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Metabolic rate and gross efficiency at high work rates in world class and national level sprint skiers

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

Abstract The present study investigated metabolic rate (MR) and gross efficiency (GE) at moderate and high work rates, and the relationships to gross kinematics and physical characteristics in elite cross-country skiers. Eight world class (WC) and eight national level (NL) male sprint cross-country skiers performed three 5-min stages using the skating G3 technique, whilst roller skiing on a treadmill. GE was calculated by dividing work rate by MR. Work rate was calculated as the sum of power against gravity and frictional rolling forces. MR was calculated using gas exchange and blood lactate values. Gross kinematics, i.e. cycle length (CL) and cycle rate (CR) were measured by video analysis. Furthermore, the skiers were tested for time to exhaustion (TTE), peak oxygen uptake (VO_{2peak}), and maximal speed (V_{max}) on the treadmill, and maximal strength in the laboratory. Individual performance level in sprint skating was determined by FIS points. WC skiers did not differ in aerobic MR, but showed lower anaerobic MR and higher GE than NL skiers at a given speed (all $P < 0.05$). Moreover, WC skiers skated with longer CL and had higher V_{max} and TTE (all $P < 0.05$). In conclusion, the present study shows that WC skiers are more efficient than NL skiers, and it is proposed that this might be due to a better technique and to technique-specific power.

Keywords Cross-country skiing · Cycle length · Skating · Work rate

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Introduction

Energy delivery and mechanical efficiency are two key factors in endurance performance. Traditionally, cross-country skiers are tested for energy delivery capacity, and research over the last few decades has shown that world class skiers have been among the endurance athletes with the highest maximal oxygen uptake (VO_{2max}) (Holmberg et al. 2007; Ingjer 1991; Saltin and Astrand 1967). Although a considerable number of studies have been done on work economy in cross-country skiing (Hoff et al. 1999; Hoffman 1992; Hoffman et al. 1990a, b, 1994; Mahood et al. 2001; Mikkola et al. 2007; Millet et al. 1998a, b, 2002, 2003; Osteras et al. 2002), limited research has been done on mechanical efficiency (Hoffman et al. 1995; Niinimaa et al. 1978). No study has compared efficiency between cross-country skiers of different performance levels.

Generally, two definitions have been used to express efficiency in endurance sports. Gross efficiency (GE) is defined as the ratio of work generated to the total energy expended metabolic rate (MR), expressed as a percentage (Sidossis et al. 1992). In addition, work economy is often studied when the work rate is unknown, determined by measuring the steady-state oxygen uptake and the respiratory exchange ratio (RER) at a given sub-maximal speed (Moseley and Jeukendrup 2001; Saunders et al. 2004). GE is regarded as reflecting the efficiency of the entire human

body in action, and may thereby provide detailed insight into how work rate affects MR (Ettema and Loras 2009). In the literature, a debate about the use of GE and various efficiencies using baseline subtractions (e.g. net efficiency, work efficiency, delta efficiency) is ongoing (Ettema and Loras 2009). In the present study, we adopt the stand-point that any baseline subtraction is essentially flawed (Cavanagh and Kram 1985; Ettema and Loras 2009), and we only use GE to express efficiency of the whole body as an energy converting system that is working against environmental resistance.

One of the major challenges when studying efficiency in outdoor sports is finding an accurate measurement of the (external) work rate (van Ingen Schenau and Cavanagh 1990). The introduction of ski-specific laboratory testing using roller skis on treadmills has opened up opportunities for measuring work rate and metabolic response, serving as a model for cross-country skiing (Watts et al. 1993). Traditionally, the MR used to calculate efficiency is based on the oxygen uptake in steady-state aerobic conditions (Ettema and Loras 2009; Hoffman et al. 1995; Niinimaa et al. 1978). However, because intensity is high in cross-country skiing competitions, it might be suggested that efficiency is more important at high intensities, with a considerable production of anaerobic MR.

To our knowledge, no studies have investigated the physical characteristics that are related to efficiency in cross-country skiers. Improved strength and power is reported to improve work economy and performance in skiers (Hoff et al. 1999; Mikkola et al. 2007; Osteras et al. 2002). Moreover, better skiers tend to use longer cycle lengths (CL) with similar cycle rate (CR), and this difference in CL is suggested to relate to strength and power (Bilodeau et al. 1996; Lindinger et al. 2009; Stoggl et al. 2007), as well as to technical aspects (Bilodeau et al. 1996; Stoggl and Muller 2009). One rationale is that improved strength and/or technique have the potential to lead to a longer CL and to higher efficiency. Because of the complex nature of cross-country skiing technique, we assume that the magnitude of produced muscle power that is transferred into external power and speed may differ considerably between different level skiers. Both efficiency and performance will thus be greatly affected by technique and technique-specific power.

The purpose of the present study was to examine MR and GE in roller ski skating, from moderate to high work rates, whilst comparing world class (WC) and national level (NL) sprint skiers. Furthermore, we measured gross kinematics (i.e. CL and CR) and the physiological characteristics (i.e. maximal speed, maximal strength, and VO_{2max}) of the skiers. We hypothesized that WC skiers had higher GE, CL, maximal strength and maximal speed.

Table 1 Anthropometric and physiological characteristics, and sprint performance level on snow (FIS points) and in treadmill roller skiing (TTE) in world class and national level sprint cross-country skiers (mean ± SD)

Subjects	World class ($n = 8$)	National level ($n = 8$)
Age (years)	26.1 ± 3.5	24.5 ± 2.3
Body height (cm)	184.8 ± 5.6	186.4 ± 6.6
Body mass (kg)	83.3 ± 6.4	82.8 ± 6.3
Body mass index (kg m^{-2})	24.4 ± 0.6	23.8 ± 1.0
Body fat (%)	8.9 ± 2.5	9.8 ± 1.5
FIS points	22.5 ± 12.0**	100.6 ± 45.8
TTE (s)	353 ± 55**	214 ± 40
VO_{2peak} (L min^{-1})	5.88 ± 0.40*	5.44 ± 0.43
VO_{2peak} (mL min^{-1} kg^{-1})	70.6 ± 3.2**	65.8 ± 3.4
Maximal speed (km h^{-1})	23.8 ± 0.6**	22.0 ± 1.0
Mean one-leg strength (N kg^{-1})	13.3 ± 2.6	13.6 ± 1.6
Upper body strength (N kg^{-1})	11.9 ± 1.2	11.4 ± 0.8
Peak BLa (mmol L^{-1})	12.3 ± 1.5	12.0 ± 1.9

Significant differences between groups are indicated by * $P < 0.05$ and ** $P < 0.01$

Methods

Subjects

Eight WC and eight NL Norwegian male sprint cross-country skiers volunteered to participate in the study. The WC group were national team skiers, all with podium rankings in the World Cup Series and including three World Champions, whereas the NL group were skiers among the 20 best in the 2008 Norwegian Cup Series. The skiers' characteristics are shown in Table 1. All skiers were fully acquainted with the nature of the study before signing written consent to participate. The study was approved by the regional ethics committee, Trondheim, Norway.

Overall design

The skiers performed three sub-maximal 5-min stages at 14, 16 and 18 km h^{-1} on a 5% inclination whilst roller skiing on a treadmill. MR was calculated using gas exchange and blood lactate values, and GE was calculated using the theoretical work rate divided by the MR. CL and CR were measured at the three sub-maximal speeds. The skiers were tested for time to exhaustion (TTE), peak oxygen uptake (VO_{2peak}) and maximal speed (V_{max}) on the treadmill, as well as maximal leg and upper body strength in the laboratory. In addition, performance level in sprint skating on snow was determined by FIS points. All roller ski tests

were performed in the G3 technique (Nilsson et al. 2004a). This technique has a symmetrical pole push synchronous to each leg push-off, often used on moderate inclines, and is also referred to as V2-skate (Boulay et al. 1994) and 1-skate (Bilodeau et al. 1992).

Instruments and materials

Gas exchange values were measured by open-circuit indirect calorimetry using an Oxycon Pro apparatus (Jaeger GmbH, Hoechberg, Germany). Before each measurement, the VO_2 and VCO_2 gas analyzers were calibrated using high-precision gases (16.00 ± 0.04% O_2 and 5.00 ± 0.1% CO_2, Riessner-Gase GmbH & Co., Lichtenfels, Germany), the inspiratory flow meter was calibrated with a 3 L volume syringe (Hans Rudolph Inc., Kansas City, MO). Heart rate (HR) was measured with a HR monitor (Polar S610, Polar Electro OY, Kempele, Finland), using a 5-s interval for data storage. Blood lactate concentration (BLa) was measured on 5 μL samples taken from the fingertip by a Lactate Pro LT-1710t (ArkRay Inc, Kyoto, Japan), validated by Medbo et al. (2000).

All treadmill tests were performed on a 6 × 3-m motor-driven treadmill (Bonte Technology, Zwolle, The Netherlands). Inclination and speed were calibrated using the Qualisys Pro Reflex system and the Qualisys Track Manager software (Qualisys AB, Gothenburg, Sweden). The treadmill belt consisted of a non-slip rubber surface that allowed skiers to use their own poles (pole length 90 ± 1% of body height) with special carbide tips. The skiers were secured with a safety harness during the treadmill testing. To exclude variations in rolling resistance, all the skiers used the same pair of Swenor skating roller skis with standard wheels (Swenor Roller skis, Troesken, Norway) and using the same Rottefella binding system (Rottefella AS, Klokkartstua, Norway). The roller skis were pre-warmed before each test through 20 min of roller skiing on the treadmill. The roller skis were tested for rolling friction force (F_f) before the test period, and the friction coefficient (μ) was determined by dividing F_f by the normal force (N) ($\mu = F_f \times N^{-1}$). This was performed in a towing test, previously described by Hoffman et al. (1990a), on three subjects (70, 80 and 90 kg) rolling passively at 14, 16 and 18 km h^{-1} for 5 min on a flat treadmill (0%) whilst connected to a strain gauge force transducer (S-type 9363, Revere Transducers Europe, Breda, The Netherlands). The measured μ was independent of speed and body mass, and the mean μ value (0.0237) was incorporated in the work rate calculations.

Because skating is performed with a gradually increasing edging angle of the roller skis during the push off, which may affect the friction coefficient, we measured μ at the minimum (straight position) and maximum edging angles of the roller skis in an experimental set-up. The maximal edging angle (when the roller skis lose ground contact) used by the skiers was roughly checked using video measurements (frontal position), and was about 35°. Thus, we tested the differences in μ by keeping the roller skis straight and at a ~35° edging angle, while rolling the roller skis with firm pressure, perpendicular to the roller skis' orientation, over two 60 × 40 cm force plates with a 1,000 Hz sampling rate (Kistler 9286AA, Kistler Instrument Corp., Winterthur, Switzerland). These were placed behind each other and covered by treadmill belt material (5 repetitions with different loads on the roller skis, up to 600 N, for both edging conditions). The use of the force plates allowed us to accurately measure normal forces under edging conditions. The roller skis showed differences in μ of <3% between the two edging conditions (mean values; straight position 0.0249 ± 0.0005 vs. ~35° edging angle 0.0256 ± 0.0007). There were no effects of load on μ. Because the skiers also skate by aligning their roller skis with the forward direction, which affects the work against friction, we compared the differences in this "angling" of the roller skis at ski plant between the two groups. Possible differences will affect rolling distance and thereby work against friction. Although the absolute angles cannot be measured accurately from the frontal video they were, however, roughly estimated for comparison reasons using the projection length of the ski in the frontal plane. This analysis indicates that the orientation angles were not different between groups (mean values all three speeds, WC 11° ± 2° and NL 12° ± 2°).

To determine CR and CL, two synchronised 50 Hz video cameras (Sony Handycam DCR-VX2000E, Sony Inc., Tokyo, Japan) were fixed to the front and on the side of the treadmill, enabling a total view of the subjects and the whole movement range of the poles. The video recordings were analysed in DartFish ProSuite 4.5 (DartFish Ltd., Fribourg, Switzerland). CR at all measured speeds was calculated from the time between every second pole plant of the left pole, and averaged over 12 cycles. CLs were determined by dividing the treadmill belt's speed by CR.

Maximal isometric single-leg squats were recorded on a Kistler 9286AA force plate with 1,000 Hz sampling rate. Upper body one repetition maximum (1RM) was tested in a LAT MACH machine (Technogym, Gambettola, Italy) with a semi-pronated rowing handlebar. Body mass was measured on the Kistler force plate and body height on a calibrated stadiometer (Holtain Ltd., Crosswell, UK). Body fat percentage was estimated on the basis of seven skinfold measurements (Holtain Skinfold caliper PE025, Holtain Ltd., Crosswell, UK), according to Withers et al. (1987).

Test protocols

After a standardized low intensity 20-min warm-up at 60% of the skiers' maximal HR, the skiers performed three 5-min stages at 14 (V14), 16 (V16) and 18 km h^{-1} (V18) at 5% inclination. BLa was measured immediately after each stage. Gas exchange (i.e. VO_2 and VCO_2), HR, CL and CR were determined by the average of the last minute during each stage.

GE was defined as the work rate divided by the MR. Work rate was calculated as the sum of the power against gravity (P_g) and the power against rolling friction (P_f), in a coordinate system moving with the treadmill belt at a constant speed. Power against gravity was calculated as the increase in potential energy per time [$P_g = m \times g \times \sin(\alpha) \times v$] and the power against friction was calculated as the work against Coulomb frictional forces at a given tangential speed [$P_f = \mu \times m \times g \times \cos(\alpha) \times v$], with v being belt speed and α the angle of incline. The MR was calculated as the sum of aerobic and anaerobic MR. The aerobic MR was determined from VO_2 and VCO_2, by calculating the product of VO_2 and the oxygen energetic equivalent using the associated measurements of RER and standard conversion tables (Peronnet and Massicotte 1991). The anaerobic MR was calculated from the obtained BLa values measured directly after each of the three sub-maximal speeds. A 1 mmol L^{-1} of BLa was regarded as equivalent to 3 mL kg^{-1} of oxygen consumed with an RER = 1.0 (di Prampero and Ferretti 1999).

The VO_{2peak} test was performed at 5% inclination in the G3 technique with a starting speed of 16 km h^{-1}. The speed was increased by 2 km h^{-1} every min up to 20 km h^{-1}, and thereafter increased by 1 km h^{-1} every minute until exhaustion. VO_2 was measured continuously, and the average of the three highest 10-s consecutive measurements determined VO_{2peak}. The test was considered to be a maximal effort if the following three criteria were met: (1) a plateau in VO_2 was obtained with increasing exercise intensity, (2) RER above 1.10, and (3) BLa exceeding 8 mmol L^{-1}. BLa was measured 2 min after the test was finished. The highest HR value during the VO_{2peak} test was defined as peak HR (HR$_{peak}$). Peak CR (CR$_{peak}$) and peak CL (CL$_{peak}$) were measured during the last completed workload (V_{peak}). TTE was recorded at the time the subject was no longer able to keep the roller skis' front wheels ahead of a marker placed 4 m from the front of the treadmill, and determined the skiers' individual treadmill performance level.

The V_{max} test was performed at 8% inclination in the G3 technique, initiated with a 30-s stage of medium intensity (14 km h^{-1}), before the treadmill speed was increased to the starting speed of 16 km h^{-1}. Speed was thereafter increased every 10 s by 1 km h^{-1} until exhaustion. Maximal speed was recorded at the time the subject was no longer able to keep the roller skis' front wheels ahead of the

marker placed 4 m from the front of the treadmill. V_{max} was calculated as $V_{max} = V_f + [(t \times T^{-1}) \times V_d]$, where V_f is the speed of the last completed workload, t is the duration of the last workload, T is the standard duration of each workload and V_d is the speed difference between the last two workloads (Holmberg et al. 2005).

Two maximal strength tests were performed in the laboratory, simulating lower and upper body work in the G3 technique in cross-country skiing. A maximal isometric single-leg squat test was performed under a fixed metal bar for the right and left leg, respectively. The bar was regulated for each subject to obtain a knee angle of 125°, close to where maximal strength in a knee extension is reported to be obtained (Hay 1992). The skiers were instructed to push maximally for 3 s. 1RM was taken as the highest average force over one-second. An upper body 1RM poling test was performed sitting with locked legs, poling maximally when holding a semi-pronated rowing handlebar with both hands, 30 cm between the hands, starting with the arms fully extended with an angle of 125° between the arms and the trunk, and ending with the elbows passing the major trochanter at the hip region. Each athlete had two attempts at each load, which was increased by 5 kg after every successful attempt. Recovery between each attempt was 2 min. 1RM was determined by the heaviest accepted trial, as evaluated by two independent investigators. The strength results were normalized relative to body mass (N kg^{-1}) to reflect the role of strength in performance in which one's own body is to be moved.

All testing sessions were completed within 2 weeks, approximately 1–3 weeks before the start of the competition season. The subjects drank a standard fluid with sugar and electrolytes during the breaks. The use of the G3 technique was chosen because unpublished observations from our group show that G3 was the predominant technique in male sprint races in World Cup the previous season.

The highest overall International Ski Federation points (FIS points), from sprint FIS races, provided a quantitative assessment of performance level differences between the groups. According to FIS (2009), a skier's rank is relative to a 0 point standard established by the top ranked skier in the world. A skier's total points for a given race are determined by adding race points (from comparing the individual skier's time to the winner's time) and race penalty based on the five best competitors' FIS points in the competition.

Statistical analysis

All data were checked for normality with a Shapiro–Wilks test and presented as mean and standard deviation (SD). Comparisons between groups in performance, physiological characteristics and training were analysed using the independent t test procedure. The effect of speed on GE and CL, and

group differences were tested using a one-way ANOVA for repeated measures, with group as a between-subjects factor. The individual metabolic–work rate relationships were analyzed using linear regression and analysis of repeated measures. The differences between individuals and groups were tested by means of an F test for the residual sum of squares, using pooled and individual fits according to Crowder and Hand (1990). Statistical significance was set at $P < 0.05$. All statistical tests were processed using SPSS 11.0 Software for Windows (SPSS Inc., Chicago, IL) and Matlab (The Math-Works Inc., Natick, MA).

Results

Metabolic rate, work rate, and efficiency

The WC skiers did not differ in VO_2, but showed lower RER and BLa (Table 2, both $P < 0.05$) than the NL skiers

Table 2 Work rate, oxygen uptake (VO_2), respiratory exchange ratio (RER), blood lactate concentration (BLa), as well as aerobic, anaerobic and total metabolic rate during three sub-maximal 5-min stages in world class and national level sprint cross-country skiers (mean ± SD)

	World class ($n = 8$)	National level ($n = 8$)
14 km h^{-1}		
Work rate (W)	234 ± 18	233 ± 17
VO_2 (L min^{-1})	4.3 ± 0.3	4.4 ± 0.4
RER	0.93 ± 0.02*	0.97 ± 0.03
BLa (mmol L^{-1})	2.7 ± 0.6*	3.9 ± 1.0
Aerobic metabolic rate (W)	1,486 ± 112	1,552 ± 128
Anaerobic metabolic rate (W)	60 ± 16*	85 ± 19
Total metabolic rate (W)	1,546 ± 115*	1,637 ± 120
16 km h^{-1}		
Work rate (W)	267 ± 20	266 ± 21
VO_2 (L min^{-1})	4.8 ± 0.3	4.9 ± 0.4
RER	0.95 ± 0.02*	1.01 ± 0.03
BLa (mmol L^{-1})	4.2 ± 0.7**	6.6 ± 1.7
Aerobic metabolic rate (W)	1,675 ± 127	1,733 ± 160
Anaerobic metabolic rate (W)	91 ± 19**	143 ± 35
Total metabolic rate (W)	1,767 ± 134*	1,876 ± 148
18 km h^{-1}		
Work rate (W)	301 ± 22	299 ± 24
VO_2 (L min^{-1})	5.2 ± 0.4	5.3 ± 0.5
RER	0.99 ± 0.02*	1.04 ± 0.05
BLa (mmol L^{-1})	6.4 ± 0.9**	9.4 ± 1.7
Aerobic metabolic rate (W)	1,819 ± 127	1,867 ± 170
Anaerobic metabolic rate (W)	139 ± 18**	205 ± 36
Total metabolic rate (W)	1,959 ± 128*	2,072 ± 160

Significant differences between groups are indicated by * $P < 0.05$ and ** $P < 0.01$

at all three sub-maximal speeds (V14, V16 and V18, respectively). Aerobic MR did not differ between groups, but tended to be consistently lower for WC skiers (Table 2, $P = \sim0.10$). Anaerobic MR was lower in the WC skier's at all three sub-maximal speeds (Table 2, $P < 0.05$). The WC skiers showed higher GE than the NL skier's at all three sub-maximal speeds (Fig. 1, $P < 0.05$). The small effect of speed on GE was not significant ($P = 0.073$). The groups were compared statistically at the three speeds, and because of inter-individual body mass differences, the skiers performed at slightly different work rates at the given speeds. Figure 2a shows the MR plotted against work rate. On an individual basis, a clear linear trend is seen with a lowest correlation coefficient of 0.979 between the three speeds. The analysis for repeated measures revealed that all subjects had a similar slope of the regression line ($P = 0.595$), but the offset (regression intercept) varied ($P < 0.001$). The same applied when comparing the two groups (slope $P = 0.872$; offset $P < 0.001$). GE is plotted against work rate in Fig. 2b, and a small, but non-significant, increase in GE with work rate was identified ($P = 0.08$). This is in accordance with the findings for speed as work rate and speed were very tightly linked in this study.

Movement and physiological characteristics

The WC skiers showed longer CL and lower CR than the NL skiers at V14, V16, V18 and V_{peak}, respectively (Fig. 3a, b, all $P < 0.05$). A significant effect of speed on CL and CR for both groups and for all skiers pooled were revealed (all $P < 0.05$). The WC skiers had $\sim7\%$ higher V_{max} ($P < 0.01$), $\sim6\%$ higher VO_{2peak} ($P < 0.05$), and about 60% higher TTE ($P < 0.01$) than the NL skiers. However, no differences in maximal lower and upper body strength were revealed.
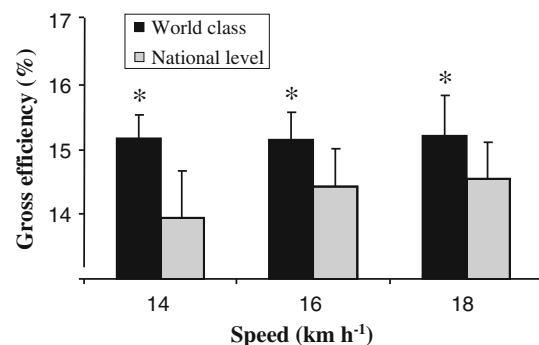

Fig. 1 Gross efficiency in world class and national level sprint cross-country skiers during 5-min stages at 14 (V14), 16 (V16) and 18 (V18) km h^{-1} at a 5% inclination using the skating G3 technique in treadmill roller skiing (mean and SD). Significant differences between groups are indicated by *$P < 0.05$
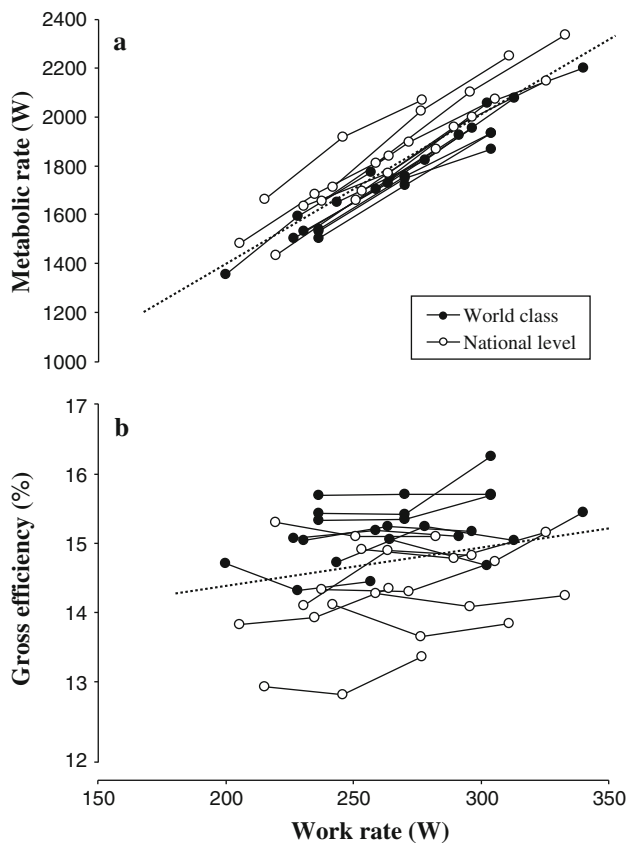
Fig. 2 Metabolic rate (**a**) and gross efficiency (**b**) plotted against work rate (individual data) in world class and national level sprint cross-country skiers during 5-min stages at 14 (V14), 16 (V16) and 18 (V18) km h^{-1} at a 5% inclination using the skating G3 technique in treadmill roller skiing. Trend lines (*dashed lines*) are estimated based on the linear regression for the entire data set
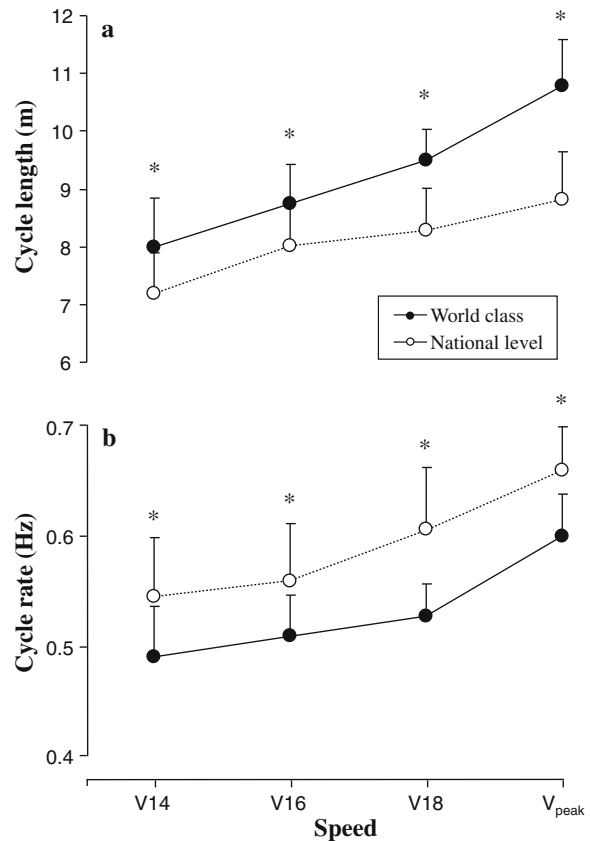
Fig. 3 Cycle length (**a**) and cycle rate (**b**) in world class and national level sprint cross-country skiers during 5-min stages at 14 (V14), 16 (V16) and 18 (V18) km h^{-1}, as well as at the skiers' last completed speed at the VO_{2peak} test (V_{peak}), at a 5% inclination using the skating G3 technique in treadmill roller skiing. *Vertical bars* indicate SD. Significant differences between groups are indicated by *$P < 0.05$

Discussion

The main finding in this study was that world class sprint cross-country skiers showed higher gross efficiency than national level sprint skiers in the G3 technique whilst roller skiing on a treadmill. WC skiers did not differ in aerobic MR, but showed lower anaerobic MR than NL skiers. WC skiers showed a higher maximal treadmill speed, TTE, and peak oxygen uptake, but similar strength for both lower and upper extremity.

Although roller skiing is a frequently used training mode for cross-country skiers, it is also a separate sport. Therefore, the results from this study may be applied to roller skiing performance level. Despite some differences between skiing on snow and roller skiing, the fundamental principles of propulsion are the same. Thus, our results are likely relevant to performance on snow as well.

Work rate and efficiency

The present study revealed a general linear relationship and strong individual trends between work rate and MR. This relationship appears to be a rather consistent outcome in other studies (Ettema and Loras 2009), and may be regarded an example of the Fenn effect as described for a muscle contraction (Fenn 1924). Thus, it seems that the same effect found in an isolated muscle contraction is also transferable to the entire system (human body) during cross-country skiing. However, GE was calculated without any baseline subtractions, and is not considered a measure for muscle efficiency. All subjects, independent of which group they belonged to, showed a similar slope of the metabolic–work rate relationship (Fig. 3a), but the NL group had a higher intercept. When adopting delta efficiency (change in work rate, divided by change in MR, e.g. Moseley and Jeukendrup (2001)), one would conclude that both groups

have similar delta efficiency, but the NL skiers have a higher MR at unloaded skiing, i.e. performing skiing movements without actual propulsion. As argued before (Cavanagh and Kram 1985; Ettema and Loras 2009), there are a number of conceptual problems with such interpretation. Still, the higher MR in NL skiers may be related to their higher CR and thus be independent of work rate.

Metabolic rate and gross efficiency

World class skiers did not differ in aerobic MR, but showed lower anaerobic MR and total MR than NL skiers at the same speeds, that is, from moderate to high work rates. The WC skiers showed higher GE than the NL skiers at all measured speeds. The present study indicates that GE differs between sprint skiers of different standards, and that high GE may be highly significant for success in cross-country skiing. To our knowledge, the present study is the first study to compare efficiency between cross-country skiers of different performance levels, but is supported by one study showing that energy cost in ski skating differs between skiers of different standards (Millet et al. 2003). It is likely, among elite cross-country skiers, that both a high level of energy delivery and an efficient transformation of this energy into external power are needed to succeed.

In other sports, more comparisons of efficiency, or work economy, between athletes at different performance levels have been investigated, but the results appear contradictory. For example, in running there seems to be a consensus that better athletes have better work economy (Saunders et al. 2004). However, in cycling this relationship seems less clear and higher efficiency in better cyclists may largely be explained by higher work rates (Ettema and Loras 2009). When considering this difference between running and cycling, one may hypothesize that the complexity of the movement plays a role in the relationship between efficiency and performance level. In other words, a relatively complex technique, such as in cross-country skiing, compared with more simple techniques, such as cycling, may be a prerequisite for efficiency to be strongly affected by the execution of the technique. Notably, the GE in this study is close to what is found in speed skating (de Koning et al. 2005) and slide boarding (Leirdal et al. 2006) with around 15%, but lower than in cycling with ∼20% (Ettema and Loras 2009).

Movement characteristics

Two of the most obvious variables that may relate to GE are CL and CR, which can be considered to be the two coupled outcomes of a "gearing principle". In this study, differences between the WC and the NL skiers in CL and CR were found at all measured speeds. Better skiers are also previously reported to have a longer CL in the skating tech-

nique (Bilodeau et al. 1996; Rundell and McCarthy 1996; Stoggl and Muller 2009). Interestingly, in this study, both CL and CR increased with speed, up to V_{peak}. This may indicate that the better skiers have a higher potential in CL. It has been proposed that faster skiers have longer CL in the skating technique for two reasons. First, a longer CL might express higher maximal strength or power (Rundell and McCarthy 1996), and second, it might express a more effective leg and pole push off (Bilodeau et al. 1996; Stoggl and Muller 2009). Particularly, this last factor is logically also related to enhanced efficiency. Still, the present study does not provide evidence for this suggestion and more research is needed for this.

Physiological characteristics

Maximal strength and power is suggested to relate to work economy and/or efficiency in skiing (Hoff et al. 1999; Mikkola et al. 2007; Osteras et al. 2002). In the current study, the maximal strength measurements did not differ between groups, suggesting that the "necessary level" of maximal strength has already been reached in these elite sprint skiers. However, the V_{max} was different between WC and NL skiers and may underline the importance of an effective technique in high speeds. It might also indicate that an ability to produce technique-specific power at high speeds may relate to efficiency at sub-maximal speeds. This is supported by Nilsson et al. (2004b) showing that 20-s sprint training improved peak power in a 30-s test, work economy at sub-maximal speeds and performance in a 6-min test.

Methodological considerations

One major challenge in measuring GE is finding accurate measures of work rate. In this study, work rate was calculated from the power used to maintain the same position on the inclined treadmill and to overcome rolling resistance. Power against gravity can be determined accurately, whereas power against friction includes some assumptions and simplifications. First, the mean normal force determines the mean frictional force when assuming a constant friction coefficient. In skating cross-country skiing, the normal forces on the skis change during a movement cycle, and, more importantly, a considerable fraction of the normal force is taken by the poles (Millet et al. 1998c). Second, the movement direction of the roller skis during skating is not aligned to the movement of the treadmill belt. This affects the skier's actual rolled distance and speed compared with the treadmill belt.

These aspects of skiing cause systematic errors in estimating efficiency. A part of the systematic error applies to all skiers because all use the poles and move the roller skis

at an orientation angle with respect to the forward direction when skating. This part is removed in the various group comparisons made in this study. Thus, this error does not affect the group comparison, but should be considered when interpreting the efficiency values reported here. A rough estimate can be made from the current data, due to the ski orientation angle when the roller skis move faster than the treadmill belt during skating [$v_{ski} = v_{belt}/\cos(\text{orientation}$ angle)]. With a 12-degree orientation angle (see "Methods"), the power against friction could have been underestimated due to using belt velocity instead of ski velocity by maximally 2%. The efficiency values reported here would thereby have been underestimated by 0.1%. Systematic differences between groups in these aspects could affect the comparisons between groups. The effect of this uncertainty is minimized by all skiers using the same technique and performing on the same speeds and inclination. Furthermore, equipment (shoes, bindings and roller skis) were standardized and we compared groups of skiers with relatively similar body mass and upper/lower-body strength ratios. Moreover, no differences between groups in orientation of the roller skis with respect to the forward direction or effects of edging the skis on friction were indicated from our rough estimates. Thus, it seems unlikely that the significant group differences could be explained by such potential differences in technique.

The WC skiers could have reduced the friction forces more than the NL skiers using more of their body mass on the poles and thus reducing the normal forces. We cannot a priori assume that the two groups would have divided supporting forces over the arms and legs in a similar way. Only the relatively similar ratio of strength and power for upper and lower limbs in both groups may point in that direction. Therefore, we performed some calculations on these effects using findings by Millet et al. (1998d), who found that good skiers generate mean poling forces (over the entire skating cycle) of about 7% of body mass. When compared with the NL skiers, the WC skiers could have decreased work against rolling friction using the poles more than the NL skiers did. In other words, we could have systematically overestimated the work rate of the WC skiers as compared to the NL skiers, and thereby their GE values. We incorporated this factor in our calculations for work rate and GE. We assumed that 7% of the body weight was supported by the poles in the WC skiers. It was only when we reduced this number for the NL skiers to <1% that the significant differences in GE between groups disappeared. It seems highly unlikely that this is actually the case.

Efficiency and work economy in cross-country skiers are traditionally based on the oxygen uptake in steady state aerobic conditions (Hoffman et al. 1990a, b, 1994, 1995; Mahood et al. 2001; Millet et al. 1998a, b, 2002, 2003; Niinimaa et al. 1978; Osteras et al. 2002). When using these measures to predict performance at high, competition intensities, it is implicitly assumed that inter-individual differences in efficiency and work economy are independent of work rate. The present study partly confirms this assumption at moderate and high work rates, and only small, non-significant group differences in VO_2 were found. However, when converting VO_2 and RER to aerobic MR and including anaerobic metabolic contribution in the calculations, the group differences were highly significant. Thus, we conclude that the anaerobic contribution is of importance when interpreting metabolic–work rate relationships. In addition, the non-significant effect of speed on GE may support the validity of the applied method at the highest work rates. The small increase in GE observed at higher speeds in the current study is in agreement with the decreasing impact of resting metabolism on efficiency at relatively high work rates (Ettema and Loras 2009). The MRs measured in the current study were calculated by the method recommended by Di Prampero and Ferretti (1999), which calculates the anaerobic MR from blood lactate levels. This method is regarded as being less accurate than its aerobic counterpart, but not invalid (di Prampero and Ferretti 1999). Because of the linear relationship between work rate and MR, we suggest that this method is a useful tool for comparing the whole body anaerobic MR in skiers during moderate and high work rates in standardised testing procedures.

Conclusions

The current results indicate that, in addition to the higher energy delivery capacity, world class sprint skiers have a higher GE, use longer CLs and lower CRs at a given speed and generate higher maximal speeds than national level sprint skiers. Therefore, the higher efficiency in world class skiers may be linked to technique and technique-specific power. The present study also indicates that GE at moderate and high work rates provide useful information about cross-country skiers who are compared in standardized conditions whilst treadmill roller skiing.

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