Changes in Technique and Efficiency After High-Intensity Exercise in Cross-Country Skiers

Christina Åsan Grasaas, Gertjan Ettema, Ann Magdalen Hegge, Knut Skovereng, and Øyvind Sandbakk

This study investigated changes in technique and efficiency after high-intensity exercise to exhaustion in elite cross-country skiers. Twelve elite male skiers completed 4 min submaximal exercise before and after a high-intensity incremental test to exhaustion with the G3 skating technique on a 5% inclined roller-ski treadmill. Kinematics and kinetics were monitored by instrumented roller skis, work rate was calculated as power against roller friction and gravity, aerobic metabolic cost was determined from gas exchange, and blood lactate values indicated the anaerobic contribution. Gross efficiency was the work rate divided by aerobic metabolic rate. A recovery period of 10 min between the incremental test and the posttest was included to allow the metabolic values to return to baseline. Changes in neuromuscular fatigue in upper and lower limbs before and after the incremental test were indicated by peak power in concentric bench press and squat-jump height. From pretest to posttest, cycle length decreased and cycle rate increased by approximately 5% (P < 0.001), whereas the amount of ski forces did not change significantly. Oxygen uptake increased by 4%, and gross efficiency decreased from 15.5% ± 0.7% to 15.2% ± 0.5% from pretest to posttest (both P < .02). Correspondingly, blood lactate concentration increased from 2.4 ± 1.0 to 6.2 ± 2.5 mmol/L (P < .001). Bench-press and squat-jump performance remained unaltered. Elite cross-country skiers demonstrated a less efficient technique and shorter cycle length during submaximal roller-ski skating after high-intensity exercise. However, there were no changes in ski forces or peak power in the upper and lower limbs that could explain these differences.

Keywords: cross-country skiing, gross efficiency, kinematics, kinetics, oxygen uptake

The ability to efficiently use metabolic energy to produce work is a key factor for endurance performance. Gross efficiency is the derivative of the relationship between work rate and total metabolic rate and expresses the energetic effectiveness of the locomotor system.1,2 Although endurance performance requires maintenance of efficiency during high-intensity exercise and/or the ability to reproduce efficiency over subsequent competitions, these aspects have gotten little scientific attention. In cycling, changes in gross efficiency after exhausting high-intensity exercise seem to be modest3 or non-existent.4 However, further examination is needed to conclude whether more technically complex movement forms are influenced by high-intensity exercise to a greater extent than cycling is.

In cross-country skiing, skiers need to adjust their technique according to the speed and the terrain, and they do this by coordinating the work between upper and lower limbs. Better skiers are generally shown to have higher gross efficiency and use longer cycle lengths than the less successful ones.5,6 In a simulated cross-country-skiing sprint competition, Zory et al7 found reduced final sprint speed over subsequent sprint heats with the double-poling technique. The lower speed was associated with a fatiguing state in the lower limbs; however, neither cycle length nor cycle-rate alternations were correlated with the reduction in speed. A fatiguing state in the lower limbs may be even more influential in the ski-skating technique where the ability to apply ski forces may be reduced. Furthermore, Cignetti et al8 reported that changes in coordination may occur due to exhaustion in cross-country skiing. In that study, they found an altered technique and reduced maximal power of the upper and lower limbs after exhausting exercise and suggested that the kinematic changes were associated with a decreased flexibility in the neuromuscular system to respond to perturbations.

The purpose of this study was to investigate the changes in technique and efficiency after high-intensity exercise to exhaustion in cross-country skiers. We hypothesized that skiers would reduce gross efficiency after high-intensity exercise and correspondingly alter their technique by reduced cycle length and ski forces.

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Methods

Subjects

Twelve male elite cross-country skiers volunteered to participate in this study. All were among the 20 best in the Norwegian Cup Series and were familiar with roller skiing as part of their daily summer training and from previous testing. Their anthropometric and physiological characteristics and performance levels (according to the International Ski Federation system) were age 25 ± 3 years, body height 181.4 ± 5.2 cm, body mass 76.3 ± 7.5 kg, body-mass index 23.2 ± 1.6 kg/m², VO₂peak 71.4 ± 3.4 mL · min⁻¹ · kg⁻¹, peak heart rate 193 ± 5 beats/min, peak respiratory exchange ratio 1.10 ± 0.04, peak blood lactate 12 ± 3 mmol/L, and International Ski Federation points 68 ± 27. The experimental procedures were approved by the Norwegian Regional Ethics Committee. Before the skiers participated, the protocol and procedures were explained verbally to each skier, and written informed consent was obtained.

Overall Experimental Design

To investigate if skiers would alter their technique and correspondingly reduce efficiency after high-intensity exercise, all participants completed 4 minutes of submaximal exercise before and after a high-intensity incremental test to exhaustion with the G3 skating technique on a 5% inclined roller-ski treadmill. Kineti

Instruments and Materials

Rolling friction force (Fᵢ) of the roller skis was determined by a towing test described previously. The friction coefficient (μ) was calculated by dividing Fᵢ by the normal force (N): μ = Fᵢ/N. The overall mean value was 0.021 and was included to calculate work rate.

The force-measurement system was assessed with the 2 roller skis, each instrumented with 2 full-bridge strain gauges (VY 41-3/350, HBM Gmb, Darmstadt, Germany) as described more in detail in Hoset et al. In front of the binding of each ski a wireless analog 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 precalibrated ski forces were validated against 2 Kistler force platforms (Kistler 9286AA, Kistler Instrument Corp, Winterthur, Switzerland), with 1 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. Three-dimensional movements of the roller skis were monitored using the Qualisys Pro Reflex system (Qualisys AB, Gothenburg, Sweden). Nine cameras captured 500 frames/s of position data from 3 passive reflective markers placed in a triangular fashion on each ski over a period of 20 seconds. Acquisition software (Qualisys Track Manager) was used to collect the data, and the evaluation of data was completed in a self-written Matlab 7.12.0 (R2011a) program designed specifically for analysis of the skating technique.

Ventilatory variables were measured employing open-circuit indirect calorimetry using an Oxycon Pro apparatus (Jaeger GmbH, Hoechberg, Germany), as validated by Foss and Hallen. Before each test, the VO₂ and VCO₂ analyzers were calibrated using a known mixture of gases (16.00% ± 0.04% O₂ and 5.0% ± 0.1% CO₂, Reissner-Gase GmbH & Co, Lichtenfels, Germany), and the expiratory flowmeter was calibrated with a 3-L syringe (Hans Rudolph Inc, Kansas City, MO). 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-1710r kit (ArkRay Inc, Kyoto, Japan), validated by Medbø et al. Rating of perceived exertion (RPE) was assessed using the Borg Scale.

Peak power of the upper limbs was determined with a concentric bench press in a standard bench, using free weights, an Olympic barbell, and a linear encoder (MuscleLab, Ergotest Technology AS, Langesund, Norway). Peak power of the lower limbs was assessed by performance of a squat jump on the Kistler force platforms.

Test Protocol

After a 15-minute low-intensity warm-up while running on treadmill, the skiers performed maximal-effort squat jump
and bench press. Thereafter, a 15-minute specific low-intensity warm-up while roller skiing on the treadmill was performed. A 4-minute submaximal pretest was performed before an incremental test to exhaustion. Directly after the incremental test, peak power for the upper and lower limbs was retested. Thereafter, a 10-minute recovery period was included before the 4-minute submaximal posttest. Previous reports indicate that this should be sufficient to normalize ventilatory variables and lactate concentration.15

The 4-minute submaximal tests were performed with the G3 technique on a 5%-inclined treadmill at a speed of 3.9 m/s. This speed was chosen based on earlier testing to induce an aerobic steady-state situation with a competition-relevant technique.16 Ventilatory steady-state values such as VO2 consumption and CO2 production, as well as the expired ventilation and heart rate, were calculated by averaging over the last minute. Kinetics and kinematics were measured over a 20-second period during the last minute. Blood lactate values and Borg RPE were assessed immediately after termination of both submaximal tests.

The incremental exercise to exhaustion with the G3 skating technique on a 5% incline was performed with an initial speed of 4.4 m/s that was increased by 0.6 m/s after the first and second minutes and thereafter by 0.3 m/s every minute until exhaustion. The test was considered to represent maximal effort if at least 2 of the following criteria were fulfilled: a plateau in VO2 despite increasing exercise intensity, a respiratory exchange ratio greater than 1.10, and blood lactate concentration exceeding 8 mmol/L. VO2 was measured every 10 seconds, and the associated respiratory exchange ratio and standard conversion tables.17 Gross efficiency was calculated as the external work rate performed by the entire body divided by the aerobic metabolic rate, presented as a percentage.

Biomechanical Variables

Kinetic and kinematical variables during ski skating were recorded from the instrumented roller skis. One cycle was defined as 1 right and 1 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 10 complete cycles. One cycle was divided into a ground-contact phase and a ski-swing phase. The ski ground-contact phase was defined as the time between ski plant and ski lift-off, whereas ski-swing phase was the time from ski lift-off to ski plant. Cycle rate was expressed as the number of cycles per second, and cycle length, as speed divided by cycle rate. Impact force was the highest force value measured during the weight-acceptance phase after ski plant. Force minimum was defined as the lowest force during ground contact with a successive increase of force to the peak force. Peak force was the maximal force value measured during ground contact. Time to peak force was calculated as the time from force minimum to peak force. Rate of force development was defined as the increase in force divided by the time from force minimum to peak force. Mean ski angle in relation to the forward direction of the treadmill belt was calculated from the 3 reflex markers on each instrumented roller ski during ground contact. Mean ski edging was defined as the edging of the roller ski rotated around an axis parallel to the roller ski during ground contact.

Statistical Analyses

All data were checked for normality and presented as mean and standard deviation (SD). Pairwise differences between the pretest and posttest 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 intraclass correlation coefficients above .95. Statistical significance was set at \( P < .05 \). 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 minutes, with a corresponding peak speed of 6.1 ± 0.5 m/s, VO2peak of 5.5 ± 0.6 L/min and 71.4 ± 3.4 mL·min\(^{-1}\)·kg\(^{-1}\), peak heart rate of 193 ± 5 beats/min, peak respiratory exchange ratio of 1.10 ± 0.04, peak ventilation of 204 ± 14 L/min, and peak blood lactate concentration of 12 ± 3 mmol/L. All ventilatory variables were reduced to resting levels before the posttest, the oxygen kinetics at onset of exercise did not differ between pretest and posttest, and all skiers reached an oxygen steady state during the last 2 minutes under both conditions.

There were no significant differences between the pretest and posttest values for bench press (359 ± 55 vs 365 ± 57 W) and squat jump (32.8 ± 3.7 vs 33.4 ± 4.2 cm).

Cycle rate increased and cycle length decreased by approximately 5% (Table 1; both \( P < 0.001 \)). Ski-swing phase and ground-contact phase decreased by 6% and 4% respectively; time to peak force decreased significantly by 3%; and the rate of force development increased by 5% (Table 1; all \( P < .05 \)). No significant changes of impact force, force minimum, and peak force were found (Table 1). Mean ski angling increased significantly by an absolute value of 1° (Table 1; \( P = .05 \)), whereas mean ski edging did not change from pretest to posttest (Table 1).

From pretest to posttest, VO2 increased significantly by 4%, heart rate by approximately 6%, ventilation by 14%, blood lactate concentration by 3.8 mmol/L, and RPE by 1.8 points, whereas the respiratory exchange ratio decreased by 0.08 (Table 2; all \( P < .01 \)). Metabolic rate increased significantly by 2%, and the corresponding gross efficiency decreased by 0.3% (Table 2; both \( P < .05 \)).

**Discussion**

The purpose of this study was to investigate the changes in technique and efficiency after high-intensity exercise to exhaustion in cross-country skiers. The main finding was that elite cross-country skiers increased oxygen uptake, ventilation, heart rate, blood lactate accumulation, and rating of perceived exertion, whereas gross efficiency and cycle lengths were reduced, during submaximal roller-ski skating after high-intensity exercise. However, the amount of ski forces and peak power in the upper and lower limbs remained similar from pretest to posttest.

The skiers in this study reduced cycle length and increased cycle rate during submaximal roller skiing after the incremental test to exhaustion. In contrast, Zory et al\(^7\) found reduced sprint speed but no significant changes in cycle length and cycle rate in a simulated cross-country-skiing sprint competition with the double-poling

<table>
<thead>
<tr>
<th>Variable</th>
<th>Pretest</th>
<th>Posttest</th>
<th>( P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle rate (Hz)</td>
<td>0.49 ± 0.04</td>
<td>0.52 ± 0.04</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Cycle length (m)</td>
<td>8.1 ± 0.6</td>
<td>7.7 ± 0.6</td>
<td>&lt;.001</td>
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<tr>
<td>Ski-swing phase (s)</td>
<td>0.82 ± 0.08</td>
<td>0.78 ± 0.07</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Ski ground-contact phase (s)</td>
<td>1.25 ± 0.08</td>
<td>1.21 ± 0.08</td>
<td>.01</td>
</tr>
<tr>
<td>Time to peak force (s)</td>
<td>0.35 ± 0.05</td>
<td>0.34 ± 0.04</td>
<td>.05</td>
</tr>
<tr>
<td>Average applied ski force (N)</td>
<td>733 ± 81</td>
<td>733 ± 77</td>
<td>.88</td>
</tr>
<tr>
<td>Impact force (N)</td>
<td>814 ± 76</td>
<td>819 ± 78</td>
<td>.37</td>
</tr>
<tr>
<td>Force minimum (N)</td>
<td>451 ± 48</td>
<td>448 ± 51</td>
<td>.60</td>
</tr>
<tr>
<td>Peak force (N)</td>
<td>978 ± 137</td>
<td>988 ± 122</td>
<td>.40</td>
</tr>
<tr>
<td>Rate of force development (N/s)</td>
<td>1525 ± 215</td>
<td>1609 ± 180</td>
<td>.03</td>
</tr>
<tr>
<td>Mean ski angling (°)</td>
<td>18.1 ± 2.2</td>
<td>19.1 ± 1.8</td>
<td>.05</td>
</tr>
<tr>
<td>Mean ski edging (°)</td>
<td>21.5 ± 2.9</td>
<td>22.2 ± 3.1</td>
<td>.30</td>
</tr>
</tbody>
</table>

All variables are calculated as the average of the left and right skis.
Since ski skating is more technically demanding than double poling, the significant changes found in our study may have been caused by the greater strain to coordinate the limbs. This is supported by Cignetti et al, who reported that changes in coordination may occur due to exhaustion in cross-country skiing. In that study, they also found reduced peak power of the upper and lower limbs after an exhausting exercise, suggesting that the kinematic changes were associated with a decreased flexibility in the neuromuscular system.

Although cycle length was reduced, the total applied ski forces and peak ski forces did not change significantly from pretest to posttest. Furthermore, the peak power tests for the upper and lower limbs did not change, indicating that neuromuscular fatigue measured with traditional methods was unlikely in our study. Notably, a small change in the distribution of ski forces was found at the posttest, with a shorter time to peak force and a higher rate of force development. Whether this influenced the force effectiveness and led to a lower propulsive component needs to be examined in more detail in future studies.

Nevertheless, the skiers were able to reproduce the same amount of ski force per cycle but probably applied the forces less effectively after high-intensity exercise to exhaustion. However, the absence of pole-force measurements is a methodological limitation in this study, and possible changes in the work distributed by the upper and lower limbs were not examined here.

Increased cycle rate has previously been reported to cost more oxygen and affect gross efficiency negatively. In this study, the increased cycle rate was followed by higher VO₂, ventilation, heart rate, and blood lactate values at the same work rate during the posttest. Thus, a small but significant reduction in gross efficiency was revealed. These findings correspond with those of Sahlin et al but contrast with those of de Koning et al, who did not find a change in gross efficiency during submaximal cycling after exercise to exhaustion. The increased oxygen uptake at the posttest found here may partly be explained by increased energy delivery from fat substrate, as indicated by the decreased respiratory exchange value. Fat oxidation demands more oxygen than glucose. However, this has been taken into consideration when calculating metabolic rate and gross efficiency. In addition, some skiers had blood lactate concentrations above the onset of blood lactate accumulation at the posttest, which could indicate an additional influence of anaerobic-energy delivery and an underestimation of the total metabolic rate. The possible contribution of additional anaerobic metabolism at the posttest would have reduced gross efficiency and thereby further strengthened our hypothesis.

Gross efficiency is an important factor for endurance performance, and since the skiers examined here were all elite athletes, the smallest worthwhile decrease in gross efficiency might be crucial for performance. However, it is not clear to what extent the average reduction of 0.3% would influence gross efficiency during exercise to exhaustion. The increased oxygen uptake at the posttest found here may partly be explained by increased energy delivery from fat substrate, as indicated by the decreased respiratory exchange value. Fat oxidation demands more oxygen than glucose. However, this has been taken into consideration when calculating metabolic rate and gross efficiency. In addition, some skiers had blood lactate concentrations above the onset of blood lactate accumulation at the posttest, which could indicate an additional influence of anaerobic-energy delivery and an underestimation of the total metabolic rate. The possible contribution of additional anaerobic metabolism at the posttest would have reduced gross efficiency and thereby further strengthened our hypothesis.

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**Practical Applications**

Although elite skiers were able to maintain the same amount of ski forces and peak power in the upper and lower limbs after high-intensity exercise, they

<table>
<thead>
<tr>
<th>Variable</th>
<th>Pretest</th>
<th>Posttest</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO₂ (L/min)</td>
<td>3.9 ± 0.4</td>
<td>4.0 ± 0.4</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>VO₂ (mL · min⁻¹ · kg⁻¹)</td>
<td>50.6 ± 2.4</td>
<td>52.8 ± 1.8</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td>162 ± 12</td>
<td>171 ± 10</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Ventilation (L/min)</td>
<td>104 ± 13</td>
<td>118 ± 14</td>
<td>.004</td>
</tr>
<tr>
<td>Blood lactate (mmol/L)</td>
<td>2.4 ± 1.0</td>
<td>6.2 ± 2.5</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Respiratory exchange ratio</td>
<td>0.93 ± 0.04</td>
<td>0.85 ± 0.03</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Rating of perceived exertion</td>
<td>11.8 ± 2.1</td>
<td>13.6 ± 1.9</td>
<td>.05</td>
</tr>
<tr>
<td>Work rate (W)</td>
<td>207 ± 20</td>
<td>207 ± 20</td>
<td>—</td>
</tr>
<tr>
<td>Metabolic rate (W)</td>
<td>1337 ± 140</td>
<td>1364 ± 134</td>
<td>.02</td>
</tr>
<tr>
<td>Gross efficiency (%)</td>
<td>15.5 ± 0.7</td>
<td>15.2 ± 0.5</td>
<td>.02</td>
</tr>
</tbody>
</table>
used shorter cycle length and higher cycle rate during submaximal roller skiing. Correspondingly, oxygen uptake, blood lactate levels, and RPE were significantly increased. Thus, it is reasonable to conclude that cross-country skiers employ a less efficient skating technique after high-intensity exercise to exhaustion. Consequently, athletes in technically complex endurance sports may enhance their performance by improved technique in an exhausting state. In cross-country skiing, the ability to maintain an effective technique and high efficiency may be especially relevant in the shorter sprint competitions where skiers perform a time-trial qualification race and 3 separate knockout heats.

Acknowledgments
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References