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ORIGINAL ARTICLE

Exercise-induced trunk fatigue decreases double poling performance in well-trained cross-country skiers

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Abstract

Purpose To examine the effects of exercise-induced trunk fatigue on double poling performance, physiological responses and trunk strength in cross-country skiers.

Methods Sixteen well-trained male cross-country skiers completed two identical pre- and post-performance tests, separated by either a 25-min trunk fatiguing exercise sequence or rest period in a randomized, controlled cross-over design. Performance tests consisted of a maximal trunk flexion and extension test, followed by a 3-min double poling (DP) test on a ski ergometer.

Results Peak torque during isometric trunk flexion (− 66%, $p < .001$) and extension (− 7.4%, $p = .03$) decreased in the fatigue relative to the control condition. Mean external power output during DP decreased by 14% ($p < .001$) and could be attributed both to reduced work per cycle (− 9%, $p = .019$) and a reduced cycle rate (− 6%, $p = .06$). Coinciding physiological changes in peak oxygen uptake (− 6%, $p < .001$) and peak ventilation (− 7%, $p < .001$) could be observed. Skiers chose a more even-pacing strategy when fatigued, with the performance difference between fatigue and control condition being most prominent during the first 2 min of the post-test.

Conclusions In well-trained cross-country skiers, exercise-induced trunk fatigue led to a substantial decrease in DP performance, caused by both decreased work per cycle and cycle rate and accompanied by reduced aerobic power. Hence, improved fatigue resistance of the trunk may therefore be of importance for high-intensity DP in cross-country skiing.

Keywords Core · Ergometer · Ski · Power output · Technique

Abbreviations

1RM	One repetition maximum
3MT	3-min test
ANOVA	Analysis of variance
BLa	Blood lactate concentration
CON	Control condition
CV	Coefficient of variation
DP	Double poling
FAT	Fatigue condition
HR_{peak}	Peak heart rate
ICC	Intra-class coefficient
RPE	Rating of perceived exertion
RER	Respiratory exchange ratio
SD	Standard deviation
VE_{peak}	Peak ventilation
VO_{2max}	Maximal oxygen uptake
VO_{2peak}	Peak oxygen uptake
W	Watt

Introduction

Cross-country skiing is a demanding endurance sport involving various skiing techniques where skiers load the upper-body, trunk and lower-body to different extents on

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the varying racing terrain. In classical style cross-country skiing, double poling (DP) is a main sub-technique with particularly large contribution from the upper-body and trunk since all propulsion comes through the poles (Hegge et al. 2016; Holmberg et al. 2005). DP has gained high scientific interest over the last two decades. The technique is nowadays more frequently used in competitions since better trained upper-bodies of skiers, higher competitive speeds and harder snow surfaces make poling highly efficient. Many events, such as sprint and mass start races, are decided in the final sprint, where skiers almost exclusively employ the DP technique. In some male races, solely DP is used throughout the entire race (Sandbakk and Holmberg 2014; Stoggl and Holmberg 2016).

To exhibit effective propulsion in DP, the involved muscles are working in a sequential order (Holmberg et al. 2005). Initially, the legs generate potential and rotational energy that can be transferred to power by efficient stabilization of the trunk and arms (Danielsen et al. 2015). At the same time, the trunk and arm muscles produce propulsion directly by activating trunk and hip flexors, followed by the shoulder and elbow extensors (Holmberg et al. 2005). In all parts of this chain, the trunk segment of the body plays a crucial role, both in the direct power production (Hegge et al. 2016) and in the transfer of body energy to propulsion during DP (Danielsen et al. 2015).

Research suggests that high maximal strength (Osteras et al. 2016) as well as high lean and muscle mass located in the trunk (Stoggl et al. 2010) appear to be advantageous for producing high power in DP. In addition, technical aspects of the trunk movement are of importance in DP, e.g. hip flexion velocity is associated with DP performance (Holmberg et al. 2005) and locomotor and respiratory movements in the corresponding trunk musculature are also closely linked (Lindinger and Holmberg 2011). This 1:1 locomotor–respiratory coupling in DP has been described during low- and high-intensity DP and is supposed to be the result of the stress imposed on the thorax during the poling phase (Holmberg et al. 2007). Altogether, reduced trunk function, due to limited physical or technical capacities or induced by fatigue, is therefore hypothesized to have a large influence on power production in DP.

While fatigue is a complex phenomenon, encompassing reduced physiological, biomechanical and psychological capacities (Seghers and Spaepen 2004), its presence would rationally influence performance in a physically and technically complex endurance sports such as cross-country skiing (Stoggl et al. 2007). A previous study looking at the effects of whole-body fatigue on DP performance demonstrated lower peak skiing speed as well as reduced hip flexion and hip flexion velocity after several 3-min maximal exercise bouts in the classical technique (Zory et al. 2009). However, while intense whole-body exercise may fatigue many inter-related aspects that potentially limit performance, the isolated effects of each component of the muscle chains of relevance for DP is not well understood.

This study aimed to examine the acute effects of exercise-induced trunk fatigue on DP performance in competitive cross-country skiers. In order to explain possible mechanisms coupled with altered DP performance, we investigated corresponding changes in trunk strength, as well as total power, work per cycle, cycle rate and physiological responses during DP.

Methods

Participants

16 male cross-country skiers (mean ± SD; age = 19.1 ± 2.6 years, body height = 177 ± 6.0 cm, body mass = 68.8 ± 7.3 kg, body fat = 8.4 ± 1.8%, running $VO_{2\max} = 62.2 \pm 6.9$ mL min^{-1} kg^{-1}, annual training = 567 ± 96 h) volunteered to participate in this study. Skiers were thoroughly informed about the nature of the investigation before providing written consent to participate. Athletes were required to compete at the national level with a minimum of 5 years of ski specific training. Skiers agreed to refrain from high-intensity training within 48 h prior to testing and not to consume caffeine on test days. The Ethics Committee of Northwestern and Central Switzerland approved this study.

Design

This randomized, controlled cross-over study was performed in spring, shortly after the competitive cross-country ski season. On the first day, participants were familiarized with equipment and test protocols and performed a running $VO_{2\max}$-test. On the second and third day, skiers performed either an experimental fatigue (FAT) or control (CON) protocol in randomized order. Pre- and post-intervention assessments on both days included an isometric and isokinetic trunk strength and a 3-min DP test (3MT), performed identically before and after a trunk fatiguing exercise sequence in FAT, or a rest period in CON. Athletes completed all three measurements at approximately the same time of the day, separated by at least 48 h between measurements within 14 days.

Procedures

Familiarization

On the first day, the anthropometric assessment was followed by a 10-min warm-up on a cycle ergometer at low intensity, controlled by ratings of perceived exertion (RPE)

3 on a 1–10 Borg Scale. One repetition maximum (1RM) was determined for both trunk flexion and extension (Cybex Abdominal/Back Extension, Cybex International, Inc., Medway, MA, USA) according to National Strength and Conditioning Association (NSCA) guidelines (Baechle and Earle 2008). 1RM measures determined the load for the fatigue protocol. Athletes practiced three additional core exercises for the trunk fatigue sequence, before performing the trunk strength tests described below. After a short break, skiers performed a stepwise incremental DP protocol with five to eight 3-min stages on a ski ergometer (SkiErg, Concept2, Morrisville, VT, USA). Skiers started at 75 W, increasing by 25 W for each increment. The test was performed in order to familiarize and to help the skiers find a target power output for the following 3-min self-paced tests. After another 30 min break, running $VO_{2\max}$ was determined on a treadmill according to previously published procedures for cross-country skiers (Sandbakk et al. 2011).

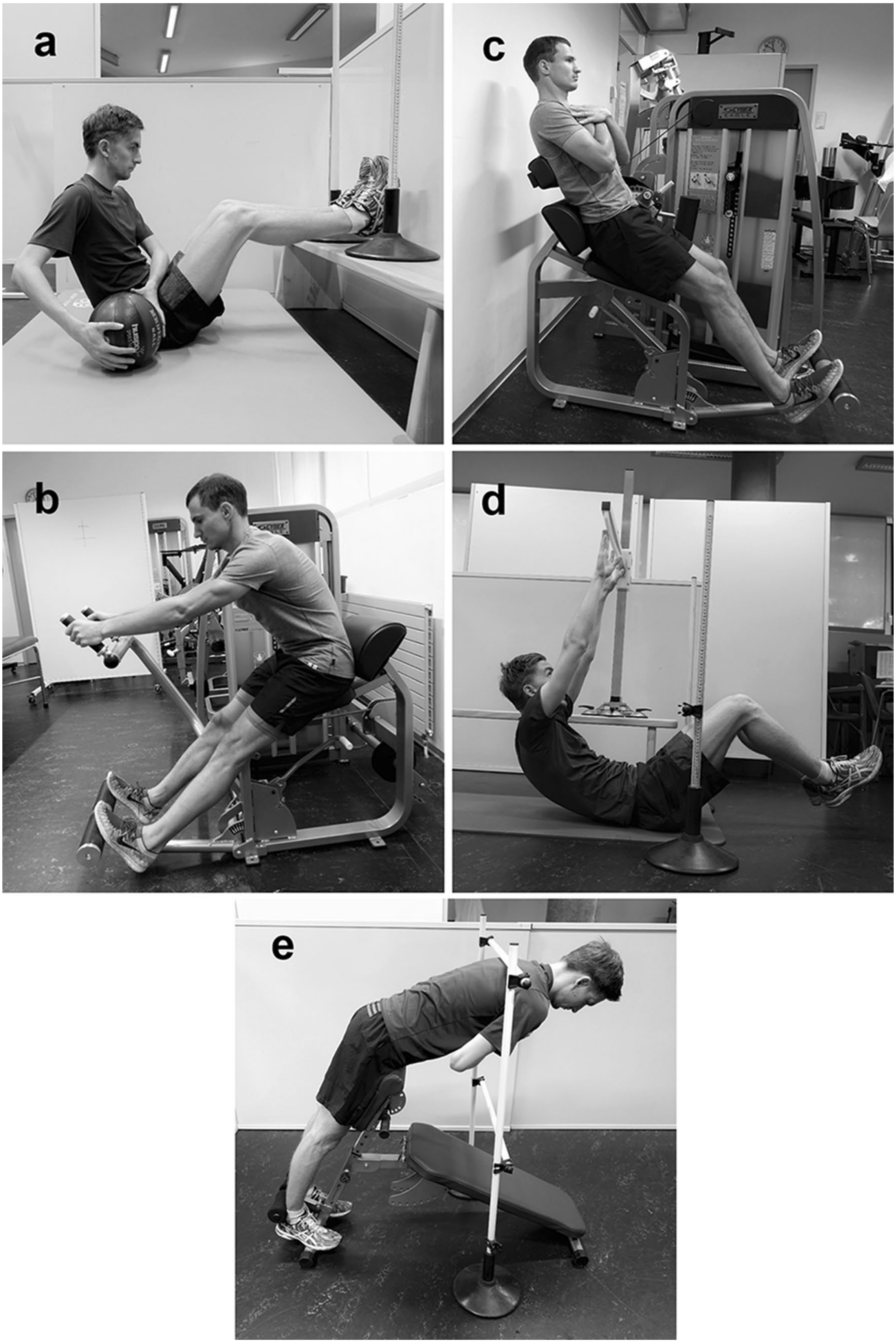
Trunk strength

Isometric and isokinetic maximal trunk strength was assessed on the first day and during both pre- and post-tests on the second and third day. Ventral and dorsal trunk strength was determined in a seated position (IsoMed 2000 backmodule dynamometer, D&R Ferstl GmbH, Hemau, Germany). Athletes performed two voluntary isometric contractions in both hip flexion and extension, separated by 30 s. Isometric contractions were performed at 85° hip angle and lasted 5 s. After another 1-min break, maximal isokinetic trunk flexion and extension were measured during five consecutive repetitions at $60°\ s^{-1}$ in a range between $-30°$ and $+30°$, with the neutral zero position at 85° hip angle. Participants received no visual feedback and a test instructor provided strong verbal encouragement. Data were recorded on a lab computer by the internal control software of the isokinetic dynamometer at a sampling rate of 200 Hz and subsequently exported to an Excel spreadsheet. Movement artifacts were processed using a second-order zero-lag low-pass Butterworth filter with a cut-off frequency of 1.5 Hz using a customized Matlab script (MathWorks, Natick, MA, USA). Highest peak torque measures during isometric and isokinetic contractions were used for further analysis. Reliability of these measurements are acceptable [coefficient of variation $(CV) \leq 9.4\%$, intra-class-correlation coefficient $(ICC) \geq 0.91$] (Roth et al. 2017).

3-min double poling test

Following a 5-min break after the trunk strength test, skiers performed a 3-min self-paced test on the modified ski ergometer. The skier simultaneously pulls two cords equipped with cross-country ski straps (Leki, Kirchheim, Germany), which propel a wind resistance flywheel during exercise. The work needed for accelerating the flywheel during each stroke depends on the airflow entering the flywheel housing, controlled by a damper on the outside. The rate of deceleration of the flywheel, called drag factor, allows for standardized and reproducible gear setting and can be displayed on the performance monitor. The drag factor setting was adjusted according to the skier's body mass as described by Faiss et al. (2015). Based on pilot tests, the drag factor was set at 100% of individual's body mass for all 3MTs, accounting for the body mass differences among athletes. Skiers were familiar with 3-min efforts, encountered regularly in sprint races and interval training. Power production and cycle rate data were continuously measured stroke by stroke with the ergometer's internal software and further extracted with a Microsoft ActiveX® software component, before being finally logged in an Excel spreadsheet as previously reported (Faiss et al. 2015). The ergometer's internal power measurement was validated (Danielsen et al. 2015) and a test–retest reliability analysis for 3MT power output with the current data demonstrated a $CV = 3.9\%$ and an $ICC = 0.96$. The average power production and cycle rate over 3 min were calculated and 20-s segments were used for pacing analysis. The performance monitor was purposely displayed during tests and skiers were instructed to attain maximal average power output, with a test instructor providing verbal encouragement throughout the test.

Respiratory air was continuously sampled and analyzed breath-by-breath (Metalyzer 3B, Cortex Biophysik GmbH, Leipzig, Germany). Respiratory test equipment was calibrated before each test in accordance with manufacturer's instructions. Peak oxygen uptake ($VO_{2\text{peak}}$) and peak ventilation (VE_{peak}) were determined as the mean of the three highest consecutive 10-s samples, measured during the last min. The presence of the distinct 1:1 locomotor–respiratory relationship observed during double poling (Holmberg et al. 2007) was determined by calculation of the mean integer ratio of the synchronized measures of cycle rate and breathing frequency (stroke frequency/breathing frequency) over the last 2 min of each 3MT, as previously described in a similar procedure for rowing exercise (Fabre et al. 2007). Heart rate was measured continuously with Polar Wearlink (Polar Electro Oy, Kempele, Finland) and synchronized with the gas analysis equipment. Peak heart rate (HR_{peak}) was determined as the highest 5-s recording. Capillary blood samples (20 µL) were obtained from the ear lobe before, 1, 3 and 5 min after the test and blood lactate concentration in hemolyzed samples were analyzed using a stationary Super GL2 lactate analyzer (Hitado GmbH, Möhnesee, Germany).


a
c
b
d
e

◂**Fig. 1** Core exercises used during the fatigue sequence in the experimental fatigue condition. **a** Russian Twist. **b** Cybex Abdominal. **c** Cybex Back Extension. **d** Bug Crunch. **e** Inclined Back Extension

Fatigue protocol

In the FAT, participants completed an exercise sequence targeting both ventral and dorsal trunk musculature to induce trunk fatigue. Participants completed three sets of five exercises within a timeframe of 23.1 ± 0.8 min. This duration is similar to workouts previously used to induce trunk fatigue (Abt et al. 2007; Tong et al. 2014). Core exercises consisted of a medicine ball Russian Twist (Fig. 1a), Cybex Abdominal (Fig. 1b), Cybex Back Extension (Fig. 1c), Bug Crunch (Fig. 1d), and Inclined Back Extension (Fig. 1e). In order to achieve an equal level of fatigue and time under load among participants, exercise load was based on either percentage 1RM or maximal repetitions during 1 min. Participants completed the exercise sequence without extra rest period besides changing to the next exercise and were accompanied by a test instructor. The Russian Twist (Fig. 1a) was performed in a sitting position, with the hip flexed at approximately 90° and feet elevated above a bench of 30 cm height. In order to limit lateral movement of the legs, a 50-cm range was marked with poles on the bench. The exercise was performed with a 3-kg medicine ball for 60 s, with the aim of completing a maximal number of lateral repetitions. The Cybex Abdominal exercise (Fig. 1b) was performed with straight arms and legs, whereas the Cybex Back Extension exercise (Fig. 1c) was executed with bent knees at ~ 120° and arms crossed in front of the chest. For both exercises, participants were instructed to perform 10–15 repetitions across the full range of motion with a resistance of 70% of 1RM. Movement execution was predetermined and controlled by an instructor at a speed of approximately 5 s per repetition. For the Bug Crunch (Fig. 1d), participants were laying on the back with a hip angle of approximately 110°, controlled by a plastic bar placed across. Knees were bent with the feet off the ground. By flexing the trunk and arms pointed upwards, participants had to touch a horizontal bar placed above, before moving back down with the shoulders touching the mat. Vertical and horizontal placements of the bar were standardized based on body height and arm length, determined on the first test day. Participants were instructed to perform the exercise for 60 s. Inclined Back Extension (Fig. 1e) was executed during 60 s on a cardiostrong BT50 (Sport-Tiedje GmBH, Schleswig, Germany) with a weight plate held to the chest by the participant. The extra weight was individually determined based on body mass: 10 kg plate < 70 kg body mass and 15 kg plate for > 70 kg body mass. Range of movement was standardized with two bars across two measure poles, which allowed hip extension between ~ 90° and ~ 160°. Detailed exercise standardization for the fatiguing sequence in video format is available in the electronic supplementary material (Fatigue_Protocol.mp4).

Statistical analysis

All data were checked for normality using the Shapiro–Wilk test and are presented as mean and standard deviation (mean ± SD). A two-way repeated-measures analysis of variance (ANOVA) (condition × time) was performed to detect overall effects of treatment (FAT vs. CON) and time (pre vs. post), as well as to identify possible interaction. The relationships between 3MT performance and trunk strength were calculated using Pearson product–moment correlation with pooled CON and FAT pre-test variables. ANOVA and correlation statistics were analyzed in SPSS v.22.0 (IBM, Chicago, IL, USA).

Absolute, percentage and standardized mean differences in change scores between FAT and CON from pre- to post-test were calculated together with 90% confidence intervals for each variable and pacing segments, using the pre-test result as a covariate, according to the magnitude-based inference approach (Batterham and Hopkins 2006). The effect sizes (ES) were classified as trivial (< 0.2), small (> 0.2–0.6), moderate (> 0.6–1.2), large (> 1.2–2.0), and very large (> 2.0) (Batterham and Hopkins 2006). In addition, we determined the likelihood of the true effect being harmful, trivial, or beneficial by means of a published Excel spreadsheet (Microsoft Corporation, Redmond, WA, USA) for pre–post cross-over designs (Hopkins 2017). A practically relevant change was assumed when the difference score was at least 0.2 of the between-subject standard deviation (Hopkins et al. 2009).

Results

Differences in mean change between FAT and CON from pre- to post-test showed very large, most likely decreases in isometric (66%) and isokinetic (37%) peak torque during trunk flexion (both $p < .001$), while only small and moderate decreases were found for extension (7 and 17%, respectively; $p = .03$ and $p = .002$) (Tables 1, 2). 3MT power output was positively correlated with isometric and isokinetic trunk flexion and extension ($r = 0.59–0.69$; $p < .001$).

For power output during 3MT, a moderate, most likely decrease (14%) was observed ($p < .001$), explained primarily by a reduction in work per cycle (9%; $p = .02$), as well as a reduced cycle rate (6%; $p = .06$) (Tables 1, 2). In addition, coinciding decreases in peak oxygen uptake (6%) and peak ventilation (7%) were found in FAT (both $p < .001$), but not in CON.

The difference in performance change from pre- to post-test between FAT and CON gradually decreased with the

Table 1 Peak torque during isometric and isokinetic trunk flexion and extension, as well as performance characteristics and physiological responses during the 3-min self-paced double poling in pre- and post-tests in the fatigue (FAT) and control (CON) condition, mean ± standard deviation

	FAT		CON		ANOVA
	Pre	Post	Pre	Post	Time × condition
Isometric peak torque flexion (Nm)	135 ± 36	49 ± 23	132 ± 31	134 ± 30	< 0.001
Isometric peak torque extension (Nm)	280 ± 80	250 ± 76	262 ± 53	255 ± 66	0.03
Isokinetic 60° s^{-1} peak torque flexion (Nm)	129 ± 27	78 ± 20	129 ± 24	125 ± 24	< 0.001
Isokinetic 60° s^{-1} peak torque extension (Nm)	301 ± 86	240 ± 71	289 ± 66	283 ± 83	0.002
Mean external power output (W)	248 ± 45	216 ± 40	242 ± 43	247 ± 43	< 0.001
Cycle rate (Hz)	1.10 ± 0.13	0.99 ± 0.13	1.14 ± 0.13	1.08 ± 0.12	0.06
Work per cycle (J)	226 ± 50	217 ± 41	216 ± 50	231 ± 49	0.02
HR$_{peak}$ (bpm)	183 ± 4.1	181 ± 5	180 ± 6	183 ± 6	< 0.001
VO_{2peak} (L min^{-1})	3.67 ± 0.50	3.54 ± 0.49	3.61 ± 0.59	3.73 ± 0.62	< 0.001
VO_{2peak} (mL kg^{-1} min^{-1})	54 ± 5.8	52 ± 5.8	53 ± 6.8	54 ± 6.1	< 0.001
VE$_{peak}$ (L min^{-1})	150 ± 19	138 ± 17	147 ± 20	148 ± 22	< 0.001
RER (VCO_2/VO_2)	1.29 ± 0.09	1.11 ± 0.07	1.32 ± 0.11	1.26 ± 0.11	< 0.001
Breathing frequency (b min^{-1})	64 ± 6.5	59 ± 9	65 ± 8	63 ± 7	0.11
Cycle rate/breathing frequency	0.98 ± 0.07	0.98 ± 0.13	1.00 ± 0.05	0.99 ± 0.06	0.64
BLa pre-test (mmol)	2.2 ± 0.8	9.4 ± 2.2	2.0 ± 0.6	4.3 ± 1.5	< 0.001
Peak BLa (mmol L^{-1})	11.6 ± 1.7	11.5 ± 1.4	11.8 ± 1.6	11.5 ± 1.6	0.64
Δ BLa (mmol L^{-1})	9.4 ± 1.5	2.1 ± 1.2	9.8 ± 1.5	7.3 ± 1.2	< 0.001
RPE pre-test (0–10)	1.2 ± 1.2	5.1 ± 2.0	0.9 ± 1.0	1.7 ± 1.1	< 0.001
RPE post-test (0–10)	8.4 ± 1.2	8.5 ± 1.2	7.8 ± 1.5	8.4 ± 1.4	0.15

HR$_{peak}$ peak heart rate, *VO_{2peak}* peak oxygen consumption, *VE$_{peak}$* peak ventilation, *RER* respiratory exchange ratio, *RPE* rating of perceived exertion, *BLa* blood lactate, *Δ BLa* delta blood lactate derived from subtracting pre-test BLa from peak post-test BLa concentration

duration of the test (see Fig. 1). Differences in pre–post change regarding cycle rate remained constant across all segments (range − 7.1 to − 9.7%). At the same time, differences in pre–post change scores for work per cycle decreased from 20 to 1.6%. Mean differences in pre–post change scores between FAT and CON are presented for 20-s segments in Table 3 (Fig. 2).

Discussion

In well-trained cross-country skiers, exercise-induced fatigue of the trunk led to a large reduction in isometric and isokinetic trunk strength during flexion (66 and 37%) and to a smaller extent also during extension (7 and 17%). During 3-min maximal DP, a 14% performance decrease in power output arising from a 9% reduction in work per cycle and a 6% reduction in cycle rate was accompanied by a decrease in peak oxygen uptake (6%) and peak ventilation (7%). In addition, skiers altered their pacing strategy when fatigued, and used a more even-paced strategy indicated by a performance reduction particularly during the first 2 min of the 3-min DP test.

DP-relevant trunk muscle groups were clearly fatigued, with a more pronounced fatigue effect in the trunk flexors. This is in accordance with other studies, where the abdominal musculature demonstrated a larger fatigue susceptibility compared with the muscle groups of the back extensors (Corin et al. 2005; Smidt et al. 1983). In our study, this phenomenon was most prominent during isometric measurements, where the relative decrease in trunk strength during flexion was six fold that of extension. Although isokinetic compared to isometric strength can be considered more functional in an athletic setting, DP performance decreased substantially despite a smaller decline in isokinetic compared to isometric trunk strength after the fatigue sequence. The high fatigue susceptibility of trunk and hip flexors is likely to have implications for the DP movement, where corresponding muscles contribute substantially to power generation (Hegge et al. 2016) being the first link of the muscle activation chain during the distinct muscle sequencing (Holmberg et al. 2005).

Changes in both poling frequency and power production per stroke were responsible for the substantial DP performance decrease in the fatigued state. Further, we found large correlations between all trunk strength variables and DP performance. These findings highlight the importance of

Table 2 Differences in mean changes from pre- to post-fatigue in FAT and CON for trunk strength and 3-min double poling, mean (90% confidence interval)

	Differences in mean change			Magnitude-based inferences					
	Absolute	Percentage	Standardized	Harmful		Trivial		Beneficial	
Isometric peak torque flexion (Nm)	− 87 (− 96; − 78)	− 66 (− 72; − 60)	− 4.0 (− 4.7; − 3.4)	100	Most likely	0	Most unlikely	0	Most unlikely
Isometric peak torque extension (Nm)	− 24 (− 42; − 5.8)	− 7.4 (− 14; − 0.46)	− 0.27 (− 0.53; − 002)	83	Likely	17	Unlikely	0	Most unlikely
Isokinetic 60° s^{-1} peak torque flexion (Nm)	− 46 (− 53; − 39)	− 37 (− 42;33)	− 2.0 (− 2.4; − 1.7)	100	Most likely	0	Most unlikely	0	Most unlikely
Isokinetic 60° s^{-1} peak torque extension (Nm)	− 55 (− 77; − 33)	− 17 (− 23; − 11)	− 0.64 (− 0.87; − 0.40)	100	Most likely	0	Most unlikely	0	Most unlikely
Mean external power output (W)	− 36 (− 45; − 27)	− 14 (− 18; − 11)	− 0.81 (− 1.0; − 0.59)	100	Most likely	0	Most unlikely	0	Most unlikely
Cycle rate (Hz)	− 0.06 (− 0.11; − 0.01)	− 5.9 (10; − 1.5)	− 0.50 (− 0.87; − 0.13)	88	Likely	11	Unlikely	0	Most unlikely
Work per cycle (J)	− 22 (− 38; − 6.7)	− 9.3 (− 15; − 3.3)	− 0.42 (− 0.70; − 0.15)	91	Likely	9	Unlikely	0	Most unlikely
HR$_{peak}$ (bpm)	− 4.0 (− 5.9; − 2.0)	− 2.2 (− 3.2; − 1.1)	− 0.71 (− 1.1; − 0.36)	99	Very likely	1	Very unlikely	0	Most unlikely
VO_{2peak} (L min^{-1})	− 0.23 (− 0.32; − 0.14)	− 6.1 (− 8.6; − 3.5)	− 0.40 (− 0.57; − 0.23)	98	Very likely	2	Very unlikely	0	Most unlikely
VE$_{peak}$ (L min^{-1})	− 11 (− 16; − 6.7)	− 7.3 (− 11; − 3.9)	− 0.50 (− 0.74; − 0.26)	99	Very likely	1	Very unlikely	0	Most unlikely
RER (VCO$_2$/VO$_2$)	− 0.13 (− 0.16; − 0.10)	− 11 (− 13; − 8.1)	− 1.4 (− 1.7; − 1.1)	100	Most likely	0	Most unlikely	0	Most unlikely
Breathing frequency (b min^{-1})	− 2.7 (− 5.6;0.10)	− 5.0 (− 9.4; − 0.28)	− 0.45 (− 0.88; − 0.02)	78	Likely	21	Unlikely	1	Very unlikely
Cycle rate/breathing freq	− 0.06 (− 0.14;0.01)	1.3 (− 5.1;2.7)	0.19 (− 0.80;0.41)	87	Possibly	8	Unlikely	5	Unlikely
Pre-test BLa (mmol L^{-1})	4.8 (4.2;5.5)	120 (94;148)	2.2 (1.8;2.5)	0	Most unlikely	0	Most unlikely	100	Most likely
Peak BLa (mmol L^{-1})	0.12 (− 0.52;0.77)	1.4 (− 4.2;7.3)	0.09 (− 0.29;0.48)	12	Unlikely	59	Possibly	29	Possibly
Δ BLa (mmol L^{-1})	− 7.0 (− 7.9; − 6.2)	− 76 (− 82; − 66)	− 8.9 (− 11; − 6.9)	100	Most likely	0	Most unlikely	0	Most unlikely
RPE (0–10)	− 0.25 (− 0.85;0.36)	− 2.3 (− 10;6.1)	− 0.12 (− 0.53;0.30)	45	Possibly	48	Possibly	7	Unlikely

Negative values indicating lower values in the fatigue condition compared to the control condition. The probabilities of an effect being harmful/trivial/beneficial are expressed as percentage values

HR_{peak} peak heart rate, VO_{2peak} peak oxygen consumption, VE_{peak} peak ventilation, *RER* respiratory exchange ratio, *RPE* rating of perceived exertion, *BLa* blood lactate, *Δ BLa* delta blood lactate derived from subtracting pre-test BLa from peak post-test BLa concentration

Table 3 Pacing analysis with pre–post change between FAT and CON for 20-s segments during the 3-min double poling test, mean difference (90% confidence interval)

Change	20 s	40 s	60 s	80 s	100 s	120 s	140 s	160 s	180 s
Power output (W)									
ABS	− 56 (− 84; − 28)	− 47 (− 76; − 17)	− 43 (− 70; − 17)	− 42 (− 66; − 17)	− 39 (− 61; − 16)	− 33 (− 54; − 12)	− 29 (− 50; − 8)	− 26 (− 48; − 4)	− 20 (− 46;6)
%	− 26 (− 35; − 15)	− 18 (− 27; − 8)	− 17 (− 25;7)	− 17 (− 25; − 7)	− 16 (− 24; − 7)	− 14 (− 22; − 5)	− 13 (− 21; − 4)	− 11 (− 20; − 2)	− 8 (− 18;2)
SMD	− 1.32 (− 1.93; − 0.72)	− 1.01 (− 1.62; − 0.41)	− 1.03 (− 1.64; − 0.43)	− 1.05 (− 1.66; − 0.45)	− 1.06 (− 1.67; − 0.46)	− 0.95 (− 1.55; − 0.34)	− 0.86 (− 1.46; − 0.25)	− 0.73 (− 1.34; − 0.13)	− 0.49 (− 1.09;0.12)
Cycle rate (Hz)									
ABS	− 0.09 (− 0.17;0.00)	− 0.07 (− 0.15;0.01)	− 0.09 (− 0.17; − 0.02)	− 0.10 (− 0.17; − 0.02)	− 0.10 (− 0.17; − 0.02)	− 0.10 (− 0.18; − 0.02)	− 0.09 (− 0.17;0.00)	− 0.09 (− 0.19;0.01)	− 0.10 (− 0.21;0.01)
%	− 8.1 (− 15; − 0.6)	− 7.1 (− 14;0.5)	− 9.3 (− 16; − 2.2)	− 9.7 (− 16; − 2.6)	− 9.5 (− 16; − 2.4)	− 9.5 (− 16; − 2.2)	− 8.3 (− 16; − 0.4)	− 8.3 (− 17;1.1)	− 8.7 (− 18;1.8)
SMD	− 0.64 (− 1.24; − 0.04)	− 0.56 (− 1.16;0.03)	− 0.77 (− 1.3; − 0.17)	− 0.81 (− 1.41; − 0.21)	− 0.79 (− 1.39; − 0.19)	− 0.77 (− 1.37; − 0.17)	− 0.63 (− 1.22; − 0.03)	− 0.53 (− 1.12;0.07)	− 0.50 (− 1.09;0.10)
Work per cycle (J)									
ABS	− 42 (− 67; − 17)	− 32 (− 60; − 2.7)	− 21 (− 49;7.6)	− 18 (− 46;11)	− 16 (− 44;11)	− 12 (− 37;13)	− 12 (− 39;16)	− 10 (− 39;19)	− 1.1 (− 35;33)
%	− 20.0 (− 29; − 9.3)	− 12.0 (− 22; − 1.0)	− 8.5 (− 19;2.9)	− 7.8 (− 18;3.8)	− 7.4 (− 18;4.2)	− 5.7 (− 16;5.3)	− 5.6 (− 16;6.4)	− 4.5 (− 16;8.4)	− 1.6 (− 15;14.0)
SMD	− 1.07 (− 1.68; − 0.47)	− 0.66 (− 1.26; − 0.05)	− 0.46 (− 1.06;0.15)	− 0.41 (− 1.02;0.19)	− 0.39 (− 1.00;0.21)	− 0.32 (− 0.93;0.28)	− 0.29 (− 0.90;0.31)	− 0.22 (− 0.83;0.38)	− 0.06 (− 0.67;0.54)

ABS absolute change, % percentage change, *SMD* standardized mean difference

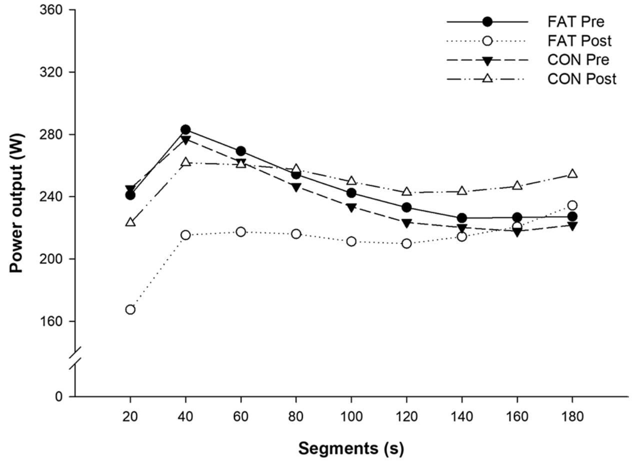


Fig. 2 Pacing strategy during pre- and post-3-min double poling test in fatigue (FAT) and control (CON) condition. Data presented as means for nine consecutive 20-s segments

maintaining strength of the trunk muscles for performance during short-duration, high-intensity DP. Only few studies investigated the influence of trunk muscle fatigue on exercise performance depending primarily on the lower extremities. In running, a 39% performance decline was demonstrated in a time-to-exhaustion test following a 24-min core muscle workout comparable to the current study (Tong et al. 2014). Another study reported changed kinematics during running resulting from trunk fatigue (Hart et al. 2009). Neuromuscular performance such as jumping (Howard et al. 2015) and balance tasks (Parreira et al. 2013) were also shown to be negatively affected by exercise-induced trunk fatigue. However, this is the first study to demonstrate the effects of trunk fatigue in an upper-body dominant exercise mode.

Since trunk muscles are highly involved in power production during DP (Holmberg et al. 2005), exercise-induced trunk fatigue potentially led to a change in both neuromuscular activation as well as coordination of active trunk and synergistic muscles during high-intensity DP. This is especially relevant in DP, due to the repetitive flexion and extension of the upper body during the poling and recovery phase, with high contribution of the trunk muscles particularly during high intensity (Bojsen-Moller et al. 2010; Holmberg et al. 2005). The reduced force potential of the ventral trunk muscles, demonstrated by the large decreases in peak torque during hip flexion, might have led to the alternative poling strategy used in FAT, with reduced cycle rate and slower repositioning after each stroke. As the DP movement is characterized by a sequential muscle activation chain, initiated by the hip flexors (Holmberg et al. 2005), fatigued trunk muscles possibly interfered with the effective beginning of this muscle activation chain. As athletic performance during complex movement-tasks require a well-coordinated activation of body segments (Kibler et al.

2006; Prieske et al. 2016), both impaired muscle activation (e.g. reduced motor unit firing rate) and timing might have simultaneously affected power output in the current task. Furthermore, the reduction in proximal stability caused by trunk muscle fatigue might have hindered the proximal to distal force generation pathway (Kibler et al. 2006), which is expected to be especially important in DP, involving the transfer of force through poles.

The 20–25-min break between subsequent 3-min exercise bouts employed for CON in the current study is comparable with sprint cross-country skiing competitions. There was unchanged pre- and post-test performance in CON, which supports studies showing no or only small performance changes within and between successive cross-country ski sprint heats of similar length (Andersson et al. 2016; Mikkola et al. 2013; Vesterinen et al. 2009; Zory et al. 2006). Overall, this strengthens the relevance of the negative performance changes following the FAT condition. Whether fatigue-resistance training for trunk flexors and/or respiratory muscles may affect repetitive DP sprint performance and the degree to which trunk muscles actually fatigue during DP performance is currently unclear and should be subject of future investigations. This would help in further understanding the limiting factors of performance in DP, both among able-bodied skiers and Nordic sit-skiers, where the trunk contributes to propulsion, body posture and respiration.

Pacing analysis revealed that the performance difference appeared most prominently during the first 2 min of the test, with a relative difference in pre–post change of 40–55 W during the first 2 min and a 20–30 W difference during the last min between FAT and CON. The positive pacing strategy observed in the pre-tests of both FAT and CON, with a fast start and a successive decline in velocity/power, is typical for sprint cross-country skiing events of 2–4 min duration (Andersson et al. 2010, 2016), as well as for distance races over 10–15 km (Losnegard et al. 2016). Exercise-induced trunk muscle fatigue appeared to interfere with the positive pacing strategy, leading to a lower, but more steady power output in the post-test in the FAT condition compared to the pre-test in FAT and both tests for CON.

Trunk fatigue affected physiological processes during DP. In FAT, skiers demonstrated lower VO_{2peak} (− 6%), VE_{peak} (− 7%) and RER. At the same time, HR_{peak}, peak blood lactate concentration and RPE remained relatively unaffected, indicating that skiers pushed themselves with the same effort to exhaustion in both conditions. Since VO_{2peak} and VE_{peak} tended to increase in CON, it is likely that several processes along the way of respiration, oxygen transport and oxygen extraction were negatively affected by the fatigued trunk musculature. As power output is lower in the post-test in FAT, a smaller fraction of maximal aerobic power is utilized and required. However, fatigued trunk muscles may also have a negative influence on respiratory muscle function, technique and body posture, all contributing to worse conditions for breathing during exercise and thereby reducing VO_{2peak} and VE_{peak}. In simulated sprint skiing using roller skis on a treadmill (Andersson et al. 2016) or on a tartan track (Vesterinen et al. 2009), VO_{2peak} did not differ between successive sprint heats with either 45 min (Andersson et al. 2016), or 20 min breaks (Vesterinen et al. 2009) in between trials. However, Stoggl et al. (2007) reported lower peak oxygen uptake in subsequent sprint heats when separated by 20–25 min.

Although it is unclear whether trunk fatigue negatively affected exercise efficiency in the 3MT, high-intensity exercise led to impaired efficiency during subsequent submaximal exercise in cross-country skiers (Asan Grasaas et al. 2014). Due to the technical complex movements utilized in skiing, effects of trunk fatigue on efficiency during submaximal double poling should be examined in future studies. Since the fatiguing exercise sequence likely affected the respiratory muscles, respiratory muscle fatigue might be part of the explanation for the decrease in VO_{2peak} and VE_{peak}, as both inspiratory (Mador and Acevedo 1991) and expiratory (Taylor and Romer 2008; Verges et al. 2007) muscle fatigue have shown to impair exercise performance. When comparing consecutive classical ski sprint heats, respiratory muscle fatigue has been suggested as an explanation for decreased VO_{2peak} (Stoggl et al. 2007) and was observed after high-intensity exercise in runners (Tong et al. 2014). However, whether the altered technical execution (e.g. lower cycle rate) observed during DP in the current study was the reason or result of the lower oxygen consumption recorded in FAT remains unknown.

The strict locomotor–respiratory coupling in DP, as a result of the stress imposed on the thorax during the distinct hip flexion of the propulsive phase, is similar to rowing (Fabre et al. 2007; Siegmund et al. 1999). Since expiratory abdominal muscles are thought to be more prone to fatigue due to their lower oxidative capacity (Verges et al. 2007) and contribute substantially to the power production during DP (Hegge et al. 2016), performance is expected to be particularly compromised by fatigued trunk muscles. With a 66% decrease in peak torque performance between pre- and post-test demonstrated in the current study, a significant level of fatigue was achieved in trunk flexors through our protocol, potentially leading to a negative impact on expiratory flow by a loss in contractile function as previously suggested (Taylor et al. 2006). Fatigued abdominal muscles may further be responsible for an increased sensation of dyspnea and therefore impaired exercise performance as proposed by Taylor and co-workers (2006). In order to evaluate the occurrence of respiratory muscle fatigue during DP, measures of maximal voluntary inspiratory and expiratory mouth pressures should be included in future investigations. The relationship between locomotion and respiration did not seem to be affected by trunk fatigue in the current study. The characteristic stroke-to-breathing frequency ratio of 1:1 during high-intensity DP remained unchanged despite severe trunk fatigue, supporting the strict locomotor–respiratory coupling in the DP technique (Bjorklund et al. 2015; Holmberg et al. 2007; Lindinger and Holmberg 2011). This forced breathing pattern should be investigated in more detail, since DP has become a dominant cross-country skiing technique in the classic style across all race distances, oftentimes being exclusively used by skiers over the entire race (Welde et al. 2017). In our experiment, trunk muscle fatigue appeared to limit both performance and respiratory capacity, underlining the important role of trunk muscles during DP, where these muscles contribute to both propulsion and respiration.

Although a complex study design was employed for the current experiment, the standardized application of fatigue across participants may have varied inter-individually. Furthermore, the exhaustive fatiguing sequence potentially affected other muscle groups and could have led to a certain level of non-local muscle fatigue and cross-over fatigue (Halperin et al. 2015; Rattey et al. 2006). Unintentional, collateral fatigue in the two-jointed hip flexors and in the elbow flexors and extensors might have negatively affected successive DP performance. This study addressed the effects of fatigued trunk musculature in only one skiing technique, where trunk fatigue likely has a larger impact than during outdoor skiing competitions and different subtechniques are used in the varying terrains and conditions. In addition, we fatigued the trunk specifically in DP-relevant muscles, which will not happen during competitions. Although this study demonstrated substantial performance decreases in DP, the performance decrement found cannot be transferred directly to real-life-skiing.

Conclusion

The current investigation demonstrated a large decrease in 3-min high-intensity DP performance in well-trained cross-country skiers, following the exercise-induced fatigue of frontal and dorsal trunk muscles. This was caused by both decreased work per cycle and cycle rate and accompanied by reduced aerobic power. Since the trunk muscles are simultaneously involved in both respiration and high force-generating propulsion during DP, improved fatigue resistance of the trunk may be particularly relevant for performance in this technique. This applies particularly to the trunk flexor muscles, which have demonstrated a high fatigue susceptibility in the current investigation. Despite new regulations in recent years by the International Ski Federation (FIS) to limit the use of DP during competition, the DP technique will likely remain important in future sprint and distance classical skiing competitions, requiring appropriate strength levels and fatigue resilience of DP-relevant trunk muscles. Further investigations should examine how trunk fatigue occurs and subsequently influences performance during cross-country skiing competitions, in particular during long distance events where DP is of high importance.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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