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

High-intensity double poling intervals improve utilization of maximal oxygen uptake and work economy in recreational cross-country skiers

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Original Investigation

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Abstract

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 like e.g. running was replaced by HIT DP. The aim was to explore if this intervention could improve VO_{2peak} in double poling (DP-VO_{2peak}), the fractional utilization of VO_{2max} in DP (%RUN-VO_{2max}), DP economy (C_{DP}), maximal aerobic speed and a 3-km DP time trial (TT). ***Methods:*** Nine non-specially DP trained cross-country skiers (intervention group), and nine national level cross-country skiers (control group) were recruited. All participants were tested for VO_{2max} in running (RUN-VO_{2max}), DP-VO_{2peak}, C_{DP}, and TT performance pre- and post a 6 weeks, 3 times per week, HIT DP intervention period. 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. RUN-VO_{2max} remained unchanged in both groups, while DP-VO_{2peak} improved by 7.1% (p=0.005) in the intervention group. %RUN-VO_{2max} thus increased by 7.3%-points (p=0.019), C_{DP} by 9.2% (p=0.047), maximal aerobic speed by 16.5% (p=0.009) and TT by 19.5% (p=0.004) in the intervention group, but remained unchanged in the control group. ***Conclusions:*** The results indicate that a 6 weeks HIT DP intervention could be an effective model to improve DP specific capacities, with maintenance of RUN-VO_{2max}.

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

Introduction

Cross-country skiing is an aerobic endurance sport, with competitions ranging between 2 – 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, has an even longer duration; from ~ 240 min (winner times) to 360 min (random recreational times). This implies 70 – 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].

DP is one of the main classical style sub-techniques, being used in 50 – 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 to 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 – 90% of 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 six weeks 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 sub-techniques, like DP, to enhance their performance. ~~However, Nilsson et al.[15] found a 4% increase in DP-VO2peak without any changes in RUN-VO2max after six weeks of aerobic interval training on a DP ergometer, meaning that %RUN-VO2max should have increased as well.~~ An improvement in %RUN-VO_{2max} should theoretically improve DP performance, even if RUN-VO_{2max} and/or oxygen cost of double-poling (C_{DP}) remains unchanged. It can therefore be hypothesized that DP specific high intensity, aerobic interval training (HIT DP) could improve %RUN-VO_{2max} in non-specially 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 weeks of HIT DP in non-specially 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 (seven males and two females) were recruited to the intervention group, while nine national level cross-country skiers (seven males and two females) were recruited to 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, four subjects (two males from the intervention group and two 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.

Table 1

Design

The present study was a 6 weeks, three 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, normally performed as e.g. running, with HIT DP.

Methodology

The 14 regional to national level cross-country skiers were assigned into two groups based on competition level, one intervention group (recreational level) and one control group (national level). A pre-test 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 six weeks, a post-test, including the same tests as in the pre-test, was performed. All tests and the training intervention were performed from August to October, i.e. pre-season.

Table 2

The subjects were tested on two following days both pre- and post the six weeks 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 two pairs of roller-skis (Swenor wheel type 2 Fiberglass, Sarpsborg, Norway) were used by all subjects during the roller-skiing tests in this study, with one of two binding systems SNS (Salomon, Annecy, France) or NNN (Rottefella, Klokkarstua, Norway). Each subject used the same pair at pre- and post-test.

All VO_2 measurements were performed using a Sensor Medics Vmax Spectra (Sensor Medics 229, Yourba Linda, Ca, USA) with a mixing chamber and with measurements 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, Kansas City, MO, USA). 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 a *SEM* of 0.1-0.2 in different tests, as reported in Helgerud et al.[18]. Heart rate was measured by using Polar s610 heart rate monitors (Polar Electro Oy, Finland).

All participants performed two treadmill familiarization sessions. The first session consisted of 45 min with different speeds, one to two days prior to pre-testing. 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 oxygen uptake (VO_2) during 5-min DP sessions (4% inclination) at three 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·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 five min of rest, a DP-VO_{2peak} test was performed, using an incremental protocol starting at 4% inclination and 2 – 4 km·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·h^{-1} every 30 s until voluntary exhaustion. DP-VO_{2peak} was set as the mean of the highest two 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 (RER) ≥ 1.0 and peak heart rate (HR_{peak}) in DP 3 – 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 a true HR_{max}, was controlled by the RUN-VO_{2max} test at day 2, where HR_{max} was defined as the 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}. Since DP-VO_{2peak} may be expressed as mL·kg^{-1}·min^{-1} and C_{DP} may be expressed as mL·kg^{-1}·m^{-1}, the product of the denominations was m·min^{-1}.

The second day of testing consisted of a RUN-VO_{2max} test and a TT performance test in DP. A Woodway PPS55sport (Waukesha, Germany), 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 km·h^{-1} (females) and 10 km·h^{-1} (males). During the first two minutes of the test, inclination was increased by 1 – 4%, dependent on the subjects' fitness level. From that point, only speed was increased every 30 s by 0.5 km·h^{-1} until voluntary exhaustion. RUN-VO_{2max} was defined as the mean of the highest two 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, RER ≥ 1.05 and HR_{peak} 3 – 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 meters, 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 – 84%, 85 – 90% and >90% HR_{max} both before and during the six weeks period. The three zones are representing moderate exercise, exercise at approximately 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 six weeks 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 three DP training sessions per week. Each session contained 4 · 4 min at 90 – 95% of HR_{peak} DP on a treadmill with 4% inclination, and was supervised by research personnel. Each session started with a minimum of 10 min warm up, and ended with a minimum of 3 min cool down, 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 two out of three sessions per week, i.e. 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 QQ-plots and Shapiro-Wilk 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 seven subjects and a standard deviation 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 were performed using the software program SPSS, version 24 (Statistical Package for Social Science, Chicago, IL, USA). Descriptive analysis were 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 in order to identify relationships between variables, and displayed by the correlation coefficient *r*, and standard error of estimate (SEE). In all cases, $P<0.05$ was set as the level of significance in two-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 hours and 8.7 ± 4.4 hours for the intervention and control group, respectively. Neither training volume nor training intensity changed from before to during the 6 weeks intervention period in any of the two groups (Table 2).

In the intervention group DP-VO_{2peak} ($L \cdot min^{-1}$) increased by 7.1% ($p=0.005$) from pre to post intervention, whereas no change was found in the control group (Table 3, Fig. 1). The intervention group also improved C_{DP} by -9.2% ($p=0.047$), as well as MAS by 16.5% ($p=0.009$) and TT performance by -19.5% ($p=0.004$). None of these variables changed in the control group. %RUN-VO_{2max} improved by 7.3 %-points ($p=0.019$) in the intervention group, whereas no increase was found in the control group (Fig. 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).

Table 3

Figure 1

A strong correlation was found between TT performance and MAS (r= 0.83, *SEE* = 11.6%) at baseline (Fig. 2). When performing a partial correlation corrected for group (intervention and control), the correlation was still strong (r= 0.81, p < 0.001). Also ΔMAS and ΔDP-VO_{2peak} (L·min^{-1}) correlated with the ΔTT performance (r= 0.61, p=0.021 and r=0.67, p=0.009 respectively). Baseline correlations are presented in Table 4.

Figure 2

Table 4

Discussion

The main novelty of the present study was that a 6 weeks 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 maximal aerobic speed

While 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 demonstrate recreational level skiers reaching the level of national level skiers in TT performance after only 6 weeks of specialized training. The improvement in time performance is in line with Nilsson et al.[15], who found 16% improvement in mean power during a 6-min double poling performance test on a DP ergometer after HIT DP three times a week for 6 weeks. 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.

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 the improvement in 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 as e.g. 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 to 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, since 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, which was performed at 90-95% of HR_{peak} in DP, and thus approximately 88-93% 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 non-specially 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 maintain 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 sub-techniques 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 shown 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 sub-technique, and thus performance as shown in the present study. This finding also points out that there may be at least two 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 % 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 to 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 to 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 non-specially DP trained skiers had performed less roller skiing DP training prior to the study compared to previous studies, but this could hardly explain the low %RUN-VO_{2max} among the national level skiers. However, since 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, like e.g. 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 vs. 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.[25] used sprint-intervals, i.e. 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 minutes 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 90-95% of HR_{peak} in DP, and thus approximately 88-93% 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, i.e. a slightly higher intensity than reported in Skovereng et al.[26] and the present study. Thus, when comparing results from the present study and 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 i.e. approximately at the lactate threshold, may be more beneficial to improve economy or efficiency at these intensities, while very high intensity training aimed to primarily improve VO_{2peak} with less amount of such moderate training may lead to decreased 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 – 10% after 4 – 8 weeks of HIT[15,22,23,24,27]. Some of these previous results are from interventions in movement patterns the participants have not been previously specialized in, like straight forward 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 a HIT intervention performed on a soccer-specific dribble track did not result in improvements in running economy tested on a treadmill. Since the skiers in the intervention group in the present study consisted of athletes competing at 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

Since the intervention group only included seven subjects there are possibilities of type 2 statistical errors. On the other hand, the improvements are large and the low number of participants thus decreases the possibilities of type 1 errors. At the beginning of the intervention period, the two groups were different in gender representation. When analyzing the intervention group both with and without the two 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, since the intervention group without the two women only consisted of five subjects, the p-values regarding within group differences were somewhat worsened, although still significant in the intervention group ($p=0.035$, $p=0.016$ and $p<0.001$ 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 to the control group, is due to better familiarization with the treadmill from pre- to posttest. However, the improvements in TT was 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 two familiarization sessions (45 and 25 minutes) before the first test, which was an incremental sub-maximal step test for measuring C_{DP}. Thus, the subjects got at least 90 minutes of familiarization before the DP-VO_{2peak} test. Since 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 since overall HIT volume did not increase during the HIT intervention. Therefore, the maintenance of RUN-VO_{2max} suggest that this training regimen ~~may not contribute to enhance overall maximal aerobic capacity, but~~ 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, in order 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 to investigate 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 weeks 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 or develop DP capacity.

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Figure legends

Figure 1 – Percentage change after the intervention period in physiological characteristics and TT performance in the intervention group and the control group. TT, time trial performance. %RUN-VO_{2max}, fractional utilization of RUN-VO_{2max} in double poling. C_{DP}, oxygen cost of double poling. DP-VO_{2peak}, peak oxygen uptake in double poling. MAS, maximal aerobic speed. *$p<0.05$ significant difference from pretest. **$p<0.01$ significant difference from pretest. $^{\#}p<0.05$ significant difference from control group. $^{\#\#}p<0.01$ significant difference from control group.

Figure 2 – Relationship between baseline maximal aerobic speed (MAS) and time trial performance (TT). The correlation is statistically significant ($p<0.001$). *r*, correlation coefficients. *SEE*, standard error of estimate.

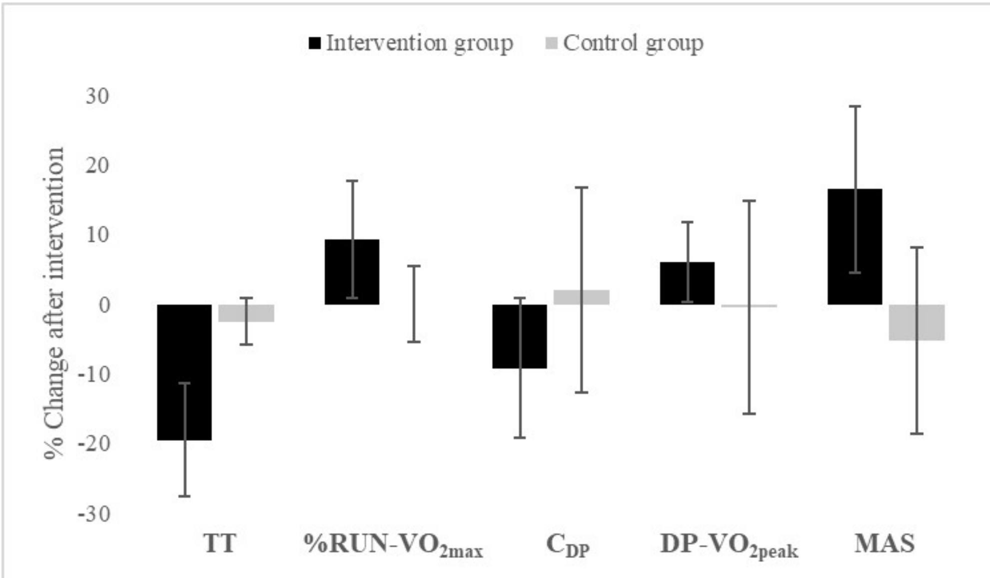

Figure 1 – Percentage change after the intervention period in physiological characteristics and TT performance in the intervention group and the control group. TT, time trial performance. %RUN-VO_{2max}, fractional utilization of RUN-VO_{2max} in double poling. C_{DP}, oxygen cost of double poling. DP-VO_{2peak}, peak oxygen uptake in double poling. MAS, maximal aerobic speed. *$p<0.05$ significant difference from pretest. **$p<0.01$ significant difference from pretest. #$p<0.05$ significant difference from control group. ##$p<0.01$ significant difference from control group.

198x115mm (96 x 96 DPI)

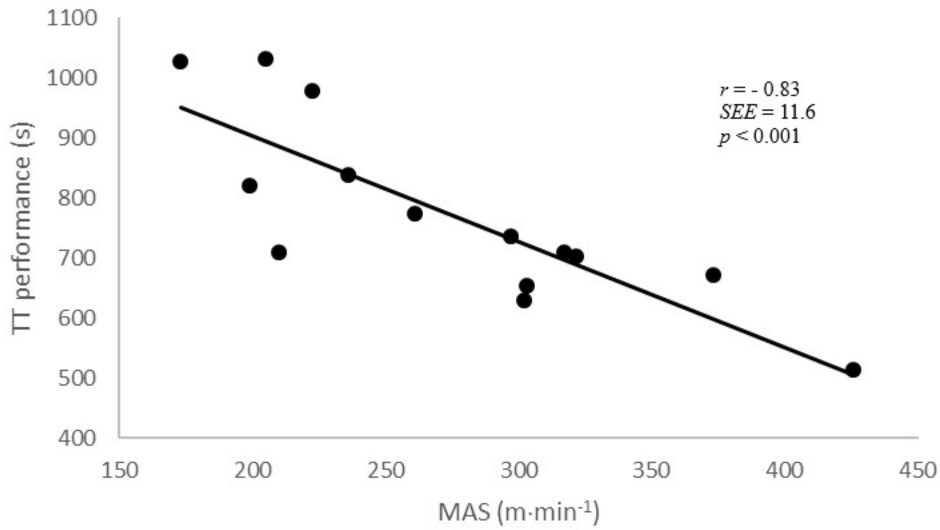

Figure 2 – Relationship between baseline maximal aerobic speed (MAS) and time trial performance (TT). The correlation is statistically significant (p<0.001). r, correlation coefficients. SEE, standard error of estimate.

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TABLE 1. Characteristics of cross-country skiers

Variables	Intervention Group n = 7		Control group n = 7	
Age (yr)	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

Values are mean ± standard deviations and variation coefficient in percentage. Yr, years. Kg, kilogram. Cm, centimeter.

TABLE 2. Training data before and during intervention, in minutes per week

	Intervention group (n = 7)		Control group (n = 7)	
% HR_{max}	Before	During	Before	During
Endurance training (min)				
60 – 84	287.1 ± 181.4	222.3 ± 91.1	382.1 ± 209.9	346.0 ± 187.7
85 – 90	54.3 ± 67.0	55.1 ± 70.7	35.6 ± 38.5	30.9 ± 45.8
≥ 90	28.9 ± 35.5	32.0 ± 21.3	47.3 ± 33.5	39.6 ±26.2
Other training (min)				
Strength	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

Values are mean ± standard deviations in minutes per week. $HR_{max,}$ maximal heart rate. min, minutes.

TABLE 3. Physiological results in the intervention and control group

	Intervention group n=7			Control group n=7			
Variables	**Pre**	**Post**	**Within(p)**	**Pre**	**Post**	**Within(p)**	**Between(p)**
3-km TT							
Time (s)	833.6 ± 175.7	671.0 ± 101.1	0.004**	710.1 ± 106.7	692.3 ± 104.8	0.096	0.002##
DP-VO_{2peak}							
$mL \cdot kg^{-1} \cdot min^{-1}$	51.5 ± 8.1	54.6 ± 8.6	0.030*	58.0 ± 7.4	57.7 ± 7.2	0.830	0.047#
$mL \cdot kg^{-0.67} \cdot min^{-1}$	212.5 ± 36.3	226.1 ± 36.4	0.017*	243.5 ± 32.1	242.0 ± 30.6	0.746	0.028#
$L \cdot min^{-1}$	3.80 ± 0.86	4.07 ± 0.82	0.005**	4.49 ± 0.68	4.44 ± 0.62	0.615	0.014#
HR_{peak}	180 ± 11	181 ± 10	0.647	183 ± 9	181 ± 11	0.386	0.322
RER_{peak}	1.08 ± 0.09	1.03 ± 0.02	0.201	1.05 ± 0.04	1.07 ± 0.05	1.000	0.045#
RUN-VO_{2max}							
$mL \cdot kg^{-1} \cdot min^{-1}$	65.8 ± 10.9	63.3 ± 8.8	0.085	71.6 ± 3.9	71.2 ± 4.2	0.735	0.223
$mL \cdot kg^{-0.67} \cdot min^{-1}$	279.8 ± 45.2	262.1 ± 36.1	0.129	300.6 ± 18.0	298.5 ± 20.2	0.642	0.335
$L \cdot min^{-1}$	4.82 ± 0.99	4.71 ± 0.83	0.294	5.54 ± 0.50	5.49 ± 0.53	0.539	0.697
HR_{peak}	183 ± 9	183 ± 9	1.000	190 ± 6	189 ± 7	0.188	0.435
RER_{peak}	1.06 ± 0.03	1.07 ± 0.04	0.917	1.05 ± 0.03	1.05 ± 0.04	0.129	0.956
%RUN-VO_{2max}							
%	78.7 ± 5.6	86.0 ± 2.4	0.019*	80.9 ± 7.8	80.9 ± 6.4	0.592	0.015#
C_{DP}							
$mL \cdot kg^{-1} \cdot m^{-1}$	0.207 ± 0.016	0.188 ± 0.015	0.047*	0.204 ± 0.039	0.208 ± 0.019	0.707	0.117
$mL \cdot kg^{-0.67} \cdot m^{-1}$	0.857 ± 0.095	0.778 ± 0.055	0.046*	0.855 ± 0.163	0.873 ± 0.084	0.722	0.116
MAS							
$m \cdot min^{-1}$	252.1 ± 52.5	293.6 ± 59.8	0.009**	297.5 ± 85.8	281.6 ± 57.5	0.298	0.007##

Values are mean ± standard deviation. Within (p), p-values of within group differences. Between (p), p-values of between group differences. 3-km TT, 3-kilometer time trial on roller skies. S, seconds. Kg, kilograms. DP-VO_{2peak}, peak oxygen uptake in double poling. RUN-VO_{2max}, maximal oxygen uptake in running. HR_{peak}, peak heart rate. RER_{peak}, peak value of respiratory exchange ratio. $L \cdot min^{-1}$, liters per minute. DP, double poling. C_{DP}, oxygen cost of double poling at 70% of DP-VO_{2peak}. $mL \cdot kg^{-67} \cdot min^{-1}$, milliliters per kg bodyweight raised to the power of 0.67 per minute. $mL \cdot kg^{-1} \cdot min^{-1}$, milliliters per kg bodyweight per minute. $mL \cdot kg^{-1} \cdot m$, milliliters per kg bodyweight per meter. MAS, maximal aerobic speed. $m \cdot min^{-1}$, meters per minute. $mL \cdot kg^{-0.67} \cdot m^{-1}$, milliliters per kg bodyweight per meter raised to the power of 0.67 per meter. %RUN-VO_{2max}, fractional utilization of RUN-VO_{2max} at DP-VO_{2peak}.
*$p < 0.05$, significantly different from preintervention value.
**$p < 0.01$, significantly different from preintervention value.
# $p < 0.05$, significantly different from Δ control value
$p < 0.01$, significantly different from Δ control value

TABLE 4. Correlations between physiological data and 3-km TT performance.

	r	*SEE* (%)	p-value
Age (yr)	0.43	18.8	0.130
BH (cm)	0.01	20.3	0.498
BW (kg)	– 0.20	20.7	0.972
DP-VO_{2peak}			
$mL \cdot kg^{-1} \cdot min^{-1}$	– 0.94	7.2	<0.001**
$mL \cdot kg^{-0.67} \cdot min^{-1}$	– 0.88	9.9	<0.001**
$L \cdot min^{-1}$	– 0.72	14.4	0.004**
RUN-VO_{2max}			
$mL \cdot kg^{-1} \cdot min^{-1}$	– 0.84	11.2	<0.001**
$mL \cdot kg^{-0.67} \cdot min^{-1}$	– 0.81	12.1	<0.001**
$L \cdot min^{-1}$	– 0.64	16.0	0.014*
%RUN-VO_{2max}	– 0.37	19.3	0.197
C_{DP}			
$mL \cdot kg^{-1} \cdot m^{-1}$	0.67	17.7	0.056
$mL \cdot kg^{-0.67} \cdot m^{-1}$	0.68	17.8	0.063
MAS			
$m \cdot min^{-1}$	– 0.83**	11.6	<0.001**

r, correlation coefficient. *SEE*, standard error of estimate in percentage. Yr, years. BH, body height. Cm, centimeters. BW, body weight. Kg, kilograms. DP-VO_{2peak}, peak oxygen uptake in double poling. RUN-VO_{2max}, maximal oxygen uptake in running. $L \cdot min^{-1}$, liters per minute. DP, double poling. C_{DP}, oxygen cost of double poling at 70% of VO_{2peak}. $mL \cdot kg^{-.67} \cdot min^{-1}$, milliliters per kg bodyweight raised to the power of 0.67 per minute. $mL \cdot kg^{-1} \cdot min^{-1}$, milliliters per kg bodyweight per minute. $mL \cdot kg^{-1} \cdot m$, milliliters per kg bodyweight per meter. MAS, maximal aerobic speed. $mL \cdot kg^{-0.67} \cdot m^{-1}$, milliliters per kg bodyweight per meter raised to the power of 0.67 per meter. %RUN-VO_{2max}, fractional utilization of VO_{2max} at VO_{2peak} in DP.

*$p < 0.05$ significant correlation

**$p < 0.01$ significant correlation