

ORIGINAL ARTICLE

Heat suit training increases hemoglobin mass in elite cross-country skiers

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Purpose: The primary purpose was to test the effect of heat suit training on hemoglobin mass (Hb_{mass}) in elite cross-country (XC) skiers.

Methods: Twenty-five male XC-skiers were divided into a group that added 5×50 min weekly heat suit training sessions to their regular training (HEAT; $n = 13$, 23 ± 5 years, 73.9 ± 5.2 kg, 180 ± 6 cm, 76.8 ± 4.6 ml·min⁻¹·kg⁻¹) or to a control group matched for training volume and intensity distribution (CON; $n = 12$, 23 ± 4 years, 78.4 ± 5.8 kg, 184 ± 4 cm, 75.2 ± 3.4 ml·min⁻¹·kg⁻¹) during the five-week intervention period. Hb_{mass} , endurance performance and factors determining endurance performance were assessed before and after the intervention.

Results: HEAT led to 30 g greater Hb_{mass} (95% CI: [8.5, 51.7], $p = 0.009$) and 157 ml greater red blood cell volume ([29, 285], $p = 0.018$) post-intervention, compared to CON when adjusted for baseline values. In contrast, no group differences were observed for changes in work economy, running velocity, and fractional utilization of maximal oxygen uptake ($\dot{V}O_{2\text{max}}$) at 4 mmol·L⁻¹ blood lactate, $\dot{V}O_{2\text{max}}$ or 15-min running distance performance trial during the intervention.

Conclusion: HEAT induced a larger increase in Hb_{mass} and red blood cell volume after five weeks with five weekly heat suit training sessions than CON, but with no detectable group differences on physiological determinants of endurance performance or actual endurance performance in elite CX skiers.

KEYWORDS

athletic performance, blood volume, endurance training, heat acclimatization, red blood cell volume

1 | INTRODUCTION

Cross-country (XC) skiing is a demanding endurance sport where energy expenditure changes with the terrain¹ and the metabolic demands often approach and exceed maximal oxygen uptake ($\dot{V}O_{2\max}$).² Accordingly, successful XC-skiing requires a high $\dot{V}O_{2\max}$,² and therefore, some of the highest $\dot{V}O_{2\max}$ values ever reported are held by elite XC-skiers.³ Hemoglobin mass (Hb_{mass}) is among the most important physiological variables determining $\dot{V}O_{2\max}$,⁴ and elite athletes strive to maximize Hb_{mass} . Traditionally, endurance athletes have applied altitude training to their training regimes to increase Hb_{mass} and thereby also increase $\dot{V}O_{2\max}$.⁵ However, due to logistical and economic burdens associated with altitude camps and travel restrictions, the elite endurance sports community has begun to explore alternative approaches for increasing Hb_{mass} and endurance performance. Among these strategies are the inclusion of heat stress combined with endurance training. Recent studies suggest that combining regular temperate training (mean temperature between 10°C and 20°C) with heat training sessions may favor the expansion of Hb_{mass} .^{6,7}

It was observed already in the 1950s that plasma volume (PV) increases during the warm summer and decreases during the cold winter, with red blood cell volume (RBCV) and circulating hemoglobin increasing and decreasing along with PV during warm and cold months, respectively,⁸ indicating that ambient temperature affects PV and erythropoietic activity. During the last decade, heat studies have revealed that if humans reside in their habitual (temperate) environment and regularly engage endurance training in combination with heat exposure (i.e., heat training), an increase of ~6% in PV can be expected after ~10 days.^{9,10} Moreover, Hb_{mass} and RBCV also increase in response to prolonged (~5 weeks) heat training performed in heat chambers.^{6,7} However, a recent review paper stated that there is a lack of prolonged studies (≥ 5 weeks) investigating the effects of heat training on hematological variables and endurance performance.⁵

A possible practical and cost-effective alternative to performing heat training in heat chambers may be to apply heat suits that retain the heat produced during exercise which has been shown to induce similar physiological responses as heat chamber exercise.¹¹⁻¹⁴ In line with this, in a recent case study, we documented the feasibility of heat suit training to increase Hb_{mass} in champion athletes.¹⁵ However, the potential effects of heat suit training compared to control training in well-trained XC-skiers remain to be investigated. Based on the above, the purpose of the present study was to examine the effects of 5 weeks of heat suit training (HEAT) combined with regular training against volume- and intensity-matched

training conducted without additional heat stress (CON) on hematological variables of importance for endurance performance and endurance performance.

2 | METHODS

2.1 | Participants

Twenty-nine elite XC-skiers and biathletes volunteered for the study. The biathletes and XC-skiers were equally distributed in each group and performed usual training during the intervention. Three athletes dropped out throughout the intervention period due to illness one withdrew due to personal reasons, and their data were excluded from the analysis. Thus, 25 athletes completed the study. A covariate adaptive randomization was performed based on the covariates maximal oxygen uptake ($\dot{V}O_{2\max}$) and age to constitute the two groups: HEAT ($n = 13$ (XC-skiers $n = 9$, biathletes $n = 4$); age, 23 (5) years; body mass, 73.9 (5.2) kg; body height, 180 (6) cm), and CON ($n = 12$ (XC-skiers $n = 11$, biathletes $n = 1$); age, 23 (4) years; body mass, 78.4 (5.8) kg; body height, 184 (4) cm). In the HEAT group, 7 participants competed nationally and 6 participants competed internationally, while in CON the number was 5 and 7 participants, respectively. All athletes signed an informed consent form before participation. The study was performed according to the ethical standards established by the Helsinki Declaration of 1975, including pre-registration in a public database (Norwegian Center for Research Data, project number 259131) and was approved by the local ethical committee at Inland Norway University of Applied Sciences (reference number: Sak 1-2020).

2.2 | Experimental design

Participants were tested (test procedures described later in this section) before and after a 5-week intervention. All testing was performed on one day and started with the measurement of hematocrit (HCT) and hemoglobin concentration ([Hb]) before the incremental running test to determine running economy, running velocity, and fractional utilization of $\dot{V}O_{2\max}$ at a blood lactate concentration ($[La^-]$) of 4 mmol·L⁻¹. After a 5-min recovery period, a $\dot{V}O_{2\max}$ test was performed after which a 10-min recovery period was given followed by a 15-min running performance test. Hb_{mass} and intravascular volumes were determined 25 min after the completion of the running performance test. The intervention was completed during the late part of the skiers' preparatory period (August-September). From two weeks prior to the start of the

intervention to after the intervention was finalized, all participants ingested 100 mg oral iron supplement daily (Nycoplus Ferro-Retard 100 mg, Takeda AS, Asker, Norway) to ensure adequate iron levels for erythropoiesis.

2.3 | Training intervention

Both groups continued to perform regular endurance training in their morning session. HEAT performed five weekly afternoon heat sessions with a low power output lasting 50 min during temperate conditions using their own bicycle mounted on a stationary power trainer (Tacx Neo Smart Trainer, Wassenaar, The Netherlands, Table 1). CON performed an equal amount of low-intensity afternoon training but was not restricted to complete this training on a bike (Table 2).

During heat training sessions, the participants were wearing clothing that limited heat loss, consisting of a wool layer on both the upper and lower body, a wool hat, nylon rain jacket, down jacket, and nylon pants with poor evaporative capacity and were instructed to drink 500 ml of water freely distributed across the 50 min of heat exercise. Fluid loss during the heat suit sessions was calculated by determining the change in nude bodyweight (813 scales, Seca GmbH & Co, Hamburg, Germany) after drying off sweat on the skin with a towel, subtracted by fluid intake. The training sessions were supervised, and room temperature, relative humidity (RH), heart rate (HR; measured with personal HR monitors), rate of perceived exertion (RPE; 6–20 scale¹⁶), thermal sensation,¹⁷ and power output were recorded after 5, 10, 15, 20, 30, 40, and 50 min and are presented as mean values (Table 1). The power output was individually adjusted to reach a rectal temperature of ~38.5°C measured 1–2 min after each session (Teknikproffset Nordic AS, Härryda,

Sweden). Fifteen minutes after each session, the participants rated their session rate of perceived exertion (SRPE 1–10 scale,¹⁸ Table 1). The participants were encouraged to rehydrate after the heat session and consume extra fluid until their urine had a normal pale yellow or straw color.¹⁹ There were no differences between HEAT and CON during the training intervention in mean weekly duration of training. Furthermore, the distribution of training time into heart rate intensity zones²⁰ (zone 1: 55–71% HR_{max}, zone 2: 72–81% HR_{max}, zone 3: 82–87% HR_{max}, zone 4: 88–92% HR_{max}, and zone 5: ≥93% HR_{max}) and total training load (calculated as time spent in intensity zone 1–5 multiplied by a factor of 1–5, respectively¹⁸) was similar in the two groups. Since all heat sessions were completed on stationary cycles, the HEAT group had a greater cycling training duration than CON, while there were no other significant differences between the groups (Table 2). Perceived training load was registered on a scale from 1 (extremely easy) to 10 (maximally heavy) daily in the training diary.

2.4 | Exercise test protocol

Both groups performed a standardized training routine during the two days preceding laboratory testing. During the first visit to the laboratory, all participants reported their three last meals and fluid intake and their training 48 h before the test. Three days prior to tests performed after the intervention period, each of the participants was informed of their training and nutritional preparations prior to the pre-intervention test and were instructed to repeat this for the post-test. During pre-test HEAT and CON consumed similar amount of water (2.8 ± 2.1 and 3.1 ± 3.1 ml·kg⁻¹, respectively, $p = 0.88$) and sports drink (5.0 ± 2.5 and 4.8 ± 3.2 ml·kg⁻¹, respectively, $p = 0.89$).

TABLE 1 Heat suit session data during the 5-week intervention period, presented as weekly average data collected during and after each session for the XC-skiers training in a heat suit in temperate conditions

Variable	Session 1–5	Session 6–10	Session 11–15	Session 16–20	Session 21–25
Room temperature (°C)	15.8 ± 1.3	16.0 ± 1.7	16.7 ± 2.2	16.3 ± 2.4	16.2 ± 2.5
Relative humidity (%)	57.0 ± 7.5	55.6 ± 5.3	53.4 ± 5.1	56.9 ± 9.4	59.7 ± 8.0
Power output (W)	142 ± 13	140 ± 15	143 ± 18	145 ± 17	149 ± 16
Heart rate (bpm)	142 ± 10	136 ± 11	134 ± 10	134 ± 9	135 ± 9
Rectal temperature (°C)	38.9 ± 0.4	38.6 ± 0.2*	38.5 ± 0.2*	38.5 ± 0.2*	38.5 ± 0.2*
Fluid loss (L)	1.61 ± 0.33	1.68 ± 0.34	1.68 ± 0.38	1.69 ± 0.37	1.73 ± 0.35
Thermal sensation (0–8)	6.3 ± 0.3	6.1 ± 0.2	6.1 ± 0.3	6.0 ± 0.2*	5.9 ± 0.4*
RPE (6–20)	11.6 ± 0.9	10.9 ± 1.4	11.0 ± 1.5	10.7 ± 1.1	10.6 ± 0.9
Session RPE (1–10)	3.7 ± 1.4	3.0 ± 1.1	3.0 ± 1.1	2.9 ± 1.0	2.7 ± 0.9

Note: Mean ± SD. Asterisk indicate different from Session 1–5 ($p < 0.05$).

Abbreviation: RPE, rate of perceived exertion.

TABLE 2 Weekly training data for the heat suit training group (HEAT) and the control group (CON) during the 5-week intervention period

	HEAT	CON	<i>p</i> -value
Total duration (h)	16.77 ± 2.37	16.55 ± 4.57	0.88
Zone 1 (h)	12.22 ± 2.23	12.40 ± 3.71	0.89
Zone 2 (h)	0.67 ± 0.63	0.71 ± 0.78	0.89
Zone 3 (h)	0.77 ± 0.27	0.86 ± 0.29	0.42
Zone 4 (h)	0.51 ± 0.22	0.55 ± 0.20	0.65
Zone 5 (h)	0.20 ± 0.13	0.15 ± 0.09	0.34
TRIMP (au)	1092 ± 226	1154 ± 275	0.55
Running (h)	4.20 ± 1.79	4.94 ± 1.97	0.35
Roller skiing (h)	5.78 ± 1.91	6.29 ± 4.44	0.72
Cross-country skiing (h)	0.30 ± 0.68	1.91 ± 3.54	0.13
Cycling (h)	4.06 ± 1.44	1.18 ± 1.17	<0.01
Strength training (h)	1.32 ± 0.54	1.26 ± 0.76	0.81
Speed/power training (h)	0.18 ± 0.13	0.20 ± 0.23	0.75
Other (h)	0.09 ± 0.14	0.21 ± 0.60	0.53
Perceived training load (1–10)	4.31 ± 1.02	4.18 ± 0.69	0.83

This intake and distribution of it were noted and replicated at post-test. All tests were performed under similar environmental conditions (16–19°C) with airflow of 2–3 m·s⁻¹ towards the participants' frontal surface. Strong verbal encouragement was given during all tests to ensure maximal effort. All tests for the individual participant were conducted at the same time of day (±1 h) to limit the influence of circadian rhythms. All testings were performed on the same treadmill (Lode Katana, Lode B.V., Groningen, The Netherlands) with a 10.5% inclination.

The blood lactate profile test started with 5-min running at 6.6 km·h⁻¹, which was subsequently increased by 0.9 km·h⁻¹ every 5 min. Between consecutive 5-min bouts, there was a 1-min break, wherein blood was sampled from a fingertip and analyzed for whole blood lactate concentration ([La⁻]) using a Biosen C-line lactate analyzer (EKF Diagnostic GmbH, Barlebe, Germany). The test was terminated when a [La⁻] of 4 mmol·L⁻¹ or higher was measured. $\dot{V}O_2$ and HR were measured during the last 3 min of each bout, and mean values were used for statistical analysis. $\dot{V}O_2$ was measured (30 s sampling time) using a computerized metabolic system with a mixing chamber (Oxycon Pro, Erich Jaeger, Hoechberg, Germany). Before every test, the gas analyzers were calibrated with certified calibration gases of known concentrations. The flow turbine (Triple V, Erich Jaeger, Hoechberg, Germany) was

calibrated before every test with a 3 l, 5530 series, calibration syringe (Hans Rudolph, Kansas City, USA). HR was recorded using the participants own heart rate monitors (same at pre- and post-testing). From this incremental running test, the running velocity at 4 mmol·L⁻¹ [La⁻] was calculated for each athlete using the relationship between [La⁻] and running velocity using linear regression between data points. In order to ensure mainly aerobic metabolism, running economy (determined by the mean $\dot{V}O_2$) was measured at the highest velocity during the blood lactate profile where the mean blood lactate across both groups was below 2 mmol·L⁻¹ [La⁻], equal to a running velocity of 8.4 km·h⁻¹ (1.63 ± 0.61 mmol·L⁻¹ [La⁻]).

After the blood lactate profile test was terminated, the participants had 5 min of recovery before completing another incremental running test for determination of $\dot{V}O_{2max}$. This test was initiated with 1-min running at 8 km·h⁻¹, where the speed was increased by 1 km·h⁻¹ every minute until exhaustion. The athletes received strong verbal encouragement to run as long as possible. $\dot{V}O_2$ was measured continuously, and $\dot{V}O_{2max}$ was calculated as the mean of the two highest subsequent 30 s measurements. Time to exhaustion (s) during this incremental running test was registered. Following the $\dot{V}O_{2max}$ test, the participants had a 10-min recovery period before they performed a 15-min running test, where the aim was to run as far as possible. Participants controlled their running velocities after the initial minute, where the velocity was set to the velocity associated with 4 mmol·L⁻¹ [La⁻] from the blood lactate profile. The participants were blinded for the running distance during the test.

2.5 | Hematology

After arrival at the laboratory, before commencing the exercise testing, the participants drank 300 ml water and were placed in a semi-recumbent position for 15 min with a heat bag in the hand (to increase the blood flow) thereafter capillary blood was sampled from a fingertip for determination of hematocrit (HCT) using the microhematocrit method (70 IU ml⁻¹ Hemato-Clad, Drummond, Scientific Company, Broomall, PA, USA), centrifuged (Heraeus PICO 17 Hematocrit Rotor, Thermo Electron LED GmbH, Osterode, Germany) for 5 min at 13500 rpm) and determination of [Hb] (ABL800; Radiometer, Copenhagen, Denmark). The mean value of three measurements for both HCT and [Hb] were used for subsequent Hb_{mass} and intravascular volumes calculations. All exercise tests were performed after obtaining this blood sample. Twenty-five minutes after finalizing the last exercise test, the participants were placed in a semi-recumbent position for 5 min before Hb_{mass} was determined using a modified version of

FIGURE 1 Individual and group-average values of hemoglobin mass (left panel) and red blood cell volume (right panel) expressed per body mass in response to training with heat suit (HEAT) and control conditions (CON). #HEAT led to increased hemoglobin mass (0.36 g kg^{-1} [0.02, 0.70], $p = 0.041$) and red blood cell volume (2.3 ml kg^{-1} [0.9, 3.8], $p = 0.003$) compared to CON

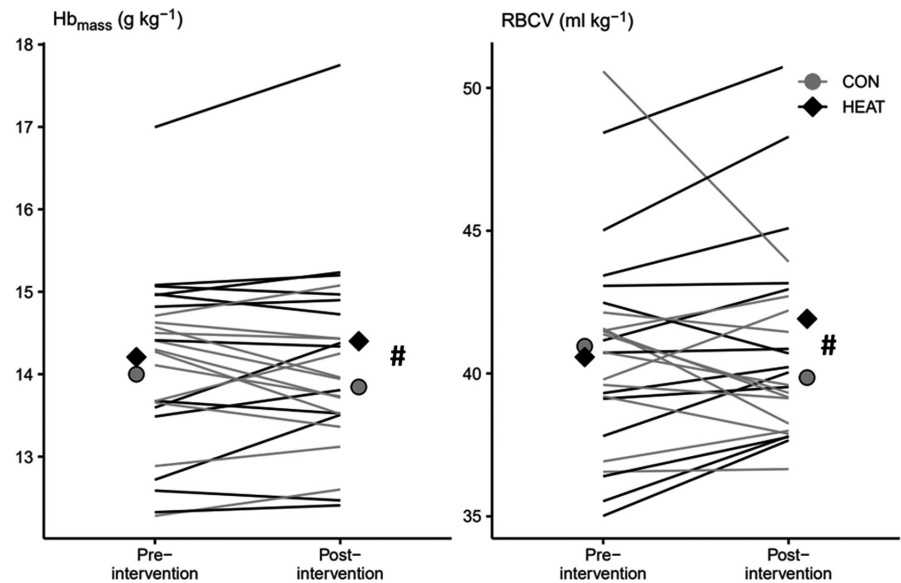


TABLE 3 Hematological variables before (Pre) and after (Post) the 5-week intervention period in the heat suit group (HEAT) and the control group (CON)

Hematological variable	Group	Pre	Post
Blood volume (ml)	CON	7088 (999)	6993 (762)
	HEAT	6535 (685)	6677 (787)
Hemoglobin ($\text{g}\cdot\text{dl}^{-1}$)	CON	15.6 (0.9)	15.7 (0.9)
	HEAT	16.1 (0.8)	16.0 (0.9)
Hemoglobin mass (g)	CON	1099 (114)	1089 (115)
	HEAT	1048 (119)	1067 (127) [#]
Hematocrit (%)	CON	45.5 (2.2)	44.8 (2.0)
	HEAT	45.7 (1.8)	46.5 (1.7) [#]
Plasma volume (ml)	CON	3865 (583)	3871 (462)
	HEAT	3544 (385)	3574 (461)
Red blood cell volume (ml)	CON	3222 (462)	3137 (359)
	HEAT	2990 (341)	3103 (365) ^a

^aHEAT had a larger increase from pre to post than CON ($p < 0.05$).

the carbon monoxide (CO) rebreathing technique (OpCO, Detalo Performance, Detalo Health, Birkerød, Denmark), described in detail elsewhere.²¹ The participant breathed 100% O₂ (AGA, Oslo, Norway) for 1 min before a blood sample was drawn from the fingertip (125 μl) and immediately analyzed in triplicate for carboxy-Hb (%HbCO) on a hemoximeter (ABL800; Radiometer). Subsequently, the participants rebreathed a bolus of chemically pure CO (AGA, Oslo, Norway) corresponding to $1.5 \text{ ml}\cdot\text{kg}^{-1}$ for 6 min. During the rebreathing period, O₂ was administered on a demand basis. The CO not taken up by the participants during the rebreathing period was determined by automatic assessments of the volume of the system multiplied with the PPMs (Dräger Pac 5500; Drägerwerk AG, Lübeck, Germany) for CO remaining in the system after the rebreathing period. Four minutes after the termination of the rebreathing, a second blood sample was drawn from the fingertip (125 μl) and immediately analyzed in

triplicate for %HbCO. All blood values were entered into the device software where Hb_{mass}, red blood cell volume (RBCV), total blood volume (BV), and plasma volume (PV) were calculated.

2.6 | Statistics

Descriptive statistics are presented as means with standard deviations (SD). Differences between groups (HEAT vs. CON) in post-intervention values (hematological, physiological, and performance variables) were modeled in linear models (ANCOVA) with pre-intervention values as the covariate and the grouping variable as the independent variable of interest. The power to detect a difference between treatments of similar magnitude as previously reported in cyclists for Hb_{mass}⁶ (effect size = 0.92) was determined to be 72% given the sample size of

the present study ($n = 25$, α -error rate = 0.05, unpaired t-test of change scores). Conclusions regarding differences between treatments were drawn using P -values < 0.05 as a cutoff to declare statistical significance. All inferential comparisons are presented with 95% confidence intervals (CI, (lower limit, upper limit)).

3 | RESULTS

3.1 | Effects of heat suit training on hematological variables

HEAT led to greater post-intervention hematocrit (1.58%-points, [0.25, 2.91], $p = 0.022$), RBCV (157 ml, [29, 285], $p = 0.018$, Figure 1) and Hb_{mass} (30.1 g, [8.5, 51.7], $p = 0.009$, Figure 1; see Table 3 for descriptive statistics) when compared to CON and adjusted for baseline values. However, HEAT did not affect post-treatment values in PV (-61 ml, [-318 , 197], $p = 0.629$), BV (131 ml, [-190 , 452], $p = 0.407$) or [Hb] (0.07 g·dL $^{-1}$, [-0.59 , 0.73], $p = 0.828$, Table 3) when compared to CON.

3.2 | Effects of heat suit training on endurance performance

HEAT did not influence $VO_{2\text{max}}$, lactate threshold, or exercise performance evaluated as the time to exhaustion in the incremental test or distance covered in the 15-min all-out test (Table 4). In addition, sub-maximal indices of exercise performance were also unaffected by heat treatment (Table 4).

4 | DISCUSSION

The main finding from the present study is that Hb_{mass} and RBCV increased after 5 weeks of HEAT when compared to CON in well-trained XC-skiers and biathletes. However, heat-induced changes in hematological profiles did not translate into group differences in physiological factors determining endurance performance or actual endurance performance.

4.1 | Heat suit training and blood variables

The present study agrees with previous observations indicating that prolonged (≥ 5 weeks) training in combination with a heat-stimuli increases or tend to increase Hb_{mass} when compared to training performed in temperate conditions.^{6,7} A heat suit represent a simple and cost-effective alternative to training in a heat chamber if the exercise intensity and insulation properties of the heat suit are adequate. Comparable effects of heating strategies are supported by the observation of similar rectal temperature, sweat loss, HR, and RPE during the present heat suit sessions as during similar sessions in a heat chamber.¹¹ Indeed, during a 10-day heat acclimation study, we observed similar heat stress responses between heat chamber and heat suit training.¹¹ The latter is in accordance with other studies indicating that overdressing while exercising in temperate conditions can induce sufficient heat stress.²²⁻²⁴ In support of the present findings, we recently showed increased Hb_{mass} in four elite endurance athletes

TABLE 4 Data from the submaximal-, maximal-incremental running and 15-min running tests at 10.5% inclination before (Pre) and after the 5-week intervention period (Post) for the XC-skiers' performing heat suit training (HEAT) and the control group (CON)

Variables	Group	Pre-Intervention	Post-intervention	Adjusted differences
Body mass (kg)	CON	78.5 (6.4)	78.6 (6.9)	
	HEAT	73.7 (5.4)	74.0 (5.5)	0.3 [−0.8, 1.4], $P = 0.582$
$VO_{2\text{max}}$ (mL min $^{-1}$)	CON	5903 (565)	6050 (613)	
	HEAT	5698 (428)	5830 (414)	−21.6 [−201.9, 158.7], $P = 0.805$
Time to exhaustion (s)	CON	464 (37)	478 (34)	
	HEAT	470 (39)	483 (39)	0.7 [−22.9, 24.3], $P = 0.951$
15-min distance (m)	CON	2662 (170)	2700 (197)	
	HEAT	2695 (180)	2698 (214)	−36.6 [−119.4, 46.1], $P = 0.367$
Lactate threshold (km h $^{-1}$)	CON	10.5 (1.0)	10.6 (1.1)	
	HEAT	10.6 (0.5)	10.7 (0.6)	−0.0 [−0.3, 0.2], $P = 0.924$
Lactate threshold (% of $VO_{2\text{max}}$)	CON	84.9 (5.6)	83.2 (5.9)	
	HEAT	84.8 (4.5)	83.4 (4.4)	0.1 [−2.3, 2.5], $P = 0.943$
Submaximal VO_2	CON	4082 (272)	4083 (254)	
	HEAT	3925 (294)	3904 (319)	−12.6 [−109.8, 84.6], $P = 0.789$

after eight weeks of heat suit training.¹⁵ In contrast, Gore et al.²⁵ observed no additional benefit on Hb_{mass} in endurance athletes exercising in warmer environments (temperature range 19–32°C) for 4 weeks. However, it should be acknowledged that the latter training study was conducted outdoor with potential for wind cooling, a rather large variation in temperature and no measurements of rectal temperature. Indoor heat suit training, where no convective air cooling is applied, is more effective than overdressing combined with outdoor training where wind cooling possibly is an influencing factor.^{13,26} Another potential explanation for the divergent findings is the shorter intervention period. It takes 3–4 weeks with chronic altitude exposure to 3454 m to increase Hb_{mass} ,²⁷ and potential effects of heat training on Hb_{mass} may not occur any earlier than this. Accordingly, after 10–14 days, and after 28 days of heat stress, no changes in Hb_{mass} have been observed.^{9,10,25}

Unfortunately, the present study cannot give in-depth insights into potential mechanisms explaining the observed increase in Hb_{mass} after HEAT vs. CON. Nonetheless, the increase in Hb_{mass} has previously been linked to heat exercise-induced increase in PV of ~6%^{9,10} where it is argued that the associated decrease in HCT may trigger erythropoiesis by a “critmeter” function within the kidney²⁸ in order to restore HCT.^{6,7} Although the increase in PV is a robust observation following short-term heat training, it is not necessarily a robust response to prolonged heat training. Indeed, we have recently performed two heat-training studies wherein the heat groups did not display elevations in PV after five weeks of training.^{6,7} However, in both studies, there was a positive correlation between changes in plasma volume and changes in Hb_{mass} .^{6,7} Also, in the present study, HEAT did not induce a significant increase in PV after the intervention period. The lack of measurable effects on PV in these long duration studies could be related to the notion that a peak in PV is present after 7–10 days, but which thereafter declines.²⁹ Another potential explanation could theoretically be a carry-over effect from the last heat training session.

While the critmeter theory provides an intuitive hypothesis to explain the heat training induced increase in Hb_{mass} , other mechanisms may also be involved. The rate of EPO synthesis is mainly regulated by the hypoxia-inducible factor (HIF) system, which, however, also has been shown to stabilize with increased heat shock protein (HSP) expression.³⁰ It may thus be speculated that the augmented Hb_{mass} occurred secondary to a heat exposure-induced increase in HSP. Indeed, 10 consecutive days of active heat training elicits increases in monocyte HSP72 and extracellular HIF-1 α in trained males.³¹

4.2 | Heat suit training and endurance performance

Following the intervention period, HEAT resulted in a 30 g increase in Hb_{mass} compared to CON. However, this did not translate into a superior effect on physiological determinants of endurance performance. Based on the strong relationship between total Hb_{mass} and $\dot{V}O_{2\text{max}}$,³² this may seem somewhat unexpected. Indeed, it has been suggested that each g increase in hemoglobin leads to a concomitant 4 ml·min⁻¹ increases in $\dot{V}O_{2\text{max}}$,³² indicating that there should be a theoretical difference in change between the two groups of ~120 ml $\dot{V}O_2$ ·min⁻¹. However, this was not the case as both HEAT and CON increased $\dot{V}O_{2\text{max}}$ to a similar extent (132 and 147 ml·min⁻¹, respectively). The latter can be linked to the observation that $\dot{V}O_{2\text{max}}$ is also influenced by factors other than Hb_{mass} ,³³ as well as the theoretical effect of ~120 ml $\dot{V}O_2$ ·min⁻¹ increase in these well-trained athletes with $\dot{V}O_{2\text{max}}$ values above 5500 ml·min⁻¹ is still within the measurement error. Together, these aspects points to the limited statistical power of the present study to detect changes in cardiorespiratory parameters and subsequent performance. The observed lack of statistical effects of heat training on $\dot{V}O_{2\text{max}}$ despite an increase in Hb_{mass} is in agreement with previous studies investigating the effects of prolonged heat training,^{6,34} though a recent meta-analysis revealed that 5–60 days of heat training can enhance $\dot{V}O_{2\text{max}}$ in thermoneutral environments by a magnitude likely missed in small scale studies.³⁵ Furthermore, there were no differences between the groups in any of the other investigated physiological determinants of endurance performance such as work economy, fractional utilization of $\dot{V}O_{2\text{max}}$, running velocity associated with 4 mmol·L⁻¹ [La⁻], or time to exhaustion during the graded $\dot{V}O_{2\text{max}}$ test to exhaustion. The present findings are partly in agreement with previous 5 weeks heat training studies where a 3–4.5% increase in Hb_{mass} failed to induce a significant performance increase.^{6,34}

The present finding of no group differences in running velocity associated with 4 mmol·L⁻¹ [La⁻] agrees with previous studies lasting 3–5 weeks.^{6,34,36} However, those studies all display numerical tendencies favoring heat training. In line with this, three weeks of post-exercise sauna bathing in trained runners improved running velocity associated with 4 mmol·L⁻¹ [La⁻] in temperate conditions to a greater extent than endurance training alone.³⁷ In accordance with the present findings of no group differences in changes of endurance performance determinants, there was also no group difference in changes in endurance performance, determined as running distance during the 15-min self-paced test. The latter is in

agreement with previous similar heat training studies lasting 5 weeks,^{6,34} but contradicts other heat training studies with different study designs of shorter duration.^{36–38} The lack of transferable effect of the small but significant improvement in Hb_{mass} in HEAT may be attributed to the athletes' high fitness level, evidenced by a $\dot{V}O_{2\text{max}}$ baseline of $\sim 76 \text{ ml}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$, while the studies showing improvement in endurance performance determining factors have participants with $\dot{V}O_{2\text{max}}$ of $\sim 53\text{--}56 \text{ ml}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$.^{36,37} It could be argued that the movement pattern of running is not exactly the same as XC-skiing, but running is a movement pattern which is frequently used in both testing and training for XC-skiers and also have the advantage of being less affected by technique changes, making it suitable for investigating any potential functional effects of increased Hb_{mass} on performance-related variables. It can be argued that the present study contains a small sample size ($n = 13$ and 12 in the two groups), and that it, therefore, is difficult to find significant group differences. However, the within-group changes are quite similar, and thus, it is not sure increasing the sample size would induce another conclusion.

Importantly, there were no group differences in TRIMP, total training volume or distribution of it into different intensity zones in the present study. However, the heat-manipulation model led to ~ 3 h more cycling training in the HEAT group than CON as all heat suit sessions were performed on stationary bicycles. It is unlikely that low intensity-cycling training itself would induce hematological effects, and thus, the observed group differences in Hb_{mass} are likely due to the heat-stimuli. However, it could be argued that cycling is not specific to the running test battery and we do not know how the result would be if the heat training was performed while running. However, there was only a small, non-significant, difference in weekly running time of ~ 0.7 h between groups, while the majority of the non-significant difference between groups was in the movement pattern of skiing (and thus not specific to the running test). Interestingly, there were no group differences in perceived training load during the intervention period, which further highlights the applicability of heat suit training for increasing Hb_{mass} without affecting the overall perceived training stress (despite no data for the power output relative to maximal capacity during the heat sessions). XC-skiers typically use altitude camps as a part of their training routines to access snow conditions, get accustomed to race pacing at altitude and increase their Hb_{mass} . The present study indicated a 2.8% increase in Hb_{mass} in response to HEAT which is comparable to 3.3% increase in Hb_{mass} after 3-weeks of altitude training, reported in a meta-analysis.³⁹ Comparable effects on Hb_{mass} indicate that heat suit training could be used

as a cost-effective alternative to altitude camps when the main aim is to boost the Hb_{mass} .

5 | PERSPECTIVE

The present study demonstrates that heat suit training can induce an increase in Hb_{mass} without increasing the perceived training load. The increased Hb_{mass} did, however, not lead to improved endurance performance. The present study indicates that heat suit training in temperate conditions can be a cost-effective and easily administrated alternative to altitude camps when the main aim is to increase Hb_{mass} .

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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