The Effect of Fatigue on Technique Transition in Classical Roller Skiing

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Abstract

Introduction: Classical cross-country skiing consists of three main sub-techniques; double poling (DP), double poling with kick (DK) and diagonal stride (DIA). The skiers' transition between these like a "gear system", where the choice of technique is influenced by the physical capabilities of the skier, and other factors like speed, inclination, glide friction and wind resistance. The current study investigated the effect of fatigue on the time and number occurrences of technique transitions and total time used (distribution) of sub-techniques in classical roller skiing at varying speed and inclines.

Methods: Eight male cross-country skiers conducted two test conditions in a randomized, counterbalanced order, in roller skiing on a treadmill using the classical technique. Both test conditions consisted of a pre-test intervention, and a post-test identical to the pre-test. The pre- and post-test consisted of 11 min of constant submaximal work rate with; 3 min on 3% incline to reach aerobic metabolic steady state, followed by an increasing incline to 11% , by 1% each min. The intervention consisted of either a fatigue exercise to total exhaustion or low intensity roller skiing. Physiological and kinematic variables were assessed by the use of open- circuit indirect calorimetry, blood lactate monitoring and Oqus 3D motion capture analysis. Work rate was calculated as the sum of power against gravity and rolling friction.

Results: Oxygen consumption, heart rate and lactate values increased significantly from pre- to post after the fatiguing compared to the low intensity exercise (0.5 vs 1.7 mL kg^{-1} min^{-1}; 0 vs 12 bpm; 0.3 vs 3.1 mmol/L; all $P < 0.05$). Technique distribution did not alter significantly after the fatigue exercise, although a tendency towards increased amount of DIA was found (54 ± 4 sec; $P = 0.064$). The mean transition point from DK to DIA occurred significantly earlier (60 ± 25 sec; $P < 0.05$), while the total number of transitions did not alter significantly after the fatigue exercise ($P > 0.38$).

Conclusion: Altogether, the results indicated that the state of fatigue led to utilization of lower gears at lower incline, and thereby an altered technique distribution. However, large individual differences related to technique transitions and choices of technique were observed.

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Introduction

Originally, cross-country skiing was used by humans to fast and effective travel across snow-covered terrain. As a consequence of the role of sport in the modern society, development of skiing equipment and skiing tracks, cross-country skiing is now a movement form used primarily for recreational activities and as a competitive sport.

The original technique in cross-country skiing is referred to as the classical style (Nilsson, Tveit, & Eikrehagen, 2004), consisting of three main sub-techniques; double poling (DP), double poling with kick (DK) and diagonal stride (DIA) (Bilodeau, Rundell, Roy, & Boulay, 1996). The sub-techniques skiers transition between can be described as a gear system, where the choice of technique is influenced by the physical capabilities of the skier, and other factors like speed, inclination, glide friction and wind resistance (Nilsson et al., 2004; Pellegrini et al., 2013). Each sub-technique has its own technical characteristics, and places varying demands on the upper and lower body, in terms of strength and coordination.

In DP, the arms move in parallel, and propel the body forward by repeated poling actions. The propulsive action starts by a flexion of the trunk, followed by a parallel pole plant which push the skier into the gliding phase (Holmberg, Lindinger, Stoggl, Eitzlmair, & Muller, 2005). The legs optimize force in the poling action, by elevating the center of mass through extension of the knee and ankle joints, followed by a rapid flexion of the same joints which culminates with a parallel pole plant (Holmberg, Lindinger, Stoggl, Bjorklund, & Muller, 2006). DP is used at high speeds and primarily in moderate downhill, flat sections and moderate uphill. DK has similarities with DP, due to the parallel arm movement during the poling action, but adds a propulsive leg kick in between each pole plant (Goepfert, Holmberg, Stoeggl, Mueller, & Lindinger, 2013). DK is most commonly used in moderately uphill sections, where the gravity places high demands on the skier in maintaining constant momentum forward (Goepfert et al., 2013). DIA is characterized by an alternating arm and leg movement, where the push of one arm is combined with the push of the contralateral leg (Kehler, Hajkova, Holmberg, & Kram, 2014; Nilsson et al., 2004). Propulsion from both arms and legs propels the skier forward. The technique is most commonly used at relatively steep uphill, where gravity makes the gliding phase harder to maintain, and the skier has to increase the propulsive phase durations to maintain as constant cycle speed as possible (Kehler et al., 2014).

Transitions between the different sub-techniques are quite prominent during both training and competition. However, the frequency of use varies between individuals.

Andersson et al. (2010) showed that in a sprint skating competition, the performance and number of transitions were negatively correlated. This was related to the ability of maintaining high speed gears at steeper inclines throughout the competition. Thus, individual differences in upper-body strength, and other factors related to performance play a central role in determining where different sub-techniques are used in cross-country skiing.

In general, technique transitions has been characterized as an abrupt shift in movement, in means of adapting to various situations and conditions (Turvey, Holt, LaFiandra, & Fonseca, 1999). In terrestrial locomotion in humans and animals, the shift in movement pattern mainly occurs for adaptations to changes in speed and incline (Alexander, 1984; Hoyt & Taylor, 1981).

Technique transitions in cross-country skiing have not been widely studied, and the few studies that exist have focused upon identifying the factors that triggers the shifts. One study (Cignetti, Schena, Zanone, & Rouard, 2009a) investigated the transition between techniques by investigating inter-limb coordination from a dynamical system perspective. By using that approach, the researchers were able to identify whether a movement could be characterized as stable or unstable. The results showed that the transitions between techniques were associated with a loss of coordination stability. Thus, they hypothesized that this deterioration was a crucial determinant for technique transitions. One more recent study (Pellegrini et al., 2013) suggested that when the inclination gradually increased, poling force (PF) reached a certain level where a technique transition was necessary to reduce the exertion on central muscles used in DP and DK. A similar trigger was illustrated on the leg thrust time, in terms of speed. In DK and DIA, the leg thrust time never went below the minimum value of 0.11 seconds in any of the skiers, which was argued to be the shortest time possible for the muscles to create propulsion. According to these triggers, the skiers will choose DIA and DK when the hill steepens and speed decreases, while DP is preferred at high speeds (Pellegrini et al., 2013). However, the designs of both studies were set up so the work rate increased or decreased with changes in speed or inclination (Cignetti et al., 2009a; Pellegrini et al., 2013). To this authors knowledge**,** no study has used constant work rate at varying speeds and inclinations, where effect of condition (incline and speed) can be isolated from effect of work rate.

The ability to maintain performance when fatigued, can be characterized as one of the most central challenges in competitive cross-country skiing. In general, fatigue is defined as an acute impairment of performance (Enoka & Stuart, 1992), and a decreased ability to maintain a level of force over time (De Luca, 1984). In cross-country skiing, maximal power production has been shown to decrease from both arms and legs when skiers get fatigued (Cignetti, Schena, & Rouard, 2009b; Mikkola, Laaksonen, Holmberg, Nummela, & Linnamo, 2013; Zory, Millet, Schena, Bortolan, & Rouard, 2006; Zory, Vuillerme, Pellegrini, Schena, & Rouard, 2009) . When this ability degrades, optimal technique execution can be affected, because each sub-technique has been suggested to place high demands on coordination and strength (Goepfert et al., 2013; Nilsson et al., 2004). In a time to exhaustion test in classical style, 8 national level skiers showed clear signs of increased local instability in their movement pattern as a result of fatigue, and speed was lowered to maintain a more stable gait (Cignetti et al., 2009b). Previous studies have highlighted that fatigue induces instability in movement patterns and degrades power production during cross-country skiing. However, how this affects the transitions between sub-techniques in the classical style needs further examinations.

The purpose of this study was to investigate how fatigue affects at what instances transitions occur, and how it affects the total use of sub-techniques in time. The main hypothesis was that at a constant workload, the skiers would prefer to use lower gears (more DK and DIA) when fatigued, compared to the fresh state. This increase would be reflected through an earlier transition from DP to DK, and DK to DIA.

Methods

Study population

Eight male national level cross-country skiers, age 22.3 ± 1.6 years, height 183.6 ± 4.4 cm, weight 80.2 ± 7.7 kg, volunteered to participate in this study. Their VO_{2peak} was 73.9 ± 6.4 mL kg^{-1} min^{-1}, measured during an incremental protocol in classical roller skiing. All participants were well informed of the protocol and procedures of the study, and signed a written informed consent before entering it. The study was also pre-approved by the regional ethics committee, Trondheim, Norway.

Overall design

In the current study, all participants conducted two test conditions in roller skiing on a treadmill using the classical technique. The test conditions, one control and one fatigue test, were conducted at separate days randomly to avoid that a first test would affect the outcome of the second one. Both test conditions consisted of a pre-test intervention, and a post-test identical to the pre-test. The pre- and post-test consisted of 11 minutes of constant submaximal work rate with; 3 minutes on 3% incline to reach aerobic metabolic steady state, followed by an incline increase to 11% , by 1% each minute. The targeted work rate was submaximal (200 w) and heavy enough to ensure technique changes, but light enough to ensure steady state throughout 11 minutes; the intervention consisted of either a fatigue exercise to total exhaustion or low intensity roller skiing. Kinematical data were recorded using a 3D motion capturing system, and respiratory variables sampled using an open circuit indirect calorimetry (Jaeger GMbH, Hoechberg, Germany).

Instruments and materials

Roller skiing was performed using a 5 x 3 motor-driven treadmill (Forcelink Technology, Zwolle, The Netherlands). All testing were done utilizing the classical technique, and all participants used the same pair of Pro ski roller skis with IDT-2 wheels, to minimize variations in rolling resistance (Pro-Ski, Sterners, Nyhammar, Sweden). Poles (Madshus UHM 100, Biri, Norway) were available in length intervals of 5 cm, and all skiers could use their preferred length.

The friction force (F_f) of the roller skis were estimated by using a towing test on the treadmill, previously described by (Sandbakk, Holmberg, Leirdal, & Ettema, 2010); $\mu = Ff \times N^{-1}$. Where (μ) is the friction coefficient, and (N) the normal force. The mean value of (μ) was found to be 0.022, and was also used in the calculations of workload.

During all trials, kinematical data were collected using the Oqus 3D motion analysis system (Qualisys AB, Gothenburg, Sweden). Six infrared cameras were fixed towards the treadmill in order to capture a three dimensional image of the six reflective markers placed on the athletes and the treadmill. Sampling rate was set to 50 Hz. A total of four markers were placed on the poles and roller-skis. One marker was placed on the lateral side of each pole, 5 cm below the handle, and one marker at the back visor of each roller ski. Two markers were also placed on the left side of the treadmill, in alignment to movement direction with a 150 cm gap, in order to continuously register incline throughout the protocol. The markers on the poles were fastened using superglue whilst those on the roller skis and treadmill with double sided tape (3M, USA). The coordinate system was calibrated with a wand and L-frame between every third participant for collecting accurate and high quality data. All of the recorded data were processed in Qualisys Track Manager software (Qualisys AB, Gothenburg, Sweden). The data were later on exported to Matlab 8.1.0. (R2013a, Mathworks Inc., Natick, MA, USA), and synchronized with the physiological measurements. A video camera (Canon Legria HF R206, Japan) also recorded all test sessions.

Respiratory variables were continuously measured by an open circuit indirect calorimetry, using an Oxycon Pro apparatus. At the beginning of each test day, the system was calibrated against a known mixture of gases (16.00 ± 0.04% O2 and 5.00 ± 0.1% CO2, Riessner-Gase GmbH & Co, Lichtenfels, Germany). Heart rate (HR) was also registered continually using a Garmin 910XT watch with HR monitor (Garmin, USA). Lactate values were taken with a Biosen C_line lactate analyzer (EKF diagnostics, Germany). The lactate samples on 20 μl were taken from the middle and ring-finger, and the same person collected the samples on all subjects.

Test protocol

The two test days were conducted in a randomized, counterbalanced order, with a control day, and a fatigue day. Part one and three were identical, while part two differed in terms of intensity, with a fatigue inducing exercise on the experimental day, and a low intensity protocol on the control day.

Pre- and post- test part consisted of a *transition protocol* lasting 11 minutes, with a total of 9 steps. The protocol began with 3 minutes on 3% incline, to ensure that the athletes had reached an aerobic metabolic steady state before the changes in slope were initiated. Thereafter, the incline increased by 1% each minute up to 11%. Speed was reduced accordingly to maintain a constant work rate (W) throughout the entire protocol (figure 1).

After the steepest incline was maintained in one minute, a 60 sec break was implemented for taking a blood lactate sample. To test other aspects of technique transitions, the protocol was continued in reversed order (lowering incline and increasing speed), lasting 11 minutes, however this part of the protocol is not considered in this study. The skiers were not given any special instructions, other than to ski as normal as possible, and utilize the techniques they preferred. Kinematical recordings was started 2 minutes into the protocol (last minute of the 3% incline condition), to ensure that the athletes had reached steady state, and ended when they had performed at the 11% incline for one minute, after a total of 11 minutes. Respiratory variables and HR were recorded continuously during the entire protocol (11 min).

A *fatigue test* was performed as part two on the experimental day, which lasted 10.49 ± 48 minutes. Protocol details were determined based upon pilot testing and calculations of work rate, with the purpose of inducing fatigue on the athletes. The protocol was continuous, and consisted of; *1)* 4 minutes DP at 3% incline, (2 minutes at 5.0 m s^{-1} and 2 minutes at 5.8 m s^{-1}), *2)* 2 minutes DK at 7% incline and 4.2 m s^{-1}, and *3)* 30 sec DS at 10 % incline and 2.8 m s^{-1}. After the consecutive 30 sec, the speed increased by 0.30 m s^{-1} per minute until exhaustion/failure. The athlete's task was to stay on the treadmill for as long as possible. The treadmill was stopped using the emergency brake when the athletes were no longer able to maintain the required position on the treadmill. All athletes received encouragement during the test to push themselves as hard as possible. After the fatigue-test, a 6.11 ± 1.04 minutes brake was implemented before the skiers started the post-test. Ventilatory measurements were sampled every 10 sec, and the peak oxygen uptake (VO_{2peak}) was calculated by averaging the 3 highest consecutive values. Lactate samples were taken 1-minute after the test.

On the control day, a *low intensity protocol* was used on part two. The duration was 12 minutes, and the subjects skied 4 minutes on each consecutive sub-technique. The purpose was to keep the athletes going at a low metabolic steady state, and utilize all techniques before part three of the protocol initiated. Lactate samples were taken both pre and post.

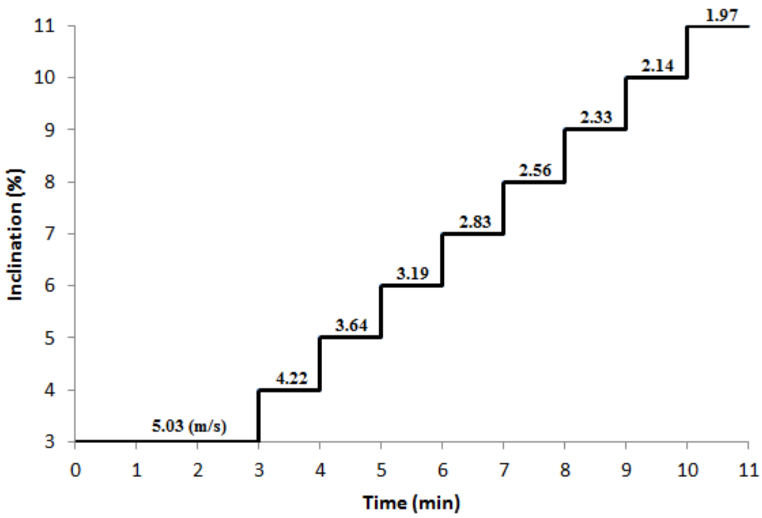

Figure 1. The pre- and post-test in terms of inclination (%), velocity (m s^{-1}) and time (min). The speed and incline combinations yielded a work rate of approximately 200W.

Calculation of Work rate

During the transition test, speed and incline were automatically adjusted by using a pre-programmed track. The aim was to keep work rate constant. Work rate was calculated, in accordance to Sandbakk and colleagues (Sandbakk et al., 2010), as the sum of power against gravity (P_g) and friction (P_f):

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

$$P_f = m \cdot g \cdot \cos \alpha \cdot \mu \cdot v$$

where *m* is the body mass of the skier, *g* the gravitational constant, α the inclination of the treadmill (in radian), *v* the speed of the treadmill, and μ the frictional coefficient (0.022). Incline were increased from 3 to 11%, and speed adjusted correspondingly to maintain constant work rate. The mean body mass of the athletes were predicted to 78 kg, which was used as reference weight in the calculations of speed. By using this setup, small differences in target work rate of 200 Watt occurred between athletes with different body weight. However, these differences were minimal, and an average of 206 ± 20 Watt was achieved.

Biomechanical variables

Technique transitions were identified in Matlab using a continuous phase algorithm applied to the movements of the skis. Each complete cycle was identified by minimum and maximum values of the relative movement in fore-aft direction, and these movement cycles were further on normalized for amplitude with zero as mean. By regarding the resultant signal sinusoidal in nature, the amplitude signals were converted to continuous angles, where the difference between left and right indicated the relative phase. This relative phase was smoothed by applying a moving average with a window width of 5 complete movement cycles. A relative phase ≥ 2 rad was regarded as an out-of-phase ski movement and identified as DIA, a phase of ≤ 0.6 regarded as an in-phase movement and identified as DP, while values between 0.6 and 2 as DK. The DK movement is partly in-phase and partly out-of-phase, which results in a continuous phase value just above 1. Transitions were identified as changes of the phase signal from one to another of the abovementioned phase ranges (figure 2).

The algorithm was quality checked by comparing the computed transition times with those observed by the experimenters during the test protocol. If there was any discrepancy in the data, the video backup of the sessions were used to determine when the transitions occurred. However, this was only necessary at three occasions. In rare occasions, periods of one skiing technique lasted less than two whole movement cycles. The accompanying transitions were considered as "quickly testing" another technique but swiftly change back and disregarded in this study.

The *permanent transition point* used in the statistical analysis is defined as the last change-over between two respective sub-techniques DP-DK, and DK-DIA without changing back again. The *total number of transitions* includes all transitions where the "new" technique is utilized longer than two whole movement cycles.

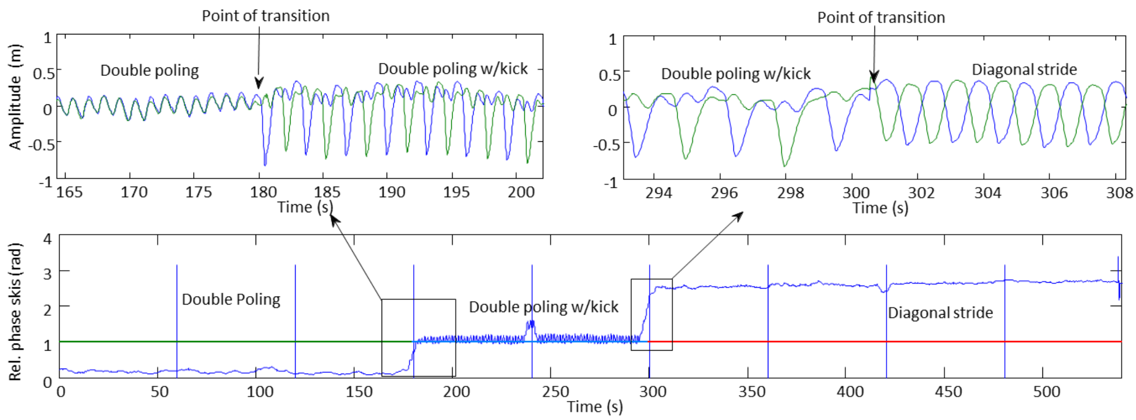

Figure 2. Presentation of relative phases and technique identifications based on ski movements. The amplitude is in the movement direction (top figure) relative to the treadmill, while the continuous difference in angles between the left and right ski movement indicates the relative phase of the technique (bottom figure).

Statistical analysis

All data was checked for normality and presented as means and standard deviations (±SD), calculated by conventional methods. To evaluate differences in the distribution of sub-techniques and occurrence of transitions on the same test day, and between test days, repeated measures ANOVA was used. The value of statistical significance was set at $P < 0.05$ for all analysis. Statistical tests were processed using Office Excel 2010 (Microsoft Corporation, Redmond, WA, USA), and SPSS 21.0 Software (SPSS Inc, Chicago, IL).

Results

Physiological variables

The oxygen consumption on the control day (a) and experimental day (b) are presented in figure 3. The mean value on each respective test condition were; PreC 45.8 ± 1.1, PostC 45.8 ± 1.1, PreF 45.8 ± 1.2 and PostF 47.6 ± 1.6 mL kg^{-1} min^{-1}. The two way ANOVA indicated a significant interaction effect (P = 0.01) between the control and the experimental day, showing significant pre- to post-test changes between conditions.

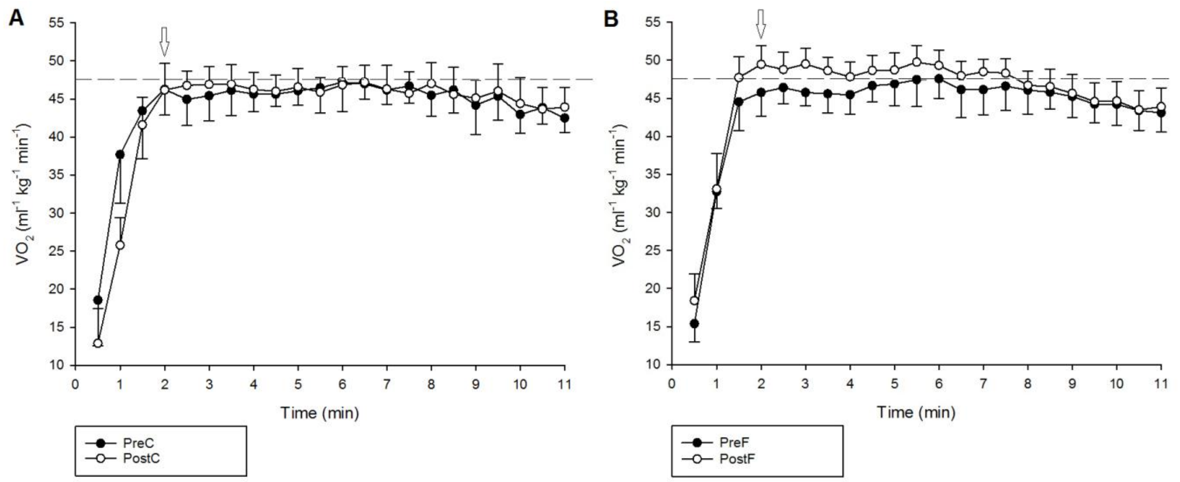

Figure 3. Oxygen consumption during the transition protocol of 11 minutes while roller skiing at constant submaximal work rates in the classical technique at increasing incline and decreasing speed. The graphs, show the pre- and post-conditions on the control day (a) and the experimental day where the skiers were fatigued between tests (b). Arrows indicate the first measure used in the statistics. Values are expressed as mean ± SD. PreC, pre-control; PostC, post-control; PreF, pre-fatigue; PostF, post-fatigue.

The heart rate on the control day (a) and experimental day (b) are presented in Fig.4. The mean value on each respective test condition were; PreC 148 ± 8, PostC 148 ± 8, PreF 149 ± 8 and PostF 161 ± 5 bpm. The two way ANOVA indicated a significant interaction effect (P = 0.01) between the control and the experimental day, when comparing the change from pre to post. Thus, the pre-post change differed significantly between conditions.

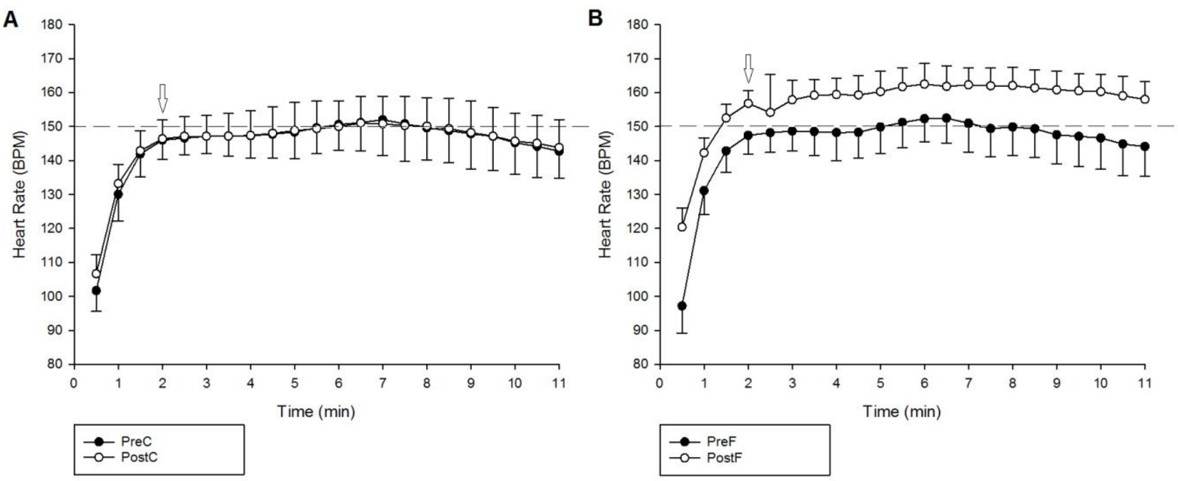

Figure 4. Heart Rate (bpm) during the transition protocol of 11 minutes while roller skiing at constant submaximal work rates in the classical technique at increasing incline and decreasing speed. The graphs, show the pre- and post-conditions on the control day (a) and the experimental day where the skiers were fatigued between tests (b). Arrows indicate the first measure used in the statistics. Values are expressed as mean ± SD. PreC, pre-control; PostC, post-control; PreF, pre-fatigue; PostF, post-fatigue.

The lactate samples taken immediately after each test condition showed the following; PreC 1.6 ± 0.5, PostC 1.9 ± 1.1, PreF 1.4 ± 0.5, PostF 4.5 ± 1.0 mmol/L. After the fatigue test, subjects had a lactate concentration of 10.5 ± 1.5 mmol/L. The two way ANOVA indicated a significant interaction effect (P = 0.005) between the control and the experimental day, illustrating a significant pre-post change between conditions.

Distribution of sub-techniques

The technique distribution between the three sub-techniques is presented in figure 5. The results show that, compared to all corresponding values in the same sub-technique, the time in DIA was not altered significantly after the fatigue inducing exercise (PostF). However, the two way ANOVA showed a tendency towards significant interaction (P = 0.064), i.e., comparing the pre-post change between conditions. The time in DP and DK did not change significantly compared to all corresponding values in the same sub-technique, and no tendencies were found (two way ANOVA, interaction P= 0.31, P=0.66, respectively).

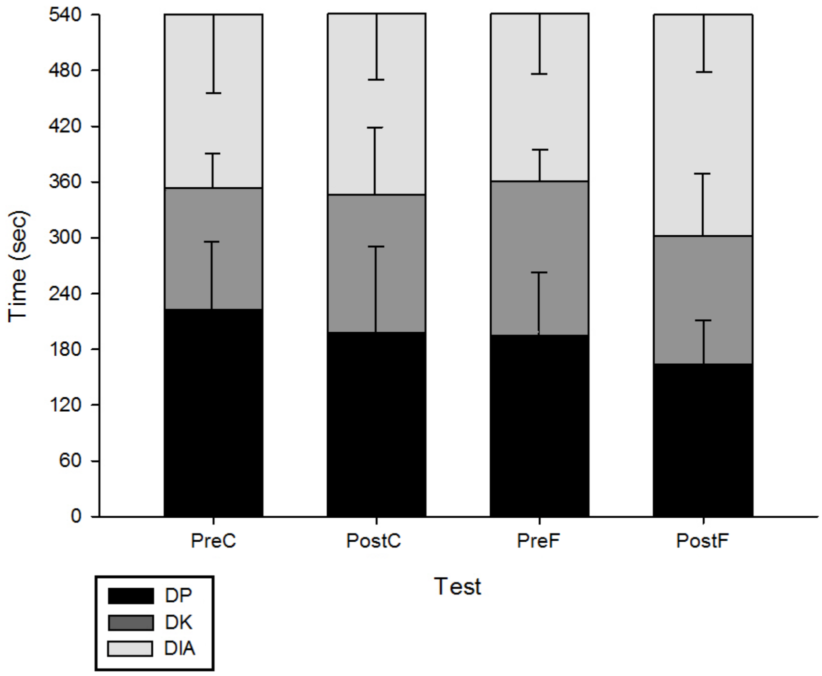

Figure 5. Distribution of double poling (DP), double poling/w kick (DK) and diagonal stride (DIA) during the transition protocol while roller skiing at constant submaximal work rates in the classical technique at increasing incline and decreasing speed, presented in time (sec). The graph, show the pre- and post-conditions on the control day and the experimental day where the skiers were fatigued between tests.
The interaction effect between the control and the fatigue day in DIA is nearly significant ($P = 0.06$). Values are expressed as means ± SD.
PreC, pre-control; PostC, post-control; PreF, pre-fatigue; PostF, post-fatigue.

Occurrence of transitions

The total number of transitions did not change after the fatigue inducing exercise (Table.1), with no values close to statistical significance ($P > 0.38$). The total range in transitions varied greatly during the test conditions, from 1-10.

The mean permanent transition points are presented in figure 6. The pre to post change between the control day and the experimental day was investigated by using a two way ANOVA for repeated measures, which showed a significant interaction effect in DK to DIA ($P = 0.043$). No significant difference was found in DP to DK ($P = 0.48$).

Table 1. Number of transitions, presented in mean ± SD and coefficient variation (CV) during the transition protocol while roller skiing at constant submaximal work rates in the classical technique at increasing incline and decreasing speed.

Test	Mean ± SD	CV
PreF	3.6 ± 2.4	0.7
PostF	3.1 ± 1.4	0.4
PreC	4.1 ± 2.4	0.6
PostC	3.6 ± 2.5	0.7

PreC, pre-control; PostC, post-control; PreF, pre-fatigue; PostF, post-fatigue.

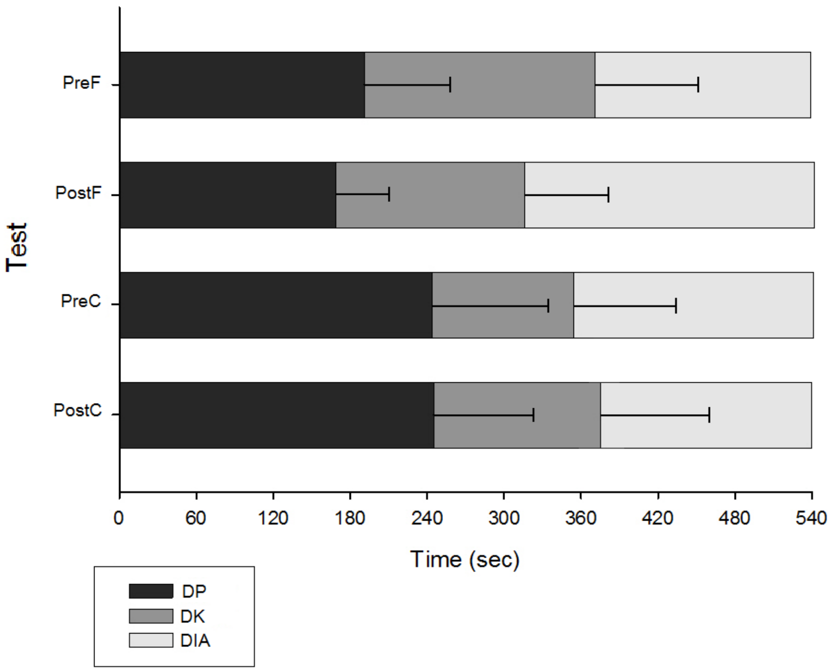

Figure 6. The permanent transition point between Double Poling (DP) to Double Poling w/kick (DK), and DK to Diagonal Stride (DIA), during the transition protocol while roller skiing at constant submaximal work rates in the classical technique at increasing incline and decreasing speed, presented in time (sec).
A significant interaction effect ($P < 0.05$) between the control and fatigue condition was found when comparing the time of shift from DK to DIA. Values are expressed as means ± SD.
PreC, pre-control; PostC, post-control; PreF, pre-fatigue; PostF, post-fatigue.

Discussion

The aim of this study was to investigate how fatigue affected the occurrence of transitions and distribution of sub-techniques in classical style cross-country roller skiing. Here, speed and incline was changed reciprocally to maintain constant work rate. The main finding was that the transition from DK to DIA occurred earlier in the protocol after fatigue, while a tendency towards increased amount of DIA were found. Thus, the hypothesis that the skiers would prefer lower gear (more DK and DIA), and shift earlier from DP and DK was partially confirmed. Furthermore, the physiological results showed that the skiers had an elevated response of VO_2, HR and lactate after the fatiguing exercise.

Physiological responses

The fatigue test elicited higher VO_2, HR and lactate values in the post fatigue condition, compared to the pre-test. These finds are in accordance with two studies on cross-country skiing and cycling that showed an elevated physiological response during submaximal exercise after high-intensity exercise to exhaustion (Grasaas, Ettema, Hegge, Skovereng, & Sandbakk, 2014; Sahlin, Sorensen, Gladden, Rossiter, & Pedersen, 2005). A possible explanation for the elevated physiological responses found here could be a lowered skiing efficiency. When skiers get fatigued, a lack of force potential most likely occur, which correspondingly increases cycle rate and/or the demand for additional recruitment from other muscles, resulting in increased use of VO_2 (Grasaas et al., 2014; Sahlin et al., 2005). Thus, the skiers produce the same work rate after fatigue, but are not able to do this as efficiently as when they are fully rested.

The fatigue intervention in this study is similar to previous ones, in terms of length and intensity (Cignetti et al., 2009b; Zory et al., 2006). However, those studies evaluated fatigue by the use of maximal power output tests on the upper and lower limbs, where a decreased ability to exert maximal force after the fatigue inducing exercise was found. In the current study, no such confirmation of fatigue was tested, but the exhaustive nature of the fatigue intervention and the high lactate values strengthens the notion that a fatiguing state was evident.

Technique distribution and time of shift

In the current study, a tendency towards increased overall use of DIA was found after the fatiguing exercise. DIA is a technique were the propulsion from arms and legs occur simultaneously (Kehler et al., 2014), and were the strain on the propulsive muscles is more evenly distributed throughout the movement. DP and DK are more force demanding for the upper body muscles, where DP places the highest demand, with all propulsive force exerted through the poles (Holmberg et al., 2005). Earlier studies on fatigue and classical roller skiing have illustrated that fatigue elicits a decreased ability to create maximal force from both arms and legs (Cignetti et al., 2009b; Zory et al., 2009). DIA could therefore be a preferred technique when fatigued, due to more continual distribution of propulsive force.

The subjects chose to shift from DK to DIA earlier in the post-fatigue condition. In this situation, most of the transitions that were made were of a permanent nature, and only occasionally a short time period was used with one technique before changing back to a previous one. Incline has earlier been found to be one of the main determining factors for technique transitions (Cignetti et al., 2009a; Pellegrini et al., 2013). According to Pellegrini et al. (2013), incline works as a triggering factor through change in poling force. They suggested that there is a limit in the force a skier wants to exert through the poles, causing a transition from DP or DK when the incline increases, and this value is reached. A possible explanation for the earlier shift to DIA could be that this threshold is reached at lower inclines when the skiers get fatigued. However, this is merely an assumption, due to the lack of variables regarding poling force in this study.

Taken together, DIA seemed to be a preferred technique when skiers got fatigued. Either in terms of earlier transition to the technique, or through a tendency for increased overall use. The two measures analyzed statistically (technique distribution and time of permanent shift) were closely related to each other, but not identical. The skiers occasionally performed short technique transitions (> two cycles) between the permanent ones, affecting the outcome of time distribution. Thus, the possible mechanisms (poling force threshold and propulsive force distribution) explaining the earlier transition from DK to DIA, and the increased overall use of DIA are most likely overlapping and affecting both results.

Number of transitions

On average, fatigue did not provoke a significant increase or decrease in the total number of transitions. This lack of significance is most likely explained by the large variation among subjects. These findings are in accordance with an earlier study, which also show great variation between the subjects during a skate sprint competition (Andersson et al., 2010). Previous studies have suggested that stability in the technique execution gets lowered when fatigued (Cignetti et al., 2009b), and that transitions are closely related to deterioration in coordination stability (Cignetti et al., 2009a). Taken together, these finds could suggest that the lowered stability would provoke more transitions when skiers are fatigued. However, these factors did not seem to cause any change in the number of transitions. The reason for this could be the dissimilar protocol design. In Cignetti et al. (2009b), the movement pattern were recorded during the fatigue inducing exercise, including the last part, where the skiers are close to exhaustion. In the current study, a break was implemented between the fatigue exercise and the post-fatigue protocol, giving the skiers an opportunity to recover for a short period. Intensity during the post- protocol was also sub-maximal, and may have been too low for challenging the skiers' technique execution, despite the increased physiological stress following the fatigue exercise.

Methodological implications

In the present study, the speed and incline on the treadmill changed in form of prominent perturbations between the different steps (every one minute). Due to software limitations a continuous change of incline and speed over 11 minutes were not possible. These perturbations gave input to the skiers on when a new change initiated, and most technique transitions occurred closely after these perturbations. In future studies, a protocol with more gradual changes would have been interesting to implicate. However, in competitive situations, the skiers get continually input on when the speed and slope changes, in terms of track variations. From a scientific perspective, a continuous change may provide more sensitive information on transitions, from a practical perspective the current protocol may have higher ecological validity.

The testing was done utilizing roller skis where the grip was simulated using a ratchet locking mechanism on the front wheels. This enabled perfect grip, avoiding accidental slipping movements as most skiers experience on snow. Thus, these differences have to be taken into account when evaluating the current results towards practical application in cross-country skiing.

Strengths and limitations

The pre-programming of the treadmill made the standardization of the protocols highly accurate, which also led to increased attention on the data recordings for the experimenters.

Transitions and technique distribution was registered using the Oqus system, by the experimenters and a video camera, resulting in a good reliability of the data.

The use of a control condition increased the reliability of the conclusion, by controlling for possible effects that were not caused by fatigue.

Number of participants in the study could have been higher, in terms of increasing the basis for the statistical analysis, giving higher statistical power.

Conclusion

In the current study, the transition from DK to DIA was found to occur significantly earlier after a fatigue inducing exercise. This was related to the tendency of increased overall use of DIA. Taken together, this indicates that skiers prefer to utilize lower gears earlier, and correspondingly alter technique distribution when fatigued. However, the variations between subjects were large, illustrating how individual differences affect choice of technique. Further research is required to increase the understanding on fatigue, and how it affects technique transitions in classical roller skiing at varying speed and incline.

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