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Research article

Physiological Responses and Predictors of Performance in a Simulated Competitive Ski Mountaineering Race

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Abstract

Competitive ski mountaineering (SKIMO) has achieved great popularity within the past years. However, knowledge about the predictors of performance and physiological response to SKIMO racing is limited. Therefore, 21 male SKIMO athletes split into two performance groups (elite: VO_{2max} 71.2 ± 6.8 ml· min^{-1}· kg^{-1} vs. sub-elite: 62.5 ± 4.7 ml· min^{-1}· kg^{-1}) were tested and analysed during a vertical SKIMO race simulation (523 m elevation gain) and in a laboratory SKIMO specific ramp test. In both cases, oxygen consumption (VO_2), heart rate (HR), blood lactate and cycle characteristics were measured. During the race simulation, the elite athletes were approximately 5 min faster compared with the sub-elite (27:15 ± 1:16 min; 32:31 ± 2:13 min; $p < 0.001$). VO_2 was higher for elite athletes during the race simulation ($p = 0.046$) and in the laboratory test at ventilatory threshold 2 ($p = 0.005$) and at maximum VO_2 ($p = 0.003$). Laboratory maximum power output is displayed as treadmill speed and was higher for elite than sub-elite athletes (7.4 ± 0.3 km h^{-1}; 6.6 ± 0.3 km h^{-1}; $p < 0.001$). Lactate values were higher in the laboratory maximum ramp test than in the race simulation ($p < 0.001$). Pearson´s correlation coefficient between race time and performance parameters was highest for velocity and VO_2 related parameters during the laboratory test ($r > 0.6$). Elite athletes showed their superiority in the race simulation as well as during the maximum ramp test. While HR analysis revealed a similar strain to both cohorts in both tests, the superiority can be explainable by higher VO_2 and power output. To further push the performance of SKIMO athletes, the development of named factors like power output at maximum and ventilatory threshold 2 seems crucial.

Key words: Performance diagnosis, predictors of performance, oxygen uptake, competition simulation, winter sports physiology, ski mountaineering.

Introduction

Ski mountaineering (SKIMO) is growing rapidly throughout the skiing world (Pröbstl-Haider and Lampl, 2017). The International Ski Mountaineering Federation (ISMF) sanctions World Cup events and is working to gain acceptance into the Olympic Winter Games (International Ski Mountaineering Federation, 2020). As a first step in this process, SKIMO was part of the Lausanne 2020 Youth Olympic Games (Olympic, 2020). SKIMO as a winter alpine sport can be divided in three segments: recreational touring, freeride touring and competitive racing (Winter, 2001). Alpine SKIMO racing consist of gaining elevation and quick transitions to ski downhill (House et al., 2019). There are three basic disciplines within the racing domain. These are “individual”, “vertical” and “sprint” races. While an “individual” is a combination of consecutive uphill and downhill sections, a “vertical” consists of only one uphill section. “sprints” are short elimination races where technical abilities like traversing, kick turns or transitioning are important (House et al., 2019).

As in any endurance sport, physical fitness is crucial for SKIMO performance. Numerous SKIMO specific publications (Duc et al., 2011; Fornasiero et al., 2018; Gaston et al., 2019) state SKIMO is one of the most strenuous endurance sports. The physiological strain can be compared to cycling (Gregory et al., 2007; Lucia et al., 2000; Padilla et al., 2000; Padilla et al., 2008; Peinado et al., 2018), 10 km running (Esteve-Lanao et al., 2008) or cross-country skiing (Mognoni et al., 2001). To estimate the strain of a SKIMO race, heart rate (HR) measurements were most commonly compared to HR and oxygen consumption (VO_2) measurements during different standardized laboratory testing protocols: Fornasiero et al. (2018) compared a maximum VO_2 step test with cross-country roller skis on a treadmill to the HR profile and power calculations during a SKIMO vertical race. Power output was calculated as the rate of work done to raise the body mass against gravity. Data of their high-level athletes (VO_{2max} 69 ±7 ml· kg^{-1}· min^{-1}) showed the importance of the power output at the second ventilatory threshold (VT2) with a $r^2 = 0.8$ compared to race performance. Those authors stated the difficulty of testing during actual racing as a primary limitation, which requires calculations and estimations of in field competition performance based on laboratory data. The HR-VO_2 relationship was also used by Duc et al. (2011) who analysed the time spent in various intensity zones, which they obtained from a maximum incremental step test in the field. Those authors used a three-zone model related to the determined ventilatory thresholds, respectively zone 1 below ventilatory threshold one (VT1), zone 2 between VT1 and respiratory compensation point (RCP) and zone 3 above RCP. When they analysed HR data during a 1:40 h individual race, most time was spent in zone 2 (51%) followed by zone 3 (41%) and zone 1 (7%). They noted that average racing HR was 93% of maximum HR. These findings are in agreement with Schenk et al. (2011) who reported high cardiopulmonary strain as well, spending 80.2% in high intensity zones. Since there are often two races on consecutive days during the ISMF World Cup season, the influence of a vertical race on the performance of an individual race on the following day was investigated as well by Gaston et al. (2019). Those authors carried out

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various cardiorespiratory measurements before and after the races and found a negative influence of a vertical race the day before an individual race and showed the necessity of a pronounced recovery.

This high intensity strain and the associated regeneration are strongly influenced by the available energy. For multi hour races, like the Patrouille des Glaciers (PDG), energy consumption can be compared to a long-distance triathlon or a mountain stage at the Tour de France (Praz et al., 2014). Praz et al. (2014) critically reviewed their estimation of the energy expenditure by the application of the VO_2-HR relationship in terms of obtaining VO_{2max} from a treadmill running test instead of a SKIMO specific test, and did not consider the athlete´s race excitement and cardiac drift during the race. But they implemented an individual high-altitude correction, which adjusted the results.

While the published literature demonstrates the strain of SKIMO racing, there is still a lack of detailed analysis during racing, especially of high-level athletes. Data acquisition during a SKIMO race is necessary as to not be dependent on the HR-VO_2 relationship and the associated equations. With respect to VO_2 measurements, collecting data during a race is not feasible due to the necessity of wearing a breathing mask and additional measurement equipment. A race simulation has the advantage of not needing to adhere to rules and being able to equip the athletes with the necessary measuring devices. In order to link race performance to the athlete´s physiological capabilities, an additional SKIMO specific laboratory test on the treadmill seems crucial. While a race simulation gets us as close to a real race as possible and targets specificity, a standardized laboratory ramp test allows reproducibility and in a sport practical context the longitudinal tracking of athlete performance.

Therefore, the first goal of this study was to measure the physiological responses of a simulated vertical race in comparison to a SKIMO specific laboratory test. The second goal was to extract performance predicting parameters based on the simulated race and the laboratory test with respect to two performance groups. We hypothesized, that (1) elite athletes would achieve higher values in key endurance performance indicators (e.g. VO_2max, maximum velocity or performance at VTs) during the specific laboratory test, that (b) elite athletes would perform at a higher fractional utilization of their VO_{2max} during the field test, and that (3) elite athletes reveal a higher cadence and longer step length to realize the expected higher walking speed.

Methods

The University ethics committee approved this study (EK-GZ: 36/2018) and all participants provided informed consent. This investigation consisted of two measurement sessions for each athlete with at least 48 hours in between and within a time period of two weeks. One session was a performance diagnostics test in the laboratory and the other was a simulated single start vertical race in the field. Due to the time between the two sessions, testing order was not a necessity.

Twenty-one male athletes were recruited personally based on their performances during the past SKIMO season (see Table 1). All are experienced athletes and participated in various SKIMO races. The following criteria were used to divide the participants into elite and sub-elite categories: participants were considered elite if they (a) were a member of the Austrian National Team, (b) had competed at European Championship, World Championship or World Cup races, or (c) had race results similar to the National Team athletes. The number of athletes tested was affected by the availability of elite athletes, which was the limiting factor. To avoid overrepresentation of sub-elite athletes, 1.5 sub-elite athletes were included per elite athlete. Skiers used their own race equipment for both the laboratory and field test and were used to races as well as to SKIMO specific VO_2 testing on the treadmill.

Measurement procedure

The same measurement systems and equipment were used in the field test as for the laboratory test. Heart rate was measured with a Wahoo Tickr HR belt (Wahoo, California, USA) and stored on a Suunto Ambit3 sports watch (Suunto, Vantaa, Finland), while a Cosmed K5 measured pulmonary characteristics and gas exchange (Cosmed, Rome, Italy). The K5 portable metabolic system was used in mixing chamber mode due to the high ventilations over an extended time period. To provide an individual index of metabolic strain, six lactate samples were taken from the earlobe. The first sample was collected at rest prior to the preparation of the participant, the second immediately after the warm-up, and then at 1, 3, 5, and 10 minutes after the test. All lactate samples were analysed with an EKF Diagnostics Biosen C-line (EKF, Magdeburg, Germany).

A Pomocup inertial sensor (Pomoca, Denges, Switzerland) was placed on the ski, in front of the toe binding, and measured stride characteristics of step cadence (C) and step length (SL). The non-accessible raw data were recorded at 1200 Hz and processed with an automatic algorithm (Gellaerts et al., 2018).

Field test procedures

The simulated vertical race took place during April in the ski area of Obertauern, Austria. The start of the run was at an altitude of 1668 m and the finish at 2200 m, which

Table 1. Age and anthropometrics.

	Overall (n = 21)	Elite (n = 8)			Sub-elite (n = 13)			
	Mean ± SD	Mean ± SD	Min	Max	Mean ± SD	Min	Max	p-values
Age (years)	31.3 ± 8.8	32.3 ± 9.5	23	47	30.7 ± 8.7	20	46	0.705
Body height (m)	1.82 ± 0.06	1.84 ± 0.06	1.71	1.91	1.81 ± 0.06	1.68	1.90	0.335
Body mass (kg)	73.7 ± 8.1	72.6 ± 7.4	61.0	81.5	74.3 ± 8.7	53.0	84.0	0.645
BMI ($kg \cdot m^{-2}$)	22.2 ± 2.0	21.4 ± 1.3	19.4	23.0	22.6 ± 2.3	18.7	24.9	0.121

BMI, body mass index; SD, standard deviation results in an altitude gain of 532 m and a length of 2710 m, representing habitual training altitude of all athletes. The ski run was labelled as a red ski run, which means being average difficulty without tremendous steepness. To ensure good conditions, all tests took place in the morning before the snow started getting wet and soft because of warm spring temperatures. Due to natural fluctuation, snow conditions were compact machine snow, as well as fresh snow and spring snow. Same variations occurred for air temperature, which was between -6° C and +7° C in the finish.

After instrumenting the athlete with the measuring set up, a standardized warm up route (150 m elevation gain) was covered by every athlete at self-selected speed. After that, all systems were set to record, and the simulated race was started. The route was easy to navigate due to several marks with no chance to go astray. Simulated race time was taken via a stopwatch and time defined as performance. Two investigators waited for the athlete at the finish of the run to stop all systems, collect blood samples and take care of the athletes.

Laboratory test procedures

The laboratory test had two main goals, first collecting anthropometric data, and second to test physiological capacities of the athletes. The performance test was completed on a 300 x 125 cm h/p/cosmos treadmill (h/p cosmos sports, Traunstein, Germany) with standard SKIMO racing equipment (same as for the field test) at an altitude of 450 m. The test included a standardized warm up of ten minutes at 20% elevation and 3.4 km·h^{-1}. After the warm up, a ramp protocol at a constant elevation of 24% was performed starting at 3.4 km·h^{-1} and accelerating 0.4 km·h^{-1} every minute with the goal to achieve maximal oxygen uptake (VO_{2max}) between 7 and 11 minutes (Astorino et al., 2004). Ventilatory thresholds were determined by a combination of the v-slope method and ventilatory equivalencies (Gaskill et al., 2001; Kroidl et al., 2015) and assessed by two researchers.

Statistical analysis

For statistical calculations SPSS (IBM Corporation, Version 25) was used. Shapiro Wilk test was used to check for normal distribution. An independent t-test or the Mann-Whitney-U test was used for comparison of mean values between performance groups. Pearson´s correlation coefficient was used to describe relationships between various parameters. Level of significance was set at $\alpha = 0.05$. Parameters with a correlation coefficient of $p < 0.1$ were integrated in the stepwise multiple regression analysis. All data are listed as mean ± standard deviation.

Results

Comparison of performance groups

The field test data are presented in Table 2. Performance, for the present study, is defined as the completion time during the simulated vertical race. Simulated race time was 5:16 min lower in the elite versus sub-elite group ($p < 0.001$), which means the sub-elite group needed 19% more time to complete the course. The same results occur for walking velocity and vertical velocity, since these parameters are derived from race time (both $p < 0.001$). Neither mean HR nor peak HR during the race were different between performance groups ($p > 0.05$). In contrast, VO_{2mean} was on average 7.6 ml·min^{-1}·kg^{-1} (13%) lower for the sub-elite athletes than the elite athletes ($p = 0.046$). Concerning breathing characteristics, elite athletes demonstrated greater ventilation (VE) ($p = 0.049$) while no difference was found in respiratory rate (RR). Lactate values for the field test are presented in Figure 1A. While peak lactate was not different between groups, lactate concentrations after minute 5 ($p = 0.044$) and 10 ($p = 0.049$) were about 20% greater in the elite group compared to the sub-elite group.

The parameters from the laboratory test are presented in Table 3. Comparison of the two performance groups revealed differences concerning their maximum velocity (elite: 7.4 ± 0.3 km·h^{-1}; sub-elite: 6.6 ± 0.3 km·h^{-1};

Table 2. In-field vertical race performance and physiological response.

	Overall (n = 21)	Elite (n = 8)			Sub-elite (n = 13)			
	Mean ± SD	**Mean ± SD**	**Min**	**Max**	**Mean ± SD**	**Min**	**Max**	**p-values**
T (mm:ss)	30:31 ± 03:13	27:15 ± 01:16	25:29	28:39	32:31 ± 2:13	30:24	37:00	**< 0.001**
V (km·h^{-1})	5.4 ± 0.6	6.0 ± 0.3	5.7	6.4	5.0 ± 0.3	4.4	5.3	**< 0.001**
V vertical ($m_{vertical}$·h^{-1})	1056 ± 111	1173 ± 56	1113	1251	985 ± 63	863	1050	**< 0.001**
HR_{mean} (bpm)	175 ± 10	174 ± 11	161	190	176 ± 9	161	192	0.636
HR_{mean} in % HR_{max}	92.3 ± 1.8	92.3 ± 1.5	89.9	94.6	92.4 ± 1.5	89.8	95.6	0.988
HR_{peak} (bpm)	183 ± 11	182 ± 14	166	203	184 ± 9	169	201	0.677
HR_{peak} in % HR_{max}	96.5 ± 2.3	96.7 ± 3.2	93.1	103.2	96.3 ± 1.8	93.6	100	0.857
VO_{2mean} (ml·min^{-1}·kg^{-1})	54.2 ± 8.3	58.9 ± 8.4	46.1	68.1	51.3 ± 7.5	39.7	66.5	**0.046**
VO_{2mean} in % VO_{2max}	82.2 ± 10.0	82.9 ± 11.7	64.3	97.3	81.8 ± 9.4	61.1	95.6	0.823
VO_{2peak} (ml·min^{-1}·kg^{-1})	62.8 ± 8.7	67.8 ± 10.3	50.8	80.5	59.6 ± 6.6	48.2	68.4	**0.040**
VO_{2peak} in % VO_{2max}	96.4 ± 11.3	98.3 ± 14.9	70.9	115.4	95.3 ± 9.1	73.9	108.8	0.591
RER_{mean}	0.92 ± 0.14	0.92 ± 0.16	0.84	1.07	0.93 ± 0.12	0.81	1.1	0.846
VE_{mean} (l·min^{-1})	137 ± 22	149 ± 21	132	182	129 ± 20	82	163	**0.049**
RR_{mean} (breaths·min^{-1})	49.8 ± 8.2	51.4 ± 6.4	41.3	62.2	48.8 ± 9.3	37.8	62.7	0.497
SL (m)	0.86 ± 0.07	0.89 ± 0.07	0.79	0.97	0.85 ± 0.06	0.75	0.99	0.194
C (steps·min^{-1})	103 ± 9	108 ± 9	93	118	101 ± 8	91	118	0.102

SD, standard deviation; t, time; v, velocity; HR, heart rate; VO_2, oxygen uptake; RER, respiratory exchange ratio; VE, ventilation; RR, respiratory rate; SL, step length; C, cadence.

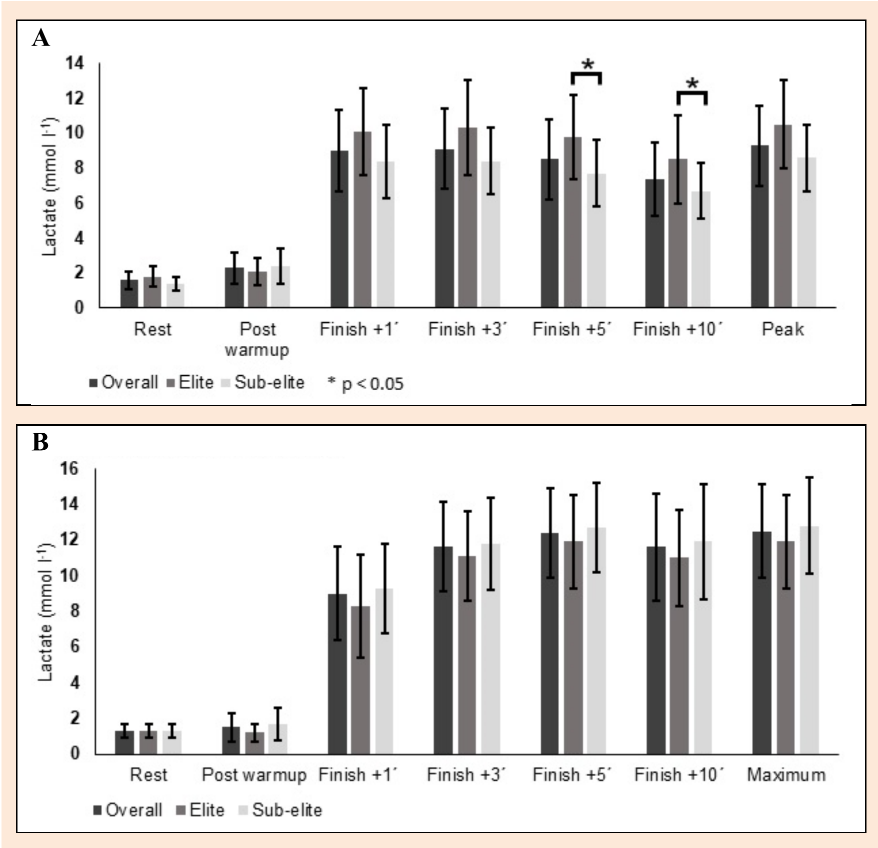

Figure 1. A. Lactate field test. B. Lactate laboratory test.

Table 3. Laboratory performance.

	Overall (n = 20)	Elite (n = 7)			Sub-elite (n = 13)			
	Mean ± SD	Mean ± SD	Min	Max	Mean ± SD	Min	Max	p-values
V @VT1 ($km \cdot h^{-1}$)	4.5 ± 0.5	4.7 ± 0.6	3.8	5.4	4.4 ± 0.4	3.8	5.0	0.157
V @VT2 ($km \cdot h^{-1}$)	5.8 ± 0.6	6.3 ± 0.6	5.8	7.4	5.5 ± 0.4	5.0	6.2	**0.008**
V_{max} ($km \cdot h^{-1}$)	6.9 ± 0.5	7.4 ± 0.3	7.0	7.8	6.6 ± 0.3	6.2	7.3	**< 0.001**
HR_{warmup} (bpm)	126 ± 14	116 ± 14	95	135	133 ± 10	118	148	**0.006**
HR @VT1 (bpm)	160 ± 13	156 ± 13	141	179	162 ± 13	137	178	0.381
HR @VT2 (bpm)	178 ± 11	179 ± 9	163	192	178 ± 12	159	195	0.815
HR_{max} (bpm)	190 ± 11	190 ± 11	174	208	190 ± 11	172	208	0.485
$VO_{2warmup}$ ($ml \cdot min^{-1} \cdot kg^{-1}$)	27.8 ± 6.2	24.3 ± 8.2	8.7	31.6	29.6 ± 3.9	21.4	35.2	0.067
VO_2 @VT1 ($ml \cdot min^{-1} \cdot kg^{-1}$)	46.4 ± 6.9	50.2 ± 8.9	36.6	60.8	44.3 ± 4.9	34.2	53.7	0.071
VO_2 @VT1 in % VO_{2max}	70.7 ± 7.5	70.1 ± 9.6	57.1	87.7	71.1 ± 6.7	62.2	81.3	0.814
VO_2 @VT2 ($ml \cdot min^{-1} \cdot kg^{-1}$)	57.8 ± 6.0	62.6 ± 5.4	55.2	68.6	55.3 ± 4.6	47.6	63.1	**0.005**
VO_2 @VT2 in % VO_{2max}	88.5 ± 7.0	88.1 ± 5.7	80.5	95.4	89.1 ± 8.1	75.3	98.7	0.840
VO_{2max} ($ml \cdot min^{-1} \cdot kg^{-1}$)	65.6 ± 6.8	71.2 ± 6.8	64.1	85.1	62.5 ± 4.7	54.1	69.5	**0.003**
RER @VT1	0.93 ± 0.07	0.92 ± 0.1	0.83	1.06	0.94 ± 0.04	0.88	1.02	0.393
RER @VT2	1.05 ± 0.1	1.05 ± 0.12	0.9	1.21	1.05 ± 0.09	0.89	1.19	0.899
RER_{max}	1.2 ± 0.1	1.16 ± 0.12	1.0	1.31	1.22 ± 0.08	1.09	1.38	0.259
VE @VT1 ($l \cdot min^{-1}$)	84 ± 14	87 ± 15	64	706	83 ± 13	62	106	0.529
VE @VT2 ($l \cdot min^{-1}$)	120 ± 17	124 ± 16	96	149	118 ± 18	78	141	0.474
VE_{max} ($l \cdot min^{-1}$)	166 ± 20	164 ± 26	132	206	167 ± 17	140	194	0.760
RR @VT1 ($breaths \cdot min^{-1}$)	30.0 ± 4.4	28.7 ± 2.4	26.4	32.8	30.7 ± 5.1	22.6	39.9	0.356
RR @VT2 ($breaths \cdot min^{-1}$)	37.6 ± 5.6	35.5 ± 3.9	31.2	41.5	38.8 ± 6.2	29.1	46.5	0.219
RR_{max} ($breaths \cdot min^{-1}$)	53.8 ± 8.0	49.5 ± 6.5	42.1	61.9	56.1 ± 8.1	40.1	68.9	0.075
SL_{mean} (m)	0.78 ± 0.07	0.83 ± 0.06	0.76	0.91	0.75 ± 0.07	0.62	0.87	**0.035**
SL_{max} (m)	0.89 ± 0.07	0.94 ± 0.06	0.85	1.03	0.87 ± 0.07	0.74	1.01	**0.046**
C_{mean} ($steps \cdot min^{-1}$)	97 ± 7	99 ± 7	87	109	96 ± 6	85	112	0.314
C_{max} ($steps \cdot min^{-1}$)	137 ± 9	141 ± 6	134	151	135 ± 9	120	149	0.139

SD, standard deviation; V, velocity; VT1, ventilatory threshold 1; VT2, ventilatory threshold 2; HR, heart rate; VO_2, oxygen uptake; RER, respiratory exchange ratio; VE, ventilation; RR, respiratory rate; SL, step length; C, cadence

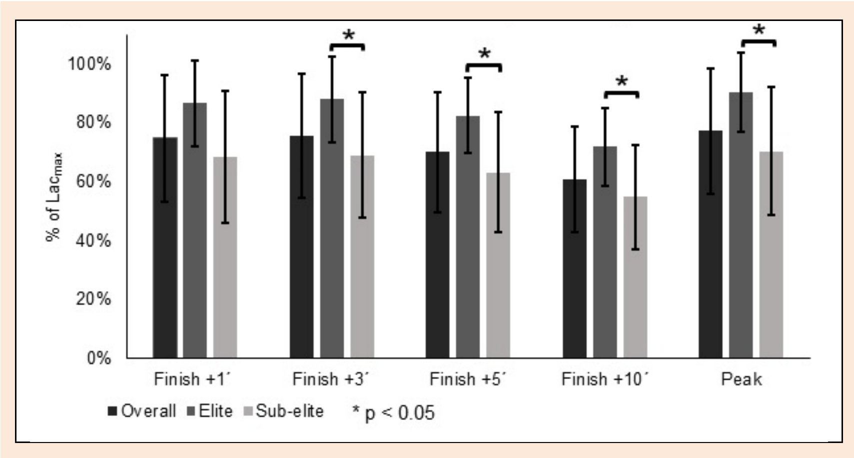

Figure 2. **Lactate after the field test in % of maximum during the laboratory test.**

Table 4. **Correlation of field parameters concerning performance.**

		BMI	Lac_{peak} in % Lac_{max}	VO_{2mean}	VO_{2peak}	VE_{mean} in % VE_{max}	VE_{peak} in % VE_{max}	RR_{mean} in % RR_{max}	SL_{mean}
Racetime	r	0.432	-0.418	-0.474	-0.501	-0.446	-0.473	-0.541	-0.483
	p	0.05	0.067	0.035	0.024	0.055	0.041	0.017	0.031

r, Pearson´s correlation coefficient; BMI, body mass index; Lac, lactate; VE, ventilation; RR, respiratory rate; SL,steplength.

Table 5. **Correlation of laboratory parameters concerning performance.**

		v_{max}	v @ VT1	v @ VT2	HR_{warmup}	VO_2 @ VT1	VO_2 @ VT2	VO_{2max}	RER_{max}	SL_{mean}	SL_{max}	C_{max}
Racetime	r	-0.783	-0.563	-0.616	0.568	-0.607	-0.694	-0.700	0.397	-0.473	-0.378	-0.452
	p	< 0.001	0.010	0.004	0.009	0.005	0.001	< 0.001	0.083	0.035	0.100	0.046

r, Pearson´s correlation coefficient; v, velocity; HR, heart rate; VO_2, oxygen uptake; RER, respiratory exchange ratio; SL, step length; C, cadence.

$p < 0.001$) and their velocity at VT2 (elite: 6.3 ± 0.6 km·h^{-1}; sub-elite: 5.5 ± 0.4 km·h^{-1}; $p = 0.008$). Similar to the simulated race, no differences were found for HR. Only during the standardized warm up, HR was significantly lower for the elite athletes ($p = 0.006$). Relative VO_2 was greater for elite athletes at VT2 ($p = 0.005$) and at maximum exertion ($p = 0.003$) compared with the sub-elite group. A strong trend for lower VO_2 during the warm up and higher VO_2 at VT1 for the elite athletes was found (both $p = 0.07$). No differences were observed between groups for ventilatory characteristics. While there was no difference between groups for step length (SL) during the race simulation, average and maximum SL was greater for elite athletes during the laboratory test ($p = 0.035$ and $p = 0.046$). Lactate values did not differ between the groups during the laboratory test (Figure 1B.).

Lactate values were also compared between the race simulation in the field and the ramp test in the laboratory independent of the performance group. After the physical exertion, except for the lactate sample in the first minute ($p = 0.96$), all lactate values were lower during the field test compared to the laboratory test ($p < 0.001$).

Furthermore, field lactate values relative to the maximum lactate values reached during the laboratory test were greater for elite athletes after three, five and ten minutes, as well as for the peak value compared to sub-elite athletes (all $p < 0.05$) (Figure 2).

Performance determining parameters

Table 4 and 5 contain those parameters which are significantly correlated with performance or show a trend ($p < 0.1$). Measuring parameters from the field reach from r = -0.418 (Lac_{peak} in % Lac_{max}) to -0.541 (RR_{mean} in % RR_{max}). While measuring parameters from the laboratory test reach from r = -0.378 (SL_{max}) to -0.783 (v_{max}).

All the parameters from Tables 4 and 5 were included in the multiple regression analysis for vertical race performance and revealed following predicting model:

$$Performance\ (time) = 4043.4 - 250.1 * v_{max} - 2.6 * Lac_{peak}\ in\ \%\ Lac_{max} - 4.8 * VO_{2peak} \qquad r^2 = 0.84;\ p < 0.001$$

While all other parameters were eliminated from the model, these three remained and explained 84% of the performance variation.

Discussion

With respect to the goals of the study, the results will now be discussed concerning the superiority of elite athletes over sub-elite athletes and SKIMO performance determining parameters. As hypothesized (1) elite athletes showed their superiority concerning performance parameters like VO_{2max} or performance at the VTs over sub elite athletes in the laboratory test. The second hypothesis could not be confirmed, since no difference in fractional VO_2 utilization during the field test was found. The third hypothesis could be confirmed partially with longer SL for elite athletes during the step test but no difference concerning C, neither during the field test, nor during the laboratory test. Schenk et al. (2011) suggest that SKIMO is one of the most strenuous endurance exercises. Duc et al. (2011) reported an average HR of 93.4 ± 1.8% of HR_{max} during a 1:40 h race and Gaston et al. (2019) reported an average of 93.1 ± 3.1% of HR_{max} for a vertical race. These findings are in agreement with those of the current study where an average HR of 175 ± 10 bpm, which corresponds to 92.3% of HR_{max}, was observed during the vertical race. While HR_{peak} reached 183 ± 11 bpm, which is equal to 96.5% of HR_{max}. Heart rate data confirms the fact that SKIMO is a strenuous sport similar to a mountain time trial performance in road cycling (96% of HR_{max}) (Padilla et al., 2000), a mountain bike cross-country time trial (92% of HR_{max}) (Gregory et al., 2007), a 10 km running race (Esteve-Lanao et al., 2008), or a cross-country skiing race (90-95%) (Mognoni et al., 2001). For the first time, VO_2 was measured on SKIMO athletes in the field during a simulated competition. In support of our interpretation of the HR data, the mean VO_2 during the race was 54.4 ± 8.6 ml· kg^{-1}· min^{-1} and VO_{2peak} was 62.8 ± 8.7 ml· kg^{-1}· min^{-1} which correspond to 82.5% and 96.4% of VO_{2max}, respectively. In addition to that, a mean respiratory exchange ratio (RER) of 0.92 during the race simulation confirms a hard effort. For three athletes, a VO_{2peak} value > 100% VO_{2max} was found. Since the laboratory test was at a fixed (maximum) grade of 24%, we would expect athletes to have troubles reproducing high velocities towards the end of the test due to technical insufficiencies.

Since athletes were stratified in two performance groups (elite vs. sub-elite), it is possible to address differences of elite athletes compared to the sub-elite athletes. Relative HR and VO_2 data during the simulated vertical race did not reveal any difference between the two groups. This indicates similar relative energetic strain for all athletes. However, the elite athletes demonstrated greater absolute VO_2 (+14.8%) and VE (+15.5%). This could lead to greater race velocity, vertical velocity and lower race time. Only lactate values at 5 and 10 minutes after the simulated vertical race indicate a greater metabolic strain for elite athletes. Furthermore, the comparison of field lactate values relative to the maximum values reached during the laboratory test (see Fig.2) suggest elite athletes were closer to their maximum values compared to the sub-elite (90.3% versus 70.2%). This can be either because of less effort of the elite during the treadmill testing or greater effort during the field test. Since lactate values in the laboratory did not differ significantly, a greater metabolic strain during or at least in the last section of the field test for the elite athletes might be an explanation. But as discussed, neither VO_2, nor HR or RER could confirm a higher strain for elite athletes.

During the SKIMO specific maximum ramp test on the treadmill, elite athletes showed their supremacy as well. Various performance related parameters such as VO_{2max}, VO_2 at VT2, v_{max} and velocity at VT2 revealed greater values for elite athletes. In accordance with the race simulation, HR data at VT1, VT2 and maximum revealed no difference, which suggests similar cardiovascular strain for both performance groups.

For the first time in reported literature, VO_2 was measured on SKIMO athletes in the field during a simulated competition. The importance of VO_2 analysis can be demonstrated in two ways. Firstly, correlation coefficients over all athletes show a significant correlation between the performance during the simulated race (time) and the VO_2 at VT1, at VT2 and maximum, as well as for the VO_{2mean} and VO_{2peak} during the field test. This demonstrates the strong connection between VO_2 and vertical race performance. Secondly, there were differences for all VO_2 parameters between the groups, which demonstrates, that those who were supposed to be elite athletes showed greater oxygen uptake and utilisation. Furthermore, VO_{2peak} was one of only three integrated parameters in the multiple regression analysis. In the link with VO_2, mean VE during the field test was greater for elite athletes. Endurance trained athletes are proven to have a better trained breathing system, compared to non-endurance trained people (Martin and Stager, 1981). But in endurance trained athletes an increase in exercise VE can not directly be linked to greater VO_2 or sports performance (Fairbarn et al., 1991). In agreement to that, we found no difference in the laboratory test for maximum VE. Our data merely allows the interpretation of elite athletes having a higher VE during the race simulation without any difference during the maximum laboratory test, which suggests a higher fractional VE.

Anthropometric data suggest possible advantages for athletes with a lower BMI over athletes with a greater one. Though the correlation of race time with BMI, and the difference in BMI between the performance groups were not significant, a trend was found ($p < 0.1$). But for this study, the sub-elite performance group was still performing on a high level and all were competitive skimountaineers. Fornasiero et al. (2018) found a significant correlation between race time and BMI, which supports our trend, that high-level skimountaineers to have a better power to weight ratio than lower level ski mountaineers do.

Basic elements of step characteristics (SL and cadence - C) were investigated as well. Aspects of these two parameters also show strong correlations with the vertical race performance. Step length correlation to performance can be explained by the necessity of optimising SL to realize faster walking speed. Furthermore, C_{max} during the laboratory test is negatively correlated to race performance. Which means, athletes who show their capability to reproduce higher C with a greater SL on the treadmill are more likely to be fast in a race. In cycling and cross-country skiing it was shown, that higher propelling frequency at constant speed, respectively power output, results in a higher VO_2 and HR (Gottshall et al., 1996; Lindinger and Holmberg, 2011). But in contrast to cycling, you cannot change gears in SKIMO. Which means, higher walking speed can only be reached by greater step length and cadence. Since step length is naturally limited, it seems plausible to aim for a broad spectrum of different cadences in SKIMO specific training.

Vertical race performance can be linked to various parameters. On the one hand the multiple regression analysis included v_{max} from the laboratory test, the ability to reach lactate levels closer to the maximum during the race simulation and VO_{2peak} during the field test. Approximately 84% of variation in race time can be explained by the regression. This analysis included not only field measurement parameters, but also parameters from the laboratory measurement, which further underlines the relevance of both sessions. Where the inclusion of VO_{2peak}, which is in line with VO_{2mean}, confirms the general more powerful aerobic system of elite athletes. The inclusion of v_{max} in the model suggests the time to exhaustion as a potent parameter for the categorization of athletes´ performance. But on the other hand, correlation coefficients link more parameters to performance. Mainly aspects of breathing, such as VE and VO_2, seem to be performance determining and should be a focus of further research as well as in the training process. In this study, velocity and VO_2 show clear evidence for power output at VT2 and maximum to be more important than at VT1. This might be explained by the average VO_2 of 89% of VO_{2max} at VT2. Which means, these two parameters are closely linked. Consequently, when preparing an athlete for a vertical race, it seems to be crucial to choose training methods to raise power at VT2 and at maximum. In this study we are not able to substantiate the importance of VT2 for longer race distances by evidence. We have observed that elite athletes are also superior in long races as shown by previous race results. But it is possible to elucidate the necessity of a sport specific performance diagnostics to estimate athletes´ capabilities and to derive training recommendation. VO_2 testing appears to be a proper choice to determine the performance at ventilatory indices and at maximum power output. This enables coaches to document the development of an athlete.

Limitations

Since field studies are a big challenge, it is difficult to provide standardized conditions. For winter sports in general weather can have a large impact on the snow, which results in a variety of snow conditions. Even though the field test was carried out on fresh snow, as well as on compact machine snow and on spring snow, conditions never were a limiting factor. Because of inclement environmental conditions, one data set of the portable metabolic system had to be removed due to a faulty signal. Altitude differences (laboratory at 440 m above sea level and race simulation 1668 m to 2200 m above sea level) were not considered. Changes in physiology are possible above 1500 m and could influence the comparison between the field and the laboratory measurements, but were expected to be small due to a good acclimatisation of ski mountaineers who spend a lot of time at higher altitudes (Park et al., 2016; Wilhite et al., 2013). A study with SKIMO athletes of Faiss et al. (2014) state a VO_{2max} reduction in simulated normobaric hypoxia (3000 m) compared to normobaric normoxia up to 18% for elite athletes and 12% for recreational skimountaineers, which indicates greater negative impact for elite athletes. But this study requested altitude absence prior to the measurements, which might wash out a possible long-term acclimatisation. On the basis of pre-test interviews with the athletes, no group differences were expected in our study.

Conclusion

For the first time, a portable metabolic system was used for field testing in a SKIMO racing simulation. In combination with other parameters, SKIMO racing can be stated as a very strenuous endurance sport. Physiology is highly involved (HR, VO_2 and lactate) and therefore must be prepared properly. It was possible to (a) name performance related parameters which correlate with the simulated vertical race time and (b) to show significant differences between the two performance groups, which might explain superiority of elite athletes. These findings might lead to a scientific analysis of training habits with the possibility to guide and optimise further training programs. To prepare athletes for a vertical race it appears crucial to maximize VO_2 and velocity at VT2. In terms of stride characteristics, athletes should aim for an optimization of SL, and work on increasing their cadence to be able to execute a faster walking speed. With the aim to further push SKIMO, athletic performance and scientific studies should target more specific the different disciplines and especially emphasize on the differences between those.

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Key points

- VO_2 measurements in the laboratory and the field confirm the high involvement of the aerobic system in SKIMO
- Elite athletes showed their supremacy in the laboratory test and the simulated vertical race
- Relative heart rate, relative VO_2 and lactate values indicate the same emphasized strain for elite and sub-elite athletes during SKIMO vertical racing.
- Peak speed, peak lactate and VO_{2max} were the highest in lab predictors of outdoor SKIMO vertical race performance.

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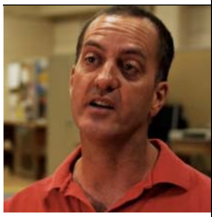

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