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Is ski boot sole abrasion a potential ACL injury risk factor for male and female recreational skiers?

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Objectives: To evaluate the potential impact of ski boot sole abrasion on the ACL injury risk of recreational skiers.
Methods: During the past two winter seasons 2016/17 and 2017/18, this retrospective case-control study was conducted in one Austrian ski area. Among a cohort of 148 ACL-injured (51.4% females) and 455 uninjured recreational skiers (43.3% females), age, sex, height, weight, and self-reported skill level were collected by questionnaire, ski length and sidecut radius were notated and sole abrasion of the toe and heel piece of the ski boot was measured using a digital caliper.
Results: ACL-injured skiers showed a higher proportion of female (51.4% vs 43.3%, $P < 0.001$) and less skilled skiers (48.6% vs 20.9%, $P < 0.001$), and ski length to height ratio was higher (94.7 ± 3.7 vs $93.8 \pm 5.0\%$, $P = 0.019$) compared to uninjured skiers. ACL-injured skiers used ski boots of greater abrasion at the toe (4.8 ± 1.8 vs 2.4 ± 2.5 mm, $P < 0.001$) and heel piece (5.4 ± 1.8 vs 3.3 ± 2.3 mm, $P < 0.001$) compared to controls. Multivariate regression analysis revealed, beside female sex (OR 6.0, 95% CI, 3.1-11.5, $P < 0.001$), lower skill level (OR 3.2, 95% CI, 1.9-5.4, $P < 0.001$) and ski length to height ratio (OR 1.1, 95% CI, 1.0-1.2, $P < 0.001$), sole abrasion at the toe (OR 1.8, 95% CI, 1.5-2.1, $P < 0.001$) and heel piece (OR 1.4, 95% CI, 1.2-1.6, $P < 0.001$) to be independently associated with an ACL injury among recreational alpine skiers.
Conclusions: Based on the underlying findings, ski boot sole abrasion was found to be an independent risk factor and may contribute to an increased ACL injury risk.

KEYWORDS
alpine skiing, equipment-related risk factors, knee injuries, prevention

1 | INTRODUCTION

Recreational alpine skiing is one of the most popular winter sports annually enjoyed by several hundred million skiers worldwide.[1,2] Despite the large number of skiers, the currently calculated injury rate in Austria is less than 1 injury per 1000 skier days.[3] The most common accident causes on ski slopes are self-inflicted falls with 80%-90%.[2-4] The most common anatomical location of an injury in alpine skiing is the knee joint with about one third of all injuries in male and female skiers.[3,5,6] The anterior cruciate ligament (ACL) is injured in about 15%-21% of all skiing injuries in adult recreational skiers.[6,7] Female skiers, however, have a twofold greater incidence of knee injuries and a threefold higher risk

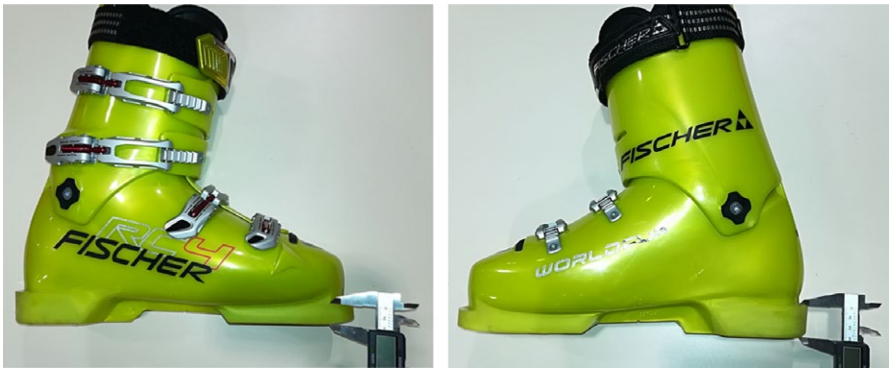

FIGURE 1 Measuring of ski boot sole abrasion at the toe and heel piece by using a digital caliper

of suffering an ACL injury than male skiers.[2,5,8] It seems important to highlight that skiing-related injuries are mostly the outcome of a complex interaction of intrinsic risk factors including age, sex, and skill level and extrinsic risk factors including the environment (weather and snow conditions) and equipment (ski boot-binding unit).[8-10] Researcher estimated that 80% of lower extremity injuries, most of which comprised of knee injuries, are equipment related, caused by the ski acting as lever to bend or twist the leg.[11] Therefore, ski injury prevention research has to put the main focus on optimizing the ski-binding-boot functional unit to reduce knee injuries in alpine skiing.[12]

Various studies investigated the impact of ski-binding settings and ski length on the sex-specific knee injury risk.[5,13,14] A link between a greater ski length and a higher risk has been reported for sustaining an ACL injury.[11,15,16] Moreover, female recreational carving skiers not using newly adjusted ski bindings have a higher risk of knee injuries than those with newly adjusted bindings.[5] Beside ski geometry, appropriate preparation of the base and the edges, and proper binding release function, the functional unit of the ski-binding-boot system depends also from the front and rear interface of the ski boot with the equivalent parts of the binding which is regularized by the ISO 5355 norm.[12] That means the boot toe (19 ± 1 mm) and heel (30 ± 1 mm) dimensions should be within the indicated tolerances.

To the best of our knowledge, only a study by Posch et al[14] yet measured the abrasion of ski boot soles of the toe and heel piece among ACL-injured male and female skiers. Although no sex-specific differences in terms of ski boot sole abrasion among ACL-injured females and males were found neither at the toe piece (5.4 ± 1.2 vs 5.5 ± 1.1 mm) nor at the heel piece (6.0 ± 1.7 vs 6.0 ± 1.6 mm), the overall mean ski boot sole abrasion was beyond the ISO standard 5355 tolerances.[14] Due to the lack of an uninjured control population, it is not clear so far if sole abrasion is a potential and additional risk factor for ACL injuries in recreational alpine skiing. To our knowledge, no published investigation included ski boot-specific parameters like sole abrasion in a risk factor analysis. We hypothesized that ACL-injured skiers and controls would not differ regarding the ski boot sole abrasion.

Therefore, the primary aim of this study was to evaluate the impact of ski boot sole abrasion on the ACL injury risk of recreational alpine skiers.

2 | MATERIALS AND METHODS

This study was conducted as a retrospective case-control study of ACL-injured and uninjured female and male recreational alpine skiers during the two winter seasons 2016/17 and 2017/18 in a large Austrian ski area. The study has been approved by the Institutional Review board of the Department of Sport Science Innsbruck and the ethical advisory board of the University of Innsbruck. Cases and controls were informed about the aims of the study and gave their written informed consent for participating.

Cases were yearly interviewed between the months December and April (23 days on average per season) using a questionnaire. The ACL injury was diagnosed via magnetic resonance imaging (MRI) in a ski clinic, which is directly located in the ski area. Inclusion criteria were a skiing-related noncontact ACL injury after a self-inflicted fall, an age >17 years, and the use of any type of carving ski (in contrast to long and unshaped traditional skis as well as to so called short ski boards).

Uninjured control participants were selected at different spots in the same ski area mostly at the same days to minimize the potential impact of environmental factors (eg, weather and slope conditions) on ACL injury risk. Controls were recruited throughout the whole skiing day. In controls, a similar questionnaire was used as in cases. Similar to cases, inclusion criteria were an age >17 years and the use of any type of carving ski.

According to the questionnaire used in a recent study by Ruedl et al,[17] Burtscher et al[8] and Burtscher et al[5] on ACL injuries among male and female recreational skiers, cases and controls in this study were asked on age, sex, height, weight, and self-reported skill level (expert, advanced, intermediate, and beginner) according to Sulheim et al[18] In addition, ACL-injured skiers were asked about a failure of binding release of the injured knee at the moment of accident. Furthermore, we divided participants into more skilled (expert and advanced) and into less skilled (intermediate and beginner) skiers as a tendency was shown to underestimate individual skiing skills, especially among female skiers.[18]

Absolute ski length and sidecut radius were directly notated from the ski. Additionally, ski length was relativized by body height and weight according to a previous study[14] to enable further analysis. In both, cases and controls, sole height of the front and rear part of the ski boot was measured by the use of a digital sliding calliper (Figure 1), and then, the difference between the norm height of ski boot soles and the measured height was calculated as a measure of sole abrasion.

In total, six intrinsic risk and six extrinsic risk variables were considered for the use in the risk factor analysis. Intrinsic risk factors comprised age (years), height (m), weight (kg), body mass index (BMI) (kg/m^2), sex (male vs female), and skiing skill level (more vs less skilled). Extrinsic equipment-related risk factors consisted of ski length (cm), ski length to height ratio (%), ski length to weight ratio (cm/kg), sidecut radius (m), and sole abrasion at the front and rear part of the ski boot (mm).

2.1 | Statistics

Data are presented as means and standard deviations as well as absolute and relative frequencies. In accordance to tests on normal distribution (Kolmogorov-Smirnov), univariate differences among metric data (age, height, weight, BMI, absolute ski length, ski length to height ratio, ski length to weight ratio, sidecut radius, and ski boot sole abrasion at the toe and heel piece) between cases and controls were evaluated either by independent *t* tests or Mann-Whitney *U* Tests and multiple testing correction was done by Bonferroni adjustment. Differences in frequencies (sex, skill level) were evaluated by chi-square tests. In addition, according to the univariate results, a binary logistic regression analysis entering all variables with $P < 0.1$ was used to calculate multivariate OR and 95% confidence interval (CI).[17] As an assumption, binary logistic regression analysis was tested for multicollinearity. SPSS 23.0 (IBM Corporation, Armonk, NY) was used for the statistical analysis. All p-values were two-tailed, and statistical differences were considered significant at $P < 0.05$.

3 | RESULTS

A total of 603 uninjured and injured skiers (54.7% males, 45.3% females) with a mean age of 40.8 ± 13.9 years volunteered for this study. Mean age, height, weight, BMI, ski length, ski length to height ratio, ski length to weight ratio, sidecut radius, and ski boot sole abrasion (toe and heel piece) and absolute and relative frequencies regarding sex and skiing skill level of cases and controls are listed in Table 1.

Compared to controls, ACL-injured skiers were significantly older and smaller, had less weight and a lower BMI

TABLE 1 Characteristics and univariate odds ratios of intrinsic and extrinsic risk factors in ACL-injured (cases) and non-injured (controls) recreational skiers

	Cases (n = 148)	Controls (n = 455)	Odds Ratio (95% CI) univariate	*P*-value
Age (y)	42.7 ± 10.5	40.2 ± 14.8		0.004
Height (cm)	172.7 ± 8.4	174.8 ± 9.8		0.006
Weight (kg)	71.5 ± 11.5	75.1 ± 12.3		0.001
Body mass index (kg/m^2)	23.8 ± 2.5	24.4 ± 2.4		0.010
Sex n (%)				
Male	72 (48.6)	258 (56.7)		
Female	76 (51.4)	197 (43.3)	1.4 (1.0-2.0)	0.088
Skill level n (%)				
More skilled	76 (51.4)	360 (79.1)		
Less skilled	72 (48.6)	95 (20.9)	3.6 (2.4-5.3)	<0.001
Ski length (cm)	163.2 ± 7.6	163.8 ± 10.4		0.485
Ski length to height ratio (%)	94.7 ± 3.7	93.8 ± 5.0		0.019
Ski length to weight ratio (cm/kg)	2.3 ± 0.3	2.2 ± 0.3		<0.001
Sidecut radius	13.7 ± 1.9	14.1 ± 3.6		0.837
Ski boot sole abrasion at the toe piece (mm)	4.8 ± 1.8	2.4 ± 2.5		<0.001
Ski boot sole abrasion at the heel piece (mm)	5.4 ± 1.8	3.3 ± 2.3		<0.001

Data are presented as mean values ±standard deviation, absolute and relative frequencies and odds ratios (95% CI)

($P < 0.05$). ACL-injured skiers showed a higher proportion of female (51.4% vs 43.3%, $P < 0.001$) and less skilled skiers (48.6% vs 20.9%, $P < 0.001$) compared to uninjured skiers. Self-reported failure of ski-binding release at the moment of accident was significantly higher in female cases when compared to male cases (86.8% vs 45.8%, $P < 0.001$). While absolute ski length did not significantly differ between cases and controls ($P = 0.485$), the ski length to height ratio was significantly higher among ACL-injured skiers compared to uninjured skiers (94.7 ± 3.7 vs 93.8 ± 5.0%, $P = 0.019$). Moreover, ski length to weight ratio was significantly higher among cases compared to controls (2.3 ± 0.3 vs 2.2 ± 0.3 cm/kg, $P < 0.001$), and no significant difference was found within the sidecut radius of the used skis between ACL-injured and uninjured skiers (13.7 ± 1.9 vs 14.1 ± 3.6 m, $P = 0.837$).

ACL-injured skiers used ski boots of greater abrasion at the toe (4.8 ± 1.8 vs 2.4 ± 2.5 mm, $P < 0.001$) and heel piece (5.4 ± 1.8 vs 3.3 ± 2.3 mm, $P < 0.001$) compared to their uninjured counterparts.

As a next step, factors with $P < 0.1$ (age, sex, skill level, ski length to height ratio, and sole abrasion at the toe and heel piece) were included in a final logistic regression model, except for height, weight, BMI, and ski length to weight ratio as severe multicollinearity was observed. Represented in Table 2, multivariate regression analysis revealed two intrinsic and three extrinsic risk factors to be significantly predictive for an ACL injury. The ACL injury risk was multiplied by 6.0 among female sex (95% confidence interval, 3.1-11.5, $P < 0.001$) and by 3.2 within skiers of a lower skill level (95% confidence interval, 1.9-5.4). A higher ski length to height ratio showed a significant association (OR 1.1, 95% confidence interval, 1.0-1.2, $P < 0.001$). With regard to ski boot-specific parameters, sole abrasion at the toe piece (OR 1.8, 95% confidence interval, 1.5-2.1, $P < 0.001$) and sole abrasion at the heel piece (OR 1.4, 95% confidence interval, 1.2-1.6, $P < 0.001$) significantly affected the ACL injury risk.

TABLE 2 Final multivariate regression model: multivariate odds ratio of risk indicators in recreational alpine skiers suffering from an ACL injury

Risk factors	Odds ratio	95% CI	p-value
Age	1.0	0.9-1.1	0.320
Sex (female)	6.0	3.1-11.5	<0.001
Skill level (less skilled)	3.2	1.9-5.4	<0.001
Ski length to height ratio (%)	1.1	1.0-1.2	<0.001
Ski boot sole abrasion at the toe piece (mm)	1.8	1.5-2.1	<0.001
Ski boot sole abrasion at the heel piece (mm)	1.4	1.2-1.6	<0.001

86.1% were correctly classified; Model: Nagelkerkes $R^2 = 0.448$

4 | DISCUSSION

The primary aim of this study was to evaluate a potential impact of ski boot sole abrasion on the ACL injury risk of recreational alpine skiers by computing a risk factor analysis including potential intrinsic and extrinsic risk variables. The main finding was that female sex, lower skill level, ski length to height ratio, and ski boot sole abrasion at the toe and at the heel piece were found to be independent risk factors and significantly predictive for ACL injury risk in recreational alpine skiers.

To the best of our knowledge, this is the first study comparing ski boot sole abrasion of ACL-injured and uninjured recreational skiers and including ski boot-specific parameters in a multivariate risk factor analysis. In an earlier study, we found no sex differences in terms of ski boot sole abrasion among ACL-injured females and males. However, the overall mean ski boot sole abrasion of both sexes was clearly beyond the ISO standard 5355 tolerances.[14]

In the present study, for the total group, a significantly higher ski boot sole abrasion was found in the group of ACL-injured skiers. Multivariate analysis revealed that ski boot sole abrasion increased the ACL injury risk 1.4-fold to 1.8-fold in the present study, representing an independent risk factor.

Ski boots play an essential role in alpine skiing as they are designed to transfer high forces from the alpine skier to the ski,[19] and therefore, abrasion of the ski boot sole can potentially influence the releasing mechanisms of the ski binding. Campbell et al[20] already proved that 69% of tested ski boots of a different sole like alpine touring boots required too much torque to release or released at much higher angular displacement than usual alpine ski boots. Alpine touring boot soles are designed for maximum traction during walking on rough terrain, while alpine skiing boot soles are designed to minimize friction between the boot and alpine ski bindings at the contact points.[21] Therefore, the question arises whether abrasion of ski boot soles leading to a decrease in friction could result in lower release torques and inadvertent binding releases. Furthermore, it is to mention, that ski boot sole abrasion does not always go in line with increased age of binding. A lot of ski rental shops in Austria replace skies and bindings after each winter season, whereas ski boots are replaced every 2-3 years on average, depending on the subjective visual inspection pursuant to ISO 11088 (personal communication).

According to the ISO 5355 standard, the toe and heel dimensions of the ski boot shall be within the indicated tolerances (toe: 19 ± 1 and heel: 30 ± 1 mm). The overall mean ski boot sole height at the toe and heel piece of cases and controls in this study (toe: 16.0 ± 2.5 and heel: 26.2 ± 2.4 mm), however, was clearly beyond the ISO tolerances. In general, ski boot sole abrasion might be caused by several factors like an elevated walking with ski boots on streets or parking grounds of a ski area. However, to investigate the influence of sole abrasion on binding release mechanisms and to clarify whether boot soles of great wear lead to inadvertent or failure of binding release, further research is crucial.

With regard to a skiing-related ACL injury, failure of binding release at the moment of accident is a major problem.[17] Various studies showed that 55%-67% of knee injured male skiers reported a failure of binding release at the moment of accident compared to 74%-88% of female alpine skiers.[10,14,17] Well in accordance, in this study, failure of ski binding was significantly lower for male compared to female ACL-injured skiers (45.8% vs 86.6%). Moreover, the date of the last professional binding adjustment (<1 year vs >1 year) was assessed in this study proving that more than 95% of cases used a newly adjusted ski binding. Thus, the date of the last binding adjustment was not considered as a risk variable for the underlying regression and risk factor analysis.

Regarding another equipment-related risk parameter, ski length to height ratio was found to be an independent risk factor associated with an ACL injury in recreational alpine skiing and did significantly differ between cases and controls (94.7 ± 3.7 vs 93.8 ± 5.0 cm). A higher ski length to height ratio increased the ACL injury risk 1.1-fold in the present study. Actually, it is well known that there is a link between a greater ski length and a higher risk for sustaining an ACL injury.[11,15,16] Longer carving skies with a wider tail act as a lever arm to bend or twist the knee and could increase forces acting on the skier.[16]

Regarding intrinsic risk factors, low skiing skill level (beginner, intermediate) showed a 3.2-fold higher risk of sustaining an ACL injury according to the results of the regression analysis. In our study, uninjured skiers showed a significantly higher proportion of more skilled skiers (79.1% vs 51.4%) compared to ACL-injured skiers. In general, a higher skill level and more skiing experience are associated with a lower injury risk among recreational skiers.[22,23] Especially, beginners suffer far more injuries than more experienced alpine skiers.[24,25]

Generally, female skiers have a twofold greater incidence of knee injuries and a threefold higher risk of suffering an ACL injury than male skiers.[2,5,8] This distinctive sex difference may be partly related to hormonal, anatomical and neuromuscular risk factors which distinguish females from males.[26-28]

In the underlying study, the evaluated ACL injury risk was even higher. According to the results of the multivariate regression analysis, the ACL injury risk was multiplied by 6.0 among female sex, well reflecting the current state of the main ACL literature in sports.[27]

As already mentioned in the introduction, a skiing-related ACL injury might be caused by a complex and multiple interaction of several risk factors. To the best of our knowledge, we do not know of any studies that included ski boot-specific parameters like sole abrasion in a risk factor analysis. According to previous studies,[5,8,17] certain potential risk factors were considered for the regression analysis, thus confounders could be reduced.

Pursuant to the results of this study, ski boot sole abrasion seems to be a further independent risk factor for an ACL injury among female and male recreational skiers, which has not been evaluated so far. Therefore, regularly checking the equipment, especially the ski boot soles, may importantly contribute to the prevention of knee injuries in female and male skiers. Moreover, ski length to height ratio, female sex, and lower skill level were found to be independent risk factors and significantly predictive for an ACL injury risk in recreational alpine skiers.

4.1 | Limitations

Due to the restriction of our patients to the ski clinic, we cannot exclude a possible selection 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 indications of any source of selection.

To clarify the influence of ski boot sole abrasion on the releasing mechanisms, more data and research in the laboratory and in the field on ski slopes are needed. However, to the best of our knowledge, this is the first study evaluating the impact of ski boot sole abrasion on the ACL injury risk in alpine skiing within a risk factor analysis.

5 | PERSPECTIVES

Based on the findings of the present study, ACL-injured skiers used ski boots of greater sole abrasion at the toe and heel piece than their uninjured controls. Ski boot sole abrasion increased the ACL injury risk 1.4-fold to 1.8-fold in the present study. As a practical implication, it is essential to let the boot-binding unit check periodically at the beginning of every winter season. This is important information as ski boot sole abrasion seems to be an additional, potential risk factor for noncontact ACL injuries in recreational alpine skiing, which has to be confirmed in future studies.

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CONFLICT OF INTERESTS

None declared.

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