The relationship between ACL injuries and physical fitness in young competitive ski racers: a 10-year longitudinal study

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ABSTRACT

Background Epidemiological studies have shown a high incidence of anterior cruciate ligament (ACL) injuries among competitive alpine skiers. Little is known regarding modifiable risk factors in young skiers. There are still uncertainties in gender-related risk factors.

Objective The purpose of this study was to determine the relationship between ACL injuries and internal risk factors.

Methods Retrospective data analyses were performed based on a group of 175 female and 195 male alpine ski racers between the ages of 14 and 19 years. The athletes underwent physical testing annually from 1996 to 2006. Z score transformations normalised the age groups. Multivariate binary logistic regressions were calculated for men and women separately to detect significant predictors of ACL ruptures. t Tests were computed to reveal the differences in test scores between injured and non-injured athletes.

Results A total of 57 (15%) ACL injuries occurred. The female–male risk ratio (RR) was higher in females (2.3, 95% CI 1.3 to 4.2). Z scores for relative leg force, ratio of absolute core flexion to extension force, relative core strength and reactive strength index were predictive variables for men. Z scores of all of these predictive variables except relative leg force were higher in the non-injured group. The ratios of absolute flexion to extension force and absolute core strength were predictive covariates for women. Z scores for absolute core strength were higher in the non-injured group.

Conclusions The risk of ACL injury was greater in female athletes. The findings suggest that core strength is a predominant critical factor for ACL injuries in young ski racers.

INTRODUCTION

Alpine skiing is considered to be the world's riskiest and fastest non-motorised sport.[1] Because it represents the most popular competitive winter sport in Austria, the high numbers of young participants raise safety concerns. Youth athletes have to compete in technical and speed disciplines. Sufficient physical requirements of these all-round skiers are responsible for their success and to ensure safe skiing. In addition to the physiological parameters, changes in skiing equipment place a high demand on young athletes. More aggressive turns due to artificial snow and challenging jumps result in a higher load on the knees.[2] Epidemiological studies have shown a high incidence of serious knee injuries among alpine skiers. The most common serious injury is the rupture of the anterior cruciate ligament (ACL).[3–5] Recently, during the XXI Winter Olympic Games in Vancouver, sports injuries were recorded.[6] Analyses revealed that, among other sports, alpine skiing must be regarded as a high-risk Olympic sport, with the knee being the most frequently injured body part. In youth sports, knee injuries account for a high portion of medical treatment costs and increase the risk of an early onset of degenerative joint diseases.[7] From the perspective of youth sports, identifying the factors associated with injuries is one of the initial steps in the process of injury prevention. Steffen and Engebretsen[8] stated in their review that a systematic injury surveillance of highly competitive young athletes is crucial to build the basis for injury prevention. To date, the majority of previous studies on skiing injuries have analysed risk factors in adult athletes and in non-organised, non-competitive skiing.[9 10] Injuries often result from a complex interaction of multiple factors. One approach to injury prevention is to conceptualise the risk factors in those who are modifiable and those who are not.[11 12] Especially in young athletes, the determination of modifiable risk factors is of great interest in terms of developing long-term intervention programmes and therefore providing better possibilities for a successful ski racing career.[13] However, most studies are descriptive in nature, and to date, little is known about the modifiable risk factors in alpine skiing. There is a consensus that female athletes are more prone to sustaining an ACL injury than their male counterparts in pivoting sports,[14] but the gender-related risk factors in alpine skiing are still unknown.[3 5 15 16] Based on retrospective analyses of registered data, we hypothesised that there is an association between the physical fitness and the occurrence of ACL injuries among competitive junior alpine skiers. Risk ratios (RRs) were determined to compare male and female athletes.

METHODS

Subjects

In all, 175 female and 195 male adolescent ski racers between 14 and 19 years of age were included in the study. Table 1 details gender distribution within the age groups. The subjects in this study were athletes of the Skigymnasium Stams. Founded in 1967, the Skigymnasium is a boarding school designed to develop high-performance athletes. It frequently serves as a role model when founding similar institutions both nationally and

Table 1 Age distribution of the subjects (n)

Age group	Males	Females	Male/female ratio
14	97	75	1.3
15	126	108	1.2
16	115	108	1.1
17	100	76	1.3
18	81	63	1.3
19	44	24	1.8

internationally. Fourteen-year-old ski racers are accepted into the programme through a selection process that comprises different sport-specific motor skills tests and a sports medicine examination. The racing performance of each athlete is evaluated by coaches and administrators after the first two seasons. If performance does not meet expectations, athletes are withdrawn from the Skigymnasium. Junior world championships results confirm that many ski racers in this study belonged to the best junior racers in the world. The International Ski Federation (FIS) ranks ski racers with a system in which the best racers have the lowest FIS points. The female racers in this study had a mean of 37.2±19.7 FIS points in their best discipline and the males averaged 50.6±23.4 FIS points in their best event. A high percentage of the racers in the Austrian Ski Federation are pupils or alumni of Stams.

A physician medically screened each athlete annually to ensure that there were no contraindications to their participation in ski racing or testing. The Tyrolean Sport Science Support Program, a provincial government initiative that provides scientific support for sports science and medical projects in elite sport, gave prior approval for the testing each year. A committee of medical doctors and sports scientists reviewed and evaluated the research proposals with a focus on ethics, quality of research and benefit to athletes. The athletes, parents and coaches were informed of any risks associated with participation in the tests, and written informed consent was obtained before testing began. The study was performed according to the declaration of Helsinki.

Procedures and injury identification

From 1996 to 2006, ski racers of the Skigymnasium have been tested three times annually with the same battery of tests. The testing started at the beginning of the preparation phase (May), with two follow-up tests in September and November, at the end of the preseason.

All ACL injuries in this study occurred during the ski training and racing season (between December and March). In the case of an ACL injury test results of November testing prior to injury were included except for the aerobic endurance test. This is due to the fact that in the fall strength and power training took priority, 'classic' endurance training was no longer carried out and therefore test results from aerobic endurance test were taken from September testing.

For each non-injured athlete, the best test result from the three testing sessions was used. These best results were understandably in November at the end of the preparation phase with the exception of the aerobic endurance test which was taken from September tests. Although each athlete underwent testing more than once throughout the 10-year period, only one set of test results per athlete was used in the non-injured group based on a random selection. Athletes who were injured were excluded as non-injured athletes. Additionally, they were not included as injured athletes in the years after when they tore their ACL twice. This means that every athlete (injured and non-injured) contributed only one set of fitness data to the study. All of those fitness data from the 14-year-old to 19-year-old athletes were then adjusted to age-related performance.

Athletes start at the age of 14 in the Skigymnasium Stams. Every injured athlete was compared to an age-matched group, therefore exposure matched non-injured athletes. Additionally, checking of exposure of male and female athletes in the same age groups indicated that there were only small differences in training time and the number of competitions throughout a year because pupils board at the school and train together.

Information of confirmed ACL injuries was obtained from health professionals. Because the athletes required medical permission for authorised absences from the training, the Skigymnasium Stams documented all occurrences of injuries.

Anthropometric measurements and physical tests

Body height was measured using a portable stadiometer (Seca 220, Seca, Germany) and body mass was recorded using the Kistler force plate (Kistler Instrumente AG, Winterthur, Switzerland). The body mass index (BMI) was calculated by dividing the body mass by the square of the height. Physical fitness was evaluated using nine laboratory tests (tables 2 and 3). A general warm-up supervised by the coaches was conducted prior to the testing.

Statistical analysis

To compare the injury rate between male and female athletes, RRs with their 95% CIs were calculated. Descriptive statistics were calculated and expressed as the means and SDs for each variable and age group. Z score transformations were calculated for all variables to normalise data of different age groups. Z scores of injured and non-injured athletes were applied to further calculations.

Multivariate binary logistic regression was used to analyse the relationship between the results in the different tests and the occurrence of ACL injuries. To avoid the effects of multicollinearity of the predictors in the binary logistic regression models, a factor analysis (principle component analyses, Kaiser criterion, varimax rotation) was administered to reduce the number of covariates. For male and female athletes factor analysis induced eight factors. The variable with the highest factor load was used to represent each factor. Variables with a p value <0.05 were chosen for inclusion in the multivariate model. Significance, OR in the adjusted model for each predictor and CIs were designated. t Tests were additionally administered for the significant predictors of the logistic regression to check group differences between injured and non-injured athletes according to their gender. A criterion of $p \leq 0.05$ defined significance. All statistical analyses were performed using SPSS V.17.0 software (SPSS Inc, Chicago, Illinois, USA).

RESULTS

Incidence of ACL ruptures

Over the 10-year period analysed in this study, a total of 57 (15%) ACL injuries occurred during skiing, either during training or competition. Of these ACL injuries, 39 (22%) were in female racers and 18 (9%) in males. The overall female–male RR was higher in females compared with males (2.3, 95% CI 1.3 to 4.2). The highest female ACL injury rate was in the 19-year-old racers, followed by the 17-year-olds. In males, the

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Table 2 Physical fitness tests

Test	Purpose	Procedure
Cooper test (CT)	Aerobic power, indirect estimation of VO_2max	The test was performed as described by McArdle *et al.*[17] Internal reliability analysis identified an intraclass correlation (ICC) of 0.93 for female and 0.94 for male athletes
Jump coordination test (JCT)	Agility and quickness	The athletes performed two-footed jumps throughout the course with the goal of completing 26 jumps as quickly as possible. The course was designed so that the athlete jumped forwards, backwards and sideways during the test with hurdles of varied heights (15–36 cm). The athlete was instructed to face forward with his/her hips and shoulders perpendicular to the forward direction. Internal studies identified an ICC of 0.89 for female and 0.91 for male young ski racers
Unilateral leg press strength test (ULST)	Maximal isometric leg extension strength in a closed kinetic chain	The athletes performed three one-leg isometric leg extensions. The greater trochanter, lateral intercondylar notch and lateral malleolus were used as landmarks to ensure that a knee angle of 100° was reached (180°=fully extended knee). The calculated strength parameters were the mean absolute leg force (ABS ULST) and the mean relative leg force (REL ULST). The reliability for isometric testing is very high.[18] An internal analysis identified an ICC of 0.95 (female) and 0.96 (male)
Counter movement jump (CMJ)	Explosive leg power	Jumps were performed on a Kistler platform. The subject started the movement standing erect and then quickly bent at the hip, knees and ankles before starting the upward motion of the jump. Both hands were held on the hip. The highest jump height was calculated by the impulse-momentum method.[19] The test–retest reliability of the CMJ on a force plate is high,[20] in young ski racers. Analyses identified an ICC of 0.96 and 0.97 for females and males, respectively
Drop jump (DJ)	Reactive leg power from a 40 cm high podium	The subjects were instructed to drop from the podium with a posture as upright as possible, and to jump as high as possible with minimal ground contact time. The subjects were allowed to use their arms to generate momentum when jumping. The reactive strength index (RSI) was calculated by dividing the jump height (mm) of the first jump by the ground contact time (ms).[21] Reliability analysis identified an ICC of 0.97 for female and 0.92 for male athletes
Specific counter movement jump (SCMJ)	Explosive leg power	Three trials were performed with ski-jumping boots (Rass, Schönheide, Germany) to restrict the ankle joint. The subject squatted down until a 110° knee angle was reached. The subject was allowed to eccentrically preload further, but was not allowed to raise the body before the preload. Hands were kept clasped behind the back. The test–retest reliability of SCMJ was similar to that of the CMJ; namely, ICCs of 0.95 and 0.96 were identified for females and males, respectively
Core strength test (CST)	Maximal isometric core strength	The self-developed test device comprises a tension belt connected to a force transducer. To measure trunk flexion strength, the subjects lie in a supine position with their knees flexed at 90°, feet flat and pelvis fixated by a padded belt. The chest belt was set above the sternum level and the hip belt was placed below the anterior iliac spine. To measure trunk extension, the subjects laid in the prone position with the tension belt placed under the axillary fossa and the hip belt over the buttocks. Isometric contraction was held for 3 s. Subjects performed three trials, and the highest force was recorded. The measured parameters were the absolute flexion and extension forces (ABS FF, ABS EF, sum of both). Relative flexion and extension forces (REL FF, REL EF, sum of both) and ratio of the absolute flexion to extension force (FLE:EXT R) were calculated. Reliability analysis identified ICCs between 0.94 and 0.98
Strength endurance test (SET)	Jump strength endurance	This test was performed similarly to the test described by Brown and Wilkinson.[22] The athletes jumped with both feet laterally onto a box (width 30 cm, length 100 cm), then to the other side, alternating back and forth for 90 s. The height of the box was adjusted to the apex of each athlete's patella. The number of jumps was recorded. Reliability analysis identified an ICC of 0.869 for female and 0.897 for male athletes
Line run test (LRT)	Anaerobic endurance	The athlete started at the first medicine ball, with one hand on the ball, and moved with side steps as quickly as possible to the second, third and fourth ball, finally touching the fourth ball until 32 contacts were completed. The line run test index (LRTI), that is, the running time divided by the number of ball contacts, was calculated. Reliability analysis identified an ICC of 0.92 for female and 0.92 for male athletes

most injuries occurred in the 17-year-old group. Figure 1 shows the injury rates in each age group according to gender.

Males: predictive risk factors for ACL injuries

The factor analysis proposed eight factors (core strength, leg strength, anaerobic performance, anthropometrics, reactive strength, flexion/extension ratio, jump power, leg strength side—dysbalance) with 89.3% of explained variance.

With this model all non-injured cases were predicted correctly, however, in the injured group, only 30% of the males were correctly classified. The multivariate logistic model explained 36.8% of the variability in male athletes (Nagelkerkes $R^2=0.368$). REL ULST (OR 2.32, 95% CI 1.00 to 5.34, p=0.049), FLE:EXT R (OR 0.24, 95% CI 0.10 to 0.57, p=0.001), REL FF and REL EF (OR 0.45, 95% CI 0.21 to 0.95, p=0.035) and RSI (OR 0.33, 95% CI 0.13 to 6.21, p=0.017) were predictive variables for male athletes. It has to be taken into account that ORs were calculated for an increase of 1 z value. Based on a t test comparison, the following Z scores were significantly higher between males who sustained no injury and those who injured their ACL: FLE:EXT R (p=0.007), REL FF and REL EF (p=0.013) and RSI (p=0.016). Table 4 presents the fitness data of all covariates which were significantly different between injured and non-injured male athletes.

Females: predictive risk factors for ACL injuries

Similar to the male athletes, the factor analysis identified eight factors (core strength, leg strength, anaerobic performance, anthropometrics, reactive strength, flexion/extension ratio, jump power, leg strength side—dysbalance) with 89.9% of explained variance. In the multivariate logistic regression model nearly all of the non-injured cases (95%) were predicted correctly; however, in the injured group, only 27% of the females were correctly classified. The regression model explained 23.6% of the variability for female skiers (Nagelkerkes $R^2=0.236$). In females, FLE:EXT R (OR 0.54, 95% CI 0.31 to 0.94, p=0.028) and ABS FF and ABS EF (OR 0.26, 95% CI 0.13 to 0.51, $p<0.001$) were predictive covariates.

t Test comparisons revealed that only ABS FF and ABS EF were significant. The Z scores of this variable were higher in the non-injured group than in the injured group (p=0.009). Table 5 presents the measured fitness data of ABS FF and ABS EF for injured and non-injured female athletes. For non significant fitness data for the athletes see supplementary data (tables 6 and 7).

DISCUSSION

This 10-year retrospective study of young alpine skiers included a broad range of fitness parameters obtained through physical screening sessions. The current study provides evidence that

Table 3 Analysed parameters of the nine physical fitness tests

Abbreviation	Test	Parameters	Category
JCT	Jump coordination test	Jump time in s	Coordination
ULST	Unilateral leg press strength test	Absolute leg force (ABS ULST) in N Relative leg force (REL ULST) in N/kg Ratio of absolute left to right leg force (L:R R)	Strength
CST	Core strength test	Absolute flexion force (ABS FF) in N Absolute extension force (ABS EF) in N Relative flexion force (REL FF) in N/kg Relative extension force (REL EF) in N/kg Ratio of absolute flexion to extension force (FLE:EXT R) Core leg strength ratio (CS:LS R)	Strength
CMJ	Counter movement jump	Jump height in cm	Explosive strength
SCMJ	Specific counter movement jump	Jump height in cm	Explosive strength
DJ	Drop jump	Jump height in cm Contact time in ms Reactive strength index (RSI) in mm/ms	Reactive strength
SET	Strength endurance test	Number of jumps	Strength endurance
LRT	Line run test	Line run test index (LRTI)	Endurance
CT	Cooper test	Total distance in m	Endurance

core strength was predictive of increased ACL injury risk in young competitive ski racers. To our knowledge, this is the first study that examined modifiable risk factors in young ski racers to prevent ACL injuries.

Incidence of ACL injuries

During the time period from 1996 to 2006, a total of 57 ACL injuries were documented in the alpine ski team of the Skigymnasium Stams. We cannot provide information regarding the mechanism and inciting event of each injury, but all of the

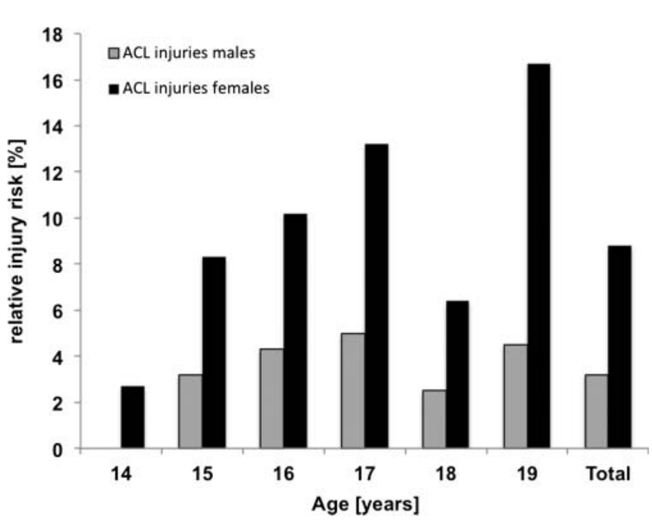

Figure 1 Anterior cruciate ligament injury rate by gender and age group. ACL, anterior cruciate ligament.

Table 4 Physical parameters of injured and non-injured male athletes

Fitness parameter	Age / ACL / N	14 Injured 0	14 Non-injured 41	15 Injured 4	15 Non-injured 33	16 Injured 5	16 Non-injured 33	17 Injured 5	17 Non-injured 28	18 Injured 2	18 Non-injured 26	19 Injured 2	19 Non-injured 16
FLE:EXT R (Index)	Mean±SD	No ACL injuries		0.79 (±0.09)	0.95 (±0.20)	0.83 (±0.23)	0.94 (±0.18)	0.65 (±0.14)	0.92 (±0.17)	0.99 (±0.16)	0.95 (±0.19)	1.10 (±0.20)	0.91 (±0.17)
	Minimum			0.68	0.57	0.64	0.55	0.51	0.57	0.88	0.61	0.90	0.61
	Maximum			0.89	1.76	1,16	1.46	0.84	1.34	1.11	1.79	1.20	1.31
REL FF and REL EF (N/kg)	Mean±SD			27.88 (± 8.38)	30.69 (±6.20)	29.81 (±4.92)	32.58 (±5.46)	33.88 (±8.08)	34.02 (±5.97)	33.27 (±2.72)	34.69 (±6.71)	28.12 (±4.61)	36.26 (±6.46)
	Minimum			23.03	16.58	22.12	22.47	25.97	21.41	31.34	20.39	24.80	24.77
	Maximum			40.38	47.97	34.34	48.44	47.18	50.92	35.19	51.98	31.32	56.35
RSI (mm/ms)	Mean±SD			1.33 (±0.36)	1.71 (±0.36)	1.73 (±0.40)	1.84 (±0.31)	1.87 (±0.36)	1.94 (±0.35)	1.76 (±0.08)	2.03 (±0.34)	2.10 (±0.24)	2.05 (±0.39)
	Minimum			0.81	0.99	1.31	1.22	1.46	1.15	1.71	1.26	1.97	1.34
	Maximum			1.62	2.76	2.23	2.60	2.36	2.81	1.82	2.99	2.34	3.41

ACL, anterior cruciate ligament; FLE:EXT R, ratio of absolute flexion to extension force; REL EF, relative extension force; REL FF, relative flexion force; RSI, reactive strength index.

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Table 5 Physical parameters of injured and non-injured female athletes

Fitness parameter	Age ACL N	14 Injured 2	14 Non-injured 33	15 Injured 9	15 Non-injured 29	16 Injured 10	16 Non-injured 26	17 Injured 10	17 Non-injured 23	18 Injured 4	18 Non-injured 15	19 Injured 4	19 Non-injured 10
ABS FF and ABS EF (N)	Mean	1487	1557	1513	1677	1767	1750	1582	1923	1373	1863	2204	1823
	±SD	(±325)	(±398)	(±350)	(±395)	(±335)	(±372)	(±196)	(±389)	(±131)	(±367)	(±239)	(±335)
	Minimum	1257	692	905	845	1470	979	1112	1230	1226	1249	1976	1256
	Maximum	1716	2500	1930	3018	2599	3244	1790	2975	1513	2782	2452	2801

ACL, anterior cruciate ligament; ABS EF, absolute extension force; ABS FF, absolute flexion force.

ACL injuries occurred during alpine skiing, either during training or competition.

The findings of this study suggest that ACL injury risk during alpine ski racing is twice as high in young females as in young males. We could not provide detailed information about gender differences in exposure between males and females; but it is assumed that training and competition volumes are similar due to the unique boarding school and the talent development system of the Austrian Ski Association.

It is well known that in pivoting sports, the risk of sustaining an ACL injury is fourfold to sixfold higher in females compared to males, independent of the age of the athletes.[14 23] However, in competitive alpine ski racing, information regarding the gender-specific RR is conflicting. Two studies from Florenes *et al*[3] and Pujol *et al*,[5] which investigated the incidence of ACL injuries among highly competitive alpine skiers, found no significant difference between men and women. In contrast, other studies reported a higher incidence of ACL injuries in female skiers.[15 16 24] Likewise, Johnson[25] reported results similar to our findings in competitive female skiers. Compared to pivoting sports, alpine skiing events are more influenced by factors such as weather and snow conditions, which can increase the technical demands placed on athletes. We believe that these conditions overrule gender-specific risk factors such as anatomical differences and hormonal influences.

The results of the present study showed that the 17-year-old and 19-year-old age groups in both female and male skiers had the highest ACL injury risk, whereas there were no injuries in males and few injuries in females in the 14-year-old group. It can be assumed that all athletes in the various age groups have similar equipment (boots, bindings and skis). However, there are differences for the youngest ski racers in exposure and therefore ACL injury risk. The 14-year-old athletes participate predominantly in Austrian competitions, whereas the older athletes compete in international events such as FIS races. The older racers also ski more races, up to 45 per season, on more difficult ski runs which increase the injury risk.

The current study provides epidemiological incidence proportions as the most basic expression of risk instead of an incidence rate that takes the time at risk into account. Even though this proportion is a valid estimator of average injury risk, it does not account for the potential variance in exposure.[26] However, given the unique sample cohort it can be assumed that the exposure did not differ between genders and athletes over 14 years of age. The school timetable was adapted to winter ski racing and training schedule. Classes were interrupted for 4 days every other week to accommodate ski training camps between October and December. During the racing season (between December and the end of March) classes in some cases did not take place at all. These conditions applied for all athletes.

Another reason why younger athletes experienced fewer ACL injuries than older athletes was the disciplines in which they raced. All age groups must compete in technical and speed disciplines; however, older athletes race more downhill and Super G. Previous studies have shown that the injury risk increased with event speed and was greatest in downhill events.[16 27] In this study, there were fewer ACL injuries within the 18-year-old male and female racers. This phenomenon may be the result of a higher dropout rate from high-level competitions. In many cases, 17-year-old skiers are attempting to qualify for the junior national team. Those who do not qualify often drop out of the high-performance racing groups. They remain in Stams to finish their school programme, and most continue to attend the normal ski training and physical testing. However, they race less and therefore have a lower risk of sustaining an injury.

Modifiable risk factors of ACL injuries

Based on a comprehensive model of injury causation, Bahr and Krosshaug[11] emphasised the need to identify the inciting event that leads to an injury situation.

Several mechanisms have been described which cause ACL injuries in skiers. In alpine skiing, the boot-induced anterior drawer mechanism is well known as one of the main causes of ACL ruptures.[28] A recent study from Bere *et al*,[27] who investigated the mechanism of ACL injuries in World Cup alpine skiers, showed that the slip-catch situation is the main mechanism of ACL injuries. However, internal risk factors need to be identified as well. Competitive alpine skiing requires a variety of qualities for both success and injury prevention. Several physiological and physical variables, such as muscle strength, aerobic and anaerobic power, coordination, flexibility and the ability to sustain stress, are required.[29] Carter and Micheli stated in their review that poor physical fitness in youth athletes is a risk factor for sports-related injuries.[13] Hergenroeder outlined the importance of a pre-season physical examination to detect conditions that may pre-dispose athletes to injury.[30] This study provides an overview of multiple physical fitness parameters which can contribute to developing risk profiles for ACL injuries. The results of regular testing can be used to detect deficits and enhance awareness not only for the athletes but also for coaches and parents.

It appears that ACL injury risk factors were more specific in male athletes, where more risk factors were observed when comparing fitness parameters of injured and non-injured racers. However, irrespective of gender, core strength seems to be a critical factor for preventing ACL injuries in young competitive skiers.

The leg and core muscles control the ski racing stance, minimising valgus knee loading and thus reducing dangerous knee torque.[31] Leg and core strength imbalances have been proposed as a knee injury risk factor.[32 33] In particular, the ratio of hamstring muscle strength to quadriceps muscle strength (HQ ratio) is often discussed as a potential ACL injury risk factor.[34 35] In our testing protocol, the maximal isometric leg extension strength was measured in a closed kinetic chain, precluding determination of the HQ ratio.

The findings of the present study revealed core strength imbalance as an ACL injury risk factor. The index of the ratio of absolute flexion to extension force was between 0.91 and 0.95 in the non-injured group. Male athletes who sustained an ACL injury showed either much higher mean values (1.10), indicating the presence of trunk flexors that were too strong, or lower values (0.65), indicating weak trunk extensor muscles. To date, there is no evidence that the core muscle ratio is a risk factor for knee injuries. However, good strength balance is important for maintaining a central position on the skis to prevent critical injury. Furthermore, it has been stated that decreased core stability may predispose athletes to knee injuries. Leeturn *et al*[3] noted that poor core stability and strength contribute to lower extremity injuries in female athletes.[36] Likewise, Willson *et al*[37] suggested that decreased core stability may predispose injury. The present study identified low core strength in both male and female injured skiers. The 19-year-old injured male skiers, in particular, showed a low relative core strength compared to their non-injured counterparts. It can be assumed that decreased core strength may contribute to an increased tendency towards valgus collapse, leading to an instable knee position during skiing and landing.[38] Knowing that core strength is a critical factor in preventing injuries, targeted preventative training programmes must include specific core strength training.[39] Next to muscle strength, neuromuscular deficits have been documented as factors contributing to ACL injuries.[38 40] Zazulak[41] investigated neuromuscular trunk control in 277 collegiate athletes and reported that a deficit was a significant predictor of knee injuries in female athletes. The trunk displacement was measured following a sudden force release. Alpine ski racers must also absorb sudden forces acting on the body. Findings of our study therefore suggest that high ground reaction forces coupled with sudden variations in postural stability may lead to a higher risk of lower-extremity injury.

Additionally, the lower reactive strength index in the injured male group likely indicates lower stretch shortening cycle activities that may be due to a higher muscular latency and therefore poorer neuromuscular activity.

Regular physical testing of the athletes allowed us to establish a long-term profile of several motor abilities. The failure to demonstrate statistical significance for other tested physical parameters may be due to the lack of sufficient statistical power given the low number of ACL injuries. The statistical model that was used to predict risk factors was highly specific, with a 100% correct prediction of uninjured male athletes and a 95% correct prediction of uninjured female athletes. However, it must be taken into consideration that the analyses accounted only for 36.8% and 23.6% of the variability in injured male and female skiers, respectively; therefore, they lack sensitivity. This allows us to draw the conclusion that there are further contributing risk factors that were not analysed in this study. For example, poor balance ability has been significantly associated with an increased risk of knee injuries in a number of sports.[42] Therefore, balance testing should be included in future studies.

Furthermore, Bahr and Krosshaug[11] emphasised the need to use a multifactorial approach to account for all the factors involved. One approach is to conceptualise the risk factors based on whether they are modifiable. Especially in young athletes, the determination of modifiable risk factors is of great interest in terms of developing long-term intervention programmes and thus providing better possibilities for a successful ski-racing career. Based on the epidemiological model of

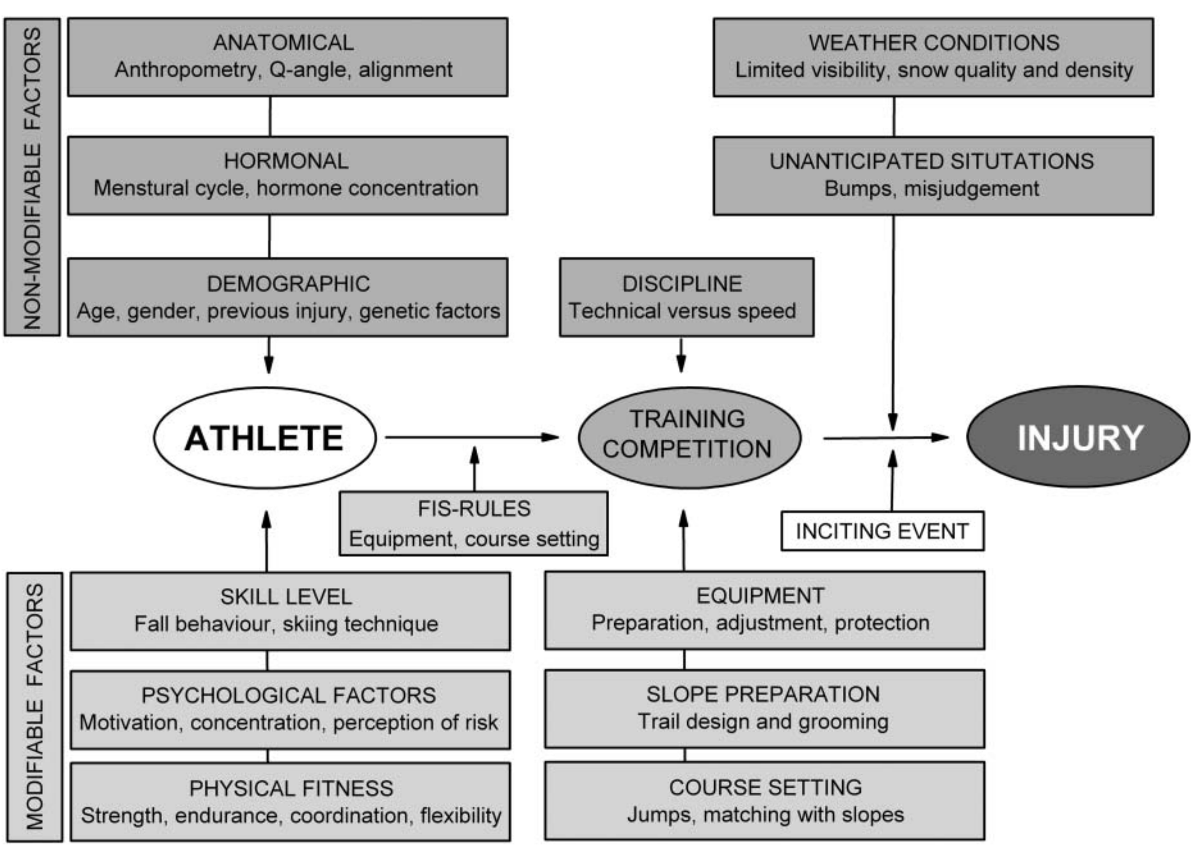

Figure 2 Sport-specific model of risk factors in alpine skiing (according to Meeuwisse[43]).

Meeuwisse[43] and the comprehensive model of Bahr and Krosshaug[11] we modified a sport-specific model as a base for further investigations (figure 2).

CONCLUSION

This study contributes to the current knowledge of physical fitness as a modifiable ACL injury risk factor by identifying one main risk factor in young ski racers: core strength deficit. Coaches must understand the importance of core training and the strength and neuromuscular aspects of core training. The current findings provide evidence that the ACL injury risk was greater in female ski racers. To further establish the cause-and-effect relationship between modifiable risk factors, gender-related aspects and injury in young alpine skiers, long-term prospective studies need to be conducted.

To satisfy the framework stated by Finch for translating research into injury prevention practice, training programmes that target modifiable risk factors need to be investigated and evaluated.[44]

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