Impact of Environmental Factors on the ACL Injury Risk in Recreational Alpine Skiing

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ABSTRACT

In recreational alpine skiing, an ACL injury represents the most common injury. Skiing is a complex activity where the skier interacts with the environment, such as weather, snow conditions, temperature, etc. Thus, the aim of this study was to evaluate the potential impact of environmental factors on ACL injury risk in recreational alpine skiers. Among a cohort of 392 ACL-injured skiers and 392 uninjured controls matched for sex and skiing skill, environmental factors were collected by questionnaire. Factors included weather conditions, snow conditions, perceived temperature, and slope difficulty at the time-point of the accident (ACL-injured skiers) or of questioning during the ski day (uninjured controls).

Multiple logistic regression revealed that in addition to age, five environmental factors were significantly predictive of an ACL injury: fresh snow (OR 10.5), grippy snow (OR 7.8), icy slope condition (OR 12.4), very cold/cold perceived temperature (OR 1.6), and skiing on easy slopes (OR 6.9). In conclusion, besides age, environmental factors such as fresh and grippy snow, icy slope conditions, low temperatures, and flat slopes are associated with an increased ACL injury risk in recreational alpine skiing. Those factors are at least partly modifiable and should be taken into consideration for preventive strategies.

Introduction

Recreational alpine skiing, a popular winter sport activity, is enjoyed annually by hundreds of millions of skiers worldwide [1, 2]. In Austria, the overall rate of skiing-related injuries is less than one injury per 1,000 skier days [3], but the total number of skiing-related injuries is high due to the large number of recreational alpine skiers [3]. Over the last few decades, there has been a continuous decrease in alpine skiing-related injuries, however, the proportion of skiing-related knee injuries has remained constant [4].

The knee joint remains the most common injured anatomical body location, representing about one-third of all injuries among female and male recreational alpine skiers [4, 5]. Moreover, 50 % of recorded knee-injured skiers suffer from an injury to the anterior cruciate ligament (ACL) [6]. Posch et al. [7] have shown that ACL

ruptures during skiing generally occur in combination with concomitant injuries to the medial collateral ligament [7].

It is well known that any skiing-related knee/ACL injury is likely the outcome of a complex interaction of multiple intrinsic and extrinsic risk factors [8]. While intrinsic risk factors for injury in skiing include age, sex (biological factors)/gender (psychological and sociological factors), skill level, etc., extrinsic risk factors are equipment (ski-boot-binding unit) or environmental-related (snow, slope, and weather conditions) [4, 9]. Given the variable conditions that exist in an open-air outdoor environment, such as alpine skiing, the combination of risk factors related to skier safety and injury risk are complex [1].

Previous research has shown that knee injury prevalence in female recreational alpine skiers is two-fold greater than male skiers [4, 10, 11]. Furthermore, ACL injury risk is three times more likely in females [4, 10, 11]. This interesting fact may be partly attributed to individual (intrinsic) risk factors [4, 8, 9], e. g. hormonal, anatomical, and neuromuscular factors and differentiated by sex [12, 13]. Also, sex-based differences in equipment-related factors have been investigated, such as ski binding adjustment regarding knee/ACL injuries in recreational alpine skiing [4, 14].

Beside sex/gender, skill level is another important intrinsic risk factors for an ACL injury in skiing. Indeed, a recent study found that beginner skiers are independently associated with a higher ACL injury risk [15]. Additionally, it is clear that lower skill level of skiers increases the overall injury risk on alpine ski slopes [16, 17]. Thus, individual skill level may represent an important confounder when evaluating injury risks in skiers.

Environmental factors such as snow conditions [18–20], slope difficulty [21], and weather conditions [4, 9, 22] have also been suggested to modify the prevalence and risk of non-contact knee injuries in recreational alpine skiing.

Specifically, low ambient temperature and snowfall have been shown to be significant environmental risk factors for knee injuries in female recreational alpine skiers [13]. In this study, the prevalence of knee injuries in females was highest when the ambient temperature was low (between -20 ° and -8 °C), while the number of knee-related injuries in male skiers did not significantly differ across different ambient temperatures [13]. In addition, knee injuries are two times greater compared to other injured body parts when skiing during snowfall (15.4 % vs. 8.6 %, respectively) [13]. In another study, no significant differences between ACL injured male and female skiers regarding snow conditions, slope difficulty, or weather conditions were found [23]. Moreover, a further case-control study investigating multiple risk factors for an ACL injury in female skiers revealed that icy snow conditions and snowfall increased ACL injury risk by 24-fold and by 17-fold, respectively [24].

However, the above-mentioned studies on the potential impact of environmental factors on the injury risk do have some limitations due to low sample size [20, 21, 24], missing control groups of uninjured skiers [13, 20, 23], and/or detailed diagnosis of the knee injury [13]. Thus, to address this gap in the literature, we undertook a large case-control study, focusing on ACL-injured female and male recreational alpine skiers compared to uninjured skiers (matched for sex and skiing skill level) based on a sufficiently large sample size, i. e. N > 780. It remains unknown if environmental factors are predictive for an ACL injury in recreational alpine skiing. Therefore, this study aimed to evaluate the impact of various environmental factors on the ACL injury risk in recreational alpine skiers across a broad age range.

Materials and Methods

Study design

This study was conducted as a retrospective matched case-control study of ACL-injured and uninjured male and female recreational alpine skiers during six consecutive winter seasons (2014/15 to 2019/20), treated in a single high-patient volume Austrian sports clinic. In order to avoid confounding by different skiing skill levels between ACL-injured skiers and controls, a sex and skill-level-matched control group was created.

In accordance with previous studies [7, 15, 25], cases were interviewed annually between December and April over 23 days on average per winter season using a standardized questionnaire. The recruitment of patients was dependent upon logistical aspects at the sports clinic (availability of rooms and personnel) and the readiness of patients to participate. In total, more than 95 % of invited patients agreed to participate [7].

Justification of the sample size is primarily based on the concept of events per variable (EPV), whereupon Peduzzi et al. [26] suggested the number of EPV analyzed in logistic regression analysis to be values of 10 or greater. In the present study, EVP is 26.1 (392 cases and 15 independent predictors, considering the intercept in the logistic regression).

All study participants were informed about the aims of the study and gave their written informed consent for taking part in the study. The survey was conducted according to the ethical guidelines for surveys approved by the Institutional Review Board (IRB) as well as the Board for Ethical Issues (BfEI) of the University of Innsbruck (25/2016).

Cases

Inclusion criteria of cases were (i) a skiing-related, non-contact ACL injury after a fall without the involvement of another skier, (ii) an age > 18 years, and (iii) the use of any type of carving skis (in contrast to long and unshaped traditional skis as well as so-called short ski boards). The ACL injury was diagnosed by a physician using magnetic resonance imaging (MRI), which is directly available at the sports clinic [7].

Controls

As described earlier [15], uninjured controls were simultaneously (i. e. on the same day) chosen at various spots from the same ski area throughout the whole skiing day on 15 days on average per winter season. Inclusion criteria were an age > 18 years and the use of any type of carving skis.

Out of a large pool of controls (N = 1425), controls were randomly matched for sex and skill level to cases (with a one-to-one basis).

Questionnaire

Beside demographic data, sex, age, and skiing skill level (expert vs. advanced vs. intermediate vs. beginner) and according to Sulheim et al. [27], ACL injured skiers were asked to report environmental

factors like weather conditions (sunny vs. overcast vs. snowfall), snow conditions (fresh snow vs. grippy snow vs. icy snow vs. slushy/soft snow), perceived temperature (very cold/cold vs. neutral vs. warm/very warm), and the difficulty of the downhill slope (easy – blue vs. moderate – red vs. difficult – black) at the timepoint of the accident [13, 24].

According to the methods described in an earlier study, controls rated the overall weather conditions, snow conditions, perceived ambient temperature and difficulty of their preferred slopes on the day of the interview [24].

Furthermore, we categorized participants into more skilled (expert and advanced) and into less skilled (intermediate and beginner) skiers, as a previous study showed a tendency to underestimate individual skill level, especially among female skiers [27].

Statistical analysis

All data are presented as means ± standard deviations, absolute and relative frequencies. According to tests on normal distribution (Kolmogorov-Smirnov), univariate differences among metric data (age) between cases and controls were evaluated either by independent t-tests or Mann-Whitney U tests.

Differences in frequencies (weather conditions, snow conditions, perceived temperature, and difficulty of the downhill slope) were evaluated by chi-square tests.

Additionally, according to the univariate results, multiple logistic regression analysis (entering all risk factor variables with $p < 0.2$) was used to calculate multivariate OR and 95 % confidence interval (CI) [14, 15]. Within variables with more than two categories, the last category was used as reference. SPSS 26.0 (IBM Corporation, Armonk, NY) was used for the statistical analysis. All p-values were two-tailed, and statistical differences were considered significant at $p < 0.05$.

Results

A total of 392 ACL injured and 392 uninjured skiers (57.9 % females) with a mean age of 39.6 ± 12.2 years participated. Differences between cases and controls regarding mean age, weather conditions, snow conditions, perceived temperature, and difficulty of the downhill slope are presented in ▶ **Table 1**.

Multiple logistic regression results are shown in ▶ **Table 2**. An increasing age is significantly associated with ACL injury. With regard to snow conditions, ACL injury risk increased by 10.5-fold for fresh snow, 7.8-fold for grippy snow, and 12.4-fold for icy conditions, respectively as compared to the reference category slushy/

▶ **Table 1** Characteristics and univariate odds ratios of environmental risk factors in uninjured (controls) and in ACL-injured (cases) recreational alpine skiers.

	Controls (n = 392)	Cases (n = 392)	p-value
Age [years]	36.4 ± 13.0	42.7 ± 10.5	< 0.001
Weather conditions [n, %]			0.167
sunny	265 (67.6)	267 (68.1)	
overcast	105 (26.8)	91 (23.2)	
snowfall	22 (5.6)	34 (8.7)	
Snow Conditions [n, %]			< 0.001
fresh snow	40 (10.2)	59 (15.1)	
grippy	209 (53.3)	244 (62.2)	
icy	39 (9.9)	72 (18.4)	
slushy/soft	104 (26.5)	17 (4.3)	
Perceived Temperature [n, %]			< 0.001
Very cold/cold	96 (24.5)	145 (37.0)	
Neutral	164 (41.8)	167 (42.6)	
Warm/very warm	132 (33.7)	80 (20.4)	
Difficulty of the downhill slope [n, %]			< 0.001
Easy (blue)	77 (19.6)	210 (53.6)	
Moderate (red)	226 (57.7)	149 (38.0)	
Hard (black)	89 (22.7)	33 (8.4)	

Data are presented as mean values ± standard deviation, absolute and relative frequencies

▶ **Table 2** Adjusted odds ratios (enter method) of individual and environmental risk factors associated with an ACL injury

Risk factors	Coefficient	Standard error	df	p-value	Odds ratio (95 % CI)
Age	0.049	0.007	1	< 0.001	1.05 (1.04–1.07)
Weather conditions					
sunny	0.280	0.366	1	0.445	1.32 (0.65–2.71)
overcast	− 0.241	0.374	1	0.520	0.79 (0.38–1.64)
Snow Conditions					
fresh snow	2.351	0.423	1	< 0.001	10.49 (4.58–24.02)
grippy	1.956	0.289	1	< 0.001	7.79 (4.12–14.72)
icy	2.634	0.321	1	< 0.001	12.43 (6.03–25.61)
Perceived Temperature					
Very cold/cold	0.495	0.252	1	0.050	1.64 (1.00–2.69)
neutral	0.014	0.232	1	0.952	1.01 (0.64–1.60)
Difficulty of the downhill slope					
Easy (blue)	1.935	0.268	1	< 0.001	6.93 (4.09–11.71)
Moderate (red)	0.461	0.253	1	0.069	1.59 (0.97–2.60)

Notes: All entered factors in the multiple logistic regression analysis were adjusted for each other. Nagelkerke R-Square = 0.356, classification table – overall percentage = 73.3 %,

soft snow. ACL injury risk increased 1.6-fold for very cold/cold perceived temperature compared to the reference category warm/very warm. On easy (blue) slopes, ACL injury risk is 6.9-fold higher when compared to the reference category difficult (black) slope.

Discussion

The primary aim of this study was to evaluate the potential impact of environmental factors on the ACL injury risk in recreational alpine skiers. To the best of our knowledge, this is the first study using a matched (for sex and skill level) case-control study design, considering both ACL-injured and uninjured male and female recreational alpine skiers to evaluate the potential impact of environmental factors on ACL injury risk.

The main findings were twofold: a) increasing age is significantly associated with ACL injury, and b) with regard to environmental factors, fresh, grippy, or icy snow conditions, very cold/cold perceived temperatures, and skiing on easy ski slopes were independent predictors for an increase in ACL injury risk.

ACL injured skiers in this study were five years older on average than uninjured controls. Results of the multiple logistic regression revealed that an increase of age by 5 years increased ACL injury risk by 25 %. In accordance, other studies also reported a higher age as a risk factor for knee/ACL injuries in recreational alpine skiing [9, 15]. A potential explanation for this result could be that increasing age is associated with a progressive loss of neuromuscular function due to a reduction of muscle mass and muscle quality as well as changes in the biology, healing capacity, and biomechanical function of tendons and ligaments [28, 29].

Regarding weather conditions, about 68 % of ACL-injuries occurred on sunny days, which seems to be in line with findings by Ruedl et al. [24] and Burtscher et al. [9], who reported that 70 % and 63 % of knee injuries occurred during sunny conditions, respectively. However, no significant differences with regard to weather conditions were found between cases and controls neither in the simple nor in the multiple analysis. Usually, skiers prefer to ski on sunny days [9, 22]. Aschauer et al. [22] found a somewhat higher overall injury risk when skiing during strong snowfall compared to sunny conditions. However, our findings do indicate that snow and slope conditions are more important predictors for ACL injury than weather conditions.

Compared to slushy/soft snow conditions, the risk to experience an ACL injury increased by 11-fold on fresh snow and by 8-fold on grippy snow in this study. Interestingly, Moore & Knerl [30] reported a negative correlation between 24-hour snowfall accumulation and injury severity among both skiers and snowboarders. Thus, one could assume that fresh snow reduces the overall severity of injury risk on ski slopes, which makes logical sense considering the protective effects of falling on soft snow as well as the overall skiing speed on fresh snow is less than on ice. Given that we did not look at the meteorological data for snowfall on the days where fresh snow was reported, we can only rely on the skiers' self-reported assessments of the snow conditions. It seems reasonable to speculate that a key reason for our increased ACL risk is due to catching an edge, which has been shown to be the main kinematic feature of how ACL ski injuries occur [7]. To explain with fresh snow accumulation, terrain variations on the slopes are less identifiable, which can lead to reduced anticipation of bumps and furrows typically evident on ski slopes. Thus, the opportunity to either catch an edge or a ski tip with enough force that leads to a fall might result in a subsequent ACL injury.

The higher ACL risk when skiing on grippy snow compared to slushy/soft snow might be partly caused by a higher mean speed on grippy slopes. Carus & Castillo [31] reported a mean skiing speed of about 58 km/h on grippy snow and about 49 km/h on wet snow, which seems comparable to slushy/soft snow conditions in this study.

Yet the snow condition with the highest risk (OR 12) of an ACL injury while alpine skiing was icy snow. In this case, icy conditions were about 1.5-fold higher risk than grippy snow conditions. This aligns with previous research that found that increased ACL injury risk on icy ski slopes was 24 times greater than slushy/soft snow conditions in female skiers [24]. Interestingly, Bouter et al. [18] found that it might not just be the overall self-report of icy conditions but also exposure to icy spots on slopes that suddenly cause a change in stance and balance, resulting in falls. Regardless, it can be agreed that skiers have less edge control on consistently icy snow slopes than grippy snow slopes and that icy spots in mixed snow conditions are associated with a more likely loss of balance and falling, which can further result in ACL injuries [24].

In the current study, low perceived temperature turned out to be an independent risk factor for ACL injuries in recreational alpine skiing. In an earlier study, Ruedl et al. [13] found a significantly higher prevalence of knee injuries in female skiers when objectively measured ambient temperature was low, while male skiers did not show such temperature-dependent differences. It is important to mention that this temperature dependent ACL injury risk might also be related to alterations in further environmental conditions that are consequential to either a rise or fall in temperature [32]. To explain, previous research has found that colder ambient temperatures are associated with harder conditions that may progress to icy surface conditions, thereby increasing risk [18, 24] of alpine skiing accidents and associated injuries. In addition, Csapo et al. [32] have suggested that cooling of the thigh and knee leads to a reduction in the capacity to generate force explosively, particularly affecting the knee flexor muscles. Moreover, a reduction in hamstring co-activation during forceful contraction of knee extensors was observed, which may further contribute to increased ACL injury risk in the cold [32]. It is well known that just one hour of skiing reduces the skin and intraarticular temperatures of the knee joint [33]. Furthermore, Piedrahita et al. [34] reported a reduced ability to maintain dynamic balance caused by the cooling of the lower leg and Dewhurst et al. [35] showed that muscle fiber conduction velocity of knee muscles was slower in a cold environment. Cooling increases the latency of soleus H-reflex, which is an important mechanism in controlling motor behavior of the lower leg [36]. Knowing that losing balance or catching an edge of the ski are the most common reported circumstances for a fall resulting in an ACL injury in recreational alpine skiers [23], it is clear that very cold ambient temperature conditions likely have a direct influence on the control of skiing, especially when a skier is turning or carving a turn. It is suggested that preventive measures to counteract cold-related effects of ambient weather conditions while alpine skiing should include adequate clothing and more frequent breaks to warm up. This recommendation is likely more important in female skiers [13].

Based on previous research [37], warming up for 15 minutes results in a higher body temperature for at least 30–45 minutes post warm-up compared to no warm-up when skiing.

The majority of ACL-injuries (54 %) occurred on easy (blue) slopes compared to uninjured controls, who reported to be mainly skiing on moderate (red) slopes. Due to matching for skiing skills, the preference of slope type should not differ much between ACL-injured and control skiers. According to the results of the logistic regression analysis, skiing on easy ski slopes is associated with a 7-fold higher risk for an ACL injury. In contrast, Demirag et al. [21] reported that hard and steep slopes increased risk for any knee ligament injury. We would surmise that a greater number of beginners choose flat slopes, especially when learning how to ski. Thus, the skill level of skiers choosing flat and moderate slopes rather than the slope itself may explain our findings. This would align with Sulheim et al. [17], who found that the overall injury risk of skiing-related injuries increases among beginners as well as total knee injuries. When considering only less skilled ACL-injured recreational alpine skiers (data not shown), about 60 % reported that the accident happened on easy slopes. In addition, carelessness and higher skiing speed of more skilled skiers skiing on easy slopes could provoke catching an edge, which potentially results in a subsequent fall, leading to an injury. Finally, there are fewer steep slopes compared to easy and intermediated slopes in most ski resorts, including those used in this study, thus the influence of skill level, total time on moderate and flat slopes, and reckless behavior of skilled skiers on moderate slopes potentially contribute to the ACL risk found in this study.

To sum up, this is the first large, matched, case-control study (N = 784) that has evaluated the potential impact of various environmental factors on the ACL injury risk in recreational alpine skiing. Our results revealed 5 environmental factors to be predictive for an ACL injury. While some intrinsic risk factors, such as sex/gender and age are not modifiable [8], extrinsic – i. e. environmental risk factors can be considered strategically by the individual skiers, e. g. avoiding icy spots on ski slopes and very cold ambient air temperatures. Recreational alpine skiers should consider adequate clothing and use more frequent breaks to warm up [13].

However, it seems difficult to avoid easy slopes, which are often leading the skier to the chair lift station at the bottom of the slope. Thus, the impact of environmental factors in this study seems limited, also due to a Nagelkerke R-Square of 0.356 as Ruedl et al. [38] recently reported, individual factors such as age, skill level, and risk-taking behavior, as well as equipment-related factors such as ski length, tip, waist width of the ski, and standing heights are predictive for an ACL injury on ski slopes with a Nagelkerke R-Square of 0.706. Nevertheless, an improved understanding of current environmental risk factors for an ACL injury could provide a valuable basis for future research, especially for preventive interventions. As these results have important implications for skiers, these findings should be used in knowledge translation to raise the importance of specific environmental factors that may cause ACL injury risk in recreational alpine skiing. In addition, as a practical preventive measure, ski lessons will be useful to improve skill level and in order to become familiar with the slide characteristics of the skis on different slopes and in different environmental conditions.

Strengths and Limitations

Due to the restriction of our patients to the ski clinic, we cannot entirely exclude a possible selection bias of ACL-injured skiers. However, a major part of knee injuries occurring in the study area were treated in the ski clinic and there are no obvious indications of any source of selection. With regard to the factor difficulty of the ski slope, some uncertainties might arise as we compared self-reported data on preferred slope difficulties for the uninjured control group and the actual slope difficulty where cases suffered the ACL injury. The inclusion of a control group (matched for sex and skiing skill level) clearly strengthens the study results, as the impact of risk factors on the onset of an injury event can be investigated using an appropriate case-control study design. Another strength of the study is that uninjured controls were interviewed mostly (95 %) on the same days when ACL-injured cases were treated in the ski clinic to enable the analysis of investigating the impact of environmental factors on the ACL injury risk. Additionally, in certain cases, poor snow and weather conditions may have been misjudged as ACL injured skiers may look for an explanation as to why the injury occurred [24].

Conclusion

An increasing age is a significant individual factor associated with an ACL injury in recreational alpine skiing. Regarding environmental factors, icy and easy slopes, fresh and grippy snow, and low ambient temperatures are associated with an increased ACL injury risk in recreational alpine skiing. Those factors are at least partly modifiable and should be taken into consideration for the implementation of preventive strategies.

Disclosure statement

The authors report that there are no competing interests to declare.

Conflict of Interest

The authors declare that they have no conflict of interest.

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