



Injury risks among elite competitive alpine skiers are underestimated if not registered prospectively, over the entire season and regardless of whether requiring medical attention

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Abstract

Purpose Prospective studies assessing the injuries occurring in elite competitive alpine skiers are lacking, and a full picture of all injuries, including those not requiring medical attention, is absent. Likewise, little is known about the sex-specific injury risks and patterns of elite skiers throughout an entire season (i.e. an off-season preparation period and a competition period). Accordingly, this study investigated the injuries of a national team cohort with respect to season period and sex.

Methods Over an entire season, all injuries occurring in 44 Swiss National Ski Team members (25 females and 19 males) were registered, regardless of whether they required medical attention. Skiers were prospectively monitored by the Oslo Sports Trauma Research Centre (OSTRC) questionnaire and by continuously updated team medical records. Finally, these data were used as a reference for supplemental interviews, in which the correctness and completeness of the prospective data were verified.

Results The risk of suffering at least one injury during an entire season was 75.0% with a 95% confidence interval (73.1%, 76.9%) for traumatic injuries, and 52.3% (50.0%, 54.5%) for overuse injuries. Traumatic injuries concerned the head, lower leg and knee, while overuse injuries affected the lumbar spine, knee and hip. During the competition period, skiers were more prone to traumatic injuries, while during the off-season preparation period, skiers' risk was higher for overuse injuries. Over an entire season, there were no sex differences. However, females were more vulnerable to traumatic injuries during the preparation period and overuse injuries during the competition period, while males had a higher risk for overuse injuries during the preparation period.

Conclusions When prospectively registering injuries among elite competitive alpine skiers over an entire season, regardless of whether the injuries required medical attention, the injury risks were alarmingly high and substantially larger than those previously reported. Moreover, since injury risks and patterns are season period and sex dependent, it is strongly recommended that (1) injury registration focuses on both the off-season preparation period and the competition period and (2) prevention efforts are specifically tailored to the sex of the athletes.

Level of evidence II.

Keywords Epidemiology · Periodization · Gender-specific injuries · Athletes · Injury prevention · Alpine ski racing

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Introduction

In various Olympic sport disciplines, injuries are highly prevalent and their reduction represents a major challenge of our time [9, 10, 20, 32]. In sports such as competitive alpine skiing, injuries are particularly frequent [10, 19, 29, 34]. On the World Cup (WC) level, the official surveillance system by the International Ski Federation (FIS) revealed injury rates of 36.7 and 36.2 injuries per 100 WC athletes per competition period [5, 11], with the knee (35.6%) and the lower back (11.5%) as the most frequently affected body parts [11, 12]. For European Cup (EC)-level skiers, a recent study within the French National Ski Association even reported injury rates being twice as high as those at the WC level [1]. In view of these rates, focus should be given to research on injuries and health protection in elite competitive alpine skiers.

The training and competition exposure of female and male elite alpine skiers differs throughout the season. During the off-season preparation period, the focus lies on general physical conditioning, including special emphasis on strength and endurance, and extensive on-snow training [15]. During the competition period, the focus lies not only on maintaining physical fitness and achieving peak on-snow performance but also on active recovery [15]. Certainly, such different exposure characteristics may have an effect on the risks and patterns of injury. Previous epidemiological studies primarily focused on injuries occurring during the competition period [5, 11, 16], whereas injuries during the off-season preparation period have received little attention [1].

By neglecting the off-season preparation period, however, the entire injury extent might be substantially underestimated [1]. Additionally, most studies used retrospective designs and a “requiring medical attention” injury definition [1, 5, 11, 16], while to the best of our knowledge, there is only one study relying on a prospective injury registration methodology and an “any complaint” injury definition to assess youth skiers [25]. In view of these limitations and restricting definitions, the full extent of the injury risks among elite competitive alpine skiers has likely been underestimated so far. To successfully promote safety in sports, however, athletes (and their professional setting) should be aware of the exact risks that they are exposed to when participating in a particular sport over a defined period of time [8]. Moreover, knowledge about the season period- and sex-dependent injury patterns among female and male elite competitive alpine skiers is of particular importance for knowing where to set prevention priorities and define effective prevention measures.

Therefore, the aims of the current study were twofold: (1) to estimate the injury risks for a national team cohort

among female and male competitive alpine skiers during the off-season preparation and competition periods based on a prospective approach and an “any complaint” injury definition; and (2) to describe the patterns of traumatic and overuse injuries with respect to injury severity, body location and injury type.

Materials and methods

Study protocol and participants

The current study was approved by the institutional review board of the Balgrist University Hospital and the cantonal ethics committee (KEK-ZH-Nr: 2017-01395), and was performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments. The study sample included 44 members of the Swiss National Ski Team, 25 females and 19 males, competing at different international levels (i.e. WC, EC, FIS races). All participants gave their written informed consent at the beginning of the study. The observation period (hereafter called “entire season”) started with the first on-snow training at the end of July, and ended after the last race at the end of April. For certain parts of the analysis, the entire season was split into two portions with characteristic training contents and competition exposures [15], i.e. an off-season preparation period (end of July until end of October) and a competition period (end of October until end of April).

Injury registration

Over the entire season, all occurring injuries were systematically registered. To do this, skiers were prospectively monitored using the Oslo Sports Trauma Research Centre (OSTRC) questionnaire on health problems [7] embedded in a custom smartphone app that was built with *LambdaNative* [26] and linked to a secured *REDCap*® database [17]. At 2-week intervals throughout the season, skiers received a text message reminding them to use the smartphone app to report any injury within the last 2 weeks. The app’s user interface was designed to automatically guide the athlete through the different questions of the OSTRC questionnaire depending on the answers provided. Every individual injury was registered by an independent OSTRC questionnaire loop. For each observation interval, the time window for questionnaire completion was limited to 7 days. Additionally, in case injuries required medical attention, the team physician continuously updated the skiers’ medical records. Finally, these two data sources were used as a fundamental reference for the supplemental interviews at the end of the season. The interviews were conducted by a physician specializing in sports medicine who was not part of the team

medical staff. During the interviews, he referred to all injuries previously reported and verified the correctness and completeness of their corresponding data entries. Additionally, the physician asked for further injuries that (due to any reason) were neither reported in the OSTRC questionnaire nor documented in the team medical records.

Data evaluation

Injury definition and classification

In accordance with Fuller et al. [14], an injury was defined as “any physical complaint sustained during training or competition, irrespective of the need for medical attention or time loss from sport activities.” Traumatic injuries referred to injuries with a clearly identifiable inciting event such as a fall [14]. In contrast, overuse injuries were defined as being the result of an accumulation of repeated microtraumas without a single identifiable event responsible for the injury [14]. All injuries were further subclassified with respect to injury type as defined by Fuller et al. [14]. If an athlete had more than one injury from the same event, every physical complaint was registered as a separate injury. Furthermore, injuries were classified as severe, when resulting in an absence of training and/or competition of more than 28 days [13].

Data fusion

In the course of the evaluation, the data of the three different injury registration sources had to be fused. In the vast majority of cases, the OSTRC entries and continuously updated team medical records were in full accordance with the information provided in the supplemental interviews. When the OSTRC entries and team medical records contradicted the supplemental interviews, prospective data entries were only corrected if they could clearly be identified as being wrong. Special emphasis was placed on the correct assignment (1) as either a traumatic or overuse injury, (2) of a subsequent injury being a new injury and (3) of the injury location. Obvious errors in data entry included traumas reported as overuse injuries or incorrectly indicated as injury localizations due to inattentiveness. In rare cases, in which an injury was neither reported in the OSTRC nor documented in the team medical records but was mentioned in the interviews (i.e. 11.8% of all incidents), prospectively collected data were supplemented by a new injury entry.

Statistical analysis

Baseline characteristics are presented as mean \pm SD and corresponding sex differences were analysed by unpaired sample *t* tests (backed-up by bias-corrected accelerated (BCa) bootstrapping with 10,000 samples). Injury

incidence was expressed as an estimator of average injury risk (i.e. *epidemiological incidence proportion*—number of injured athletes in a season or period/number of athletes at risk at the start of season or period) and, for better comparability with previous studies, as the *absolute injury rate* (i.e. the number of injuries/100 athletes per season or period), also called the clinical incidence [22]. Risk ratios between females vs. males and competition period vs. off-season preparation period were presented as dimensionless quotients. For all three of these measures, corresponding 95% confidence intervals were calculated in accordance with Knowles et al. [22] and are reported in parenthesis. Finally, the distribution of all injuries with respect to body location, severity (classified according to the number of days absent from training and/or competition) and injury type were expressed as the number of incidents. Based on comparable data from an epidemiological study in youth competitive alpine skiers, the assumed effect sizes were $d = 1.155$ for sex differences, and $d = 1.655$ for season period differences (Schoeb et al., unpublished data). A corresponding a priori power analysis with $\alpha = 0.05$ and $1 - \beta = 0.95$ revealed that a sample size of at least $n = 34$ (for sex comparison) and 18 (for season period comparison) would provide sufficient power for the analysis purpose in this study. Our study sample ultimately included 44 subjects to be fully representative of the Swiss National Ski Team cohort.

Results

Participant characteristics

The baseline characteristics of the entire cohort and its subgroups are presented in Table 1.

Females and males were of comparable mean age. However, males were on average 13.4 cm taller and 16.9 kg heavier than females, with a higher average body mass index.

Table 1 Baseline characteristics of the participants

Parameter	Total (<i>n</i> = 44)	Females (<i>n</i> = 25)	Males (<i>n</i> = 19)
Age [years]	21.4 \pm 2.8	21.0 \pm 2.7	21.8 \pm 3.0
Height [cm]	172.3 \pm 8.7	166.6 \pm 5.4	180.0 \pm 5.7***
Weight [kg]	72.9 \pm 10.7	65.6 \pm 6.6	82.5 \pm 6.8***
BMI [kg/m ²]	24.4 \pm 2.0	23.6 \pm 1.9	25.5 \pm 1.67***

All data are expressed as mean \pm SD. Level of significance based on unpaired sample *t* tests and backed-up by bias-corrected accelerated (BCa) bootstrapping with 10,000 samples: *** $p < 0.001$. BMI body mass index

Injury risks and rates over an entire season

The epidemiological incidence proportions with corresponding 95% CIs over the entire season were 75.0% (73.1%, 76.9%) for traumatic injuries, 52.3% (50.0%, 54.5%) for overuse injuries and 93.0% (92.1%, 94.3%) for all injuries. This corresponds to absolute injury rates of 120.5 (traumatic), 63.6 (overuse) and 184.1 (all) injuries per 100 athletes per entire season.

Injury risks and rates during the competition period

Table 2 illustrates the injury risks among female and male elite competitive alpine skiers during the competition period. During the competition period, the epidemiological incidence proportions for traumatic, overuse and all injuries were 54.5%, 18.2%, and 63.6%, respectively. Coinciding absolute injury rates were 77.3 (traumatic), 18.2 (overuse),

and 95.5 (all) injuries per 100 athletes per competition period. Overall, there were significantly higher epidemiological incidence proportions for traumatic injuries than for overuse injuries, regardless of their severity. Females showed a higher risk for overuse injuries than males, while for traumatic injuries no sex difference was present.

Injury risks and rates during the off-season preparation period

During the off-season preparation period, for traumatic, overuse and all injuries, epidemiological incidence proportion magnitudes of 36.4%, 43.2% and 70.5% were observed (Table 3). The absolute injury rates were 43.2, 45.5 and 88.6 injuries per 100 athletes per preparation period. In this period of the season, skiers were more likely to suffer from overuse injuries than from traumatic injuries. However, with respect to severe injuries, the

Table 2 Injury incidence (expressed as the epidemiological injury proportion) among female and male elite competitive alpine skiers during the competition period

Injury classification	Injury incidence ^a (# injured athletes/100 athletes during one competition period)		
	Total (n=44)	Female (n=25)	Male (n=19)
Traumatic injuries			
All	54.5 (52.3, 56.8)	52.0 (48.1, 55.9)	57.9 (52.8, 63.0)
Severe (> 28 days of absence)	20.5 (18.7, 22.3)	20.0 (16.9, 23.1)	21.1 (16.8, 25.3)
Overuse injuries			
All	18.2 (16.5, 19.9)	24.0 (20.7, 27.3)	10.5 (7.4, 13.7)
Severe (> 28 days of absence)	0.0 (0.0, 0.0)	0.0 (0.0, 0.0)	0.0 (0.0, 0.0)
Total			
All	63.6 (61.5, 65.8)	64.0 (60.2, 67.8)	63.2 (58.2, 68.1)
Severe (> 28 days of absence)	20.5 (18.7, 22.3)	20.0 (16.9, 23.1)	21.1 (16.8, 25.3)

^aData are expressed as percentage values with 95% confidence intervals in parenthesis

Table 3 Injury incidence (expressed as the epidemiological injury proportion) among female and male elite competitive alpine skiers during the off-season preparation period

Injury classification	Injury incidence ^a (# injured athletes/100 athletes during one off-season preparation period) ^a		
	Total (n=44)	Female (n=25)	Male (n=19)
Traumatic injuries			
All	36.4 (34.2, 38.5)	44.0 (40.1, 47.9)	26.3 (21.8, 30.9)
Severe (> 28 days of absence)	18.2 (16.5, 19.9)	24.0 (20.7, 27.3)	10.5 (7.4, 13.7)
Overuse injuries			
All	43.2 (41.1, 45.4)	36.0 (32.2, 39.8)	52.6 (47.5, 57.8)
Severe (> 28 days of absence)	6.8 (5.7, 7.9)	4.0 (2.5, 5.5)	10.5 (7.4, 13.7)
Total			
All	70.5 (68.4, 72.5)	68.0 (64.3, 71.7)	73.7 (69.1, 78.2)
Severe (> 28 days of absence)	25.0 (23.1, 26.9)	28.0 (24.5, 31.5)	21.1 (16.8, 25.3)

^aData are expressed as percentage values with 95% confidence intervals in parenthesis

average risk was higher for traumatic injuries than for overuse injuries. There were significantly more female skiers reporting a traumatic injury than male skiers. In contrast, there were significantly more male skiers affected by overuse injuries.

Risk ratios for season period- and sex-dependent differences

Table 4 highlights the season period- and sex-related comparisons of the epidemiological incidence proportion among elite competitive alpine skiers. The female-to-male risk ratio was of similar magnitude for traumatic, overuse and all injuries. However, the risk of traumatic injuries was 1.5 times higher during the competition period, while the risk of overuse injuries was substantially larger during the off-season preparation period.

Injury location

Table 5 gives an overview of the distribution of all injuries with respect to body location and severity. Over an entire season, a total of 81 injuries were reported by the 44 athletes. With respect to traumatic injuries, the most frequently injured body locations were the head (e.g. concussion), lower leg (e.g. fractures or ski boot contusions) and knee (e.g. knee sprains). Overuse injuries primarily affected the lumbar spine (e.g. recurrent low back pain), knee (e.g. patellar tendon complaints) and hip (e.g. femoro-acetabular impingement syndrome (FAIS)).

Injury type

The distribution with respect to injury type and severity is presented in Table 6. With respect to traumatic injuries, contusions were the largest group. Fractures and bone stress were the second most frequent injury type, followed by injuries of the nervous system (most of them concussions). The highest percentages of severe injuries per injury type were observed for joint and ligament injuries and fractures/bone

Table 4 Risk ratios for sex and season period differences among elite competitive alpine skiers

Injury classification	Risk ratio ^a	
	Females vs. males (entire season)	Competition vs. preparation period
Traumatic injuries	1.031 (0.630, 1.690)	1.500 (0.951, 2.367)
Overuse injuries	0.988 (0.549, 1.779)	0.421 (0.224, 0.791)
All injuries	0.971 (0.626, 1.507)	0.903 (0.629, 1.297)

^aData are expressed as risk ratios with 95% confidence intervals in parenthesis

Table 5 Distribution of all injuries with respect to body location and severity (classified according to number of days absent for training and or competition)

Body location	Traumatic injuries		Overuse injuries	
	All	Severe (> 28 days)	All	Severe (> 28 days)
Head/face	10	3	0	0
Neck/cervical spine	2	1	1	0
Shoulder/clavicle	2	1	0	0
Upper arm	0	0	0	0
Elbow	2	0	0	0
Forearm	5	0	0	0
Wrist	2	1	0	0
Hand/finger	5	0	0	0
Thorax/rib	1	0	0	0
Abdomen	0	0	0	0
Thoracic spine	1	0	1	0
Lumbar spine	2	0	10	0
Pelvis/sacrum	0	0	0	0
Hip/groin	2	0	5	1
Thigh	2	0	0	0
Knee	8	4	8	1
Lower leg	9	4	1	0
Ankle	4	4	1	1
Foot/toe	1	1	1	0
Other	0	0	0	0
Total	53	19	28	3

Data are expressed as number of incidents

stress. The most frequent types of overuse injuries were muscle- and tendon-related complaints, followed by fractures/bone stress and joint/ligament injuries.

Table 6 Distribution of all injuries with respect to type and severity (classified according to number of days absent for training and or competition)

Injury type	Traumatic injuries		Overuse injuries	
	All	Severe (> 28 days)	All	Severe (> 28 days)
Fractures/bone stress	14	7	2	0
Joint/ligament	9	5	2	0
Muscle/tendon	4	1	7	1
Contusion	15	2	0	0
Skin/laceration	0	0	0	0
Nervous system	11	4	0	0
Other	0	0	17	2
Total	53	19	28	3

Data are expressed as number of incidents

Discussion

The major findings of this study were as follows: (1) the risk of suffering from at least one injury during one alpine skiing season was 75.0% for traumatic injuries, 52.3% for overuse injuries and 93% for all kinds of injuries, which coincides with absolute injury rates of 120.5, 63.6 and 184.1 injuries per 100 athletes per entire season, respectively; (2) while during the competition period, there was a higher risk for traumatic injuries, during the off-season preparation period, a higher risk for overuse injuries was observed; (3) over an entire season, there were no sex differences; however, females had a higher risk for traumatic injuries during the preparation period and for overuse injuries during the competition period, while males were more prone to overuse injuries during the preparation period; (4) traumatic injuries predominately concerned the head, lower leg and knee, while overuse injuries most frequently affected the lumbar spine, knee and hip; and (5) the most frequent types of severe traumatic injuries were fractures/bone stress and joint/ligament injuries, while overuse injuries primarily accounted for muscle- and tendon-related complaints.

Substantially higher injury rates during the competition period than reported previously: have we only looked at the tip of the iceberg until now?

Compared to previous elite competitive alpine skiing-related studies [1, 5, 11, 16], the current study found substantially higher absolute injury rates. On the WC level, the official surveillance system by FIS revealed injury rates between 36.7 and 36.2 injuries per 100 WC athletes per competition period [5, 11, 16]. On the EC level, a recent study within the French National Ski Association reported injury rates being twice as high as those at the WC level [1]. However, in our investigation, this rate was found to be as high as 95.5 injuries per 100 athletes per competition period. One explanation for this substantial discrepancy might be found in the slightly longer competition period, when not only including the WC competitions [5, 11, 16], but also EC races [1] and FIS races, as was done in our study. A second reason might be that (similar to [1]) our data originate from a national, not an international, injury registration program [5, 11, 16], with the team medical/research team having more direct access to health-related information on the athletes. A third explanation might be related to differences in the registration method and injury definition. Across the literature, retrospective interviews and “time-loss” and/or “medical attention” conditions are

the most commonly used methodologies and criteria for injury definition [3, 6]. The same applies to most alpine skiing-related epidemiological studies [1, 5, 11, 12, 16, 33, 35]. However, such data collection methods imply a certain risk for missing the registration of less severe yet relevant injuries and thereby to underestimate the true risks to which athletes are exposed [3, 6]. Accordingly, the true burden of overuse injuries and minor injuries might have been missed or underestimated so far. In contrast, the current study applied a prospective registration method and an “any physical complaint” injury definition, most likely providing a more complete picture of the actual injury risks among elite competitive alpine skiers.

Injuries during the off-season preparation period: time to give them more attention?

As demonstrated previously, recording injuries only during the competition period may substantially underestimate the actual extent of the injury problem, as more than 40% of all injuries occur during the off-season preparation period [1]. This conclusion further supports the findings of this study. The overall injury risk during the off-season preparation period was even slightly higher than that during the competition period. Moreover, when comparing the absolute injury rate of 184.1 injuries per 100 athletes per entire season (observed in this study), with those previously reported for WC skiers (between 36.7 and 36.2 injuries per 100 athletes per competition period [5, 11, 16]), the magnitudes are markedly different. Certainly, the three explanations stated above (i.e. WC vs. all competition levels, national vs. international registration, and retrospective design/medical attention definition vs. prospective design/“any complaint” definition) may also have influenced this discrepancy. It is, however, likely that the restricted, less representative observation time (competition period vs. entire season) played the most important role in the previous underestimation of the full injury extent in elite competitive alpine skiing.

Season-specific differences in injury risk and rates among competitive alpine skiers

As revealed in this study, the average risk for traumatic injuries was 1.5 times higher during the competition period than during the off-season preparation period. This is particularly remarkable as the quantity of skiing and off-snow training exposure, as well as the overall training load, is higher during the preparation period [15]. Thus, with respect to traumatic injuries, greater risk-taking behaviour during competitions or qualification trainings, as well as tight competition schedules, may overpower the smaller risk exposure during the competition period [29]. In contrast, with respect to overuse injuries, there was a significantly higher

risk during the off-season preparation period than during the competition period. Here, intensive physical training sessions combined with large amounts of volume-oriented ski training, which are typical for the off-season preparation period [15], plausibly have a significant effect on overuse-related physical complaints. Overall, the findings of the current study are consistent with those of a previous study in competitive adolescent alpine skiers [18], and with those of a recent study in EC level skiers [1], further highlighting the evident need to consider season period-specific aspects in injury prevention efforts.

Sex-specific differences in injury risk and rates among competitive alpine skiers

Including all types of injuries over the entire season, no difference in injury risk was found between the sexes. This is in line with the results of two previous studies in youth and adolescent competitive alpine skiers [25, 35]; however, it contradicts previous data from the FIS injury surveillance system [5, 11], which reported higher absolute injury rates in males. The only two studies comparing the preparation and competition periods did not find any sex-specific differences in the frequency or distribution of injuries between the season periods [1, 18]. In contrast, our study revealed that females have a higher risk of traumatic injuries during the off-season preparation period and of overuse injuries during the competition period and that males are more prone to overuse injuries during the preparation period. Thus, again, our findings highlight the importance of also considering sex-specific aspects in our injury prevention efforts, particularly in combination with season period-specific aspects.

Most frequent injury locations and types among competitive alpine skiers: where should prevention priorities be set?

Most of the traumatic injuries concerned the head, the lower leg and especially the knee. This is in line with earlier studies on WC competitive alpine skiers [11, 12]; however, in direct comparison, with a relatively high number of head injuries such as concussion in our study. In view of the high skiing speeds and the hard snow surfaces that are typically involved in the impacts and mechanisms leading to head injuries [31], high frequencies are entirely plausible, and it comes without saying that the prevention of head injuries should be a priority within the sport of alpine ski racing. The remarkably higher number of head injuries in this study compared to those in previous studies, however, might be primarily related to the different methodological approaches used since head injuries such as concussion are demonstrably lacking clear indicators and athletes' grasp of a precise definition [23, 24], they are likely to be underreported within

the retrospective interviews used in earlier studies [5, 11] but can be more trustworthily reported using a prospective data collection method as used in the current study. In contrast, the high number of lower leg and knee injuries was no surprise, as it represents a well-documented scientific fact [5, 11, 12, 25, 27, 33, 35], and coincides with the major injury mechanisms in elite competitive alpine skiing described previously [4]. Accordingly, these types of injuries remain a major preventative challenge in alpine ski racing.

Overuse injuries were most often located in the lumbar spine, the knee, and the hip, which is why future overuse injury prevention efforts in competitive alpine skiers should primarily focus on these body locations. The current data availability on overuse injuries in elite alpine skiing, however, is scarce. A study evaluating elite adolescent alpine skiers identified the trunk/back to be the most common overuse injury location, followed by the lower extremities, which is in line with our findings [18]. A potential biomechanical explanation for the high number of back overuse injuries in alpine ski racing was given by Spörri et al. [28, 30]. In addition to an overall training load-induced accumulation of heavy mechanical loads acting on the spinal structures, the typical loading patterns while skiing include an unfavourable occurrence of frontal bending, lateral bending, and torsion in the highly loaded spine, as well as excessive exposure to adverse low-frequency vibrations. With respect to knee overuse injuries, representing the second largest group, it has been shown that the loads and moments acting on the knee joints while skiing are relatively high [21, 36]. Such adverse loading conditions make the knee joint particularly prone to overuse injuries. Regarding overuse injuries at the hip, Aminoff et al. demonstrated that young elite alpine skiers have a higher prevalence of cam morphologies of their hip joints than age-matched controls [2]. However, the exact cause for the relatively high number of overuse injuries of the hip remains unclear.

The most frequent types of severe traumatic injuries in elite competitive alpine skiers were fractures/bone stress and joint/ligament injuries, while overuse injuries primarily accounted for muscle and tendon-related complaints. This widely coincides with the injury patterns observed in previous studies across different age and level groups [11, 18, 25], and, accordingly, highlights where to set the general focus of injury prevention.

Despite providing valuable insights into the injury risks among elite competitive alpine skiers, this study was challenged by several methodological limitations. First, injury registration primarily relied upon precise self-reporting of the participating athletes. However, athletes may have forgotten or been unwilling to report them. Thus, there is a certain risk for suffering from a *recall* and/or *reporting bias*. However, this study tried to reduce the *recall bias* by applying a prospective OSTRC

questionnaire-based injury registration, and to counteract any reporting bias by including the team medical records. Moreover, supplemental interviews at the end of the season were used to verify the correctness and completeness of the data. Second, the relatively small cohort number presents another limitation of this study. Larger cohorts should be investigated to further support the generalizability of the current findings to other age/level groups, such as youth athletes. Nevertheless, this study provides a highly representative overview of the injury epidemiology within a National Ski Team cohort, as almost the entire population was participating. Third, there would have been alternative measures of incidence to focus on, such as *incidence rate* (i.e. the number of injuries divided by the number of athlete exposures) [22]. However, to successfully promote injury prevention in sports, athletes (and their professional setting) must be aware of the exact risks that they are exposed to. In this regard, the *epidemiological incidence proportion* (i.e. the number of injured athletes per season or period divided by the number athletes at risk) provides a more intuitive measure than the incidence rate because an athlete typically participates in an entire season, not only for a couple of off-snow training or skiing hours [22]. Based on these considerations, it was decided to primarily focus on investigating the *epidemiological incidence proportion* and (for better comparability with previous studies) the *absolute injury rates*.

Finally, it should be emphasized that this study's results highlight the complexity and context dependency of the patterns and potential causes of injury in elite competitive alpine skiers. Effective injury prevention strategies must simultaneously consider different distinct classes, severities, locations and types of injuries, namely traumatic injuries to the head (e.g. concussion), lower leg (e.g. fractures or ski boot contusions) and knee (e.g. knee sprains), as well as overuse injuries to the lumbar spine (recurrent low back pain), knee (e.g. patellar tendon complaints), and hip (e.g. femoro-acetabular impingement syndrome (FAIS)) should be a major prevention focus. Moreover, the presence of a season period and sex dependency in skiers' injury risk was clearly demonstrated, implying an unmet need for specially tailored countermeasures. Although the current investigation may help to redefine future research and injury prevention priorities, speculating on potential effective prevention approaches would go beyond the validity of our data and the scope of this study. However, it goes without saying that the aforementioned complexity of the skiing-specific injury situation cannot be resolved by a single approach, and further interdisciplinary studies involving methodological pluralism are needed.

Conclusion

In conclusion, injury risks among elite competitive alpine skiers were alarmingly high and substantially larger than those previously reported. Our results demonstrated that the entire injury extent is likely to be underestimated if not registered prospectively, over the entire season and regardless of whether requiring medical attention. Furthermore, injury risks and patterns are season period and sex dependent, which is why injury registration should focus on the entire season (including the off-season preparation and competition periods) and prevention efforts should be specifically tailored to the sex of the athletes.

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Author contributions JS conceptualised and designed the study. JS recruited the participants and organised the data collection. WK and JS designed, built and maintained the digital assessment tools. SF, MH, LP and JS collected the data. SF, MH, LP and JS processed the data and performed the statistical analysis. All authors substantially contributed to the interpretation of data. SF, MH and JS drafted the manuscript; all authors revised it critically, approved the final version of the manuscript, and agreed to be accountable for all aspects of the work.

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Compliance with ethical standards

Conflict of interest The authors have no relevant conflict of interest to declare.

Ethical approval The current study was approved by the institutional review board of the Balgrist University Hospital and the cantonal ethic committee (KEK-ZH-NR: 2017-01395), and was performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments.

Informed consent Written informed consent was obtained from all participants.

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