Influence of Training Load and Altitude on HRV Fatigue Patterns in Elite Nordic Skiers

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ABSTRACT

We aimed to analyse the relationship between training load/intensity and different heart rate variability (HRV) fatigue patterns in 57 elite Nordic-skiers. 1063 HRV tests were performed during 5 years. R-R intervals were recorded in resting supine (SU) and standing (ST) positions. Heart rate, low (LF), high (HF) frequency powers of HRV were determined. Training volume, training load (TL, a.u.) according to ventilatory threshold 1 (VT1) and VT2 were measured in zones I ≤ VT1; VT1 < II ≤ VT2; III > VT2, IV for strength. TL was performed at 81.6 ± 3.5 % in zone I, 0.9 ± 0.9 % in zone II, 5.0 ± 3.6 % in zone III, 11.6 ± 6.3 % in zone IV. 172 HRV tests matched a fatigue state and four HRV fatigue patterns (F) were statistically characterized as F(HF-LF-) SU_ST for 121 tests, F(LF + SULF-ST) for 18 tests, F(HF-SUHF + ST) for 26 tests and F(HF + SU) for 7 tests. The occurrence of fatigue states increased substantially with the part of altitude training time (r2 = 0.52, p < 0.001). This study evidenced that there is no causal relationship between training load/intensity and HRV fatigue patterns. Four fatigue-shifted HRV patterns were sorted. Altitude training periods appeared critical as they are likely to increase the overreaching risks.

Introduction

In elite endurance sport, the goal of training is to optimally distribute intensity and load to improve aerobic capacity [11, 35], and it is known that this distribution has to be individualised [11]. Some training periods are characterised by very high training load (TL) aimed at the maximal stress supportable by the athlete, followed by periods of lighter TL in order to induce supercompensation. The monitoring of fitness and fatigue is essential, but it remains difficult to diagnose training-induced fatigue. It is complex to differentiate the fatigue instrumental in enhanced physiological adaptations from the fatigue that overtakes the recovery capacities of the athlete and leads to nonfunctional overreaching (NFOR) or overtraining (OTS) [20]. Heart rate variability (HRV) has been presented as a promising tool to differentiate fatigue states, and many studies have reported the influence of the training components (intensity and volume) on HRV due to a modulation in autonomic nervous system (ANS) activity [2, 10, 14, 17, 20, 25, 46]. In a preceding study, we reported that HRV spectral analysis permits sorting four different patterns of fatigue in elite Nordic skiers [33], whereas a swimming Olympic champion displayed three different patterns [31].

For several years, the French national Nordic ski teams based their annual training plan on the "polarised" principle [35, 36]. This training method emphasises a major influence of high training volume performed at an intensity below the first ventilatory threshold (LIT). On the other side of the intensity spectrum, high-intensity training (HIT) is also a critical component in the training of all successful endurance athletes [39]. However, two to three HIT training sessions per week seems to be sufficient to induce positive adaptations and subsequent performance enhancement without causing excessive stress over the long term.

It has been suggested [35] that a 75-5-20 TL distribution across the three intensity zones demarcated by ventilatory threshold 1 (VT1) and VT2 would be optimal in high-performance endurance athletes. Such a distribution has been observed in junior male skiers [35], elite rowers [40, 41], gold-medal-winning track cyclists [34] and international-level marathon runners [5].

Training at an intensity below VT1 (or first lactate threshold) has been related to the enhancement of parasympathetic autonomic activity [2, 17, 18, 22, 26, 37, 47] and is associated with a good state of health and fitness through better homeostasis balance and protection against fatigue [3, 9, 15, 44]. Accordingly, polarised training with most of the TL performed below VT1 should minimise the occurrence of fatigue states throughout the annual training program.

Many elite endurance athletes carry out altitude training aimed at performance enhancement [21]. Hypoxia represents an additional stress factor due to reduced PIO2 (partial pressure of inspired oxygen) and has been shown to induce specific HRV responses [30] with a combination of increased sympathetic and decreased parasympathetic nervous activities [24, 38]. It is recommended to reduce the high-intensity component of the training particularly during the first 7–10 days of an altitude training camp in order to facilitate the athletes' acclimatisation [24]. Due to the sympathovagal balance alteration, one may speculate that altitude training could induce more fatigue cases and/or more severe fatigue levels. However, whether altitude training modifies the relationships between TL and the prevalence of fatigue is not well documented.

To our knowledge, there is no longitudinal study monitoring HRV in elite athletes over several years that investigates the influence of TL on the number of different fatigue-shifted HRV patterns. Therefore, it is of interest to analyse the relationships between the training load undertaken during a five-year polarised program (including altitude camps) and HRV measurements of fatigue states. We hypothesised that TLs are related to the number of HRV fatigue patterns and that altitude training camps induced an increase in the number of fatigue states in elite Nordic skiers.

Methods

Subjects

The subjects were 57 members of the French national biathlon, Nordic combined and cross-country skiing teams including 8 Olympics Games, World Championships or World Cup medallists. The characteristics of the subjects are listed in ▶ **Table 1**.

Experimental design

The study was performed at the French National Nordic-Ski Centre of Premanon, Jura, France, over a 5-year period. It was a part of the follow-up of the athletes of the French national teams of biathlon, Nordic combined and cross-country skiing, and a component of Olympic preparation. The Nordic skiers undertook a training program developed and supervised by the national coaching team. The study was approved by the local ethical committee (French National Conference of Research Committees; n° CPP EST I: 2014/33; Dijon, France), and all subjects provided written voluntary informed consent before participation. The study protocol was in accordance with the Helsinki Declaration of 1975, revised in 2017 [13].

The protocol for the HRV tests has been previously described [32]. Briefly, the HRV test relied on a 15-min RR interval (time in milliseconds between two R waves of the electrocardiogram complex) recorded at rest for 8 min supine (SU) followed by 7 min standing (ST). HRV analyses were performed on RR intervals between the 3rd and 8th min supine, and between the 9th and 14th min standing. Measurement of the interval duration between two R waves of the cardiac electrical activity was performed with an HR monitor (T6, Suunto®, Vantaa, Finland). A Fast Fourier Transform (FFT) was then used to establish the spectral power using commercially available software (Nevrokard® HRV, Medistar, Ljubljana, Slovenia). The power of spectral density was measured by frequency bands in $ms^2 \cdot Hz^{-1}$ and the spectral power was expressed in ms^2 [43]. The high-frequency (HF) power band (0.15 to 0.40 Hz) reflects modulation of parasympathetic influence to the heart and is related to respiratory sinus arrhythmia [28]. The low-frequency (LF) power band (0.04 to 0.15 Hz) is considered as carrying vagal resonances either to changes in vasomotor tone (often sympathetic) or in central modulation of sympathetic tone [29]; the spectral power in this frequency band has been found to be related to fluctuations in arterial blood pressure [1, 28] and to baroreflex activity [12]. In both the supine and standing positions, LF and HF were calculated in absolute spectral power units (ms^2), and the total spectral power (TP) was calculated by adding LF and HF. In this study, the spectral powers are expressed as normalised units (nu), LF(nu) and HF(nu), and the LF/HF ratios were not considered because they carry information redundant with absolute values and they do not expand information in statistical clustering. The variables retained were thus HR, LF, HF and TP in both the supine (SU) and standing (ST) positions. The details of the experimental protocol have been presented previously (Schmitt et al. 2015) [33]. In short, the HRV test relied on a 15-min RR interval (time in milliseconds between two R waves of the electrocardiogram complex) recording at rest, in the morning before breakfast, during 8 min supine (SU) followed by 7 min standing (ST). HRV analyses were performed on two 5-min periods, the 3rd–8th min supine and the 9th–14th min standing.

During the 5-year study, the recordings of HRV were not prospectively scheduled, but the athletes were requested to regularly perform the HRV test, and therefore measurements were taken during every training period and in all types of conditions, including during the exposure to altitude. Regular HRV testing revealed baselines of HRV when athletes were "fresh" so that changes in HRV when they were fatigued could be contextualised. During the altitude training camps, HRV tests were performed after at least 8 days

Table 1 Anthropometric characteristics and VO_{2max} of the subjects at the time of their inclusion in the study. Data are expressed as mean (± SD).

	Gender (n)	Age (years)	Weight (kg)	Height (cm)	VO_{2max} ($mL.min^{-1}.kg^{-1}$)
Biathlon	9 m	22.6 ± 4.0	71.8 ± 5.2	180.2 ± 4.8	78.0 ± 5.0
Biathlon	18 w	23.7 ± 4.1	58.5 ± 6.1	167.4 ± 4.7	58.1 ± 4.4
NC	13 m	22.7 ± 4.3	63.4 ± 5.2	176.2 ± 5.5	67.7 ± 4.5
XCS	5 m	20.4 ± 0.9	73.2 ± 2.7	183.0 ± 3.2	79.8 ± 3.2
XCS	12 w	23.2 ± 3.7	58.0 ± 3.8	166.3 ± 2.6	56.6 ± 3.8
All	**57**	**22.9 ± 3.9**	**62.9 ± 7.7**	**172.6 ± 7.6**	**65.1 ± 10.0**

NC = Nordic combined; XCS = cross-country skiing; m = men; w = women.

in order to avoid recording biased changes related to the first critical period of adaptation (acclimatisation phase). All participants lived at an altitude between 800 and 1200 m but had experience in altitude training. However, every altitude training camp was preceded by a period of training near sea level or at an altitude ≤ 1200 m. It is important to note that fatigue state diagnosis was based on an objective threshold from responses from a previous validated questionnaire (as described in our previously published article [32]. The states of fatigue were identified according to the scoring on the questionnaire of the French Society of Sports Medicine (QSFMS) which was completed after the RR interval recording procedure. This questionnaire is used routinely by French national teams in various sports (rugby, swimming, Nordic ski, triathlon) and was developed by the French Society of Sports Medicine [19]. This standardised description of the psychological/behavioural state takes into account different contributions to fatigue linked to physical exercise. A score calculated from the answers to the QSFMS quantifies the clinical symptoms of overtraining. The state of fatigue was registered when the score exceeded 20 negative items out of 54. This score was shown to correlate with markers of muscle damage such as creatine kinase or with haematological variables such as plasma viscosity [4]. Practically speaking, one may argue that it is unlikely that elite athletes would perform a 15-min HRV recording protocol on a regular basis. Numerous articles have claimed that a time domain analysis of HRV requiring less time (~1–5 min) would be more practical [8, 27]. The present procedure has been performed for more than 15 years by a large number of elite athletes. The HRV recording was always performed under the same conditions in the morning before breakfast and started immediately after awakening and voiding the urinary bladder. No training session at an intensity above the second ventilatory threshold took place during the two days preceding the HRV tests.

Training and quantification of the training load

Training was organised into four types of training sessions depending on intensity. They were intensity I for endurance training at an intensity below the first ventilatory threshold (VT1), intensity II for endurance training at an intensity between VT1 and the second ventilatory threshold (VT2), intensity III for competitions and interval training at an intensity above VT2, and intensity IV for strength and speed training sessions. Training load was quantified using methods previously detailed [23] but adapted to Nordic skiing. TL was calculated weekly by the main experimenter (LS) from the training diary completed daily by every athlete as follows. The ventilatory levels of VT1 and VT2 delimit three intensity zones: I ≤ VT1; VT1 < II ≤ VT2; III > VT2; a fourth zone (IV) corresponds to strength and speed training. TL, expressed in arbitrary units (a.u.), was calculated by multiplying the training duration (in min) spent in each zone by a coefficient (i. e. 1, 2, 4 and 8 for the zones I, II, III and IV, respectively). TL corresponds to the sum of the values calculated in each of these four zones [23]. In intensity zones I and II, the effort is constant without recovery times, whereas in zones III and IV the training sessions may include interval training or repeated sprints with TL being calculated from the exercise time only. In order to normalise the TL to the average load for each individual and to take into account the variation across the season, we calculated the mean TL over the five-year period of each athlete (set as 100 %). Then we calculated the difference from the mean (%) for each year.

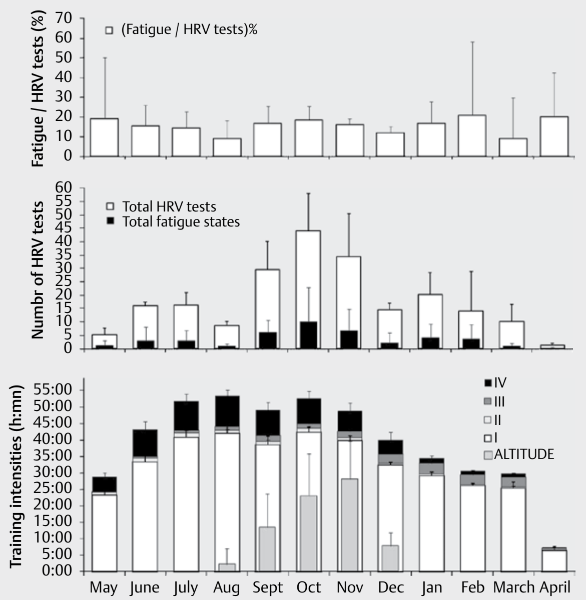
Statistical analysis

The statistical method used to distinguish the different HRV fatigue patterns has been described previously [33]. First, the analysis focuses on the difference in absolute values between no-fatigue and fatigue conditions, and a nonparametric Mann-Whitney test was used to analyse the differences. Then we calculated the relative difference between the mean of all no-fatigue conditions and each fatigue HRV condition. The set of relative differences was submitted to a hierarchical clustering on principal components, which comprised two steps. Firstly, a principal component analysis (PCA) was performed to disclose the organisation of variables and to select the PCA dimensions which embed the main part of the variance. Secondly, a hierarchical ascendant classification was performed based on the first dimensions of the PCA. This process limited the statistical signal-to-noise ratio and delineated clusters of individuals with similar characteristics. Afterwards, the nonparametric Wilcoxon test was used to compare, in each fatigue pattern, the mean of the no-fatigue states and fatigue states. The analyses were conducted using the R statistics software (V3.1.2) with the FactoMineR package. The Pearson product moment correlation was calculated to analyse the relationship between the HRV fatigue patterns and the TL. Statistical analyses were performed using SigmaStat 3.5 software. Alpha level was set to 0.05.

Results

HRV fatigue patterns

Each of the 57 athletes performed between 6 and 51 HRV tests over the studied period [32]. The mean monthly number of fatigue pat-



▶ **Fig. 1** Top: mean (± SD) of the number of fatigue states as percent of the total number of HRV tests. Middle: mean (± SD) of the heart rate variability tests (HRV tests) and fatigue states reported during each month over the 5-year period. Bottom: volumes of training completed (in hours; hrs) in each intensity zone and at altitude. I = endurance training at intensity lower than first ventilatory threshold (VT1) ; II = endurance training at intensity between VT1 and the second ventilatory threshold (VT2); III = competition and interval training at intensity higher than VT2; IV = strength training, alactic speed training; and ALTITUDE = altitude training.

terns is displayed in ▶ **Figs. 1** and ▶ **2**. Among the 1,063 HRV tests performed, 172 matched a fatigue state, and four distinct patterns were statistically sorted, namely $F(HF^-LF^-)_{SU\_ST}$ for 121 tests, $F(LF^+_{SU}LF^-_{ST})$ for 18 tests, $F(HF^-_{SU}HF^+_{ST})$ for 26 tests and $F(HF^+_{SU})$ for 7 tests, with F for fatigue, LF for low and HF for high frequencies in supine (SU) and standing (ST) positions. The characteristics of each fatigue pattern were described in a previous report [33].

▶ **Table 2** shows the monthly absolute and relative (% of total HRV tests) number of fatigue states over the 5-year period of the study.

Training content

The upper panel of ▶ **Fig. 1** displays the mean (± SD) monthly number of fatigue states as a percent of the total number of HRV tests. The middle panel shows the number of HRV tests performed and fatigue states reported. The lower panel of ▶ **Fig. 1** displays the training volume (hours) achieved in each intensity zone and the volume of altitude training. No significant changes in this distribution across the different months was observed, and aerobic (zone I) training was consistently dominant year-round. The monthly **(**mean ± SD) training volume (h:min) in each intensity zone and altitude training volume were averaged over the 5-year period as displayed in ▶ **Table 3**. The intrasubject differences (%) between the monthly TL averaged over the 5-year period and the monthly TL were: May, 13.0 ± 11.0 %; June, 8.2 ± 5.8 %; July, 9.7 ± 8.2 %; August, 8.8 ± 7.4 %; September, 11.2 ± 7.6 %; October, 7.7 ± 6.2 %; November, 8.9 ± 5.8 %; December, 11.5 ± 11.3 %; January, 11.5 ± 10.3 %; February, 10.1 ± 10.2 %; March, 12.7 ± 14.3 %; April, 14.7 ± 13.3 %.

In altitude training camps, nights were spent at 2000 m of altitude and the training sessions were performed on glaciers at ~3000 m from August to October. In November and December, both living and training altitudes were ~1800 m. The duration of altitude training camps (in days by month during the studied period) was: August, 2.2 ± 1.4 d; September, 7.4 ± 3.0 d; October, 12.2 ± 3.7 d; November, 14.4 ± 3.2 d; December, 4.2 ± 1.2 d. No relationship was found between the monthly training volumes or training load and the relative number of the different fatigue patterns (i. e. number of fatigue states as a percent of the total number of HRV tests performed during each month) (▶ **Table 4**). ▶ **Fig. 3** illustrates the relationship ($r^2 = 0.52$, $p < 0.001$) between the monthly accumulated training hours at altitude (as a percent of the monthly total training hours) and the number of fatigue states (as a percent of the monthly number of HRV tests performed) during the months with altitude training camps (August to December).

Discussion

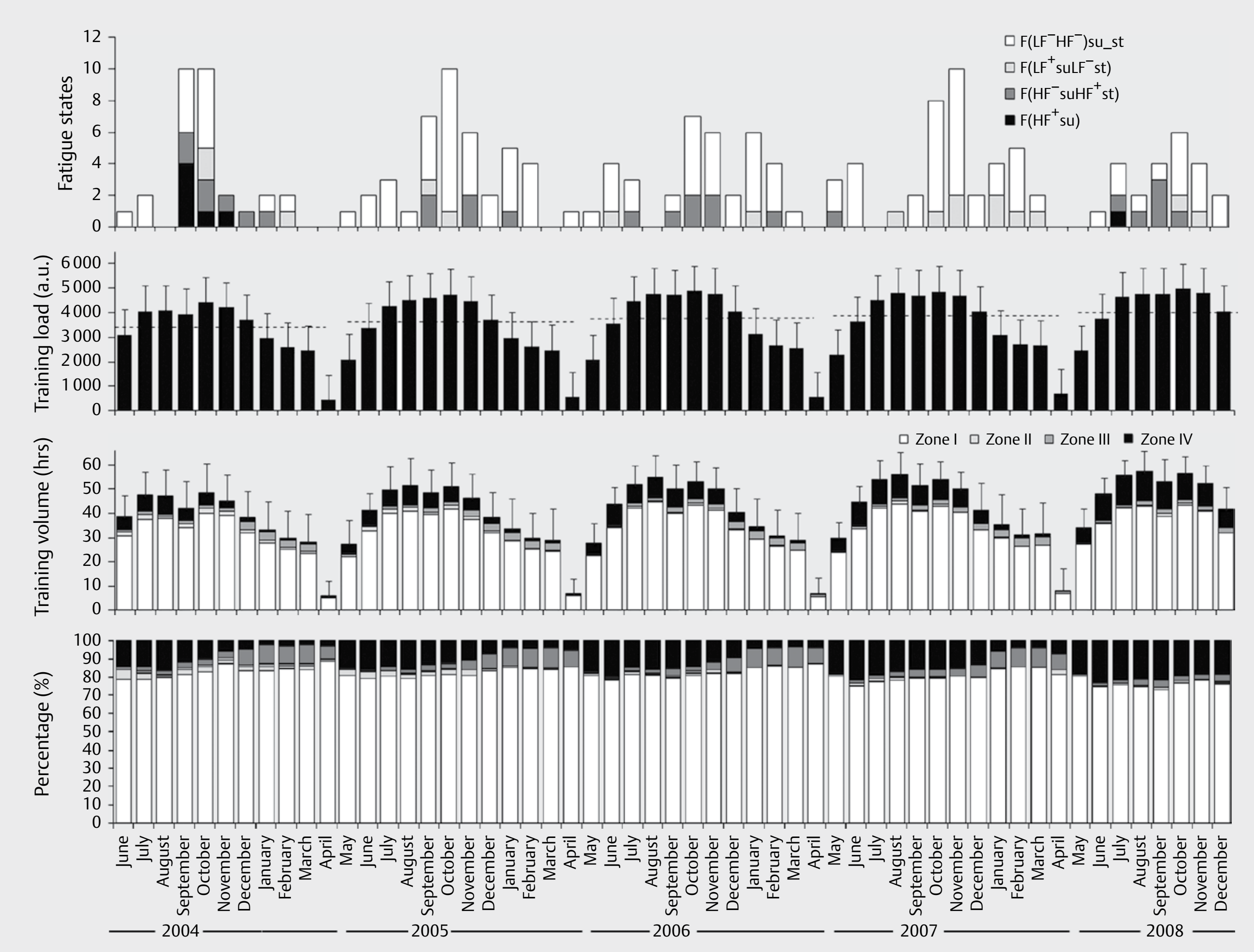
The main results of the present study were:

1) No relationship was observed between the number of HRV fatigue patterns and the total training load accumulated or the training load accumulated in each intensity zone.
2) There was a relationship between the monthly time of altitude training (as a percent of the monthly total training time) and the number of fatigue states (according to the number of HRV tests performed monthly). Altitude training periods thus appeared critical to the occurrence of fatigue and would require careful monitoring of training load and intensity.

The present report (▶ **Table 3** and ▶ **Fig. 2)** of the training-intensity distribution used by the French national Nordic ski teams confirms the predominant component (> 80 %) of low intensity (below the first ventilatory threshold), with a steady distribution across the months and seasons, which is in line with the periodisation model first presented by Seiler and Kjerland [35] and subsequently reported in many other studies of different endurance sports. However, despite the strong predominance of low-intensity training, our study disclosed several states of fatigue of different severity levels in these elite Nordic skiers. Specifically, fatigue occurred mainly during the pre-competition period (▶ **Fig. 1** and ▶ **Fig. 2**) with a high training load and a substantial volume of altitude training.

Influence of training load on HRV fatigue patterns

No relationship between TL and the occurrence of fatigue states was noted, indicating that one cannot investigate the influence of training on fatigue assessed solely on the quantitative component of the training load. TL is an important factor when considering the causes of fatigue or overreaching, but several others can favour or trigger it (sleep quality, psychological states, diseases, wounds, stresses, intellectual workload, hypoxia, diet, hydration, weather) [20]. The polarised training method implemented in our study seemed efficient in preventing fatigue, so the training load alone could not explain the fatigue occurrences. HRV has been described



▶ **Fig. 2** Quantity of each of the 4 fatigue patterns, global training load, volume of training and percentage of training spent in the four intensity zones, during each month of the 5-year follow-up period. Dotted line = average value of the training load in each macrocycle of the study. The fatigue patterns are F(LF − HF −)SU_ST: F(LF + SULF − ST); F(HF − SUHF + ST) and F(HF + SU). The global training load is in arbitrary unit (a. u.); the volume of training is in hours (hr); the lower panel displays the percent of training volume spent in each intensity zone.

as a promising method for diagnosing overreaching/overtraining [20], but its contribution to the prevention of overtraining remains highly debated. In the present study with elite Nordic skiers, we confirmed the ability to diagnose fatigue and no-fatigue states with HRV tests. Moreover, in addition to our previous studies [32, 33] where subcategories of fatigue were identified, the present study underscores the potentially strong influence of altitude training on the prevalence of fatigue in elite endurance athletes. Interestingly, these findings were reproduced in a recent case study [31] involving an Olympic swimming champion (2008 Olympic champion in 100 m freestyle) when the coach determined no-fatigue versus fatigue states according to chronometric performance during the daily training sessions. Among the different patterns of HRV changes during fatigue states described in Nordic skiers [33] and in an elite swimmer [31], the most common type, $F(LF^-HF^-)_{SU\_ST}$, was consistently observed because it occurred every month of the yearly season (▶ **Fig. 2**). However, its occurrence was greatly increased during the September–November period (▶ **Fig. 2** and ▶ **Table 2**). The other fatigue HRV patterns of $F(LF^+{}_{SU}LF^-{}_{ST})$, $F(HF^-{}_{SU}HF^+{}_{ST})$ and $F(HF^+su)$ occurred mainly during the periods with the highest TL (▶ **Table 2**). Interestingly, the $F(HF^+su)$ type occurred mainly with the highest training load (> 4000 a.u.). A similar large increase in HF power has already been described in chronic overtraining syndrome [20]. It has been hypothesised that after an early stage of overtraining with continuous alteration of the sympathetic system, the activity of the sympathetic branch of the autonomic nervous system would be inhibited during advanced overtraining, resulting in a marked dominance of parasympathetic control [16]. A recent report [31] on an Olympic 100-m swimming champion confirms the suggestion that this fourth type of fatigue could be related mainly to endurance athletes performing a high aerobic training load. However, to date, there is no comprehensive epidemiological study comparing the prevalence of these fatigue patterns between different sports or groups.

Influence of altitude load on HRV fatigue patterns

Like other Nordic ski teams [45], French Nordic skiers and athletes in many other endurance sports have a long history of altitude

▶ **Table 2** Quantity (Q) of fatigue patterns as absolute and relative number (% of total 1063 HRV tests) values reported in each month of the 5 year-study for the 57 Nordic skiers.

		$F(LF^-HF^-)_{SU\_ST}$	$F(LF^+_{SU}LF^-_{ST})$	$F(HF^-_{SU}HF^+_{ST})$	$F(HF^+_{SU})$	Total
May	Q	4	0	1	0	5
	%	15.4	0.0	3.8	0.0	19.2
Jun.	Q	10	1	0	0	11
	%	14.3	1.4	0.0	0.0	15.7
Jul.	Q	9	0	2	1	12
	%	10.8	0.0	2.4	1.2	14.5
Aug.	Q	2	1	1	0	4
	%	4.4	2.2	2.2	0.0	8.9
Sept.	Q	12	1	8	4	25
	%	8.1	0.7	5.4	2.7	16.8
Oct.	Q	30	5	5	1	41
	%	13.6	2.3	2.3	0.5	18.6
Nov.	Q	19	3	5	1	28
	%	11.0	1.7	2.9	0.6	16.2
Dec.	Q	8	0	1	0	9
	%	10.8	0.0	1.4	0.0	12.2
Jan.	Q	12	3	2	0	17
	%	11.9	2.9	2.0	0.0	16.7
Feb.	Q	12	2	1	0	15
	%	16.7	2.8	1.4	0.0	20.8
Mar.	Q	2	2	0	0	4
	%	4.5	4.5	0.0	0.0	9.1
Apr.	Q	1	0	0	0	1
	%	20.0	0.0	0.0	0.0	20.0

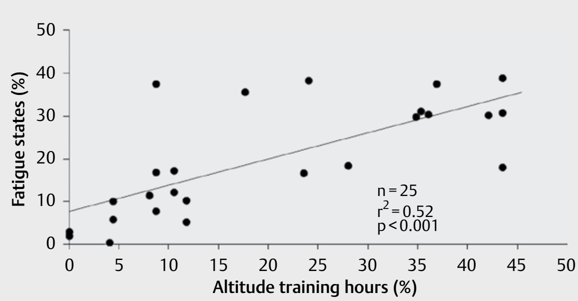
▶ **Table 3** Monthly ▶ **(**mean ± SD) training volume (h:min) according to intensity zones. Values were averaged over the 5-year period. Data are expressed as mean (± SD).

	I	II	III	IV
May	23:22 ± 2:34	0:39 ± 0:30	0:06 ± 0:04	4:37 ± 1:23
June	33:24 ± 1:56	1:00 ± 0:42	0:35 ± 0:10	8:14 ± 2:18
July	40:48 ± 2:08	1:13 ± 0:47	0:57 ± 0:05	8:44 ± 2:15
August	42:02 ± 2:41	0:53 ± 0:20	1:10 ± 0:22	9:17 ± 1:43
September	38:36 ± 2:35	0:58 ± 0:22	1:44 ± 0:16	7:44 ± 2:26
October	42:18 ± 1:23	1:09 ± 0:34	1:28 ± 0:10	7:40 ± 2:15
November	39:52 ± 1:28	0:51 ± 0:34	1:48 ± 0:21	6:10 ± 2:31
December	32:27 ± 0:42	0:30 ± 0:31	2:44 ± 0:35	4:20 ± 2:16
January	29:10 ± 1:03	0:32 ± 0:29	3:13 ± 0:08	1:37 ± 0:36
February	26:04 ± 0:49	0:18 ± 0:18	3:01 ± 0:06	1:10 ± 0:15
March	25:25 ± 1:47	0:20 ± 0:17	3:00 ± 0:21	1:01 ± 0:16
April	6:25 ± 1:03	0:03 ± 0:04	0:38 ± 0:09	0:25 ± 0:14

training [21], particularly during autumn when the snow conditions are good on glaciers at ~3000 m altitude for training in specific skiing conditions. The training plan is organised with two to four altitude training camps separated by 7 to 21 days of training at low altitude (▶ **Table 3**). During these training camps, the nights are spent at 1800–2000 m altitude, and the training takes place in the morning at 2800–3200 m altitude and in the afternoon at 1800–2000 m altitude. The effects of altitude on the activity of the autonomic nervous system have been described in the literature. As usual in hypoxia, during the period of acute exposure, sympathetic activity is stimulated and parasympathetic activity depressed [24, 38]. If the acclimatisation period, around 5 to 8 days, is properly conducted, parasympathetic activity increases without resuming the pre-altitude baseline [7] depending on the training performed. It is known that immune function is unaffected by acute exposure or exercise in hypoxia as shown by Swendsen et al. (2016) [42] or by Born et al. (2015) [6]. However, the present study investigated prolonged exposure and whether fatigue and/or illnesses increased during altitude training. The present report of a higher prevalence of fatigue states during a period of altitude training em-

▶ **Table 4** Absolute (Q) and relative (%) number of fatigue states, training volume (hours), training load (a.u., arbitrary units), and hours of training in altitude training camps, reported by month in the annual training periods of the 5 year-study for the 57 Nordic skiers. Data are expressed as mean (± SD).

Months		Fatigue states	Training volume (hours)	Training load (a.u.)	Altitude training (hours)
May	Q	1.0 ± 1.2	28:48 ± 8:47	2190 ± 587	0
	%	19.2	6.1	5.2	0
June	Q	2.2 ± 1.3	43:20 ± 7:43	3524 ± 659	0
	%	15.7	9.2	8.4	0
July	Q	2.4 ± 1.5	51:50 ± 8:39	4424 ± 681	0
	%	14.5	11.0	10.6	0
August	Q	0.8 ± 0.8	53:37 ± 10:10	4645 ± 765	2:18 ± 4:42
	%	8.9	11.4	11.1	3.1
September	Q	5.0 ± 3.5	49:20 ± 10:14	4602 ± 912	13:30 ± 10:10
	%	16.8	10.5	11.0	18.1
October	Q	8.2 ± 1.8	52:44 ± 9:15	4816 ± 756	23:02 ± 12:46
	%	18.6	11.2	11.5	30.9
November	Q	5.6 ± 3.0	48:50 ± 9:08	4633 ± 944	28:07 ± 11:35
	%	16.2	10.4	11.1	37.7
December	Q	1.8 ± 0.5	40:06 ± 10:09	3961 ± 1045	7:40 ± 3:57
	%	12.2	8.5	9.5	10.3
January	Q	3.4 ± 2.4	34:34 ± 12:15	3093 ± 1261	0
	%	16.7	7.3	7.4	0
February	Q	3.0 ± 2.0	30:35 ± 10:40	2706 ± 1150	0
	%	20.8	6.5	6.5	0
March	Q	0.8 ± 0.8	29:50 ± 12:16	2598 ± 1284	0
	%	9.1	6.3	6.2	0
April	Q	0.2 ± 0.5	7:30 ± 7:33	623 ± 626	0
	%	20.0	1.6	1.5	0



▶ **Fig. 3** Relationship between monthly altitude training hours (as percent of the total monthly hours of training) and quantity of fatigue states (expressed as percent of each monthly-performed number of HRV tests).

phasises the need to moderate intensity training. Because the maximal aerobic power is lowered, absolute intensity (e. g. power output, speed) must be decreased in order to keep the same relative intensity (% $\dot{V}O_{2max}$). In addition, it is known that altitude impairs recovery by altering sleep quality. Altogether these alterations are likely to increase the risks of overreaching. If the training performed is too intensive or the training load too high, a fatigue state can rapidly develop. ▶ **Figs. 1** and ▶ **2** show that the number of fatigue states increased in altitude training camps during the pre-competitive period of training (September to November). In addition, a sizable relationship ($r^2 = 0.52$, $p < 0.001$) was disclosed between the training time at altitude (as a percent of monthly total training time) and the number of fatigue states (relative to the number of HRV tests performed (▶ **Fig. 3**). With intrasubject, interyear monthly variability in TL ranging between 7.7 and 14.7 %, a stable periodisation with a relatively similar TL for a given month over the period is observed. Therefore, the training was relatively consistent across the 5-year period. The HRV outcomes did not change with this normalisation of TL to the average of the 5-year period. This reinforces the findings of the important specific influence of altitude training on the fatigue state of athletes. ▶ **Table 2** shows that the F(HF^{+}_{SU}) pattern occurred during this precompetitive period when the highest TLs were met in altitude training camps, i. e. when very high TLs were combined with hypoxic exposure. These cases are consistent with this latter HRV fatigue pattern underscoring a severe state of fatigue. Moreover, during months at a similar TL but at a lower altitude, various fatigue patterns were found without this particular pattern (▶ **Table 2**). Hence this occasional observation suggests altitude training is more likely to induce overreaching in endurance athletes. Because altitude training camps were relatively short, one cannot rule out that the physiological stress might be higher during the acclimatisation phases and that longer (e. g. 3–4 weeks) altitude camps might lead to a lower prevalence of HRV patterns.

Conclusions

The number of HRV patterns was observed throughout the season (i. e. every month and at different stages) in elite endurance athletes and indicated no causal relationship between training load/intensity and HRV fatigue patterns. We observed the prevalence of four fatigue-shifted HRV patterns with a predominance of the $F(LF^-HF^-)_{SU\_ST}$ pattern at all levels of training load and a combination of $F(LF^+{}_{SU}LF^-{}_{ST})$, $F(HF^-{}_{SU}HF^+{}_{ST})$ and $F(HF^+{}_{SU})$ fatigue patterns at high training loads. Because the prevalence of fatigue increased with the training time spent at altitude, this suggests that training load should not be considered as the sole cause of fatigue and that altitude training is likely to increase the risk of overreaching.

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Conflict of Interest

This study was done with no funding sources and no conflict of interest.

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