applied sciences

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The Impact of Ski Geometry Data and Standing Height on the Risk of Falling in Recreational Alpine Skiers

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Abstract: The aim of this study was to evaluate the impact of individual, equipment-related and environmental factors associated with falls among adult recreational skiers. Individual, equipment-related (ski geometry data) and environmental data were collected by questionnaire among uninjured skiers with and without reported falls during the skiing day. Ski length, side cut radius, and width of the waist were directly recorded from the ski and standing height was measured using a digital sliding caliper. Absolute ski length was relativized to body height. A total of 1174 recreational skiers participated in this study, of whom 13.5% (n = 158) reported at least one fall during the skiing day. Results of the multiple logistic regression analysis found that a lower age, a very good/good fitness level, a moderate skiing speed, a lower relativized ski length, and fresh and grippy snow conditions decreased, while a lower skill level, a larger sidecut radius and an easy slope difficulty increased risk of falling on ski slopes. Besides individual and environmental factors, a lower relativized ski length and a lower sidecut radius decreased the risk of falling. Considering these ski geometry parameters when buying new skis could potentially decrease the risk of falling and thus prevent injuries in recreational skiers.

Keywords: recreational alpine skiing; falls; standing height; ski geometry; risk factors; prevention

Citation: Ruedl, G.; Posch, M.; Greier, K.; Faulhaber, M.; Burtscher, M. The Impact of Ski Geometry Data and Standing Height on the Risk of Falling in Recreational Alpine Skiers. *Appl. Sci.* **2021**, *11*, 9912. https://doi.org/10.3390/app11219912

Academic Editor: Matej Supej

Received: 22 September 2021
Accepted: 21 October 2021
Published: 23 October 2021

1. Introduction

Recreational alpine skiing is one of the most popular winter sports annually enjoyed by several hundred million skiers worldwide [1]. Although the injury risk of less than two injuries per 1000 ski days seems low nowadays in Austria, the total number of injuries per year remains high because of the huge population at risk [2,3].

In Austria, self-inflicted falls, i.e., falls without influence of other persons, are the most common accidental causes leading to an injury on ski slopes, at 80–90% [2,3], as well as leading to a traumatic death on ski slopes, at about 47% [4]. As falling during skiing is the most important reason for injuries and traumatic fatalities on ski slopes, studies identifying risk factors for falling seem important to implement evidence-based preventive measures. Marshall [5] recommends, for case-control studies, evaluating the impact of ski helmet use on skiing-related head injuries, not only using "other injuries" as controls but also uninjured people who fell, because a helmet cannot protect the head until a fall occurs. Thus, according to Marshall [5] it seems logical to also include skiers who fell but were not injured in a study population when evaluating the impact of ski equipment on the occurrence of crashes.

Burtscher et al. [6] found in an earlier study that younger age, alcohol consumption on the skiing day, poor skiing skills, soft snow conditions, higher altitudes and smoking are associated with falls in a cohort of 1607 recreational skiers and 373 recreational snowboarders. In a follow-up study by Philippe et al. [7], due to the introduction of short and shaped carving skis compared to the so-called long and unshaped traditional skis,

soft snow conditions and a lower skill level were predictive for falls in carving skiers. In addition, incidence of falls was substantially lower when compared to the 2009 study which might also be due to the generally shorter length of the new carving skis [7].

Skiing is a highly complex activity where the individual skier interacts with skiing equipment (e.g., ski, binding, boot) and the environment (e.g., snow, weather and slope conditions) [1]. In recent years, research has focused more and more on the impact of ski geometry data as ski length, sidecut radius, waist width or standing height on severe injuries, but mainly in ski racing. The sidecut radius of a ski determines the turning radius of the skier and the lower the sidecut radius the more a self-steering effect is given and a carved turn will result [8]. In alpine ski racing, a greater side cut radius potentially reduces the self-steering effects of the skis [9] and helps in preventing knee positioning into excessive internal rotation and valgus [10], and therefore has been suggested as a preventive measure. Another potential and still poorly explored risk factor regarding injuries in alpine skiing is the standing height (i.e., the distance between the bottom of the running surface of the ski and the ski boot sole) [11]. Generally, the introduced lifter plates (between the ski and binding) in 1988 led to an increase in standing height, that allows more angling of the skis and also improves the torsional stiffness, dampens vibrations and potentially enhances the release of ski bindings [8]. However, it is assumed that an increased standing height fosters skidding and therefore possibly leads to higher strain on the knee [8]. Gilgien et al. [12] investigated the effect of modifications in ski geometry (ski length, ski width) and standing height of downhill skis on speed and kinetic energy while skiing a World Cup downhill course. They found that, during downhill ski racing, longer skis with reduced width and standing height showed a significantly decreased mean kinetic energy in the steep section of a downhill course [12].

Up to now the impact, especially of ski geometry data, on risk of falls or risk of injuries due to falls are scarce in recreational alpine skiing. Thus, due to the complex interaction of the skiers with skiing equipment and the environment, the aim of this study was to evaluate individual, equipment-related and environmental factors associated with falls among recreational alpine skiers.

2. Materials and Methods

2.1. Study Design

This study was conducted as an observational study, including uninjured recreational skiers during four consecutive winter seasons between 2016/17 and 2019/20 in a large Austrian ski area. Skiers were interviewed annually between the months December and April on 23 days on average per winter season using a predefined standardized questionnaire. Skiers were selected at various spots in the ski area throughout the whole skiing day. In total, more than 85% of invited skiers agreed to participate in the study.

All study participants were informed about the aims of the study and gave their written informed consent to participate. Patients or the public were not involved in the design, conduct, reporting, or dissemination plans of the underlying research. 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 (Certificate of good standing 29/2016).

2.2. Subjects

Inclusion criteria for cases were at least one reported self-inflicted fall during the skiing day, an age >17 years and the use of any type of carving skis (in contrast to long and unshaped traditional skis as well as so-called short ski boards). Similar to those of cases, inclusion criteria for controls were age >17 years and the use of any type of carving ski and no reported fall.

2.3. Questionnaire

According to questionnaires used in previous studies [6,7,13], individual factors (sex, age, body height and weight, fitness level, skill level, risk-taking behavior, preferred skiing speed), equipment-related factors (ski length, sidecut radius, standing heights) and environmental factors (snow and weather conditions, difficulty of the preferred slopes) of the participants were evaluated.

Participants had to rate their current perceived fitness level on a five-point Likert scale (very good, good, medium, weak, very weak) which was further divided into three fitness categories (very good/good vs. medium vs. weak/very weak). Skiers were also asked to self-report their skiing skill level (expert, advanced, intermediate and beginner) according to Sulheim et al. [14] and risk-taking behavior (more risky vs. more cautious) according to Ruedl et al. [15]. Furthermore, study participants were divided 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 [14].

According to Brunner et al. [16] skiers had to rate their preferred skiing speed on a five-point Likert scale (very fast, fast, moderate, slow, very slow) which was further divided into three speed categories (very fast/fast vs. moderate vs. slow/very slow).

Ski geometry data (ski length and sidecut radius as well as waist width) were directly recorded from the carving ski of the subject. Additionally, ski length was relativized by body height as literature displays evidence of a positive link between ski length and risk of falling [7] and/or sustaining an injury [17]. The standing height (i.e., the distance between the bottom of the running surface of the ski and the ski boot sole) at the front and rear component of the ski binding was measured using a digital sliding caliper. In addition, a percentage ratio between front and rear component heights of the ski binding was calculated. This standing height ratio relates to the angle of the boot sole when inserted into the ski binding. A previous study has shown that ski boot orientation can influence knee kinematics and would be likely to alter the loads experienced at the knee [18].

Participants' self-rated perceived environmental factors in the skiing day consisted of snow conditions (fresh snow, grippy, icy, slushy/soft), weather conditions (sunny, overcast, snowfall) and difficulty of the preferred downhill slopes (easy, moderate, hard according to the blue, red and black signs on the ski slopes) [19].

Finally, skiers were asked about their frequency of falling (never, 1–3 times, more than 3 times) during the skiing day.

2.4. Statistics

All data are presented as means ± standard deviations, absolute and relative frequencies. According to the tests on normal distribution (Kolmogorov–Smirnov), univariate differences among metric data (age, body height and weight, ski length relativized to body height, waist width, as well as sidecut radius and standing heights of the front and rear components of the ski binding as well as standing height ratio) between skiers without and with falls were evaluated either by independent t-tests or Mann–Whitney-U tests. In addition, differences in frequency (sex, fitness level, skiing skill level, risk taking behavior, preferred skiing speed, snow condition, weather condition, preferred slope difficulty) were evaluated by Chi-square tests. According to types of data, Cohen's d (small: 0.2, medium: 0.5, large: 0.8) and Phi coefficient (small: 0.1, medium: 0.3, large: 0.5) were calculated as effect sizes [20].

All significant factors ($p < 0.05$) of the univariate comparisons were additionally entered in a logistic regression analysis to estimate adjusted odds ratios (OR) and their 95% confidence intervals (CI) for risk of falls. We provided for an easier understanding percentage of increasing or decreasing risk of falling which are the respective difference between the result of the OR and 1, e.g., an OR of 0.40 corresponds to a decrease in the risk of falling by 60%. In addition, significant factors of the simple analysis with more than two categories (fitness level, preferred skiing speed, snow condition, weather condition, preferred slope difficulty) were dummy coded (no = 1 and yes = 2) before entering the

multiple logistic regression, e.g., easy ski slope (yes/no) vs. moderate ski slope (yes/no) vs. hard ski slope (yes/no), etc. SPSS 26.0 (IBM Corporation, Armonk, NY, USA) 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 1174 recreational skiers participated in this study, of whom 13.5% (n = 158) reported at least one fall during the skiing day. Mean age of the total cohort was 37.8 ± 13.3 years, mean height was 173.7 ± 8.8 cm, mean weight was 75.1 ± 14.2 kg and 46.7% (n = 571) were females. In total, 81.7% of skiers (n = 959) reported to be more skilled and 33.5% (n = 393) participants reported to display more risky behavior during skiing.

Table 1 presents the results of the univariate comparisons of risk factors between recreational skiers without and with reported falls. The two groups significantly differ within age, fitness level, skill level, preferred skiing speed, relativized ski length, sidecut radius, waist width of the ski, standing height of the front and rear components of the ski binding, snow and weather conditions and slope difficulty.

Table 1. Univariate comparisons of individual, equipment-related and environmental factors between recreational skiers without and with falls.

Risk Factors	Skier without Falls	Skier with Falls	p Value	Effect Size
Individual factors				
Sex (%)			0.844	Phi: 0.006
Male	51.5 (n = 523)	50.6 (n = 80)		
Female	48.5 (n = 493)	49.4 (n = 78)		
Age, mean ± sd	38.2 ± 13.4 (n = 1016)	35.3 ± 12.3 (n = 158)	0.019	Cohen's d: 0.219
Body height (cm) mean ± sd	173.6 ± 8.6 (n = 1016)	174.2 ± 10.2 (n = 158)	0.763	Cohen's d: −0.068
Body weight (kg) mean ± sd	75.1 ± 14.2 (n = 1014)	75.3 ± 14.1 (n = 157)	0.765	Cohen's d: −0.014
Fitness level (%)			<0.001	Phi: 0.246
Very good/good	73.1 (n = 743)	44.3 (n = 70)		
Medium	24.4 (n = 248)	43.0 (n = 68)		
Weak/very weak	2.5 (n = 25)	12.7 (n = 20)		
Skill level (%)			<0.001	Phi: 0.323
More skilled	86.6 (n = 880)	50.0 (n = 79)		
Less skilled	13.4 (n = 136)	50.0 (n = 79)		
Risk-taking behavior (%)			0.375	Phi: −0.026
More cautious	66.0 (n = 671)	69.6 (n = 110)		
More risky	34.0 (n = 463)	30.4 (n = 48)		

Table 1. *Cont.*

Risk Factors	Skier without Falls	Skier with Falls	*p* Value	Effect Size
Preferred skiing speed (%)			<0.001	Phi: 0.285
Very fast/fast	54.1 (*n* = 550)	38.0 (*n* = 60)		
Moderate	41.7 (*n* = 424)	36.7 (*n* = 58)		
Slow /very slow	4.1 (*n* = 42)	25.3 (*n* = 40)		
Equipment-related factors				
Relativized ski length (%), mean ± sd	95.4 ± 3.6 (*n* = 1016)	93.1 ± 4.1 (n = 158)	<0.001	Cohen's d: 0.627
Sidecut radius (m), mean ± sd	14.6 ± 2.9 (*n* = 1016)	13.8 ± 2.9 (*n* = 158)	<0.001	Cohen's d: 0.276
Waist width (mm), mean ± sd	76.1 ± 9.5 (*n* = 1016)	73.5 ± 7.3 (*n* = 185)	0.001	Cohen's d: 0.282
Standing height front component (mm)	40.3 ± 5.7 (*n* = 1014)	38.9 ± 5.6 (*n* = 157)	0.002	Cohen's d: 0.246
Standing height rear component (mm)	45.5 ± 6.0 (*n* = 1016)	43.8 ± 6.5 (*n* = 158)	0.003	Cohen's d: 0.280
Standing height ratio (%), mean ± sd	88.6 ± 6.7 (*n* = 1014)	88.9 ± 7.3 (*n* = 157)	0.511	Cohen's d: −0.044
Environmental factors				
Snow condition (%)			<0.001	Phi: 0.155
Fresh snow	13.8 (*n* = 140)	7.0 (*n* = 11)		
Grippy	57.5 (*n* = 584)	43.7 (*n* = 69)		
Icy	8.0 (*n* = 81)	13.3 (*n* = 21)		
Slushy/soft	20.8 (*n* = 211)	36.1 (*n* = 57)		
Weather condition (%)			<0.040	Phi: 0.074
Sunny	63.9 (*n* = 649)	74.1 (*n* = 117)		
Overcast	27.8 (*n* = 282)	20.9 (*n* = 33)		
Snow fall	8.4 (*n* = 85)	5.1 (*n* = 8)		
Difficulty of preferred slope (%)			<0.001	Phi: 0.296
Easy (blue slope)	6.0 (*n* = 61)	31.0 (*n* = 49)		
Moderate (red slope)	70.2 (*n* = 713)	56.3 (*n* = 89)		
Hard (black slope)	23.8 (*n* = 242)	12.7 (*n* = 20)		

Table 2 presents the significant adjusted results of the multiple logistic regression analysis. Age, fitness level, skill level, moderate preferred speed, relativized ski length, sidecut radius, fresh and grippy snow conditions and an easy slope difficulty were found to be factors independently associated with the risk of falling in recreational adult skiers. Risk of falling decreased (OR < 1) with a lower age (OR 0.966), a very good/good fitness level (OR 0.251), a moderate preferred skiing speed (OR 0.435), a lower relativized ski length (OR 0.901), and fresh (OR 0.375) and grippy snow conditions (OR 0.451). In contrast,

associations with an increase in the risk of falling (OR > 1) were found for a lower skill level (OR 2.785), a larger sidecut radius (1.092), and an easy slope difficulty (OR 2.991).

Table 2. Significant results of adjusted odds ratios of individual, equipment-related and environmental factors associated with risk of falls.

Risk Factor	Coefficient	Standard Error	df	*p*	Odds Ratio	95% CI
Age	−0.035	0.008	1	<0.001	0.966	0.951–0.981
fitness level						
Very good/good	−1.380	0.412	1	0.001	0.251	0.112–0.564
Skill level						
Less skilled	1.024	0.260	1	<0.001	2.785	1.672–4.638
Preferred skiing speed						
Moderate	−0.833	0.341	1	0.014	0.435	0.223–0.848
Relativized ski length (%)	−0.104	0.030	1	0.001	0.901	0.850–0.956
Sidecut radius (m)	0.088	0.043	1	0.041	1.092	1.004–1.188
Snow condition						
Fresh snow	−0.982	0.477	1	0.039	0.375	0.147–0.954
Snow condition						
Grippy	−0.797	0.249	1	0.001	0.451	0.277–0.735
Slope difficulty						
Easy	1.095	0.415	1	0.008	2.991	1.325–6.748
Intercept	13.081	3.767	1	0.001	479,772.284	

Nagelkerkes R-Square = 0.287, classification table—overall percentage = 88.4%.

4. Discussion

The aim of this study was to evaluate individual, equipment-related and environmental factors associated with falls among adult recreational alpine skiers. Results of the multiple logistic regression analysis found a lower age, a very good/good fitness level, a moderate preferred skiing speed, a lower relativized ski length, and fresh and grippy snow conditions were associated with a decreasing risk of falling while a lower skill level, a larger sidecut radius and an easy slope difficulty were associated with an increase in the risk of falling.

In this study about 14% of participants reported at least one fall during recreational skiing which seems comparable with the 16% of skiers who fell in the study by Philippe et al. [7].

4.1. Individual Factors

A lower age (OR 0.966) was associated with a decreasing risk of falling by 3% when adjusted for other factors although the simple analysis found a lower mean age in skiers with falls (Table 1). This result of the multiple analysis (Table 2) seems to be in contrast to the earlier results by Burtscher et al. [6] and Philippe et al. [7] who, however, also included child and adolescent skiers and snowboarders (Range: 6–80 years) while we only asked adult skiers >17 years (Range: 18–80 years). In addition, the snowboard population is generally younger than the skier population and younger people are more prone to use fun or snow parks where they can jump over a variety of man-made features potentially increasing risk of falling [21]. In addition, aging is associated with a progressive loss of neuromuscular function [22,23] which in general is an important function in keeping balance and in steering and turning skis on slopes.

Results of the logistic regression analysis revealed that a high fitness level (OR 0.251) decreased the risk of falling by 75%. A higher fitness level might also be associated with younger age [22,23] and therefore could prevent falls. It is widely recommended that proper conditioning prior to the skiing season would be beneficial for injury prevention as increased muscular strength would help to splint the joints during a fall [24].

The proportion of less skilled skiers in the univariate comparison was higher in skiers with falls compared to those without a fall (50 vs. 13%). The result of the logistic regression also revealed a lower skill level associated with about a 2.8-fold elevated risk for falling

(OR 2.785). Well in accordance, Burtscher et al. [6] and Philippe et al. [7] reported lower skiing skills as predictive for falls. In general, a lower skill level seems to be also associated with a higher overall injury risk in recreational alpine skiing [25,26].

Results of the regression analysis revealed for the factor 'moderate speed' an odds ratio of 0.435 which corresponds to a decreased risk for falling by about 56%. One can assume that a moderate skiing speed is connected to the individual skill level of the skier for not skiing beyond individual boundaries.

4.2. Equipment-Related Factors

A lower relativized ski length was associated with a decreasing risk of falling by about 10% (OR 0.901) in the multiple analysis (Table 2). There seems some evidence that injury risk on ski slopes decreased after the introduction of the short and shaped carving skis about 2–3 decades ago compared to the long and unshaped traditional skis with a general ski length about 10 cm above body height [2]. Well in accordance, Posch et al. [17] found a significantly higher ski length to height ratio in recreational skiers suffering from an ACL injury after a self-inflicted fall compared to uninjured controls, indicating the impact of greater ski length on ACL injury risk in recreational skiers.

Results of the regression analysis found an odds ratio of 1.092 for the factor 'sidecut radius' which corresponds to an increase in the risk of falling by 9%. Mean sidecut radius in this study was 14.5 ± 2.9 m (Range: 7.2–27.5 m). Interestingly, the univariate comparison found a significant higher mean sidecut radius in skiers reporting no falls; however, when adjusted to other factors, a larger sidecut radius was associated with an increase in the risk of falling by 9% (OR 1.092). As we found a significant correlation of r = 0.67 ($p < 0.001$) between absolute ski length and sidecut radius in this study, there seems some evidence that longer carving skis have larger sidecut radii which potentially makes the steering of the skis more difficult. Especially beginners could benefit from shorter and livelier carving skis, which simplify the use of edges and ski turns [8].

The univariate comparison (Table 1) found a significantly lower width at the waist of the ski as well as lower standing heights at the front and rear components of the ski binding within skiers who fell. One could speculate that during carved turns it seems easier to slip away on the ski boot when using skis with lower waist width and lower standing heights, resulting in a fall. However, results of the multiple logistic regression did not reveal these ski geometry factors as independent factors for falling.

4.3. Environmental Factors

Connected to a lower skill level might be the result that skiing on easy slopes increased risk for falling by about three-fold (OR 2.785). About 30% of skiers with a reported fall preferred easy slopes compared to 6% of skiers without falls (Table 1). In Austria, easy slopes are so-called blue slopes which are mostly relatively flat and wide slopes for beginners and families compared to the very steep and bumpy black slopes for experts.

In this study, fresh snow (OR 0.375) and grippy snow (OR 0.451) are associated with a decreased risk of falling by 62% and 55%, respectively. Grippy snow conditions mostly depend on the grooming and preparation of ski slopes by the owner of the ski lifts in the ski area. Bergstrom and Ekeland [27] found an inverse relationship between grooming hours and the number of injuries on ski slopes. For comparison, Burtscher et al. [6] reported slushy/soft snow condition as a relevant cause for falling and Ruedl et al. [28] found icy snow conditions to be an independent risk factor for an ACL injury after a self-inflicted fall among female recreational skiers. It could be speculated that when skiing on slopes with soft or slushy snow conditions it might be easier to catch an edge or the tip of the ski, and within icy conditions to slip out or lose balance resulting in a fall.

Summing up, although a fall does not always lead to an injury, falls are the overwhelming cause of injuries and fatalities on alpine ski slopes [6,7,25]. In accordance with an earlier study by Ruedl et al. [28] on the complex interaction of individual, equipment-related and environmental factors causing an ACL injury in female skiers after a self-inflicted fall,

results of this study also found a complex interaction of individual, equipment-related and environmental factors for the risk of falling when skiing on ski slopes.

4.4. Limitations

Although every effort was made to avoid sampling and response bias, we cannot entirely exclude its occurrence. For instance, some skiers may have become aware of our check spots and did not pass them. Moreover, self-estimation of the individual skill level and/or preferred skiing speed may have differed between skiers and does not necessarily represent an objective measure. Nevertheless, the presented findings are strengthened by the relatively large sample size including male and female skiers and considering both results from the questionnaire and objectively recorded ski geometry and standing height data.

5. Conclusions

In conclusion, younger age, higher fitness, a higher skill level and a moderate skiing speed are independent individual factors in preventing falls on ski slopes. Skiing on fresh snow and grippy snow conditions was associated with a decrease while skiing as a less skilled skier on beginner slopes was associated with an increase in risk of falling. In addition, a lower relativized ski length and a lower sidecut radius decreased the risk of falling. Considering these ski geometry parameters when buying new skis could potentially decrease the risk of falling and thus prevent injuries in recreational skiers.

Author Contributions: Conceptualization, G.R., M.P., K.G., M.F. and M.B.; methodology, G.R., and M.P.; data curation, K.G., M.F. and M.B.; writing—original draft preparation, G.R., M.P., K.G., M.F. and M.B.; writing—review and editing, G.R., M.P., K.G., M.F. and M.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board (IRB) as well as the Board for Ethical Issues (BfEI) of the University of Innsbruck (Certificate of good standing 29/2016).

Informed Consent Statement: Written informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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