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The effects of an exhausting exercise on physiological responses and technique in elite cross-country skiers.

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Abstract

The ability to reproduce a high energy delivery capacity and an efficient conversion of energy to work rate and speed, is essential for performance in sports with several competitions during a day, such as in cross-country skiing sprint. The purpose of this study was to investigate whether gross efficiency (GE), kinematic variables and ski kinetics during roller ski skating were influenced by an incremental exercise to exhaustion. Therefore, twelve elite male cross-country skiers completed 4-minute submaximal stages in the G3 skating technique pre and post to an incremental test to exhaustion. There was a recovery period of 10 minutes from the finish of the incremental test until the post submaximal test to obtain steady state conditions. During the submaximal tests, physiological responses were measured by gas exchange and blood lactate, kinematic variables from a motion capture system and ski kinetics from force measurements on instrumented roller skis. Prior to the pre submaximal test and directly after the incremental test, peak power for the upper and lower limbs was assessed in concentric bench press and squat jump, in order to assess possible changes in neuromuscular capacity. The result showed a 4% increased VO_2 and decreased GE (15.5±0.7% vs. 15.2±0.5%, P=0.02) at post-test. Additionally, the blood lactate concentration increased from 2.4±1.0 to 6.2±2.5 mmol L^{-1} (P<0.001). Cycle length decreased (8.1±0.6 m vs. 7.7±0.6 m, P<0.001) and cycle rate increased (0.49±0.04 Hz vs. 0.51±0.04 Hz, P<0.001) from pre to post test. The ski forces did not change significantly from pre- to post-test, and the peak power tests remained unchanged. In conclusion, the skiers demonstrated higher physiological stress during the submaximal post-test, with corresponding shorter cycle length and higher cycle rate. This indicates a reduced ability to produce propulsive power and an efficient technique. However, no differences were found in the applied ski forces or in upper and lower limb peak power. Thus, the differences in GE and cycle length may be related to changes in technique, such as alternations in the work done by poling or reduced force effectiveness of the push-off.

Keywords: cross-country skiing; gross efficiency; kinematic; ski kinetic

Introduction

Cross-country skiing is a demanding endurance sport (Saltin 1997) where high-energy delivery and efficiency are demonstrated to be important for performance (Stoggl, Muller et al. 2008, Sandbakk, Welde et al. 2011). In recent years, shorter sprint competitions have become popular, where skiers perform a time-trial qualification race and three separate knockout heats. The duration of each heat is approximately 3-4 min, with recovery phases down to 15 minutes between the heats (Sandbakk 2012). Thus, the ability to reproduce energy, high efficiency and a subsequent technique over several heats has become increasingly important in cross-country skiing (Mikkola, Laaksonen et al. 2010, Sandbakk, Ettema et al. 2011).

Fatigue induced by a sprint competition may affect the ability to reproduce maximal performance in the subsequent heat. Fatigue can be defined as lack of ability to maintain a level of neuromuscular strength (De Luca 1984) and is normally tested with a Maximal Voluntary Contraction (MVC) (Enoka, Baudry et al. 2011). It has been reported that spurt performance decreased after several sprint heats in the classical technique, which was associated to a fatiguing state in the lower limbs, measured with MVC (Zory, Vuillerme et al. 2009). These changes after an exhausting exercise are assumed to be caused by a number of fatigued related mechanisms, amongst others, decreased neuromuscular capacity, i.e. the capacity to maximally generate force and or power in one single MVC (Gandevia, Enoka et al. 1995). The fatiguing state measured with MVC in the lower limb may also affect the skier's ability to apply ski forces. However, it has not yet been investigated how a fatigue induced exercise alter the neuromuscular capacity or how it coincides with applied ski forces in ski skating.

Changes in neuromuscular capacity or technique may influence the efficiency of the movement, which is regarded to be of importance to performance in endurance sports (Benedict and Cathcart 1913, Ettema and Loras 2009). A way to reflect the efficiency of the entire human body in action is using gross efficiency (GE) (Ettema and Loras 2009), which is defined as the ratio of work rate to the total energy consumed, expressed as a percentage (Sidossis, Horowitz et al. 1992). Differences in GE seem to account for differences in cycling and running performance, especially in athletes matched for high VO_{2max} (Lucia, Hoyos et al. 2002, Foster and Lucia 2007, Ingham, Whyte et al. 2008). In cycling, changes in GE due to fatigue seem to be modest (Sahlin, Sorensen et al. 2005) or even non-existent (de Koning, Noordhof et al. 2012). In cross-country skiing, several studies have investigated the GE in ski skating technique (Sandbakk, Holmberg et al. 2010, Leirdal, Sandbakk et al. 2011, Sandbakk, Holmberg et al. 2011, Sandbakk, Welde et al. 2011, Sandbakk, Ettema et al. 2012), demonstrating a higher GE in world-class skiers compared to national-class skiers, which was linked to better execution of technique. However, little is known about the ability to reproduce efficiency and effective skiing skating technique over subsequent performances after exhaustion.

In cross-country skiing, kinematic parameters such as cycle length (CL) and cycle rate (CR) seem to influence GE and performance in ski skating (Sandbakk, Holmberg et al. 2010, Leirdal and Ettema 2011, Leirdal, Sandbakk et al. 2011). An increase in CR affects GE negatively (Leirdal, Sandbakk et al. 2011), whereas long CL has been reported to differentiate world class from national class skiers, to be an important mechanism to achieve high speed and to be correlated to performance in sprint races (Stoggl, Lindinger et al. 2007, Stoggl and Muller 2009, Sandbakk, Holmberg et al. 2010, Stoggl, Kampel et al. 2010). Still, how the kinematics changes in ski skating after an exhausting exercise has not yet been investigated.

The purpose of this study was to investigate whether GE, kinematic variables and ski kinetics during roller ski skating were influenced by an exhausting exercise. It is hypothesized that GE, CL and ski forces would decrease together with an increase in CR. Additionally, it was hypothesized that peak power in upper and lower limb would decrease after the exhausting exercise.

Methodology

Subjects

Twelve male elite cross-country skiers volunteered to participate in this study. All skiers were among the 20 best in the Norwegian Cup Series. All skiers were familiar with roller skiing as part of their daily summer training. Their anthropometric, physiological characteristics and performance level (in accordance to the FIS system) (FIS 2012) are described in Table 1. The experimental procedures were pre-approved by the Norwegian Regional Ethics Committee. Before the skiers participated, the protocol and procedures were explained verbally to each skier and a written informed consent was contained.

Table 1. Anthropometrics, physiological characteristics and performance level in 12 elite male cross-country skiers (mean ± SD).

N = 12	Mean ± SD
Age (yr)	25±3
Body height (cm)	181.4±5.2
Body mass (kg)	76.3±7.5
Body mass index (kg·m^{-2})	23.2±1.6
VO_{2peak}L min^{-1})*	5.5±0.6
VO_{2peak} (mL min^{-1} kg^{-1})*	71.4±3.4
Peak HR (bpm)*	193±5
Peak respiratory exchange ratio*	1.10±0.04
Peak BLa (mmol L^{-1})*	12±3
International ski federation points	68±27

* Measured during the incremental test to exhaustion in roller ski skating on a treadmill.

Overall design

To measure the influence of an exhausting exercise on physiological responses and technique in roller ski skating, a 4-min submaximal test was performed pre and post to an incremental exercise to exhaustion. Peak power of the upper and lower limbs was assessed before the pre-submaximal test and directly after the incremental test. After the test to exhaustion, a recovery period was conducted before the post-submaximal test. The overall design is illustrated in Fig. 1. All roller ski tests were performed on a treadmill using the G3 skating technique with a 5% incline. Ventilatory variables were measured using an open circuit indirect calorimeter and blood lactate concentration using standard procedures. Roller ski forces, cycle characteristics and ski angles were measured with special made roller skis equipped with strain gauges and from motion capture system. The study was carried out after the competition season.

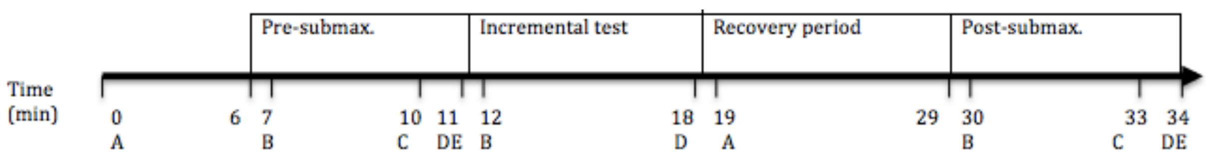

Fig.1. The figure illustrates the overall design, with the chronology and the approximate duration of the tests and the recovery period along the time axis. The different measurements are illustrated with letters; A: Peak power tests for upper and lower limbs, B: Physiological measurements, C: Ski kinetics and kinematic measurements, D: Blood lactate concentration measurements, E: Borg RPE scale assessment.

Instruments and materials

Roller ski skating was performed on a 6 × 3-m motor-driven treadmill (Bonte Technology, Zwolle, The Netherlands). The incline and velocity were calibrated using the Qualisys Pro Reflex system and Qualisys Track Manager software (Qualisys AB, Gothenburg, Sweden). The surface of the treadmill belt was covered with non-slip rubber that allowed the skiers to use their own poles (pole length = 90±1% of body height) with special carbide tips. During the incremental test, the skiers were secured with a safety harness. To minimize variations in rolling resistance, all skiers used the same pair of Start roller skating skis with standard wheels (Start Skating 80, Startex, Hollola, Finland).

Rolling friction force (F_f) of the roller skis was determined by a towing test described previously (Sandbakk, Holmberg et al. 2010). The friction coefficient (μ) was calculated by dividing F_f by the normal force (N), i.e., $\mu = F_f \times N^{-1}$. Variation between the friction coefficients was less than 5%, which was determined at different velocities and inclines. The overall mean value was 0.021 and was included to calculate work rate.

The force measurement system consisted of two roller skis (Fig. 2), each instrumented with two full bridge strain gauges (VY 41-3/350, HBM Gmbh, Darmstadt, Germany). In front of the binding of each ski a wireless analogue sensor node with an internal battery and a radio transmitter (V-Link MXRS, Microstrain Inc, Williston, VT, USA) provided excitation for the full bridge strain gauges. The data were logged and transmitted wirelessly to a base station. The accompanying software Node Commander 2.3.0 acquired all data. The magnitude and direction of the pre-calibrated ski forces were validated against two Kistler force platforms (Kistler 9286AA, Kistler Instrument Corp., Winterthur, Switzerland), with one wheel on each platform. The error in the measurements was linear with the magnitude of the applied forces, and therefore removed by multiplying with a calibration coefficient for each strain gauge. The results have been similar during 400 tests and six months of use. There were no differences between the left and right ski, indicating a high reproducibility. The data were evaluated using a MATLAB 7.12.0 (R2011a) program. See the more detailed description of the equipment elsewhere (Hoset, Rognstad et al. 2013).

Three-dimensional movements of the roller skis were monitored using the Qualisys Pro Reflex system (Qualisys AB, Gothenburg, Sweden). Nine cameras captured 500 frames per second of position data from 3 passive reflective markers on each of the skis over a period of

20 seconds. To measure angling and edging of each ski, the spherical reflective markers were placed in a triangular fashion on the outside of each instrumented ski (Fig. 2). The markers provided X (anteroposterior), Y (mediolateral), and Z (vertical) coordinate values during the 20 seconds monitoring period. Acquisition software (Qualisys Track Manager) was used to collect the data, and than the evaluation was completed in a MATLAB 7.12.0 (R2011a) self-compiled program designed specifically for analysis of the skating technique.

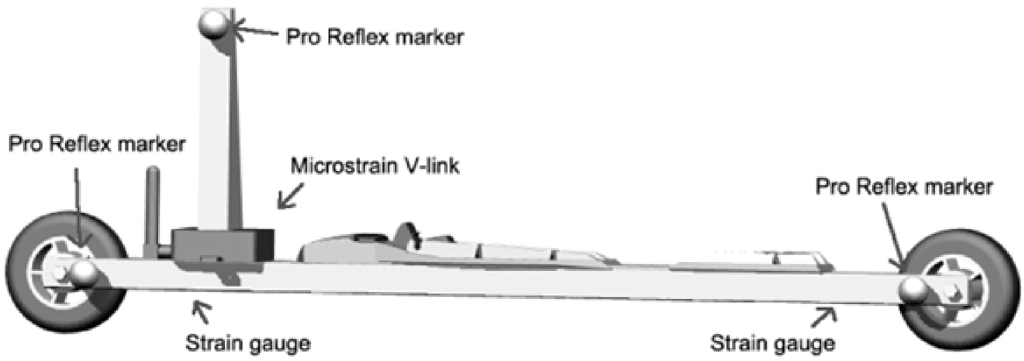

Fig. 2. A model of the instrumented roller ski with the location of the strain gauges and the spherical reflective markers.

Ventilatory variables were measured employing open-circuit indirect calorimeter using an Oxycon Pro apparatus (Jaeger GmbH, Hoechberg, Germany), as validated by (Foss and Hallen 2005). Prior to each test, the VO_2 and VCO_2 analyzers were calibrated using a known mixture of gases (16.00±0.04% O_2 and 5.00±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) (Sandbakk, Ettema et al. 2012). Heart rate was recorded with a heart rate monitor (Polar RS800, Polar Electro OY, Kempele, Finland). Blood lactate concentration of 5-µL of blood was collected from the fingertip, and analyzed using the Lactate Pro LT-1710*t* kit (ArkRay Inc, Kyoto, Japan), validated by Medbø and co-workers (Medbo, Mamen et al. 2000). Rating of perceived exertion (RPE) was assessed using the Borg Scale (Borg 1970), and has been reported to be a valid measure of exercise intensity (Chen, Fan et al. 2002)

Body mass and body height were measured on the Kistler force plate and a calibrated stadiometer (Holtain Ltd., Crosswell, UK), respectively.

Peak power of the upper limbs was executed with a concentric bench press using free weights, an Olympic barbell (20kg) and calculated using a linear encoder (MuscleLab, Ergotest Technology AS, Langesund, Norway). The device is based on a precise measurement of load displacement of any machine using gravitational loads as external resistance. The MuscleLab has been found to have a high reliability and is suitable for evaluation of athlete's performing skills (Bosco, Belli et al. 1995). Peak power of the lower limbs was assessed performing a Squat jump on a Kistler force plate.

Test protocol

Initially, the peak power tests were executed, followed by a 4-minute pre-submaximal test and an incremental test to exhaustion. There was a recovery period of 10 minutes from the finish of the incremental test to the post submaximal test in order to have steady state conditions. Directly after the incremental test the peak power of upper and lower limbs was retested, these tests lasted for 6 minutes, and were included in the 10-minute recovery period after the incremental test. Pilot testing from our lab indicated that these peak power exercises did not influence the physiological demands at post-submaximal test. Finally, the skiers performed a post-submaximal test. The purpose of the recovery period was to normalize blood and muscle lactate concentration and VO_2 level, in order to measure GE at post conditions. Prior to testing, a standardized, test-specific 20-min warm-up was performed, and 5 minutes warm-up with roller skis to become familiar to the instrumented roller skis. Training on the days before testing was standardized with low intensity training and the skiers drank a standard fluid with sugar and electrolytes during all breaks.

Incremental exercise to exhaustion

An incremental exercise was chosen to exhaust the skiers. To control time to exhaustion and to make sure that every skier would reach a state of exhaustion, the incremental protocol was assessed. The incremental exercise to exhaustion was performed using G3 technique on a 5% incline. The initial speed of 4.4 m s^{-1} was increased by 0.6 m s^{-1} after 1 and 2 min and thereafter by 0.3 m s^{-1} every minute until exhaustion. Exhaustion was defined as the time-point at which the skier was no longer able to keep the forefoot in front of a marker on the treadmill. The test was considered to represent maximal effort, if the following three criteria were fulfilled; 1) a plateau in VO_2 despite increasing exercise intensity; 2) a RER value greater than 1.10; and 3) BLa exceeding 8 mmol·L^{-1} (Bassett and Howley 2000). VO_2 was measured continuously and the average of the three highest consecutive 10-second values during the last minute, was determined as the peak oxygen uptake (VO_{2peak}). The blood lactate concentration was measured within 1 min after termination of the test. The highest HR value attained during the test was defined as peak HR.

Pre- and post-submaximal test

Submaximal physiological responses were tested in the G3 technique in a 4-minute session on a 5% inclined treadmill with a speed of 3.9 m s^{-1}. This speed was chosen, based on earlier testing of these skiers to induce an aerobic steady state situation with a competition relevant technique (Sandbakk, Ettema et al. 2011). It has also been demonstrated that treadmill testing at this submaximal speed, testing GE, kinematics and kinetics, is relevant for performance in sprint ski skating on snow (Sandbakk, Ettema et al. 2011). Ventilatory steady state values, such as O_2 consumption and CO_2 production, as well as the expired ventilation and heart rate were estimated by averaging over the last minute. During the final minute, kinetics and kinematics were measured over a 20-second period. BLa and Borg RPE were assessed immediately after termination of both submaximal tests.

Peak power tests

In the current study peak power in the upper and lower limbs was tested in the pre- and post-test conditions to define possible changes in neuromuscular capacity. The exercise was based on a simple movement and familiar exercises from the skiers' strength-training program were chosen. Since the peak power tests are not sensitive enough for testing neuromuscular fatigue in detail, the operational term in the current study is neuromuscular capacity. Both tests were performed with three trails, using the best results for further analyses. Between each set there was a 1-min recovery, with the total duration of the peak power tests of approximately 6 minutes.

The concentric bench press (Fig. 3) was performed with a load of 50% of the skier's body mass. Prior to the test, the skiers were given a detailed instruction on how to perform the exercise. During the arm movement, the heel, shoulder blade and m. gluteus maximus had to have constant contact with the ground and the bench. These instructions were given to prevent arching of the back and the use of legs during the test. The handgrip on the barbell was self-selected by the skiers, with the instruction of having a handgrip that allowed the skiers to achieve as high power as possible during the exercise. Members of the test team assisted in lowering the bar to the skier´s sternum into a static position. On command of the test leader, the barbell was pressed to extended arms with maximal voluntary effort. Infrared photo interrupter on the muscleLab calculated velocity, force and power during the concentric movement.

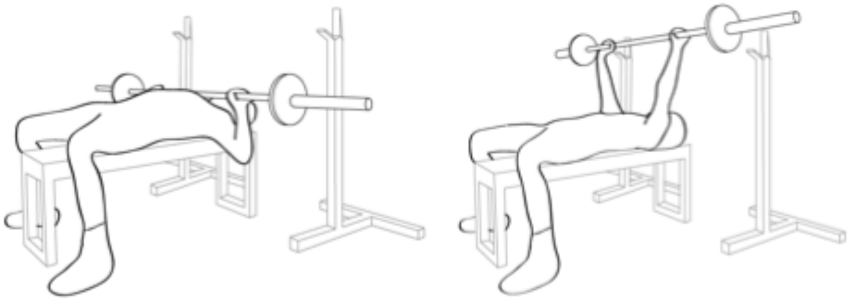

Fig. 3. Illustrations of the starting and ending positions during the concentric bench press.

The squat jump was performed on a Kistler force plate (Fig. 4). Prior to the jump the skiers were instructed how to perform the jump. The skier started with a self-selected squatted knee angle in order to perform the highest jump possible. The criteria for approval were that no countermovement was allowed, and the hands had to be located on the crista iliaca. The concentric push-off phase was defined as the time period of upward movement. During this phase, the vertical velocity of the center of mass was determined by integration of acceleration over time, which, in turn, was calculated from the vertical ground reaction forces. Position of the center of mass was determined by time integration of the vertical velocity, and the highest position determined jump height.

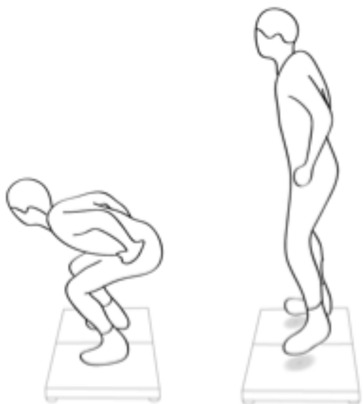

Fig. 4. Illustrations of the starting and ending positions during the squat jump.

Calculation of work rate, metabolic rate and gross efficiency

Work rate was calculated, in accordance with Sandbakk et al. (2010), as the sum of power against gravity (P_g) and friction (P_f):

$$P_g = m \cdot g \cdot sin\ (\alpha) \cdot v$$

$$P_f = m \cdot g \cdot cos\ (\alpha) \cdot \mu \cdot v_{ski}$$

Where *m* is the body mass of the skier, *g* the gravitational constant (acceleration), *α* the angle of treadmill incline (5% converted to radians), *v* the belt velocity, *μ* the frictional coefficient (0.021) and v_{ski} the speed of the ski during ground contact. Individual values of $v_{ski} = v/cos$ (orientation angle) were included in the calculation because the skis move faster than the treadmill belt due to angling of the skis during ski skating (Sandbakk, Holmberg et al. 2010).

The aerobic metabolic rate was calculated as the product of VO_2 and the oxygen energetic equivalent using the associated respiratory exchange ratio and standard conversion tables (Peronnet and Massicotte 1991).

Gross efficiency was calculated as the external work rate performed by the entire body divided by the aerobic metabolic rate, presented as a percentage, in accordance with (Sandbakk, Holmberg et al. 2010).

Cycle characteristics and calculation of kinetics- and kinematics variables

During the test sessions the skiers used G3 ski skating technique. This technique, also called V2, is performed in level terrain and at moderate inclines (Nilsson, Tveit et al. 2004, Kvamme, Jakobsen et al. 2005, Andersson, Supej et al. 2010). G3 is performed with a symmetrical pole stroke in synchrony with each leg push-off (Nilsson, Tveit et al. 2004). During sprint competitions, G3 has been demonstrated to be the predominant technique (Mikkola, Laaksonen et al. 2010, Sandbakk, Ettema et al. 2011).

Kinetic and kinematical variables during ski skating were all recorded from the instrumented roller skis. One cycle was defined as encompassing one right and one left skating stroke. Thus, the cycle began at ski lift-off of the left ski and ended at the next ski lift-off of the left ski. All variables were calculated as an average of ten complete cycles. One cycle was divided into a ground contact phase and a ski swing phase (Fig. 5). Ski ground contact phase was defined as the time between ski plant and ski lift-off, whereas ski swing phase as the time from ski lift-off to ski plant. *Cycle rate* (CR) was expressed as the number of cycles per second. *Cycle length* (CL) was defined as the covered distance on the treadmill during one cycle, calculated as speed divided by CR. *Average applied ski force* was calculated as the mean force value measured during ten cycles. *Impact force* was the highest force value measured directly after ski plant. *Force minimum* was defined as the lowest force applied with a successive increase of force to the peak force. *Peak force* was the maximal force value measured during ground contact phase. *Time to peak* was calculated as the time from force minimum to peak force. *Rate of force development* was defined as force divided by time, from force minimum to peak force. *Force impulse* was defined as the total force produced from force minimum to ski lift-off, and calculated as the integral of force over this time. The term force impulse was used as an indicator of the push-off force. It does not give the exact measure of propulsion since it contains both the eccentric and concentric phase, whereas the propulsion from the push-off phase is mostly depended on the concentric part. This requires additional movement analysis. Ski angles in relation to the forward direction of the treadmill belt were calculated from the three reflex markers on each instrumented roller ski during ground contact. *Mean ski angle* was the angle of the roller ski relative to the forward movement direction during ground contact phase. *Mean ski edging* was defined as the edging of the roller ski rotated around an axis parallel to the roller ski during ground contact phase.

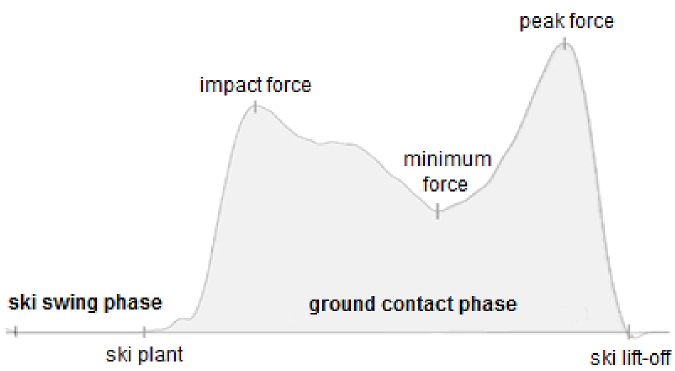

Fig. 5. An illustration of the roller ski force distribution and definition of the different phases during the swing and ground contact phase for one ski.

Statistical Analyses

All data were checked for normality and presented as mean and standard deviation (SD). Pair-wise differences between the pre- and post-submaximal tests and the peak power tests were identified by a paired samples *t*-test. Repeated measurement of the work rate, physiological variables, ski forces and cycle characteristics on the treadmill and the peak power tests demonstrated interclass correlation coefficients>0.95. Statistical significance was set at

P<0.05. All statistical tests were processed using SPSS 18.0 Software for Mac (SPSS Inc., Chicago, IL).

Results

Time to exhaustion during the incremental test was 5.9±1.7 min, with a corresponding peak speed of 6.1±0.5 m s^{-1}, VO_{2peak} of 5.5±0.6 L min^{-1} and 71.4±3.4 ml min kg^{-1}, peak HR of 193±5 bpm, peak RER of 1.10±0.04, peak VE 204±14 L min^{-1} and peak BLa of 12±3 mmol L^{-1}. After the 10-minute recovery period the skiers' VO_2 level was declined to about resting level.

Effects of exhausting exercise on neuromuscular capacity, physiological responses and gross efficiency

There were no significant differences between the pre- and post-test values for chest press (9.4±1.5 vs. 9.6±1.7 W) or squat jump (32.8±3.7 vs. 33.4±4.2 cm). During the submaximal tests, VO_2 increased by 4% from pre- to post-test, whereas HR increased by approximately 6%, VE by 14%, BLa by 4 mmol L^{-1}, whereas RER decreased by 0.08 (Table 2; all P<0.01). Metabolic rate increased significantly by 2% and the corresponding GE decreased significantly at post-test (Table 2; both P<0.05). There was a significant increase in Borg RPE (11.8±2.1 vs. 13.6±1.9, P=0.05) at post-test.

Table 2. Physiological responses, work rate and gross efficiency for 12 elite skiers while roller skiing in the G3 skating technique at 3.9 m s^{-1} pre- and post-test to incremental exercise to exhaustion (mean ± SD).

Variables	Pre-test	Post-test	P-value
VO_2 (L min^{-1})	3.9±0.4	4.0±0.4	<0.001
VO_2 (ml min kg^{-1})	50.6±2.4	52.8±1.8	<0.001
HR (bpm)	162±12	171±10	<0.001
VE (L min^{-1})	104±13	118±14	0.004
BLa (mmol L^{-1})	2.4±1.0	6.2±2.5	<0.001
Respiratory exchange ratio	0.93±0.04	0.85±0.03	<0.001
Work rate (W)	207±20	207±20	
Metabolic rate (W)	1337±140	1364±134	0.02
Gross Efficiency (%)	15.5±0.7	15.2±0.5	0.02

Effect of exhausting exercise on kinematic and kinetics

Kinematic and kinetic variables at pre- and post-tests are shown in Table 3. Cycle length decreased significantly by 5% and CR increased significantly by 4% (Table 3; both P<0.001). The post-test showed a significant reduction in ski swing phase of 0.07 s and ground contact phase of 0.09 s, whereas time to peak force decreased significantly by 0.02 s, and the RFD increased significantly by 167 N s^{-1} at post-test (Table 3; all $P<0.05$).

The average applied ski forces did not differ between the two conditions, and no significant changes of impact force, force minimum, peak force and force impulse were found at post-test (Table 3). Mean ski angling increased significantly by 1° (Table 3; $P=0.05$), whereas mean ski edging showed no significant changes from pre- to post test (Table 3).

Table 3. Cycle characteristics and kinetics variables during one cycle movement for 12 elite skiers while roller skiing in the G3 skating technique at 3.9 m s^{-1} pre and post to an incremental exercise to exhaustion (mean ± SD). All variables are calculated as the sum of left and right ski.

Variables	Pre-test	Post-test	*P*-value
Cycle rate (Hz)	0.49±0.04	0.51±0.04	<0.001
Cycle length (m)	8.1 ± 0.6	7.7 ± 0.6	<0.001
Ski swing phase (s)	1.65±0.15	1.55±0.14	<0.001
Ski ground contact phase (s)	2.50±0.2	2.41±0.15	<0.001
Time to peak force (s)	0.69±0.01	0.67±0.01	0.04
Rate of force development (N s^{-1})	3051±430	3218±360	0.03
Average applied ski force (N)	733±81	733±77	0.88
Impact force (N)	1628±152	1638±155	0.60
Force minimum (N)	901±96	896±102	0.60
Peak force (N)	1956±274	1977±244	0.39
Force impulse (N s^{-1})	661±124	650±121	0.08
Mean ski angling (°)	18.1±2.2	19.1±1.8	0.05
Mean ski edging (°)	21.5±2.9	22.2±3.1	0.30

Discussion

The purpose of this study was to investigate whether GE, kinematic variables and ski kinetics during roller ski skating were influenced by an incremental exercise to exhaustion. The main findings were that the physiological stress increased from the pre- to post-test in terms of a higher O_2 consumption and BLa level. The RER was lower at the post-test, whereas gross efficiency showed a significant reduction from pre- to post-test conditions. Furthermore, CL decreased and CR increased from pre- to post-test, and the corresponding swing and ground contact phases decreased. However, no changes in the ski forces were revealed and no difference in peak power in the upper and lower limbs occurred across trails. Since the peak power test did not differ from pre- to post-test, the decreased GE and CL cannot be associated to neuromuscular capacity. Nevertheless, the results from the incremental test showed that all skiers met the three criteria that defined maximal effort. Together with a significant increase in rating of perceived exertion it is reasonable to assume that the skiers were exhausted after the incremental test and that other mechanisms than the maximal power production have led to the shorter CL and increased physiological stress at post-test conditions.

A higher VO_2, HR, VE and BLa at the same work rate were demonstrated during the post-test performed after the incremental test to exhaustion. Furthermore, a significant reduction in GE was revealed. These findings of increased physiological responses and a decreased GE after maximal work are reported in cycling by Sahlin and colleagues (2005). In contrast de Koning et al. (2012) reported no difference in GE during submaximal work after an exercise to exhaustion in cycling. Still, it might be that the increased physiological responses occurred in this study are different from cycling due to the more coordinative demanding movement in ski skating.

The increased oxygen uptake at the post-test condition in the current study could also be due to increased energy delivery from fat substrate as indicated by the decreased RER value. The oxidation of fat is a more O_2 demanding process compared to the oxidation of glucose (Schibye and Klausen 2005), which has been taken into consideration in the calculations of GE. The reduction of RER after a maximal exercise has also been reported by Shalin et al. (2005). The efficiency of energy conservation of glucose and fatty acid oxidation aggregates to about 40%, whereas 60% dissipate as heat (McArdle, Katch et al. 2001). Still, there can be small differences between the amount of heat production at the oxidation of fat and glucose, which could have influenced the current GE result.

Reduced GE can also be linked to the execution of technique, as previously proposed by Sandbakk et al. (2010). The skiers in this study demonstrated a decreased CL and increased CR after the incremental test to exhaustion, which has previously been reported to affect GE negatively (Leirdal and Ettema 2011). One explanation of the decreased CL at the post-test can be the increased mean ski angulation that was found at the post-test. An increased ski angle has been suggested to counteract the possibility to achieve long CL (Stoggl, Muller et al. 2008). Another reason may be a change in the applied ski force. However, the skiers in this study showed no difference in total average applied ski force or in force impulse from pre- to post-test, but they showed a change in the distribution of ski forces. At post-test the skiers demonstrated a higher RFD and a shorter time to peak. This means that after an exhausting exercise the skiers are able to reproduce the same amount of ski force per cycle, but are utilizing it differently. Due to the shorter CL they apparently applied less total propulsive forces. This indicates that the leg force effectiveness and/or that the propulsive forces from poling must have been reduced. Since cross-country skiing is depending on propulsive forces from both arms and legs (Sandbakk, Ettema et al. 2012), it is reasonable to assume that an exhausting exercise may have affected the ability to coordinate the timing of the limbs.

Other changes in the kinematics during post conditions were a reduction in ski swing phase. The reduction in ski swing phase may limit leg recovery and blood flow, and thereby increase blood lactate concentration as suggested by Kagaya and Ogita (1992). This may counteract the possibility to coordinate and time the legs optimal when skiing after an exhausting exercise. Cignetti and co-workers support that changes in a skier´s coordination may occur due to exhaustion (Cignetti, Schena et al. 2009). They demonstrated a modification of the kinematics when the skiers were fatigued. However, they also found a reduced maximal power of upper and lower limb after an exhausting exercise, suggesting the modification to be associated with a decreased flexibility in the neuromuscular system to respond to perturbations. In that study, the maximal power tests were performed as a 30-second maximal diagonal stride for the upper body and 30-second jumps for the lower body. However, in the present study, we opted for a simple, coordination wise less demanding exercise that consisted of one maximal effort contraction. This was done in the attempt to catch the maximal neuromuscular capacity, with a minimal bearing on endurance and coordination. Thus, our results are not comparable with Cignetti and co-workers (2009). Zory and colleagues examined the changes in CL and CR in a simulated cross-country skiing sprint competition with double poling technique. They did not found any changes in CR and CL as a consequence of fatigue (Zory, Vuillerme et al. 2009). However, ski skating is a more technically demanding movement than double poling, which indicates that the changes occurred in our result may be caused by constrains to coordinate the limbs due to fatigue. Still, there is clearly need for further investigation of how exhausting exercise affects the kinematics and GE.

The absolute change in GE at post-test was not more than 0.3% compared to thee pre-test condition. Although gross efficiency has been reported an important factor for performance (Joyner 1991, Joyner and Coyle 2008) it is not clear to what extent a reduction in GE of 0.3% would influence ski skating performance. Since the skiers are all elite athletes, the smallest worthwhile decrease in GE may still be crucial for performance. Hettinga and colleagues (2007) showed that a reduction in GE of 0.9% resulted in a decrease of 25.6 s in time over a

20 km race for well-trained cyclists (Hettinga, De Koning et al. 2007). A decreased performance time of 0.3-0.5% has been demonstrated to be essential in elite runners, competing in a distance less than 3 km, which is similar to the cross-country skiing sprint distance. Altogether, these findings of small but worthwhile decreases in performance highlights that a reduction in GE of 0.3% may influence the skiers' performance negatively. Future studies should examine the relation between a reduction in GE and performance in cross-country skiing.

Methodological considerations

Gross efficiency has to be measured during an aerobic steady state condition. Here, the physiological variables showed a steady state for all skiers during pre-test. However, during the post-test the lactate concentration was above the onset of blood lactate accumulation for some skiers, which could indicate a small additional influence of anaerobic energy delivery. Because some skiers might not have been in a full steady state condition when GE was measured during the post-test, the possible influence of anaerobic metabolic contribution may have further affected the GE measures and led to an underestimation of GE after exhaustion. However, if that had been the case it would have further strengthened the current conclusions of reduced GE during the post-test.

In this study only ski forces were measured. However, the understanding of the total dynamics between force application, movement pattern and GE is dependent of the total forces applied from arms and legs. The absent of pole force measurement is therefore a methodological limitation in this study.

The peak power tests may have been not sensitive enough for measuring possible changes in neuromuscular fatigue. However, the results from the post-test showed a trend of increased peak power indicating that neuromuscular fatigue in this study is very unlikely. Still, the measurement of neuromuscular fatigue may need further attention in future studies.

Prior to the post-test blood lactate was not assessed so we do not know the exact initial blood lactate values when the skiers started this test. However, it has previously been reported that a recovery period of 10 minutes is sufficient to normalize lactate concentration in the blood after a similar protocol (Moxnes and Sandbakk 2012). Additionally, the O_2 levels of the skiers were examined at the beginning of the post-submaximal test, demonstrating no increased resting values or indications of changes in the oxygen kinetics from pre- to post-test.

Conclusions

The current study demonstrated increased physiological stress and reduced GE during submaximal roller skiing after an incremental exercise to exhaustion, with corresponding shorter cycle length and higher cycle rate. Since none of the ski forces differed after the exhausting exercise, this indicates changes in force effectiveness of the ski forces or different distributions of ski and pole forces at post-test conditions. Furthermore, the peak power tests, measuring neuromuscular capacity, showed no changes at post-test conditions. Thus, the differences in GE and cycle length may be related to changes in technique, such as alternations in the work done by poling or reduced force effectiveness of the push-off.

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