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Human Kinetics
ORIGINAL INVESTIGATION

Improving Utilization of Maximal Oxygen Uptake and Work Economy in Recreational Cross-Country Skiers With High-Intensity Double-Poling Intervals

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Purpose: To investigate the effect of a double-poling (DP) high-intensity aerobic interval-training (HIT) intervention performed without increasing total HIT volume. This means that regular HIT training (eg, running) was replaced by HIT DP. The aim was to explore whether this intervention could improve peak oxygen uptake in DP, the fractional utilization of maximal oxygen uptake (VO_2max) in DP, oxygen cost of DP, maximal aerobic speed, and a 3-km DP time trial. ***Methods:*** Nine non-specially-DP-trained cross-country skiers (intervention group) and 9 national-level cross-country skiers (control group) were recruited. All participants were tested for VO_2max in running, peak oxygen uptake in DP, oxygen cost of DP, and time-trial performance before and after a 6-wk, 3-times-per-week HIT DP intervention. The intervention group omitted all regular HIT with HIT in DP, leaving the total weekly amount of HIT unchanged. ***Results:*** Seven participants in each group completed the study. VO_2max in running remained unchanged in both groups, whereas peak oxygen uptake in DP improved by 7.1% ($P = .005$) in the intervention group. The fractional utilization of VO_2max in DP thus increased by 7.3% ($P = .019$), oxygen cost of DP by 9.2% ($P = .047$), maximal aerobic speed by 16.5% ($P = .009$), and time trial by 19.5% ($P = .004$) in the intervention group but remained unchanged in the control group. ***Conclusions:*** The results indicate that a 6-wk HIT DP intervention could be an effective model to improve DP-specific capacities, with maintenance of VO_2max in running.

Keywords: cross-country skiing, peak oxygen uptake, oxygen cost of double poling, time-trial performance, maximal aerobic speed

Cross-country skiing is an aerobic endurance sport, with competition durations ranging between 2 and 120 min.[1] In addition, Vasaloppet and other classical-style long-distance races, which nowadays are performed solely by double poling (DP) both by elite and recreational skiers, have an even longer duration from ~240 (winner times) to 360 min (random recreational times). This implies 70% to 99% dependency on aerobic metabolism, in which maximal oxygen uptake (VO_2max), fractional utilization of VO_2max, and work economy are regarded, across all these disciplines.[2–9]

Double poling is one of the main classical-style subtechniques being used in 50% to 100% of the distance in classical cross-country skiing events.[10,11] Although 100% DP is mostly banned from World Cup races, this is allowed in long-distance races such as Vasaloppet. DP puts more stress on the upper body and trunk[12] compared with other skiing techniques,[13] and a high-fractional utilization of VO_2max (%RUN-VO_2max) is needed to perform well in DP.[1] Accordingly, previous studies have found peak oxygen uptake in DP (DP-VO_2peak) to be approximately 80% to 90% of VO_2max in running (RUN-VO_2max).[12,14–17]

No studies have investigated the effect of training designed specifically to improve %RUN-VO_2max in DP, although Nilsson et al[15] found a 4% increase in DP-VO_2peak without any changes in RUN-VO_2max after 6 wk of aerobic interval training on a DP ergometer. This means that %RUN-VO_2max should have increased as well. Sandbakk and Holmberg[1] have previously proposed that cross-country skiers should attempt to elevate their %RUN-VO_2max in subtechniques, like DP, to enhance their performance. An improvement in %RUN-VO_2max should theoretically improve DP performance, even if RUN-VO_2max and/or oxygen cost of DP (C_{DP}) remain unchanged. It can, therefore, be hypothesized that DP-specific high-intensity aerobic interval training (HIT DP) could improve %RUN-VO_2max in nonspecially DP trained, but competitive, cross-country skiers. HIT DP may also improve C_{DP}, maximal aerobic speed in DP (MAS), and DP time-trial performance (TT) in such a cohort of skiers.

Therefore, the primary aim of this study was to investigate the effects of 6 wk of HIT DP in nonspecially DP trained, but competitive, skiers on DP-VO_2peak and %RUN-VO_2max, without increasing total HIT volume or total training volume. A secondary aim was to investigate if this intervention also could improve C_{DP}, MAS, and TT.

Methods

Subjects

Nine recreational-level cross-country skiers (7 males and 2 females) were recruited to the intervention group, and 9 national-level cross-country skiers (7 males and 2 females) were recruited to

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a control group. This study was carried out in accordance with the recommendations of the regional ethics committee of Southeast Norway (REK) with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the regional ethics committee of Southeast Norway (REK). During the training period and during testing prior to the intervention period, 4 subjects (2 males from the intervention group and 2 females from the control group) were excluded due to illness or injuries not related to the intervention. Thus, in total, 14 subjects were included for the statistical analyses. Subject characteristics of the remaining participants are presented in Table 1.

Design

The present study was a 6-wk, 3 times per week, HIT DP intervention, with a pre–post design and a control group. During the intervention period, both the intervention group and the control group trained as normal, with one exception: the intervention group replaced all HIT training (eg, running) with HIT DP.

Methodology

The 14 regional- to national-level cross-country skiers were assigned into 2 groups based on competition level, 1 intervention group (recreational level) and 1 control group (national level). A pretest proceeded the intervention period. The intervention group replaced all other HIT (mostly running and cycling) with DP-specific HIT, exclusively during the intervention period (Table 2). The control group continued their training as normal (Table 2). After the 6 wk, a posttest, including the same tests as in the pretest, was performed. All tests and the training intervention were performed from August to October (ie, preseason).

The subjects were tested on 2 consecutive days both before and after the 6-wk period. A Rodby RL2500E roller skiing treadmill (Rodby Innovation AB, Vänge, Sweden) calibrated for inclination and speed was used in all the DP tests. Only 2 pairs of roller skis (Swenor wheel type 2 Fiberglass; Swenor, Sarpsborg, Norway) were used by all subjects during the roller skiing tests in this study, with 1 of 2 binding systems: SNS (Salomon Nordic System; Salomon, Annecy, France) or NNN (New Nordic Norm; Rottefella AS, Klokkarstua, Norway). Each subject used the same pair during the pretest and posttest.

All oxygen uptake (VO_2) measurements were performed using a Sensor Medics V_{max} Spectra (Sensor Medics 229; SensorMedics, Yourba Linda, CA) with a mixing chamber and with measurements in every 20 s. Before each test, the metabolic test system was calibrated. Certified calibration gases (26% and 16% O_2/4% CO_2) and ambient air were used to calibrate the gas analyzers. The flow sensor was calibrated with a 3-L calibration syringe (Hans Rudolph Inc, Kansas City, MO). According to the manufacturer, the Sensor Medics Vmax Spectra is accurate within a range of ±3%. However, test–retest variations in the present laboratory are shown to be less than ±1%, with an SEM of 0.1 to 0.2 in different tests, as reported in Helgerud et al.[18] Heart rate was measured by Polar s610 heart rate monitors (Polar Electro Oy, Kempele, Finland).

All participants performed 2 treadmill familiarization sessions. The first session consisted of 45 min with different speeds, 1 to 2 d prior to pretesting. The second session was performed prior to the first test on the first day of testing. This session consisted of at least 25 min of DP at a low intensity, <70% of maximal heart rate (HR_{max}). After the second familiarization session, the first day of testing consisted of measurements of heart rate and VO_2 during 5-min DP sessions (4% inclination) at 3 different submaximal speeds for determination of C_{DP}. The subjects started with a speed assumed to be approximately 60% of their DP-VO_2peak. The speed increased by 1.5 $km{\cdot}h^{-1}$ between each session. C_{DP} at 70% of DP-VO_2peak was calculated by the VO_2 data from these submaximal 5-min sessions.

After 5 min of rest, a DP-VO_2peak test was performed using an incremental protocol starting at 4% inclination and 2 to 4 $km{\cdot}h^{-1}$ below 80% of expected HR_{max}. Every 30 s, the inclination increased by 0.5% until reaching approximately 80% of expected HR_{max}. Then, the speed was increased by 0.5 $km{\cdot}h^{-1}$ every 30 s until voluntary exhaustion. DP-VO_2peak was set as the mean of the highest 2 consecutive 20 s measurements of VO_2. The following criteria were used to evaluate if VO_2peak was reached: voluntary exhaustion, flattening of the VO_2 curve, respiratory exchange ratio ≥ 1.0, and peak heart rate (HR_{peak}) in DP 3 to 5 beats below HR_{max}. HR_{peak} was defined as the highest heart rate obtained during the DP-VO_2peak test. HR_{max} was defined as the highest HR obtained regardless of movement pattern, and for all participants achieved in running. All participants knew their HR_{max} prior to their participations. Whether or not this was true, HR_{max} was controlled by the RUN-VO_2max test at day 2, where HR_{max} was defined as the

Table 1 Characteristics of Cross-Country Skiers

Variable	Intervention group (n = 7) Mean (SD)	Intervention group (n = 7) CV, %	Control group (n = 7) Mean (SD)	Control group (n = 7) CV, %
Age, y	29.1 (12.5)	43.1	22.3 (3.1)	13.6
Weight, kg	73.5 (10.1)	13.8	77.5 (5.5)	7.1
Height, cm	178.4 (9.5)	5.3	185.4 (4.8)	2.6

Abbreviation: CV, coefficient of variation.

Table 2 Training Data Before and During Intervention ($min{\cdot}wk^{-1}$)

	Intervention group (n = 7)		Control group (n = 7)	
	Before	During	Before	During
Endurance training, min				
60–84% HRmax	287.1 (181.4)	222.3 (91.1)	382.1 (209.9)	346.0 (187.7)
85–90% HRmax	54.3 (67.0)	55.1 (70.7)	35.6 (38.5)	30.9 (45.8)
≥90% HRmax	28.9 (35.5)	32.0 (21.3)	47.3 (33.5)	39.6 (26.2)
Strength training, min	28.0 (26.9)	36.9 (44.6)	58.0 (50.2)	84.3 (70.6)
Total training	398.2 (280.8)	346.8 (213.6)	524.7 (263.1)	502.4 (238.3)

Abbreviation: HR_{max}, maximal heart rate.

highest heart rate obtained during the RUN-VO_2max test + 3 beats. MAS was defined as the product of DP-VO_2peak divided by C_{DP}. As DP-VO_2peak may be expressed as $mL \cdot kg^{-1} \cdot min^{-1}$, and C_{DP} may be expressed as $mL \cdot kg^{-1} \cdot m^{-1}$, the product of the denominations was $m \cdot min^{-1}$.

The second day of testing consisted of a RUN-VO_2max test and a TT performance test in DP. A Woodway PPS55sport (Woodway, Waukesha, WI), calibrated for inclination and speed, was used for the RUN-VO_2max test. An incremental protocol, starting at 6% inclination, was used in this test. The initial speed was set to 8 (females) and 10 $km \cdot h^{-1}$ (males). During the first 2 min of the test, inclination was increased by 1% to 4%, dependent on the subjects' fitness levels. From that point, only speed was increased every 30 s by 0.5 $km \cdot h^{-1}$ until voluntary exhaustion. RUN-VO_2max was defined as the mean of the highest 2 consecutive 20 s measurements of VO_2. The following criteria were used to evaluate if RUN-VO_2max was reached: voluntary exhaustion, flattening of the VO_2 curve, respiratory exchange ratio ≥1.05, and HR_{peak} 3 to 5 beats below HR_{max}.

After 40 min of rest, a TT in DP, at 4% inclination, was performed on the same treadmill as the first day. The speed increased to what the subjects thought they could manage to sustain through the whole test, and the test started when this speed was obtained. During the test, the subjects could give physical signs with fingers or head to increase or decrease the speed. All participants were given feedback on the remaining distance from 2000 m, but not on time spent. Heart rate was measured every minute from 3 min and to the end of the test. The time used on this TT was used as the performance result.

Training

To control the weekly training performed by the participants, each subject had to report the exact amount of time in the different training intensity zones 60% to 84%, 85% to 90%, and >90% HR_{max} both before and during the 6-wk period. The 3 zones are representing moderate exercise, exercise at approximate lactate threshold, and HIT, as previously used and described in Støren et al[19] and Sunde et al.[20] All training in the intervention group and in the control group was reported for the last 6 wk prior to the baseline testing. During the intervention period, the control group was instructed to continue their normal training. This training was logged and did not differ from their normal training prior to the intervention (Table 2).

The HIT intervention consisted of 3 DP training sessions per week. Each session contained 4 × 4 min at 90% to 95% of HR_{peak} DP on a treadmill with 4% inclination and was supervised by research personnel. Each session started with a minimum of a 10-min warm-up, and ended with a minimum of a 3-min cooldown, and each 4-min period was separated by 3 min at 70% HR_{peak}. The inclusion criterion for adherence was set to a mean of 2 out of 3 sessions per week (ie, 67%; 12 sessions). The amount of HIT DP during the intervention period equaled the total amount of HIT (running and cycling) performed prior to the intervention.

Statistical Analysis

Normality was tested by Q–Q plots and the Shapiro–Wilk test for %RUN-VO_2max and TT performance and found to be normally distributed. Although a low number of participants, parametric statistics were, therefore, used. Based on previous findings, HIT can be expected to improve VO_2max by approximately 10% in recreational athletes. With 7 subjects and a SD of the same size as the improvement (10%), the statistical power was calculated to be 84% given an alpha error level of 5%. Statistical analysis was performed using the software program SPSS (version 24; Statistical Package for Social Science, Chicago, IL). Descriptive analysis was performed for display of mean, SD, and 95% confidence intervals. Paired samples *t* tests and independent samples *t* tests were used for comparing means within groups and between groups. Pearson correlation tests were used to identify relationships between variables and displayed by the correlation coefficient *r* and standard error of estimate. In all cases, $P < .05$ was set as the level of significance in 2-tailed tests.

Results

The intervention group completed, on average, 14.4 (2.3) (80%) of the 18 planned HIT DP sessions. The mean weekly effective training volume (pauses and brakes excluded) before the intervention period was 6.6 (4.7) and 8.7 (4.4) h for the intervention and control group, respectively. Neither training volume nor training intensity changed from before to during the 6-wk intervention period in any of the 2 groups (Table 2).

In the intervention group, DP-VO_2peak ($L \cdot min^{-1}$) increased by 7.1% ($P = .005$) from pretest to posttest, whereas no change was found in the control group (Table 3, Figure 1). The intervention group also improved C_{DP} by −9.2% ($P = .047$), MAS by 16.5% ($P = .009$), and TT performance by −19.5% ($P = .004$). None of these variables changed in the control group. %RUN-VO_2max improved by 7.3% points ($P = .019$) in the intervention group, whereas no increase was found in the control group (Figure 1). No significant difference in either groups was found in RUN-VO_2max, body weight, RER_{peak}, or HR_{peak} in DP after the intervention (Table 3).

A strong correlation was found between TT performance and MAS ($r = .83$, standard error of estimate = 11.6%) at baseline (Figure 2). When performing a partial correlation corrected for group (intervention and control), the correlation was still strong ($r = .81$, $P < .001$). Also ΔMAS and ΔDP-VO_2peak ($L \cdot min^{-1}$) correlated with the ΔTT performance ($r = .61$, $P = .021$ and $r = .67$, $P = .009$, respectively). Baseline correlations are presented in Table 4.

Discussion

The main novelty of the present study was that a 6-wk HIT DP intervention was an effective model to enhance DP-specific capacities, with maintenance of RUN-VO_2max. Concurrent improvements in DP-VO_2peak, %RUN-VO_2max, and C_{DP} after the work-specific HIT intervention were found, and these improvements proved to be highly performance determining, as shown by large improvements in MAS and TT performance. It is noteworthy that these improvements were achieved without any increase in the total amount of training in general or in the total amount of HIT.

TT Performance and MAS

Although the intervention group improved their TT by −19.5%, the control group was left unchanged. As the control group initially had 15% better TT performance than the intervention group, the improvement of the intervention group resulted in the same TT level as the control group after the intervention, with maintenance of RUN-VO_2max. To our knowledge, this is the first study to

Table 3 Physiological Results in the Intervention and Control Groups

	Intervention group (n = 7)			Control group (n = 7)			
Variable	Pre	Post	Within (*P*)	Pre	Post	Within (*P*)	Between (*P*)
3-km TT							
Time, s	833.6 (175.7)	671.0 (101.1)	.004**	710.1 (106.7)	692.3 (104.8)	.096	.002****
DP-VO_2peak							
mL·kg^{-1}·min^{-1}	51.5 (8.1)	54.6 (8.6)	.030*	58.0 (7.4)	57.7 (7.2)	.830	.047***
mL·$kg^{-0.67}$·min^{-1}	212.5 (36.3)	226.1 (36.4)	.017*	243.5 (32.1)	242.0 (30.6)	.746	.028***
L·min^{-1}	3.80 (0.86)	4.07 (0.82)	.005**	4.49 (0.68)	4.44 (0.62)	.615	.014***
HR_{peak}	180 (11)	181 (10)	.647	183 (9)	181 (11)	.386	.322
RER_{peak}	1.08 (0.09)	1.03 (0.02)	.201	1.05 (0.04)	1.07 (0.05)	1.000	.045***
RUN-VO_2max							
mL·kg^{-1}·min^{-1}	65.8 (10.9)	63.3 (8.8)	.085	71.6 (3.9)	71.2 (4.2)	.735	.223
mL·$kg^{-0.67}$·min^{-1}	279.8 (45.2)	262.1 (36.1)	.129	300.6 (18.0)	298.5 (20.2)	.642	.335
L·min^{-1}	4.82 (0.99)	4.71 (0.83)	.294	5.54 (0.50)	5.49 (0.53)	.539	.697
HR_{peak}	183 (9)	183 (9)	1.000	190 (6)	189 (7)	.188	.435
RER_{peak}	1.06 (0.03)	1.07 (0.04)	.917	1.05 (0.03)	1.05 (0.04)	.129	.956
%RUN-VO_2max							
%	78.7 (5.6)	86.0 (2.4)	.019*	80.9 (7.8)	80.9 (6.4)	.592	.015***
C_{DP}							
mL·kg^{-1}·m^{-1}	0.207 (0.016)	0.188 (0.015)	.047*	0.204 (0.039)	0.208 (0.019)	.707	.117
mL·$kg^{-0.67}$·m^{-1}	0.857 (0.095)	0.778 (0.055)	.046*	0.855 (0.163)	0.873 (0.084)	.722	.116
MAS							
m·min^{-1}	252.1 (52.5)	293.6 (59.8)	.009**	297.5 (85.8)	281.6 (57.5)	.298	.007****

Abbreviations: %RUN-VO_2max, fractional utilization of RUN-VO_2max at DP-VO_2peak; TT, time trial on roller skis; Between (*P*), *P* values of between-groups differences; C_{DP}, oxygen cost of DP at 70% of DP-VO_2peak; DP, double poling; DP-VO_2peak, peak oxygen uptake in DP; HR_{peak}, peak heart rate; MAS, maximal aerobic speed; RER_{peak}, peak value of respiratory exchange ratio; RUN-VO_2max, maximal oxygen uptake in running; TT, time trial; Within (*P*), *P* values of within-group differences. *Significantly different from pretest value ($P < .05$). **Significantly different from pretest value ($P < .01$). ***Significantly different from Δ control value ($P < .05$). ****Significantly different from Δ control value ($P < .01$).

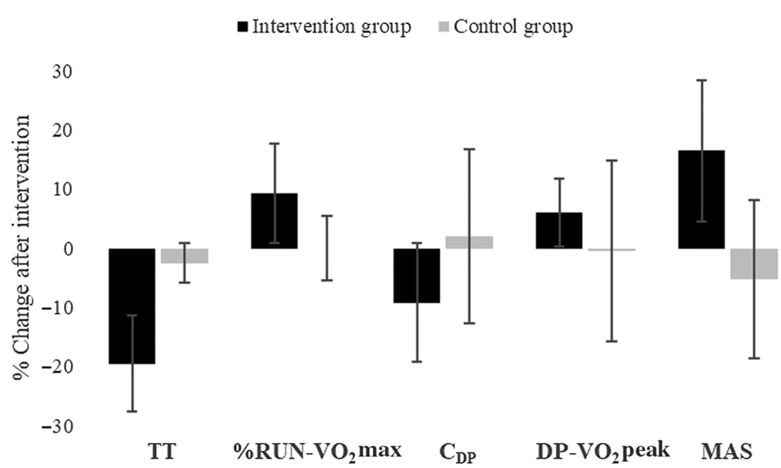

Figure 1 — Percentage change after the intervention period in physiological characteristics and TT performance in the intervention group and the control group. %RUN-VO_2max indicates fractional utilization of maximal oxygen uptake in double poling; C_{DP}, oxygen cost of double poling; DP-VO_2peak, peak oxygen uptake in double poling; MAS, maximal aerobic speed; TT, time trial.

demonstrate recreational-level skiers reaching the level of national-level skiers in TT performance after only 6 wk of specialized training. The improvement in time performance is in line with Nilsson et al,[15] who found a 16% improvement in mean power during a 6-min DP performance test on a DP ergometer after HIT DP 3 times a week for 6 wk. We suggest that the improvement in TT performance in the present study was due to the improvement in MAS, which was at the approximate same level. This is in accordance with the framework of Joyner and Coyle,[7] defining performance velocity as the product of performance VO_2 (VO_2max and lactate threshold), performance O_2 deficit, and gross mechanical efficiency.

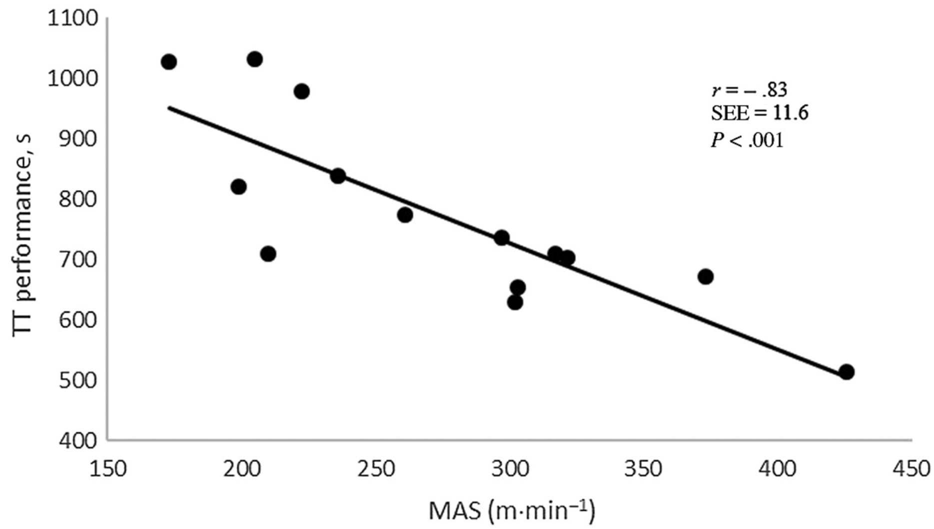

Figure 2 — Relationship between baseline MAS and TT performance. The correlation is statistically significant ($P < .001$). MAS indicates maximal aerobic speed; SEE, standard error of estimate; TT, time trial.

Table 4 Correlations Between Physiological Data and 3-km Time-Trial Performance

	r	SEE, %	*P*
Age, y	.43	18.8	.130
Height, cm	.01	20.3	.498
Body weight, kg	−.20	20.7	.972
DP-VO_2peak			
mL·kg^{-1}·min^{-1}	−.94	7.2	<.001**
mL·kg$^{-0.67}$·min^{-1}	−.88	9.9	<.001**
L·min^{-1}	−.72	14.4	.004**
RUN-VO_2max			
mL·kg^{-1}·min^{-1}	−.84	11.2	<.001**
mL·kg$^{-0.67}$·min^{-1}	−.81	12.1	<.001**
L·min^{-1}	−.64	16.0	.014*
%RUN-VO_2max	−.37	19.3	.197
C_{DP}			
mL·kg^{-1}·m^{-1}	.67	17.7	.056
mL·kg$^{-0.67}$·m^{-1}	.68	17.8	.063
MAS, m·min^{-1}	−.83**	11.6	<.001**

Abbreviations: %RUN-VO_2max, fractional utilization of VO_2max at VO_2peak in DP; C_{DP}, oxygen cost of DP at 70% of VO_2peak; DP, double poling; DP-VO_2peak, peak oxygen uptake in DP; RUN-VO_2max, maximal oxygen uptake in running; SEE, standard error of estimate.
*$P < .05$. **$P < .01$.

As MAS is the product of DP-VO_2peak divided by C_{DP}, the improvement in MAS should be due to the improvement in DP-VO_2peak and C_{DP}. Several studies have shown an improved MAS after improvement in either VO_2peak or work economy, leaving the other variable more or less unchanged.[14,19–24] When improving both variables at the same time, as in the present study, it was natural that the improvement in MAS was large. However, it may also be hypothesized that the improvement in %RUN-VO_2max observed in the intervention group also played a role in the large TT improvement seen in this group.

DP-VO_2peak and %RUN-VO_2max

The improvement in DP-VO_2peak observed in the intervention group seemed to be highly DP specific, as RUN-VO_2max did not change in either groups. This may reflect that the skiers adapted specifically to the load they were provided. Likely, DP did not provide enough muscle mass to tax the aerobic system to the same extent (eg, running).[7] As discussed in Joyner and Coyle,[7] performance VO_2 may be a strong performance indicator, and this may be understood as the aerobic capacity in the specific movement patterns being an equally great performance predictor compared with overall aerobic capacity (RUN-VO_2max). This is further supported by the significant correlation between increase in DP-VO_2peak and improvement in TT observed in this study.

The maintenance of RUN-VO_2max was as expected, as the intervention group did not increase total training volume or HIT volume (Table 2). They merely substituted their regular HIT volume (running and cycling) with HIT DP. On the other hand, HIT DP that was performed at 90% to 95% of HR_{peak} in DP, and thus approximately 88% to 93% of HR_{max}, proved to be a sufficient training stimulus to maintain overall aerobic capacity. The improvement in DP-VO_2peak, therefore, lifted the specific aerobic capacity of the nonspecially DP-trained subjects almost to the level of the more skilled subjects in the control group, despite a still much lower overall aerobic capacity. Together with the improvement in time performance in the present study, these results highlight the possibility for enhancing DP performance by improving specific aerobic capacity and maintaining overall aerobic capacity. This is well in line with the discussion of Sandbakk and Holmberg[1] that a better ability to utilize overall aerobic capacity in subtechniques like DP may be a key determinant for performance. The findings in the present study may also have further implications for the last months of preparation for cross-country skiers aiming for peak performance in specific DP events.

It has been previously presented in Støren et al[21] that VO_2peak in cycling was improved after HIT performed as running. In Støren et al,[21] VO_2peak in cycling followed an improvement in RUN-VO_2max, without an increase in %RUN-VO_2max. However, the intervention group in the present study increased %RUN-VO_2max by 7.3% points as a result of the improvement in DP-VO_2peak.

To our knowledge, this is a novel finding highlighting the importance of specific HIT training to improve %RUN-VO_2max in any cross-country skiing subtechnique, and thus performance as shown in the present study. This finding also specified that there may be at least 2 ways to improve work-specific VO_2peak. The first way, as demonstrated in Støren et al[21] in cycling, is by improving overall aerobic capacity and leaving the percentage of work-specific VO_2peak unchanged. The second way, as demonstrated in the present study, is increasing work-specific VO_2peak and leaving the overall aerobic capacity unchanged.

The results from the present study are in contrast to results from previous studies who did not find significant improvements in %RUN-VO_2max in DP after interventions, including increased upper body endurance training.[15,17,25] However, these interventions were not directly comparable with that of the present study, as they were using either a DP ergometer,[15] additional upper body muscular endurance training,[17] or sprint intervals.[25]

The results from the present study showed a low %RUN-VO_2max at baseline (79% in the intervention group and 81% in the control group) compared with previous studies,[14–17,25] ranging from approximately 80% to 90%. However, in the study of Hegge et al,[12] female cross-country skiers showed %RUN-VO_2max values in DP closer to our findings. One possible explanation for the low %RUN-VO_2max at baseline in the present study could be that the nonspecially DP-trained skiers had performed less roller skiing DP training prior to the study compared with previous studies, but this could hardly explain the low %RUN-VO_2max among the national-level skiers. However, as the national-level skiers also had quite low %RUN-VO_2max at baseline, we may speculate that they would benefit from having periods with extra DP focus as well.

Oxygen Cost of Double Poling

One of the main novelties of the present study was the concurrent improvements in DP-VO_2peak and C_{DP}. This combination is in contrast to previous studies showing slightly reduced work economy or gross efficiency when boosting VO_2max over a short period, as in Skovereng et al[26] and Vandbakk et al.[25] Skovereng et al[26] found a moderate correlation between improved VO_2max and deteriorated gross efficiency in cycling, which may indicate a deteriorated work economy, although care should be taken when comparing oxygen cost results with gross efficiency results. One possible explanation of the contrasting results observed in the present study and Vandbakk et al[25] was that Vandbakk et al used sprint intervals, that is, a much shorter interval duration and a much higher intensity than in the present study. On the other hand, the mean intensity for 4 × 4-min protocol in Skovereng et al[26] was 89% HR_{max}. This is in line with the durations and intensities of the present study, which was 90% to 95% of HR_{peak} in DP, and thus approximately 88% to 93% of HR_{max}. However, the results from the present study are in agreement with the findings in Nilsson et al[15] who found improved work economy after HIT, where the intensity was 85% of maximal power output, which is a slightly higher intensity than reported in Skovereng et al[26] and the present study. Thus, when comparing results from the present study with the results from Vandbakk et al,[25] Skovereng et al,[26] and Nilsson et al,[15] improvement or deterioration of C_{DP} seems to have little to do with the training intensity, bearing in mind that in all these studies, the intensities were above 85% of HR_{max}. It is, however, speculated in Skovereng et al[26] that training at moderate intensity (ie, approximately at the lactate threshold) may be more beneficial to improve work economy or efficiency at these intensities, whereas very high-intensity training aimed to primarily improve VO_2peak with less amount of such moderate training may lead to decreased work economy or efficiency.

The improvement in C_{DP} in the intervention group in the present study is in close agreement with several previous studies, showing improvements of approximately 5% to 10% after 4 to 8 wk of HIT.[15,22–24,27] Some of these previous results are from interventions in movement patterns the participants have not been previously specialized in, like straightforward running in soccer players.[22] HIT interventions performed in athletes in their specific movement patterns may not result in oxygen cost improvements, as shown in Støren et al.[21] McMillan et al[24] have showed a good example of the specificity in oxygen cost improvements, where an HIT intervention performed on a soccer-specific dribble track did not result in improvements in running economy tested on a treadmill. As the skiers in the intervention group in the present study consisted of athletes competing at the regional level, they were familiar with DP movement patterns, but had not previously performed HIT DP regularly. Therefore, more DP in general in the intervention group could be one of the main reasons for the improvement in C_{DP}.

Methodological Concerns

As the intervention group only included 7 subjects, there are possibilities of type II statistical errors. On the other hand, the improvements are large, and the low number of participants thus decreases the possibilities of type I errors. At the beginning of the intervention period, the 2 groups were different in gender representation. When analyzing the intervention group both with and without the 2 women, mean improvement in DP-VO_2peak was the same (0.27 vs 0.27 $L\cdot min^{-1}$) and with approximately same SD (0.17 vs 0.19 $L\cdot min^{-1}$). This was echoed in the results regarding %RUN-VO_2max and TT performance. Between-groups differences (intervention vs control) were thus approximately the same and still statistically significant both with and without women in the intervention group. However, as the intervention group without the 2 women only consisted of 5 subjects, the P values regarding within-group differences were somewhat worsened, although still significant in the intervention group ($P = .035$, $P = .016$, and $P < .001$ for DP-VO_2peak, %RUN-VO_2peak, and TT performance, respectively).

We cannot completely rule out that some of the improvements seen in the intervention group, compared with the control group, are due to better familiarization with the treadmill from pretest to posttest. However, the improvements in TT were at approximately the same level as the improvement in MAS. This suggests a physiological explanation for the TT improvement rather than a result of treadmill familiarization. In addition, the subjects got 2 familiarization sessions (45 and 25 min) before the first test, which was an incremental submaximal step test for measuring C_{DP}. Thus, the subjects got at least 90 min of familiarization before the DP-VO_2peak test. As the TT was performed on day 2, we considered the skiers well familiarized with the treadmill testing.

Practical Implications

The present study has shown that HIT DP may be an effective way to improve DP-VO_2peak, C_{DP}, and time performance in DP among recreational cross-country skiers. In addition, the intervention maintained overall aerobic capacity, which was as expected as overall HIT volume did not increase during the HIT intervention. Therefore, the maintenance of RUN-VO_2max suggests that this training regimen may be sufficient to maintain it. We, therefore, suggest a training regimen with HIT DP as a supplement to, and not a substitution for, regular HIT, to improve both specific and overall aerobic capacity. This should be of special interest for skiers aiming for specialization in DP and for those who need to further develop their DP capacity.

The control group differed from the intervention group at baseline in RUN-VO_2max and TT performance, but not in %RUN-VO_2max. This indicates a potential for improvement in %RUN-VO_2max also in skiers at a national level. We, therefore, suggest investigating the effects of the same HIT DP intervention as in the present study on skiers on a national level in future studies.

Conclusion

A 6-wk HIT DP intervention was shown to be an effective training model to improve DP-specific capacities, with maintenance of RUN-VO_2max. Accordingly, HIT DP should be considered an effective training strategy to enhance DP performance in competitive skiers at a recreational level and should be of special interest for skiers aiming to specialize in or develop DP capacity.

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