup>-1</sup> kg <sup>-1</sup> ) <sup>TBM</sup>	69.5 ± 3.7**	60.8 ± 3.8
VO <sub>2max</sub> (mL min <sup>-1</sup> kg <sup>-1</sup> ) <sup>FFBM</sup>	76.0 ± 4.1*	71.1 ± 4.3
Peak HR (bpm)	193 ± 6	196 ± 7
Peak RER	1.12 ± 0.03	1.11 ± 0.02
Peak BLA (mmol L <sup>-1</sup> )	13.3 ± 1.5	12.0 ± 1.9
ΔBLA (mmol L <sup>-1</sup> )	4.9 ± 0.9	4.8 ± 1.0
Peak cycle length (m)	9.9 ± 0.9**	8.2 ± 0.7
Peak cycle rate (Hz)	0.63 ± 0.04	0.64 ± 0.03

All values presented are means ± SD

ΔBLA blood lactate clearance 10 min after the test, BLA blood lactate concentration, HR heart rate, RER respiratory exchange ratio, TTE time to exhaustion, TBM normalized for total body mass, FFBM normalized for fat-free body mass

\*  $P < 0.05$  and \*\*  $P < 0.01$  compared to women

<sup>a</sup> note that men and women use different protocols

62.3 ± 3.5 mL kg<sup>-1</sup> min<sup>-1</sup> ( $P = 0.59$ ) and 3.4 ± 0.1 vs. 3.3 ± 0.2 W kg<sup>-1</sup> ( $P = 0.28$ ), respectively).

### Maximal aerobic capacity

As documented in Table 3, men exhibited 17% higher peak speed at a 62% higher peak work rate in the VO<sub>2max</sub> test ( $P < 0.05$ ). After normalization for total and fat-free body mass, the gender differences in peak work rates were 17 and 9%, respectively ( $P < 0.05$  in both cases). Comparison of the regression lines reveals gender differences in the intercepts ( $P < 0.05$ ), but not in the slopes (Fig. 2A, B).

In absolute terms the men exhibited a 59% higher VO<sub>2max</sub>, whereas relative to total and fat-free body mass the gender difference in this parameter was only 14 and 7%, respectively ( $P < 0.05$  in all cases). In the graphs of VO<sub>2max</sub> against total and fat-free body mass, the regression lines for the women were significantly below those for the men ( $P < 0.05$  in both cases). No significant gender differences in peak BLA, maximal HR, peak RER or clearance of blood lactate were found in connection with the VO<sub>2max</sub> test. The women's hemoglobin levels were ~10% lower than the men's (~13.5 vs. ~15.0 g dL<sup>-1</sup>).

### Testing at maximal treadmill speed

The maximal treadmill speed ( $V_{max}$ ) was 6.6 ± 0.2 m s<sup>-1</sup> for the men and 5.6 ± 0.1 m s<sup>-1</sup> for the women (a difference of 17%) and the time to exhaustion demonstrated by the men was 35 s longer ( $P < 0.05$  in both cases). This corresponds to 63, 17 and 10% higher work rates in the men expressed as absolute values (557 ± 47 vs. 342 ± 27 W), or relative to total (6.7 ± 0.2 vs. 5.7 ± 0.1 W kg<sup>-1</sup>) or fat-free body mass (7.3 ± 0.3 vs. 6.7 ± 0.2 W kg<sup>-1</sup>), respectively ( $P < 0.05$  in all cases).

### Kinematics

At the same absolute submaximal speed (3.9 m s<sup>-1</sup>), the men employed 11% longer cycle lengths at 11% slower cycle rates (Table 2,  $P < 0.05$  in both cases). At peak speed during the VO<sub>2max</sub> test, the men's cycle lengths were 21% longer ( $P < 0.05$ ), with no significant difference in cycle rates (Table 3). Neither cycle length nor rate showed any relationship to total or fat-free body mass or height.

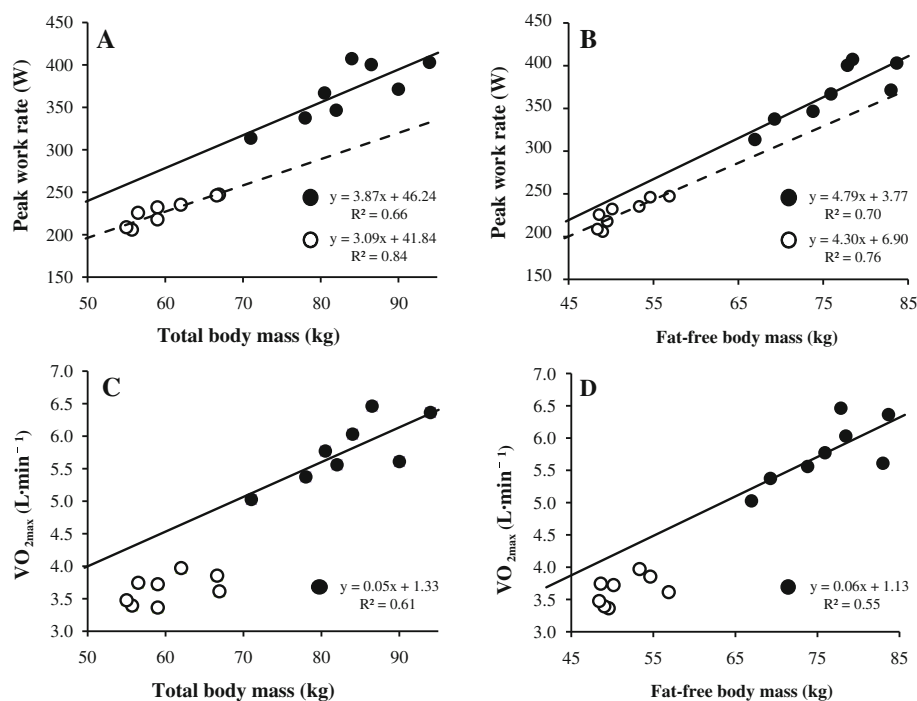
### Discussion

In the present examination of possible gender differences among elite sprint cross-country skiers with respect to performance, physiological parameters and kinematics while using the G3 skating technique, the major findings were as follows: (1) the men attained a 17% higher peak speed and maximal treadmill speed (i.e., work rates) in connection with the VO<sub>2max</sub> test (approximately 5 min in duration) and the  $V_{max}$  test (approximately 1 min); (2) normalized for fat-free, rather than total body mass, the gender differences in peak and maximal work rates in both performance tests were approximately ~50% smaller; (3) absolute VO<sub>2max</sub> values were 59% higher in the men, whereas relative to total and fat-free body mass the relative VO<sub>2max</sub> values were only 14 and 7% higher, respectively; (4) at the same submaximal speed, the gross efficiency and work economy of the men and women did not differ; (5) at OBLA, women utilized a higher proportion of their VO<sub>2max</sub>; and (6) the male skiers employed 11% longer cycle lengths at lower cycle rates at the same absolute submaximal speed, as well as 21% longer cycle lengths at peak speed in the VO<sub>2max</sub> test.

### Performance

The 17% gender difference in peak speed and maximal treadmill speed observed in the current study is greater than the ~12% gender differences in performance reported in

**Fig. 2 A-D** Peak work rates and  $VO_{2max}$  in relationship to total and fat-free body mass in male and female elite sprint cross-country skiers while performing treadmill roller-ski skating. Individual values and significant trend lines (based on linear regression) are shown for both the men (filled circles and straight line) and women (open circles and dashed line)



connection with running, cycling, swimming or speed skating (Coast et al. 2004; Maldonado-Martin et al. 2004; Schumacher et al. 2001; Seiler et al. 2007). Several investigations have highlighted the importance of upper body strength and endurance, as well as sufficient muscle mass in the upper body to skiing performance (Hoff et al. 1999; Larsson and Henriksson-Larsén 2008; Nilsson et al. 2004; Stöggl et al. 2010; Terzis et al. 2006). Whether male skiers have an advantageous upper body composition and/or more well-trained upper body muscles are important questions for further examination.

Performance in the tests employed here, with time to exhaustion during incremental protocols, is strongly correlated to sprint time-trial performance (Sandbakk et al. 2010b) and was therefore considered appropriate for comparison to other reports that have assessed endurance performance on the basis of time over a given distance. Moreover, the 17% gender differences observed here are similar to the differences in mean speed between men and women in sprint time-trials over similar tracks during the two previous World Cup seasons (FIS 2009).

In agreement with Batterham et al. (1999), when work rate and  $VO_2$  were plotted against total and fat-free body mass, a mass exponent of 1 gave a reasonable good fit. Thus, normalizing for total and fat-free body mass appears to be more appropriate than applying allometric principles. Normalized for fat-free body mass, the gender differences in peak and maximal work rate in both performance tests were 50% less than when normalized for total body mass,

but were nonetheless still statistically significant. Apparently, the natural difference in fat percentage between genders strongly affects this comparison. However, fat-free body mass, i.e., an indirect measure of the size of the work generating muscle mass (assuming non-fat/muscular mass is unaffected by training and behaviour), does not explain all of the gender differences. This observation indicates that factors other than percentage body fat and muscle mass contribute to the differences in the performance of male and female cross-country skiers. In this connection, differences in  $VO_{2max}$ , fractional utilization of  $VO_{2max}$ , gross efficiency and anaerobic capacity have been proposed as potential explanations for performance variations among sprint skiers (Sandbakk et al. 2010a, b). Therefore, these parameters were analyzed in the current study and will be further discussed in the following sections of this paper.

#### Physiological parameters

The 59% higher absolute  $VO_{2max}$  exhibited by the male skiers was reduced to 14% when normalized for total body mass. Such gender differences in  $VO_{2max}$  are in agreement with comparisons of male and female elite cross-country skiers'  $VO_{2max}$  made across several decades (Ingjer 1991; Saltin and Astrand 1967). Thus, the gender difference in  $VO_{2max}$  among elite cross-country skiers might be somewhat higher than the approximately 10% difference found in elite endurance athletes engaged in other sports (Joyner and Coyle 2008; Pate et al. 1987).

Most investigators conclude that gender differences in  $VO_{2\max}$  reflect the higher percentage of body fat and lower hemoglobin levels in women (Astrand 1956; Calbet and Joyner 2010). Here, relative to fat-free body mass, the gender difference in  $VO_{2\max}$  was no more than 7%. The women's hemoglobin levels were approximately 10% lower than the men's ( $\sim 13.5$  vs.  $\sim 15.0$  g dL<sup>-1</sup>), which explains most of this remaining difference in this parameter.

In the current study, the women achieved a higher proportional utilization of  $VO_{2\max}$  at OBLA, a factor regarded as being of paramount importance to performance in endurance sports (Joyner and Coyle 2008; Saltin 1997) and in agreement with earlier investigations (Maldonado-Martin et al. 2004). Explanations for such differences have involved substrate utilization (Jeukendrup and Wallis 2005; Tarnopolsky et al. 1990), with more pronounced oxidation of fat during submaximal exercise by women. However, in the current study the respiratory exchange ratio does not indicate that this is the case. Gender differences in mean speeds during races over the distance of 10–50 km, with more pronounced importance for fat oxidation than sprint races, are slightly smaller than in the case of sprint races (FIS 2009). Whether this reflects higher fractional utilization of oxygen in women over longer distances remains to be determined. At the same time, less specialization among women participating in sprint skiing may also be of significance in this context.

The relationship between metabolic rate and work rate was strongly linear for both gender groups, with no significant differences in slopes or intercepts (see Fig. 1A). Work economy was similar in the men and women and there was only a small, statistically insignificant difference in gross efficiency, due solely to the higher male work rates. Thus, we conclude that male and female sprint skiers possess the same ability to convert metabolic rate into work rate and speed. A similar linear relationship was observed by Sandbakk et al. (2010a) in male world-class and national level sprint skiers. However, the gross efficiency was higher in the world-class skiers, possibly indicating differences in this parameter between different levels of performance, but not between men and women performing at the same level.

### Kinematics

At the same absolute speed, our male subjects employed 11% longer cycle lengths at lower cycle rates than the women. At peak speed, this gender difference in cycle length was enhanced to 21%, but the difference in cycle rate disappeared (0.63 vs. 0.64 Hz). Explosive strength and efficiency have recently been proposed as explanations for differences in cycle length when the G3 skating technique is utilized (Sandbakk et al. 2010a; Stöggl et al. 2010; Stöggl and Müller 2009). In the current study, where gross

efficiency was not associated with any gender difference, the difference in cycle length probably reflects the differences in  $VO_{2\max}$ , strength and power. This conclusion is supported by previous findings on the cycle lengths employed by skiers with different physical capacities while skating (Bilodeau et al. 1996; Sandbakk et al. 2010a; Stöggl et al. 2007). The difference in cycle rate vanishes at peak speed, because the male skiers reached higher skiing speeds. This is in line with earlier findings where cycle rate is shown not to be related to the differences in skating speed between skiers of different performance levels (Bilodeau et al. 1996; Stöggl and Müller 2009; Sandbakk et al. 2010b). However, this study is the first to explicitly compare men and women and provide novel information about gender differences in kinematics.

### Conclusions

Our present findings reveal larger gender differences in performance and  $VO_{2\max}$  than those reported for comparable endurance sports, differences that reflect primarily the higher  $VO_{2\max}$  and lower percentage of body fat in men. Although no gender differences in the ability to convert metabolic rate into work rate and speed were observed, our results demonstrate that women exhibit higher proportional utilization of  $VO_{2\max}$  at OBLA. With regards to kinematics, the differences between men and women were explained by cycle length, not by cycle rate.

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