JOMH
Journal of Men's Health

J. Mens. Health **2022**; 18(9): 187
https://doi.org/10.31083/j.jomh1809187

Original Research

Effects of LHTH Training at 1600 m on Exercise Performance, Complete Blood Count and Erythropoietin: A Case Study of South Korean Elite Male Cross-Country Skiers

Jun Chao Wang[1], Ki Tae Yim[2,*], Yong Chul Choi[3,*]

[1]Department of Physical Education, XinXiang University, 453003 Xinxiang, Henan, China
[2]College of Creative Future Talent, Daejin University, 1007 Hoguk-ro, 11159 Pocheon, Republic of Korea
[3]Laboratory of Exercise Physiology, Department of Physical Education, College of Arts & Physical Education, Gangneung-Wonju National University, 25457 Gangneung-si, Republic of Korea
*Correspondence: yimkt@daejin.ac.kr (Ki Tae Yim); skicyc@gwnu.ac.kr (Yong Chul Choi)

Submitted: 29 April 2022 Revised: 14 June 2022 Accepted: 28 June 2022 Published: 6 September 2022

Abstract

Background: In altitude training for elite athletes, altitudes below 1700 m are generally known to have low physiological stimulation and training effects. Therefore, the purpose of this study is to investigate the effect of live high train high (LHTH) altitude training at an altitude of 1600 m on athletic performance, complete blood count (CBC), and erythropoietin (EPO) in cross-country skiers. **Methods**: In this study, South Korean Six male cross-country skiers participated. Exercise performance, CBC, and EPO were measured 3 days before altitude training and 4 days after the end of altitude training. The training program in this study was the LHTH altitude training method, and the polarized (POL) training program was applied. For exercise performance analysis the Bruce protocol was applied using a treadmill and gas analyzer. Blood variables CBC (red blood cell; RBC, white blood cell; WBC, hemoglobin; Hb, hematocrit; Hct, platelets) and EPO were measured at rest and immediately after exercise. **Results**: The effect of 3 weeks of LHTH altitude training on male cross-country skiers was as follows. There were no differences in body weight, muscle mass, body fat mass, or body fat percentage ($p > 0.05$). Although maximal oxygen uptake (VO_2max) increased ($p < 0.05$), there was no significant difference in exercise time and maximum heart rate (HRmax) ($p > 0.05$). The heart rate measured at 2 minutes after the end of exercise decreased rapidly ($p < 0.05$). At rest, RBC, Hb, and Hct were increased ($p < 0.001$), but there was no significant difference between WBC and platelets ($p > 0.05$). Immediately after exercise, there was no significant difference in RBC and Hb ($p > 0.05$), but WBC ($p < 0.001$), platelets ($p < 0.01$), and Hct ($p < 0.05$) were significantly decreased. EPO was significantly decreased after training compared to before altitude training at rest and immediately after exercise ($p < 0.001$). **Conclusions**: The results of this study suggested that 3 weeks of LHTH training at an altitude of 1600 m could stimulate RBC, Hb, and Hct. Also, improved VO_2max and recovery capacity along with increases in RBC and Hb mean that LHTH training at an altitude of 1600 m could induce a positive effect on physiological and performance changes in male cross-country skiers. We did not have a control group, and we do admit some limitations, including height adjustment, length of altitude training, and training program (intensity and volume). Nevertheless, LHTH training at an altitude of 1600 m can be a desirable intervention program when planning short-term altitude training for technical and physiological improvement in male cross-country skiers. In addition, it is suggested that exercise and living at high altitude stimulate blood variables and cardiopulmonary function, which will have a positive effect on exercise performance and health promotion not only for athletes but also for men in general.

Keywords: altitude training; LHTH; exercise performance; complete blood count; erythropoietin

1. Introduction

Cross-country skiing is the most complex endurance sport, as it competes with both upper and lower body equipment in a cold environment, relatively high altitude, and hilly terrain [1,2]. World-class cross-country skiers who secured the second position at the Winter Olympics and Nordic World Championships are reported to be superior to national-level athletes in terms of maximum oxygen uptake (VO_2max), VO_2 plateau time, anaerobic power, and upper-body power [3–6]. In particular, aerobic capacity, such as VO_2max and VO_2 plateau time, are physiological factors that should be developed first in the performance of cross-country skiers. As the main training methods for improving aerobic capacity, endurance training, interval training, and lactate tolerance training, along with high-altitude training, are also being used [7–9]. Altitude training refers to training or living at an altitude of ≥1500 m. The purpose of altitude training for endurance athletes, such as cross-country skiing and marathon athletes, is to induce a physiological response in the human body to adapt to an altitude hypoxic environment, thereby inducing blood variables (red blood cell volume [RBC], hemoglobin mass [Hb]) that affects oxygen transport. This is because, through the improvement of Hb and erythropoietin (EPO), aerobic exercise performance, such as the increase in VO_2max, exercise efficiency, and lactate tolerance, can be improved [10–12]. In addition, as the frequency of Winter Olympics held at altitudes of 1000 m or higher has increased over the past 20–30 years, altitude training is essential [8]. Altitude training is divided into three types, according to the method of stay and training. Live High-Train Low (LHTL) is the traditional method of living at high altitudes and training at low altitudes. Live Low-Train High (LLTH) is to live at low altitudes and train at high altitudes, and the Live High-Train High (LHTH) method is a combination of living and training at high altitudes [13–19].

Cross-country skiers use the LHTH method for three reasons: First, to prepare for important events such as the Winter Olympics and World Championships held at high altitudes, high-altitude adaptation training is essential. Second, by maximizing the physiological benefits of exposure to hypoxia at high altitudes, competitiveness in competitions held at sea level can be expected. Third, cross-country skiers need to increase their annual ski training time in the snow; however, due to the influence of the weather, the seasons and places where ski training can be conducted are limited. Low temperatures at altitudes have the advantage of enabling ski training in the snow earlier than in winter, thereby increasing the training rate for technical skills and physiological specificity [6,20,21].

In LHTH training, it is very important to set an appropriate altitude and period because the higher the altitude, the greater the negative physiological burden, whereas the lower the altitude, the lesser physiological stimulation. In general, 3–4 weeks are recommended for a settingsetitudeaining period. This is because changes in blood variables start 2 weeks after starting altitude training, increase significantly between 3 and 4 weeks, and then reach a plateau after 4 weeks [22–25]. Although the optimal altitude for altitude training is 1500–3000 m, training at an altitude of 2000–3000 m is the most effective because physiological stimulation is insufficient at an altitude of less than 1700 m [26–28]. When perfor ming altitude training, the higher the altitude, the higher the rate of muscle injury caused by the cold. In addition, negative effects such as upper respiratory infection, immune suppression, sleep disturbance, and weight loss due to maladaptation to high altitude which can reduce exercise ability should not be overlooked [11,29,30]. In particular, cross-country skiers perform altitude training mainly in autumn and winter and are exposed to cold environments [6,31]. Altitude training for cross-country skiers can improve ski training and physiology, but it is necessary to consider the relatively low altitude that can prevent the negative effect of cold.

Therefore, the purpose of this study is to investigate the effect of live high train high (LHTH) altitude training at an altitude of 1600 m on athletic performance, complete blood count (CBC), and erythropoietin (EPO) in cross-country skiers.

2. Materials and Methods

Six male cross country ski (XC) skiers over the age of 20 (21 ± 1.67) from South Korea participated in this study. The six players included two national team players and four reserve national players. The training location was S Resort in Canada. The physical characteristics of the participants are presented in Table 1.

2.1 Design and Procedures

To analyze the effect of short-term altitude training on exercise performance, CBC, and erythropoietin, measurements were taken 3 days before altitude training and 4 days after the end of altitude training. This study was conducted for three weeks using the LHTH altitude training method. The base (village) elevation was 1609 m, and the ski training was performed at an elevation of approximately 1609–1915 m.

The altitude training program was planned by mixing the POL training program by Kim with Choi (2020) and the ski training program at the altitude by Choi (2018) [32,33]. The altitude training applied a polarized (POL) training program most commonly used by world-class cross-country skiers. The POL training program is a training method that combines high-intensity interval training (approx. 12–15%) and a lot of exercise at low intensity (approx. 70–80% of the total amount of exercise). In addition, maintaining the same training intensity at sea level as training intensity can cause overtraining and immune suppression in athletes, so the amount of high-intensity training was reduced and applied at sea level [9,32,34–37]. The total amount of exercise performed in this study was as follows: low-intensity training (LIT), 75.19%; medium-intensity training (MIT), 2.32%; high-intensity training (HIT), 6.2%; strength training, 11.62%; and running, 4.65% (Table 2).

2.2 Exercise Performance Test

Exercise performance was measured 3 days before the altitude field training and 4 days after the end of training in consideration of the travel time from the altitude camp to the laboratory. The Bruce protocol was applied for the exercise load test using a treadmill and gas analyzer (COMED Quark CPET, Italy). After starting at 1.7 mph at 10% of the initial incline, every 3 min, the incline was increased to 2%, and the speed was increased from 0.8 to 0.9 mph so that the treadmill speed could not be maintained, and the maximum heart rate was more than 90% of the target heart rate (THR). The respiratory exchange rate was 1.15 or more, the movement awareness was $\geq$17, and it was set as the all-out time [23,38–40]. Recovery ability was measured after sitting and resting for 2 min from the end of the submaximal exercise, and heart rate was measured [32,35,41–43].

2.3 Blood Collection and Analysis

The test subjects fasted for more than 10 h from the measurement time, and blood was collected. After the subject arrived at the test site and rested for at least 30 min, the nurse collected 3 mL of blood at rest and immediately after exercise, appropriate for the purpose and procedure of the

Table 1. Physical characteristics of participants (Mean Values ± SD).

	Age (yr)	High (cm)	Body mass (kg)	Muscle mass (kg)	Body fat mass (kg)	Body fat percentage (%)
n = 6	21 ± 1.67	173.33 ± 9.17	66.30 ± 3.50	34.21 ± 3.50	6.48 ± 2.08	9.73 ± 2.79

Table 2. Training program.

Day		AM training	PM training
Mon	Event	Ski training (skate)	Ski training (classic)
	Time	100 min	40–40–30 min (5 min (ex)/3 min (re) × 5 set)
	Intensity	LIT	LIT-HIT-LIT
Tue	Event	Ski training (classic)	Ski training (skate) + Weight training
	Time	120 min	Ski 60 min (LIT) + W/T 60 min
	Intensity	LIT	80% (1 RM) × 8rd × 3 set recovery time 90 sec
Wed	Event	Ski training (skate)	REST
	Time	150 min	
	Intensity	LIT	
Thu	Event	Ski training (classic)	Ski training (skate)
	Time	100 min	30–30–30 min
	Intensity	LIT	LIT-MIT-LIT
Fri	Event	Ski training (skate)	Weight Training + Core Training
	Time	40–40–30 minute (5 min (ex)/3 min (re) × 5 set)	90 min
	Intensity	LIT-HIT-LIT	80% (1 RM) × 8rd × 3 set recovery time 90 sec
Sat	Event	Ski training (classic+skate)	REST
	Time	180 min	
	Intensity	LIT	
Sun	Event	Rest	RUN
	Time		60 min
	Intensity		LIT

Intensity	Low intensity	Middle intensity	High intensity	Weight training	Other sports	Total
%HRmax	60–82%	82–87%	88–100%			
Exercise Time (minute)	970 min	30 min	80 min	150 min	60 min	1290 min
Training as a % Total volume	75.19%	2.32%	6.2%	11.62%	4.65%	100%
Section (1 week)	7	1	2	2	1	11
Weight event	65% (1 RM) × 15 rd × 3 set, Recovery time 90 sec Bench press (put legs on the bench, not on the floor) & Pull-down Triceps Pull Downs, DeadliftRowing/arm-pull while sitting & Arm-press with dumbbells using incline bench, Legs: Squats & hamstring curl, single-leg squat, side squat					
Core training	Exercise 5 set, Recovery 30 sec Supine plank, prone plank, side plank, side plank-leg motions statically, spine in a neutral position, Swiss ball training (inclined press-ups, the top position, the single-leg holds, quadruped motions)					

analysis. The collected blood was centrifuged (FLETAS, Korea) at 5000 rpm for 10 min and then analyzed.

CBC (RBC, WBC, Hb, Hct, platelet) and erythropoietin were diagnosed using flow cytometry, serum samples, and refrigerated storage. Reagents were analyzed with SYSMEX-XE2100D (SYSMEX, JAPAN) using the cell pack, cell sheath, stromatolyser-FB, and Sulforlyser kit [33].

2.4 Statistical Analyses

We used SPSS software (v.25.0; IBM SPSS, New York, USA) to calculate the mean value and standard deviation (SD) for all data. The verification of exercise performance, CBC, and erythropoietin before and after altitude training in the same group was analyzed using the paired *t*-test. Statistical significance was set at $p < 0.05$.

Table 3. Change in body composition (Mean Values ± SD).

Variable	Pre test	Post test	p
Body mass (kg)	66.30 ± 3.50	65.86 ± 7.06	0.380
Body muscle mass (kg)	34.21 ± 3.50	34.11 ± 3.72	0.604
Body fat mass (kg)	6.48 ± 2.08	6.41 ± 2.10	0.530
Body fat percentage (%)	9.73 ± 2.79	9.71 ± 2.70	0.920

SD, standard deviation.

3. Results

3.1 Changes in Body Composition

Table 3 shows the changes in body composition when living at 1600 m and training atana altitude for 3 weeks. There was no significant difference in body mass before (66.30 ± 3.50 kg) and after altitude training (65.86 ± 7.06 kg) ($p > 0.05$). There was no significant difference in body muscle mass before (34.21 ± 3.50 kg) and after (34.11 ± 3.72 kg) altitude training ($p > 0.05$). There was no significant difference in body fat mass before (6.48 ± 2.08 kg) and after high-altitude training (6.41 ± 2.10 kg) ($p > 0.05$). There was no significant difference in body fat percentage before (9.73 ± 2.79%) and after (9.71 ± 2.70%) high-level training ($p > 0.05$).

3.2 Changes in Exercise Performance

Table 4 shows the changes in exercise performance when living at 1600 m and training at altitude for a week. VO_2max showed a statistically significant difference before (77.41 ± 4.95 mL·kg^{-1} min^{-1}) and after (78.33 ± 4.36 mL·kg^{-1} min^{-1}) altitude training ($p < 0.05$). There was no significant difference in exercise time before (1135.16 ± 50.79 sec) and after (1137.16 ± 48.47 sec) altitude training ($p > 0.05$). In addition, there was no significant difference in HRmax before (198.00 ± 16.09 bpm) and after (198.50 ± 14.52 bpm) altitude training ($p > 0.05$). The heart rate recovery time immediately after exercise was significantly lower after altitude training (117.83 ± 13.05 bpm) as compared to before altitude training (136.16 ± 11.25 bpm) ($p < 0.05$).

3.3 Changes in CBC and EPO

Table 5 shows the changes in CBC and EPO when living at 1600 m and training at an altitude for a week.

RBC at rest was significantly increased afte (4.94 ± 0.32 g/dL) altitude training than before (4.94 ± 0.32 g/dL) altitude trainin ($p < 0.001$), and immediately after exercise, there was no significant difference between before (15.11 ± 0.71 g/dL) training and after (5.25 ± 0.34 g/dL) training ($p > 0.05$).

At rest, Hb was significantly increased after (15.73 ± 0.37 g/dL) altitude training than before (15.11 ± 0.71 g/dL) altitude training ($p < 0.001$), and there was no significant difference after exercise before (16.11 ± 0.77 g/dL) and after (16.18 ± 0.57 g/dL) altitude training ($p > 0.05$).

At rest, Hct was significantly increased after (47.43 ± 0.94 g/dL) altitude training than before (45.70 ± 1.73 g/dL) altitude training ($p < 0.001$), and immediately after exercise, it was significantly decreased after (49.66 ± 1.30 g/dL) altitude training than before (51.18 ± 2.32 g/dL) altitude training ($p < 0.05$). At rest, there was no significant difference in WBC before (4.93 ± 0.36 g/dL) and after (5.05 ± 0.71 g/dL) altitude training ($p > 0.05$), but immediately after exercise, it was significantly decreased after (7.16 ± 1.01 g/dL) altitude training than before (9.17 ± 0.74 g/dL) altitude training ($p < 0.001$). There was no significant difference in platelets at rest before (264.00 ± 24.29 g/dL) and after (258.00 ± 27.59 g/dL) altitude training ($p > 0.05$), but immediately after exercise, it was significantly decreased after altitude (279.33 ± 10.48 g/dL) training than before (304.83 ± 28.31 g/dL) altitude training ($p < 0.01$). EPO at rest was significantly decreased after (10.32 ± 10.78 mIU/mL) altitude training than before (12.82 ± 10.80 mIU/mL) altitude training ($p < 0.001$), and even immediately after exercise was significantly decreased after (10.70 ± 11.41 mIU/mL) altitude training than before (14.21 ± 10.48 mIU/mL) altitude training ($p < 0.001$).

4. Discussion

4.1 Exercise Performance

Body composition and cardiorespiratory function affect the health and exercise performance of adult men, including endurance athletes. It is desirable to maintain a low body fat percentage and a large amount of muscle mass [44,45]. In general, the VO_2max is used as an index to evaluate the cardiorespiratory function, and has been widely used for a long time as a standard to evaluate aerobic capacity or cardiorespiratory endurance [46]. Body composition and VO_2max are closely correlated with the training method, training intensity, and training volume. Methods to improve VO_2max include altitude training, a lot of low-intensity exercises, and high-intensity exercise [47,48]. Continuous high-intensity training, too much training volume, and too high a training altitude can have a negative effect on athletes, leading to loss of muscle mass and weight [11,49]. On the other hand, low-intensity exercise and volume can lead to a decline in cardiorespiratory function in male athletes. Cardiopulmonary function decline primarily reduces energy consumption, and surplus energy is accumulated as triglycerides in muscle and adipose tissue, increasing body fat in subcutaneous and visceral fat. Among them, it is known that the accumulation of triglycerides in skeletal muscle acts as a direct cause of the decrease in insulin function in skeletal muscle [50]. In our study, there was little change in body composition of male cross-country skiers, and the improvement in VO_2max can be judged to be appropriate for training altitude, training volume, and training intensity. Therefore, it is suggested that training and living at an altitude of 1600 m can have a positive effect on the improvement of men's health including cardiorespiratory function.

Table 4. Change in exercise performance (Mean Values ± SD).

Variable	Pre test	Post test	p
VO_2max (mL kg^{-1} min^{-1})	77.41 ± 4.95	78.33 ± 4.36	0.021*
Exercise time (second)	1135.16 ± 50.79	1137.16 ± 48.47	0.749
HRmax (heart rate maximum) (beats/min)	198.00 ± 16.09	198.50 ± 14.52	0.580
RHR (Rest heart rate) (beats/min)	136.16 ± 11.25	117.83 ± 13.05	0.011*

SD, standard deviation. *$p < 0.05$ pre test *vs.* post test. RHR; 2 minutes after the end of the exercise.

Table 5. Change in CBC and erythropoietin. (Mean Values ± SD).

Variable		Pre test	Post test	p
RBC (g/dL)	Rest	4.94 ± 0.32	5.14 ± 0.26	0.001***
	After exercise	5.27 ± 0.39	5.25 ± 0.34	0.881
Hb (g/dL)	Rest	15.11 ± 0.71	15.73 ± 0.37	0.001***
	After exercise	16.11 ± 0.77	16.18 ± 0.57	0.713
Hct (g/dL)	Rest	45.70 ± 1.73	47.43 ± 0.94	0.001***
	After exercise	51.18 ± 2.32	49.66 ± 1.30	0.021*
WBC (g/dL)	Rest	4.93 ± 0.36	5.05 ± 0.71	0.634
	After exercise	9.17 ± 0.74	7.16 ± 1.01	0.001***
Platelet (g/dL)	Rest	264.00 ± 24.29	258.00 ± 27.59	0.365
	After exercise	304.83 ± 28.31	279.33 ± 10.48	0.009**
EPO (mIU/mL)	Rest	12.82 ± 10.80	10.32 ± 10.78	0.001***
	After exercise	14.21 ± 10.48	10.70 ± 11.41	0.001***

SD, standard deviation.

*$p < 0.05$ pre test *vs.* post test, **$p < 0.01$ pre test *vs.* post test, ***$p < 0.001$ pre test *vs.* post test.

In the treadmill test, maximum exercise time was used to measure the speed and performance of athletes. It is also a good method for monitoring physiological factors such as VO_2max, anaerobic threshold, maximum heart rate, average heart rate, blood lactate concentration, and recovery ability [39,51]. Endurance athletes, such as those who participate in marathons and cross-country skiing events, will be able to win competitions if they can run faster than their competitors, even if physiological factors such as VO_2max, HRmax, average heart rate, and blood lactate concentration are not superior to their competitors. Most studies have reported that altitude training increases blood variables, such as RBC and Hb, and that an increase in VO_2max leads to improved performance at sea level; however, in the case of well-trained elite athletes, many studies have reported that there is no significant change [20,28,52,53]. Although VO_2max, RBC, and Hb also increased in our study, the difference in training specificity was considered as the reason for no change in the maximum exercise time on a treadmill [54,55]. During the general training period before altitude training, a lot of running, roller-skiing, and strength training is performed; however, in altitude training, mostly skiing and skill training are performed. Therefore, it was confirmed that the treadmill exercise time did not increase because the movements of the muscles and joints that are mainly used are different.

It has been reported that HRmax and resting heart rate are highly correlated with age, sex, and physical fitness level. During exercise, VO_2max and HRmax form a proportional relationship. The slope of this straight line changes with your level of physical training or fitness. A person with good physical strength can carry the same amount of oxygen at a lower heart rate than a person with low physical strength [41–43,47]. Athletes with superior cardiorespiratory function show higher maximum oxygen intake and lower heart rate at the same load intensity [56–59]. Due to the negative effect of altitude, exercise ability may decrease when returning to low ground, and VO_2max may increase at the same intensity. This is because, as the altitude increases, the oxygen intake and the HRmax decrease are common physiological phenomena, and side effects such as an increase in blood viscosity, decrease in protein synthesis ability and increase in oxidative stress occur [60,61]. In this study, changes in VO_2max, exercise time, and HRmax measured at the same load intensity before and after altitude training was hardly observed. Therefore, there were no negative factors for the deterioration of athletic ability or physical condition due to altitude training.

Cross-country skiers utilize primarily aerobic energy metabolism on flat terrain. However, as the slope increases, the athlete's heart rate rises to its maximum level, which requires strong anaerobic power. To win the race, it is very important to quickly recover the increased heart rate and lactic acid on the uphill slope and the flat ground [28,62,63]. Also, quick physiological recovery is important in team sprint competitions in which two skiers run the sprint course three times in relay format [9,41]. In general, a common method for assessing the recovery capacity of cross-country skiers is heart rate monitoring. It is evaluated as the rate at which the heart rate decreases from the maximum heart rate level [64]. The results of our study also confirmed that the heart rate recovered quickly. As mentioned above, it is thought that blood variables and VO_2max, which were improved through altitude training, induced the rapid recovery of heart rate. Therefore, it is expected that the heart rate monitoring recovery evaluation method and altitude training will be helpful not only for cross-country skiers but also for cardiopulmonary health of general adult men.

4.2 Changes in CBC and EPO

The human body increases the production of EPO in the kidneys to adapt to the low partial pressure and hypoxic environment at high altitudes, and RBC and Hb, which play a role in binding and transporting oxygen, also increase. On the other hand, inadequate training at altitude, insufficient iron stores in the body, and the presence of infection can negatively affect hematological parameters [65,66]. It is known that EPO and Hb increase together with altitude training, but there are also reports that the correlation between EPO and Hb mass may be inconsistent due to individual variability [67–69]. Existing studies also reported that EPO, RBC, Hb, and Hct all increased with altitude training, and conflicting research results reported that EPO increased but RBC, Hb, and Hct did not change. The conflicting results in high-altitude training are due to differences in training altitude, training duration, and stay method [70,71]. In addition, it should be taken into account that EPO, which increases due to exposure to hypoxia at high altitudes, remains elevated for 24–48 hours after sea level return, and then decreases sharply after 72 hours, returning to normal levels before training [72,73]. In this study, RBC, Hb, and Hct increased due to altitude training, but the slight decrease in EPO was judged to be due to blood sampling and individual differences 92 hours after reaching sea level. Therefore, although EPO decreased slightly, RBC and Hb increased, suggesting that LHTH training at 1600 m may be recommended for male cross-country skiers.

It has been reported that RBC and Hb are highly correlated with improvement in exercise performance, including VO_2max [18,69]. High RBC and Hb are more likely due to a genetic predisposition rather than endurance training but are somewhat increased by altitude training [74,75]. Intense athletic training can lead to low levels of hemoglobin, which can lead to maladaptation. Athletes need to avoid low levels of Hb during strenuous athletic training [74]. At rest, Hct can be increased with altitude training. The physiological mechanism that decreases immediately after endurance training and high-intensity training is because the lower the Hct, the lower the blood viscosity, which can improve blood flow and help oxygen transport [76–79]. In this study, it was observed that RBC, Hb, and Hct were increased at rest, and Hct decreased immediately after the high-intensity treadmill test. Therefore, it can be concluded that LHTH training for 3 weeks at an altitude of 1600 m has a positive effect on the physiological stimulation of male cross-country skiers.

Exercise-induced leukocytosis refers to an increase in WBC immediately after exercise. Although there have been previous studies that the number of WBC decreased as a result of LHTH training, it is generally reported that the activation of white blood cells is increased by excessive exercise and high-intensity training rather than the effect of altitude [80–82]. Platelets play an important role in blood coagulation and hemostasis and living at altitude and vigorous exercise can increase the number of platelets, and excessive increase in the number of platelets can increase bleeding tendency or cause thromboembolism [83,84]. Conversely, acute high-altitude exposure may decrease platelets but return to normal with a compensatory effect after short-term adaptation [85,86]. Also, there is a study result that regular exercise of elite endurance athletes inhibits platelet adhesion and aggregation, and that the platelet count can decrease after vigorous exercise [87–89]. In this study, there was no difference in WBC and platelets at rest with altitude training, and the decrease immediately after exercise suggests that LHTH training at 1600 m for 3 weeks did not have a negative physiological effect on male cross-country skiers.

Combining our study, it was confirmed that RBC and Hb, which are factors that have an important influence on oxygen transport and cardiorespiratory health level, can be stimulated at a relatively low altitude of 1600 m. Therefore, it is thought that high-altitude training and living will have a positive effect on men's health promotion by improving the function of blood factors related to oxygen use.

5. Conclusions

The results of this study suggested that 3 weeks of LHTH training at an altitude of 1600 m could stimulate RBC, Hb, and Hct. Also, improved VO_2max and recovery capacity along with increases in RBC and Hb mean that LHTH training at an altitude of 1600 m could induce a positive effect on physiological and performance changes in male cross-country skiers. We did not have a control group, and we do admit some limitations, including height adjustment, length of altitude training, and training program (intensity and volume). Nevertheless, LHTH training at an altitude of 1600 m can be a desirable intervention program when planning short-term altitude training for technical and physiological improvement in male cross-country skiers. In addition, it is suggested that exercise and living at high altitude stimulate blood variables and cardiopulmonary function, which will have a positive effect on exercise performance and health promotion not only for athletes but also for men in general.

6. Future Perspectives

For cross-country skiers, the higher the altitude, the better for training and physiological stimulation. Compared to previous LHTL studies, the implications of this study are that it was conducted at a lower altitude than typical altitude training. In this study, the effect of 3 weeks of LHTH training at 1600 m on hematology and exercise performance was confirmed. This means that even at 1600 m it can cause hypoxia. We acknowledge some research limitations that must be considered for data interpretation, and furthermore, practical recommendations should be limited to cross-country skiers and coaches. In particular, this study had a limitation in that there was no control group and only male athletes were targeted. Future studies will require more detailed studies of training altitude setting, training duration, training intensity, and training method using a large number of subjects and control groups. Nevertheless, what can suggest LHTH training at 1600 m to male cross-country skiers is that training at relatively low altitudes can experience similar performance benefits to training at high altitudes.

Author Contributions

JCW and YCC designed the research study. JCW performed the research. KTY provided help and advice on YCC analyzed the data. JCW, KTY and YCC wrote the manuscript. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

Ethics Approval and Consent to Participate

We obtained informed consent from all. Ethical approval for our study was obtained from the Institutional Review Board (IRB) of Gangneung-Wonju national university (approval number: GWNUIRB-2021-11), and all study procedures were in accordance with relevant guidelines.

Acknowledgment

Not applicable.

Funding

This research received no external funding.

Conflict of Interest

The authors declare no conflict of interest.

References

[1] Holmberg HC. The elite cross-country skier provides unique insights into human exercise physiology. Scandinavian Journal of Medicine & Science in Sports. 2015; 25: 100–109.

[2] Holmberg HC. Integrative biomechanics and physiology in cc skiing. Materials for Tomorrow 2014. Chalmers: Göteborg. 2014.

[3] Sandbakk Ø, Hegge AM, Losnegard T, Skattebo Ø, Tønnessen E, Holmberg H. The Physiological Capacity of the World's Highest Ranked Female Cross-country Skiers. Medicine & Science in Sports & Exercise. 2016; 48: 1091–1100.

[4] Mahood NV, Kenefick RW, Kertzer R, Quinn TJ. Physiological determinants of cross-country ski racing performance. Medicine and Science in Sports and Exercise. 2001; 33: 1379–1384.

[5] Alsobrook NG, Heil DP. Upper body power as a determinant of classical cross-country ski performance. European Journal of Applied Physiology. 2009; 105: 633–641.

[6] Sandbakk Ø, Holmberg H. A Reappraisal of Success Factors for Olympic Cross-Country Skiing. International Journal of Sports Physiology and Performance. 2014; 9: 117–121.

[7] Stray-Gundersen J, Chapman RF, Levine BD. "Living high-training low" altitude training improves sea level performance in male and female elite runners. Journal of Applied Physiology. 2001; 91: 1113–1120.

[8] Chapman RF, Stickford JL, Levine BD. Altitude training considerations for the winter sport athlete. Experimental Physiology. 2010; 95: 411–421.

[9] Sandbakk Ø, Holmberg H-, Leirdal S, Ettema G. The physiology of world-class sprint skiers. Scandinavian Journal of Medicine & Science in Sports. 2011; 21: e9–e16.

[10] Lee JY, Han TY, Choi YC. Effects of 3 Week High Altitude Training on Aerobic and Anaerobic Exercise Performance and Recovery Capability in Cross-country Skier. The Korea Journal of Sports Science. 2014; 23: 1171–1186.

[11] Flaherty G, O'Connor R, Johnston N. Altitude training for elite endurance athletes: a review for the travel medicine practitioner. Travel Medicine and Infectious Disease. 2016; 14: 200–211.

[12] Carroll S. The Making of the Fittest: The DNA Record of Evolution. Darwin. 2010; 23: 121–126.

[13] Lundby C, Robach P. Does 'altitude training' increase exercise performance in elite athletes? Experimental Physiology. 2016; 101: 783–788.

[14] Levine BD, Friedman DB, Engfred K, Hanel B, Kjaer M, Clifford PS, *et al*. The effect of normoxic or hypobaric hypoxic endurance training on the hypoxic ventilatory response. Medicine & Science in Sports & Exercise. 1992; 24: 769–775.

[15] Levine BD, Stray-Gundersen J. "Living high-training low": effect of moderate-altitude acclimatization with low-altitude training on performance. Journal of Applied Physiology. 1997; 83: 102–112.

[16] Levine BD. Intermittent Hypoxic Training: Fact and Fancy. High Altitude Medicine & Biology. 2002; 3: 177–193.

[17] Zheng K. Research on the Physiological Monitoring and Evaluation of Pre-Competition Altitude Training for Zhejiang Elite Swimmers. Physical Activity and Health. 2021; 5: 64–70.

[18] Nummela A, Eronen T, Koponen A, Tikkanen H, Peltonen JE. Variability in hemoglobin mass response to altitude training camps. Scandinavian Journal of Medicine & Science in Sports. 2021; 31: 44–51.

[19] Lukanova-Jakubowska A, Piechota K, Grzywacz T, Ambroży T, Rydzik Ł, Ozimek M. The Impact of Four High-Altitude Training Camps on the Aerobic Capacity of a Short Track PyeongChang 2018 Olympian: A Case Study. International Journal of Environmental Research and Public Health. 2022; 19: 3814.

[20] Solli GS, Tønnessen E, Sandbakk Ø. The Training Characteristics of the World's Most Successful Female Cross-Country Skier. Frontiers in Physiology. 2017; 8: 1069.

[21] Svedenhag J, Piehl-Aulin K, Skog C, Saltin B. Increased left ventricular muscle mass after long-term altitude training in athletes. Acta Physiologica Scandinavica. 1997; 161: 63–70.

[22] Gore CJ, Hahn AG, Aughey RJ, Martin DT, Ashenden MJ, Clark SA, *et al*. Live high:train low increases muscle buffer capacity and submaximal cycling efficiency. Acta Physiologica Scandinavica. 2001; 173: 275–286.

[23] Gough CE, Saunders PU, Fowlie J, Savage B, Pyne DB, Anson JM, *et al*. Influence of altitude training modality on performance and total haemoglobin mass in elite swimmers. European Journal of Applied Physiology. 2012; 112: 3275–3285.

[24] Saunders PU, Ahlgrim C, Vallance B, Green DJ, Robertson EY, Clark SA, *et al*. An Attempt to Quantify the Placebo Effect from a Three-Week Simulated Altitude Training Camp in Elite Race Walkers. International Journal of Sports Physiology and Performance. 2010; 5: 521–534.

[25] Garvican-Lewis LA, Halliday I, Abbiss CR, Saunders PU, Gore CJ. Altitude Exposure at 1800 m Increases Haemoglobin Mass in Distance Runners. Journal of Sports Science and Medicine. 2015; 14 :413–417.

[26] Friedmann-Bette B. Classical altitude training. Scandinavian Journal of Medicine & Science in Sports. 2008; 18: 11–20.

[27] Burtscher M, Nachbauer W, Baumgartl P, Philadelphy M. Benefits of training at moderate altitude versus sea level training in amateur runners. European Journal of Applied Physiology and Occupational Physiology. 1996; 74: 558–563.

[28] Yong-Chul C. The effect of 3 weeks high altitude skiing training on isokinetic muscle function of cross-country skierst. Journal of the Korea Convergence Society. 2018; 9: 465–477.

[29] Pugliese L, Serpiello FR, Millet GP, La Torre A. Training Diaries during Altitude Training Camp in Two Olympic Champions: An Observational Case Study. Journal of Sports Science and MedicineJournal of Sports Science and Medicine. 2014; 13: 666–672.

[30] Lee BH, Kim JK, Kwon HJ, Choi YC. Effects of Living Low and Training High on Body Composition, Exercise Performance, Blood CK, Lactate and Oxidative Stress Makers Responses in Cross Country Skiers. Journal of Sport and Leisure Studies. 2013; 53: 695–710.

[31] Sandbakk Ø, Solli GS, Talsnes RK, Holmberg H. Preparing for the Nordic Skiing Events at the Beijing Olympics in 2022: Evidence-Based Recommendations and Unanswered Questions. Journal of Science in Sport and Exercise. 2021; 3: 257–269.

[32] Kim JK, Choi YC. The effect of short-term off-season cross-country ski training on body composition, physical fitness, and isokinetic muscle functions of cross-country skiers. Journal of Men's Health. 2019; 16: 63–74.

[33] Kim JK, Lee BW, Kim NJ, Choi YC. Effects of High Altitude Training on Maximal Exercise Capacity, RBC, and Hb Concentration in Cross-country Skier. The Korea Journal of Sports Science. 2013; 22: 1313–1324.

[34] Stöggl T, Sperlich B. Polarized training has greater impact on key endurance variables than threshold, high intensity, or high volume training. Frontiers in Physiology. 2014; 5: 33.

[35] Rønnestad BR, Hansen J, Thyli V, Bakken TA, Sandbakk Ø. 5-week block periodization increases aerobic power in elite cross-country skiers. Scandinavian Journal of Medicine & Science in Sports. 2016; 26: 140–146.

[36] Mujika I, Sharma AP, Stellingwerff T. Contemporary Periodization of Altitude Training for Elite Endurance Athletes: a Narrative Review. Sports Medicine. 2019; 49: 1651–1669.

[37] Sharma AP, Saunders PU, Garvican-Lewis LA, Périard JD, Clark B, Gore CJ, *et al*. Training Quantification and Periodization during Live High Train High at 2100 M in Elite Runners: An Observational Cohort Case Study. Journal of Sports Science and Medicine. 2018; 17: 607–616.

[38] George JD, Paul SL, Hyde A, Bradshaw DI, Vehrs PR, Hager RL, *et al*. Prediction of Maximum Oxygen Uptake Using both Exercise and Non-Exercise Data. Measurement in Physical Education and Exercise Science. 2009; 13: 1–12.

[39] Bruce RA, Kusumi F, Hosmer D. Maximal oxygen intake and nomographic assessment of functional aerobic impairment in cardiovascular disease. American Heart Journal. 1973; 85: 546–562.

[40] Will PM, Walter JD. Exercise testing: Improving performance with a ramped Bruce protocol. American Heart Journal. 1999; 138: 1033–1037.

[41] Mikkola J, Laaksonen M, Holmberg H, Vesterinen V, Nummela A. Determinants of a Simulated Cross-Country Skiing Sprint Competition using V2 Skating Technique on Roller Skis. Journal of Strength and Conditioning Research. 2010; 24: 920–928.

[42] Rusko H. The Handbooks of Sports Medicine and Science: Cross Country Skiing. John Wiley & Sons. Jyväskylä. 2008.

[43] Martin SA, Hadmaș RM. Individual Adaptation in Cross-Country Skiing Based on Tracking during Training Conditions. Sports. 2019; 7: 211.

[44] Loucks AB. Energy balance and body composition in sports and exercise. Journal of Sports Sciences. 2004; 22: 1–14.

[45] American Dietetic Association; Dietitians of Canada; American College of Sports Medicine, Rodriguez NR, Di Marco NM, Langley S. American College of Sports Medicine position stand. Nutrition and athletic performance. Medicine & Science in Sports & Exercise. 2009; 41: 709–731.

[46] Lee J, Zhang XL. Physiological determinants of VO2max and the methods to evaluate it: a critical review. Science & Sports. 2021; 36: 259–271.

[47] Losnegard T, Mikkelsen K, Rønnestad BR, Hallén J, Rud B, Raastad T. The effect of heavy strength training on muscle mass and physical performance in elite cross country skiers. Scandinavian Journal of Medicine & Science in Sports. 2011; 21: 389–401.

[48] Stöggl T, Enqvist J, Müller E, Holmberg H. Relationships between body composition, body dimensions, and peak speed in cross-country sprint skiing. Journal of Sports Sciences. 2010; 28: 161–169.

[49] Kim TH, Han JK, Lee JY, Choi YC. The Effect of Polarized Training on the Athletic Performance of Male and Female Cross-Country Skiers during the General Preparation Period. Healthcare. 2021; 9: 851.

[50] Bertoli A, Di Daniele N, Ceccobelli M, Ficara A, Girasoli C, De Lorenzo A. Lipid profile, BMI, body fat distribution, and aerobic fitness in men with metabolic syndrome. Acta Diabetologica. 2003; 40: s130–s133.

[51] Singh SJ, Morgan MD, Hardman AE, Rowe C, Bardsley PA. Comparison of oxygen uptake during a conventional treadmill test and the shuttle walking test in chronic airflow limitation. European Respiratory Journal. 1994; 7: 2016–2020.

[52] Bonne TC, Lundby C, Jørgensen S, Johansen L, Mrgan M, Bech SR, *et al*. "Live High–Train High" increases hemoglobin mass in Olympic swimmers. European Journal of Applied Physiology. 2014; 114: 1439–1449.

[53] Truijens MJ, Toussaint HM, Dow J, Levine BD. Effect of high-intensity hypoxic training on sea-level swimming performances. Journal of Applied Physiology. 2003; 94: 733–743.

[54] Choi YC, Khuyagbaatar B, Cheon M, Batbayar T, Lee S, Kim YH. Kinematic Comparison of Double Poling Techniques between National and College Level Cross-Country Skiers Using Wearable Inertial Measurement Unit Sensors. International Journal of Precision Engineering and Manufacturing. 2021; 22: 1105–1112.

[55] Fellin RE, Rose WC, Royer TD, Davis IS. Comparison of methods for kinematic identification of footstrike and toe-off during overground and treadmill running. Journal of Science and Medicine in Sport. 2010; 13: 646–650.

[56] Jeukendrup A, Diemen AV. Heart rate monitoring during training

and competition in cyclists. Journal of Sports Sciences. 1998; 16: 91–99.

[57] Benson R, Connolly D. Heart Rate Training. Human Kinetics. Champaign, IL. 2019.

[58] Nieuwland W, Berkhuysen MA, Van Veldhuisen DJ, Rispens P. Individual assessment of intensity-level for exercise training in patients with coronary artery disease is necessary. International Journal of Cardiology. 2002; 84: 15–20.

[59] Sylta O, Tønnessen E, Seiler S. From Heart-Rate Data to Training Quantification: a Comparison of 3 Methods of Training-Intensity Analysis. International Journal of Sports Physiology and Performance. 2014; 9: 100–107.

[60] Basset F. Effects of Short-term normobaric hypoxia on anaerobic and aerobic performance in highly trained athletes. 14th International Hypoxia Symposium. 2005; 91: 391–402.

[61] Bailey DM, Davies B. Physiological implications of altitude training for endurance performance at sea level: a review. British Journal of Sports Medicine. 1997; 31: 183–190.

[62] Larsson P, Olofsson P, Jakobsson E, Burlin L, Henriksson-Larsén K. Physiological predictors of performance in cross-country skiing from treadmill tests in male and female subjects. Scandinavian Journal of Medicine & Science in Sports. 2002; 12: 347–353.

[63] Bergh U. Physiology of cross-country ski racing. Human Kinetics. Champaign: Ill. 1982.

[64] Choi Y. The Study of Sprint Cardiorespiratory Index and Body Composition according to Period in National and Reserve Cross-country Skier. Korean Journal of Sports Science. 2018; 27: 993–1005.

[65] Breda FL, Manchado-Gobatto FB, de Barros Sousa FA, Beck WR, Pinto A, Papoti M, *et al*. Complex networks analysis reinforces centrality hematological role on aerobic–anaerobic performances of the Brazilian Paralympic endurance team after altitude training. Scientific Reports. 2022; 12: 1148.

[66] Rusko H, Tikkanen H, Peltonen J. Altitude and endurance training. Journal of Sports Sciences. 2004; 22: 928–945.

[67] Baranauskas MN, Fulton TJ, Fly AD, Martin BJ, Mickleborough TD, Chapman RF. High Intraindividual Variability in the Response of Serum Erythropoietin to Multiple Simulated Altitude Exposures. High Altitude Medicine & Biology. 2022; 23: 85–89.

[68] Friedmann B. Individual variation in the erythropoietic response to altitude training in elite junior swimmers. British Journal of Sports Medicine. 2005; 39: 148–153.

[69] Wachsmuth NB, Völzke C, Prommer N, Schmidt-Trucksäss A, Frese F, Spahl O, *et al*. The effects of classic altitude training on hemoglobin mass in swimmers. European Journal of Applied Physiology. 2013; 113: 1199–1211.

[70] Manh PH, Viet DH, Van Linh NT, Van Thal L. The effects of simulated altitude training on physiological and biochemical functions in national male cyclists. Science Technology for Sports Performance Enhancement. 2018; 28–35.

[71] Volkan Gürses V, Şakir Akgül M. The Effects of Low Altitude Training on Erythropoietin Response and Hematological Variables in Elite Female Fencers. Universal Journal of Educational Research. 2018; 6: 2169–2174.

[72] Chapman RF, Karlsen T, Resaland GK, Ge RL, Harber MP, Witkowski S, *et al*. Defining the "dose" of altitude training: how high to live for optimal sea level performance enhancement. Journal of Applied Physiology. 2014; 116: 595–603.

[73] Pottgiesser T, Garvican LA, Martin DT, Featonby JM, Gore CJ, Schumacher YO. Short-Term Hematological Effects upon Completion of a Four-Week Simulated Altitude Camp. International Journal of Sports Physiology and Performance. 2012; 7: 79–83.

[74] Wehrlin JP, Steiner T. Is Hemoglobin Mass at Age 16 a Predictor for National Team Membership at Age 25 in Cross-Country Skiers and Triathletes? Frontiers in Sports and Active Living. 2021; 3: 580486.

[75] Baart AM, Klein Gunnewiek JMT, Balvers MGJ, Zwerver J, Vergouwen PCJ. Pitfalls in interpreting red blood cell parameters in elite high-altitude and sea-level athletes: a unique case series. Physiological Reports. 2021; 9: e14891.

[76] Weng X, Chen H, Yu Q, Xu G, Meng Y, Yan X, McConell G, *et al*. Intermittent Hypoxia Exposure Can Prevent Reductions in Hemoglobin Concentration After Intense Exercise Training in Rats. Frontiers in Physiology. 2021; 12: 627708.

[77] Hu M, Lin W. Effects of Exercise Training on Red Blood Cell Production: Implications for Anemia. Acta Haematologica. 2012; 127: 156–164.

[78] Wehrlin JP, Zuest P, Hallén J, Marti B. Live high-train low for 24 days increases hemoglobin mass and red cell volume in elite endurance athletes. Journal of Applied Physiology. 2006; 100: 1938–1945.

[79] Tilahun Muche Z, Haile Wondimu D, Bayissa Midekssa M, Chekol Abebe E, Mengie Ayele T, Abebe Zewdie E. A Comparative Study of Hematological Parameters of Endurance Runners at Guna Athletics Sport Club (3100 Meters above Sea Level) and Ethiopian Youth Sport Academy (2400 Meters above Sea Level), Ethiopia. Journal of Sports Medicine. 2021; 2021: 1–9.

[80] Pyne DB, Smith JA, Baker MS, Telford RD, Weidemann MJ. Neutrophil oxidative activity is differentially affected by exercise intensity and type. Journal of Science and Medicine in Sport. 2000; 3: 44–54.

[81] Thake CD, Mian T, Garnham AW, Mian R. Leukocyte counts and neutrophil activity during 4 h of hypocapnic hypoxia equivalent to 4000 m. Aviation, Space, and Environmental Medicine. 2004; 75: 811–817.

[82] Yalcin O, Bor-Kucukatay M, Senturk UK, Baskurt OK. Effects of swimming exercise on red blood cell rheology in trained and untrained rats. Journal of Applied Physiology. 2000; 88: 2074–2080.

[83] Al-Sweedan SA, Alhaj M. The effect of low altitude on blood count parameters. Hematology/Oncology and Stem Cell Therapy. 2012; 5: 158–161.

[84] Glotov AS, Zelenkova IE, Vashukova ES, Shuvalova AR, Zolotareva AD, Polev DE, *et al*. RNA Sequencing of Whole Blood Defines the Signature of High Intensity Exercise at Altitude in Elite Speed Skaters. Genes. 2022; 13: 574.

[85] Wang Y, Huang X, Yang W, Zeng Q. Platelets and High-Altitude Exposure: a Meta-Analysis. High Altitude Medicine & Biology. 2022; 23: 43–56.

[86] Ke JB, Li JB, Zhang JH, Bian SZ, Yang J, Liu C, *et al*. Influence of acute high altitude exposure and short-term acclimation on platelet-associated parameters in healthy young man. Medical Journal of Chinese People's Liberation Army. 2018; 43: 251–256.

[87] Wang J, Jen CJ, Chen H. Effects of Exercise Training and Deconditioning on Platelet Function in Men. Arteriosclerosis, Thrombosis, and Vascular Biology. 1995; 15: 1668–1674.

[88] Wang JS, Jen CJ, Chen HI. Effects of chronic exercise and deconditioning on platelet function in women. Journal of Applied Physiology. 1997; 83: 2080–2085.

[89] Wang JS, Jen CJ, Kung HC, Lin LJ, Hsiue TR, Chen HI. Different effects of strenuous exercise and moderate exercise on platelet function in men. Circulation. 1994; 90: 2877–2885.