Risk Factors for Anterior Cruciate Ligament Injury in Competitive Adolescent Alpine Skiers

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Background: There is a high risk for anterior cruciate ligament (ACL) injuries in alpine skiers. To reduce or try to prevent these injuries, intrinsic and extrinsic risk factors need to be identified.

Purpose: To identify possible intrinsic and extrinsic ACL injury risk factors among competitive adolescent alpine skiers.

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

Methods: Between 2006 and 2009, a cohort of 339 alpine ski students (176 male, 163 female) from Swedish ski high schools were prospectively observed in terms of ACL injuries. First-time ACL injuries were recorded. In September, prior to each ski season, the skiers were clinically examined according to a specific knee protocol.

Results: Overall, 11 male and 14 female skiers sustained a total of 25 first-episode ACL injuries. The majority of injuries occurred in the left knee ($P < .05$). Skiers who had participated in alpine skiing for >13 years (hazard ratio, 0.83; 95% CI, 0.68-1.00; $P < .05$) had a reduced risk of sustaining an ACL injury. Eighteen ACL injuries occurred during training, 12 in the technical discipline of giant slalom, and 8 in slalom. Fourteen skiers reported not to be fatigued at all at the time of injury, and 8 skiers reported that they were somewhat fatigued.

Conclusion: ACL injuries occurred more often in the left knee than the right. This should be taken into consideration in the design of ACL injury prevention programs. Those who reported a higher number of active years in alpine skiing showed a reduced risk of sustaining an ACL injury. No other factor among those studied could be identified as an independent risk factor for ACL injury.

Keywords: alpine skiing; downhill skiing; functional tests

Alpine skiing is one of the most popular winter sports worldwide.[21] The skiing population represents a range of ages and skill levels, from beginners to advanced ski racers. To participate at the highest level of competition, the skier needs a license from the International Ski Federation (FIS). In Sweden, about 700 skiers hold an FIS license, and nearly all Swedish skiers between 16 and 20 years who are trying to reach the national team have studied at a Swedish ski high school. Almost 50% of the skiers attending a Swedish ski high school sustain at least 1 injury during their years of studying at the school, and the knee joint is the most commonly injured body part irrespective of sex.[40] From the FIS Injury Surveillance System, there have been 3 studies reporting an anterior cruciate ligament (ACL) injury to be the most common diagnosis.[6,13,15] In a 25-year follow-up study on elite French alpine skiers, Pujol et al[33] found one-third of the skiers to be absent from skiing at least 1 period owing to an ACL injury. Haaland et al[15] reported that the ACL injury rate in FIS World Cup alpine skiing did not change between 2006 and 2015. Moreover, an ACL injury may seriously influence a young alpine skier's career, not only in terms of pain and a long, strenuous rehabilitation, but also with regard to absence from competition during at least 1 season.

ACL injuries have been reported to have far-reaching consequences, with cartilage damage and knee arthrosis

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being the most serious.[30] Therefore, prevention of these knee injuries is important. The concept "sequence of prevention" by van Mechelen et al[39] has for many years served as a model for developing injury prevention programs. The prevention programs should be based on injury mechanisms as well as intrinsic and extrinsic injury risk factors for the specific sport. Several intrinsic and extrinsic risk factors have been suggested for ACL injuries.[35,36] However, to our knowledge, only a few are sport specific for competitive alpine skiers. On the basis of an interview of expert stakeholders of the World Cup ski racing community, Spörri et al[37] found superior fitness level to be an important factor for injury prevention. Furthermore, Raschner et al[34] reported insufficient core strength to be a critical risk factor for sustaining an ACL injury in competitive adolescent ski racers. Moreover, a previous study by our group found an almost twofold risk of sustaining an ACL injury if 1 of the parents had had an ACL injury.[41]

Despite these suggested ACL injury risk factors, only a few studies have been carried out to evaluate ACL injury risk factors in competitive alpine skiing. Therefore, the objective of this investigation was to study potential intrinsic and extrinsic risk factors for ACL injuries in competitive adolescent alpine skiers between 16 and 20 years of age.

METHODS

Participants

All alpine ski students at Swedish ski high schools between September 2006 and May 2010 were invited to participate in the study. During this period, a total of 384 skiers (191 male and 193 female) attended 10 ski high schools. Skiers at a ski high school study for 3 or 4 years and are exposed to skiing for approximately 200 days per season. Seventeen skiers were excluded from the study because they had not completed a full year studying at the school, and 28 skiers (4 male, 24 female) were excluded because they had suffered a previous ACL injury. Consequently, the present study was based on 339 skiers (176 male, 163 female) without an earlier ACL injury.

Before entering the study, the skiers received verbal and written information about the study, and informed consent was collected. The skiers answered a questionnaire, including age, number of years in alpine skiing, importance of skiing, an ongoing injury, or possible previous injuries. Prior to each ski season, the skiers were examined clinically according to a specific knee protocol. Thereafter, the skiers were prospectively followed during the actual year, and each first-time ACL injury that occurred during skiing was recorded.

Clinical Examination

The clinical examination included anthropometric data, 5 muscle flexibility tests, and three 1-legged hop tests for functional evaluation. An experienced sports physical therapist (M.W.) performed all manual tests within the clinical examination, and 2 experienced therapists (M.A., S.W.) supervised the functional performance tests. The intraclass correlation coefficient values of the intrarater reliability of the clinical examiner were as follows: general joint laxity[4] (1.0), knee/foot alignment[28] (1.0), anterior knee laxity[9] (0.93), valgus-varus stress test of the knee[20] (1.0), leg length discrepancy[3] (0.98), ankle dorsiflexion with knee extended[10] (0.83), ankle dorsiflexion with knee flexed[10] (0.73), flexibility of the hip flexors[10] (0.81), flexibility of the hip extensors[10] (0.92), and flexibility of the knee extensors[1] (0.86).

Anthropometric Data. Anthropometric data included control of knee and foot alignment,[28] valgus-varus stress test of the knee,[20] anterior knee laxity (KT-1000; MEDmetric Corp),[9] general joint laxity (Beighton score),[4] and leg length discrepancy.[3]

Muscle Flexibility Tests. Flexibility of the hip extensors was performed as a modified flexion test according to Ekstrand et al[10] to measure the length of the hamstring muscles. The skiers were measured in the supine position with a flexometer (Myrin; Follo A/S) applied at the base of the patella. The pelvis and the contralateral leg were manually fixed. The skier's test leg was passively raised with the knee kept in extension until a maximal hip flexion was reached. The result was given in degrees.

Flexibility of the hip flexors[11] was measured with a flexometer applied at the base of the patella. The skier was lying in the supine position, and the test leg was hanging outside the bench. The contralateral lower extremity was manually fixed in maximal hip and knee flexion. The skier was instructed to keep the test leg relaxed. At this position, the degree of hip extension was recorded. The result was given in degrees.

Flexibility of the knee extensors was performed according to Alricsson and Werner.[1] The skier was measured in the prone position lying on a bench with the knee of the contralateral leg slightly flexed and the foot supported on the floor. The pelvis was manually fixed to the bench. Maximal passive knee flexion was performed. The distance between the calcaneus and the buttock was measured with a ruler in centimeters.

Ankle dorsiflexion was measured with a goniometer.[10] The measurements were performed with the knee joint in extension and flexion. The skier was standing with 1 leg in front of the other. With the rear leg in full knee extension and the heel maintained against the floor during loading of the flexed front leg, ankle dorsiflexion of the rear leg was measured in degrees.

For each muscle flexibility test, 1 trial of each leg was performed. To determine whether an asymmetry between the left and right legs was present, the side-to-side difference was calculated for each test. The cutoff level was 5° for ankle dorsiflexion with extended and flexed knee as well as for hip extension with flexed knee. The cutoff was 10° for hip flexion with extended knee and 5 cm for knee flexion with extended hip.

Functional Performance Hop Tests. The following functional performance hop tests were carried out: 1-legged hop test for distance, square hop test, and side hop test. All hop tests have been described and tested for reliability in healthy athletes and in patients with ACL deficiency.[23,32,38]

The tests were selected to evaluate different physical demands and to be easy to administer in the field. The square hop test and the side hop test were video recorded and analyzed by the main test leader.

In all functional performance hop tests, the skiers kept their hands behind their back. One trial each was carried out for the square hop test and the side hop test and 3 trials for the 1-legged hop test for distance. The skiers were allowed to perform a few trials of the hop tests prior to testing.

For each functional performance hop test, the side-to-side difference between the left and right legs was calculated to decide whether an asymmetry was present. In the 1-legged hop test for distance, the cutoff was <10 cm, and in the square hop test and side hop test, the cutoff was 5 jumps.

ACL Injury Registration: Extrinsic Risk Factors

After the diagnosis had been verified by experienced orthopaedic surgeons as well as by magnetic resonance imaging, the skiers reported their injuries to the lead author (M.W.). Only complete ACL ruptures were included. To ensure that all ACL injuries were reported, the lead author maintained monthly contact, through mail and telephone, with the coaches at the different ski high schools. Each ACL injury was recorded with a questionnaire that included variables such as date of injury, ski discipline, weather condition, visibility, slope condition (icy, wet snow, loose snow, or aggressive snow), and temperature in Celsius. Furthermore, the survey included a question about physiologic fatigue at the time of injury and history of injuries.

Statistics

Descriptive statistics are presented as mean and SD, median and range, and frequency and percentage. Differences in continuous variables between the study groups were analyzed with a Student *t* test. For categorical variables, the χ^2 test was used. Time of exposure was calculated as the total number of months attending a ski high school, and the injury rates were reported as the total number of ACL injuries per 100 months attending a ski high school. To investigate intrinsic risk factors, the values of the latest clinical examination before the first-time ACL injury were used, and for the uninjured skiers, the values of the latest clinical examination during their participation in the project were used. A Cox proportional hazard regression model was used to identify intrinsic risk factors for ACL injuries. The time to the first injury was considered important because of the risk that clinical tests may change after injury. Univariate analyses were performed, with each variable entered separately into the Cox regression model. Variables with a *P* value ≤.05 in the Cox model were illustrated with Kaplan-Meier curves. The results were reported as hazard ratios with 95% CIs. All *P* values were 2-tailed, with $P \le .05$ considered statistically significant. Data were analyzed with Statistica (v 12; StatSoft Inc).

TABLE 1
Demographic and Anthropometric Data of the Alpine Skiers at Baseline Start of the Study[a]

	Skiers		
Variable	ACL Injury (n = 25)	No ACL Injury (n = 314)	*P* Value
Sex, male: female	11: 14	165: 149	.41
Age, y	17.6 ± 1.1	17.7 ± 1.2	.26
Body mass index, kg/m^2	23.3 ± 2.0	23.2 ± 2.0	.96
Skiing experience, y			
Alpine	11.0 ± 1.7	11.4 ± 2.1	**.05**
Competitive	8.8 ± 2.0	8.5 ± 2.4	.90
Lower extremity injury	11 (44)	132 (42)	.85
Generalized joint laxity ≥5 points	4 (16)	34 (11)	.38
Knee alignment, varus:valgus			
Left	0: 4 (16)	13 (4): 19 (6)	.10
Right	0: 4 (16)	12 (4): 25 (8)	.25
Foot alignment, pes cavus:pes planus			
Left	0: 5 (20)	13 (4): 50 (16)	.53
Right	1 (4): 4 (16)	16 (5): 42 (14)	
Leg-length discrepancy ≥2 cm (yes)	1 (4)	7 (2)	.53
Valgus stress test: 30° of knee flexion[b]			
Left	2 (8)	47 (14)	.34
Right	1 (4)	47 (14)	.13
Anterior knee laxity: side difference ≥3 mm[b]	3 (12)	42 (13)	.85

[a]Values are presented as mean ± SD or n (%). Group differences were analyzed with χ^2 test and the Student *t* test. Bolded text indicates statistically significant between-group difference. ACL, anterior cruciate ligament.
[b]Positive results shown.

RESULTS

Over the 4-season study period, a total of 25 first-time ACL injuries (11 male, 14 female) occurred, with a prevalence of 9.8% and an incidence rate of 0.5 first-time ACL injuries per 100 months attending a ski high school.

Clinical Examination

Sixteen ACL injuries (64%) occurred in the left knee and 9 (36%) in the right knee ($P < .05$). There were no significant differences between skiers who sustained a first-time ACL injury and skiers who did not with respect to sex, age, body mass index, skiing experience, or previous injuries (Table 1). A significantly higher percentage of skiers who sustained an ACL injury had an unequal side-to-side performance on the 1-legged hop test for distance ($P = .05$) (Table 2). The Cox regression analysis showed that skiers who had practiced alpine skiing for >13 years had a reduced probability of sustaining an ACL injury ($P < .05$).

TABLE 2
Results of the Muscle Flexibility Tests and Functional Performance Hop Tests[a]

Variable	Skiers: ACL Injury (n = 25)	Skiers: No ACL Injury (n = 314)	*P* Value
Flexibility of the hip extensors, deg			
Left leg	105 (75 to 130)	102 (70 to 138)	.84
Right leg	104 (80 to 130)	102 (62 to 140)	.95
>10° side difference	2 (8)	30 (10)	.26
Flexibility of the hip flexors, deg			
Left leg	–8 (–22 to 10)	–7 (–25 to 14)	.82
Right leg	–6 (–20 to 8)	–5 (–28 to 20)	.27
>5° side difference	5 (20)	107 (34)	.15
Flexibility of the knee extensors, cm			
Left leg	0 (0 to 10)	0 (0 to 23)	NA
Right leg	0 (0 to 13)	0 (0 to 25)	
>5-cm side difference	0	21 (7)	.18
Ankle dorsiflexion with extended knee, deg			
Left foot	39 (30 to 53)	39 (23 to 54)	.98
Right foot	40 (32 to 51)	40 (23 to 58)	.28
>5° side difference	2 (8)	32 (10)	.71
Ankle dorsiflexion with flexed knee, deg			
Left foot	45 (36 to 56)	46 (29 to 62)	.16
Right foot	45 (36 to 57)	46 (25 to 62)	.45
>5° side difference	1 (4)	26 (8)	.44
One-legged hop test for distance, cm			
Left leg	158 (119 to 198)	157 (104 to 235)	.35
Right leg	150 (105 to 191)	156 (102 to 227)	.08
Unequal side performance (≥10 cm)	9 (36)	72 (23)	**.05**
Square hop test, correct jumps			
Left leg	76 (63 to 90)	74 (52 to 108)	.88
Right leg	76 (56 to 86)	75 (50 to 104)	.96
Unequal side performance (>5)	15 (60)	136 (43)	.27
Side hop test, correct jumps[b]			
Left leg	66 (49 to 73)	61 (31 to 81)	.26
Right leg	63 (51 to 74)	62 (33 to 82)	.69
Unequal side performance (>5)	10 (63)	132 (50)	.59

[a]Values are presented as median (range) or n (%). Group differences were analyzed with χ^2 test for categorical variables and the Student *t* test for continues variables. Bolded text indicates statistically significant between-group difference. ACL, anterior cruciate ligament; NA, not applicable.

[b]Skiers with (n = 16) and without (n = 265) an ACL injury (clinical examination was added in second year of the study).

ACL Injury Registration: Extrinsic Risk Factors

Of the 25 ACL injuries, 18 (72%) occurred during training. Twelve ACL injuries (48%) occurred in giant slalom, 8 (32%) in slalom, and 4 (16%) in speed disciplines (super G and downhill). One ACL injury occurred on the prepared slope but outside the course. Twenty-three ACL injuries occurred on prepared slopes and 2 on unprepared slopes.

Snow conditions at the time of injury was aggressive (mix of artificial and dry cold snow) for 10 skiers, icy for 7 skiers, loose for 5 skiers, and wet when 2 skiers tore their ACL; data was unavailable for 1 injury occasion. Furthermore, 14 skiers sustained their ACL injury in sunny weather and 7 when it was cloudy. The temperature was between –10°C and 0°C in 18 of the 25 injuries.

Sixteen skiers (64%) reported the visibility to be good and 7 that the visibility was moderately good. Fourteen skiers reported that they were not fatigued, 8 were somewhat fatigued, and 1 was fatigued at the time of injury. Data regarding visibility and fatigue were unavailable for 2 injury occasions. Most ACL injuries (n = 7) occurred during December. There were 5 in March; 3 each in November, February, and April; 2 in October; and 1 each in September and January.

DISCUSSION

The present prospective cohort study of adolescent alpine skiers showed an incidence rate of 0.5 ACL injuries per 100 months attending a ski high school and a prevalence of 9.8%, which is lower than the 15% reported earlier by Raschner et al.[34] In our experience, the number of ACL injuries varied during the different studied seasons. Therefore, one explanation for these differences could be that

Raschner et al[34] had observed their skiers for a longer period: 10 years versus our 4 years.

For two-thirds of alpine skiers sustaining a first-time ACL injury, the left knee was the side of injury. One potential reason is that alpine skiing is an equilateral sport characterized by the same physical demands on each leg. In the present study, a higher number of skiers with ACL injury, as compared with those without an ACL injury, presented with side-to-side differences in all 3 functional hop tests. Although the worse performance was not necessarily of the ACL-injured side, a side-to-side difference during the functional hop tests may play a significant role as a possible injury risk factor.

The 1-legged hop test for distance suggests a measure of explosive muscle strength/power, which was reported to be a typical factor of demands in alpine skiing.[22] A side-to-side difference of 10 cm was indicated as a predictor for ACL injury. In view of earlier published normative data, the choice of a cutoff value of 10 cm regarding the side-to-side difference is not too small for determining a significant side difference.[17,29]

Neither a side-to-side difference of the side hop test alone nor the square hop test alone turned out to be a predictor of ACL injury. Both these tests require a complex movement pattern represented by endurance muscle strength as well as neuromuscular/postural control.[23,32] In these 2 hop tests, the number of correct jumps is counted irrespective of the performance quality. According to Hewett et al,[19] the knee angle at landing after a jump is important, as increased hip adduction and knee valgus were identified as ACL injury risk factors. The results of the present investigation indicate that skiers with prominent knee valgus alignment were somewhat more prone to injury than those with a normal knee alignment. Thus, in analyzing hop test performance with respect to alignment and side-to-side difference, valuable information may be found leading to possibilities for predicting injury risk.

The 3 hop tests evaluated in this study indicated a side-to-side difference as a predictor for ACL injury. Hewett et al[18] highlighted the importance of taking into account the side-to-side leg difference in terms of impaired neuromuscular control and reduction of muscle strength and muscle flexibility. These aspects most probably play an important role when it comes to alpine skiing, an equilateral sport that makes same physical demands on both legs. Decreased[7] as well as increased[42] muscle flexibility has been discussed as a possible injury risk factor. However, to our knowledge, no "normal" values in terms of muscle flexibility have been published. Furthermore, skiers with a high number of active years in alpine skiing (>13 years) showed a lower risk of sustaining an ACL injury than did those with less skiing experience. Since we included only students without a previous ACL injury, it might be that students with the same number of active years in alpine skiing were not included owing to an ACL injury. Staying out of injury for >13 active years, possibly passing the period of growth spurt, may decrease the risk of sustaining an ACL injury. However, this has to be further investigated in future studies. In contrast to earlier studies on ACL injury risk factors,[16,27] previous injuries to the lower extremity were not found to be ACL injury risk factors in the present investigation. Again, since students with an ACL injury prior to the start of the present study were excluded, only other previous injuries to the lower extremities were included in the calculations and thus might be an explanation to the findings.

The literature is inconsistent when it comes to sex differences regarding the incidence of ACL injury in competitive alpine skiers. In the present cohort, we did not find any sex-based differences between skiers with and without ACL injury. This finding corresponds well with those published by Pujol et al[33] and Bere et al[6] for adult alpine skiers. However, in contrast with our findings, Raschner et al[34] reported a twofold-increased risk of sustaining an ACL injury in female versus male adolescent ski racers. A reason for these study variations might depend on differences in the populations studied.

This investigation was conducted over a period of 4 ski seasons to evaluate a number of potential ACL injury risk factors, both intrinsic and extrinsic. However, no intrinsic risk factor was identified as an independent risk factor for ACL injuries. In the literature, only a few studies have evaluated extrinsic risk factors in competitive alpine skiing. Spörri et al[37] and Bere et al[5] reported that icy conditions are safer than aggressive snow conditions. In the present study, most injuries occurred on aggressive snow. However, given that we did not have any data on the percentage of days with different types of snow, it cannot be concluded that icy conditions are safer than other snow qualities. In the present study, the majority of the ACL injuries occurred during training. This may be because of the time of exposure, which is considerably higher during training than during competition, meaning a longer time for being at a possible injury risk. However, the risk per time unit, not calculated in the present study, may be higher during competition. The majority of the ACL injuries in the present study occurred in the technical disciplines of giant slalom and slalom. This is in accordance with the findings of Gilgien et al[14] but in contrast to earlier studies of World Cup skiers,[6,13] where downhill racing accounted for the highest number of injuries.

To the best of our knowledge, this is the first study among competitive adolescent alpine skiers to include a comprehensive clinical knee examination protocol. It is also the first cohort study conducted prospectively over 4 ski seasons, including anthropometric data, functional performance tests, and a questionnaire to identify intrinsic and extrinsic ACL injury risk factors.

Despite the large prospective cohort design, there are limitations to take into account with interpretation of the results. The clinical and functional performance tests were not carried out in a laboratory environment, owing to the widely spread geographic locations of the Swedish ski high schools. To be able to include all Swedish ski high schools, the tests were performed at each school. The reliability of the tests in the clinical knee examination protocol used has been published previously, and to minimize possible measurement errors, the present study had 1 examiner with a good to excellent intratest reliability for the manual clinical tests. More advanced evaluation instruments, such as isokinetic muscle testing, may have been preferable to identify skiers at a high risk of ACL injuries. Jordan et al[24,25] evaluated lower limb asymmetry and rapid hamstring/quadriceps strength, comparing alpine ski racers with and without ACL injuries. They found a greater asymmetry index among the skiers with ACL injury despite full return to alpine skiing.

Other limitations in the present study concern the extrinsic factors and the lack of complete data of snow conditions and time spent in training versus competition during the studied ski seasons. Only the snow conditions at the time of injury were registered; therefore, these results are of limited value. In future studies, it would be interesting to capture data from all occasions and calculate absolute risk.

The complex interaction among different types of variables makes the study design of injury risk factors somewhat complicated. In the area of sports medicine, Finch[11] and Bahr and Holme[2] recommended prospective cohort studies with multivariate statistical approaches to detect injury risk factors. Twenty to 50 injury cases are suggested for a moderate to strong association, and the choice of the participants should be representative for the actual sport. Dallinga et al,[8] however, recommended a prospective design with different age groups, which is similar to the present investigation, including almost all Swedish competitive alpine skiers in the age group of 16 to 20 years.

In the future, it would be interesting to analyze the effect of the skier's equipment. For example, it has been shown that adjustment of ski bindings is highly inadequate in competitive alpine skiers.[31,37] Moreover, Hewett et al[18] and Finch et al[12] have suggested studying male and female alpine skiers separately. Physical performance and muscle flexibility often vary between male and female athletes[18,26]; therefore, an analysis between sexes might have shown different ACL injury risk factors. However, in spite of the large sample size of the present investigation, the occurrence of only 25 ACL injuries did not allow a separate analysis with respect to sex.

CONCLUSION

In this study, most ACL injuries occurred in the left knee of competitive adolescent alpine skiers. None of the potential ACL injury risk factors were identified as independent ACL injury risk factors. A side-to-side difference was found in functional performance, as measured with the 1-legged hop test for distance, the side hop test, and the square hop test, for those skiers who sustained an ACL injury. Having many years of alpine skiing experience (>13 years) led to a reduced risk of sustaining an ACL injury.

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