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ORIGINAL RESEARCH

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Elite skiers' experiences of heat- and moisture-exchanging devices and training and competition in the cold: A qualitative survey

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Abstract

Background and Aims: Winter endurance athletes have a high prevalence of exercise-induced bronchoconstriction (EIB) and asthma, probably due to repeated and prolonged inhalation of cold and dry air. Heat- and moisture-exchanging devices (HME) warm and humidify inhaled air and prevent EIB. The aim of this study was to share cross-country skiers and biathletes' experiences of training and competition in low temperatures, views on temperature limits, usage of HME, and consequences of cold exposure on their health.

Methods: Eleven Swedish World Championship or Olympic medalists in cross-country skiing and biathlon were interviewed and transcripts were analyzed using qualitative content analysis.

Results: Participants described how cold temperatures predominantly affected the airways, face, and extremities. During training, extreme cold was managed by choosing warmer clothing, modification of planned sessions, use of HME, delaying training, or changing location. In competition, participants described limited possibility for such choices and would prefer adjustment of existing rules (i.e., more conservative temperature limits), especially since they understood elite skiing in low temperatures to present an occupational hazard to their health. Participants had at times used HMEs during training in cold environments but described mixed motives for their use—that HMEs warm and humidify cold inhaled air but introduce additional resistance to breathing and can cause problems due to mucus and ice build-up. Skiers also perceived that they had become more sensitive to cold during the latter part of their careers.

Conclusions: The present study gives a unique insight into the "cold" reality of being an elite athlete in skiing and biathlon. Cold exposure results in negative health consequences that are preventable, which means that rules must be followed, and organizers should acknowledge responsibility in protecting athletes from occupational hazards. Development of evidence-based guidelines for protection of athletes' respiratory health should be a focus for future translational research.

KEYWORDS

asthma, "athletes voice", exercise-induced bronchoconstriction, frostbite, humidity, race cough, temperature limits

1 | INTRODUCTION

It is well established that participation in high-ventilation winter sports at the elite level is associated with lower airway dysfunction,[1,2] characterized by airway hyperresponsiveness, exercise-induced bronchoconstriction (EIB), and/or asthma among 21%–30% of athletes.[2,3] Engaging in winter sports, and in particular, high-level cross-country skiing training, has been highlighted as an independent risk factor for asthma development, which also appears to have a later age of onset than classical allergic asthma.[4,5] As hyperpnea in subzero temperatures presents a challenge to adequately warm and condition the inspired air, heavy ventilation can damage the airway epithelium through physical, thermal, and osmotic stress.[2,6,7] Repeated epithelial damage and restitution may over time lead to airway hyperresponsiveness and asthma, but may also manifest as airway inflammation and respiratory symptoms, such as cough, in athletes without clinical signs of asthma.[8,9] Although exercise intensity appears to be the primary determinant of adverse airway responses to exercise in cold air, additional factors such as exercise modality, environment, and season may affect the likelihood of eliciting bronchoconstriction, respiratory symptoms, or detecting biomarkers of airway inflammation.[10–13] Thus, it is possible that athletes themselves have experienced fluctuations in their respiratory function while training and competing and may, consciously or subconsciously, adjust their training and exposure to hazardous conditions accordingly.

For international competitions in cross-country skiing and biathlon, the rules state that competitions must be postponed or canceled if the temperature is below −20°C (for long-distance mass-start races in cross-country skiing, the lower limit is −25°C) measured at the coldest point of the course (https://www.fis-ski.com; https://www.biathlonworld.com). However, these thresholds are described mainly in the context of preventing frostbite than to protecting the airways. Furthermore, national competitions usually have higher limits. In Sweden, −15°C is applied as the lower limit for youth in both sports and −17°C for junior/senior competitions in cross-country skiing. However, for junior/senior biathlon competitions, −20°C also applies nationally (https://www.skidor.com; https://www.skidskytte.se). The rules also state that duration of exposure and the wind chill factor must be taken into consideration when a decision is made regarding cold weather. However, during training, self-selected temperature limits apply, potentially based on skiers' own experiences as well as advice from parents, coaches, federations, and medical advisors.

EIB in individuals with asthma can be prevented by inspiring warm and humid air.[14] A simple surgical face mask retaining warm and humid air from expired air has been shown to alleviate EIB in children with asthma.[15] A range of HME have since been developed and shown to attenuate EIB in both healthy subjects[16,17] and patients with asthma.[18] In fact, HME may attenuate EIB as effectively as short-acting β_2-agonists.[19]

In Sweden, HMEs are commonly used by adolescent competitive cross-country skiers.[20] These skiers experience relief by using a HME and almost all believe that HMEs prevent airway problems associated with exercise in cold environments. The most common temperature threshold for using an HME reported by a cohort of adolescent skiers in recent years was −15°C, and overall, the usage of and attitudes toward HMEs did not differ between skiers with and without asthma.[20] Nevertheless, despite >30 years of research and clinical awareness that winter endurance athletes are at heightened risk of lower airway dysfunction, and apparent understanding of both the risks and mitigation strategies within this population, the prevalence of asthma and EIB appears unchanged. In fact, it was recently reported that the incidence rate of physician-diagnosed asthma among Swedish elite endurance athletes is more than 17–25 times higher than in the general population, with being a skier an independent risk factor.[21] We suggest that this observation may in part be explained by a lack of translation of clinical understanding of the mechanisms and risk factors, to training planning and implementation among coaches and athletes.

Athletes themselves are crucial stakeholders in protecting their health and the need to incorporate athletes' voices and perspectives in sports medicine research has been recently highlighted.[22] Indeed, elite athletes have described how they may prioritize performance over health.[23] To be able to implement effective prevention programs in the future, it is therefore vital to understand athletes' experiences and perspectives on training and competing in subzero environments, the eventual consequences for health, and the perceived compatibility of competing at the elite level with protection of respiratory health. However, currently, there is a lack of research examining athletes' perspectives in these areas in the sports of cross-country skiing and biathlon.

The aim of this study was therefore to incorporate athletes' voice in sports medicine research by conveying internationally successful cross-country skiers and biathletes' experiences of training and competition in low temperatures, views on temperature limits and HME usage, as well as any existing and lasting consequences of cold exposure on their health.

Key points

- Most former elite skiers had experience of using heat- and moisture-exchanging devices and felt they were able to protect the airways from damage, but that there was potential for improved ergonomics.
- Skiers expressed that current competition temperature limits may be too low to protect athletes' health.
- Skiers cited diminished responsibility for their own health when partaking in competitions than their own training; in competitions, they were likely to participate so long as the race was going ahead.
- The "athletes voice" on training and competing in the cold should be considered by other stakeholders in winter sports.

2 | METHOD

2.1 | Study design

In this study, a qualitative approach was used,[24] where data were collected in individual semistructured interviews, and subsequently analyzed using qualitative content analysis.[25] The approach and data collection methods were selected to facilitate an in-depth understanding of participants' experiences in relation to cold exposure.

2.2 | Subjects

A total of 39 Swedish previous World Championships and/or Olympic medalists in cross-country skiing and biathlon received written information and were invited to participate in the study. Of the 15 who indicated an interest to participate, it was possible to arrange interviews with 11 (five men and six women; age, median (interquartile range, IQR): 40 (36–43) years). Six had been prescribed medication for asthma, of which two for almost their entire career while the other four toward the end of their career. Before the interviews started the subjects gave their written consent to participate in the study, which was approved by the Ethics Review Authority in Sweden (Dnr 2021-04741).

2.3 | Interviews

All interviews were performed by the first author (M. J.) in Swedish and took place using online video-conferencing services ($n = 10$) or by telephone ($n = 1$). Before the start of the interview, information regarding the aim of the study as well as aspects of informed consent were repeated. In preparation for participation, participants received an interview guide that provided them with detailed information about the topics to be discussed. The interview guide included topic areas relating to cold temperature exposure during their early career, training, and competition, use and experience of HMEs, health consequences, views, and experiences of existing temperature limits, and how information and advice regarding cold exposure is perceived and dealt with. To stimulate a "narrative" in the interview situation, each interview started by asking the participant to recall how their junior career began and thereafter the interview guide was used as a tool to pose supportive questions to keep the participant on topic. The audio from all interviews was digitally recorded and transcribed as soon as possible after the interviews. The duration of the interviews ranged from 18 to 48 min (mean 38 min) and represented 106 pages of transcribed text (single-spaced).

2.4 | Data analysis

The data analysis was performed with inspiration from the method for qualitative content analysis as described by Graneheim and Lundman.[25] As a first step of the analysis, all transcribed text was read several times by all authors, to obtain an initial understanding of the interview content on a manifest level. Thereafter (second step), the author team met to share and discuss their impressions from reading the texts. As a third step, the first author (M. J.) identified all meaning units with relevance to the study aim. A meaning unit was usually represented by a sentence or a paragraph. The meaning units were tagged with a code that gave an overall sense of what was said. In the fourth step, all identified meaning units were deductively sorted into the four different domains predefined in the study aim: Experiences of training and competition in low temperatures; perceptions and views on temperature limits; experiences of HME usage; and health consequences from cold exposure and elite skiing. As a fifth step, two categories within each of the four domains were identified using inductive analysis (Table 1). To ensure the trustworthiness of the analysis, and the categories' grounding in the text, all authors engaged collaboratively in the process of identifying category names.

Quotes (translated from Swedish to English) are consistently used in the results section to substantiate "what was said" and provided the basis for formulating category names. Each quote is "tagged" with an identifying code "Interview Person (IP) 1–11" to illustrate that all 11 participants are represented in the results.

TABLE 1 Overview of data management.

Domains			
Experiences of training and competition in low temperature	Perceptions and views on temperature limits	Experiences of HME usage	Health consequences from cold exposure and elite skiing
Categories			
Bodily sensations—Face, extremities, and airways	Incentives for keeping or adjusting existing rules	Mixed motives for the use of HME	Sensitive airways and/or cold/exertion asthma
Cold management—preventive measures—adaptation	Skiing as work and cold exposure as an occupational hazard	HME—comfort and discomfort	Long-term problems as an expected consequence of being an elite athlete

Note: Data were systematically sorted into two categories within each of the four domains that were predefined for the aim of the study.
Abbreviation: HME, Heat- and moisture-exchanging device.

3 | RESULTS

The four domains and eight categories identified through the content analysis are illustrated in the text below. See also Table 1 for an overview.

3.1 | Experiences of training and competition in low temperatures

In general, participants described that they had experienced more direct symptoms in their face and extremities than in their airways when training and competing in severe cold (commonly described as −17°C and below). Training in temperatures below 0°C was described as presenting a range of challenges depending on how the body reacts, partly to the temperature and partly to what participants described as air humidity.

3.1.1 | Bodily sensations—Face, extremities, and airways

A common issue was that face and fingers are directly exposed to cold and wind, as two participants express:

> it was these kinds of classic things—that your face or ears would get cold (IP4)

> I haven't had problems with my airways, so maybe that wasn't the biggest problem, but more with my fingers and face … going downhill is quite fast as well, so the cooling effect is enormous (IP1)

There were a couple of comments about how the cooling of body parts also affects breathing negatively, that this is connected:

> If you get cold in the body, you also get cold in the airways (IP9)

Another participant described that in addition to challenges with cooling and discomfort in the extremities, airway problems developed during the time of transition from junior to senior age groups:

> I cannot recall having so many problems during my junior years, with coughing, irritation and phlegm—they started around the beginning of my senior years (IP10)

The same participant continued to explain how they perceived that airway problems would occur under specific circumstances, other than objectively cold weather.

> Cold made my muscles feel really tight, so it was hard to dress to keep my hands and feet warm … still it could be humid and −3°C, and even more challenging for my airways—I would have more of a race cough after those competitions than when it had been colder (IP10)

Another participant described how more humid conditions could lead to reduced performance as well as postrace symptoms.

> I had problems with humid air … it did not actually need to be that cold to still be a problem. I could get really wheezy during the days after or directly after a race, really deep in my chest, it sounded terrible and I coughed up big lumps of phlegm. It could continue for several days. Sometimes during competition, it felt as if I was breathing through a straw. At times we measured (lung function, authors remark) before and after a competition and once in Gällivare [Northern inland Sweden] I think … then my lung capacity was reduced by 17% after the race (IP11)

3.1.2 | Cold management—preventive measures—adaptation

A certain connection could be discerned between how careful the interviewees said they were when it came to protecting themselves against the cold and the problems they had experienced. A participant who said they had been very careful not to take unnecessary risks in training had no major problems with their airways, other than racing cough.

> It doesn't matter if my airways are blocked or if my nose is blocked. The body is not 100% fit and therefore you should not exercise. It's really been what I've lived by, so for me bronchial problems are as much as a cold, simply (IP8)

The exact opposite of this was crystallized by another participant who had major problems with infections during their career.

> Perhaps it was that you competed when you were not completely fit. Over the years, I got exercise-induced asthma and the airways simply contracted. I had a big problem with that at the end of my career, but it's hard to say when it started, really. I think it was in certain weather conditions. My personality is probably a bit more that I've really just pushed on until the problems have come (IP11)

During training

Participants described various strategies to deal with severe cold during training. These included rescheduling training to a later time the same day, choosing training routes on higher ground or areas with warmer temperatures, or training inside. Some expressed more flexibility and chose to maintain training outside at lower intensities, and with warmer clothes. Some adaptive approaches are expressed in quotes below:

> When really cold: I would try to find other options, for example to perform my interval training indoors on a treadmill. But that was more challenging when I was younger and spending time [in Northern Sweden]. [In central Sweden], it is seldom cold for longer periods. Sometimes I can choose to postpone interval sessions until lunchtime, but rarely to another day (IP10)

> If it was on my training plan to train and I wanted to do so, then I would adjust my training according to what was possible. If it was −17°C, I would not do a high-intensity session. I could maybe do a moderate-intensity session because you don't ventilate quite as much, but if it was really cold … it is so beautiful to be outside and train. Then I would go for it, cover my face, use thicker gloves and so on (IP3)

Several participants described using HMEs during training mostly to be able to maintain low to moderate-intensity, long-distance training sessions at temperatures between −15°C and −30°C. There are also some contrasting cases among the participants: Some never used HMEs, no matter how cold it was, and some chose to use them to complete interval training sessions when colder than −15°C:

> If it started to be colder than −15°C and I was supposed to do intervals, then I chose to use the HME as a preventive measure, it was never that I really felt that I needed it, but just in case (IP4)

In competition

Only one participant described how specific conditions at competitions might lead them to decide not to compete. The person had a history of persistent airway problems, especially in warmer and more humid conditions, and described:

> There was a race in France—I had recently competed in another race, my airways were doing badly, and the conditions were bad. I think it was very humid. Then I thought to myself; no, I will skip this race! Partly because of my airways weren't in good shape, and partly because of the bad conditions. That was towards the end of my career, but otherwise it almost didn't matter how bad my airways were, I would just compete anyway… (IP11)

When competing in cold conditions, participants describe how they sometimes use a neck/face tube to cover the neck and ears for protection against frostbite. Most participants had also tried to use these over the mouth but did not routinely do so due to discomfort associated with the wetness that occurs, and the tendency of this moisture to subsequently freeze. Other ways of protecting exposed areas against cold included putting protective tape on the cheeks, nose, and chin, as well as the use of single-use heating pads taped to the wrists.

Participants had rarely used HMEs during races. One participant mentions an occasion as a junior and another during a long-distance race when the temperature was as low as −25°C. Their experience was that it felt good to use the HME, but they noted that ventilation is lower during long-distance races than in shorter races. HMEs had been used by some when testing skis before a race or during the prerace warm-up, as illustrated by one participant who motivated their HME use during warm-up:

> If I knew beforehand it would be cold, perhaps even borderline whether we would be allowed to start or not, then I felt that if I could protect my airways, I wanted to do so (IP10)

In contrast, some participants also described that they chose not to use HMEs while warming up, or in that case only in the beginning of the warm-up, because the thermal shock when starting the race without the HME may be too large, in a negative sense.

One of the skiers commented on HME use during the cool-down after competition:

> then it has been very nice to breathe in warmer and slightly more moist air (IP3)

Three participants pointed out that it is important to warm up even more carefully to get used to the cold. Two of these, without asthma medications as seniors, noted:

> Since I was [a child], and because it was always cold when I competed in [city], I was always careful to warm up. Some just sat indoors until there were a few minutes left and then they went out to compete (IP6)

> Making the warm-up much longer, maybe 10-15 minutes longer. I'd usually start warming up 30 minutes before the start, but on a cold day maybe give it 40 minutes before the start and begin a little slower, so that you really get going. For me, it's also about getting the airways up and running so that they accept cold - then it has worked (IP8)

The third participant, who had used asthma medication for most of their career:

> It has been important with warm-up then, that you do it the right way. There have been times when I have felt that if you have not been well warmed up, they (airways) have closed, that they have become inflamed with poorer air flow, so to speak (IP5)

Responsibility of the organizers versus individual responsibility/ choice

As described above, participants rarely decided by themselves whether to abstain from participating in a competition due to cold temperatures. The motivation to compete was stronger than the perceived individual risk associated with deciding to race. The participants would instead give the organizers the responsibility to make the decision as to whether a race should start or not, even when they feel that it is a borderline case for them:

> I have always relied on the decision of the organizers! (IP10)

However, participants also described relief when organizers would take the decision to cancel a race:

> It was a form of relief really because I get cold so easily. Then I didn't have to make the decision myself as to whether to race or not (IP3)

With hindsight, participants also expressed that some races should never have been allowed to start due to cold conditions, especially at the World Cup level.

3.2 | Perceptions and views on temperature limits

As described in the background, there are some variations regarding Swedish national and international rules regarding temperature limits for junior and senior athletes. During the interviews, participants were asked to openly reflect on their individual perceptions of limits and compare them with sports standards. While athletes are able to adapt their training routines to their own preferences to some extent, during competitions it is the local organizers who take the decision to let a race start or not when temperature conditions are borderline.

3.2.1 | Incentives for keeping or adjusting existing rules

Some of the participants reflected that when the limit of −20°C is applied for seniors it is frequently slightly colder on some segments of the race course, and considerations for wind or wind chill due to racing speed do not seem to be accounted for. From the participants' statements, it is possible to interpret that they have a view that international limits should be adjusted to −17°C instead of −20°C for seniors. Participants also acknowledge a concern that organizers are eager for competitions to go ahead and thereby at times push or stretch the written limits. An incentive is also expressed in that for athletes at this level, skiing is more or less full-time work, and that being exposed to cold temperatures, especially during competition when maximal exertion is expected, can be seen as an occupational hazard. Therefore, regulations should be appropriate to prevent short- and long-term health consequences:

> I think the temperature limits are ok as they are, but I don't know how the wind chill factor affects the airways. What I find unpleasant is when it's −20°C and windy, because I get so cold in my hands, feet, and body, but I don't really think it's worse for my airways. The experience is that it is really cold for my body … it's not like my lungs feel the worst when I breathe, but more how my ears and face sting. There should be more considerations of the wind-chill factor than there are today, and the temperature should be measured from the coldest parts of the course (IP10)

Similarly, another participant expressed:

> Personally, I think that −17°C would be a more appropriate limit than −20°C. Every degree makes a difference, and often if it is −20°C, it is also even colder in some parts of the course. If the limit would be −17°C, the margins would be larger (IP1)

A view is also expressed that organizers tend to "bend the rules," and that accepting that it may be colder in specific parts of the course can be a contributing factor to athletes contracting health problems. One of the participants expressed:

> Many times the limits are pushed to −21°C to −23°C, and I think that's when the damage occurs. This needs to be reviewed and the limits should **never** be stretched (IP11)

3.2.2 | Skiing as work and cold exposure as an occupational hazard

Several participants expressed that in preparing for a season of competition and international championships, they are pressing themselves to the utmost to succeed. Hence, if races are "permitted," athletes will partake when organizers give the go-ahead. In that sense, they argue that regulations need to be clear and

minimize risks for the athletes. One of the participants gave voice to this concern:

> Well, it's more that you want someone to look this over, it is a work-related injury for those who compete, I hope that FIS take this seriously and review the limits (IP11)

3.3 | Experiences of HME usage

HMEs are mainly used during training in severe cold temperatures and sometimes during preparations for a race, but rarely during an actual race. Participants describe below their motives to use HMEs and aspects of how and when they are used, as well as experiences of comfort and discomfort.

3.3.1 | Mixed motives for the use of HME

Among the participants, there was no consistency in their explanations as to why they chose to use HMEs or not. A few had been recommended to use HMEs by their coaches during their time at "ski high schools," as a means to be able to continue training when it is colder than −15°C. Others described these devices as a chance and/or as a trend when producers of HMEs offer them as sponsor items, but some also mentioned that they feel they really work.

> When I was in the development team, B team or national team, we were sponsored by them [HME manufacturers] a bit. Then it was kind of like "these are good to use!", but there was also some talk of someone who had used them and thought they were good, so then they were used more and more (IP3)

Furthermore, participants indicated a personal understanding or conviction that it would be good for them as a driving force, as one response to a question about circumstances in which they would use an HME described:

> If it was about −15°C, and I had an interval session to do, then I would choose to use the HME as a precaution. I never really felt that I needed it, but just in case (IP4)

Following an invitation to further explain their perception of what they were preventing, they respond:

> Yes, good question! I must have heard that you could develop problems with your airways, that it could get worse when it was cold, probably some form of asthma I imagine (IP4)

Another participant described using HME on the basis of their own perception of need, independent of whether it was cold or not:

> It's when I have a bit of pricking sensation in my throat and airways, probably when it has been humid and cold, in really dry cold air I did not have problems (IP3)

Some participants also mentioned that they felt HMEs fulfilled their purpose effectively:

> Yes, it hasn't felt so cold to breathe the air. I absolutely think it was a good thing (IP4)

3.3.2 | HME: Comfort and discomfort

HMEs appeared to offer some sense of comfort in keeping the mouth, chin, and nose warm, as well as the warmer-inspired air providing comfort mostly during low-intensity training. On the other hand, HMEs were also described as having negative impacts on both comfort and performance, a consideration as to why they are not consistently used in training or during races. However, as one of the participants put it:

> It's the attitude as well. I'm going to wear a mask if I want to protect my airways in the best way, so there haven't been any problems in sense, at least I think … I think this AirTrim has been good (IP5)

Humidity and moisture

Moisture that freezes in or around the HME was a widely cited problem impacting usage. One participant described that a specific design of HME works relatively well in terms of moisture accumulation:

> The Lungplus tends to end up with icicles hanging from it, which you sometimes need to try and clear. Then it can get a bit humid, but I think it has worked best for me (IP3)

Another participant described their experience of using another model of HME with greater facial coverage:

> The model covers the mouth and nose using a kind of foam material that weighs almost nothing. I found that when breathing through one of those, moisture would leak out around the sides onto your face, cheeks and below the eyes, and when that humid air meets −20°C, it gets really cold, so I think there is a limit for how cold it can be (IP4)

Reduced performance

Restriction of ventilation is brought forward as a reason not to use HMEs because they are perceived to reduce performance. One person described how "extra air" is needed to improve ventilation:

> I remember that air would bypass (the HME) around the sides sometimes. If you were working hard it was also hard work to breathe through it. I remember that air would come in around the sides when breathing hard on steep hills (IP11)

Further reflecting on reduced performance in connection to hypothetically using HME in a competition:

> I believe that if you would have reduced performance on the race, then you might as well skip the race. That's my feeling, that you get less access to oxygen (with a HME). It's hard to say, but say if it leads to a 1–1 ½ minute longer finish time, there's not much point in competing (IP11)

Obstruction while shooting

In biathlon, the use of HMEs poses a challenge in being an additional obstruction. One of the participants described that they used HME while ski training but not during shooting:

> I maybe used it (HME) a few times, but then took if off when shooting, because it's kind of in the way (IP1)

3.4 | Health consequences from cold exposure and elite skiing

Almost all participants described health consequences from cold exposure, either intermittently during their active career or in the long term after retiring from skiing. Airway problems and exercise-induced asthma arose as the most common issues. Participants also described that frequent exposure to cold has led to a higher sensitivity to frostbite in the extremities. Finally, participants frequently reflected that a career as an elite skier takes its toll on the body but that it was a price they were willing to accept for success.

3.4.1 | Sensitive airways and/or cold/exertion asthma

Symptoms arising from the airways due to cold exposure during training and competition appeared to increase over time. One participant, still active at the time of the interview, described:

> I would say that I am getting worse now every year. It is more uncomfortable when it's cold and, I freeze more easily and feel unwell when I come inside—I think it's harder to deal with (IP10)

Participants also described how problems that were persistent during their active years gradually became less of a problem or even resolved after retiring from skiing:

> It was during my last years of competing that I experienced lots of coughing (after races)—it would take a while before it stopped, a day or overnight. I was prescribed some form of asthma medication, but after I stopped (skiing) I haven't used anything (IP3)

Worse long-term consequences are also described, as illustrated by a participant when asked to elaborate on their present (unmedicated) problems:

> I don't really need to push myself when training before my airways constrict after 20 minutes. Then I need to walk, it's not enough to just reduce the pace, but I need to walk for around two minutes and calm my breathing before I can start over again. Then it's usually fine, but if I head out with someone and run too hard, not even close to maximum but at a comfortable pace, it can still be like (makes noise) so that I can't get air. It's never that bad that I think I'm going to pass out or something, but I just have to stop and walk for 2-3 minutes before I can start up again. Even if I'm out shovelling snow it can almost burn so that I have to breathe with my mouth closed, even if it's not particularly cold outside (IP11)

3.4.2 | Long-term problems as an expected consequence of being an elite athlete

Among those participants who had already retired from elite-level competition, long-term health problems were frequently described that had in some cases persisted after retirement:

> I have big issues with back pain and also knee pain. I never had problems with my knees while competing, but now afterwards I've had it confirmed through magnetic resonance imaging that there is some wear and tear that came on at an earlier age than normal. Knees, back, neck—I guess I have worked my body hard, but you never really know (IP2)

Another participant reflected in a broader sense on what skiers generally accept or expect:

> It's as if we have accepted it … we take it for granted that you cannot become a (elite) skier unless you, at least in the later years of your career, develop respiratory problems. It's the same for everyone, but you might not even think that it might not have to be that way, it's more like "well, I'm prepared for that to happen" (IP10)

4 | DISCUSSION

This study aimed to share internationally successful Swedish cross-country skiers' and biathletes' experiences of training and competition in low temperatures and views on temperature limits and HME usage, as well as any existing and lasting consequences of cold exposure on their health. The study participants' descriptions illustrated how skiing in cold temperatures challenged their ability to train and perform at their best, ultimately as bodily symptoms related to the environment emerged. During training, athletes can adapt to their environment by dressing warmer, changing training location, timing, or intended intensity, according to the prevailing conditions, and at times using HMEs. These modifications are implemented to prevent negative health consequences, while still allowing athletes to maintain training and promote adaptation and development as far as possible. During competitions at temperatures close to predefined thresholds for cancellation, athletes experienced that their health and well-being were less in their own hands, and more in the hands of the competition organizers, who would appear to balance International Ski Federation (FIS)/International Biathlon Union (IBU) regulations against the stakes and demands from media, sponsors, and athletes. As for protecting the airways through the use of HMEs, participants had generally avoided usage during competition due to the perception that HMEs make ventilation more difficult and likely limit performance. We believe that the results indicate the importance of developing clearer regulations and stricter temperature limits and possibly recommend the use of HMEs during training in less extreme conditions.

4.1 | Experiences of training and competition in low temperatures

All participants had, to varying degrees, experienced problems with severe cold and/or high humidity, and some mentioned that the problems had increased during their careers. We divided the perceived problems into two categories: exposure of skin and extremities and specific symptoms localized to the respiratory tract. There were a couple of comments about how the cooling of body parts also affects breathing negatively. Previous research has also shown that facial cooling can exacerbate airway obstruction in both asthmatics and nonasthmatics.[26]

The cooling of extremities and exposed skin, such as hands, feet, and face, occurs due to radiation of heat away from the body during exposure to extreme cold, in combination with high convection (*forced convection*) via wind chill that occurs both in windy conditions and at high speeds, especially in downhill segments.[27,28] Biathletes mentioned the problem of conduction during the shooting moment, as physical contact conducts heat from the cheek and fingers to the weapon and magazine. There were also comments about acquired cold injuries on skin surfaces, leading to a reduced ability to cope with temperatures that previously did not disturb them. Skiers are most exposed to the cold during competition when thinly dressed in race suits and thin base layers to optimize aerodynamics and obtain good freedom of movement during dynamic skiing. However, it is of course important to select the right type of material and number of base layers according to the weather conditions, balancing needs for sweat evaporation and insulation, as described by Gatterer et al.[29]

Unlike the competition, training sessions provide the individual a greater opportunity to make their own conscious choices on how to avoid the impact of severe cold on the body and airways. The participants described that they were usually good at adapting and changing planned training in the event of severe cold. They mentioned the possibility to adopt a lower exercise intensity and to use an HME, two measures that appear to be effective in at least mitigating acute airway problems,[16–19,30,31] as well as an openness to move sessions to another environment, outdoors or indoors, where the temperature was higher. It was also, as two of the participants put it, about motivation and attitude: to dress carefully and to use HME if you want to protect your extremities, face, and airways from the cold. The former biathletes also expressed that the HME gets in the way during the shooting moment. During training, however, skiers would on occasion alter their priorities—for example, the extra time it takes to remove an HME in the shooting moment could be acceptable on the few occasions where severe cold arises.

Something that most of the participants mentioned was "racing cough," which manifests itself as coughing and hoarseness due to increased irritation and mucus formation in the airways. Race cough occurred after high exertion, especially after competitions in severe cold or when the air was both cold and humid. One of the subjects expressed it as though they would feel like a heavy smoker for a while after a race. Race cough is common in athletes, especially among those who compete in winter endurance sports, and occurs in both asthmatics and nonasthmatics.[32] The cause is assumed to be due to normal reflexes from mechanical and chemical nerve endings induced by inhalation of cold dry air or allergens/irritants that penetrate the mucosa, which can also induce bronchoconstriction in hyperresponsive subjects.[32] Race cough usually disappears within a few hours after finishing exercise.[32] However, in this study, the racing cough was described at times to last for several days, with at least one participant experiencing continued problems with hoarseness and coughing after their career, as well as a perception that they were still sensitive to respiratory infections. Thus, our participants collectively described a number of potential interrelated respiratory health consequences related to cold exposure.

Some of the participants spontaneously made the comparison that they could experience greater problems with muscles, breathing, phlegm, and racing cough during and after competitions with very high humidity and only a few minus degrees compared to very cold and dry conditions. The thermal conductivity of water and water vapor is more than 20 times higher and ~3/4th of dry air, respectively (1 bar, 0°C).[33] Although air in subzero temperatures has a significantly lower capacity for vapor saturation compared to a temperate climate, conditions of relatively high air humidity and fog in subzero temperatures seem to have a decisive impact on cooling of skiers' body surfaces and airways.

A certain connection could be discerned between how careful the interviewees said they were when it came to protecting themselves against the cold and the magnitude or extent of health problems they had experienced. A participant who said they had been very careful not to take unnecessary risks in training had no major problems with the airways, other than the "unavoidable" racing cough, while the exact opposite of this was crystallized by another participant who had experienced major problems with infections during their career.

4.2 | Perceptions and views on temperature limits

There was a common theme among the participants that current temperature limits in competitions are actually set too low from an airway and dermatological health perspective. It was also pointed out that it is not just a matter of the temperature per se, but that greater consideration should be given by governing bodies and/or organizers to the cooling effect induced by windy conditions and headwinds during the downhills. By combining the air temperature with wind speed, a so-called wind chill temperature can be obtained. With a racing speed of 5–15 m/s, depending on discipline, subtechnique, and terrain, a temperature of −20°C gives an effective wind chill temperature corresponding to −30°C to −36°C,[27] in calm conditions with only headwind present due to the skiers' speed. An additional wind coming from the side or front will further decrease the effective wind chill temperature. One participant wanted governing bodies to take this into account to a greater degree and to be more careful that organizers do not stretch the temperature limits determined in the regulations. While competition rules often state that the wind chill factor must be taken into consideration when a decision is made regarding cold weather, there are typically no limits for effective wind chill temperature specified, which leaves it entirely up to organizers to determine the importance of the wind factor in context.

An example of the potential risks of stretching limits arose during the 2020–2021 competition season, where a skier (outside the context of this study), who was one of the favorites in the Visma Ski Classics, had large parts of her season spoiled due to frostbite in her feet.[34,35] She sustained the injuries in a race that was carried out despite −27°C in some parts of the course, which could have led to effective wind chill temperatures corresponding to −38°C to −45°C.

A couple of the participants also expressed an understanding of the other side of the coin: that a higher temperature limit would likely result in more canceled races. Temperature limits must therefore be balanced against the risk of how many races will have to be canceled. Several of the participants also stated that the regulations must govern and be followed by organizers and that it should not be up to individual competitors to choose to compete or refrain based on prevailing climatic conditions.

4.3 | Experiences of HME usage

Some of the participants felt that HMEs preheat cold inhaled air and believed that they can prevent both short- and long-term respiratory problems. While research is lacking in terms of the ability of HME to prevent long-term respiratory problems, there is some evidence to suggest that HME can prevent short-term respiratory problems.[16–19,31] However, our participants also raised some practical problems with the two types of HME that they had experience with. Their views illustrate the potential for product development of the market's various types of HME. The model that is held in the mouth (Lungplus) was preferred by some, but at the same time they complained that the passage is narrow and that they experienced a resistance to breathing, as well as that saliva and ice can obstruct the filter, forming icicles that hang down from the mouth that have to be removed from time to time. A certain degree of breathing resistance and ice in the filter was also mentioned with another type of HME, the mask (AirTrim), that participants had experience using. Although laboratory tests have shown that both these HME models have low resistance to breathing, these tests[36] assume that mucus and ice do not block the filter. Masks also provide a small increase in anatomical dead space with a negative impact on pulmonary O_2 and CO_2 fractions.[36] In a study by Tutt et al.,[17] performance was impaired 1.4% when using an HME mask among participants without asthma. The filter for the AirTrim mask consists of a paper-like material[36] and was reported by the participants to have poor durability. They also experienced problems with saliva and moisture inside the mask and a poor fit that causes leakage between the skin surface and the mask. This could result in warm and moist exhaled air condensing on the skin surfaces around the mask and around the eyes, which was experienced as a strong cooling of the face.

4.4 | Health consequences from cold exposure and elite skiing

We observed a relationship between the degree of perceived airway problems, which approximately half of the participants experienced as a major problem, and asthma. Six of the participants had been prescribed asthma medication, of which two for almost their entire career, while the other four more toward the end of their career. These observations align with previous evidence that cross-country skiing training is an independent risk factor for asthma

development.[4,5] Participants in this study also described awareness of the respiratory health risks associated with cross-country skiing, and thus when severe cold had occurred, they had often made adjustments to their planned training (intensity, environment, and clothing, including the use of HME), and so in a way had taken responsibility for their own health. However, skiers also reflected that, with hindsight, they would have chosen to protect their airways even more in training than they did, including by using the HME to a greater degree and at even higher temperatures.

Most elite sports carry sport-specific health hazards, and for skiers, the combination of heavy exercise and cold air exposure poses health risks, something that the participants referred to as a work-related illness. Indeed, several of the participants pointed out that they understood that being a skier at the elite level is associated with certain health risks, but that these are risks that they are prepared to take for the possible success that elite ambitions can bring; an incitement in line with previous research from athletics competitors.[23]

4.5 | Methodological considerations

The methodological design holds several strengths and limitations. Strengths are, for example, related to the sampling procedure and steps taken to ensure trustworthiness. This study included participants with a purposive sampling procedure, that is, directed toward those who had the potential to provide the most relevant information on the topic under study.[24] Of the 39 invited elite skiers, 11 agreed to participate and the subsequent interviews provided rich and diverse data containing valuable information,[37] which supports the argument that the results are transferrable to similar groups of elite skiers. As additional steps to ensure the trustworthiness of the results, all authors were involved in the process of analysis (reading transcripts, coding, identifying categories) to ensure credibility, dependability, and transferability. The categories are also presented with supporting quotes, which gives the reader the opportunity to validate trustworthiness.[25] Even so, the elite skiers who did not respond to the invitation could have had a lot more valuable information to contribute to a clearer picture of the findings, but we hope that stakeholders in the skiing community will critically evaluate the results, and their implications for elite skiing. Based on our qualitative material, we propose that IBU and FIS conduct quantitative surveys among skiers and biathletes to investigate which temperature limits they would prefer in future competitions, nationally and internationally.

5 | PERSPECTIVE

The present study gives a unique insight into the "cold" reality of being an elite athlete in cross-country skiing and biathlon. In summary, all participants had experienced problems with severe cold and/or high humidity. The problems included exposure of skin and extremities and specific symptoms localized to the respiratory tract. There was a common theme that current temperature limits in competitions are actually set too low from an airway and dermatological health perspective. It was also pointed out that it is not just a matter of the temperature per se, but that greater consideration should be given by organizers to the cooling effect induced by windy conditions and headwinds during the downhills. Further, governing bodies should be more careful that organizers do not stretch the temperature limits determined in the regulations. Perhaps, unexpectedly, several of the participants experienced greater problems with muscles, breathing, phlegm, and racing cough during and after competitions with very high humidity and only a few minus degrees compared to dry conditions and very cold. Some of the participants felt that HMEs preheat cold inhaled air and believed that they can prevent both short- and long-term respiratory problems. However, they also raised some practical problems with HMEs such as increased resistance to breathing, saliva inside the mask, and ice that can obstruct the filter. Also, they reflected that, with hindsight, they would have chosen to protect their airways even more than they did.

The results of the present study shed light on the fact that all stakeholders in cross-country skiing and biathlon have a responsibility to protect athletes' health. The FIS/IBU and National Federations have a responsibility not only to follow the advice of medical experts but also to consider the views of skiers when setting temperature limits for competitions. The organizers, in turn, have the responsibility to follow this advice strictly and not be tempted to "stretch the rules," as the participants in this study perceived would sometimes occur. Finally, skiers also have a responsibility for their own health. Even if competitions are conducted according to the regulations, individual athletes must make their own decision as to whether to compete or refrain based on the conditions and the potential consequences of environmental exposures on their health in the short and long term.

Our results support the notion that it is time to move toward prevention. Recommendations for clubs and national organizations should be initiated early in skiers' careers, including evidence-based guidelines for health protection encompassing appropriate use of temperature limits, clothing, and protective equipment during training and competition.

AUTHOR CONTRIBUTIONS

Mats Jong: Conceptualization; investigation; methodology; writing—original draft; writing—review and editing. **Helen G. Hanstock**: Conceptualization; methodology; writing—original draft; writing—review and editing. **Nikolai Stenfors**: Conceptualization; methodology; writing—original draft; writing—review and editing. **Mats Ainegren**: Conceptualization; methodology; project administration; writing—original draft; writing—review and editing.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

TRANSPARENCY STATEMENT

The lead author Mats Ainegren affirms that this manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

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