Skill-Specific Differences in Equipment-Related Risk Factors for ACL Injury in Male and Female Recreational Skiers

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Background: In recreational alpine skiing, the anterior cruciate ligament (ACL) is affected in approximately 50% of serious knee injuries. There are established sex-based and skill-based differences in ACL injury risk, but the potential impact of equipment used (eg, skis, bindings, and boots) has not been evaluated.

Purpose: To evaluate individual and equipment-related risk factors for an ACL injury depending on sex and skill level.

Study Design: Case-control study; Level of evidence, 3.

Methods: This was a retrospective questionnaire-based, case-control study of female and male skiers with and without ACL injuries during 6 winter seasons (from 2014-2015 to 2019-2020). Demographic data, skill level, equipment specifications, risk-taking behavior, and ownership of ski equipment were recorded. Ski geometry (ski length; sidecut radius; and widths of the tip, waist, and tail) was taken from each participant's ski. The standing heights of the front and back part of the ski binding were measured using a digital sliding caliper, and the standing height ratio was calculated. Abrasion of the ski boot sole was also measured at the toe and heel. Participants were divided by sex into less and more skilled skiers.

Results: A total of 1817 recreational skiers participated in this study, of whom 392 (21.6%) sustained an ACL injury. A greater standing height ratio and more abrasion at the toe of the boot sole were associated with increased ACL injury risk in both sexes, independent of the skill level. Riskier behavior increased the injury risk only in male skiers, independent of the skill level, and longer skis increased the injury risk only in less skilled female skiers. Older age, the use of rented/borrowed skis, and more abrasion at the heel of the boot sole were independent risk factors for ACL injury in the more skilled skiers of both sexes.

Conclusion: Individual and equipment-related risk factors for an ACL injury partly differed according to skill level and sex. Consideration of the demonstrated equipment-related factors should be implemented in order to reduce ACL injuries in recreational skiers.

Keywords: recreational alpine skiing; ACL injury; standing height; ski geometry; ski boot

Alpine skiing is considered to be one of the most popular winter sport activities, with an estimated 400 million skier-days per year worldwide.[13] The injury risk decreased from 5 to 8 injuries per 1000 skier-days before the 1970s to 2 to 3 injuries per 1000 skier-days in the early 1990s, and in more recent years to even less than 1 injury per 1000 skier-days in some countries.[5,25,28] Despite the steady downward trend in the risk of alpine skiing injuries, it is notable that the proportion of knee injuries did not benefit from this decline.[5] In alpine skiing, the knee joint is still the most affected anatomic injury location, with about one-third of all injuries.[5,8] Moreover, the anterior cruciate ligament (ACL) is affected in approximately 50% of serious knee injuries.[11,26] However, there are decisive sex differences in the rates of knee injuries; that is, female recreational skiers have twice the knee injury incidence of male skiers, and the ACL injury risk is 3 times greater in female skiers,[2,5,6,9] and this is true for recreational skiing[25] as well as for ski racing.[1] On an individual (intrinsic) level, this difference between the sexes has been attributed to hormonal, anatomic, and neuromuscular risk factors that distinguish men from women.[3,14,29]

As skiing is a highly complex activity in which the individual skier interacts with skiing equipment (eg, skis,

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bindings, and boots) and the environment (eg, snow, slope conditions, and temperature), the injury risk in alpine skiing depends largely on the interaction of both intrinsic and extrinsic risk factors.[13] One of the most important intrinsic risk factors in skiing is the individual skill level of the skier. There is clear evidence that the lower the skill level of winter sport participants, the higher the overall injury risk on alpine ski slopes.[12,38] Also, studies investigating ACL injuries in recreational skiing found that a lower skill level is independently associated with an increase in ACL injury risk.[24,31,32] On the other hand, the equipment used (eg, skis, bindings, and boots) represents an important extrinsic risk factor. It has been estimated that 80% of lower extremity injuries, most of which comprise knee injuries, are equipment-related, caused by the ski acting as lever to bend or twist the leg.[22] Therefore, ski injury prevention research should also aim to optimize the ski-binding-boot functional unit to reduce knee injuries on ski slopes.[34]

In recent years, research has focused on the potential impact of ski geometry data (ski length, sidecut radius [curvature along the ski's edge from tip to tail], tip width, waist width, and tail width) and the skier's standing height above the snow on overall injury risk and on knee/ACL injury risk in recreational alpine skiing[24,25,32,41] as well as in alpine ski racing.[10,18,35,36]

The turning radius during skiing depends on the sidecut radius of the skis, with lower sidecut radii being associated with a higher self-steering effect, which determines carved turns as a result.[34] In recreational skiing, however, studies have not found significant differences between recreational skiers with and without ACL injuries regarding the sidecut radius of their skis.[24,32] The sidecut radius depends on the length as well as the widths of the tip, waist, and tail of the ski.[32] In a recently published study by Ruedl et al,[32] the impact of ski geometry parameters on ACL injury risk in recreational alpine skiers was evaluated by comparing the length and widths of the skis between skiers with and without ACL injuries. Although a greater ski length increased the ACL injury risk, the results of the ski widths seemed to be inconsistent because a wider ski tip increased the likelihood of an ACL injury, while a wider ski waist decreased the likelihood of an ACL injury.[32]

Among the factors that may increase the risk of injuries in recreational skiing, the standing height (the distance between the bottom of the skis' running surface and the sole of the boot) has yet to be explored with more attention.[35] The increase in standing height with the introduction of lifter plates between skis and bindings in 1988 allows more angling of the skis and enhances the torsional stiffness of the skis; furthermore, it reduces vibrations and may even improve the release of ski bindings during accidents.[34] However, this feature may also lead to higher chances of skidding and, as a consequence, increased risk of knee strain issues.[34] Thus, in alpine ski racing, because of major safety concerns, the International Ski Federation regulated standing height from the 1998-1999 winter season on in the equipment rules, with a limit of 50-mm standing height for both male and female ski racers.[35] Ruedl et al[32] recently introduced the "standing height ratio" between the standing heights of the front and rear part of the ski binding as a new parameter with regard to ACL injury risk in recreational skiing. These authors found that a lower standing height ratio (rear component of the ski binding is more elevated compared with the front component) was independently associated with a decrease in the ACL injury risk.[32]

Other elements that contribute to the ski-binding-boot functional unit include the front and rear interface of the ski boots and the corresponding binding parts, regularized by the International Organization for Standardization (ISO) standard 5355. This standard provides tolerance ranges in the dimensions of the boot toe and heel.[34] Posch et al,[24] however, found that recreational skiers with ACL injuries had ski boots with greater sole abrasion at the toe and heel compared with uninjured controls, leading to a 1.4- to 1.8-fold increased risk for sustaining an ACL injury.

Despite the still existing sex-based differences in the ACL injury risk and the fact that skill level represents a major risk factor, to the best of our knowledge, no study has evaluated the potential impact of equipment-related risk factors on the ACL injury risk depending on the skill level separately for male and female recreational alpine skiers. Thus, the aim of this study was to conduct a sex-specific comparison of ski geometry parameters, standing height, and abrasion of the ski boot sole between recreational skiers of lower and higher skill levels with ACL injuries and without.

METHODS

Study Design

This study was conducted as a retrospective case-control study of recreational skiers with and without ACL injuries during 6 consecutive winter seasons from 2014-2015 to 2019-2020 at an Austrian sport clinic (an emergency clinic specializing in treating sport-related injuries) situated in a large ski area. The protocol for this study received ethics committee approval, and all study participants provided written informed consent.

In accordance with previous studies,[24,32] the study participants (cases) with ACL injuries were interviewed using a predefined standardized questionnaire. The interviews occurred between the months of December and April (on average, 23 days) per winter season. As described in a previous study,[32] the random recruitment of patients was dependent on logistical aspects at the sport clinic (availability of rooms and personnel) and the willingness of patients to volunteer. In total, more than 95% of the invited patients agreed to participate in the study. Skiers (controls) without ACL injuries were randomly selected at different spots in the same ski area throughout the day.

Study Cohort

The inclusion criteria of cases were a skiing-related noncontact ACL injury after a self-inflicted fall, age older than 17 years, and the use of any type of carving skis (in contrast to long, unshaped traditional skis as well as so-called short ski boards). In accordance with previous studies,[24,32] ACL injuries were diagnosed by a present physician using magnetic resonance imaging (MRI), which is located in the sport clinic.

Similar to cases, the inclusion criteria of the controls were age older than 17 years and the use of any type of carving ski.

Questionnaire

According to the questionnaire used in previous studies,[24,32] cases and controls of both sexes were asked about demographic factors such as age, sex, and body height and weight. In addition, skiers were asked to self-report their skiing skill level (expert, advanced, intermediate, or beginner) according to Sulheim et al[37] and their risk-taking behavior (riskier vs more cautious) according to Ruedl et al.[27] Study participants were categorized into more skilled (expert and advanced) and less skilled (intermediate and beginner) skiers, as a tendency was shown to underestimate individual skiing skills, especially among female skiers.[37] In addition, skiers were asked whether they owned their equipment or not (ie, rented from a ski shop or borrowed from family/friends), and responses were transformed to a dichotomous variable (own vs rent/borrow ski equipment).

Ski Geometry, Standing Height Ratio, and Sole Abrasion

The ski length; sidecut radius; and widths of the tip, waist, and tail of the ski were directly notated from the alpine carving ski of the participant. The standing height (distance between the bottom of the running surface of the ski and the sole of the ski boot) was measured at the front and back part of the ski binding using a digital sliding caliper, and the percentage ratio between the front and back was calculated as the standing height ratio.

To measure sole abrasion, the sole heights of the toe and heel parts of the ski boot were measured with a digital sliding caliper, and we calculated the difference between the ISO 5355 standard height of ski boot soles (19 ± 1 mm at the toe and 30 ± 1 mm at the heel) and the measured heights.[24]

Because of the ongoing nature of this study, the evaluations of the ski geometry, standing height ratio, and sole abrasion were started at different time points. Thus, the sample size varied within single variables.

Statistical Analysis

All data are presented as means ± standard deviations or absolute values and relative frequencies. Depending on the tests on normal distribution (Shapiro-Wilk test and visual inspection of normal probability q-q plots), univariate differences among metric data (age; body height and weight; ski length; sidecut radius; tip, waist, and tail widths; standing height ratio; abrasion at the toe and heel of the boot sole) between cases and controls were evaluated either by independent t tests or Mann-Whitney U tests for both skill levels of both sexes separately. In addition, sex-specific differences in frequencies (risk-taking behavior and ski ownership) of less and more skilled skiers were evaluated by chi-square tests.

All individual factors as well as equipment-related parameters with $P < .1$ were additionally entered in a multiple logistic regression analysis to estimate adjusted odds ratios (ORs) and their 95% confidence intervals (CIs) for ACL injury risk among male and female skiers of both lower and higher skill levels.

SPSS Version 26.0 (IBM) was used for the statistical analysis. All P values were 2-tailed, and statistical differences were considered significant at $P < .05$.

RESULTS

A total of 1817 recreational skiers (49.1% female) participated in this study, of whom 21.6% (n = 392) sustained an ACL injury and 78.4% (n = 1425) were uninjured. The mean age, height, and weight for the total cohort were 39.1 ± 12.9 years, 173.7 ± 8.8 cm, and 74.7 ± 13.8 kg, respectively. In total, 71.3% of skiers (n = 1295) self-reported to be "more skilled," while "riskier behavior" during skiing was reported by 33.9% (n = 616) participants. A total of 66.3% (n = 1205) owned their skis, while 31.6% (n = 575) rented skis in a ski shop and 2.0% (n = 37) borrowed their skis from family or friends.

The mean ski length (n = 1770), sidecut radius (n = 1710), tip width (n = 1068), waist width (n = 1593), and tail width (n = 1068) of the total cohort were 164.6 ± 9.7 cm, 14.3 ± 2.7 m, 121.0 ± 8.0 mm, 75.1 ± 8.4 mm, and 106.6 ± 7.9 mm, respectively. The mean standing height ratio (n = 1370) was 89.7% ± 6.9%, and the abrasion values of the boot sole (n = 1540) were 3.0 ± 2.5 mm at the toe and 3.9 ± 2.7 mm at the heel.

Table 1 shows the univariate comparison of risk factors between female skiers of lower and higher skill levels with and without ACL injuries. In less skilled female skiers, cases and controls significantly differed by age, ski length, sidecut radius, standing height ratio, and boot sole abrasion at the toe and heel. In more skilled female skiers, age, ski ownership, standing height ratio, and boot sole abrasion at the toe and heel were significantly different between participants with ACL injuries and those without.

The results of the multiple logistic regression analysis for less skilled female skiers indicated that longer ski length, greater standing height ratio, and more abrasion at the toe of the boot sole were independently associated with an increase in ACL injury risk (Table 2). The results of the multiple logistic regression analysis for more skilled female skiers indicated that older age, using rented/borrowed skis, greater standing height ratio, and more abrasion at the toe and heel of the ski boot sole were independently associated with an increase in ACL injury risk (Table 2).

The univariate comparison of risk factors between male skiers of lower and higher skill levels with and without ACL injuries is shown in Table 3. In less skilled male skiers,

TABLE 1
Univariate Comparison of Individual and Ski Geometry–Related Risk Factors Between Female Skiers of Lower and Higher Skill Levels With and Without ACL Injuries[a]

	Less Skilled Female Skiers			More Skilled Female Skiers		
Risk Factor	Controls Without ACL Injuries	Patients With ACL Injuries	*P*	Controls Without ACL Injuries	Patients With ACL Injuries	*P*
Age, y	39.0 ± 14.4 (n = 212)	42.1 ± 10.6 (n = 137)	**.032**[b]	36.0 ± 12.5 (n = 454)	40.6 ± 10.5 (n = 90)	**<.001**[b]
Body height, cm	166.5 ± 5.5 (n = 212)	167.1 ± 5.3 (n = 137)	.367	167.1 ± 5.5 (n = 454)	167.6 ± 5.3 (n = 90)	.796
Body weight, kg	64.6 ± 9.5 (n = 210)	64.1 ± 7.2 (n = 137)	.870	64.4 ± 8.8 (n = 454)	64.4 ± 8.2 (n = 90)	.659
Risk-taking behavior			.059[b]			.200
More cautious	94.8 (n = 201)	89.1 (n = 122)		70.7 (n = 321)	77.8 (n = 70)	
Riskier	5.2 (n = 11)	10.9 (n = 15)		29.2 (n = 133)	22.5 (n = 20)	
Ski ownership, %						
Own	42.0 (n = 89)	46.0 (n = 63)	.507	79.7 (n = 362)	44.4 (n = 40)	**<.001**[b]
Rent/borrow	58.0 (n = 123)	54.0 (n = 74)		20.3 (n = 92)	55.6 (n = 50)	
Ski geometry						
Ski length, cm	154.8 ± 7.0 (n = 207)	158.9 ± 6.6 (n = 129)	**.010**[b]	159.6 ± 7.8 (n = 454)	159.0 ± 6.8 (n = 82)	.357
Sidecut radius, m	12.7 ± 1.8 (n = 204)	13.2 ± 1.7 (n = 111)	**<.001**[b]	13.6 ± 2.3 (n = 451)	13.7 ± 1.7 (n = 65)	.922
Tip width, mm	119.9 ± 7.1 (n = 103)	119.8 ± 6.8 (n = 64)	.683	121.1 ± 8.0 (n = 339)	121.2 ± 8.2 (n = 37)	.633
Waist width, mm	71.9 ± 4.8 (n = 205)	73.0 ± 5.8 (n = 66)	.352	75.4 ± 8.7 (n = 451)	73.7 ± 4.6 (n = 37)	.731
Tail width, mm	104.7 ± 7.6 (n = 103)	105.5 ± 5.9 (n = 64)	.478	106.5 ± 7.5 (n = 339)	107.1 ± 6.5 (n = 37)	.227
Standing height ratio, %	88.3 ± 7.3 (n = 145)	95.2 ± 4.2 (n = 68)	**<.001**[b]	88.4 ± 6.7 (n = 425)	94.5 ± 5.7 (n = 37)	**<.001**[b]
Boot sole abrasion, mm						
At the toe	1.9 ± 1.8 (n = 145)	5.1 ± 1.4 (n = 133)	**<.001**[b]	1.7 ± 2.1 (n = 426)	5.1 ± 1.8 (n = 79)	**<.001**[b]
At the heel	3.7 ± 2.5 (n = 145)	5.7 ± 1.6 (n = 133)	**<.001**[b]	3.1 ± 2.8 (n = 426)	6.2 ± 2.1 (n = 79)	**<.001**[b]

[a]Data are reported as mean ± SD or as percentage of participants. Boldface *P* values indicate a statistically significant difference between patients and controls ($P < .05$).
[b]Risk factor included in multiple logistic regression analysis ($P < .01$).

TABLE 2
Adjusted Odds Ratios of Individual and Equipment-Related Risk Factors Associated With an ACL Injury in Less Skilled and More Skilled Female Skiers[a]

Risk Factor	Coefficient	SE	df	*P*	OR (95% CI)
Less skilled female skiers[b]					
Age	0.037	0.020	1	.064	1.038 (1.998-1.080)
Risk-taking behavior: riskier	0.634	1.113	1	.569	1.885 (0.213-16.709)
Ski length	0.135	0.048	1	**.005**	1.144 (1.041-1.257)
Sidecut radius	–0.274	0.174	1	.115	0.761 (0.541-1.069)
Standing height ratio	0.229	0.056	1	**<.001**	1.257 (1.127-1.402)
Boot sole abrasion at the toe	0.936	0.156	1	**<.001**	2.550 (1.880-3.458)
Boot sole abrasion at the heel	0.099	0.109	1	.362	1.104 (0.893-1.366)
Intercept	–45.1376	9.460	1	**<.001**	0.000
More skilled female skiers[c]					
Age	0.063	0.024	1	**.010**	1.065 (1.015-1.117)
Ski ownership: rented/borrowed	2.081	0.618	1	**.001**	8.011 (2.385-26.910)
Standing height ratio	0.252	0.053	1	**<.001**	1.286 (1.159-1.428)
Boot sole abrasion at the toe	1.164	0.209	1	**<.001**	3.203 (2.125-4.828)
Boot sole abrasion at the heel	0.265	0.115	1	**.021**	1.304 (1.042-1.632)
Intercept	–36.370	5.913	1	**<.001**	0.000

[a]Boldface *P* values indicate statistical significance ($P < .05$). df, degrees of freedom; SE, standard error.
[b]Nagelkerke $R^2 = 0.724$; classification table, overall percentage = 89.1%.
[c]Nagelkerke $R^2 = 0.698$, classification table, overall percentage = 95.2%.

patients and controls significantly differed within body weight, risk-taking behavior, standing height ratio, and boot sole abrasion at the toe and heel. In more skilled male skiers, age, body height and weight, risk-taking behavior, ski ownership, ski length, ski waist width, tail width, standing height ratio, and boot sole abrasion at the toe and heel were significantly different between skiers with and without ACL injuries.

TABLE 3
Univariate Comparison of Individual and Ski Geometry–Related Risk Factors Between Male Skiers of Lower and Higher Skill Levels With and Without ACL Injuries[a]

	Less Skilled Male Skiers			More Skilled Male Skiers		
Risk Factor	Controls Without ACL Injuries	Patients With ACL Injuries	*P*	Controls Without ACL Injuries	Patients With ACL Injuries	*P*
Age, y	41.3 ± 12.3 (n = 124)	42.6 ± 10.3 (n = 49)	.511	38.8 ± 13.5 (n = 634)	45.1 ± 12.3 (n = 116)	**<.001**[b]
Body height, cm	180.5 ± 7.0 (n = 124)	177.9 ± 5.6 (n = 49)	.089[b]	180.6 ± 5.9 (n = 635)	178.8 ± 5.4 (n = 116)	**.001**[b]
Body weight, kg	85.3 ± 10.1 (n = 123)	79.6 ± 8.1 (n = 49)	**<.001**[b]	85.4 ± 10.3 (n = 633)	81.0 ± 8.1 (n = 116)	**<.001**[b]
Risk-taking behavior, %			**<.001**[b]			**<.001**[b]
More cautious	85.5 (n = 106)	36.7 (n = 18)		52.6 (n = 334)	25.0 (n = 29)	
Riskier	14.5 (n = 18)	63.3 (n = 31)		47.4 (n = 301)	75.0 (n = 87)	
Ski ownership, %						
Own	49.2 (n = 61)	55.1 (n = 27)	.504	80.3 (n = 510)	45.7 (n = 53)	**<.001**[b]
Rent/borrow	50.8 (n = 63)	44.9 (n = 22)		19.7 (n = 125)	54.3 (n = 63)	
Ski geometry						
Ski length, cm	166.9 ± 8.1 (n = 123)	165.8 ± 6.7 (n = 42)	.389	171.9 ± 7.3 (n = 631)	169.0 ± 6.1 (n = 102)	**.001**[b]
Sidecut radius, m	14.3 ± 2.2 (n = 120)	14.0 ± 1.9 (n = 39)	.858	15.6 ± 2.9 (n = 624)	15.2 ± 2.3 (n = 96)	.666
Tip width, mm	119.4 ± 7.7 (n = 42)	118.8 ± 6.5 (n = 30)	.904	121.6 ± 8.8 (n = 391)	121.3 ± 4.7 (n = 62)	.164
Waist width, mm	73.9 ± 6.0 (n = 120)	71.9 ± 3.8 (n = 30)	.051[b]	76.8 ± 9.9 (n = 622)	73.0 ± 3.6 (n = 62)	**<.001**[b]
Tail width, mm	106.4 ± 7.8 (n = 42)	103.3 ± 8.5 (n = 30)	.128	108.2 ± 8.4 (n = 391)	102.8 ± 7.2 (n = 62)	**<.001**[b]
Standing height ratio, %	87.6 ± 7.4 (n = 68)	96.0 ± 5.0 (n = 30)	**<.001**[b]	89.1 ± 6.7 (n = 533)	96.0 ± 3.8 (n = 64)	**<.001**[b]
Boot sole abrasion, mm						
At the toe	3.2 ± 2.2 (n = 70)	5.7 ± 1.6 (n = 44)	**<.001**[b]	2.7 ± 2.4 (n = 533)	5.3 ± 1.4 (n = 110)	**<.001**[b]
At the heel	3.4 ± 2.3 (n = 70)	6.2 ± 1.8 (n = 44)	**<.001**[b]	3.3 ± 2.5 (n = 533)	5.8 ± 1.8 (n = 110)	**<.001**[b]

[a]Data are reported as mean ± SD or as percentage of participants. Boldface *P* values indicate a statistically significant difference between patients and controls ($P < .05$).

[b]Risk factor included in multiple logistic regression analysis ($P < .01$).

The results of the multiple logistic regression analysis for less skilled male skiers indicated that riskier behavior, greater standing height ratio, and more abrasion at the toe of the boot sole were independently associated with an increased ACL injury risk (Table 4). The results of the multiple logistic regression analysis for more skilled male skiers indicated that older age, riskier behavior, using rented/borrowed skis, greater standing height ratio, more boot sole abrasion at the toe, and more boot sole abrasion at the heel are independently associated with an increase in ACL injury risk (Table 4).

DISCUSSION

The findings of the current study indicated that greater standing height ratio and more abrasion at the toe of the boot sole were associated with an increased ACL injury risk in female skiers independent of the skill level. In less skilled female skiers, additional risk factors were longer ski length, and in more skilled female skiers, the additional risk factors were higher age, the use of rented/borrowed skis, and more abrasion at the heel of the boot sole. Similarly, in male skiers independent of skill level, greater standing height ratio, more abrasion at the toe of the boot sole, and riskier behavior were associated with increased ACL injury risk. For more skilled male skiers, additional risk factors were older age, the use of rented/borrowed skis, and more abrasion at the heel of the boot sole.

Age and Risk-Taking Behavior

In general, the populations at greatest risk for skiing injuries are children and adolescents as well as adults older than 50 years of age.[8] In the present cohort with a mean age of about 39 years, female and male skiers with ACL injuries are on average about 5 years older than uninjured controls (data not shown). Our results revealed increasing age as a significant risk factor for an ACL injury in both more skilled female and male skiers. Interestingly, in less skilled skiers of both sexes, age was not a significant predictor (less skilled female with $P = .064$). Higher age as a risk factor for knee/ACL injuries is well known from the literature.[6,24] A potential explanation for this result could be that with increasing age, a progressive loss of neuromuscular function results via reduction of muscle mass and muscle quality and with changes in the biology, healing capacity, and biomechanical function of tendons and ligaments.[20,21]

Earlier work found that riskier behavior is associated with ACL injury risk in recreational skiing.[31] This might be caused by the fact that compared with cautious skiers, self-reported risk-taking skiers run significantly faster on ski slopes[30] and have shown higher scores on the Sensation Seeking Scale Form V,[27] which might cause self-inflicted falls resulting in ACL injuries. Also, Niedermeier et al[23] reported that winter sport participants with treated injuries showed significantly higher sensation seeking compared with uninjured people. In this study, risk-taking behavior was an independent risk factor in male skiers of

TABLE 4
Adjusted Odds Ratios of Individual and Equipment-Related Risk Factors Associated With an ACL Injury in Less Skilled and More Skilled Male Skiers[a]

Risk Factor	Coefficient	SE	df	*P*	OR (95% CI)
Less skilled male skiers[b]					
Body height	–0.220	0.150	1	.142	0.802 (0.598-1.076)
Body weight	0.042	0.085	1	.618	1.043 (0.883-1.233)
Risk-taking behavior: riskier	3.254	0.976	1	**.001**	25.900 (3.828-175.248)
Waist width	–0.197	0.117	1	.092	0.821 (0.653-1.033)
Standing height ratio	0.252	.085	1	**.003**	1.287 (1.089-1.521)
Boot sole abrasion at the toe	0.559	0.273	1	**.040**	1.750 (1.025-2.987)
Boot sole abrasion at the heel	0.539	0.303	1	.075	1.714 (0.947-3.105)
Intercept	16.110	17.384	1	.354	9920424.932
More skilled male skiers[c]					
Age	0.067	.023	1	**.003**	1.069 (1.023-1.118)
Body height	0.041	0.073	1	.572	1.042 (0.904-1.028)
Body weight	–0.042	0.035	1	.233	0.959 (0.894-1.028)
Risk-taking behavior: riskier	1.371	0.561	1	**.015**	3.941 (1.312-11.834)
Ski ownership: rented/borrowed	2.347	0.656		**<.001**	10.457 (2.893-37.799)
Ski length	–0.008	0.047	1	.864	0.992 (0.905-1.088)
Waist width	–0.016	0.060	1	.787	0.984 (0.875-1.107)
Tail width	–0.034	0.046	1	.455	0.966 (0.884-1.057)
Standing height ratio	0.322	.058	1	**<.001**	1.380 (1.231-1.547)
Boot sole abrasion at the toe	0.680	0.202	1	**.001**	1.975 (1.330-2.931)
Boot sole abrasion at the heel	0.407	0.150	1	**.007**	1.502 (1.120-2.015)
Intercept	–43.303	13.786	1	**.003**	0.000

[a]Boldface *P* values indicate statistical significance ($P < .05$). df, degrees of freedom; SE, standard error.
[b]Nagelkerke $R^2 = 0.783$, classification table, overall percentage = 88.8%.
[c]Nagelkerke $R^2 = 0.801$, classification table, overall percentage = 96.2%.

both skill levels, but not in female skiers. Accordingly, there is evidence that risk-taking behavior on alpine ski slopes is associated with male sex[27,30,31] which is confirmed by the result of this study, in which riskier male skiers show a 4- to 25-fold higher risk for sustaining an ACL injury than cautious male skiers of both skill levels.

Ownership of Equipment and Ski Geometry Parameters

The proportion of rented/borrowed equipment was more than 20% points higher among both female and male skiers with ACL injuries compared with controls (data not shown). While in less skilled skiers of both sexes using rented/borrowed equipment was not an independent risk factor, this was the case for more skilled skiers, in whom ACL injury risk increased by nearly 8-fold for more skilled female skiers and by about 10-fold for more skilled male skiers. It could be speculated that compared with less skilled skiers, more skilled skiers are more prone to try out new and innovative ski equipment from a ski rental shop, as widths and shapes of skis have evolved in the past years, for example, with the introduction of so-called rocker skis. In general, Hume et al[15] reported in their meta-analysis of skiers and snowboarders who rent snow equipment an odds ratio of 2.6 for sustaining a snow sport injury. These authors,[15] however, also mentioned that it was not clear from the included studies whether it was the equipment per se, its maintenance, or the people who used rental equipment that resulted in rental equipment being a risk factor. Johnson et al[16] pointed out that the injury rate for rental equipment might be higher than that for user-owned equipment because the former is most often used by entry-level skiers. However, in this study on ACL injuries, ownership of equipment was an independent risk factor in more skilled skiers only.

Recently, Ruedl et al[32] found in a case-control study including female and male skiers that an increase in ski length and in the tip width of the ski was significantly associated with an ACL injury for the total study cohort; however, we did not analyze ski geometry parameters according to sex and skill differences. In the case of an accident, a longer ski acts as a longer lever at the knee joint to bend or twist the leg. In the present study, only in less skilled female skiers was greater ski length associated with increased ACL injury risk. In general, longer skis are associated with an increased sidecut radius. For beginners, shorter ski length with a lower sidecut radius facilitates turning because of the self-steering of the ski. In contrast, with longer skis it could be easier to catch the front part of the ski edge, as the main self-reported cause leading to an ACL injury is catching an edge of the carving ski.[33]

The sidecut radius per se was not a risk factor for ACL injury in either less skilled or more skilled skiers of either sex. As aforementioned, the sidecut radius depends on the ski length and on the tip, waist, and tail widths of the ski. Surprisingly, in contrast to our recent results with the total cohort,[32] the present multiple analyses did not reveal any width of the ski as an independent risk factor for the 4 subgroups. However, this result might also be because in the present study additional equipment-related parameters, such as ski ownership and boot sole abrasion, were added to the analyses.

Standing Height Ratio

A previous study on ACL injuries has confirmed the role of standing height ratio as an independent risk factor in recreational skiing.[32] Nonetheless, the roles of sex and skills are yet to be fully explored in this regard. Our findings suggest that higher standing height ratio may increase the risk of ACL injuries regardless of skiers' level and independent from sex. In fact, a value of 88% to 89% for the standing height ratio, that is, similar to plantarflexion rotation of the soles of ski boots, was found for all uninjured skiers regardless of skill and sex; this value raised to approximately 95% to 96% in skiers with ACL injuries, reflecting a more horizontal position of the ski boot sole. The potential influence of ski boot orientation on knee kinematics has been demonstrated in previous research.[40] Indeed, with an elevated heel position of the ski boot, skiers tend to lean their trunk further forward and likely cause a higher knee flexion (moving the knee further from an extended position). In contrast to the previously suggested increased ACL tension in quadriceps loading at small knee angles (closer to knee extension), when knee flexion is higher, it seems that the load on the ACL decreases and may even be in a fully unloaded condition.[39] Bending forward seems to trigger an increase in hamstring activity at the same time as quadriceps are less active (and vice versa in backward bending),[17] which may be key in the prevention of ACL injuries because the hamstring co-contraction helps reduce the load on the ACL during knee flexion through lower internal rotation and anterior translation.[19] Regardless of the mechanisms involved, the position of the heel part of the ski binding may be deemed as an essential equipment-related parameter to be taken into account in the field of ACL injury prevention, even more as it seems to be independent of sex or skiers' levels. Despite the importance of these findings, more studies are necessary to explore the association between ski boot's heel position and ACL injury risk and to explain which (if any) mechanisms are involved in it.

Abrasion of the Ski Boot Sole

Research on the role of ski boot sole abrasion in ACL injury risk has shown that abrasion at the toe and heel may increase such risk 1.4 to 1.8 times.[24] Nonetheless, these values did not consider possible differences based on skiers' levels and sex.[24]

The present study shows that more abrasion at the toe increases the risk of injuries of ACL regardless of skill level or sex. On the contrary, abrasion at the heel is significantly associated with ACL injuries only in the more skilled skiers, independent of their sex. However, in the simple analysis, abrasion at the heel was also significantly higher in all 4 groups of skiers with ACL injuries ($P < .001$), indicating that abrasion at the heel as well as at the toe are relevant parameters for injury prevention.

There are several reasons for ski boots to cause abrasion, among them excessive walking on ski boots on surfaces different from snow, often the streets or parking areas of ski resorts.[24] Considering the cornerstone role of ski boots in transferring the high forces produced by alpine skiers into the skis,[4] and the significant part played by their soles as they decrease the friction between boots and ski bindings at the contact points,[7] it seems obvious that abrasion of the ski boot sole can influence the releasing mechanisms of the ski binding. More studies in the field are needed to examine the abovementioned role of sole abrasion on bindings' release mechanisms as well as to better understand whether it is an independent factor determining failures in the release of the bindings and to what extent.

To sum up regarding individual factors, because age as a risk factor is not changeable and skill level is a dependent variable in the present study, especially male skiers should be aware of risk-taking as a major risk factor for an ACL injury in skiing and thus should adapt their behavior and skiing speed to current environmental circumstances.

Regarding equipment as a preventive measure for ACL injuries, it seems better for some groups to own skis than to rent skis. However, once new equipment leaves the ski shop after purchase, its effectiveness begins to decline because of its use on ski slopes.[16] Thus, the skier should have his or her equipment checked by a qualified ski shop at least once per season.[16] In general, longer skis act as a longer lever at the knee joint during a fall. Thus, especially in less skilled (female) skiers also including a certain number of beginners, shorter skis are recommended as a valuable preventive measure.

Standing height ratio and boot sole abrasion are equipment-related factors that could be easily considered for the prevention of an ACL injury on ski slopes. When buying new skis, the rear part of the ski binding should be more elevated than the front part, indicating a lower standing height ratio for injury prevention. In addition, skiers should avoid walking longer distances with their ski boots on hard surfaces (eg, streets) so as to minimize abrasion on the sole.

Limitations

In this study, all skiers with ACL injuries were recruited from a ski clinic in a specific skiing area. However, it is possible that some of the skiers who sustained such injuries while skiing in the selected skiing area were not attended at the clinic: They may have chosen to not receive immediate treatment or to use other medical facilities not in the area. Because of the nature of an ongoing study, the evaluation of various ski geometry parameters, standing height ratio, and ski boot sole abrasion was started at different time points, leading to different sample sizes within variables. However, to the best of our knowledge, this is the first study evaluating the impact of equipment-related data on ACL injury risk in female and male recreational skiers of lower and higher skill levels including the highest number of recreational skiers with and without ACL injuries so far worldwide.

CONCLUSION

Study findings indicated that there are some specific differences in individual and equipment-related risk factors in recreational skiers of different skill levels and sex. Elevated standing height ratio and more abrasion at the toe of the boot sole were associated with an increased ACL injury risk in both sexes independent of the skill level. While riskier behavior increases the ACL injury risk only in male skiers (independent of the skill level) and a higher ski length only in less skilled female skiers, a higher age, the use of rented/borrowed skis, and more abrasion at the heel of the boot sole were independent risk factors for ACL injury in advanced skiers of both sexes.

Besides improving skill level as a general preventive measure and adapting individual behavior on ski slopes according to the International Ski Federation ski slope rules, individual consideration of the demonstrated equipment-related factors should be implemented in order to reduce ACL injuries in recreational skiers.

REFERENCES

1. Barth M, Platzer HP, Giger A, Nachbauer W, Schröcksnadel P. Acute on-snow severe injury events in elite alpine ski racing from 1997 to 2019: the Injury Surveillance System of the Austrian Ski Federation. *Br J Sports Med*. Published online October 6, 2020. doi:10.1136/bjsports-2020-102752
2. Beynnon BD, Ettlinger CF, Johnson RJ. Epidemiology and mechanisms of ACL injury in alpine skiing. In: Hewett TE, Shultz SJ, Griffin LY, eds. *Understanding and Preventing Noncontact ACL Injuries*. American Orthopaedic Society for Sports Medicine, Human Kinetics; 2007: 183-188.
3. Beynnon BD, Johnson RJ, Braun S, Sargent M. The relationship between menstrual cycle phase and anterior cruciate ligament injury: a case-control study of recreational alpine skiers. *Am J Sports Med*. 2006;34:757-764.
4. Böhm H, Senner V. Effect of ski boot settings on tibio-femoral abduction and rotation during standing and simulated skiing. *J Biomech*. 2008;41(3):498-505.
5. Burtscher M, Gatterer H, Flatz M, et al. Effects of modern ski equipment on the overall injury rate and the pattern of injury location in alpine skiing. *Clin J Sport Med*. 2008;18(4):355-357.
6. Burtscher M, Sommersacher R, Ruedl G, et al. Potential risk factors for knee injuries in alpine skiers. In: Johnson RJ, Shealy JE, Langran M, eds. *Skiing Trauma and Safety*. Vol 17. ASTM International; 2009:1-4.
7. Colonna M, Nicotra M, Moncalero M. Materials, designs and standards used in ski-boots for alpine skiing. *Sports*. 2013;1(4):78-113.
8. Davey A, Endres NK, Johnson RJ, Shealy Jasper. Alpine skiing injuries. *Sports Health*. 2019;11(1):18-26. doi:10.1177/1941738118813051
9. Ekeland A, Rødven A. Skiing and boarding injuries on Norwegian slopes during two winter seasons. In: Johnson RJ, Shealy JE, Senner V, eds. *Skiing Trauma and Safety*. Vol 18. ASTM International; 2011: 139-149.
10. Gilgien M, Spörri J, Kröll J, et al. Effect of ski geometry and standing height on kinetic energy: equipment designed to reduce risk of severe traumatic injuries in alpine downhill ski racing. *Br J Sports Med*. 2016; 50(1):8-13.
11. Greenwald RM, Toelcke T. Gender differences in alpine skiing injuries: a profile of the knee-injured skier. In: Johnson RJ, Mote CD, Ekeland E, eds. *Skiing Trauma and Safety*. Vol 11. ASTM; 1997:111-121.
12. Hagel B. Skiing and snowboarding injuries. *Med Sport Sci*. 2005;48: 74-119.
13. Hermann A, Senner V.Knee injury prevention in alpine skiing. A technological paradigm shift towards a mechatronic ski binding. *J Sci Med Sport*. 2021;24(10):1038-1043. doi:10.1016/j.jsams.2020.06.009
14. Hewett TE, Myer GD, Ford KR. Anterior cruciate ligament injuries in female athletes: part 1, mechanisms and risk factors. *Am J Sports Med*. 2006;34(2):299-311.
15. Hume PA, Lorimer AV, Griffiths PC, Carlson I, Lamont M. Recreational snow-sports injury risk factors and countermeasures: a meta-analysis review and Haddon matrix evaluation. *Sports Med*. 2015;45(8): 1175-1190. doi:10.1007/s40279-015-0334-7
16. Johnson RJ, Ettlinger CF, Shealy JE. Myths concerning alpine skiing injuries. *Sports Health*. 2009;1(6):486-492. doi:10.1177/1941738109347964
17. Koyonagi M, Shino K, Yoshimoto Y, et al. Effects of changes in skiing posture on the kinetics of the knee joint. *Knee Surg Sports Traumatol Arthosc*. 2006;14(1):88-93.
18. Kröll J, Spörri J, Gilgien M, et al. Sidecut radius and kinetic energy: equipment designed to reduce risk of severe traumatic knee injuries in alpine giant slalom ski racing. *Br J Sports Med*. 2016;50(1):26-31.
19. MacWilliams BA, Wilson DR, DesJardins JD, et al. Hamstrings cocontraction reduces internal rotation, anterior translation, and anterior cruciate ligament load in weight-bearing flexion. *J Orthop Res*. 1999;17(6):817-822.
20. McCarthy MM, Hannafin JA. The mature athlete: aging tendon and ligament. *Sports Health*. 2014;6(1):41-48. doi:10.1177/1941738113485691
21. McLeod M, Breen L, Hamilton DL, Philip A. Live strong and prosper: the importance of skeletal muscle strength for healthy ageing. *Biogerontology*. 2016;17(3):497-510. doi:10.1007/s10522-015-9631-7
22. Natri A, Beynnon BD, Ettlinger CF, et al. Alpine ski bindings and injuries. *Current findings. Sports Med*. 1999;28(1):35-48.
23. Niedermeier M, Ruedl G, Burtscher M, et al. Injury-related behavioral variables in alpine skiers, snowboarders and ski tourers—a matched and enlarged re-analysis. *Int J Environ Res Public Health*. 2019;16(20): 3807. doi.org/10.3390/ijerph16203807
24. Posch M, Ruedl G, Schranz A, et al. Is ski boot sole abrasion a potential ACL injury risk factor for male and female recreational skiers? *Scand J Med Sci Sports*. 2019;29(5):736-741.
25. Posch M, Schranz A, Lener M, et al. In recreational alpine skiing, the ACL is predominantly injured in all knee injuries needing hospitalisation. *Knee Surg Sports Traumatol Arthrosc*. 2021;29(6):1790-1796.
26. Pressman A, Johnson DH. A review of ski injuries resulting in combined injury to the anterior cruciate ligament and medial collateral ligaments. *Arthroscopy*. 2003;19(2):194-202.
27. Ruedl G, Abart M, Ledochowski L, et al. Self-reported risk taking and risk compensation in skiers and snowboarders are associated with sensation seeking. *Accid Anal Prev*. 2012;48:292-296.
28. Ruedl G, Philippe M, Sommersacher R, et al. Current incidence of accidents on Austrian ski slopes. *Sportverletz Sportschaden*. 2014; 28(4):183-187.
29. Ruedl G, Ploner P, Linortner I, et al. Are oral contraceptive use and menstrual cycle phase related to anterior cruciate ligament injury risk in female recreational skiers? *Knee Surg Sports Traumatol Arthrosc*. 2009;17(9):1065-1069.
30. Ruedl G, Pocecco E, Sommersacher R, et al. Factors associated with self reported risk taking behaviour on ski slopes. *Br J Sports Med*. 2010;44(3):204-206. doi:10.1136/bjsm.2009.066779
31. Ruedl G, Posch M, Niedermeier M, et al. Are risk-taking and ski helmet use associated with an ACL injury in recreational alpine skiing? *Int J Environ Res Public Health*. 2019;16(17):3107. doi:10.3390/ijerph16173107
32. Ruedl G, Posch M, Tecklenburg K, et al. Impact of ski geometry data and standing height ratio on the ACL injury risk and its use for prevention in recreational skiers. *Br J Sports Med*. 2022.

33. Ruedl G, Webhofer M, Linortner I, et al. ACL injury mechanisms and related factors in male and female carving skiers: a retrospective study. *Int J Sports Med*. 2011;32(10):801-806.
34. Senner V, Michel FI, Lehner S, et al. Technical possibilities for optimising the ski-binding-boot functional unit to reduce knee injuries in recreational alpine skiing. *Sports Eng*. 2013;16(4): 211-228.
35. Spörri J, Kröll J, Fasel B, et al. Standing height as a preventive measure for overuse injuries of the back in alpine ski racing: a kinematic and kinetic study of giant slalom. *Orthop J Sports Med*. 2018;6(1): 2325967117747843.
36. Spörri J, Kröll J, Gilgien M, et al. Sidecut radius and the mechanics of turning-equipment designed to reduce risk of severe traumatic knee injuries in alpine giant slalom ski racing. *Br J Sports Med*. 2016;50(1): 14-19.
37. Sulheim S, Ekeland A, Bahr R. Self-estimation of ability among skiers and snowboarders in alpine skiing resorts. *Knee Surg Sports Traumatol Arthrosc*. 2007;15(5):665-670.
38. Sulheim S, Holme I, Rodven A, et al. Risk factors for injuries in alpine skiing, telemark skiing and snowboarding—case-control study. *Br J Sports Med*. 2011;45(16):1303-1309.
39. Wascher DC, Markolf KL, Shapiro MS, et al. Direct in vitro measurement of forces in the cruciate ligaments: part I: the effect of multiplane loading in the intact knee. *J Bone Joint Surg Am*. 1993;75(3):377-386.
40. Wilson SA, Dahl KD, Dunford KM, et al. Ski boot canting adjustments affect kinematic, kinetic, and postural control measures associated with fall and injury risk. *J Sci Med Sport*. 2020;24(10):1015-1020.
41. Zorko M, Nemec B, Babič J, et al. The waist width of skis influences the kinematics of the knee joint in alpine skiing. *J Sports Sci Med*. 2015;14(3):606.