Effects of Individual Changes in Training Distribution on Maximal Aerobic Capacity in Well-Trained Cross-Country Skiers: A Follow-Up Study

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The purpose of this study was to evaluate individual changes in training distribution and the subsequent effects on maximal oxygen uptake ($VO_{2\text{max}}$). The participants were well-trained cross-country skiers who had performed a year with no substantial changes in training prior to this study. Six cross-country skiers, who were participants in a larger previous study, volunteered for a follow-up study. All skiers performed self-motivated changes in training distribution for a new preparation period in this follow-up, generally by more high-intensity training (HIT). All training characteristics were registered from training diaries. During the follow-up period, all skiers performed an incremental $VO_{2\text{max}}$ test in February 2020 and August 2020. Training were categorized into three different training periods; (1) February 2019 to February 2020 ($P_1$) representing the training performed prior to the follow-up, (2) February 2020 to July 2020 ($P_2$), and (3) July 2020 to August 2020 ($P_3$). On average, the skiers increased their $VO_{2\text{max}}$ by 5.8 ± 5.0% (range: −1.8 to +10.2%) during the follow-up study compared with the average $VO_{2\text{max}}$ during the preceding year. Total training volume increased on average by 10.0 and 25.7% in $P_2$ and $P_3$, respectively, compared with $P_1$. The average volume of HIT was similar between $P_1$ and $P_2$ but increased 62.8% in $P_3$. However, large individual differences in training changes were observed. In conclusion, the present study revealed that individual changes in training distribution generated an increased $VO_{2\text{max}}$ in four out of six already well-trained cross-country skiers. Reduced total training volume (three out of six) and increased (four out of six) HIT volume were the most marked changes.

Keywords: endurance, $VO_{2\text{max}}$, total training volume, cross country skiing, training characteristic

INTRODUCTION

Maximal oxygen uptake ($VO_{2\text{max}}$) is regarded as the most important single physiological factor for aerobic endurance performance in endurance sports, such as cross-country skiing (Ingjer, 1991; di Prampero, 2003; Sandbakk and Holmberg, 2017). Accordingly, strong relationships have been established between improved $VO_{2\text{max}}$ and improved performance level in cross-country skiers.
Cross-country skiers traditionally dedicate 80–90% of their endurance training at lower intensities (LIT), <82% of maximal heart rate (HR\textsubscript{max}) (Sandbakk and Holmberg, 2017). Therefore, less time has been spent in moderate- (MIT), 82–87% HR\textsubscript{max}, and high-intensity training (HIT), >87% HR\textsubscript{max}, throughout the preparation period (Lossnagel et al., 2013; Sandbakk et al., 2016; Johansen et al., 2020). HIT has been shown to be an efficient way to improve VO\textsubscript{2max} in both healthy moderately trained individuals (Helgerud et al., 2007; Støren et al., 2017) and highly trained endurance athletes (Storen et al., 2012; Sandbakk et al., 2013; Ronnestad et al., 2014, 2016). However, higher amount of HIT has been criticized for being too demanding and hamper physiological and performance adaptations in elite endurance athletes (Esteve-Lanao et al., 2007; Seiler, 2010; Slivka et al., 2010; Svendsen et al., 2016). In contrast, there have been few indications of a positive relationship between LIT and improved VO\textsubscript{2max}. However, LIT may serve as important to improve other performance-determining factors, i.e., technique-specific work economy (Haugnes et al., 2019).

Few studies have observed a significant improvement of aerobic capacity without considerable changes in training characteristics (i.e., training intensity distribution). A recent study by Johansen et al. (2020) revealed no improvements in aerobic capacity in well-trained national-level cross-country skiers within 6 months of season preparation (May to October). No to minor changes in training intensity distribution and time in different intensity zones were observed in that study. Additionally, few studies have followed well-trained cross-country skiers with initially no to minor improvements in aerobic capacity after a high LIT–low HIT program, to then change training characteristics considerably and study the subsequent physiological adaptations. To our knowledge, only Gaskill et al. (1999) did show positive adaptations of VO\textsubscript{2max} and performance in a group of cross-country skiers after a year with higher amounts of HIT and maintained training volume, after no response was observed after a year with a high LIT–low HIT program. This is in accordance with the positive adaptations in both VO\textsubscript{2max} and performance over shorter training periods in cyclists (Storen et al., 2012; Ronnestad et al., 2014) and cross-country skiers (Sandbakk et al., 2013; Ronnestad et al., 2016). However, there is still a need for more longitudinal investigations to better understand how to further develop VO\textsubscript{2max} of national-level cross-country skiers.

Thus, the main purpose of this study was to evaluate changes in training distribution and subsequent effects on VO\textsubscript{2max} among skiers who participated in the Johansen et al. (2020) study.

**METHODS**

**Study Design**

The present study was a follow-up study to the “no change-no gain” study (Johansen et al., 2020). In Johansen et al. (2020), none of the participants changed their training habits substantially. As a follow-up, six of the skiers volunteered to participate motivated by self-induced changes in training including more HIT. The main purpose of the present study was thus to evaluate these changes in training and the concurrent effects on VO\textsubscript{2max}. After the termination of tests in October 2019 in the Johansen et al. (2020) study, the participants returned to the laboratory for a VO\textsubscript{2max} test in February 2020 and halfway into a new preparation period in August 2020. All daily training was registered throughout the follow-up period.

**Subjects**

Six national level cross-country skiers (three males and three females) participated in the present follow-up study, after previous participation in Johansen et al. (2020). In the Johansen et al. (2020) study, all included skiers were defined as well-trained cross-country skiers with VO\textsubscript{2max} values ± 62 and ± 70 ml·kg\textsuperscript{-1}·min\textsuperscript{-1} for females and males, respectively, well above gender means (Åstrand et al., 2003). Also, the skiers were labeled as well-trained based on competition results and training history (Johansen et al., 2020). The participants in the present study volunteered to continue their training registration and test participation of VO\textsubscript{2max} after the termination of the study of Johansen et al. (2020). There were thus no separate inclusion criteria for participation in the present study. Subject characteristics for the six skiers are presented in Table 1. In accordance with the Declaration of Helsinki, all skiers gave their written informed consent to participate in the present study after receiving all necessary information about the study. The regional ethics committee of Southeast Norway (REC) evaluated and approved the follow-up study.

**VO\textsubscript{2max} Measurements**

The VO\textsubscript{2max} measurements were conducted on a Woodway PPS 55 sport treadmill (Waukesha, WI, United States), calibrated for speed and incline, while running. All VO\textsubscript{2} measurements were taken by the metabolic test system, Cortex MetaLyzer II (Biophysics GmbH, Leipzig, Germany), with measurements every 10 s. According to the manufacturer’s instructions, the gas analyzers were calibrated with ambient air and certified calibration gases (16% O\textsubscript{2} and 4% CO\textsubscript{2}) before each test. A 3-L calibration syringe (Biophysics GmbH, Leipzig, Germany) was used to calibrate the flow sensors. The heart rate (HR) of each participant was measured by Polar s610 HR monitors (Kempele, Finland) or by his or her own HR monitors.

The testing procedures of VO\textsubscript{2max} measurements were similar to the protocols used in Johansen et al. (2020) and described in detail in Sunde et al. (2019). In brief, all participants were instructed to do only light training 24 h before attending to the laboratory. Prior to the VO\textsubscript{2max} test, all participants were instructed to consume similar meals and drinks as prior to

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(Ingjer, 1991; Mahood et al., 2001; Sandbakk et al., 2013; Johansen et al., 2020, 2021). In addition, more successful skiers have displayed higher VO\textsubscript{2max} values compared with less successful skiers (Lossnagel et al., 2013; Tennessen et al., 2015; Sandbakk et al., 2016). Consequently, improvements of every individual skier’s VO\textsubscript{2max} should be highly prioritized to improve performance level.
To determine VO$_\text{2max}$ be important in order to compare VO$_\text{2max}$ with previous results on cross-country skiers, allometric scaling (Bergh and Forsberg, 1992). To compare the present results different anthropometries and to compare individuals across perceived exertion (Borg scale 6–20) ≥VO$_\text{2max}$ and 9–10 km starting intensity was set to an inclination of 6% and an 8–8.5 previous VO$_\text{2max}$ tests in Johansen et al. (2020). Warm-up procedures were self-selected and lasted for at least 10 min. The starting intensity was set to an inclination of 6% and an 8–8.5 and 9–10 km h$^{-1}$ for females and males, respectively. During the first minute of the test, inclination was increased by 1% every 30 s until 8% was reached. From that point, only speed was increased by 0.5 km h$^{-1}$ every 30 s until voluntary exhaustion. To determine VO$_\text{2max}$, the mean of the three highest consecutive VO$_2$ measurements were used. To objectively evaluate if a true VO$_\text{2max}$ was reached, a flattening of the VO$_2$ curve, HR ≥ 97% of HR$_\text{max}$, respiratory exchange ratio (RER) ≥1.05, and rate of perceived exertion (Borg scale 6–20) ≥17 was used as criteria. Allometric scaling has in previous studies been shown to be important in order to compare VO$_\text{2max}$ in athletes with different anthropometries and to compare individuals across sexes (Bergh and Forsberg, 1992). To compare the present results with previous results on cross-country skiers, allometric scaling with body weight raised to the power of 0.67 was used in addition to relative and absolute VO$_\text{2max}$ values.

**Training Registration**

All recruited skiers were instructed to train according to their own training programs and worked out by themselves and by their coaches throughout the whole study period. However, after the winter tests (February 2020), all participants voluntarily chose to change their training characteristics gradually until August 2020. Primarily, the skiers and their coaches planned these changes after their own wishes, while research personnel did only contribute to training discussions with the participants. Training performed from February 2019 to February 2020 ($P_1$) represented the training performed during the study of Johansen et al. (2020). The next 6 months from February to August 2020 were divided into two periods; training from February to July ($P_2$) and training from July to August ($P_3$). Training registration was performed similar to the procedures described in detail in Johansen et al. (2020). Briefly, the same research personnel registered and controlled every training session by use of training diaries throughout the whole study period. All endurance training were registered based on HR measurements and categorized into three separate HR intensity zones as “time in zone.” These three intensity zones were low-intensity training (LIT, <82% HR$_\text{max}$), moderate-intensity training (MIT, 82–87% HR$_\text{max}$), and high-intensity training (HIT, >87% HR$_\text{max}$). The set HR zones used in the training registration were chosen to be below (LIT), around (MIT), and above LT (HIT) and corresponds to the intensity zones provided by the Norwegian Olympic Federation (Tønnessen et al., 2015). This training intensity categorization into three different zones has previously been used in several studies investigating training effects on VO$_\text{2max}$ (Losnegard et al., 2013; Tønnessen et al., 2015; Sandbakk et al., 2016; Storen et al., 2017; Johansen et al., 2020, 2021). The HIT zone is also representative for the zone shown to be an effective training intensity to provoke VO$_\text{2max}$ changes in already fit individuals (Helgerud et al., 2007; Storen et al., 2012; Bratland-Sanda et al., 2020).

The participants were asked to report if anything, included nutritional aspects, deviated from normal living during the study period. However, blood variables, such as iron or vitamin status, were not measured during the same period.

**Statistical Analyses**

The data from the present study was presented and interpreted both as individual results from each participant and as mean ± standard deviation (SD) with coefficient of variance (CV) in parenthesis from the test in February 2020. TP, testperson; BW, body weight; ΔBW, change in body weight from summer 2019 to summer 2020; kg, kilogram; Cm, centimeters.

| TP | Gender | Age (years) | BW (kg)  | ΔBW  | Height (cm) |
|----|--------|-------------|----------|-------|-------------|
| 1  | Female | 32          | 76.5     | +1.2  | 175         |
| 2  | Female | 24          | 61.4     | +4.3  | 175         |
| 3  | Male   | 17          | 72.2     | +3.4  | 182         |
| 4  | Female | 26          | 69.1     | +1.0  | 174         |
| 5  | Male   | 31          | 75.9     | +0.3  | 183         |
| 6  | Male   | 25          | 71.1     | −3.4  | 175         |

Mean ± SD (CV) – 25.8 ± 5.4 (21.0) 71.0 ± 5.5 (7.7) 1.1 ± 2.7 (238.2) 177.3 ± 4.0 (2.3)

**RESULTS**

A total of 4,293 training sessions were registered and analyzed from February 2019 to August 2020 for all skiers combined, with an interindividual range of 6–12 training sessions per week$^{-1}$ on average. None of the participants reported any long training
breaks due to injuries or sickness during the study period. In addition, no periods of altitude training were reported. No deviations from their normal diets were reported, and body weight did not change significantly during the study period for any participants during the whole follow-up period (Table 1). Training characteristics for total training volume and HIT volume for the three training periods are presented in Table 2.

In general, training characteristics in P1 were representative for the training performed in Johansen et al. (2020) for all skiers. On a group level, no statistically significant differences were detected in either total training volume or HIT volume between the different training periods. This was found despite an average increase of 25.7 and 14.2% in total training volume, and a 62.8 and 84.1% increase in HIT volume in P3 compared with P1 and P2, respectively. The lack of significant changes in training distribution on a group level was due to large individual differences in training changes.

Mean VO₂max decreased slightly (−2.8%) but not significantly from August 2019 to February 2020. A significant increase in VO₂max (ml·kg⁻¹·min⁻¹) was observed from the mean 2019/2020 value to August 2020 (Table 3, p < 0.05).

Four out of six skiers increased HIT volume (+59.5–281.5%), one skier maintained HIT volume, and one skier slightly reduced HIT volume in P3. Changes from P1 to P2 were largely characterized by maintenance or reductions in HIT for all skiers. Four out of six skiers increased total training volume, while two reduced total training volume (Table 2) during the follow-up period (P2 + P3). VO₂max improved in four out of six skiers (7.9–10.2%), while one maintained and one decreased VO₂max (Table 3; Figure 1). Due to the individual responses in VO₂max after the performed changes in training distribution by the participants, no significant correlations were observed between delta VO₂max and delta total training volume or HIT volume.

**DISCUSSION**

The main findings of the present study were the individual changes in training intensity distribution and VO₂max. The six skiers had previously showed no effect on VO₂max after maintaining high-volume LIT and low-volume HIT. Four of these skiers, as well as the mean of all skiers, improved VO₂max after individual changes in training intensity distribution. The most markedly change in training was an increase in HIT volume by four of the six skiers. Three of the six skiers lowered their total training volume. The largest improvements in VO₂max were among those lowering the total training volume and/or increasing the amount of HIT. However, one skier also improved VO₂max after increased total training volume. The skiers who increased total training volume and the amount of HIT concurrently improved VO₂max the least.

Four of the skiers measured their highest VO₂max-value after the follow-up period. This improvement was observed after an average increase of 60–85% in HIT volume the last month prior to the last VO₂max-test (August 2020) compared with the preceding 17 months. The increase in HIT was accompanied by a decrease in total training volume, mainly LIT, in three of the four skiers.
TABLE 3 | Development of VO$_{2max}$ (ml·kg$^{-1}$·min$^{-1}$).

| TP  | August 2019 | October 2019 | February 2020 | Mean 2019/2020 | August 2020 | ΔVO$_{2max}$ (%) |
|-----|-------------|--------------|---------------|----------------|-------------|------------------|
| 1   | 64.1        | 62.3         | 61.3          | 62.6           | 68.3        | +9.1             |
| 2   | 59.5        | –            | 57.8          | 58.7           | 59.3        | +1.0             |
| 3   | 70.8        | 71.2         | 69.0          | 70.3           | 77.5        | +10.2            |
| 4   | 63.2        | 61.1         | 63.6          | 62.6           | 61.5        | −1.8             |
| 5   | 68.9        | 69.5         | 63.6          | 67.3           | 72.2        | +7.3             |
| 6   | 72.4        | 71.4         | 72.2          | 72.0           | 78.5        | +9.0             |

Mean ± SD (CV) 66.5 ± 5.0 (7.5) 67.1 ± 5.0 (7.5) 64.6 ± 5.2 (8.0) 65.6 ± 5.1 (7.8) 69.6 ± 8.0 (11.5) 5.8 ± 5.0 (6.1)

Values are mean, and mean ± standard deviation (SD) with coefficient of variance (CV) in percentage in parenthesis. TP, test person; VO$_{2max}$, maximal oxygen uptake; ml·kg$^{-1}$·min$^{-1}$, milliliters oxygen per kilogram bodyweight per minute; ΔVO$_{2max}$, delta percentage change in VO$_{2max}$ from mean 2019/2020 to August 2020.

* $p < 0.05$ significantly different from mean VO$_{2max}$ 2019/2020 and February 2020.

The results from skiers 1, 3, and 5 are in agreement to the case study of Støren et al. (2012), where a national-level cyclist displayed considerable enhancements in VO$_{2max}$ and cycling performance after lower total training volumes and higher volumes of HIT. In addition, a similar training program generated positive adaptations in VO$_{2max}$ and performance among American cross-country skiers (Gaskill et al., 1999). These studies thus suggest that athletes may benefit from lowering their total training volume and/or increase HIT volume for a certain period to develop their aerobic capacity. In addition, a lower total training volume may generate sufficient restitution and physiological and mental surplus between HIT sessions. Accordingly, Sandbakk and Holmberg (2017) has proposed that the quality of each HIT session may be as important as the amount of HIT in already well-trained cross-country skiers. However, in the present study, skier 6 actually increased VO$_{2max}$ after an increase in total training volume, but not HIT. This underlines the large individual responses to the individual changes in training.

Several previous studies have reported increased HIT volume to hamper further development in both endurance performance and VO$_{2max}$ (Slivka et al., 2010; Svendsen et al., 2016) and induce higher risk of overtraining syndrome (Seiler, 2010). However, in those same studies, both HIT and total training volume (higher volumes of LIT, MIT, and HIT) are increased considerably (Slivka et al., 2010; Svendsen et al., 2016). This leads to a large increase in total training load not only generated by the increased HIT volume. Accordingly, the skiers in the present study that showed no improvement in VO$_{2max}$ (skiers 2 and 4) did increase both total training volume and HIT volume considerably. Thus, we may speculate that the increased training volume combined with the increased HIT volume may have led to some sort of over-reaching in these skiers, as previously indicated in Bratland-Sanda et al. (2020). In contrast, the four responding skiers did not increase both factors at the same time. We therefore speculate that increments in HIT volume should be performed at least without increased, or preferably reduced, total training volume to generate beneficial adaptations in VO$_{2max}$ in already well-trained cross-country skiers.

Skier 6 differed considerably compared with the other skiers in the present study, with the highest amount of total training and lowest amount of HIT. He actually lowered his HIT volume in P2 and P3 compared with P1, while he displayed a 9.0% improvement in VO$_{2max}$ after the follow-up period. This result is in contrast to previous findings of more HIT generating beneficial adaptations for overall aerobic capacity.
FIGURE 1 | Development of VO2max from August 2019 to August 2020. VO2max, maximal oxygen uptake; ml·kg⁻¹·min⁻¹, milliliters per kilogram bodyweight per minute; L·min⁻¹, liters per minute; ml·kg⁻⁰.₆⁷·min⁻¹, milliliters per kilogram bodyweight raised to the power of 0.67 per minute.

However, it is worth mentioning that this male skier reported 10–15 min more HIT per week and the highest monthly amount if HIT throughout all training periods approximately 3 months before the last VO2max test. This period was combined with a ~30% reduction in total training volume compared with the mean in both P2 and P3, and one of the lowest monthly training volumes recorded in the whole 18 months study period. One might speculate that this intensive training period with reduced total training volume and increased HIT volume could have generated a beneficial effect for VO2max in this skier, and that this has been maintained until the last VO2max test. Such intensive short-duration training periods have previously proved effective for improvement of VO2max in well-trained endurance athletes (Laursen et al., 2005; Rønnestad et al., 2014, 2016).

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**Practical Implications, Strengths, and Limitations**

The large individual differences in total training volume and HIT volume leading to comparable responses in VO2max observed in the present study, highlights the need for highly individualized training protocols to provoke further adaptations in already well-trained endurance athletes. In addition, well-trained cross-country skiers experiencing no further improvements in aerobic capacity over longer periods may benefit from changes in training distribution large enough to generate physiological responses. These training changes could include increased HIT volume and/or reduced total training volume over a certain time period, but other changes could of course also prove beneficial. In the present skiers, the most common beneficial change in terms of improvements in VO2max was an increased or maintained amount of HIT combined with a reduced amount of total training during the follow-up period. This change was apparent in three out of four skiers that also improved their VO2max during the study period. However, as observed in the present skiers, well-trained skiers should be careful with training changes leading to concurrent increments in total training volume and HIT volume. Thus, the present results should be of great interest for already well-trained, but stagnated cross-country skiers and their coaches aiming for higher VO2max.

One limitation of the present study was that we were unable to measure the direct impact of the increased VO2max and changes in training distribution on cross-country skiing performance the following competitive season, due to the COVID-19 pandemic. It would have been interesting to also investigate the effect of such training changes on other relevant performance-determining factors (e.g., work economy).

The sample size in the present study is too small for generalization purposes. However, the study is one of very few investigations observing individual changes in training in already well-trained endurance athletes, and the subsequent responses on VO2max. A strength of the present study is thus that it evaluates what high-level athletes actually choose to do. The main purpose of this study was to evaluate and observe the effects of self-motivated changes in training distribution. Although the training
and changes in training in itself could be difficult to replicate, we argue that the principle of observing skiers doing self-induced changes in training and test, i.e., aerobic capacity may be easy to replicate. However, the results may not be directly replicated due to the freely chosen change in training distribution and individual response to the performed change.

Thus, the scope of future investigations should be the effect of similar training changes on other relevant performance determining variables (e.g., work economy), combined with the effects on performance and VO$_{2\max}$. In addition, larger cohorts of well-trained to elite endurance athletes should be emphasized in future investigations.

**CONCLUSION**

The present follow-up study revealed that individual changes in training distribution generated an increased VO$_{2\max}$ in four out of six already well-trained cross-country skiers. Reduced total training volume in three out of six skiers and increased HIT volume in four out of six skiers were the most marked changes. However, training changes leading to an increased total training volume combined with an increased HIT volume seemed less beneficial, in two out of six already well-trained cross-country skiers.

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**DATA AVAILABILITY STATEMENT**

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

**ETHICS STATEMENT**

The studies involving human participants were reviewed and approved by the Regional Ethics Committee of Southeast Norway. Written informed consent to participate in this study was provided by the participants’ legal guardian/next of kin.

**AUTHOR CONTRIBUTIONS**

J-MJ, ØS, and JH participated significantly in the planning and design of this study. J-MJ, ØS, AS, and LG participated in data collection. J-MJ, ØS, JH, AS, and LG participated in the writing of the manuscript. All authors read and approved the manuscript.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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