

## ORIGINAL ARTICLE

# Effects of a heat and moisture exchanger on respiratory function and symptoms post-cold air exercise

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**Purpose:** Exercise at temperatures below  $-15^{\circ}\text{C}$  induces drying and cooling of lung airways which causes exercise-induced bronchoconstriction (EIB) and respiratory symptoms, especially in winter sport athletes. The objective of this study was to evaluate whether a heat and moisture exchanger (HME) worn during intense cold air exercise improves lung function and reduces respiratory symptoms in healthy winter sport athletes.

**Methods:** Seven active males and six active females (maximum oxygen uptake  $61.9 \pm 6.9$  and  $52.2 \pm 5.3$  mL/kg/min), all active or former winter sport athletes, completed running trials with and without HME in random order on 2 days in an environmental chamber ( $-20^{\circ}\text{C}$  temperature, humidity 46.2%). Forced vital capacity (FVC), forced expiratory volume in 1 second ( $\text{FEV}_1$ ), forced expiratory flow at 25%–75% ( $\text{FEF}_{25\%-75\%}$ ), and FEF at 50% ( $\text{FEF}_{50\%}$ ) were measured pre- and post-exercise (3, 6, 10, 15, and 20 minutes). Respiratory symptoms were reported after exercise.

**Results:** Significant interaction effects were observed for  $\text{FEV}_1$  and  $\text{FEF}_{25\%-75\%}$ . Mean decrease of FVC ( $-5.9\%$ ,  $P \leq .001$ ) and  $\text{FEV}_1$  ( $-4.2\%$ ,  $P = .003$ ) was largest 3 minutes post-exercise without HME. There was an increase of  $\text{FEV}_1$ ,  $\text{FEF}_{25\%-75\%}$ , and  $\text{FEF}_{50\%}$  post-exercise compared to pre-exercise with HME. More respiratory symptoms overall were reported without HME ( $P = .046$ ).

**Conclusion:** Intense cold air exercise likely causes transient acute bronchoconstriction and symptoms of cough in individuals participating in winter sports. However, this study finds that the application of an HME during intense cold air exercise improves lung function and reduces prevalence of EIB-associated symptoms compared to unprotected intense cold air exercise.

## KEYWORDS

cold temperature, cough, exercise-induced asthma, exercise-induced bronchospasm, extreme cold, spirometry

## 1 | INTRODUCTION

There is evidence that exercise in cold air at temperatures  $<0^{\circ}\text{C}$  may cause frostbite, hypothermia, respiratory dysfunction, and symptoms.<sup>1</sup> Respiratory dysfunction due to cold air exercise has been attributed to the increased ventilation during physical activity, especially aerobic activity leading to progressive loss of the airways' capability to heat and to humidify inhaled air.<sup>2</sup> When the airway is not humidified adequately, dehydration of the airway occurs, causing smooth muscle constriction and release of inflammatory mediators,<sup>3</sup> resulting in bronchoconstriction.<sup>4</sup> The magnitude of bronchoconstriction is more severe while breathing very cold air<sup>5</sup> as well as in individuals with diagnosed exercise-induced bronchoconstriction (EIB).<sup>6</sup> In addition, competing in any high ventilation sport regardless of temperature increases the risk of EIB and bronchial hyperresponsiveness (BHR)<sup>7</sup> due to airway drying and this affect is magnified in cold air high ventilation sports.<sup>8</sup>

The acute effects of cold air exercise have been shown to also reduce maximal oxygen uptake<sup>9</sup> and exercise performance,<sup>10</sup> increase respiratory symptoms such as cough,<sup>5</sup> and depress lung function up to 30 minutes post-exercise<sup>5</sup> in healthy athletes. Given the vigorous and negative influence cold air exercise can have on respiratory function and symptoms, recommendations such as not to exercise in temperatures  $<-15^{\circ}\text{C}$  or to cover one's mouth<sup>11</sup> have been provided. However, there are few other recommendations regarding the use of lung protective devices such as a heat and moisture exchanger (HME) despite the fact that these devices could reduce drying and cooling of the airway.

The concept of an HME is widely used for medical purposes in artificial breathing, such as to heat and humidify the lower airways, while the upper airways are bridged during intubation.<sup>12</sup> However, the application of an HME as a lung protective device during cold air exercise is not well known. Furthermore, media attention was gained when athletes of the 23rd Olympic Winter Games in Pyeongchang (February, mean low temperature of  $-11^{\circ}\text{C}$ ) used HMEs where interviewed athletes said it was helpful in protecting their lungs. Of the available research, asthmatic and EIB-positive patients have a smaller decrease in post-exercise spirometry after cold air exercise between  $-15$  and  $-25^{\circ}\text{C}$ <sup>13</sup> or  $-10^{\circ}\text{C}$ <sup>14</sup> with an HME. However, healthy athlete research on efficacy of HME devices is limited to finding no difference in maximal oxygen uptake<sup>15</sup> but more pleasant subjective feelings, while cold air temperatures exposure.<sup>16</sup> Thus, to the best of our knowledge, no previous study has determined the effects of an HME device on respiratory function after cold air exercise in healthy athletes. Furthermore, there is a lack of data regarding the impact of an HME device on the occurrence of respiratory symptoms, potentially seen after intense cold air exercise, competitions, or repeated bouts of racing.<sup>8</sup>

Thus, the primary aim of this study was to examine the influence of an HME during intense exercise (sufficient to induce hyperpnea) in cold air temperatures (sufficient to provoke decreases in respiratory function) on acute post-exercise respiratory function and symptoms. Second, because covering one's mouth during heavy ventilation can increase work of breathing and shortness of breath, we aimed to determine participants' subjective assessment of breathing with and without the HME device. We hypothesized that the use of an HME would lead to smaller decreases in acute respiratory function and less respiratory symptoms after cold air exercise. We also hypothesized that participants would feel greater interference with the HME device, and this would influence perceived exertion with the HME.

## 2 | MATERIALS AND METHODS

### 2.1 | Participants and experimental design

Potential participants were aerobically fit females (maximal oxygen uptake  $[\text{VO}_{2\text{max}}] > 45$  mL/min/kg) and males ( $\text{VO}_{2\text{max}} > 50$  mL/min/kg) between 20 and 30 years of age. Participants had to have participated competitively in winter sports (at least one competitive winter sports season in the past) to ensure all athletes had similar cold air exposure experiences preceding the study.<sup>17</sup> Exclusion criteria were as follows: (1) existing pregnancy assessed with a customary pregnancy test; (2) lactation; (3) chronic or acute diseases including allergy/atopy (already existing or diagnosed during the study); (4) severe symptoms of EIB during low ( $<4$  metabolic equivalent [MET]) where one MET is equal to 3.5 mL/kg/min of  $\text{VO}_2$  (according to the definition of the American College of Sports Medicine) or moderate (4-6 MET) intensity cold air activity/training or another pathological lung disease; (5) the inability to be physically active assessed by the six-item Physical Activity Readiness Questionnaire<sup>18</sup>; and (6) habitual smoking above five cigarettes per day. Exclusion criteria (2-6) were assessed in an initial anamnesis by self-report of the participants. No participant was confused or did not know what low or moderate intensity was, and no participant that was recruited pondered whether they had severe EIB. No incentives were provided for the six females and seven males recruited to this study. No a priori power analysis was conducted for the present study. However, in existing studies referring to the use of an HME in cold air exercise, sample sizes of 5-13 participants were reported.<sup>13-15</sup>

The investigation was a crossover design with a randomized starting order where the same exercise protocol was repeated with and without HME at the same exercise air temperature and humidity. A crossover design was used to reduce error variance associated with inter-individual differences. The exercise protocol was based on a previously published

study.<sup>5</sup> All participants provided written informed consent to participate in the study after obtaining written and spoken information and explanation about study procedures. The study received approval from the Board for Ethical Questions in Science (number: 23\_2018). The tests were completed between March and June 2018.

## 2.2 | Exercise testing

During participants' first visit at the laboratory, baseline spirometry was conducted before participants completed a graded treadmill test (h/p/cosmos sports & medical GmbH) in ambient conditions. Participants ran at a standard grade of 5% with 3-minute stages starting at 6 km/h and increased 1 km/h to volitional fatigue. Expired gas analysis parameters (Oxycon Pro) and heart rate (HR) (chest belt, Polar) were continuously recorded. At the end of each stage, rating of perceived exertion (RPE) according to the Borg scale<sup>19</sup> was determined. The velocity of the last completed stage was regarded as severe intensity above respiratory compensation threshold<sup>20</sup> and, thus, used as the target velocity in the following cold air exercise trials. The highest 30-second average was defined as maximal oxygen uptake and maximal ventilation ( $VE_{max}$ ).  $VE_{max}$  of the graded exercise test was subsequently used for correlation analyses with the parameters of the spirometry test.

The cold air exercise trials were performed in a custom environmental chamber (Siemens AG), which was digitally controlled in both temperature and humidity, and enabled an operating range of  $-25$  to  $35^{\circ}\text{C}$ . The chamber contained a customized treadmill (h/p/cosmos sports & medical GmbH). The mean temperature in the chamber for both cold air exercise trial with and without HME was  $-20.0^{\circ}\text{C}$  (46.2% humidity). Recent investigations showed greatest decreases in post-exercise spirometry results in  $-20^{\circ}\text{C}$  cold air exercises<sup>5</sup>; thus, this temperature was assumed to be sufficient to provoke decreases in respiratory function and thereby detect potential effects of an HME application. Before conducting each cold air exercise, participants completed pre-exercise spirometry. At the beginning of each cold air exercise trial, each participant completed a standardized warm-up protocol of 5-minute easy walking at 1% grade to familiarize themselves with the air temperature and to reduce any cold pressure effect that might occur.<sup>21</sup> HR (chest belt, Polar) was measured at the end of the 5-minute easy walking stage. A 10-minute individual warm-up at 1% grade at a freely chosen speed was next. The selected speed documented in the first cold air exercise trial was used in the second trial. HR was measured every 2 minutes, and RPE was recorded at the end of the warm-up. This warm-up protocol is based on a standardized exercise pattern used in a previously published study.<sup>5</sup> After a 1-minute transition period, participants completed an 8-minute intense

cold air exercise at 5% grade and velocity equal to the last completed stage in the graded treadmill test. HR and RPE were measured every 2 minutes, and distance covered was documented at the end of each cold air exercise trial. In case of preliminary fatigue, speed was decreased progressively by 0.5 km/h to reach a manageable speed and ensure the completion of each 8-minute cold air exercise trial. At the end of each cold air exercise trial, participants left the environmental chamber to perform post-exercise spirometry, which took place at 3, 6, 10, 15, and 20 minutes post-exercise, based on previous methods evaluating post-exercise spirometry.<sup>22</sup> Throughout this period, participants were free to walk around slowly in order to provide a typical cool down.

Participants were allowed to wear temperature appropriate clothing. They were not allowed to cover the face or mouth in any manner (scarf, buff, hand). Moreover, participants could add or remove pieces of clothing during the cold air exercise, thus reducing the chance that thermoregulation influenced exercise performance. Participants were asked to refrain from heavy meals 6 hours prior to each cold air trial and caffeine intake 2 hours prior to each cold air trial and to perform no intense exercise the same day or the day prior to each cold air trial. Between each cold air trial, a period of at least 48 hours but not more than 2 weeks was allowed.

## 2.3 | Heat and moisture exchanger

The applied HME (LungPlus, DOL Environmental Engineering & Consulting; Figure 1) was a mouth-held breathing aid which had to be used according to the manufacturer's recommendations during the entire stay in the chamber. It consisted of a plastic case and a nucleus coil of corrugated aluminum foil, which provided a heat and moisture exchange area of  $1200\text{ cm}^2$ . According to the manufacturer, breathing resistance should be minimal when using this device even during heavy ventilation. However, it was not possible to blow out or rid the nose and mouth of mucus unless the mucus caused severe restriction. In



FIGURE 1 The applied heat and moisture exchanger

those instances, participants were allowed to wipe mucus off with a handkerchief to reduce discomfort and improve air transmission. The HME devices were disinfected after each trial to avoid any potential contamination, and two equal HMEs were used with equal usage for each device.

## 2.4 | Respiratory function testing

All spirometry tests were completed according to the American Thoracic Society guidelines<sup>23</sup> in a sitting position using a portable electronic spirometric device (SP1; Schiller). The device was calibrated after each measurement according to the manufacturer's recommendations. All spirometry tests were performed during ambient laboratory conditions (mean temperature of 25.7°C and 31.9% humidity). Each spirometry measurement at each time point consisted of three trials, where the mean of the best two trials that were the lowest and within 150 mL of each other was used for analysis. All tests were performed by trained staff to ensure consistency of the measurements. The main outcome measures were FVC (forced vital capacity), FEV<sub>1</sub> (forced expiratory volume in 1 second), FEF<sub>25%-75%</sub> (forced expiratory flow at 25%-75%), and FEF<sub>50%</sub> (FEF at 50%). Pre- and post-exercise changes in spirometry measures were calculated in raw units as well as percentage change from maximum as per previous investigations.<sup>24</sup>

## 2.5 | Questionnaires

After post-exercise spirometry (20 minutes post-cold air exercise), a questionnaire was administered to the participants to record the acute impact of cold air exercise with and without HME on respiratory symptoms. It was based on a previously published exercise-induced asthma questionnaire<sup>25</sup> and was aiming at the four common symptoms of BHR: coughing, wheezing, chest tightness/trouble breathing, and excessive mucus secretion (0: symptom not present, 1: symptom present). The sum of the four items was used as an index for respiratory symptoms (frequency). Additionally, participants were asked to rate via a visual analog scale (VAS) how much the HME interfered with breathing during exercise. No interference was rated with a 0, while maximal interference was a 10. Participants were also asked after the completion of both cold air exercise conditions, "in a subjective way, which exercise felt better regarding perceived exertion and comfort while breathing." The possible answers were with HME, without HME, or no difference.

## 2.6 | Statistical analysis

All statistical analyses were done using SPSS version 24.0 (IBM). Unless otherwise stated, data are reported as

means  $\pm$  standard deviations. Normal distribution of data was tested by a Shapiro-Wilk test. In a primary approach, the impact of an HME application on respiratory function (FVC, FEV<sub>1</sub>, FEF<sub>25%-75%</sub>, FEF<sub>50%</sub>) was analyzed using  $6 \times 2$  repeated-measures ANOVAs with time (pre-exercise, 3, 6, 10, 15, and 20 minutes post-exercise) and condition (with and without HME) as within-factor variables. We contrasted pre-exercise as the reference time point and used simple contrasts to show significant interactions between with HME and without HME. A significant time by condition interaction was assumed as effect of an HME on post-exercise respiratory function. In a second approach, we used  $6 \times 1$  repeated-measures ANOVAs for each outcome measure (FVC, FEV<sub>1</sub>, FEF<sub>25%-75%</sub>, FEF<sub>50%</sub>) with time (pre-exercise, 3, 6, 10, 15, and 20 minutes post-exercise) as within-factor to determine the effect of time for each condition. We used simple contrasts to show significant differences in spirometry measurements post-exercise, contrasting pre-exercise as the reference time point. Whenever the assumption of sphericity in ANOVA was not met, Greenhouse-Geisser correction was applied. Partial eta-squared ( $\eta_p^2$ ) was calculated as an effect size in ANOVAs.

Pearson's correlation coefficient or Spearman's rank correlation, as appropriate due to normal distribution (Shapiro-Wilk), was used to determine the relationships between condition differences in post-exercise spirometry changes and VE<sub>max</sub> measured in the graded treadmill exercise test. Differences in distance covered, HR, and frequency of symptoms were analyzed using paired-sample *t* test. In case of non-normal distribution, Wilcoxon test was used. Wilcoxon signed-rank test determined differences in RPE. McNemar test was applied to test differences in symptoms categorically. The level of significance was set at  $P \leq .05$  (two-tailed).

## 3 | RESULTS

Descriptive data and baseline respiratory functions of the 13 participants (46% female, 23% alpine skiers, 31% ski mountaineers, 46% cross-country skiers) can be found in Table 1. Predicted mean values of baseline FVC and FEV<sub>1</sub> were 100% or greater and were considered normal.<sup>26</sup>

### 3.1 | Absolute change in spirometry within and between conditions

There was a significant main effect of condition for all spirometry measures indicating greater post-exercise spirometry reductions in condition without HME (see Table 2). A significant time by condition interaction was found for FEV<sub>1</sub> and FEF<sub>25%-75%</sub>,  $F(5, 60) > 2.54$ ,  $P < .005$ ,  $\eta_p^2 > 0.175$  where at 3, 10, and 15 minutes post-exercise FEV<sub>1</sub> showed a significantly



**TABLE 1** Descriptive data and baseline respiratory functions

Variable	Total (n = 13)	Male (n = 7)	Female (n = 6)
Age (y)	24 ± 2	24 ± 2	24 ± 2
Height (cm)	175 ± 8	180 ± 5	168 ± 6
Weight (kg)	67 ± 9	74 ± 4	59 ± 6
BMI (kg/m <sup>2</sup> )	22.0 ± 1.7	22.8 ± 1.7	20.9 ± 1.0
FVC (L)	6.49 ± 1.24	7.27 ± 1.00	5.58 ± 0.82
FVC (% predicted)	139 ± 21	135 ± 23	144 ± 22
FEV <sub>1</sub> (L)	5.25 ± 0.94	5.82 ± 0.83	4.58 ± 0.53
FEV <sub>1</sub> (% predicted)	132 ± 17	129 ± 21	135 ± 13
FEV <sub>1</sub> /FVC ratio	0.81 ± 0.05	0.80 ± 0.04	0.83 ± 0.06
FEF <sub>25%-75%</sub> (L/s)	5.36 ± 1.08	5.74 ± 1.13	4.91 ± 0.92
FEF <sub>50%</sub> (L/s)	6.10 ± 1.14	6.41 ± 1.14	5.74 ± 1.13
VO <sub>2 max</sub> (mL/min/kg)	57.4 ± 7.8	61.9 ± 6.9	52.2 ± 5.2

Note: Values are presented as means ± SD. Spirometry was taken as baseline value after participants had completed declaration of consent.

Abbreviations: BMI, body mass index; FEF<sub>25%-75%</sub>, forced expiratory flow at 25%-75%; FEF<sub>50%</sub>, FEF at 50%; FEV<sub>1</sub>, forced expiratory volume in 1 second; FVC, forced vital capacity; VO<sub>2 max</sub>, maximum oxygen uptake.

larger decrease in non-HME condition compared to HME condition. FEF<sub>25%-75%</sub> showed a significantly larger decrease at 10, 15, and 20 minutes in non-HME condition compared to HME condition (Table 2). Absolute changes (pre-exercise to the time points post-exercise) for all spirometry measures (FVC, FEV<sub>1</sub>, FEF<sub>25%-75%</sub>, and FEF<sub>50%</sub>) in the HME condition were positive (increased mean compared to pre-exercise) with the exception of FVC at time points 3 and 6 minutes and FEF<sub>50%</sub> at time point 6 minutes post-exercise. In contrast, all spirometry measures at each time point were less than pre-exercise in the without HME condition (see Table 2).

### 3.2 | Percentage of pre-exercise changes in spirometry by condition

FVC was reduced at all time points post-exercise in the without HME condition (significant at 3 and 6 minutes post-exercise), where maximum FVC reduction of 5.9% occurred at 3 minutes post-exercise. FVC was not significantly reduced in the HME condition. As illustrated in Figure 2, FEV<sub>1</sub> was significantly reduced at time points 3, 6, and 10 minutes without HME, with a maximum reduction of 4.2% at 3 minutes post-exercise. There were no reductions of FEV<sub>1</sub> with HME seen at any time post-exercise. In total, two participants showed reduction of FEV<sub>1</sub> after cold air exercise between ≥ 10 and < 25% compared to pre-exercise, indicating mild EIB.<sup>27</sup> Both participants had maximum reduction 6 minutes post-exercise, where one participants' maximum reduction was after exercising without HME (decrease of 12.7%), and in the other participants' maximum reduction was with HME (decrease of 11.0%). All other participants' FEV<sub>1</sub> measures post-exercise were <10% compared to pre-exercise and

classified as normal.<sup>27</sup> Examination of post-exercise spirometry for FEF<sub>25%-75%</sub> and FEF<sub>50%</sub> found reductions at all time points post-exercise in condition without HME. Specifically, maximum decreases were found for FEF<sub>25%-75%</sub> at 6 minutes (6.2%) and for FEF<sub>50%</sub> at 10 minutes (6.0%) post-exercise without HME. In contrast, the HME condition had increases in post-exercise spirometry for both, FEF<sub>25%-75%</sub> and FEF<sub>50%</sub> for all time points post-exercise (only exception at FEF<sub>50%</sub> at 6 minutes).

### 3.3 | Correlations between VE<sub>max</sub> and spirometry measures

Correlation analysis revealed a significant correlation between condition differences in FEV<sub>1</sub> and VE<sub>max</sub> ( $r_s = .632$ ,  $P = .021$ ) at 3 minutes post-exercise, indicating greater condition differences in FEV<sub>1</sub> with a larger VE<sub>max</sub>. With HME, FVC reduction correlated with VE<sub>max</sub> at 6 minutes ( $r_s = -.637$ ,  $P = .019$ ), 10 minutes ( $r_s = -.602$ ,  $P = .029$ ), and 20 minutes ( $r_s = -.626$ ,  $P = .022$ ) post-exercise, indicating smaller reduction in FVC with a greater VE<sub>max</sub>.

### 3.4 | Respiratory symptoms

As shown in Table 3, there were significantly more respiratory symptoms reported overall in condition without HME and frequency of cough and chest tightness/trouble breathing was greater in condition without HME compared to condition with HME. Excessive mucus secretion was reported as the most frequent symptom overall (Table 3) and also most frequent in the HME condition with 11 reported incidences (84.6%).

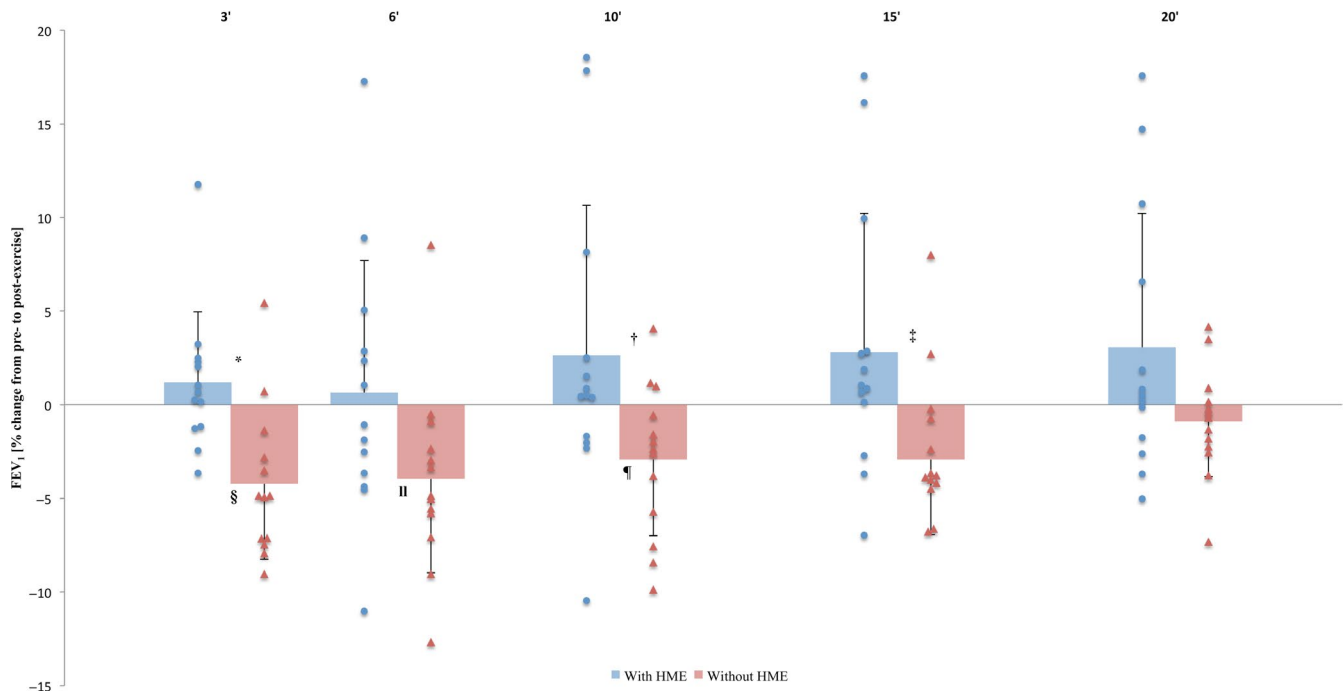
**TABLE 2** Delta change in FVC, FEV<sub>1</sub>, FEF<sub>25%-75%</sub>, and FEF<sub>50%</sub> at the time points 3, 6, 10, 15, and 20 min post-exercise for the conditions with and without HME expressed as absolute change from pre-exercise

Variable	Without HME												
	With HME					Without HME							
	Mean ± SD	Range	Time	Contrasts	P-value	Mean ± SD	Range	Time	Contrasts	P-value			
FVC (L)	3'	-0.16 ± 0.22	-0.70 to 0.17	.057	.020	-0.43 ± 0.27	-0.96 to 0.00	≤.001*	≤.001*	.004*	.032*	.088	≤.001
	6'	-0.08 ± 0.17	-0.32 to 0.34	.136	.136	-0.28 ± 0.39	-1.33 to 0.34	.025*	.025*				.013
	10'	0.09 ± 0.36	-0.39 to 1.02	.356	.356	-0.16 ± 0.46	-1.14 to 0.70	.238	.238				.753
	15'	0.07 ± 0.41	-0.35 to 1.08	.558	.558	-0.16 ± 0.39	-1.09 to 0.63	.169	.169				.625
	20'	0.04 ± 0.30	-0.42 to 0.72	.627	.627	-0.06 ± 0.37	-1.08 to 0.46	.599	.599				.910
FEV <sub>1</sub> (L)	3'	0.08 ± 0.27	-0.27 to 0.83	.285	.292	-0.26 ± 0.26	-0.60 to 0.30	≤.001*	.003*	.088	.035*	.037*	.011*
	6'	0.03 ± 0.47	-0.76 to 1.22	.814	.814	-0.26 ± 0.33	-0.91 to 0.47	.016*	.016*				.104
	10'	0.14 ± 0.49	-0.72 to 1.31	.318	.318	-0.16 ± 0.25	-0.71 to 0.27	.038*	.038*				.030*
	15'	0.16 ± 0.44	-0.48 to 1.14	.215	.215	-0.14 ± 0.24	-0.49 to 0.44	.059	.059				.038*
	20'	0.18 ± 0.43	-0.37 to 1.04	.164	.164	-0.04 ± 0.16	-0.32 to 0.24	.359	.359				.094
FEF <sub>25%-75%</sub> (L/s)	3'	0.30 ± 0.47	-0.82 to 1.01	.147	.040	-0.18 ± 0.62	-1.03 to 1.13	.127	.306	.308	.025*	.022*	.055
	6'	0.04 ± 0.75	-1.80 to 1.08	.858	.858	-0.41 ± 0.70	-1.83 to 1.23	.060	.060				.134
	10'	0.30 ± 0.78	-1.40 to 1.68	.190	.190	-0.34 ± 0.53	-1.61 to 0.37	.039	.039				.018*
	15'	0.54 ± 0.50	-0.12 to 1.45	.057	.057	-0.36 ± 0.60	-1.02 to 1.17	.054	.054				.003*
	20'	0.35 ± 0.63	-0.69 to 1.32	.070	.070	-0.24 ± 0.34	-0.80 to 0.55	.025	.025				.004*
FEF <sub>50%</sub> (L/s)	3'	0.08 ± 0.54	-0.95 to 0.70	.052	.605	-0.19 ± 0.76	-1.62 to 1.16	.397	.399	.134	.036*	.126	.583
	6'	-0.05 ± 0.87	-1.75 to 1.13	.827	.827	-0.37 ± 0.90	-2.32 to 1.32	.160	.160				.081
	10'	0.34 ± 0.88	-0.96 to 2.33	.187	.187	-0.34 ± 1.05	-2.58 to 1.13	.261	.261				.993
	15'	0.30 ± 0.76	-1.36 to 1.81	.188	.188	-0.28 ± 0.88	-1.68 to 1.16	.279	.279				.959
	20'	0.56 ± 0.63	-0.39 to 1.78	.008	.008	-0.29 ± 0.58	-1.03 to 0.64	.098	.098				.163

Note: Data are reported as means ± SD and range for 13 participants. 6 × 1 repeated measures ANOVA's were performed for time effects at each condition, and 6 × 2 repeated measures ANOVA's for time effects, condition effects and interactions between the conditions with and without HME. Simple contrasts with pre-exercise as the reference time point were used for differences at the time points post-exercise.

Abbreviations: FEF<sub>25%-75%</sub>, forced expiratory flow at 25%-75%; FEF<sub>50%</sub>, FEF at 50%; FEV<sub>1</sub>, forced expiratory volume in 1 second; FVC, forced vital capacity; HME, heat and moisture exchanger.

\*Regarded as significant with P ≤ .05.



**FIGURE 2** Change in FEV<sub>1</sub> at the time points 3, 6, 10, 15, and 20 minutes post-exercise for the conditions with and without HME expressed as percent change from pre-exercise. Data are reported as means  $\pm$  SD for 13 participants (bars and error bars) and values of each participant (circles and triangles). Significance value was set at  $P \leq .05$ . Interaction contrasts in  $6 \times 2$  repeated-measures ANOVA as follows: \*3-minute time by condition interaction,  $P = .011$ ,  $\eta_p^2 = 0.430$ ; †10-minute time by condition interaction,  $P = .030$ ,  $\eta_p^2 = 0.335$ ; ‡15-minute time by condition interaction,  $P = .038$ ,  $\eta_p^2 = 0.311$ . Difference contrasts in  $6 \times 1$  repeated-measures ANOVA as follows: §3 minutes different than pretest without HME,  $P = .003$ ,  $\eta_p^2 = 0.525$ ; ¶6 minutes different than pretest without HME,  $P = .016$ ,  $\eta_p^2 = 0.394$ ; ¶¶10 minutes different than pretest without HME,  $P = .038$ ,  $\eta_p^2 = 0.31$ . Abbreviations: FEV<sub>1</sub>, forced expiratory volume in 1 second; HME, heat and moisture exchanger

Cough, wheeze, and chest tightness/trouble breathing were not reported by any participant with an HME (see Table 3).

### 3.5 | Perceived exertion, interference, and subjective feelings of the HME

Participants' self-reported RPE was significantly lower in the HME condition (see Table 3), and this was associated with a lower HR (both absolute and as a percentage of maximum HR). Participants reported that interference of the HME during exercise was  $5.6 \pm 2.2$  on the VAS (no interference = 0; maximal interference = 10). Nine participants (69%) reported a better subjective feeling running in  $-20^\circ\text{C}$  air regarding perceived exertion using an HME, compared to 4 (31%) said without HME. Ten (77%) of 13 participants reported a better subjective comfort while breathing through the HME, compared to 1 (8%) participant said without HME and 2 (15%) participants who reported no difference. One participant complained about lack of oxygen due to the HME device. Two participants reported gingival pain caused by the HME, and in one of these cases, the HME device caused minor bleeding. No other symptoms or medical issues which required treatment or medical consultation were reported by participants.

## 4 | DISCUSSION

The major findings of this study were that wearing an HME during intense cold air exercise can improve post-exercise spirometry. All measures of lung function increased from pre-exercise values with the use of an HME, except in FVC ( $-0.16$  l) and FEV<sub>50%</sub> ( $-0.05$  l) where slight spirometry reductions were seen up to 6 minutes post-exercise. Comparatively, the non-HME condition showed a typical reduction in post-cold air exercise lung function with repressed FVC, FEV<sub>1</sub>, FEV<sub>25%-75%</sub>, and FEV<sub>50%</sub> values up to 20 minutes post-exercise.<sup>5</sup> In FEV<sub>1</sub> and FEV<sub>25%-75%</sub> values, the increase in post-exercise spirometry in the HME condition resulted in significant interaction effects, suggesting a protective effect on post-exercise lung function after intense cold air exercise by an HME. Furthermore, these results indicate that the prevalence of respiratory symptoms associated with cold air exercise exposure can be significantly reduced by using an HME.

### 4.1 | Respiratory function

As this is the first study that has observed the effects of an HME on lung function after cold air exercise in healthy athletes, comparison with other results is limited. Regardless, the

**TABLE 3** Distance covered, HR, relative HR, self-reported perceived exertion, respiratory symptoms, and respiratory symptoms categorically for each condition with and without HME

Variable	With HME	Without HME	P-value
Distance (m)	1729 ± 171 (1317-2167)	1735 ± 180 (1467-2117)	.279
HR (L/min)	184.5 ± 8.6 (168.0-201.0)	186.9 ± 8.0 (168.0-202.0)	.077
Relative HR (%)	93.0 ± 3.5 (88.3-99.5)	94.2 ± 3.1 (89.8-100.0)	.073
Physical exertion (RPE)	16.3 ± 1.3 (14.0-18.0)	17.2 ± 1.4 (15.0-19.0)	.027*
Respiratory symptoms (frequency)	0.9 ± 0.4 (0-1.0)	1.5 ± 1.1 (0-3.0)	.046*
Respiratory symptoms categorically			
Cough	0 (0)	8 (61.5)	.008*
Wheezing	0 (0)	1 (7.7)	1.000
Chest tightness/ trouble breathing	0 (0)	7 (53.9)	.016*
Excessive mucus secretion	11 (84.6)	3 (23.1)	.008*

Note: Data are reported as means ± SD (range) or numbers (%) for 13 participants. Wilcoxon signed-rank test (two-tailed) was applied for differences between conditions with and without HME in distance covered, HR, relative HR, self-reported perceived exertion, and respiratory symptoms. McNemar test (two-sided) was used for differences between conditions with and without HME in respiratory symptoms categorically.

Abbreviations: HME, heat and moisture exchanger; HR, heart rate; RPE, rating of perceived exertion.

\*Regarded as significant with  $P \leq .05$ .

current results have shown that the use of an HME not only reduces the magnitude but in fact can improve airway function post-cold air exercise. Others have also found improved lung function post-cold air exercise using a HME device.<sup>13,14</sup> In those previous studies, a decrease in percentage of FEV<sub>1</sub> with the HME was reported,<sup>13,14</sup> whereas in the present study, the HME condition resulted in increased spirometry parameters post-exercise compared to pre-exercise. The differences in the study results might be at least partly explained by differences in the study samples (asthma- or EIB-diagnosed in,<sup>13,14</sup> compared to healthy athletes in the present study). Thus, our results indicate that in healthy winter sport athletes, an HME can not only protect lung function during cold air exercise but might actually enhance lung function post-exercise.

Further analysis of the data indicates that improved lung function in the HME condition as measured by FEV<sub>1</sub> occurred at each time point post-exercise in all participants and that the magnitude of the improvement increased from 3 to 20 minutes post-exercise (see Table 2). This is a similar pattern in the recovery of lung function for FEV<sub>1</sub> in condition without HME; however, without HME, the recovery was

from a maximum decrease of -260 mL at 3 and 6 minutes to -40 mL at 20 minutes post-exercise. Thus, to contrast these conditions, using an HME might on average improve lung function by up to 200 mL compared to not using an HME. Post hoc analysis found that improved lung function of more than 200 mL distinction between the conditions occurred in 10 out of 13 participants, which was a mixture of high ventilation and low ventilation athletes. The remaining three athletes below 200 mL improvement came from all the three different winter sports. Thus, we feel that both low ventilation and high ventilation athletes benefited from the HME, providing preliminary evidence regarding the protective nature of an HME device for a wide variety of winter sport athletes.

We also think that the improved FEV<sub>1</sub> is a key finding because of its importance in screening for BHR and EIB<sup>17</sup> in otherwise healthy athletes across the spectrum of bronchial provocation tests. The influence of using an HME on FEF<sub>25%-75%</sub> and FEF<sub>50%</sub> was also quite striking when you contrast these measures between HME and non-HME conditions. This is because FEF<sub>25%-75%</sub> and FEF<sub>50%</sub> are used regularly to understand how a bronchial provocation test influences middle and small airway constriction.<sup>28</sup> Thus, these results reflect that an HME may prevent constriction throughout the bronchial tree when a healthy athlete is exposed to a known bronchial provocation (ie, intense exercise at a cold temperature). Beside this acute effect on preventing bronchoconstriction of an HME, one should also bear in mind that cold air leads to increased airway inflammation and epithelial damage over time.<sup>8</sup> It can be assumed, although speculative, that using an HME for a longer period of training might also reduce potential long-term airway remodeling.

Others have shown that an HME increases breathing resistance<sup>15</sup> which can influence shear stress in the airway. Our results indicate that any influence that increased resistance had on increased shear stress and associated airway narrowing was negligible. Thus, the influence of the HME on spirometry measures might be considered beneficial against detrimental effects of unprotected free breathing during cold air exercise.<sup>5,9,10</sup> However, to ascertain this is the case future research should aim to understand whether (a) there is increased resistance to both inhalation and exhalation phases during intense exercise with an HME and (b) how this influences overall work of breathing when using an HME device.

To understand how an HME might protect against cooling and drying of the airway, we also explored how total capacity of the respiratory system as measured via VE<sub>max</sub> influenced post-exercise differences between conditions or the magnitude of change within a condition. We found that at 3 minutes post-exercise, VE<sub>max</sub> correlated positively with condition differences in FEV<sub>1</sub> reductions, indicating even greater post-exercise FEV<sub>1</sub> improvement in the HME condition for individuals with greater respiratory minute volume. However, this result should be interpreted with caution, since



the relationship is likely to be influenced by confounding variables (eg, sex, body height). Specifically, females show lower  $VE_{max}$  values<sup>29</sup> and female's lung function affects the response to exercise due to stature.<sup>30</sup> In our study, we can confirm FVC was also related to  $VE_{max}$ , where between 6 and 20 minutes post-exercise, FVC reductions in the HME condition were negatively correlated with  $VE_{max}$ . This illustrates that greater respiratory minute volume leads to smaller FVC reductions post-exercise although we cannot discern whether this may be due to differences in tidal volume, respiratory rate, or both in a large  $VE_{max}$  person compared to a small  $VE_{max}$  person.

We also think these results are more meaningful when you examine the non-HME condition, where significant reductions were seen 3 minutes post-exercise in FVC (maximum of 5.9%) and  $FEV_1$  (maximum of 4.2%), indicating bronchoconstriction post-cold air exercise. Similar maximum decrease values in FVC and  $FEV_1$  of 4%-5% and 4%-7% were found in a temperature range between  $-23$  and  $+4^{\circ}C$ .<sup>5,31</sup> Thus, we feel that the cold air exercise trial was sufficient to provoke the airway and adds to the evidence that unprotected cold air exercise leads to mild EIB in healthy winter sport athletes. Furthermore, the decreases in respiratory function are transient and start to recover back to baseline within 20 minutes, like others have previously reported.<sup>5</sup>

## 4.2 | BHR-associated respiratory symptoms

Our findings indicate that intense cold air exercise provokes the common respiratory symptoms associated with unprotected cold air exercise. Although we found lower frequency of symptoms compared to others for the same respiratory symptoms<sup>5</sup> at similar temperatures and intensities of exercise, our lower frequencies could be explained by the fact that females are more mechanically constrained during hyperpnea, leading to greater potential of airway narrowing<sup>32</sup> and thus more symptoms compared to a mixed-gender cohort like our study. Like other studies, the most common symptom without HME was cough (67.5%).<sup>32,33</sup> We also found that chest tightness/trouble breathing was common (over 50% of participants) which fits with other research in cold weather athletes.<sup>11</sup> However, the most striking finding from our study is that with an HME device, prevalence of cough, wheeze, and chest tightness/trouble breathing was abolished. This might be explained due to the etiology of coughing where cold air exercises have been shown to be a result of significant water loss.<sup>34</sup> Hence, the observed reduction in coughing may be due to improved moisture exchanging capability and thus reduced water loss in the HME condition. We found excessive mucus was frequently reported in the HME condition and there is no clear explanation for this finding. Finally, considering

the absence of cough, wheeze, and chest tightness/trouble breathing symptoms seen with the use of the HME, these results support using an HME to significantly reduce respiratory symptoms associated with cold air exercise.

## 4.3 | HR, perceived exertion, interference, and subjective feelings of the HME

Given the fact that relative HR was about 93.0%-94.2% of maximum and this HR intensity is above respiratory compensation threshold,<sup>35</sup> we are certain that hyperpnea was likely induced in each cold air exercise condition. Both absolute HR and relative HR showed no difference between the conditions, indicating no cardiovascular effect of HME usage. A previous investigation reported no difference in time to exhaustion as well as oxygen uptake when using a heat exchanger or not in  $-5^{\circ}C$  cold air exercise.<sup>15</sup> Thus, although speculative, the fact that time to exhaustion and HR were not different between conditions indicates that an HME does not influence exercise performance (as measured by distance run) or associated cardiovascular intensity (as measured by percentage of maximum HR). However, the HME condition resulted in a lower RPE overall (mean decrease of 0.9) compared to the non-HME condition. In addition, more than two-thirds of all participants recorded an improved subjective feeling regarding perceived exertion and breathing comfort with the HME device. These results lead to the assumption that an HME device might lower perceived effort at similar physiological intensity and performance outcome (as indicated by HR and running distance, respectively) in cold air exercise. However, it cannot be discounted that an HME in some individuals is uncomfortable and leads to feelings of lack of oxygen, shortness of breath, or bleeding gums. Furthermore, whether an HME is restrictive during the exercise seems to strongly depend on individual differences, considering the observed neutral VAS score of 5.6 and the wide standard deviation of values associated with this VAS score ( $\pm 2.2$ ). At this point, it remains uncertain whether an HME could be applied for exercises longer than 8 minutes. We would surmise that longer duration workouts with an HME would be well tolerated because they are of lower intensity than our study intensities and thus result in less mucosal response. However, future studies should examine longer duration exercise with an HME.

## 4.4 | Limitations

We feel that the cold air chamber protocol we used simulated harsh ambient outdoor conditions for winter sport athletes

well. To explain, the ambient relative mean humidity in the chamber was 46.2% which equates to a low actual ambient water content of 0.45 g/m<sup>3</sup><sup>36</sup> which is known to dry the airway vigorously. Thus, the inhaled air was not only cold but dry ensuring that maximum provocation of the airways and our findings strengthen the potential benefit of the HME as an ergogenic aid to cold air exercise.

In regard to post-cold air exercise reductions, it must be noted that all spirometry tests pre- and post-exercise were taken at ambient laboratory temperatures. There is evidence that inhalation of ambient laboratory air after cold air exercises may increase EIB,<sup>2</sup> caused by greater water loss rate through this temperature change.<sup>37</sup> Since both conditions were the same post-exercise, results can be seen as reliable for identifying differences between the conditions. Also, total yearly hours of training and atopic predisposition were not collected in this study and these variables have been shown to have an impact on BHR,<sup>8,38</sup> and should be considered in future investigations. Furthermore, removal rates of the HME due to wiping off mucus should be documented in future studies, since periods of breathing without HME might influence the potential maximum effect of the device.

## 5 | PERSPECTIVE

The findings of the present study give evidence that a HME usage during cold air exercise has a beneficial effect on some parameters of respiratory function post-exercise. The magnitude of protective lung effects is likely to be related to ventilation maximum of the participant, although further investigation is required to gain greater insight into other influencing factors like lung size and tidal volume. The prevalence of BHR-associated symptoms after cold air exercise may decrease with the use of an HME. Since the exercise intensity was 90%-95% of maximal HR, we are confident that these results translate to the intensities found in cross-country skiing<sup>39</sup> as well as ski mountaineering.<sup>40</sup> Our results add support to the use of an HME to reduce harm in the lung<sup>13,14</sup> without influencing exercise performance.<sup>15</sup> We feel this is an important applied outcome of the study because it is understood that long-term exposure to cold temperatures over years<sup>24</sup> or over seasons<sup>8</sup> can lead to significant airway dysfunction and symptoms. Thus, these findings provide new information on cold air exercise guidelines and expand the scope of recommendation provided for cold air exercise.

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### CONFLICT OF INTEREST

The authors declare no conflict of interest. Thus, the authors declare no role of study sponsors in the design of the study; in

the collection, analyses, or interpretation of data; in the writing of the manuscript, or deciding to submit the manuscript for publication.

### AUTHORS' CONTRIBUTION

CF, MF, and MK contributed to the design. CF performed data acquisition. CF and MF analyzed the data. CF and MN performed the statistical analysis. CF drafted the manuscript. MK and MF supervised and edited the manuscript draft. All authors reviewed the manuscript. All authors provided final approval of this version of the manuscript for publication and agreed to be accountable for all aspects of the work.

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