The Effect of Exhaustive Exercise on the Choice of Technique and Physiological Response in Classical Roller-Skiing

Gertjan Ettema, Magne Øksnes, Espen Kveli, Øyvind Sandbakk

Centre for Elite Sports Research, Department of Neuromedicine and Movement Science,
Faculty of Medicine and Health, Norwegian University of Science and Technology,
Trondheim, Norway

Correspondence:
Gertjan Ettema
Centre for Elite Sports Research
Department of Neuromedicine and Movement Science
Faculty of Medicine and Health Sciences
Norwegian University of Science and Technology
7491 Trondheim, Norway
Email: gertjan.ettema@ntnu.no
Phone: +47 48112969
ORCID: 0000-0002-3370-0957

Running title: Exhaustive Exercise and Technique in Classical Roller-Skiing

Abstract

Purpose: The aim of this study was to investigate the effect of exhaustive exercise on technique preference and the accompanying physiological response during classic skiing at constant workload, but with varying incline-speed combinations.

Methods: Seven male competitive cross-country skiers performed four tests, each lasting 23 minutes, at constant 200 W workload roller skiing on a treadmill using classic style, three in unfatigued state, and one after exhaustion. The incline and speed combination (that determined the 200 W) was altered each minute during the tests. The athletes were allowed to change sub-technique at free will. Physiological variables and cycle rate were recorded continuously as well as the incline-speed combinations at which sub-technique was changed.

Results: Exhaustive exercise did not (or hardly) affect cycle rate and choice of technique. The physiological response was most prominent in slight incline – high speed conditions, independent of exercise duration. Exhaustive exercise affected the physiological response in a differentiated manner. *HR* and *RER* remained respectively higher and lower after fatigue, while $\dot{V}O_2$ (and thereby *GE*) were affected only during approximately the first 8 minutes of post exhaustion exercise.

Conclusions: Exhaustive exercise has a minimal effect on choice of technique in classic cross-country skiing with free choice of sub-technique, even though physiological stress is increased.

Keywords: Fatigue, Cross-country skiing, Technique

Abbreviations:

CR	Cycle rate
DK	double poling with kick
DP	double poling
DS	diagonal stride
EPOC	Excessive post-exercise oxygen consumption
GE	Gross efficiency
HR	Heart rate
P_{target}	Target power
RER	Respiratory exchange ratio
$\dot{V}O_2$	Oxygen uptake
$\dot{V}O_{2max}$	Maximal oxygen uptake

Introduction

In cross-country skiing, the preference for, and physiological response of sub-technique depends partly on terrain characteristics, particularly the steepness of incline and associated speed (e.g., Dahl et al. 2017; Ettema et al. 2017; Pellegrini et al. 2013). In the classic style, double poling (DP), double poling with kick (DK) and diagonal stride (DS) are the main sub-techniques used in flat to steep uphill terrain, respectively.

When considering effects of fatigue on performance during cross-country skiing competition, the outcome is likely multi-faceted because fatigue may affect the choice of sub-technique (like in gearing in cycling) and workload. Both these factors likely affect the physiological response alongside the direct physiological changes due to fatigue. Thus, a strong interdependency of a variety of variables likely exists. Many studies on fatigue focus on the physiological response and movement dynamics under invariable conditions and of relatively short duration (e.g., Cignetti et al. 2010; Cignetti et al. 2009; Grasaas et al. 2014; Zoppirolli et al. 2016). Although such studies shed light on the mechanisms of fatigue effects, they cannot target the interdependency of the different variables that are intertwined in the fatigue-performance relationship.

The physiological response in classic cross-country skiing at a given workload is strongly dependent on terrain (incline-speed combination) (e.g., Dahl et al. 2017; Ettema et al. 2017; Pellegrini et al. 2013). For example, DP is less demanding at slight than at a steep incline, while the opposite applies to DS (Dahl et al. 2017). This is in accordance with the terrain dependent preference of these sub-techniques (Ettema et al. 2017; Pellegrini et al. 2013). It is however not known (a) if fatigue affects this terrain-dependent choice of sub-technique, (b) how this choice may affect the physiological response, thereby potentially damping or intensifying fatigue effects on performance. Thus, by allowing the athlete to freely choose technique (and other aspects of task solutions), studying the fatigue effect on the physiological response becomes ecologically more relevant than forcing one particular technical solution onto the athlete. As such, the current study may contribute with knowledge about how fatigue is handled in a practical setting and what the consequences will be for the physiological load. Yet, the interpretation of such findings may be somewhat compromised because choice of technique and terrain effects on the physiological response during fatigue become entangled. To partly solve this latter problem, we applied a protocol in which terrain was altered in a structured manner.

Thus, our aim was to investigate the effect of fatigue through exhaustive exercise on technique preference and the accompanying physiological response during classic skiing at constant workload, but with varying incline-speed combinations.

Methods

Participants

Seven male competitive cross-country skiers (age 22.4 ± 1.7 years, body height 183.7 ± 4.4 cm, body mass 80.3 ± 7.7 kg, and $\dot{V}O_{2max}$ 73.9 ± 6.4 ml kg^{-1} min^{-1}) volunteered to participate in this study. All procedures were explained verbally to each athlete. Informed consent was obtained from all individual participants included in the study. All participants were informed that could withdraw at any time without giving any reason. The study was registered and approved by Norwegian Social Science Data Services, and was conducted in accordance with the Declaration of Helsinki.

Experimental Design

The same main protocol as in Ettema et al. (2017) was applied and depicted in Fig.1 top diagram. Briefly, all participants completed two sessions of warm-up and then twice the same test sequence at a 200 Watts constant work rate lasting 23 minutes, with varying incline and speed. These two test sequences were interrupted either by an exhaustion - or an ‘easy pace’ intervention.

The constant work rate protocol started at a 3% incline which was increased by 1% each minute up to 11%. The speed was decreased simultaneously to obtain the same and constant external workload (‘upward’ protocol). The first incline-speed combination was maintained 3 minutes rather than one to give the athlete time to reach steady state physiological conditions. After a short 1-minute break, the same protocol was executed in reversed order (from 11 to 3%; ‘downward’ protocol). This reversed order allowed for disentanglement of the effect of incline-speed settings from time.

The intervention protocol, on average lasting about 12 minutes, with either an incremental protocol leading to exhaustion or an intervention with roller skiing at an easy pace (keeping warmed up). Directly after this intervention (maximally 1 min interval for practical reasons) the same protocol as before the intervention was repeated. Thus, the main protocol was executed three times in an unfatigued state, once in a, presumably, fatigued state (in the remainder of the text we refer to this as ‘post-exhaustion’ to avoid the presumption that fatigue is present throughout the entire protocol).

The exhaustion intervention consisted of an incremental load protocol using the DS, preceded by moderate intensity DP (2 minutes at 3% - 5 ms^{-1}; 2 minutes at 3% - 5.8 ms^{-1}) and DK (2 minutes at 7% - 4.2 ms^{-1}). The incremental DS protocol was executed at 10% starting at 2.8 ms^{-1}, which speed was increased afterward by 0.3 ms^{-1} each minute until exhaustion. Exhaustion was defined as when the athlete was no longer able to maintain the centre position on the treadmill. All athletes received encouragement during the test to push themselves as hard as possible. After the exhaustion intervention, a 6 minutes brake was implemented before the skiers started the post-test.

The easy pace intervention was performed at about 160 Watts using incline-speed combinations appropriate for DP (3% - 4.17ms^{-1}), DK (6% - 2.5 ms^{-1}), and DS (10% - 1.67 ms^{-1}), which were all performed for 4 minutes.

The speeds to obtain the target work rates were calculated according to (Sandbakk et al. 2010):

$$P_{target} = mg\ v\ (sin\alpha + \mu\ cos\alpha)\ \leftrightarrow v = P_{target}\ (mg\ (sin\alpha + \mu\ cos\alpha))^{-1}$$

With P_{target} the targeted work rate (200 Watts), v the target speed, m the participants' expected average body mass (78 kg), μ (≈0.022) the friction coefficient as established by a towing test (Sandbakk et al. 2010), g gravitational acceleration, and α incline.

Instruments and Materials

The data collection and protocol was similar as presented by Ettema et al. (2017), and are summarized here. The participants skied on a 5x3-meter treadmill (Forcelink Technology, Zwolle, The Netherlands), using the same pair of roller skis (Pro-Ski, Sterners, Nyhammar, Sweden) with wheels from IDT (IDT Sports, Lena, Norway, resistance category 2). All athletes used the same type of poles (Madshus UHM 100, Biri, Norway) with own preferred length.

Physiological variables

Oxygen uptake ($\dot{V}O_2$) was measured by using open-circuit indirect calorimetry (Oxygen Pro apparatus, Jaeger GmbH, Hoechberg, Germany). The aerobic metabolic rate was calculated as the product of $\dot{V}O_2$ and the oxygen energetic equivalent using the associated respiratory exchange ratio (*RER*) and standard equations based on the conversion tables in Peronnet and Massicotte (1991). Gross efficiency (*GE*) was calculated as the ratio between external work rate and aerobic metabolic rate. Heart rate (*HR*) was recorded with a heart-rate monitor

(Garmin, USA), at a sample rate of 1Hz. Respiratory variables were recorded continuously during the entire session.

Kinematic variables and technique identification

Kinematic data were collected using the Oqus motion capture system with six cameras (Qualisys AB, Gothenburg, Sweden) at 50 Hz. Using two markers, one placed on each ski, ski technique (DP, DK, and DS) as well as cycle rate (*CR*) could be identified according to (Ettema et al. 2017).

Statistical analysis

All data were checked for normality and presented as means and standard deviations. To test if the exhaustive intervention affected the incline-speed condition at which technique shift was chosen, beyond 'daily' variation and influence by the duration of protocol, time at which technique shifts occurred were compared as dependent variables in a 2-way ANOVA for repeated measures: intervention ('easy' versus fatiguing) × (pre versus post). An interaction effect between these two factors would indicate a fatigue effect, whereas the main effects are also affected by day-by-day variation and duration of the activity. Time, rather than the actual incline-speed combination, was used in the statistical analysis because it allows for more precision (each incline-speed combination was maintained for one minute). However, the results are presented according to incline because of its ecological relevance. Because we had no interest in the investigation of potential hysteresis (see Ettema et al. 2017), techniques shifts in the 'upward' and 'downward' protocol were treated separately in the statistical analysis.

The effect of exhaustion and duration (during the 21 min protocol) on *CR* and the physiological response variables was examined by first visual inspection of the time development traces, before paired t-test or regression analysis on specific data were applied to statistically verify any observed trends of interest (see Fig. 3 and the related text).

Results

Fig. 2 shows the incline of technique shifts for all protocols. No intervention × pre-post interaction effects were found for these inclines (times), indicating that fatigue did not affect the shifts beyond trial-to-trial variability. Only for the DK-DS transition during the 'upward' part of the protocol a tendency (p=0.069) was noted, indicating a slightly earlier shift after fatigue in the first half of the protocol.

The lower diagrams in Fig. 1 show a typical example of $\dot{V}O_2$ and *HR* during both protocols. $\dot{V}O_2$ recordings were interrupted in periods between the upward-downward and intervention protocols for practical reasons. After the intervention, $\dot{V}O_2$ reached similar values independent of the type of intervention before increasing again during the post exercise. Note that *HR* shows a similar pattern, but remains elevated during the 6 minutes rest after the exhaustion intervention compared to the 'easy' one.

CR and detailed physiological response are presented in Fig. 3. The first striking aspect of the time traces are that, with regard to general trends, the 'upward' and 'downward' parts seem mirror images of each other. In other words, incline-speed condition rather than the time passed determines the outcome most. Except for *HR* ('upward'), all tests showed slopes for linear regression of the time slot – variable relationship. Still, the 'mirrored' changes during the protocol are not identical in amplitude (applies to all slopes of the trends 'upward' versus 'downward', paired t-test, $p \leq 0.01$). For $\dot{V}O_2$ and *GE,* these differences are (at least partly) due to diminishing effect of fatigue on the response. At onset of the post-exhaustion test ('upward' protocol, incline 3 degrees), $\dot{V}O_2$, *RER*, *HR*, and *GE* were different from the unfatigued condition ($p \leq 0.004$; paired t-test, both pre-exhaustion test and mean of all three unfatigued states). Where *HR* and *RER* show a more or less continuous difference between the unfatigued and post-exhaustion state during the entire protocol, this difference diminishes for $\dot{V}O_2$ and had disappeared after about 8 min after onset of post-exercise (incline 9 degrees, prior to DK-DS shift). Because of the impact of *RER* on metabolic rate, *GE* differences diminish quicker but in a similar manner as and $\dot{V}O_2$. For both variables, the unfatigued - post-exhaustion differences were different between the 3 degrees and 11 degrees condition ($p < 0.005$). During the 'downward' part of the protocol, no differences between the post-exhaustion and unfatigued state are apparent ($p > 0.129$).

Discussion

In the present study we investigated the effect of exhaustion on the physiological response during roller skiing at submaximal constant work rate but with changing incline-speed conditions and free choice of technique and cycle rate in the classical style. The main findings are that:

1. Exhaustion did not (or hardly) affect movement behaviour with regard to cycle rate and choice of technique.
2. Independent of the condition (post-exhaustion or unfatigued) and exercise duration, the physiological response was most prominent in the slight incline – high speed condition.
3. Exhaustion affected the physiological response in a differentiated manner. *HR* and *RER* remained respectively higher and lower after exhaustion, while $\dot{V}O_2$ (and thereby *GE*) were affected only during approximately the first 8 minutes of post exhaustion exercise.

Kinematic variables and technique identification

The current study indicates that choice of technique is hardly (if at all) affected by fatigue. In a previous study, we examined the effect of incline and speed on transitions between techniques in classical cross-country skiing, where we found that, independent of intensity, incline, and not speed was the main factor that athletes complied with when changing between techniques (Ettema et al. 2017). These current and previous findings, together with changed physiological response by fatigue suggests that mechanical mechanisms rather than physiological ones dominate the motor behaviour in the search for optimal movement solutions during submaximal endurance exercise. In other words, it supports the notion that minimising physiological load or energy cost may be a goal that is strived for, it does not seem to steer the technique shift in a direct manner. This is in agreement with findings by Raynor et al. (2002) on walk-run transitions, who also found that kinetics rather than physiological response contained the key triggers for transition. Still, the decreased efficiency during the first period in the post-exhaustion state indicates that more subtle changes (undetectable in the current study) in the technical execution of the exercise may have occurred. For example, with a similar design as ours, but only allowing DP under one unchanged terrain condition, Zoppirolli et al. (2016) found that propulsion kinematics were unaffected by fatigue, but that recovery time (and thereby cycle time) was reduced. A refined study on kinematics and propulsion dynamics is necessary if technique changes may have affected the physiological response.

One should be careful though when extrapolating the current findings to maximal work rates, where one may still see techniques changes after fatigue. Yet, given the current findings, such changes may be related to reduced physical capacities rather than finding ‘optimal’ (efficient) movement solutions. For example, DP in steep terrain requires considerable strength in the arms. Local strength reduction by fatigue may hamper performance in DP at steep inclines and thus, one may choose DK or DS earlier, at a lesser incline.

Physiological response

The effect of incline-speed conditions on metabolic rate (as indicated by $\dot{V}O_2$ and GE) are in accordance with our previous studies both for classic and free-style (e.g., Dahl et al. 2017; Ettema et al. 2017; Sandbakk et al. 2012; Sandbakk et al. 2013). The $\dot{V}O_2$, GE and RER dependence on incline-speed condition are in agreement with each other and indicate a mere difference in physiological load and carbohydrate-fat metabolism ratio, despite the constant external work rate. This is only partly reflected by *HR*, being almost constant in the 'upward' protocol. The reader is referred to the above-mentioned studies for further discussion on this issue.

The physiological response was affected by fatigue in a differentiated manner. $\dot{V}O_2$ and metabolic rate were elevated at onset after exhaustion for about 8 minutes, but then regressed to the same level as in the unfatigued state. On the other hand, *HR* and *RER* were elevated and reduced, respectively, during the entire post-exhaustion exercise which lasted 23 minutes. The reduced *RER* value implies a shift in metabolism substrate from carbohydrates to fat, indicating reduction in glycogen availability that is common after exhaustion exercise (see e.g., Ortenblad et al. 2013). While the enhanced *HR* at the onset of post-exhaustion exercise can be explained by elevated metabolic rate, this is harder for the fact that *HR* remains elevated after metabolic rate has become the same as in the unfatigued state. One reason may be moderate dehydration (see e.g., Cheuvront et al. 2010; Rizzo and Thompson 2017). However, if dehydration were a major contributor, one would have expected a somewhat enhanced *HR* during the third unfatigued condition test (post 'easy pace' intervention) as well as an increasing deviation during the post-exhaustion condition. Another likely reason is a change in autonomic heart rate regulation after intensive exercise (e.g., Lepretre et al. 2012; Martinmäki and Rusko 2008). Even though *HR* after the exhaustive exercise was reduced to well below the 200 W submaximal level and seemed to level off during the 6 minutes recovery period (see Fig. 1), it was considerably higher than after ‘easy pace’ exercise. This indicates a consistently elevated *HR* that continues during the subsequent exercise period.

The current findings regarding the first minutes post-exhaustion are in agreement with Grasaas et al. (2014) (ski-skating) and Zoppirolli et al. (2016) (DP). Both studies examined effects of exhaustive exercise in roller skiing on subsequent submaximal exercise (at comparable intensity), but only lasting for 4 and 5 minutes, respectively. Their physiological response findings agree almost completely with our current results, but *CR* was increased rather than maintained. However, Grasaas et al. (2014) and Zoppirolli et al. (2016) could not establish if enhanced metabolic rate (and reduced efficiency) was maintained over a longer period. The current study clearly demonstrates that enhanced metabolic rate is only short lasting (about 6 minutes). This triggers the question if the short lasting enhanced metabolic rate is a mere result of oxygen deficit and/or excessive post-exercise oxygen consumption (EPOC) (see Gaesser and Brooks 1984). We tried to avoid the effect of oxygen deficit by implementing a 6 minutes brake after intervention. Indeed, $\dot{V}O_2$ was reduced to similar values as the pre-condition (see Fig. 1 for indication), suggesting the oxygen deficit did not play a role of importance. On the other hand, EPOC under resting conditions may last at least an hour (Cunha et al. 2016; Gaesser and Brooks 1984; Tucker et al. 2016), which suggests that the enhanced $\dot{V}O_2$, lasting 8 minutes, during post-exercise submaximal activity is not related to EPOC.

Efficiency

If the enhanced $\dot{V}O_2$ during the first 8 minutes during submaximal exercise after exhaustion is not due to oxygen deficit or EPOC, it most likely represents an increased energy consumption that is related directly to the generated power. In other words, *GE* is likely reduced likely because of subtle technique changes that are not reflected in *CR* or choice of technique (DP, DK, and DS). In ski skating we found a similar reduction in *GE* after exhaustion, but that coincided with increased *CR* (Grasaas et al. 2014) as was the case in Zoppirolli et al. (2016) for DP. For the present study, a more detailed analysis of motion is required to elucidate what may have caused the enhanced metabolic cost. It should be noted that during this period of enhanced metabolic cost, DP and DK were the predominant techniques and differences in *GE* disappeared at about the time athletes shifted to DS. We can therefore not conclude if in DS similar differences were to be found. Still, because differences in efficiency did not reappear during the 'downward' protocol when DK and DP were used again while signs of fatigue were still present (*HR* and *RER* remained altered), suggests that the diminishing fatigue-induced metabolic cost enhancement is not related to type of technique. To further disentangle the effect of technique and duration of protocol, however, the reverse order of protocols should be applied, i.e., first the 'downward' protocol followed by the 'upward', which would make DS the preferred technique directly after the intervention. The current study did not allow for this extension given the total load and time available for the high-level competitive athletes.

In conclusion, the current study demonstrates that fatigue hardly affects the choice of technique. While the state of fatigue is indicated for the entire 23 minute post-test, metabolic cost after fatigue is only enhanced for about 8 minutes from the start of post-exhaustion exercise. No indications were found for changes in technical execution, but the enhanced metabolic rate suggests that more subtle (undetectable by the current measurements) but equally important changes may have occurred.

The results indicate that after a bout of exhaustive exercise, more fat oxidation is mobilised during subsequent submaximal activity and that *HR* may not be a valid indicator for work rate during exercise with variable intensity.

Conflict of Interest The authors declare that they have no conflict of interest.

References

Cheuvront SN, Kenefick RW, Montain SJ, Sawka MN (2010) Mechanisms of aerobic performance impairment with heat stress and dehydration. J Appl Physiol (1985) 109 (6):1989-1995. doi:10.1152/japplphysiol.00367.2010

Cignetti F, Schena F, Mottet D, Rouard A (2010) A limit-cycle model of leg movements in cross-country skiing and its adjustments with fatigue. Hum Mov Sci 29 (4):590-604. doi:https://doi.org/10.1016/j.humov.2010.03.001

Cignetti F, Schena F, Rouard A (2009) Effects of fatigue on inter-cycle variability in cross-country skiing. J Biomech 42 (10):1452-1459. doi:https://doi.org/10.1016/j.jbiomech.2009.04.012

Cunha FA, Midgley AW, McNaughton LR, Farinatti PTV (2016) Effect of continuous and intermittent bouts of isocaloric cycling and running exercise on excess postexercise oxygen consumption. J Sci Med Sport 19 (2):187-192. doi:https://doi.org/10.1016/j.jsams.2015.02.004

Dahl C, Sandbakk Ø, Danielsen J, Ettema G (2017) The Role of Power Fluctuations in the Preference of Diagonal vs. Double Poling Sub-Technique at Different Incline-Speed Combinations in Elite Cross-Country Skiers. Front Physiol 8 (94). doi:10.3389/fphys.2017.00094

Ettema G, Kveli E, Øksnes M, Sandbakk Ø (2017) The Role of Speed and Incline on the Spontaneous Choice of Technique in Classical Roller-Skiing. Hum Mov Sci 55:100-107. doi:10.1016/j.humov.2017.08.004

Gaesser GA, Brooks GA (1984) Metabolic bases of excess post-exercise oxygen consumption: a review. Med Sci Sports Exerc 16 (1):29-43

Grasaas CÅ, Ettema G, Hegge AM, Skovereng K, Sandbakk Ø (2014) Changes in technique and efficiency after high-intensity exercise in cross-country skiers. Int J Sports Physiol Perform 9 (1):19-24. doi:10.1123/IJSPP.2013-0344

Lepretre PM, Lopes P, Thomas C, Hanon C (2012) Changes in cardiac tone regulation with fatigue after supra-maximal running exercise. ScientificWorldJournal 2012:281265. doi:10.1100/2012/281265

Martinmäki K, Rusko H (2008) Time-frequency analysis of heart rate variability during immediate recovery from low and high intensity exercise. Eur J Appl Physiol 102 (3):353-360. doi:10.1007/s00421-007-0594-5

Ortenblad N, Westerblad H, Nielsen J (2013) Muscle glycogen stores and fatigue. J Physiol 591 (18):4405-4413. doi:10.1113/jphysiol.2013.251629

Pellegrini B, Zoppirolli C, Bortolan L, Holmberg HC, Zamparo P, Schena F (2013) Biomechanical and energetic determinants of technique selection in classical cross-country skiing. Hum Mov Sci 32 (6):1415-1429. doi:10.1016/j.humov.2013.07.010

Peronnet F, Massicotte D (1991) Table of nonprotein respiratory quotient: an update. Can J Sport Sci 16 (1):23-29

Raynor AJ, Yi CJ, Abernethy B, Jong QJ (2002) Are transitions in human gait determined by mechanical, kinetic or energetic factors? Hum Mov Sci 21 (5–6):785-805. doi:http://dx.doi.org/10.1016/S0167-9457(02)00180-X

Rizzo L, Thompson MW (2017) Cardiovascular adjustments to heat stress during prolonged exercise. J Sports Med Phys Fitness. doi:10.23736/s0022-4707.17.06831-1

Sandbakk Ø, Ettema G, Holmberg HC (2012) The influence of incline and speed on work rate, gross efficiency and kinematics of roller ski skating. Eur J Appl Physiol 112 (8):2829-2838. doi:10.1007/s00421-011-2261-0

Sandbakk Ø, Hegge A, Ettema G (2013) The role of incline, performance level, and gender on the gross mechanical efficiency of roller ski skating. Front Physiol 4 (293). doi:10.3389/fphys.2013.00293

Sandbakk Ø, Holmberg HC, Leirdal S, Ettema G (2010) Metabolic rate and gross efficiency at high work rates in world class and national level sprint skiers. Eur J Appl Physiol 109 (3):473-481. doi:10.1007/s00421-010-1372-3

Tucker WJ, Angadi SS, Gaesser GA (2016) Excess Postexercise Oxygen Consumption After High-Intensity and Sprint Interval Exercise, and Continuous Steady-State Exercise. J Strength Cond Res 30 (11):3090-3097. doi:10.1519/jsc.0000000000001399

Zoppirolli C, Pellegrini B, Bortolan L, Schena F (2016) Effects of short-term fatigue on biomechanical and physiological aspects of double poling in high-level cross-country skiers. Hum Mov Sci 47:88-97. doi:https://doi.org/10.1016/j.humov.2016.02.003

Titles and legends to figures

Fig. 1 Protocol and typical physiological response for both ‘easy pace’ (dashed traces) and ‘exhaustion’ intervention (solid traces). For the intervention protocol, the required techniques (DP, DK, and DS) are indicated. Horizontal dashed lines indicate approximate initial values during pre-test for $\dot{V}O_2$ and *HR*

Fig. 2 Incline at which technique shifts (DP-DK and DK-DS) occurred during all pre- and post-tests, in ‘upward’ protocol (upper diagrams) and ‘downward’ protocol (lower diagrams). White bars indicate three unfatigued conditions. Solid bars indicate post-exhaustion condition)

Fig. 3 Cycle rate and physiological response during all pre- and post-tests. Local differences ($p<0.05$) between the post-exhaustion and unfatigued condition (mean of all three unfatigued tests) are indicated by $*$. For more details statistical outcome, see main text