

Sportspecific performance diagnosis in ski mountaineering – comparison of a sportspecific cardiopulmonary exercise test on a treadmill versus outdoors and at altitude, a pilot study

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Original article

Abstract

Background: Ski mountaineering is a competitive sport that has gained popularity during the last years. As most competitions are held in altitudes between 1500 m and 3500 m, a considerable amount of training occurs at various hypobaric hypoxia degrees. It was establishing a sport-specific cardiopulmonary exercise protocol using standard ski mountaineering equipment on a treadmill. This study investigated altitude's effects on a self-regulated incremental exercise field test at 3100 m with this protocol.

Methods: Six athletes were tested (24.2 ± 4.2 years) from the German Ski Mountaineering National Team with a portable telemetric cardiopulmonary exercise test equipment. First, an incremental indoor step test with skis on a treadmill (altitude 310 m) and four days later outdoor on glacier snow (3085 m) after three days of acclimatization. All athletes were exposed to repetitive intermittent hypoxia during the weeks before the test. Standard cardiopulmonary exercise parameters were recorded while individual training zones were defined according to ventilatory thresholds.

Results: In highly trained athletes, mean $\dot{V}O_{2peak}$ (72/ml kg KG/min) was reduced by 25% or 9% per 1000 m altitude gain and by 18% and 23% at the first and second ventilatory thresholds, respectively. Mean maximum heart rate and the heart rate at the ventilatory thresholds were reduced at altitude compared to sea-level, as was the O_2 pulse.

Conclusion: Due to distinctive individual reactions to hypoxia, cold, etc., an individual and sport-specific field performance analysis, representing the daily training environment, is highly useful in world-class athletes for precise training control. Our self-regulated cardiopulmonary field protocol could well prove to serve in such a way.

Keywords

- spiroergometry
- performance testing
- ski mountaineering
- exercise testing
- CPEC

Contribution

- A - the preparation of the research project
- B - the assembly of data for the research undertaken
- C - the conducting of statistical analysis
- D - interpretation of results
- E - manuscript preparation
- F - literature review
- G - revising the manuscript

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Article info

Article history

- Received: 2020-04-28
- Accepted: 2021-09-21
- Published: 2021-09-27

Publisher

University of Applied Sciences in Tarnow
ul. Mickiewicza 8, 33-100 Tarnow, Poland

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Conflict of interest

None declared.

Financing

This research did not received any grants
from public, commercial or non-profit
organizations.

Introduction

Ski mountaineering (skimo) consists of ascending and downhill skiing snow-covered slopes and peaks. This is achieved using nylon or mohair skins under the skis for ascents which can be taken off for the downhill. As a competitive sport, it consists mainly of three types of races: 1) individual races in which uphill and downhill sections alternate interspersed with steep climbing sections where the athletes have to carry the skis attached to their backpacks (duration 90-150 min. [1]), 2) vertical races which are made up of only one uphill section (duration approximately 30 min.) and 3) sprint races in which short bouts of uphill and downhill sections alternate (duration 5 min.). Most of the World Cup athletes undertake all three types of races during the competition circuit. Thus, ski mountaineering at the elite athlete level demands a good endurance performance and high-intensity capacity for the sprint and vertical races. Skimo has therefore been rated as among the most strenuous endurance sports [1-3]. The cardiopulmonary demands of a sport can be estimated using sports-specific cardiopulmonary exercise testing (CPET).

Another aspect of ski mountaineering is that most races are conducted at higher altitudes eliciting specific physiological reactions during activity. The most notable observation for exercise at altitude is a decline in maximum oxygen consumption (with increasing elevation representing a greater relative exercise intensity for given power output [4]. As the rate of oxygen consumption is a function of blood flow (cardiac output, CO) and tissue utilization difference (arteriovenous difference of O_2 [$a-vO_2$ diff]), these parameters need to be examined in skimo athletes at altitude in order to obtain more insight into the physiological demands of skimo. As a consequence of the reduced oxygen content of blood, CO is increased through heart rate before acclimatization and then reduces slightly, whereas stroke volume (SV) is already reduced from initial exposure and then further declines over time at altitude [4]. The $a-vO_2$ diff is influenced by muscle blood flow, in which oxygen delivery to exercising muscle matches demand, and oxygen diffusing capacity is not a limiting factor at altitude [4]. In general, these parameters cannot easily be accessed during cardiopulmonary exercise testing, especially during freezing conditions.

Due to the demands of training and competing at higher altitudes, skimo is believed to be the endurance sport with the highest “hypoxic dose” [5]. A loss of performance and $\dot{V}O_{2max}$ is more pronounced in trained endurance athletes than in non-trained individuals [5-8].

Yet, the amount of reduction or the existence of a threshold altitude is still under discussion [4-9]. As a consequence of these altered demands during competitions in the mountains, estimating the individual loss of aerobic performance is of particular interest.

So far, it is well established in sports exercise testing that athletes need to be tested as sport-specific as possible [10]. To establish a sport-specific protocol on a treadmill, we established a method during which the athletes used their skimo skis combined with their poles on a large treadmill [10]. However, such a laboratory test protocol cannot mimic ski mountaineering conditions with the specific friction of skis on snow. Furthermore, the effect of the environments (coldness and altitude) are not adequately reflected in laboratory test protocols.

To gain more insight into the effect of altitude and the real environment usually encountered during training and competition, we compared the German national skimo team athletes’ sports-specific laboratory test with an outdoor test on a glacier. Especially gaining a better understanding of the shift in ventilatory thresholds due to altitude is essential for providing better training recommendations in athletes.

Material and Methods

The Ethics Committee of the University of Erlangen-Nuremberg approved the study (No. 306_19 Bc, 2019).

Participants

Six athletes were enrolled for the study from the German Ski Mountaineering National Team (4 m, 2 f; 24.2 ± 4.2 years). Written informed consent was obtained from each participant. All participants were Caucasian, non-obese (mean BMI 20.3), and healthy. All athletes were exposed to intermittent hypoxia due to altitude training of up to 3500 m of elevation according to their individual training schedule in the weeks before testing. Prior to each test, a sports-medical examination including ECG, echography, blood cell count, physical examination, and completion of a standard questionnaire according to the recommendations of the national and international Olympic Committee were performed.

Laboratory Skimountaineering Test

The indoor ski mountaineering test (LST) followed our previous protocol with some minor modifications [10]. The original protocol used a step test with a constant

incline and a stepwise increasing speed [10]. This protocol has since been improved in cooperation with our national team members to a protocol with continual speed and increasing incline. The athletes described such a protocol as a more realistic representation of the demands of their sport. In our opinion it is paramount that the test resembles the demands of the sport most accurately. We therefore used the new protocol and even though this particular protocol has not been compared to the previous one we are convinced that the changes would not have led to differing results. The standards of general performance diagnosis and stress tests were fulfilled (temperature 18-24°C, relative humidity 30-60%). All participants had a minimum rest period of 48 hours before the test from athletic or any other energy-demanding activity. Caffeine intake and other lifestyle factors that might influence exercise diagnosis were kept constant during the pre-test and test periods [10]. The altitude for the laboratory test was 310 m. All participants undertook the indoor test first for recording a valid 12-lead stress ECG (MAC 2000, GE® Healthcare, Chicago, US), which is not feasible during the outdoor test setting.

The following conditions defined the LST: incremental step test on the running treadmill (Woodway®, Weil am Rhein, Germany) with ski mountaineering competition skis (in accordance to the IFSM regulations; <http://www.ismf-ski.org>), competition skimo boots, ski poles, no skins, skimo binding with medium heel raiser (climbing aid) (Fig. 1).

The starting speed was 5.5 km/h for all participants, and the initial inclination of the treadmill was 17°. The increase of each step consisted of 3° up to a maximum of 32°. After that, the speed was increased further by 0.5 km/h at 32° inclination till exhaustion. Each step's duration was 3 min with a 15 sec break for drawing capillary blood lactate (BL) samples from the ear lobe which was analyzed with the Lactate Scout® (EKF, Cardiff – United Kingdom). BL was collected before and after every step, at the end of the test, and two consecutively five minutes after test termination. BL. The cardiopulmonary exercise parameters were recorded using a Metamax 3B (Metamax® 3B, Cortex, Germany). Heart rate (HR) was recorded using a HR monitoring device (Polar®, Kempele, Finland). In addition to the HR monitor, a standard 12-lead exercise ECG was recorded for the entire test. We use ECG in combination with a HR monitoring device for ensuring accurate measurements of Heart rate during each test. The Borg-RPE (rating of perceived exertion) scale was recorded at the end of each step [11].



Figure 1. Laboratory test (LST)

Field Test

After completing the LST, all athletes moved to a glacier in the Austrian alps (Pitztal glacier, Austria) on the same day where they started training for three days according to the principle: train high (2720 m – 3430 m), live low (1680 m). After a day of easy recovery training, the outdoor test was performed.

For the outdoor field test (FST), a ski slope at the Pitztal glacier with an average 24° inclination at an altitude of 3020 m to 3150 m was used; the temperature ranged between -4 and -16°C. After warming up, the athletes performed an uphill step test in which they performed four uphill runs with increasing speed for each step which lasted 3 min each. The athletes were instructed to start very slow during the first step, increasing to medium, then fast, and finally maximum speed during their last (Fig. 2). After termination of each step, the athletes were asked about the exertion (Borg-RPE scale) and then skied back down to the starting position with skins attached. As a consequence, the test distance increased in accordance with the increase in speed.

The Borg-RPE scale for altitude was validated prior through Küpper and Basnyat [12] up to 5000 m altitude. Due to the coldness, BL samples were not possible. Cardiopulmonary exercise test parameters and heart rate were recorded using the same equipment as during the laboratory test. As a consequence of the cold temperatures, we changed the sample line after each participant so as to avoid freezing of the sample line.



Figure 2. Field Test (FST)

Data processing

All cardiopulmonary exercise data were visualized and interpreted with the MetaSoft Studio® Software (Cortex®, Leipzig, Germany). Due to the small number of participants, a statistical analysis above calculation of means and standard deviations was not appropriate.

$\dot{V}O_{2peak}$ and HRmax Determination

The highest mean and HR values obtained during the incremental step tests over a minimum of 15 sec were defined as peak and HRmax, respectively. Exhaustion criteria were defined as follows: calculated maximum heart rate (HR 208 minus 0.7 x years of age [13]), Borg scale > 18, respiratory exchange ratio (RER) > 1.1, plateau (levelling off) and the inability of the subjects to further maintain the desired speed [1,3].

VT1 and VT2 Determination

The first ventilatory threshold (VT1) [14] was determined by visual analysis of the breakpoints of ventilatory equivalents for oxygen ($\dot{V}E / \dot{V}O_2$) and carbon dioxide ($\dot{V}E / \dot{V}CO_2$), and minute ventilation ($\dot{V}E$) changes over time that featured an increase of $\dot{V}E / \dot{V}CO_2$ without an increase of $\dot{V}E / \dot{V}O_2$ [1,15-17]. The second ventilatory threshold (VT2) [16] was determined by visual analysis of the breakpoints of ventilatory equivalents for oxygen, carbon dioxide, and minute ventilation changes over time with an increase in both $\dot{V}E / \dot{V}O_2$ and $\dot{V}E / \dot{V}CO_2$ [1,15,17].

Results

Six athletes were tested (4 m, 2 f). For their age and anthropometric data, see Tab. 1.

Test profile feasibility

The athletes were able to fulfill both test protocols following the given instructions. All athletes were able to reach the second ventilatory threshold (VT2) in both tests. The ventilatory thresholds were easily detectable as the equipment worked perfectly in the tests we were able to analyze. In the tests with the faulty CO_2 -sensor, the ventilatory thresholds were still easily recognizable so that they were included in the results. The maximum Borg-RPE scale reached was 19 or 20 in both tests for all athletes (LST: Borg 19: 1, Borg 20: 5, FST: Borg 19: 2, Borg 20: 4). During the outdoor test on the glacier, they did not reach the same HRmax as on the treadmill, and their HRmax was also lower than the predicted HRmax. We were not able to collect any BL measurements on the glacier due to freezing.

Data from cardiopulmonary exercise testing

The results from the two cardiopulmonary exercise tests are presented in Tab. 2 at the first and second

Table 1. Anthropometrics of the test athletes

	1	2	3	4	5	6	MEAN	STD
Gender	m	m	m	m	f	f	-	-
Age	26	25	19	29	19	18	22.7	4.19
BMI	23.4	20.1	20.7	21.5	18.1	17.8	20.3	1.93

Table 2. Overview of the test results

	LST	FST	Difference
HR at VT1 [min^{-1}]	160	153	-4.4%
HR at VT2 [min^{-1}]	181	173	-4.4%
HR max [min^{-1}]	193	181	-6.2%
$\dot{V}O_{2\text{peak}}$ [ml/kg KG/min]	72	54	-25%
$\dot{V}O_2$ at VT 1 [ml/kg KG/min]	51	39	-23.5%
$\dot{V}O_2$ at VT 2 [ml/kg KG/min]	61	50	-18%
O_2 -pulse max [ml/heart beat]	25	21	-16%
BF max [min^{-1}]	67	69	+3%
RER max	0.95**	1.15	+21.1%**
$\dot{V}E$ max	177	176	-0.6%

Note: HR = heart rate, VT1 = ventilatory threshold 1, VT2 = ventilatory threshold 2, $\dot{V}O_2$ = oxygen uptake, O_2 -pulse = oxygen uptake per heart beat, BF = breathing frequency, RER = respiratory exchange ration, $\dot{V}E$ = minute ventilation.

** results compromised due to a problem with the CO_2 sensor.

ventilatory thresholds (VT1 and VT2) and peak was higher in the LST than in the FST. The same HR results were found at thresholds, which were lower on the glacier than on the treadmill. As a consequence, the $O_{2\text{pulse}}$ was lower during FST than during LST. Interestingly, maximum breathing frequency (BFmax) and the resulting minute ventilation ($\dot{V}E$) was comparable between both tests. In comparing LST and FST, no statistical analysis was conducted due to the small and heterogeneous sample. In highly trained athletes (mean $\dot{V}O_2$ peak: 72/ml kg KG/min), the peak between LST and FST was reduced by 25% or 9.0%/1000 m altitude gain.

The overall results showed an inhomogeneous variation between both tests and various athletes. The individual results of each athlete will be presented in Tab. 3.

Exemplary results of one athlete are presented with the LST results in Fig. 3 and the results of the FST in Fig. 4.

Discussion

Consequently, the long period spent just below and above the respiratory compensation point (RCP = RER of 1), ski mountaineering is rated as one of the sports with the highest demand on endurance [1-3]. The best method to plan and undertake endurance sports training is using ventilatory and lactate thresholds determined using cardiopulmonary exercise testing. The

most reliable way to determine these thresholds is through sports-specific CPET [18]. To estimate the demands of skimo using CPET, a sport-specific protocol has been developed in which athletes are tested using an incremental exercise test with increasing slope and speed on a treadmill with their skis and their poles [10]. However, most of the training sessions as well as the competitions take place in the mountains at elevated altitudes. The physiological responses to exercise at altitude are unique, and typical parameters like heart rate and even workload are distinctly different at altitude than in laboratory conditions at sea level. Therefore, it is essential to develop a sport specific exercise test that can be performed at altitude to provide the athletes with exact parameters for VT1 and VT2 when training in the mountains. Such a protocol has been proposed by Duc et al. [1] using a field test during which the athletes were asked to walk up a ski-slope at an altitude of 1941 m using their standard equipment. They were instructed to increase their speed by 0.5 km/h every minute until exhaustion, with flags marking the distance they were supposed to cover during each step. The difficulty with such a protocol is mainly the reliance on the subject to adequately time the distance to not go too fast or too slow during each step. Furthermore, the test duration varies according to each individual's fitness, whereas a fixed test duration would make comparability between tests more reliable. We were able to show that a field test in which children were

Table 3. Comparison of indoor and outdoor glacier cardiopulmonary exercise test

	1	2	3	4	5	6
Gender	m	m	m	m	f	f
Age	26	25	19	29	19	18
HR maxLST (min ⁻¹)	190	195	198	183	187	203
HR maxFST (min ⁻¹)	175	180	178	171	182	197
HR VT1 LST (min ⁻¹)	159	158	163	157	165	-
HR VT1 FST (min ⁻¹)	147	156	153	137	152	171
HR VT2 LST (min ⁻¹)	180	183	187	170	178	190
HR VT2 FST (min ⁻¹)	165	171	174	165	174	189
$\dot{V}O_{2peak}$ LST [ml/kg KG/min]	68	85	81	80	58	59
$\dot{V}O_{2peak}$ FST [ml/kg KG/min]	49	64	61	60	45	46
$\dot{V}O_2$ VT1 LST [ml/kg KG/min]	48	57	54	57	41	-
$\dot{V}O_2$ VT1 FST [ml/kg KG/min]	38	45	46	45	30	27
$\dot{V}O_2$ VT2 LST [ml/kg KG/min]	59	74	68	66	48	51
$\dot{V}O_2$ VT2 FST [ml/kg KG/min]	46	58	59	58	42	39
O ₂ -pulse max LST [ml/bpm]	30	31	27	29	19	15
O ₂ -pulse maxFST [ml/bpm]	25	26	23	23	15	12
BF maxLST [min ⁻¹]	74	73	70	60	60	63
BF maxFST [min ⁻¹]	78	72	74	62	62	64
RER max LST	1.03	1.05	1.03	0.95**	0.80**	0.84**
RER max FST	1.11	1.16	1.15	1.12	1.18	1.18
Borg max LST	19	20	20	20	20	20
Borg max FST	19	20	20	19	20	20
Borg at VT1 LST	13	13	13	13	15	-
Borg at VT1 FST	11	12	15	13	12	8
Borg at VT2 LST	17	16	16	17	17	19
Borg at VT2 FST	16	17	20	17	18	18
$\dot{V}E$ max LST	222	216	207	160	135	119
$\dot{V}E$ max FST	206	214	206	167	136	128
BL max LST (mmol/L)	10.2	10.4	10.3	14.7	6.6	19.3

Note: HR = heart rate, VT1 = ventilatory threshold 1, VT2 = ventilatory threshold 2, $\dot{V}O_2$ = oxygen uptake, O₂-pulse = oxygen uptake per heart beat, BF = breathing frequency, RER = respiratory exchange ration, $\dot{V}E$ = minute ventilation, BL = blood lactate.

** malfunction of CO₂ sensor.

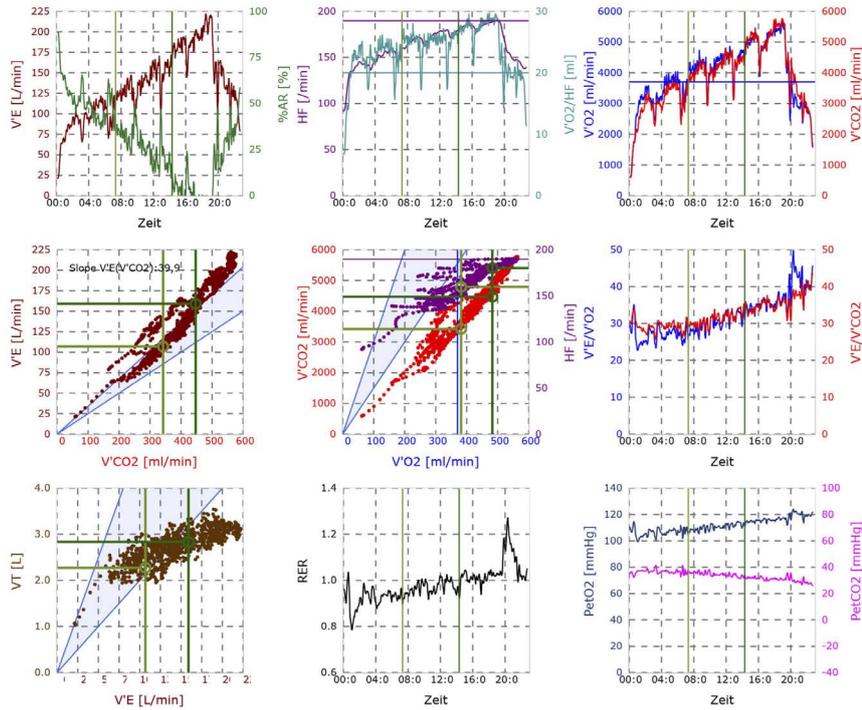


Figure 3. Athlete 1 in LST. VT1 is visualized as a light green line and VT2 as a dark green line

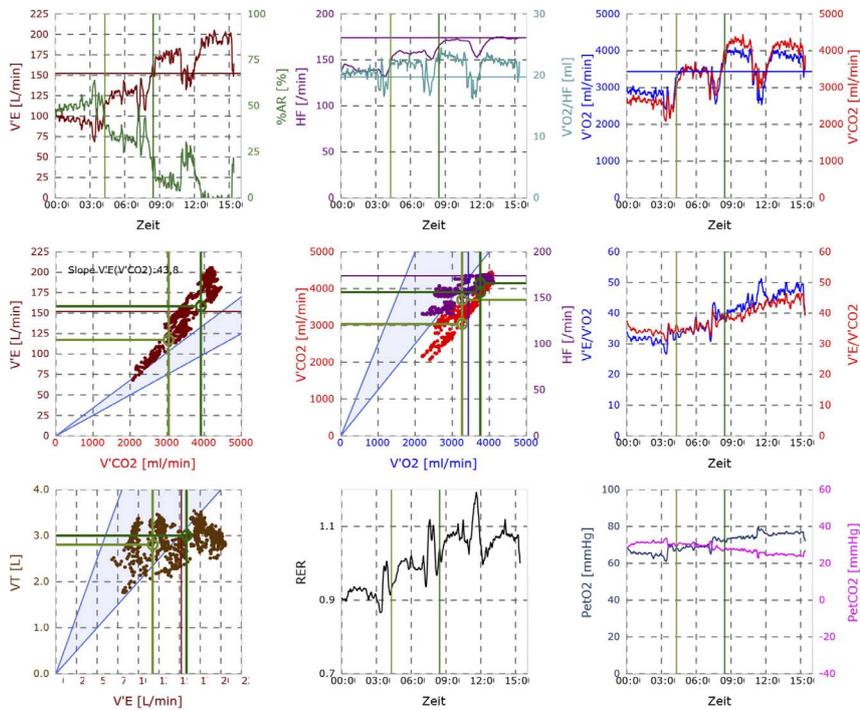


Figure 4. Athlete 2 in FST. VT1 is visualized as a light green line and VT2 as a dark green line

allowed to choose their own speed according to their respective fitness, allowed them to achieve exhaustion within a timeframe of 6-8 minutes while still enabling the researcher to clearly distinguish ventilatory thresholds [19]. In this study, we therefore chose to use a comparable approach in order to determine the ventilatory thresholds of elite skimo athletes at altitude.

With increasing altitude, the partial pressure of oxygen in the ambient air (PIO₂) declines, and as a consequence, so does the extent of hypoxia or the arterial oxygen saturation (SaO₂) [4]. Consequently, essential physiological and metabolic adjustments are needed to maintain proper tissue oxygenation [4]. Thus, when performing at altitude, greater relative exercise intensity is elicited. Even though at submaximal exercise the same oxygen consumption $\dot{V}O_2$ is observed, this given power output represents a greater relative exercise intensity as a result of the decline in $\dot{V}O_2$ with increasing elevation [4]. In our study $\dot{V}O_{2peak}$ decreased by 25% comparable to other studies [20-23]. However, these studies were performed at a higher altitude of 4000 m. If a linear decrease of $\dot{V}O_{2peak}$ of about 6.3% is assumed [9] the loss of $\dot{V}O_{2peak}$ should have been only 17,5%. $\dot{V}O_{2peak}$ was also significantly lower than in a previous study with skimo athletes using field testing at altitude with a mean value of 68 ml/kg/min at 1941 m of altitude [1] compared to 54 ml/kg/min in our study conducted at 3100 m of altitude. Even taking into consideration the difference in altitude the results from our study are lower. However, in a review article by Fulco et al. [24], the authors observe a greater decline of $\dot{V}O_{2peak}$ at altitude for highly fit individuals which are defined by having a $\dot{V}O_{2peak}$ greater than 63 ml/kg/min than in those less fit (51 ml/kg/min). In this review the decrease in $\dot{V}O_{2peak}$ was around 10% for the fitter individuals and was therefore comparable to our collective which reached a mean $\dot{V}O_{2peak}$ of 72 ml/kg/min during the indoor test and can therefore be considered very fit.

$\dot{V}O_{2peak}$ is a function of cardiac output and tissue oxygenation utilization difference. Of these two components, only cardiac output can be examined using cardiopulmonary exercise testing as it is made up of heart rate (HR) and stroke volume (SV). The most obvious adaptation to altitude, which can be observed upon arrival at altitude, increases HR at rest and during submaximal exercise [4]. HR measured in our study at altitude during maximal (HR at $\dot{V}O_{2peak}$) as well as during submaximal (HR at VT1 and HR at VT2) exercise was lower than in laboratory conditions at 300 m elevation. This is in consensus with findings of Friedmann et al. [25], who showed reduced HR at metabolic thresholds in hypoxia compared to normoxia. It has also been observed that the HR is higher at altitude for the same

workload than performed in normoxia [4]. An increase in stroke volume cannot explain this as it declines even more than HR when comparing the field test with the laboratory test. However, a decrease in stroke volume is regular at altitude and apparently independent of acclimatization [4]. Comparing However, in a review article by Fulco et al. [24], the authors observe a greater decline of $\dot{V}O_{2peak}$ at altitude for highly fit individuals which are defined by having a $\dot{V}O_{2peak}$ greater than 63 ml/kg/min than in those less fit (51 ml/kg/min). In this review the decrease in $\dot{V}O_{2peak}$ was around 10% for the fitter individuals and was therefore comparable to our collective which reached a mean $\dot{V}O_{2peak}$ of 72 ml/kg/min during the indoor test and can therefore be considered very fit. Examining VT1 and VT2 in proportion to $\dot{V}O_{2peak}$ (LST: VT1 71%, VT2 85%; FST: VT1 72%, VT2 93%), both thresholds shift to the right, i.e. $\dot{V}O_{2peak}$ is reduced disproportionately to $\dot{V}O_2$ at VT1 and mainly VT2. Interestingly, there were intraindividual differences in the amount of threshold change between LST and FST. Therefore, individual determination of thresholds at altitude is necessary for optimizing training and competition performance [25,26]. The effect of cold temperatures on the performance is very complex and probably needs to be evaluated on its own. Testing in realistic conditions, as we did on the glacier, allows for a better understanding of the extreme environment on the performance of the athletes.

However, one important thing to recognize is that the mean RER achieved during the field test at altitude was much higher than during the treadmill test. This reflects the superiority of self-regulated field tests for achieving maximal exertion [19]. These results need to be considered with caution due to a malfunction of the CO₂-sensor in three indoor tests. Furthermore, we believe that attaining similar test durations for all athletes allows for a better inter-and intra-individual comparability. Since ventilatory thresholds were easy to discern, such a test protocol still allows for reliable test results, which can be used for training and competition planning.

Limitations

The minimal number of participants in this study is clearly a severe limitation. This is especially true since the two female athletes cannot be considered elite athletes as the national performance level among female athletes was significantly lower. Thus, the national team's admission criteria were more moderate.

Lactate measurements would have made the arguments stronger about maximal exertion and discerning thresholds. A setting in which the glacier's freezing

conditions are circumvented should be envisioned when undertaking future studies.

Finally, there was a loss of continuity in exercise data when the athletes skied back down to the slope's beginning. With more researchers on the glacier being able to collect data after every step along a longer slope, a continuous step test can be envisioned. The athletes would not have to ski down to the start but would just carry on, and the loss of continuity could be avoided.

Conclusions

To evaluate ventilatory thresholds and maximum oxygen consumption at altitude, a self-regulated field test represents a reasonable alternative or supplement to indoor laboratory testing at sea level. Field tests and a realistic test setting are paramount to guarantee optimal training control.

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